

# VAMP, Version 1.0: Vegas AMPlified: Anisotropy, Multi-channel sampling and Parallelization

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## **Abstract**

We present an new implementation of the classic Vegas algorithm for adaptive multi-dimensional Monte Carlo integration in Fortran95. This implementation improves the performance for a large class of integrands, supporting stratified sampling in higher dimensions through automatic identification of the directions of largest variation. This implementation also supports multi channel sampling with individual adaptive grids. Sampling can be performed in parallel on workstation clusters and other parallel hardware. Note that for maintenance of the code, and especially its usage within the event generator WHIZARD, some features of Fortran2003 have been added.

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## *Program Summary:*

- **Title of program:** VAMP, Version 1.0 (October 1999)
- **Program obtainable** by anonymous `ftp` from the host `crunch.ikp.physik.th-darmstadt.de` in the directory `pub/ohl/vamp`.
- **Licensing provisions:** Free software under the GNU General Public License.
- **Programming language used:** From version 2.2.0 of the program: Fortran2003 [8] Until version 2.1.x of the program: Fortran95 [9] (Fortran90 [7] and F [14] versions available as well)
- **Number of program lines in distributed program, including test data, etc.:**  $\approx 4300$  (excluding comments)
- **Computer/Operating System:** Any with a Fortran95 (or Fortran90 or F) programming environment.
- **Memory required to execute with typical data:** Negligible on the scale of typical applications calling the library.
- **Typical running time:** A small fraction (typically a few percent) of the running time of applications calling the library.
- **Purpose of program:**
- **Nature of physical problem:**
- **Method of solution:**
- **Keywords:** adaptive integration, event generation, parallel processing

# —1—

## INTRODUCTION

We present a reimplementation of the classic Vegas [1, 2] algorithm for adaptive multi-dimensional integration in Fortran95 [9, 13]<sup>1</sup> (Note that for the maintenance of the program and especially its usage within the event generator WHIZARD parts of the program have been adapted to Fortran2003). The purpose of this reimplementation is two-fold: for pedagogical reasons it is useful to employ Fortran95 features (in particular the array language) together with literate programming [4] for expressing the algorithm more concisely and more transparently. On the other hand we use a Fortran95 abstract type to separate the state from the functions. This allows multiple instances of Vegas with different adaptations to run in parallel and in paves the road for a more parallelizable implementation.

The variable names are more in line with [1] than with [2] or with [17, 18, 19], which is almost identical to [2].

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    !
```

---

<sup>1</sup>Fully functional versions conforming to preceeding Fortran standard [7], High Performance Fortran (HPF) [10, 11, 15], and to the Fortran90 subset F [14] are available as well. A translation to the obsolete FORTRAN77 standard [6] is possible in principle, but extremely tedious and error prone if the full functionality shall be preserved.

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! contain the documentation in full detail.  
!!

## —2— ALGORITHMS

 The notation has to be synchronized with [3]!

We establish some notation to allow a concise discussion. Notation:

$$\text{expectation: } E(f) = \frac{1}{|\mathcal{D}|} \int_{\mathcal{D}} dx f(x) \quad (2.1a)$$

$$\text{variance: } V(f) = E(f^2) - (E(f))^2 \quad (2.1b)$$

$$\text{estimate of expectation (average): } \langle X|f \rangle = \frac{1}{|X|} \sum_{x \in X} f(x) \quad (2.1c)$$

$$\text{estimate of variance: } \sigma_X^2(f) = \frac{1}{|X| - 1} (\langle X|f^2 \rangle - \langle X|f \rangle^2) \quad (2.1d)$$

Where  $|X|$  is the size of the point set and  $|\mathcal{D}| = \int_{\mathcal{D}} dx$  the size of the integration region. If  $\mathcal{E}(\langle f \rangle)$  denotes the ensemble average of  $\langle X|f \rangle$  over random point sets  $X$  with  $|X| = N$ , we have for expectation and variance

$$\mathcal{E}(\langle f \rangle) = E(f) \quad (2.2a)$$

$$\mathcal{E}(\sigma^2(f)) = V(f) \quad (2.2b)$$

and the ensemble variance of the expectation is also given by the variance

$$\mathcal{V}(\langle f \rangle) = \frac{1}{N} V(f) \quad (2.2c)$$

Therefore, it can be estimated from  $\sigma_X^2(f)$ . Below, we will also use the notation  $\mathcal{E}_g$  for the ensemble average over random point sets  $X_g$  with probability distribution  $g$ . We will write  $E_g(f) = E(fg)$  as well.

## 2.1 Importance Sampling

If, instead of uniformly distributed points  $X$ , we use points  $X_g$  distributed according to a probability density  $g$ , we can easily keep the expectation constant

$$\mathcal{E}_g(\langle f \rangle) = E_g \left( \frac{f}{g} \right) = E(f) \quad (2.3)$$

while the variance transforms non-trivially

$$\mathcal{V}_g(\langle f \rangle) = \frac{1}{N} V_g \left( \frac{f}{g} \right) = \frac{1}{N} \left( E_g \left( \frac{f^2}{g^2} \right) - \left( E_g \left( \frac{f}{g} \right) \right)^2 \right) \quad (2.4)$$

and the error is minimized when  $f/g$  is constant, i.e.  $g$  is a good approximation of  $f$ . The non-trivial problem is to find a  $g$  that can be generated efficiently and is a good approximation at the same time.

One of the more popular approaches is to use a mapping  $\phi$  of the integration domain

$$\begin{aligned} \phi : \mathcal{D} &\rightarrow \Delta \\ x &\mapsto \xi = \phi(x) \end{aligned} \quad (2.5)$$

In the new coordinates, the distribution is multiplied by the Jacobian of the inverse map  $\phi^{-1}$ :

$$\int_{\mathcal{D}} dx f(\phi(x)) = \int_{\Delta} d\xi J_{\phi^{-1}}(\xi) f(\xi) \quad (2.6)$$

A familiar example is given by the map

$$\begin{aligned} \phi : [0, 1] &\rightarrow \mathbf{R} \\ x &\mapsto \xi = x^0 + a \cdot \tan \left( \left( x - \frac{1}{2} \right) \pi \right) \end{aligned} \quad (2.7)$$

with the inverse  $\phi^{-1}(\xi) = \text{atan}((\xi - x_0)/a)/\pi + 1/2$  and the corresponding Jacobian reproducing a resonance

$$J_{\phi^{-1}}(\xi) = \frac{d\phi^{-1}(\xi)}{d\xi} = \frac{a}{\pi} \frac{1}{(\xi - x^0)^2 + a^2} \quad (2.8)$$

Obviously, this works only for a few special distributions. Fortunately, we can combine several of these mappings to build efficient integration algorithms, as will be explained in section 2.4 below. Another approach is to construct the approximation numerically, by appropriate binning of the integration domain (cf. [1, 2, 20]). The most popular technique for this will be discussed below in section 2.3.

## 2.2 Stratified Sampling

The technique of importance sampling concentrates the sampling points in the region where the contribution to the integrand is largest. Alternatively we can also concentrate the sampling points in the region where the contribution to the variance is largest.

If we divide the sampling region  $\mathcal{D}$  into  $n$  disjoint subregions  $\mathcal{D}^i$

$$\mathcal{D} = \bigcup_{i=1}^n \mathcal{D}^i, \quad \mathcal{D}^i \cap \mathcal{D}^j = \emptyset \quad (i \neq j) \quad (2.9)$$

a new estimator is

 Bzzzt! Wrong. These multi-channel formulae are incorrect for partitionings and must be fixed.

$$\overline{\langle X|f \rangle} = \sum_{i=1}^n \frac{N_i}{N} \langle X_{\theta_i} | f \rangle \quad (2.10)$$

where

$$\theta_i(x) = \begin{cases} 1 & \text{for } x \in \mathcal{D}^i \\ 0 & \text{for } x \notin \mathcal{D}^i \end{cases} \quad (2.11)$$

and

$$\sum_{i=1}^n N_i = N \quad (2.12)$$

since the expectation is linear

$$\mathcal{E}(\overline{\langle f \rangle}) = \sum_{i=1}^n \frac{N_i}{N} \mathcal{E}_{\theta_i}(\langle f \rangle) = \sum_{i=1}^n \frac{N_i}{N} E_{\theta_i}(f) = \sum_{i=1}^n \frac{N_i}{N} E(f\theta_i) = E(f) \quad (2.13)$$

On the other hand, the variance of the estimator  $\overline{\langle X|f \rangle}$  is

$$\mathcal{V}(\overline{\langle f \rangle}) = \sum_{i=1}^n \frac{N_i}{N} \mathcal{V}_{\theta_i}(\langle f \rangle) \quad (2.14)$$

This is minimized for

$$N_i \propto \sqrt{V(f \cdot \theta_{\mathcal{D}^i})} \quad (2.15)$$

as a simple variation of  $\mathcal{V}(\overline{\langle f \rangle})$  shows.



Figure 2.1: **vegas** grid structure for non-stratified sampling (left) and for genuinely stratified sampling (right), which is used in low dimensions. N.B.: the grid and the weight functions  $p_{1,2}$  are only in qualitative agreement.



Figure 2.2: One-dimensional illustration of the **vegas** grid structure for pseudo stratified sampling, which is used in high dimensions.

## 2.3 Vegas

Under construction!

### 2.3.1 Vegas' Inflexibility

The classic implementation of the Vegas algorithm [1, 2] treats all dimensions alike. This constraint allows a very concise FORTRAN77-style coding of the algorithm, but there is no theoretical reason for having the same number of divisions in each direction. On the contrary, under these circumstances, even a dimension in which the integrand is rather smooth will contribute to the exponential blow-up of cells for stratified sampling. It is obviously beneficial to use a finer grid in those directions in which the fluctuations are stronger, while a coarser grid will suffice in the other directions.

One small step along this line is implemented in Version 5.0 of the package `BASES/SPRING` [20], where one set of “wild” variables is separated from “smooth” variables [21].

The present reimplementaion of the Vegas algorithm allows the application to choose the number of divisions in each direction freely. The routines that reshape the grid accept an integer array with the number of divisions as an optional argument `num_div`. It is easy to construct examples in which the careful use of this feature reduces the variance significantly.

Currently, no attempt is made for automatic optimization of the number of divisions. One reasonable approach is to monitor Vegas’ grid adjustments and to increase the number of division in those directions where Vegas’ keeps adjusting because of fluctuations. For each direction, a numerical measure of these fluctuations is given by the spread in the  $m_i$ . The total number of cells can be kept constant by reducing the number of divisions in the other directions appropriately. Thus

$$n_{\text{div},j} \rightarrow \frac{Q_j n_{\text{div},j}}{\left(\prod_j Q_j\right)^{1/n_{\text{dim}}}} \quad (2.16)$$

where we have used the damped standard deviation

$$Q_j = \left( \sqrt{\text{Var}(\{m\}_j)} \right)^\alpha \quad (2.17)$$

instead of the spread.

### 2.3.2 Vegas’ Dark Side



Under construction!

A partial solution of this problem will be presented in section 2.5.

## 2.4 Multi Channel Sampling

Even if Vegas performs well for a large class of integrands, many important applications do not lead to a factorizable distribution. The class of integrands that can be integrated efficiently by Vegas can be enlarged substantially by using multi channel methods. The new class will include almost all integrals appearing in high energy physics simulations.



The first version of this section is now obsolete. Consult [3] instead.



## 2.5 *Revolving*



Under construction!

## 2.6 *Parallelization*

Traditionally, parallel processing has not played a large rôle in simulations for high energy physics. A natural and trivial method of utilizing many processors will run many instances of the same (serial) program with different values of the input parameters in parallel. Typical matrix elements and phase space integrals offer few opportunities for small scale parallelization.

On the other hand, parameter fitting has become possible recently for observables involving a phase space integration. In this case, fast evaluation of the integral is essential and parallel execution becomes an interesting option.

A different approach to parallelizing Vegas has been presented recently [22].

### 2.6.1 *Multilinear Structure of the Sampling Algorithm*

In order to discuss the problems with parallelizing adaptive integration algorithms and to present solutions, it helps to introduce some mathematical notation. A sampling  $S$  is a map from the space  $\pi$  of point sets and the space  $F$  of functions to the real (or complex) numbers

$$\begin{aligned} S : \pi \times F &\rightarrow \mathbf{R} \\ (p, f) &\mapsto I = S(p, f) \end{aligned}$$

For our purposes, we have to be more specific about the nature of the point set. In general, the point set will be characterized by a sequence of pseudo random numbers  $\rho \in R$  and by one or more grids  $G \in \Gamma$  used for importance or stratified sampling. A simple sampling

$$\begin{aligned} S_0 : R \times \Gamma \times A \times F \times \mathbf{R} \times \mathbf{R} &\rightarrow R \times \Gamma \times A \times F \times \mathbf{R} \times \mathbf{R} \\ (\rho, G, a, f, \mu_1, \mu_2) &\mapsto (\rho', G, a', f, \mu'_1, \mu'_2) = S_0(\rho, G, a, f, \mu_1, \mu_2) \end{aligned} \tag{2.18}$$

estimates the  $n$ -th moments  $\mu'_n \in \mathbf{R}$  of the function  $f \in F$ . The integral and its standard deviation can be derived easily from the moments

$$I = \mu_1 \tag{2.19a}$$

$$\sigma^2 = \frac{1}{N-1} (\mu_2 - \mu_1^2) \tag{2.19b}$$

while the latter are more convenient for the following discussion. In addition,  $S_0$  collects auxiliary information to be used in the grid refinement, denoted by  $a \in A$ . The unchanged arguments  $G$  and  $f$  have been added to the result of  $S_0$  in (2.18), so that  $S_0$  has identical domain and codomain and can therefore be iterated. Previous estimates  $\mu_n$  may be used in the estimation of  $\mu'_n$ , but a particular  $S_0$  is free to ignore them as well. Using a little notational freedom, we augment  $\mathbf{R}$  and  $A$  with a special value  $\cdot$ , which will always be discarded by  $S_0$ .

In an adaptive integration algorithm, there is also a refinement operation  $r : \Gamma \times A \rightarrow \Gamma$  that can be extended naturally to the codomain of  $S_0$

$$\begin{aligned} r : R \times \Gamma \times A \times F \times \mathbf{R} \times \mathbf{R} &\rightarrow R \times \Gamma \times A \times F \times \mathbf{R} \times \mathbf{R} \\ (\rho, G, a, f, \mu_1, \mu_2) &\mapsto (\rho, G', a, f, \mu_1, \mu_2) = r(\rho, G, a, f, \mu_1, \mu_2) \end{aligned} \quad (2.20)$$

so that  $S = rS_0$  is well defined and we can specify  $n$ -step adaptive sampling as

$$S_n = S_0(rS_0)^n \quad (2.21)$$

Since, in a typical application, only the estimate of the integral and the standard deviation are used, a projection can be applied to the result of  $S_n$ :

$$\begin{aligned} P : R \times \Gamma \times A \times F \times \mathbf{R} \times \mathbf{R} &\rightarrow \mathbf{R} \times \mathbf{R} \\ (\rho, G, a, f, \mu_1, \mu_2) &\mapsto (I, \sigma) \end{aligned} \quad (2.22)$$

Then

$$(I, \sigma) = PS_0(rS_0)^n(\rho, G_0, \cdot, f, \cdot, \cdot) \quad (2.23)$$

and a good refinement prescription  $r$ , such as Vegas, will minimize the  $\sigma$ .

For parallelization, it is crucial to find a division of  $S_n$  or any part of it into *independent* pieces that can be evaluated in parallel. In order to be effective,  $r$  has to be applied to *all* of  $a$  and therefore a synchronization of  $G$  before and after  $r$  is appropriately. Furthermore,  $r$  usually uses only a tiny fraction of the CPU time and it makes little sense to invest a lot of effort into parallelizing it beyond what the Fortran compiler can infer from array notation. On the other hand,  $S_0$  can be parallelized naturally, because all operations are linear, including the computation of  $a$ . We only have to make sure that the cost of communicating the results of  $S_0$  and  $r$  back and forth during the computation of  $S_n$  do not offset any performance gain from parallel processing.

When we construct a decomposition of  $S_0$  and prove that it does not change the results, i.e.

$$S_0 = \iota S_0 \phi \quad (2.24)$$

where  $\phi$  is a forking operation and  $\iota$  is a joining operation, we are faced with the technical problem of a parallel random number source  $\rho$ . As made explicit in (2.18),  $S_0$  changes the state of the random number general  $\rho$ , demanding *identical* results therefore imposes a strict ordering on the operations and defeats parallelization. It is possible to devise implementations of  $S_0$  and  $\rho$  that circumvent this problem by distributing subsequences of  $\rho$  in such a way among processes that results do not depend on the number of parallel processes.

However, a reordering of the random number sequence will only change the result by the statistical error, as long as the scale of the allowed reorderings is *bounded* and much smaller than the period of the random number generator<sup>1</sup> Below, we will therefore use the notation  $x \approx y$  for “equal for an appropriate finite reordering of the  $\rho$  used in calculating  $x$  and  $y$ ”. For our purposes, the relation  $x \approx y$  is strong enough and allows simple and efficient implementations.

Since  $S_0$  is essentially a summation, it is natural to expect a linear structure

$$\bigoplus_i S_0(\rho_i, G_i, a_i, f, \mu_{1,i}, \mu_{2,i}) \approx S_0(\rho, G, a, f, \mu_1, \mu_2) \quad (2.25a)$$

where

$$\rho = \bigoplus_i \rho_i \quad (2.25b)$$

$$G = \bigoplus_i G_i \quad (2.25c)$$

$$a = \bigoplus_i a_i \quad (2.25d)$$

$$\mu_n = \bigoplus_i \mu_{n,i} \quad (2.25e)$$

for appropriate definitions of “ $\oplus$ ”. For the moments, we have standard addition

$$\mu_{n,1} \oplus \mu_{n,2} = \mu_{n,1} + \mu_{n,2} \quad (2.26)$$

and since we only demand equality up to reordering, we only need that the  $\rho_i$  are statistically independent. This leaves us with  $G$  and  $a$  and we have to discuss importance sampling and stratified sampling separately.

---

<sup>1</sup>Arbitrary reorderings on the scale of the period of the random number generators could select constant sequences and have to be forbidden.

### *Importance Sampling*

In the case of naive Monte Carlo and importance sampling the natural decomposition of  $G$  is to take  $j$  copies of the same grid  $G/j$  which is identical to  $G$ , each with one  $j$ -th of the total sampling points. As long as the  $a$  are linear themselves, we can add them up just like the moments

$$a_1 \oplus a_2 = a_1 + a_2 \quad (2.27)$$

and we have found a decomposition (2.25). In the case of Vegas, the  $a_i$  are sums of function values at the sampling points. Thus they are obviously linear and this approach is applicable to Vegas in the importance sampling mode.

### *Stratified Sampling*

The situation is more complicated in the case of stratified sampling. The first complication is that in pure stratified sampling there are only two sampling points per cell. Splitting the grid in two pieces as above provide only a very limited amount of parallelization. The second complication is that the  $a$  are no longer linear, since they correspond to a sampling of the variance per cell and no longer of function values themselves.

However, as long as the samplings contribute to disjoint bins only, we can still “add” the variances by combining bins. The solution is therefore to divide the grid into disjoint bins along the divisions of the stratification grid and to assign a set of bins to each processor.

Finer decompositions will incur higher communications costs and other resource utilization. An implementation based on PVM is described in [22], which minimizes the overhead by running identical copies of the grid  $G$  on each processor. Since most of the time is usually spent in function evaluations, it makes sense to run a full  $S_0$  on each processor, skipping function evaluations everywhere but in the region assigned to the processor. This is a neat trick, which is unfortunately tied to the computational model of message passing systems such as PVM and MPI [12]. More general paradigms can not be supported since the separation of the state for the processors is not explicit (it is implicit in the separated address space of the PVM or MPI processes).

However, it is possible to implement (2.25) directly in an efficient manner. This is based on the observation that the grid  $G$  used by Vegas is factorized into divisions  $D^j$  for each dimension

$$G = \bigotimes_{j=1}^{n_{\text{dim}}} D^j \quad (2.28)$$

and decompositions of the  $D^j$  induce decompositions of  $G$

$$\begin{aligned} G_1 \oplus G_2 &= \left( \bigotimes_{j=1}^{i-1} D^j \otimes D_1^i \otimes \bigotimes_{i=j+1}^{n_{\text{dim}}} D^j \right) \oplus \left( \bigotimes_{j=1}^{i-1} D^j \otimes D_2^i \otimes \bigotimes_{i=j+1}^{n_{\text{dim}}} D^j \right) \\ &= \bigotimes_{j=1}^{i-1} D^j \otimes (D_1^i \oplus D_2^i) \otimes \bigotimes_{j=i+1}^{n_{\text{dim}}} D^j \quad (2.29) \end{aligned}$$

We can translate (2.29) directly to code that performs the decomposition  $D^i = D_1^i \oplus D_2^i$  discussed below and simply duplicates the other divisions  $D^{j \neq i}$ . A decomposition along multiple dimensions is implemented by a recursive application of (2.29).

In Vegas, the auxiliary information  $a$  inherits a factorization similar to the grid (2.28)

$$a = (d^1, \dots, d^{n_{\text{dim}}}) \quad (2.30)$$

but not a multilinear structure. Instead, *as long as the decomposition respects the stratification grid*, we find the in place of (2.29)

$$a_1 \oplus a_2 = (d_1^1 + d_2^1, \dots, d_1^i \oplus d_2^i, \dots, d_1^{n_{\text{dim}}} + d_2^{n_{\text{dim}}}) \quad (2.31)$$

with “+” denoting the standard addition of the bin contents and “ $\oplus$ ” denoting the aggregation of disjoint bins. If the decomposition of the division would break up cells of the stratification grid (2.31) would be incorrect, because, as discussed above, the variance is not linear.

Now it remains to find a decomposition

$$D^i = D_1^i \oplus D_2^i \quad (2.32)$$

for both the pure stratification mode and the pseudo stratification mode of vegas (cf. figure 2.1). In the pure stratification mode, the stratification grid is strictly finer than the adaptive grid and we can decompose along either of them immediately. Technically, a decomposition along the coarser of the two is straightforward. Since the adaptive grid already has more than 25 bins, a decomposition along the stratification grid makes no practical sense and the decomposition along the adaptive grid has been implemented. The sampling algorithm  $S_0$  can be applied *unchanged* to the individual grids resulting from the decomposition.

For pseudo stratified sampling (cf. figure 2.2), the situation is more complicated, because the adaptive and the stratification grid do not share bin boundaries. Since Vegas does *not* use the variance in this mode, it would be theoretically possible to decompose along the adaptive grid and to mimic the



Figure 2.3: Forking one dimension  $d$  of a grid into three parts  $ds(1)$ ,  $ds(2)$ , and  $ds(3)$ . The picture illustrates the most complex case of pseudo stratified sampling (cf. fig. 2.2).

incomplete bins of the stratification grid in the sampling algorithm. However, this would be a technical complication, destroying the universality of  $S_0$ . Therefore, the adaptive grid is subdivided in a first step in

$$\text{lcm} \left( \frac{\text{lcm}(n_f, n_g)}{n_f}, n_x \right) \quad (2.33)$$

bins,<sup>2</sup> such that the adaptive grid is strictly finer than the stratification grid. This procedure is shown in figure 2.3.

### 2.6.2 State and Message Passing

### 2.6.3 Random Numbers

In the parallel example sitting on top of MPI [12] takes advantage of the ability of Knuth's generator [16] to generate statistically independent subse-

<sup>2</sup>The coarsest grid covering the division of  $n_g$  bins into  $n_f$  forks has  $n_g / \text{gcd}(n_f, n_g) = \text{lcm}(n_f, n_g) / n_f$  bins per fork.

quences. However, since the state of the random number generator is explicit in all procedure calls, other means of obtaining subsequences can be implemented in a trivial wrapper.

The results of the parallel example will depend on the number of processors, because this effects the subsequences being used. Of course, the variation will be compatible with the statistical error. It must be stressed that the results are deterministic for a given number of processors and a given set of random number generator seeds. Since parallel computing environments allow to fix the number of processors, debugging of exceptional conditions is possible.

### 2.6.4 Practice

In this section we show three implementations of  $S_n$ : one serial, and two parallel, based on HPF [10, 11, 15] and MPI [12], respectively. From these examples, it should be obvious how to adapt VAMP to other parallel computing paradigms.

#### *Serial*

Here is a bare bones serial version of  $S_n$ , for comparison with the parallel versions below. The real implementation of `vamp_sample_grid` in the module `vamp` includes some error handling, diagnostics and the projection  $P$  (cf. (2.22)):

```
14  $\langle$ Serial implementation of  $S_n = S_0(rS_0)^n$  14 $\rangle \equiv$ 
  subroutine vamp_sample_grid (rng, g, iterations, func)
    type(tao_random_state), intent(inout) :: rng
    type(vamp_grid), intent(inout) :: g
    integer, intent(in) :: iterations
     $\langle$ Interface declaration for func 22 $\rangle$ 
    integer :: iteration
    iterate: do iteration = 1, iterations
      call vamp_sample_grid0 (rng, g, func)
      call vamp_refine_grid (g)
    end do iterate
  end subroutine vamp_sample_grid
```

#### *HPF*

The HPF version of  $S_n$  is based on decomposing the grid `g` as described in section 2.6.1 and lining up the components in an array `gs`. The elements of `gs` can then be processed in parallel. This version can be compiled with any

Fortran compiler and a more complete version of this procedure (including error handling, diagnostics and the projection  $P$ ) is included with VAMP as `vamp_sample_grid_parallel` in the module `vamp`. This way, the algorithm can be tested on a serial machine, but there will obviously be no performance gain.

Instead of one random number generator state `rng`, it takes an array consisting of one state per processor. These `rng(:)` are assumed to be initialized, such that the resulting sequences are statistically independent. For this purpose, Knuth's random number generator [16] is most convenient and is included with VAMP (see the example on page 16). Before each  $S_0$ , the procedure `vamp_distribute_work` determines a good decomposition of the grid `d` into `size(rng)` pieces. This decomposition is encoded in the array `d` where `d(1,:)` holds the dimensions along which to split the grid and `d(2,:)` holds the corresponding number of divisions. Using this information, the grid is decomposed by `vamp_fork_grid`. The HPF compiler will then distribute the `!hpf$ independent` loop among the processors. Finally, `vamp_join_grid` gathers the results.

```

15 <Parallel implementation of  $S_n = S_0(rS_0)^n$  (HPF) 15>≡
  subroutine vamp_sample_grid_hpf (rng, g, iterations, func)
    type(tao_random_state), dimension(:), intent(inout) :: rng
    type(vamp_grid), intent(inout) :: g
    integer, intent(in) :: iterations
    <Interface declaration for func 22>
    type(vamp_grid), dimension(:), allocatable :: gs, gx
    !hpf$ processors p(number_of_processors())
    !hpf$ distribute gs(cyclic(1)) onto p
    integer, dimension(:,:), pointer :: d
    integer :: iteration, num_workers
    iterate: do iteration = 1, iterations
      call vamp_distribute_work (size (rng), vamp_rigid_divisions (g), d)
      num_workers = max (1, product (d(2,:)))
      if (num_workers > 1) then
        allocate (gs(num_workers), gx(vamp_fork_grid_joints (d)))
        call vamp_create_empty_grid (gs)
        call vamp_fork_grid (g, gs, gx, d)
        !hpf$ independent
        do i = 1, num_workers
          call vamp_sample_grid0 (rng(i), gs(i), func)
        end do
        call vamp_join_grid (g, gs, gx, d)
        call vamp_delete_grid (gs)
        deallocate (gs, gx)
      end if
    end do
  end subroutine

```



```

        else
            call vamp_sample_grid0 (rng(1), g, func)
        end if
        call vamp_refine_grid (g)
    end do iterate
end subroutine vamp_sample_grid_hpf

```

Since `vamp_sample_grid0` performs the bulk of the computation, an almost linear speedup with the number of processors can be achieved, if `vamp_distribute_work` finds a good decomposition of the grid. The version of `vamp_distribute_work` distributed with VAMP does a good job in most cases, but will not be able to use all processors if their number is a prime number larger than the number of divisions in the stratification grid. Therefore it can be beneficial to tune `vamp_distribute_work` to specific hardware. Furthermore, using a finer stratification grid can improve performance.

For definiteness, here is an example of how to set up the array of random number generators for HPF. Note that this simple seeding procedure only guarantees statistically independent sequences with Knuth's random number generator [16] and will fail with other approaches.

```

16 <Parallel usage of  $S_n = S_0(rS_0)^n$  (HPF) 16>≡
    type(tao_random_state), dimension(:), allocatable :: rngs
    !hpf$ processors p(number_of_processors())
    !hpf$ distribute gs(cyclic(1)) onto p
    integer :: i, seed
    ! ...
    allocate (rngs(number_of_processors()))
    seed = 42 ! can be read from a file, of course ...
    !hpf$ independent
    do i = 1, size (rngs)
        call tao_random_create (rngs(i), seed + i)
    end do
    ! ...
    call vamp_sample_grid_hpf (rngs, g, 6, func)
    ! ...

```

## MPI

The MPI version is more low level, because we have to keep track of message passing ourselves. Note that we have made this synchronization points explicit with three `if ... then ... else ... end if` blocks: forking, sampling, and joining. These blocks could be merged (without any performance gain) at the expense of readability. We assume that `rng` has been initialized

in each process such that the sequences are again statistically independent.

17  $\langle$ Parallel implementation of  $S_n = S_0(rS_0)^n$  (MPI) 17 $\rangle \equiv$

```

subroutine vamp_sample_grid_mpi (rng, g, iterations, func)
  type(tao_random_state), dimension(:), intent(inout) :: rng
  type(vamp_grid), intent(inout) :: g
  integer, intent(in) :: iterations
   $\langle$ Interface declaration for func 22 $\rangle$ 
  type(vamp_grid), dimension(:), allocatable :: gs, gx
  integer, dimension(:,:), pointer :: d
  integer :: num_proc, proc_id, iteration, num_workers
  call mpi90_size (num_proc)
  call mpi90_rank (proc_id)
  iterate: do iteration = 1, iterations
    if (proc_id == 0) then
      call vamp_distribute_work (num_proc, vamp_rigid_divisions (g), d)
      num_workers = max (1, product (d(2,:)))
    end if
    call mpi90_broadcast (num_workers, 0)
    if (proc_id == 0) then
      allocate (gs(num_workers), gx(vamp_fork_grid_joints (d)))
      call vamp_create_empty_grid (gs)
      call vamp_fork_grid (g, gs, gx, d)
      do i = 2, num_workers
        call vamp_send_grid (gs(i), i-1, 0)
      end do
    else if (proc_id < num_workers) then
      call vamp_receive_grid (g, 0, 0)
    end if
    if (proc_id == 0) then
      if (num_workers > 1) then
        call vamp_sample_grid0 (rng, gs(1), func)
      else
        call vamp_sample_grid0 (rng, g, func)
      end if
    else if (proc_id < num_workers) then
      call vamp_sample_grid0 (rng, g, func)
    end if
    if (proc_id == 0) then
      do i = 2, num_workers
        call vamp_receive_grid (gs(i), i-1, 0)
      end do
      call vamp_join_grid (g, gs, gx, d)
      call vamp_delete_grid (gs)
    end if
  end do
end subroutine vamp_sample_grid_mpi

```

```

        deallocate (gs, gx)
        call vamp_refine_grid (g)
    else if (proc_id < num_workers) then
        call vamp_send_grid (g, 0, 0)
    end if
end do iterate
end subroutine vamp_sample_grid_mpi

```

A more complete version of this procedure is included with VAMP as well, this time as `vamp_sample_grid` in the MPI support module `vampi`.

# —3—

## DESIGN TRADE OFFS

There have been three competing design goals for vegas, that are not fully compatible and had to be reconciled with compromises:

- *Ease-Of-Use*: few procedures, few arguments.
- *Parallelizability*: statelessness
- *Performance and Flexibility*: rich interface, functionality.

In fact, parallelizability and ease-of-use are complementary. A parallelizable implementation has to expose *all* the internal state. In our case, this includes the state of the random number generator and the adaptive grid. A simple interface would hide such details from the user.

The modern language features introduced to Fortran in 1990 [7] allows to reconcile these competing goals. Two abstract data types `vamp.state` and `tao.random.state` hide the details of the implementation from the user and encapsulate the two states in just two variables.

Another problem with parallelizability arised from the lack of a general exception mechanism in Fortran. The Fortran90 standard [9] forbids *any* input/output (even to the terminal) as well as `stop` statements in parallelizable (`pure`) procedures. This precludes simple approaches to monitoring and error handling. In Vegas we use a simple hand crafted exception mechanism (see chapter B) for communicating error conditions to the out layers of the applications. Unfortunately this requires the explicit passing of state in argument lists.

An unfortunate consequence of the similar approach to monitoring is that monitoring is *not* possible during execution. Instead, intermediate results can only be examined after a parallelized section of code has completed.

### 3.1 *Programming Language*

We have chosen to implement VAMP in Fortran90/95, which some might consider a questionable choice today. Nevertheless, we are convinced that Fortran90/95 (with all its weaknesses) is, by a wide margin, the right tool for the job.

Let us consider the alternatives

- FORTRAN77 is still the dominant language in high energy physics and all running experiment's software environments are based on it. However, the standard [6] is obsolete now and the successors [7, 9] have added many desirable features, while retaining almost all of FORTRAN77 as a subset.
- C/C++ appears to be the most popular programming language in industry and among young high energy physicists. Large experiments have taken a bold move and are basing their software environment on C++.
- Typed higher order functional programming languages (ML, Haskell, etc.) are a very promising development. Unfortunately, there is not yet enough industry support for high performance optimizing compilers. While the performance penalty of these languages is not as high as commonly believed (research compilers, which do not perform extensive processor specific optimizations, result in code that runs by a factor of two or three slower than equivalent Fortran code), it is relevant for long running, computing intensive applications. In addition, these languages are syntactically and idiomatically very different from Fortran and C. Another implementation of VAMP in ML will be undertaken for research purposes to investigate new algorithms that can only be expressed awkwardly in Fortran, but we do not expect it to gain immediate popularity.

## —4— USAGE

### 4.1 Basic Usage

`type(vamp_grid)`

`subroutine vamp_create_grid (g, domain [, num_calls] [, exc])`

Create a fresh grid for the integration domain

$$\mathcal{D} = [D_{1,1}, D_{2,1}] \times [D_{1,2}, D_{2,2}] \times \dots \times [D_{1,n}, D_{2,n}] \quad (4.1)$$

dropping all accumulated results. This function *must not* be called twice on the first argument, without an intervening

`vamp_delete_grid`. Iff the variable `num_calls` is given, it will be the number of sampling points per iteration for the call to `vamp_sample_grid`.

`subroutine vamp_delete_grid (g [, exc])`

`subroutine vamp_discard_integral (g [, num_calls] [, exc])`

Keep the current optimized grid, but drop the accumulated results for the integral (value and errors). Iff the variable `num_calls` is given, it will be the new number of sampling points per iteration for the calls to `vamp_sample_grid`.

`subroutine vamp_reshape_grid (g [, num_calls] [, exc])`

Keep the current optimized grid and the accumulated results for the integral (value and errors). The variable `num_calls` is the new number of sampling points per iteration for the calls to `vamp_sample_grid`.

`subroutine vamp_sample_grid (rng, g, func, iterations  
[, integral] [, std_dev] [, avg_chi2] [, exc] [, history])`

Sample the function `func` using the grid `g` for `iterations` iterations and optimize the grid after each iteration. The results are returned in `integral`, `std_dev` and `avg_chi2`. The random number generator uses and updates the state stored in `rng`. The explicit random number state is inconvenient, but required for parallelizability.

```
subroutine vamp_integrate (rng, g, func, calls [, integral]
  [, std_dev] [, avg_chi2] [, exc] [, history])
```

This is a wrapper around the above routines, that is steered by a integer, dimension(2,:) array `calls`. For each `i`, there will be `calls(1,i)` iterations with `calls(2,i)` sampling points.

```
subroutine vamp_integrate (rng, domain, func, calls
  [, integral] [, std_dev] [, avg_chi2] [, exc] [, history])
```

A second specific form of `vamp_integrate`. This one keeps a private grid and provides the shortest—and most inflexible—calling sequence.

```
22 <Interface declaration for func 22>≡ (14 15 17 86c 94d 104 113–15 120b 135d 137 139–42 170 176 182 183)
interface
  function func (xi, data, weights, channel, grids) result (f)
    use kinds
    use vamp_grid_type !NODEP!
    import vamp_data_t
    real(kind=default), dimension(:), intent(in) :: xi
    class(vamp_data_t), intent(in) :: data
    real(kind=default), dimension(:), intent(in), optional :: weights
    integer, intent(in), optional :: channel
    type(vamp_grid), dimension(:), intent(in), optional :: grids
    real(kind=default) :: f
  end function func
end interface
```

#### 4.1.1 Basic Example

In Fortran95, the function to be sampled *must* be pure, i.e. have no side effects to allow parallelization. The optional arguments `weights` and `channel` *must* be declared to allow the compiler to verify the interface, but they are ignored during basic use. Their use for multi channel sampling will be explained below. Here's a Gaussian

$$f(x) = e^{-\frac{1}{2} \sum_i x_i^2} \quad (4.2)$$

```

23a <basic.f90 23a>≡
    module basic_fct
        use kinds
        implicit none
        private
        public :: fct
    contains
        function fct (x, weights, channel) result (f_x)
            real(kind=default), dimension(:), intent(in) :: x
            real(kind=default), dimension(:), intent(in), optional :: weights
            integer, intent(in), optional :: channel
            real(kind=default) :: f_x
            f_x = exp (-0.5 * sum (x*x))
        end function fct
    end module basic_fct
23b >

```

In the main program, we need to import five modules. The customary module `kinds` defines `double` as the kind for double precision floating point numbers. The model `exceptions` provides simple error handling support (parallelizable routines are not allowed to issue error messages themselves, but must pass them along). The module `tao_random_numbers` hosts the random number generator used and `vamp` is the adaptive iteration module proper. Finally, the application module `basic_fct` has to be imported as well.

```

23b <basic.f90 23a>+≡
    program basic
        use kinds
        use exceptions
        use tao_random_numbers
        use vamp
        use basic_fct
        implicit none
23c <23a 23c>

```

Then we define four variables for an error message, the random number generator state and the adaptive integration grid. We also declare a variable for holding the integration domain and variables for returning the result. In this case we integrate the 7-dimensional hypercube.

```

23c <basic.f90 23a>+≡
    type(exception) :: exc
    type(tao_random_state) :: rng
    type(vamp_grid) :: grid
    real(kind=default), dimension(2,7) :: domain
    real(kind=default) :: integral, error, chi2
    domain(1,:) = -1.0
    domain(2,:) = 1.0
23b <23b 24a>

```



Initialize and seed the random number generator. Initialize the grid for 10 000 sampling points.

```
24a <basic.f90 23a>+≡ <23c 24b>
    call tao_random_create (rng, seed=0)
    call clear_exception (exc)
    call vamp_create_grid (grid, domain, num_calls=10000, exc=exc)
    call handle_exception (exc)
```

Warm up the grid in six low statistics iterations. Clear the error status before and check it after the sampling.

```
24b <basic.f90 23a>+≡ <24a 24c>
    call clear_exception (exc)
    call vamp_sample_grid (rng, grid, fct, 6, exc=exc)
    call handle_exception (exc)
```

Throw away the intermediate results and reshape the grid for 100 000 sampling points—keeping the adapted grid—and do four iterations of a higher statistics integration

```
24c <basic.f90 23a>+≡ <24b>
    call clear_exception (exc)
    call vamp_discard_integral (grid, num_calls=100000, exc=exc)
    call handle_exception (exc)
    call clear_exception (exc)
    call vamp_sample_grid (rng, grid, fct, 4, integral, error, chi2, exc=exc)
    call handle_exception (exc)
    print *, "integral = ", integral, "+/-", error, " (chi^2 = ", chi2, ")"
end program basic
```

Since this is the most common use, there is a convenience routine available and the following code snippet is equivalent:

```
24d <Alternative to basic.f90 24d>≡
    integer, dimension(2,2) :: calls
    calls(:,1) = (/ 6, 10000 /)
    calls(:,2) = (/ 4, 100000 /)
    call clear_exception (exc)
    call vamp_integrate (rng, domain, fct, calls, integral, error, chi2, exc=exc)
    call handle_exception (exc)
```

## 4.2 Advanced Usage



Caveat emptor: no magic of literate programming can guarantee that the following remains in sync with the implementation. This has to be maintained manually.

All `real` variables are declared as `real(kind=default)` in the source and the variable `double` is imported from the module `kinds` (see appendix A.1). The representation of real numbers can therefore be changed by changing `double` in `kinds`.

#### 4.2.1 Types

```
type(vamp_grid)
type(vamp_grids)
type(vamp_history)
type(exception)
  (from module exceptions)
```

#### 4.2.2 Shared Arguments

Arguments keep their name across procedures, in order to make the Fortran90 keyword interface consistent.

```
real, intent(in) :: accuracy
```

Terminate  $S_n$  after  $n' < n$  iterations, if relative error is smaller than `accuracy`. Specifically, the termination condition is

$$\frac{\text{std\_dev}}{\text{integral}} < \text{accuracy} \quad (4.3)$$

```
real, intent(out) :: avg_chi2
```

The average  $\chi^2$  of the iterations.

```
integer, intent(in) :: channel
```

Call `func` with this optional argument. Multi channel sampling uses this to emulate arrays of functions

```
logical, intent(in) :: covariance
```

Collect covariance data.

```
type(exception), intent(inout) :: exc
```

Exceptional conditions are reported in `exc`.

```
type(vamp_grid), intent(inout) :: g
```

Unless otherwise noted, `g` denotes the active sampling grid in the documentation below.

```
type(vamp_histories), dimension(:), intent(inout) ::  
  histories
```

Diagnostic information for multi channel sampling.

```
type(vamp_history), dimension(:), intent(inout) ::  
  history
```

Diagnostic information for single channel sampling or summary of multi channel sampling.

```
real, intent(out) :: integral
```

The current best estimate of the integral.

```
integer, intent(in) :: iterations
```

```
real, dimension(:,:), intent(in) :: map
```

```
integer, intent(in) :: num_calls
```

The number of sampling points.

```
integer, dimension(:), intent(in) :: num_div
```

Number of divisions of the adaptive grid in each dimension.

```
logical, intent(in) :: quadrupole
```

Allow “quadrupole oscillations” of the sampling grid (cf. section 2.3.1).

```
type(tao_random_state), intent(inout) :: rng
```

Unless otherwise noted, `rng` denotes the source of random numbers used for sampling in the documentation below.

```
real, intent(out) :: std_dev
```

The current best estimate of the error on the integral.

```
logical, intent(in) :: stratified
```

Try to use stratified sampling.

```
real(kind=default), dimension(:), intent(in) :: weights
```

```
...
```

### 4.2.3 Single Channel Procedures

```
subroutine vamp_create_grid (g, domain, num_calls
    [, quadrupole] [, stratified] [, covariance] [, map] [, exc])

    real, dimension(:, :), intent(in) :: domain

subroutine vamp_create_empty_grid (g)

subroutine vamp_discard_integral (g [, num_calls]
    [, stratified] [, quadrupole] [, covariance] [, exc])

subroutine vamp_reshape_grid (g [, num_calls] [, num_div]
    [, stratified] [, quadrupole] [, covariance] [, exc])

subroutine vamp_sample_grid (rng, g, func, iterations
    [, integral] [, std_dev] [, avg_chi2] [, accuracy] [, channel]
    [, weights] [, exc] [, history])

    func

     $S_n$  with  $n = \text{iterations}$ 

subroutine vamp_sample_grid0 (rng, g, func, [, channel]
    [, weights] [, exc])

    func

     $S_0$ 

subroutine vamp_refine_grid (g, [, exc])

    r

subroutine vamp_average_iterations (g, iteration, integral,
    std_dev, avg_chi2)

    integer, intent(in) :: iteration
    Number of iterations so far (needed for  $\chi^2$ ).

subroutine vamp_integrate (g, func, calls [, integral]
    [, std_dev] [, avg_chi2] [, accuracy] [, covariance])

    type(vamp_grid), intent(inout) :: g
    func
```

```

integer, dimension(:,:), intent(in) :: calls

subroutine vamp_integratex (region, func, calls [, integral]
[, std_dev] [, avg_chi2] [, stratified] [, accuracy] [, pancake]
[, cigar])

real, dimension(:,:), intent(in) :: region
func
integer, dimension(:,:), intent(in) :: calls
integer, intent(in) :: pancake
integer, intent(in) :: cigar

subroutine vamp_copy_grid (lhs, rhs)

type(vamp_grid), intent(inout) :: lhs
type(vamp_grid), intent(in) :: rhs

subroutine vamp_delete_grid (g)

type(vamp_grid), intent(inout) :: g

```

#### 4.2.4 *Inout/Output and Marshling*

```

subroutine vamp_write_grid (g, [, ...])

type(vamp_grid), intent(inout) :: g

subroutine vamp_read_grid (g, [, ...])

type(vamp_grid), intent(inout) :: g

subroutine vamp_write_grids (g, [, ...])

type(vamp_grids), intent(inout) :: g

subroutine vamp_read_grids (g, [, ...])

type(vamp_grids), intent(inout) :: g

pure subroutine vamp_marshall_grid (g, integer_buffer,
double_buffer)

```

```

type(vamp_grid), intent(in) :: g
integer, dimension(:), intent(inout) ::
    integer_buffer
real(kind=default), dimension(:), intent(inout)
    :: double_buffer

```

Marshal the grid `g` in the integer array `integer_buffer` and the real array `double_buffer`, which must have at least the sizes obtained from call `vamp_marshall_grid_size (g, integer_size, double_size)`.



Note that we can not use the `transfer` intrinsic function for marshalling types that contain pointers that substitute for allocatable array components. `transfer` would copy the pointers in this case and not where they point to!

```

pure subroutine vamp_marshall_grid_size (g, integer_size,
    double_size)

```

```

type(vamp_grid), intent(in) :: g
integer :: words

```

Compute the sizes of the arrays required for marshaling the grid `g`.

```

pure subroutine vamp_unmarshal_grid (g, integer_buffer,
    double_buffer)

```

```

type(vamp_grid), intent(inout) :: g
integer, dimension(:), intent(in) ::
    integer_buffer
real(kind=default), dimension(:), intent(in) ::
    double_buffer

```

Marshaling and unmarshaling need to use two separate buffers for integers and floating point numbers. In a homogeneous network, the intrinsic procedure `transfer` could be used to store the floating point numbers in the integer array. In a heterogenous network this will fail. However, message passing environments provide methods for sending floating point numbers. For example, here's how to send a grid from process 0 to process 1 in MPI [12]

```

29 <MPI communication example 29>≡
    call vamp_marshall_grid_size (g, isize, dsize)

```

```

allocate (ibuf(isize), dbuf(dsize))
call mpi_comm_rank (MPI_COMM_WORLD, proc_id, errno)
select case (proc_id)
  case (0)
    call vamp_marshall_grid (g, ibuf, dbuf)
    call mpi_send (ibuf, size (ibuf), MPI_INTEGER, &
                  1, 1, MPI_COMM_WORLD, errno)
    call mpi_send (dbuf, size (dbuf), MPI_DOUBLE_PRECISION, &
                  1, 2, MPI_COMM_WORLD, errno)
  case (1)
    call mpi_recv (ibuf, size (ibuf), MPI_INTEGER, &
                  0, 1, MPI_COMM_WORLD, status, errno)
    call mpi_recv (dbuf, size (dbuf), MPI_DOUBLE_PRECISION, &
                  0, 2, MPI_COMM_WORLD, status, errno)
    call vamp_unmarshal_grid (g, ibuf, dbuf)
end select

```

assuming that double is such that MPI\_DOUBLE\_PRECISION corresponds to real(kind=default). The module `vampi` provides two high level functions `vamp_send_grid` and `vamp_receive_grid` that handle the low level details:

```

30 <MPI communication example' 30>≡
  call mpi_comm_rank (MPI_COMM_WORLD, proc_id, errno)
  select case (proc_id)
    case (0)
      call vamp_send_grid (g, 1, 0)
    case (1)
      call vamp_receive_grid (g, 0, 0)
  end select

  subroutine vamp_marshall_history_size (g, [, ...])

    type(vamp_grid), intent(inout) :: g

  subroutine vamp_marshall_history (g, [, ...])

    type(vamp_grid), intent(inout) :: g

  subroutine vamp_unmarshal_history (g, [, ...])

    type(vamp_grid), intent(inout) :: g

```

#### 4.2.5 Multi Channel Procedures

$$g \circ \phi_i = \left| \frac{\partial \phi_i}{\partial x} \right|^{-1} \left( \alpha_i g_i + \sum_{\substack{j=1 \\ j \neq i}}^{N_c} \alpha_j (g_j \circ \pi_{ij}) \left| \frac{\partial \pi_{ij}}{\partial x} \right| \right). \quad (4.4)$$

31a  $\langle$ Interface declaration for phi 31a $\rangle \equiv$  (113–16 137 183a)

```
interface
  pure function phi (xi, channel) result (x)
    use kinds
    real(kind=default), dimension(:), intent(in) :: xi
    integer, intent(in) :: channel
    real(kind=default), dimension(size(xi)) :: x
  end function phi
end interface
```

31b  $\langle$ Interface declaration for ihp 31b $\rangle \equiv$  (113c)

```
interface
  pure function ihp (x, channel) result (xi)
    use kinds
    real(kind=default), dimension(:), intent(in) :: x
    integer, intent(in) :: channel
    real(kind=default), dimension(size(x)) :: xi
  end function ihp
end interface
```

31c  $\langle$ Interface declaration for jacobian 31c $\rangle \equiv$  (113c 114a)

```
interface
  pure function jacobian (x, data, channel) result (j)
    use kinds
    use vamp_grid_type !NODEP!
    import vamp_data_t
    real(kind=default), dimension(:), intent(in) :: x
    class(vamp_data_t), intent(in) :: data
    integer, intent(in) :: channel
    real(kind=default) :: j
  end function jacobian
end interface
```

```
function vamp_multi_channel (func, phi, ihp, jacobian, x,
  weights1, grids)

  real(kind=default), dimension(:), intent(in) :: x
```



```

real(kind=default), dimension(:), intent(in) ::
    weights
integer, intent(in) :: channel
type(vamp_grid), dimension(:), intent(in) :: grids

function vamp_multi_channel0 (func, phi, jacobian, x,
    weights1)

    real(kind=default), dimension(:), intent(in) :: x
    real(kind=default), dimension(:), intent(in) ::
        weights
    integer, intent(in) :: channel

subroutine vamp_check_jacobian (rng, n, channel, region,
    delta, [, x_delta])

    type(tao_random_state), intent(inout) :: rng
    integer, intent(in) :: n
    integer, intent(in) :: channel
    real(kind=default), dimension(:,:), intent(in) ::
        region
    real(kind=default), intent(out) :: delta
    real(kind=default), dimension(:), intent(out),
        optional :: x_delta

```

Verify that

$$g(\phi(x)) = \frac{1}{\left| \frac{\partial \phi}{\partial x} \right| (x)} \quad (4.5)$$

```

subroutine vamp_copy_grids (lhs, rhs)

    type(vamp_grids), intent(inout) :: lhs
    type(vamp_grids), intent(in) :: rhs

subroutine vamp_delete_grids (g)

    type(vamp_grids), intent(inout) :: g

```

```

subroutine vamp_create_grids (g, domain, num_calls, weights
[, maps] [, stratified])

    type(vamp_grids), intent(inout) :: g
    real, dimension(:,:), intent(in) :: domain
    integer, intent(in) :: num_calls
    real, dimension(:), intent(in) :: weights
    real, dimension(:,:,:), intent(in) :: maps

subroutine vamp_create_empty_grids (g)

    type(vamp_grids), intent(inout) :: g

subroutine vamp_discard_integrals (g [, num_calls]
[, stratified])

    type(vamp_grids), intent(inout) :: g
    integer, intent(in) :: num_calls

subroutine vamp_refine_weights (g [, power)

    type(vamp_grids), intent(inout) :: g
    real, intent(in) :: power

subroutine vamp_update_weights (g, weights [, num_calls]
[, stratified])

    type(vamp_grids), intent(inout) :: g
    real, dimension(:), intent(in) :: weights
    integer, intent(in) :: num_calls

subroutine vamp_reshape_grids (g, num_calls [, stratified])

    type(vamp_grids), intent(inout) :: g
    integer, intent(in) :: num_calls

subroutine vamp_reduce_channels (g, [, ...])

    type(vamp_grid), intent(inout) :: g

```

```

subroutine vamp_sample_grids (g, func, iterations [, integral]
    [, std_dev] [, accuracy] [, covariance] [, variance])

    type(vamp_grids), intent(inout) :: g
    func
    integer, intent(in) :: iterations

function vamp_sum_channels (x, weights, func)

    real, dimension(:), intent(in) :: x
    real, dimension(:), intent(in) :: weights
    func

```

#### 4.2.6 Event Generation

```

subroutine vamp_next_event (g, [, ...])

subroutine vamp_warmup_grid (g, [, ...])

    type(vamp_grid), intent(inout) :: g
    func
    integer, intent(in) :: iterations

subroutine vamp_warmup_grids (g, [, ...])

    type(vamp_grids), intent(inout) :: g
    func
    integer, intent(in) :: iterations

```

#### 4.2.7 Parallelization

```

subroutine vamp_fork_grid (g, [, ...])

    type(vamp_grid), intent(inout) :: g

subroutine vamp_join_grid (g, [, ...])

    type(vamp_grid), intent(inout) :: g

```

```

subroutine vamp_fork_grid_joints (g, [, ...])

    type(vamp_grid), intent(inout) :: g

subroutine vamp_sample_grid_parallel (g, [, ...])

    type(vamp_grid), intent(inout) :: g

subroutine vamp_distribute_work (g, [, ...])

    type(vamp_grid), intent(inout) :: g

```

#### 4.2.8 Diagnostics

```

subroutine vamp_create_history (g, [, ...])

    type(vamp_grid), intent(inout) :: g

subroutine vamp_copy_history (g, [, ...])

    type(vamp_grid), intent(inout) :: g

subroutine vamp_delete_history (g, [, ...])

    type(vamp_grid), intent(inout) :: g

subroutine vamp_terminate_history (g, [, ...])

    type(vamp_grid), intent(inout) :: g

subroutine vamp_get_history (g, [, ...])

    type(vamp_grid), intent(inout) :: g

subroutine vamp_get_history_single (g, [, ...])

    type(vamp_grid), intent(inout) :: g

subroutine vamp_print_history (g, [, ...])

    type(vamp_grid), intent(inout) :: g

```



Discuss why the value of the integral in each channel differs.

#### 4.2.9 *Other Procedures*

```
subroutine vamp_rigid_divisions (g, [, ...])  
    type(vamp_grid), intent(inout) :: g  
function vamp_get_covariance (g, [, ...])  
    type(vamp_grid), intent(inout) :: g  
subroutine vamp_nullify_covariance (g, [, ...])  
    type(vamp_grid), intent(inout) :: g  
function vamp_get_variance (g, [, ...])  
    type(vamp_grid), intent(inout) :: g  
subroutine vamp_nullify_variance (g, [, ...])  
    type(vamp_grid), intent(inout) :: g
```

#### 4.2.10 *(Currently) Undocumented Procedures*


```
subroutine (... , [, ...])  
function (... , [, ...])
```

## —5—

# IMPLEMENTATION

### 5.1 *The Abstract Datatype `division`*

```
37a <divisions.f90 37a>≡
! divisions.f90 --
<Copyleft notice 1>
module divisions
  use kinds
  use exceptions
  use vamp_stat
  use utils
  use iso_fortran_env
  implicit none
  private
  <Declaration of divisions procedures 38a>
  <Interfaces of divisions procedures 61b>
  <Variables in divisions 46a>
  <Declaration of divisions types 37b>
  <Constants in divisions 65a>
  character(len=*), public, parameter :: DIVISIONS_RCS_ID = &
    "$Id: divisions.nw 314 2010-04-17 20:32:33Z ohl $"
  contains
    <Implementation of divisions procedures 38b>
end module divisions
```

 `vamp_apply_equivalences` from `vamp` accesses `%variance ...`

```
37b <Declaration of divisions types 37b>≡ (37a) 58a>
  type, public :: division_t
  ! private
  !!! Avoiding a g95 bug
```

```

real(kind=default), dimension(:), pointer :: x => null ()
real(kind=default), dimension(:), pointer :: integral => null ()
real(kind=default), dimension(:), pointer &
    :: variance => null ()
!
! public :: variance => null ()
! real(kind=default), dimension(:), pointer :: efficiency => null ()
real(kind=default) :: x_min, x_max
real(kind=default) :: x_min_true, x_max_true
real(kind=default) :: dx, dxg
integer :: ng = 0
logical :: stratified = .true.
end type division_t

```

### 5.1.1 Creation, Manipulation & Injection

38a *<Declaration of divisions procedures 38a>*≡ (37a) 43a>

```

public :: create_division, create_empty_division
public :: copy_division, delete_division
public :: set_rigid_division, reshape_division

```

38b *<Implementation of divisions procedures 38b>*≡ (37a) 39a>

```

elemental subroutine create_division &
    (d, x_min, x_max, x_min_true, x_max_true)
type(division_t), intent(out) :: d
real(kind=default), intent(in) :: x_min, x_max
real(kind=default), intent(in), optional :: x_min_true, x_max_true
allocate (d%x(0:1), d%integral(1), d%variance(1))
! allocate (d%efficiency(1))
d%x(0) = 0.0
d%x(1) = 1.0
d%x_min = x_min
d%x_max = x_max
d%dx = d%x_max - d%x_min
d%stratified = .false.
d%ng = 1
d%dxg = 1.0 / d%ng
if (present (x_min_true)) then
    d%x_min_true = x_min_true
else
    d%x_min_true = x_min
end if
if (present (x_max_true)) then
    d%x_max_true = x_max_true

```

```

else
    d%x_max_true = x_max
end if
end subroutine create_division

```

39a  $\langle$ Implementation of divisions procedures 38b $\rangle + \equiv$  (37a)  $\triangleleft$ 38b 39b $\triangleright$

```

elemental subroutine create_empty_division (d)
    type(division_t), intent(out) :: d
    nullify (d%x, d%integral, d%variance)
! nullify (d%efficiency)
end subroutine create_empty_division

```

39b  $\langle$ Implementation of divisions procedures 38b $\rangle + \equiv$  (37a)  $\triangleleft$ 39a 39c $\triangleright$

```

elemental subroutine set_rigid_division (d, ng)
    type(division_t), intent(inout) :: d
    integer, intent(in) :: ng
    d%stratified = ng > 1
    d%ng = ng
    d%dxg = real (ubound (d%x, dim=1), kind=default) / d%ng
end subroutine set_rigid_division

```

$$dxg = \frac{n_{div}}{n_g} \quad (5.1)$$

such that  $0 < \text{cell} \cdot dxg < n_{div}$

39c  $\langle$ Implementation of divisions procedures 38b $\rangle + \equiv$  (37a)  $\triangleleft$ 39b 43b $\triangleright$

```

elemental subroutine reshape_division (d, max_num_div, ng, use_variance)
    type(division_t), intent(inout) :: d
    integer, intent(in) :: max_num_div
    integer, intent(in), optional :: ng
    logical, intent(in), optional :: use_variance
    real(kind=default), dimension(:), allocatable :: old_x, m
    integer :: num_div, equ_per_adap
    if (present (ng)) then
        if (max_num_div > 1) then
            d%stratified = ng > 1
        else
            d%stratified = .false.
        end if
    else
        d%stratified = .false.
    end if
    if (d%stratified) then

```



```

    d%ng = ng
    <Initialize stratified sampling 42>
else
    num_div = max_num_div
    d%ng = 1
end if
d%dxg = real (num_div, kind=default) / d%ng
allocate (old_x(0:ubound(d%x,dim=1)), m(ubound(d%x,dim=1)))
old_x = d%x
<Set m to (1,1,...) or to rebinning weights from d%variance 40a>
<Resize arrays, iff necessary 40b>
d%x = rebin (m, old_x, num_div)
deallocate (old_x, m)
end subroutine reshape_division

```

40a *<Set m to (1,1,...) or to rebinning weights from d%variance 40a>*≡ (39c)

```

if (present (use_variance)) then
    if (use_variance) then
        m = rebinning_weights (d%variance)
    else
        m = 1.0
    end if
else
    m = 1.0
end if

```

40b *<Resize arrays, iff necessary 40b>*≡ (39c)

```

if (ubound (d%x, dim=1) /= num_div) then
    deallocate (d%x, d%integral, d%variance)
    ! deallocate (d%efficiency)
    allocate (d%x(0:num_div), d%integral(num_div), d%variance(num_div))
    ! allocate (d%efficiency(num_div))
end if

```

Genuinely stratified sampling will superimpose an equidistant grid on the adaptive grid, as shown in figure 5.2. Obviously, this is only possible when the number of cells of the stratification grid is large enough, specifically when  $n_g \geq n_{\text{div}}^{\min} = n_{\text{div}}^{\max}/2 = 25$ ). This condition can be met by a high number of sampling points or by a low dimensionality of the integration region (cf. table 5.1).

For a low number of sampling points and high dimensions, genuinely stratified sampling is impossible, because we would have to reduce the number  $n_{\text{div}}$  of adaptive divisions too far. Instead, we keep `stratified` false which will tell the integration routine not to concentrate the grid in the regions where



Figure 5.1: **vegas** grid structure for non-stratified sampling. N.B.: the grid and the weight functions  $p_{1,2}$  are only in qualitative agreement.



Figure 5.2: **vegas** grid structure for genuinely stratified sampling, which is used in low dimensions. N.B.: the grid and the weight functions  $p_{1,2}$  are only in qualitative agreement.

$n_{\text{dim}}$	$N_{\text{calls}}^{\text{max}}(n_g = 25)$
2	$1 \cdot 10^3$
3	$3 \cdot 10^4$
4	$8 \cdot 10^5$
5	$2 \cdot 10^7$
6	$5 \cdot 10^8$

Table 5.1: To stratify or not to stratify.

the contribution to the error is largest, but to use importance sampling, i. e. concentrating the grid in the regions where the contribution to the value is largest.

In this case, the rigid grid is much coarser than the adaptive grid and furthermore, the boundaries of the cells overlap in general. The interplay of the two grids during the sampling process is shown in figure 5.3. First we determine the (integer) number  $k$  of equidistant divisions of an adaptive cell for at most  $n_{\text{div}}^{\text{max}}$  divisions of the adaptive grid

$$k = \left\lfloor \frac{n_g}{n_{\text{div}}^{\text{max}}} \right\rfloor + 1 \quad (5.2a)$$

and the corresponding number  $n_{\text{div}}$  of adaptive divisions

$$n_{\text{div}} = \left\lfloor \frac{n_g}{k} \right\rfloor \quad (5.2b)$$

Finally, adjust  $n_g$  to an exact multiple of  $n_{\text{div}}$

$$n_g = k \cdot n_{\text{div}} \quad (5.2c)$$

42 *⟨Initialize stratified sampling 42⟩*≡ (39c)

```

if (d%ng >= max_num_div / 2) then
  d%stratified = .true.
  equ_per_adap = d%ng / max_num_div + 1
  num_div = d%ng / equ_per_adap
  if (num_div < 2) then
    d%stratified = .false.
    num_div = 2
    d%ng = 1
  else if (mod (num_div,2) == 1) then
    num_div = num_div - 1
    d%ng = equ_per_adap * num_div
  else

```



Figure 5.3: One-dimensional illustration of the **vegas** grid structure for pseudo stratified sampling, which is used in high dimensions.

```

        d%ng = equ_per_adap * num_div
    end if
else
    d%stratified = .false.
    num_div = max_num_div
    d%ng = 1
end if

```

Figure 5.3 on page 43 is a one-dimensional illustration of the sampling algorithm. In each cell of the rigid equidistant grid, two random points are selected (or  $N_{\text{calls}}$  in the not stratified case). For each point, the corresponding cell and relative coordinate in the adaptive grid is found, *as if the adaptive grid was equidistant* (upper arrow). Then this point is mapped according to the adapted grid (lower arrow) and the proper Jacobians are applied to the weight.

$$\prod_{j=1}^n (x_i^j - x_{i-1}^j) \cdot N^n = \text{Vol}(\text{cell}') \cdot \frac{1}{\text{Vol}(\text{cell})} = \frac{1}{p(x_i^j)} \quad (5.3)$$

```

43a  <Declaration of divisions procedures 38a>+≡ (37a) <38a 44c>
      public :: inject_division, inject_division_short

43b  <Implementation of divisions procedures 38b>+≡ (37a) <39c 44b>
      elemental subroutine inject_division (d, r, cell, x, x_mid, idx, wgt)
        type(division_t), intent(in) :: d
        real(kind=default), intent(in) :: r
        integer, intent(in) :: cell
        real(kind=default), intent(out) :: x, x_mid
        integer, intent(out) :: idx
        real(kind=default), intent(out) :: wgt
        real(kind=default) :: delta_x, xi
        integer :: i
        xi = (cell - r) * d%dxg + 1.0

```

```

    <Set i, delta_x, x, and wgt from xi 44a>
    idx = i
    x_mid = d%x_min + 0.5 * (d%x(i-1) + d%x(i)) * d%dx
end subroutine inject_division

```

44a <Set i, delta\_x, x, and wgt from xi 44a>≡ (43b 44b)

```

    i = max (min (int (xi), ubound (d%x, dim=1)), 1)
    delta_x = d%x(i) - d%x(i-1)
    x = d%x_min + (d%x(i-1) + (xi - i) * delta_x) * d%dx
    wgt = delta_x * ubound (d%x, dim=1)

```

44b <Implementation of divisions procedures 38b>+≡ (37a) <43b 44d>

```

    elemental subroutine inject_division_short (d, r, x, idx, wgt)
        type(division_t), intent(in) :: d
        real(kind=default), intent(in) :: r
        integer, intent(out) :: idx
        real(kind=default), intent(out) :: x, wgt
        real(kind=default) :: delta_x, xi
        integer :: i
        xi = r * ubound (d%x, dim=1) + 1.0
        <Set i, delta_x, x, and wgt from xi 44a>
        idx = i
    end subroutine inject_division_short

```

### 5.1.2 Grid Refinement

44c <Declaration of divisions procedures 38a>+≡ (37a) <43a 45d>

```

    public :: record_integral, record_variance, clear_integral_and_variance
    ! public :: record_efficiency

```

44d <Implementation of divisions procedures 38b>+≡ (37a) <44b 45a>

```

    elemental subroutine record_integral (d, i, f)
        type(division_t), intent(inout) :: d
        integer, intent(in) :: i
        real(kind=default), intent(in) :: f
        d%integral(i) = d%integral(i) + f
        if (.not. d%stratified) then
            d%variance(i) = d%variance(i) + f*f
        end if
    end subroutine record_integral

```

45a  $\langle$ Implementation of divisions procedures 38b $\rangle + \equiv$  (37a)  $\triangleleft$ 44d 45c $\triangleright$   
 elemental subroutine record\_variance (d, i, var\_f)  
   type(division\_t), intent(inout) :: d  
   integer, intent(in) :: i  
   real(kind=default), intent(in) :: var\_f  
   if (d%stratified) then  
     d%variance(i) = d%variance(i) + var\_f  
   end if  
end subroutine record\_variance

45b  $\langle$ Implementation of divisions procedures (removed from WHIZARD) 45b $\rangle \equiv$  60d $\triangleright$   
 elemental subroutine record\_efficiency (d, i, eff)  
   type(division\_t), intent(inout) :: d  
   integer, intent(in) :: i  
   real(kind=default), intent(in) :: eff  
   ! d%efficiency(i) = d%efficiency(i) + eff  
end subroutine record\_efficiency

45c  $\langle$ Implementation of divisions procedures 38b $\rangle + \equiv$  (37a)  $\triangleleft$ 45a 45e $\triangleright$   
 elemental subroutine clear\_integral\_and\_variance (d)  
   type(division\_t), intent(inout) :: d  
   d%integral = 0.0  
   d%variance = 0.0  
   ! d%efficiency = 0.0  
end subroutine clear\_integral\_and\_variance

45d  $\langle$ Declaration of divisions procedures 38a $\rangle + \equiv$  (37a)  $\triangleleft$ 44c 47a $\triangleright$   
 public :: refine\_division

45e  $\langle$ Implementation of divisions procedures 38b $\rangle + \equiv$  (37a)  $\triangleleft$ 45c 46b $\triangleright$   
 elemental subroutine refine\_division (d)  
   type(division\_t), intent(inout) :: d  
   character(len=\*), parameter :: FN = "refine\_division"  
   d%x = rebin (rebinning\_weights (d%variance), d%x, size (d%variance))  
end subroutine refine\_division

Smooth the  $d_i = \bar{f}_i \Delta x_i$

$$\begin{aligned}
d_1 &\rightarrow \frac{1}{2}(d_1 + d_2) \\
d_2 &\rightarrow \frac{1}{3}(d_1 + d_2 + d_3) \\
&\dots \\
d_{n-1} &\rightarrow \frac{1}{3}(d_{n-2} + d_{n-1} + d_n) \\
d_n &\rightarrow \frac{1}{2}(d_{n-1} + d_n)
\end{aligned} \tag{5.4}$$

As long as the initial `num_div`  $\geq 6$ , we know that `num_div`  $\geq 3$ .

46a *<Variables in divisions 46a>*  $\equiv$  (37a) 60a  $\triangleright$   
`integer, private, parameter :: MIN_NUM_DIV = 3`

Here the Fortran90 array notation really shines, but we have to handle the cases `nd`  $\leq 2$  specially, because the `quadrupole` option can lead to small `nds`. The equivalent Fortran77 code [2] is orders of magnitude less obvious<sup>1</sup> Also protect against vanishing  $d_i$  that will blow up the logarithm.

$$m_i = \left( \frac{\frac{\bar{f}_i \Delta x_i}{\sum_j \bar{f}_j \Delta x_j} - 1}{\ln \left( \frac{\bar{f}_i \Delta x_i}{\sum_j \bar{f}_j \Delta x_j} \right)} \right)^\alpha \tag{5.5}$$

46b *<Implementation of divisions procedures 38b>*  $\equiv$  (37a) <45e 47c>  

```

pure function rebinning_weights (d) result (m)
  real(kind=default), dimension(:), intent(in) :: d
  real(kind=default), dimension(size(d)) :: m
  real(kind=default), dimension(size(d)) :: smooth_d
  real(kind=default), parameter :: ALPHA = 1.5
  integer :: nd
  <Bail out if any (d == NaN) 47b>
  nd = size (d)
  if (nd > 2) then
    smooth_d(1) = (d(1) + d(2)) / 2.0
    smooth_d(2:nd-1) = (d(1:nd-2) + d(2:nd-1) + d(3:nd)) / 3.0
    smooth_d(nd) = (d(nd-1) + d(nd)) / 2.0
  else
    smooth_d = d
  end if
  if (all (smooth_d < tiny (1.0_default))) then

```

---

<sup>1</sup>Some old timers call this a feature, however.

```

    m = 1.0_default
else
    smooth_d = smooth_d / sum (smooth_d)
    where (smooth_d < tiny (1.0_default))
        smooth_d = tiny (1.0_default)
    end where
    where (smooth_d /= 1._default)
        m = ((smooth_d - 1.0) / (log (smooth_d)))**ALPHA
    elsewhere
        m = 1.0_default
    endwhere
end if
end function rebinning_weights

```

47a  $\langle$ Declaration of divisions procedures 38a $\rangle + \equiv$  (37a)  $\langle$ 45d 48a $\rangle$   
 private :: rebinning\_weights



The NaN test is probably not portable:

47b  $\langle$ Bail out if any (d == NaN) 47b $\rangle \equiv$  (46b)  
 if (any (d /= d)) then  
 m = 1.0  
 return  
 end if

Take a binning  $x$  and return a new binning with  $\text{num\_div}$  bins with the  $m$  homogeneously distributed:

47c  $\langle$ Implementation of divisions procedures 38b $\rangle + \equiv$  (37a)  $\langle$ 46b 48e $\rangle$   
 pure function rebin (m, x, num\_div) result (x\_new)  
 real(kind=default), dimension(:), intent(in) :: m  
 real(kind=default), dimension(0:), intent(in) :: x  
 integer, intent(in) :: num\_div  
 real(kind=default), dimension(0:num\_div) :: x\_new  
 integer :: i, k  
 real(kind=default) :: step, delta  
 step = sum (m) / num\_div  
 k = 0  
 delta = 0.0  
 x\_new(0) = x(0)  
 do i = 1, num\_div - 1  
 $\langle$ Increment  $k$  until  $\sum m_k \geq \Delta$  and keep the surplus in  $\delta$  48b $\rangle$   
 $\langle$ Interpolate the new  $x_i$  from  $x_k$  and  $\delta$  48c $\rangle$   
 end do  
 x\_new(num\_div) = 1.0  
end function rebin





Figure 5.4: Typical weights used in the rebinning algorithm.

48a  $\langle$ Declaration of divisions procedures 38a $\rangle + \equiv$  (37a)  $\langle$ 47a 48d $\rangle$   
`private :: rebin`

We increment  $k$  until another  $\Delta$  (a.k.a. **step**) of the integral has been accumulated (cf. figure 5.4). The mismatch will be corrected below.

48b  $\langle$ Increment  $k$  until  $\sum m_k \geq \Delta$  and keep the surplus in  $\delta$  48b $\rangle \equiv$  (47c)  
`do`  
`if (step <= delta) then`  
`exit`  
`end if`  
`k = k + 1`  
`delta = delta + m(k)`  
`end do`  
`delta = delta - step`

48c  $\langle$ Interpolate the new  $x_i$  from  $x_k$  and  $\delta$  48c $\rangle \equiv$  (47c)  
`x_new(i) = x(k) - (x(k) - x(k-1)) * delta / m(k)`

### 5.1.3 Probability Density

48d  $\langle$ Declaration of divisions procedures 38a $\rangle + \equiv$  (37a)  $\langle$ 48a 49a $\rangle$   
`public :: probability`

$$\xi = \frac{x - x_{\min}}{x_{\max} - x_{\min}} \in [0, 1] \quad (5.6)$$

and

$$\int_{x_{\min}}^{x_{\max}} dx p(x) = 1 \quad (5.7)$$

48e  $\langle$ Implementation of divisions procedures 38b $\rangle + \equiv$  (37a)  $\langle$ 47c 49b $\rangle$   
`elemental function probability (d, x) result (p)`  
`type(division_t), intent(in) :: d`  
`real(kind=default), intent(in) :: x`

```

real(kind=default) :: p
real(kind=default) :: xi
integer :: hi, mid, lo
xi = (x - d%x_min) / d%dx
if ((xi >= 0) .and. (xi <= 1)) then
  lo = lbound (d%x, dim=1)
  hi = ubound (d%x, dim=1)
  bracket: do
    if (lo >= hi - 1) then
      p = 1.0 / (ubound (d%x, dim=1) * d%dx * (d%x(hi) - d%x(hi-1)))
      return
    end if
    mid = (hi + lo) / 2
    if (xi > d%x(mid)) then
      lo = mid
    else
      hi = mid
    end if
  end do bracket
else
  p = 0
end if
end function probability

```

#### 5.1.4 *Quadrupole*

- 49a  $\langle$ Declaration of divisions procedures 38a $\rangle + \equiv$  (37a)  $\langle$ 48d 49c $\rangle$   
 public :: quadrupole\_division
- 49b  $\langle$ Implementation of divisions procedures 38b $\rangle + \equiv$  (37a)  $\langle$ 48e 50a $\rangle$   
 elemental function quadrupole\_division (d) result (q)  
 type(division\_t), intent(in) :: d  
 real(kind=default) :: q  
 !!! q = value\_spread\_percent (rebinning\_weights (d%variance))  
 q = standard\_deviation\_percent (rebinning\_weights (d%variance))  
 end function quadrupole\_division

#### 5.1.5 *Forking and Joining*

The goal is to split a division in such a way, that we can later sample the pieces separately and combine the results.

- 49c  $\langle$ Declaration of divisions procedures 38a $\rangle + \equiv$  (37a)  $\langle$ 49a 54c $\rangle$   
 public :: fork\_division, join\_division, sum\_division



Caveat emptor: splitting divisions can lead to `num_div < 3` and the application *must not* try to refine such grids before merging them again!

50a *<Implementation of divisions procedures 38b>+≡* (37a) *<49b 50b>*

```

pure subroutine fork_division (d, ds, sum_calls, num_calls, exc)
  type(division_t), intent(in) :: d
  type(division_t), dimension(:), intent(inout) :: ds
  integer, intent(in) :: sum_calls
  integer, dimension(:), intent(inout) :: num_calls
  type(exception), intent(inout), optional :: exc
  character(len=*), parameter :: FN = "fork_division"
  integer, dimension(size(ds)) :: n0, n1
  integer, dimension(0:size(ds)) :: n, ds_ng
  integer :: i, j, num_div, num_forks, nx
  real(kind=default), dimension(:), allocatable :: d_x, d_integral, d_variance
! real(kind=default), dimension(:), allocatable :: d_efficiency
  num_div = ubound (d%x, dim=1)
  num_forks = size (ds)
  if (d%ng == 1) then
    <Fork an importance sampling division 51a>
  else if (num_div >= num_forks) then
    if (modulo (d%ng, num_div) == 0) then
      <Fork a pure stratified sampling division 52b>
    else
      <Fork a pseudo stratified sampling division 54a>
    end if
  else
    if (present (exc)) then
      call raise_exception (exc, EXC_FATAL, FN, "internal error")
    end if
    num_calls = 0
  end if
end subroutine fork_division

```

50b *<Implementation of divisions procedures 38b>+≡* (37a) *<50a 55a>*

```

pure subroutine join_division (d, ds, exc)
  type(division_t), intent(inout) :: d
  type(division_t), dimension(:), intent(in) :: ds
  type(exception), intent(inout), optional :: exc
  character(len=*), parameter :: FN = "join_division"
  integer, dimension(size(ds)) :: n0, n1
  integer, dimension(0:size(ds)) :: n, ds_ng
  integer :: i, j, num_div, num_forks, nx
  real(kind=default), dimension(:), allocatable :: d_x, d_integral, d_variance

```

```

! real(kind=default), dimension(:), allocatable :: d_efficiency
num_div = ubound (d%x, dim=1)
num_forks = size (ds)
if (d%ng == 1) then
  ⟨Join importance sampling divisions 51b⟩
else if (num_div >= num_forks) then
  if (modulo (d%ng, num_div) == 0) then
    ⟨Join pure stratified sampling divisions 52c⟩
  else
    ⟨Join pseudo stratified sampling divisions 54b⟩
  end if
else
  if (present (exc)) then
    call raise_exception (exc, EXC_FATAL, FN, "internal error")
  end if
end if
end subroutine join_division

```

### *Importance Sampling*

Importance sampling ( $d\%ng == 1$ ) is trivial, since we can just sample `size(ds)` copies of the same grid with (almost) the same number of points

51a *⟨Fork an importance sampling division 51a⟩*≡ (50a)

```

if (d%stratified) then
  call raise_exception (exc, EXC_FATAL, FN, &
    "ng == 1 incompatible w/ stratification")
else
  call copy_division (ds, d)
  num_calls(2:) = ceiling (real (sum_calls) / num_forks)
  num_calls(1) = sum_calls - sum (num_calls(2:))
end if

```

and sum up the results in the end:

51b *⟨Join importance sampling divisions 51b⟩*≡ (50b)

```

call sum_division (d, ds)

```

Note, however, that this is only legitimate as long as  $d\%ng == 1$  implies  $d\%stratified == .false.$ , because otherwise the sampling code would be incorrect (cf. `var_f` on page 90).

### *Stratified Sampling*

For stratified sampling, we have to work a little harder, because there are just two points per cell and we have to slice along the lines of the stratification

grid. Actually, we are slicing along the adaptive grid, since it has a reasonable size. Slicing along the stratification grid could be done using the method below. However, in this case *very* large adaptive grids would be shipped from one process to the other and the communication costs will outweigh the gains from parallel processing.

52a  $\langle$ Setup to fork a pure stratified sampling division 52a $\rangle \equiv$  (52)

```
n = (num_div * (/ (j, j=0,num_forks) /)) / num_forks
n0(1:num_forks) = n(0:num_forks-1)
n1(1:num_forks) = n(1:num_forks)
```

52b  $\langle$ Fork a pure stratified sampling division 52b $\rangle \equiv$  (50a)

```
 $\langle$ Setup to fork a pure stratified sampling division 52a $\rangle$ 
do i = 1, num_forks
  call copy_array_pointer (ds(i)%x, d%x(n0(i):n1(i)), lb = 0)
  call copy_array_pointer (ds(i)%integral, d%integral(n0(i)+1:n1(i)))
  call copy_array_pointer (ds(i)%variance, d%variance(n0(i)+1:n1(i)))
  ! call copy_array_pointer (ds(i)%efficiency, d%efficiency(n0(i)+1:n1(i)))
  ds(i)%x = (ds(i)%x - ds(i)%x(0)) / (d%x(n1(i)) - d%x(n0(i)))
end do
ds%x_min = d%x_min + d%dx * d%x(n0)
ds%x_max = d%x_min + d%dx * d%x(n1)
ds%dx = ds%x_max - ds%x_min
ds%x_min_true = d%x_min_true
ds%x_max_true = d%x_max_true
ds%stratified = d%stratified
ds%ng = (d%ng * (n1 - n0)) / num_div
num_calls = sum_calls ! this is a misnomer, it remains "calls per cell" here
ds%dxg = real (n1 - n0, kind=default) / ds%ng
```

Joining is the exact inverse, but we're only interested in d%integral and d%variance for the grid refinement:

52c  $\langle$ Join pure stratified sampling divisions 52c $\rangle \equiv$  (50b)

```
 $\langle$ Setup to fork a pure stratified sampling division 52a $\rangle$ 
do i = 1, num_forks
  d%integral(n0(i)+1:n1(i)) = ds(i)%integral
  d%variance(n0(i)+1:n1(i)) = ds(i)%variance
  ! d%efficiency(n0(i)+1:n1(i)) = ds(i)%efficiency
end do
```



Figure 5.5: Forking one dimension  $d$  of a grid into three parts  $ds(1)$ ,  $ds(2)$ , and  $ds(3)$ . The picture illustrates the most complex case of pseudo stratified sampling (cf. fig. 5.3).

### *Pseudo Stratified Sampling*

The coarsest grid covering the division of  $n_g$  bins into  $n_f$  forks has  $n_g / \gcd(n_f, n_g) = \text{lcm}(n_f, n_g) / n_f$  bins per fork. Therefore, we need

$$\text{lcm}\left(\frac{\text{lcm}(n_f, n_g)}{n_f}, n_x\right) \quad (5.8)$$

divisions of the adaptive grid (if  $n_x$  is the number of bins in the original adaptive grid).

Life would be much easier, if we knew that  $n_f$  divides  $n_g$ . However, this is hard to maintain in real life applications. We can try to achieve this if possible, but the algorithms must be prepared to handle the general case.

53  $\langle \text{Setup to fork a pseudo stratified sampling division 53} \rangle \equiv$  (54)

```

nx = lcm (d%ng / gcd (num_forks, d%ng), num_div)
ds_ng = (d%ng * (/ (j, j=0,num_forks) /)) / num_forks
n = (nx * ds_ng) / d%ng
n0(1:num_forks) = n(0:num_forks-1)
n1(1:num_forks) = n(1:num_forks)
```

54a *<Fork a pseudo stratified sampling division 54a>≡* (50a)  
*<Setup to fork a pseudo stratified sampling division 53>*  
allocate (d\_x(0:nx), d\_integral(nx), d\_variance(nx))  
! allocate (d\_efficiency(nx))  
call **subdivide** (d\_x, d%x)  
call **distribute** (d\_integral, d%integral)  
call **distribute** (d\_variance, d%variance)  
! call **distribute** (d\_efficiency, d%efficiency)  
do i = 1, num\_forks  
call **copy\_array\_pointer** (ds(i)%x, d\_x(n0(i):n1(i)), lb = 0)  
call **copy\_array\_pointer** (ds(i)%integral, d\_integral(n0(i)+1:n1(i)))  
call **copy\_array\_pointer** (ds(i)%variance, d\_variance(n0(i)+1:n1(i)))  
! call **copy\_array\_pointer** (ds(i)%efficiency, d\_efficiency(n0(i)+1:n1(i)))  
ds(i)%x = (ds(i)%x - ds(i)%x(0)) / (d\_x(n1(i)) - d\_x(n0(i)))  
end do  
ds%x\_min = d%x\_min + d%dx \* d\_x(n0)  
ds%x\_max = d%x\_min + d%dx \* d\_x(n1)  
ds%dx = ds%x\_max - ds%x\_min  
ds%x\_min\_true = d%x\_min\_true  
ds%x\_max\_true = d%x\_max\_true  
ds%stratified = d%stratified  
ds%ng = ds\_ng(1:num\_forks) - ds\_ng(0:num\_forks-1)  
num\_calls = sum\_calls ! this is a misnomer, it remains “calls per cell” here  
ds%dxg = real (n1 - n0, kind=default) / ds%ng  
deallocate (d\_x, d\_integral, d\_variance)  
! deallocate (d\_efficiency)

54b *<Join pseudo stratified sampling divisions 54b>≡* (50b)  
*<Setup to fork a pseudo stratified sampling division 53>*  
allocate (d\_x(0:nx), d\_integral(nx), d\_variance(nx))  
! allocate (d\_efficiency(nx))  
do i = 1, num\_forks  
d\_integral(n0(i)+1:n1(i)) = ds(i)%integral  
d\_variance(n0(i)+1:n1(i)) = ds(i)%variance  
! d\_efficiency(n0(i)+1:n1(i)) = ds(i)%efficiency  
end do  
call **collect** (d%integral, d\_integral)  
call **collect** (d%variance, d\_variance)  
! call **collect** (d%efficiency, d\_efficiency)  
deallocate (d\_x, d\_integral, d\_variance)  
! deallocate (d\_efficiency)

54c *<Declaration of divisions procedures 38a>+≡* (37a) <49c 56a>  
private :: **subdivide**  
private :: **distribute**

```

private :: collect

55a  <Implementation of divisions procedures 38b>+≡ (37a) <50b 55b>
pure subroutine subdivide (x, x0)
  real(kind=default), dimension(0:), intent(inout) :: x
  real(kind=default), dimension(0:), intent(in) :: x0
  integer :: i, n, n0
  n0 = ubound (x0, dim=1)
  n = ubound (x, dim=1) / n0
  x(0) = x0(0)
  do i = 1, n
    x(i:n) = x0(0:n0-1) * real (n - i) / n + x0(1:n0) * real (i) / n
  end do
end subroutine subdivide

55b  <Implementation of divisions procedures 38b>+≡ (37a) <55a 55c>
pure subroutine distribute (x, x0)
  real(kind=default), dimension(:), intent(inout) :: x
  real(kind=default), dimension(:), intent(in) :: x0
  integer :: i, n
  n = ubound (x, dim=1) / ubound (x0, dim=1)
  do i = 1, n
    x(i:n) = x0 / n
  end do
end subroutine distribute

55c  <Implementation of divisions procedures 38b>+≡ (37a) <55b 55d>
pure subroutine collect (x0, x)
  real(kind=default), dimension(:), intent(inout) :: x0
  real(kind=default), dimension(:), intent(in) :: x
  integer :: i, n, n0
  n0 = ubound (x0, dim=1)
  n = ubound (x, dim=1) / n0
  do i = 1, n0
    x0(i) = sum (x((i-1)*n+1:i*n))
  end do
end subroutine collect

```

### Trivia

```

55d  <Implementation of divisions procedures 38b>+≡ (37a) <55c 56b>
pure subroutine sum_division (d, ds)
  type(division_t), intent(inout) :: d
  type(division_t), dimension(:), intent(in) :: ds
  integer :: i

```



```

    d%integral = 0.0
    d%variance = 0.0
!   d%efficiency = 0.0
    do i = 1, size (ds)
        d%integral = d%integral + ds(i)%integral
        d%variance = d%variance + ds(i)%variance
!       d%efficiency = d%efficiency + ds(i)%efficiency
    end do
end subroutine sum_division

```

56a *<Declaration of divisions procedures 38a>+≡* (37a) <54c 57a>

```

public :: debug_division
public :: dump_division

```

56b *<Implementation of divisions procedures 38b>+≡* (37a) <55d 56c>

```

subroutine debug_division (d, prefix)
    type(division_t), intent(in) :: d
    character(len=*), intent(in) :: prefix
    print "(1x,a,2(a,1x,i3,1x,f10.7))", prefix, ": d%x: ", &
        lbound(d%x,dim=1), d%x(lbound(d%x,dim=1)), &
        " ... ", &
        ubound(d%x,dim=1), d%x(ubound(d%x,dim=1))
    print "(1x,a,2(a,1x,i3,1x,f10.7))", prefix, ": d%i: ", &
        lbound(d%integral,dim=1), d%integral(lbound(d%integral,dim=1)), &
        " ... ", &
        ubound(d%integral,dim=1), d%integral(ubound(d%integral,dim=1))
    print "(1x,a,2(a,1x,i3,1x,f10.7))", prefix, ": d%v: ", &
        lbound(d%variance,dim=1), d%variance(lbound(d%variance,dim=1)), &
        " ... ", &
        ubound(d%variance,dim=1), d%variance(ubound(d%variance,dim=1))
!   print "(1x,a,2(a,1x,i3,1x,f10.7))", prefix, ": d%e: ", &
!       lbound(d%efficiency,dim=1), d%efficiency(lbound(d%efficiency,dim=1)), &
!       " ... ", &
!       ubound(d%efficiency,dim=1), d%efficiency(ubound(d%efficiency,dim=1))
end subroutine debug_division

```

56c *<Implementation of divisions procedures 38b>+≡* (37a) <56b 57b>

```

subroutine dump_division (d, prefix)
    type(division_t), intent(in) :: d
    character(len=*), intent(in) :: prefix
!   print "(2(1x,a),100(1x,f10.7))", prefix, ":x: ", d%x
    print "(2(1x,a),100(1x,f10.7))", prefix, ":x: ", d%x(1:)
    print "(2(1x,a),100(1x,e10.3))", prefix, ":i: ", d%integral
    print "(2(1x,a),100(1x,e10.3))", prefix, ":v: ", d%variance
!   print "(2(1x,a),100(1x,e10.3))", prefix, ":e: ", d%efficiency

```

end subroutine dump\_division

### 5.1.6 Inquiry

Trivial, but necessary for making divisions an abstract data type:

- 57a  $\langle$ Declaration of divisions procedures 38a $\rangle + \equiv$  (37a)  $\langle$ 56a 58b $\rangle$   
 public :: inside\_division, stratified\_division  
 public :: volume\_division, rigid\_division, adaptive\_division
- 57b  $\langle$ Implementation of divisions procedures 38b $\rangle + \equiv$  (37a)  $\langle$ 56c 57c $\rangle$   
 elemental function inside\_division (d, x) result (theta)  
   type(division\_t), intent(in) :: d  
   real(kind=default), intent(in) :: x  
   logical :: theta  
   theta = (x >= d%x\_min\_true) .and. (x <= d%x\_max\_true)  
 end function inside\_division
- 57c  $\langle$ Implementation of divisions procedures 38b $\rangle + \equiv$  (37a)  $\langle$ 57b 57d $\rangle$   
 elemental function stratified\_division (d) result (yorn)  
   type(division\_t), intent(in) :: d  
   logical :: yorn  
   yorn = d%stratified  
 end function stratified\_division
- 57d  $\langle$ Implementation of divisions procedures 38b $\rangle + \equiv$  (37a)  $\langle$ 57c 57e $\rangle$   
 elemental function volume\_division (d) result (vol)  
   type(division\_t), intent(in) :: d  
   real(kind=default) :: vol  
   vol = d%dx  
 end function volume\_division
- 57e  $\langle$ Implementation of divisions procedures 38b $\rangle + \equiv$  (37a)  $\langle$ 57d 57f $\rangle$   
 elemental function rigid\_division (d) result (n)  
   type(division\_t), intent(in) :: d  
   integer :: n  
   n = d%ng  
 end function rigid\_division
- 57f  $\langle$ Implementation of divisions procedures 38b $\rangle + \equiv$  (37a)  $\langle$ 57e 58c $\rangle$   
 elemental function adaptive\_division (d) result (n)  
   type(division\_t), intent(in) :: d  
   integer :: n  
   n = ubound (d%x, dim=1)  
 end function adaptive\_division

### 5.1.7 Diagnostics

- 58a *<Declaration of divisions types 37b>+≡* (37a) <37b>  

```

type, public :: div_history
  private
  logical :: stratified
  integer :: ng, num_div
  real(kind=default) :: x_min, x_max, x_min_true, x_max_true
  real(kind=default) :: &
    spread_f_p, stddev_f_p, spread_p, stddev_p, spread_m, stddev_m
end type div_history

```
- 58b *<Declaration of divisions procedures 38a>+≡* (37a) <57a 58d>  

```

public :: copy_history, summarize_division

```
- 58c *<Implementation of divisions procedures 38b>+≡* (37a) <57f 58e>  

```

elemental function summarize_division (d) result (s)
  type(division_t), intent(in) :: d
  type(div_history) :: s
  real(kind=default), dimension(:), allocatable :: p, m
  allocate (p(ubound(d%x,dim=1)), m(ubound(d%x,dim=1)))
  p = probabilities (d%x)
  m = rebinning_weights (d%variance)
  s%ng = d%ng
  s%num_div = ubound (d%x, dim=1)
  s%stratified = d%stratified
  s%x_min = d%x_min
  s%x_max = d%x_max
  s%x_min_true = d%x_min_true
  s%x_max_true = d%x_max_true
  s%spread_f_p = value_spread_percent (d%integral)
  s%stddev_f_p = standard_deviation_percent (d%integral)
  s%spread_p = value_spread_percent (p)
  s%stddev_p = standard_deviation_percent (p)
  s%spread_m = value_spread_percent (m)
  s%stddev_m = standard_deviation_percent (m)
  deallocate (p, m)
end function summarize_division

```
- 58d *<Declaration of divisions procedures 38a>+≡* (37a) <58b 60b>  

```

private :: probabilities

```
- 58e *<Implementation of divisions procedures 38b>+≡* (37a) <58c 59a>  

```

pure function probabilities (x) result (p)
  real(kind=default), dimension(0:), intent(in) :: x
  real(kind=default), dimension(ubound(x,dim=1)) :: p

```

```

integer :: num_div
num_div = ubound (x, dim=1)
p = 1.0 / (x(1:num_div) - x(0:num_div-1))
p = p / sum(p)
end function probabilities

```

59a *<Implementation of divisions procedures 38b>+≡* (37a) <58e 59b>

```

subroutine print_history (h, tag)
  type(div_history), dimension(:), intent(in) :: h
  character(len=*), intent(in), optional :: tag
  call write_history (output_unit, h, tag)
  flush (output_unit)
end subroutine print_history

```

59b *<Implementation of divisions procedures 38b>+≡* (37a) <59a 61c>

```

subroutine write_history (u, h, tag)
  integer, intent(in) :: u
  type(div_history), dimension(:), intent(in) :: h
  character(len=*), intent(in), optional :: tag
  character(len=BUFFER_SIZE) :: pfx
  character(len=1) :: s
  integer :: i
  if (present (tag)) then
    pfx = tag
  else
    pfx = "[vamp]"
  end if
  if ((minval (h%x_min) == maxval (h%x_min)) &
    .and. (minval (h%x_max) == maxval (h%x_max))) then
    write (u, "(1X,A11,1X,2X,1X,2(ES10.3,A4,ES10.3,A7))") pfx, &
      h(1)%x_min, " <= ", h(1)%x_min_true, &
      " < x < ", h(1)%x_max_true, " <= ", h(1)%x_max
  else
    do i = 1, size (h)
      write (u, "(1X,A11,1X,I2,1X,2(ES10.3,A4,ES10.3,A7))") pfx, &
        i, h(i)%x_min, " <= ", h(i)%x_min_true, &
        " < x < ", h(i)%x_max_true, " <= ", h(i)%x_max
    end do
  end if
  write (u, "(1X,A11,1X,A2,2(1X,A3),A1,6(1X,A8))") pfx, &
    "it", "nd", "ng", "", &
    "spr(f/p)", "dev(f/p)", "spr(m)", "dev(m)", "spr(p)", "dev(p)"
  iterations: do i = 1, size (h)
    if (h(i)%stratified) then
      s = "*"
    end if
  end do
end subroutine write_history

```

```

        else
            s = ""
        end if
        write (u, "(1X,A11,1X,I2,2(1X,I3),A1,6(1X,F7.2,A1))" pfx, &
            i, h(i)%num_div, h(i)%ng, s, &
            h(i)%spread_f_p, "%", h(i)%stddev_f_p, "%", &
            h(i)%spread_m, "%", h(i)%stddev_m, "%", &
            h(i)%spread_p, "%", h(i)%stddev_p, "%")
    end do iterations
    flush (u)
end subroutine write_history

```

60a *<Variables in divisions 46a>+≡ (37a) <46a 62a>*  
integer, private, parameter :: BUFFER\_SIZE = 50

60b *<Declaration of divisions procedures 38a>+≡ (37a) <58d 61a>*  
public :: print\_history, write\_history

60c *<Declaration of divisions procedures (removed from WHIZARD) 60c>≡*  
public :: division\_x, division\_integral  
public :: division\_variance, division\_efficiency

60d *<Implementation of divisions procedures (removed from WHIZARD) 45b>+≡ <45b 60e>*  
pure subroutine division\_x (x, d)  
real(kind=default), dimension(:), pointer :: x  
type(division\_t), intent(in) :: d  
call copy\_array\_pointer (x, d%x, 0)  
end subroutine division\_x

60e *<Implementation of divisions procedures (removed from WHIZARD) 45b>+≡ <60d 60f>*  
pure subroutine division\_integral (integral, d)  
real(kind=default), dimension(:), pointer :: integral  
type(division\_t), intent(in) :: d  
call copy\_array\_pointer (integral, d%integral)  
end subroutine division\_integral

60f *<Implementation of divisions procedures (removed from WHIZARD) 45b>+≡ <60e 60g>*  
pure subroutine division\_variance (variance, d)  
real(kind=default), dimension(:), pointer :: variance  
type(division\_t), intent(in) :: d  
call copy\_array\_pointer (variance, d%variance, 0)  
end subroutine division\_variance

60g *<Implementation of divisions procedures (removed from WHIZARD) 45b>+≡ <60f>*  
pure subroutine division\_efficiency (eff, d)  
real(kind=default), dimension(:), pointer :: eff  
type(division\_t), intent(in) :: d

```

    call copy_array_pointer (eff, d%efficiency, 0)
end subroutine division_efficiency

```

### 5.1.8 I/O

61a *<Declaration of divisions procedures 38a>+≡* (37a) <60b 66c>

```

public :: write_division
private :: write_division_unit, write_division_name
public :: read_division
private :: read_division_unit, read_division_name
public :: write_division_raw
private :: write_division_raw_unit, write_division_raw_name
public :: read_division_raw
private :: read_division_raw_unit, read_division_raw_name

```

61b *<Interfaces of divisions procedures 61b>≡* (37a)

```

interface write_division
    module procedure write_division_unit, write_division_name
end interface
interface read_division
    module procedure read_division_unit, read_division_name
end interface
interface write_division_raw
    module procedure write_division_raw_unit, write_division_raw_name
end interface
interface read_division_raw
    module procedure read_division_raw_unit, read_division_raw_name
end interface

```

It makes no sense to read or write d%**integral**, d%**variance**, and d%**efficiency**, because they are only used during sampling.

61c *<Implementation of divisions procedures 38b>+≡* (37a) <59b 62b>

```

subroutine write_division_unit (d, unit, write_integrals)
    type(division_t), intent(in) :: d
    integer, intent(in) :: unit
    logical, intent(in), optional :: write_integrals
    logical :: write_integrals0
    integer :: i
    write_integrals0 = .false.
    if (present(write_integrals)) write_integrals0 = write_integrals
    write (unit = unit, fmt = descr_fmt) "begin type(division_t) :: d"
    write (unit = unit, fmt = integer_fmt) "ubound(d%x,1) = ", ubound (d%x, dim=1)
    write (unit = unit, fmt = integer_fmt) "d%ng = ", d%ng
    write (unit = unit, fmt = logical_fmt) "d%stratified = ", d%stratified

```

```

write (unit = unit, fmt = double_fmt) "d%dx = ", d%dx
write (unit = unit, fmt = double_fmt) "d%dxg = ", d%dxg
write (unit = unit, fmt = double_fmt) "d%x_min = ", d%x_min
write (unit = unit, fmt = double_fmt) "d%x_max = ", d%x_max
write (unit = unit, fmt = double_fmt) "d%x_min_true = ", d%x_min_true
write (unit = unit, fmt = double_fmt) "d%x_max_true = ", d%x_max_true
write (unit = unit, fmt = descr_fmt) "begin d%x"
do i = 0, ubound (d%x, dim=1)
  if (write_integrals0 .and. i/=0) then
    write (unit = unit, fmt = double_array_fmt) &
      i, d%x(i), d%integral(i), d%variance(i)
  else
    write (unit = unit, fmt = double_array_fmt) i, d%x(i)
  end if
end do
write (unit = unit, fmt = descr_fmt) "end d%x"
write (unit = unit, fmt = descr_fmt) "end type(division_t)"
end subroutine write_division_unit

```

62a *<Variables in divisions 46a>+≡* (37a) *<60a*

```

character(len=*), parameter, private :: &
  descr_fmt = "(1x,a)", &
  integer_fmt = "(1x,a15,1x,i15)", &
  logical_fmt = "(1x,a15,1x,l1)", &
  double_fmt = "(1x,a15,1x,e30.22)", &
  double_array_fmt = "(1x,i15,1x,3(e30.22))"

```

62b *<Implementation of divisions procedures 38b>+≡* (37a) *<61c 63b>*

```

subroutine read_division_unit (d, unit, read_integrals)
  type(division_t), intent(inout) :: d
  integer, intent(in) :: unit
  logical, intent(in), optional :: read_integrals
  logical :: read_integrals0
  integer :: i, idum, num_div
  character(len=80) :: chdum
  read_integrals0 = .false.
  if (present(read_integrals)) read_integrals0 = read_integrals
  read (unit = unit, fmt = descr_fmt) chdum
  read (unit = unit, fmt = integer_fmt) chdum, num_div
  <Insure that ubound (d%x, dim=1) == num_div 63a>
  read (unit = unit, fmt = integer_fmt) chdum, d%ng
  read (unit = unit, fmt = logical_fmt) chdum, d%stratified
  read (unit = unit, fmt = double_fmt) chdum, d%dx
  read (unit = unit, fmt = double_fmt) chdum, d%dxg
  read (unit = unit, fmt = double_fmt) chdum, d%x_min

```

```

read (unit = unit, fmt = double_fmt) chdum, d%x_max
read (unit = unit, fmt = double_fmt) chdum, d%x_min_true
read (unit = unit, fmt = double_fmt) chdum, d%x_max_true
read (unit = unit, fmt = descr_fmt) chdum
do i = 0, ubound (d%x, dim=1)
  if (read_integrals0 .and. i/=0) then
    read (unit = unit, fmt = double_array_fmt) &
      & idum, d%x(i), d%integral(i), d%variance(i)
  else
    read (unit = unit, fmt = double_array_fmt) idum, d%x(i)
  end if
end do
read (unit = unit, fmt = descr_fmt) chdum
read (unit = unit, fmt = descr_fmt) chdum
if (.not.read_integrals0) then
  d%integral = 0.0
  d%variance = 0.0
!   d%efficiency = 0.0
end if
end subroutine read_division_unit

```



What happened to d%efficiency?

- 63a *<Insure that ubound (d%x, dim=1) == num\_div 63a>≡* (62b 65b 67b)
- ```

if (associated (d%x)) then
  if (ubound (d%x, dim=1) /= num_div) then
    deallocate (d%x, d%integral, d%variance)
!   deallocate (d%efficiency)
    allocate (d%x(0:num_div), d%integral(num_div), d%variance(num_div))
!   allocate (d%efficiency(num_div))
  end if
else
  allocate (d%x(0:num_div), d%integral(num_div), d%variance(num_div))
! allocate (d%efficiency(num_div))
end if

```
- 63b *<Implementation of divisions procedures 38b>+≡* (37a) <62b 64a>
- ```

subroutine write_division_name (d, name, write_integrals)
  type(division_t), intent(in) :: d
  character(len=*), intent(in) :: name
  logical, intent(in), optional :: write_integrals
  integer :: unit
  call find_free_unit (unit)
  open (unit = unit, action = "write", status = "replace", file = name)

```



```

        call write_division_unit (d, unit, write_integrals)
        close (unit = unit)
    end subroutine write_division_name
64a  <Implementation of divisions procedures 38b>+≡ (37a) <63b 64b>
    subroutine read_division_name (d, name, read_integrals)
        type(division_t), intent(inout) :: d
        character(len=*), intent(in) :: name
        logical, intent(in), optional :: read_integrals
        integer :: unit
        call find_free_unit (unit)
        open (unit = unit, action = "read", status = "old", file = name)
        call read_division_unit (d, unit, read_integrals)
        close (unit = unit)
    end subroutine read_division_name
64b  <Implementation of divisions procedures 38b>+≡ (37a) <64a 65b>
    subroutine write_division_raw_unit (d, unit, write_integrals)
        type(division_t), intent(in) :: d
        integer, intent(in) :: unit
        logical, intent(in), optional :: write_integrals
        logical :: write_integrals0
        integer :: i
        write_integrals0 = .false.
        if (present(write_integrals)) write_integrals0 = write_integrals
        write (unit = unit) MAGIC_DIVISION_BEGIN
        write (unit = unit) ubound (d%x, dim=1)
        write (unit = unit) d%ng
        write (unit = unit) d%stratified
        write (unit = unit) d%dx
        write (unit = unit) d%dxg
        write (unit = unit) d%x_min
        write (unit = unit) d%x_max
        write (unit = unit) d%x_min_true
        write (unit = unit) d%x_max_true
        do i = 0, ubound (d%x, dim=1)
            if (write_integrals0 .and. i/=0) then
                write (unit = unit) d%x(i), d%integral(i), d%variance(i)
            else
                write (unit = unit) d%x(i)
            end if
        end do
        write (unit = unit) MAGIC_DIVISION_END
    end subroutine write_division_raw_unit

```

```

65a  <Constants in divisions 65a>≡ (37a)
      integer, parameter, private :: MAGIC_DIVISION = 11111111
      integer, parameter, private :: MAGIC_DIVISION_BEGIN = MAGIC_DIVISION + 1
      integer, parameter, private :: MAGIC_DIVISION_END = MAGIC_DIVISION + 2

65b  <Implementation of divisions procedures 38b>+≡ (37a) <64b 66a>
      subroutine read_division_raw_unit (d, unit, read_integrals)
        type(division_t), intent(inout) :: d
        integer, intent(in) :: unit
        logical, intent(in), optional :: read_integrals
        logical :: read_integrals0
        integer :: i, num_div, magic
        character(len=*), parameter :: FN = "read_division_raw_unit"
        read_integrals0 = .false.
        if (present(read_integrals)) read_integrals0 = read_integrals
        read (unit = unit) magic
        if (magic /= MAGIC_DIVISION_BEGIN) then
          print *, FN, " fatal: expecting magic ", MAGIC_DIVISION_BEGIN, &
            ", found ", magic
          stop
        end if
        read (unit = unit) num_div
        <Insure that ubound (d%x, dim=1) == num_div 63a>
        read (unit = unit) d%ng
        read (unit = unit) d%stratified
        read (unit = unit) d%dx
        read (unit = unit) d%dxg
        read (unit = unit) d%x_min
        read (unit = unit) d%x_max
        read (unit = unit) d%x_min_true
        read (unit = unit) d%x_max_true
        do i = 0, ubound (d%x, dim=1)
          if (read_integrals0 .and. i/=0) then
            read (unit = unit) d%x(i), d%integral(i), d%variance(i)
          else
            read (unit = unit) d%x(i)
          end if
        end do
        if (.not.read_integrals0) then
          d%integral = 0.0
          d%variance = 0.0
        !   d%efficiency = 0.0
        end if
        read (unit = unit) magic

```

```

        if (magic /= MAGIC_DIVISION_END) then
            print *, FN, " fatal: expecting magic ", MAGIC_DIVISION_END, &
                ", found ", magic
            stop
        end if
    end subroutine read_division_raw_unit
66a  <Implementation of divisions procedures 38b>+≡ (37a) <65b 66b>
        subroutine write_division_raw_name (d, name, write_integrals)
            type(division_t), intent(in) :: d
            character(len=*), intent(in) :: name
            logical, intent(in), optional :: write_integrals
            integer :: unit
            call find_free_unit (unit)
            open (unit = unit, action = "write", status = "replace", &
                form = "unformatted", file = name)
            call write_division_unit (d, unit, write_integrals)
            close (unit = unit)
        end subroutine write_division_raw_name
66b  <Implementation of divisions procedures 38b>+≡ (37a) <66a 66d>
        subroutine read_division_raw_name (d, name, read_integrals)
            type(division_t), intent(inout) :: d
            character(len=*), intent(in) :: name
            logical, intent(in), optional :: read_integrals
            integer :: unit
            call find_free_unit (unit)
            open (unit = unit, action = "read", status = "old", &
                form = "unformatted", file = name)
            call read_division_unit (d, unit, read_integrals)
            close (unit = unit)
        end subroutine read_division_raw_name

```

### 5.1.9 Marshaling

Note that we can not use the `transfer` intrinsic function for marshalling types that contain pointers that substitute for allocatable array components. `transfer` will copy the pointers in this case and not where they point to!

```

66c  <Declaration of divisions procedures 38a>+≡ (37a) <61a 68a>
        public :: marshal_division_size, marshal_division, unmarshal_division
66d  <Implementation of divisions procedures 38b>+≡ (37a) <66b 67a>
        pure subroutine marshal_division (d, ibuf, dbuf)
            type(division_t), intent(in) :: d

```

```

integer, dimension(:), intent(inout) :: ibuf
real(kind=default), dimension(:), intent(inout) :: dbuf
integer :: num_div
num_div = ubound (d%x, dim=1)
ibuf(1) = d%ng
ibuf(2) = num_div
if (d%stratified) then
    ibuf(3) = 1
else
    ibuf(3) = 0
end if
dbuf(1) = d%x_min
dbuf(2) = d%x_max
dbuf(3) = d%x_min_true
dbuf(4) = d%x_max_true
dbuf(5) = d%dx
dbuf(6) = d%dxg
dbuf(7:7+num_div) = d%x
dbuf(8+ num_div:7+2*num_div) = d%integral
dbuf(8+2*num_div:7+3*num_div) = d%variance
! dbuf(8+3*num_div:7+4*num_div) = d%efficiency
end subroutine marshal_division

```

67a *<Implementation of divisions procedures 38b>+≡* (37a) <66d 67b>

```

pure subroutine marshal_division_size (d, iwords, dwords)
    type(division_t), intent(in) :: d
    integer, intent(out) :: iwords, dwords
    iwords = 3
    dwords = 7 + 3 * ubound (d%x, dim=1)
    ! dwords = 7 + 4 * ubound (d%x, dim=1)
end subroutine marshal_division_size

```

67b *<Implementation of divisions procedures 38b>+≡* (37a) <67a 68b>

```

pure subroutine unmarshal_division (d, ibuf, dbuf)
    type(division_t), intent(inout) :: d
    integer, dimension(:), intent(in) :: ibuf
    real(kind=default), dimension(:), intent(in) :: dbuf
    integer :: num_div
    d%ng = ibuf(1)
    num_div = ibuf(2)
    d%stratified = ibuf(3) /= 0
    d%x_min = dbuf(1)
    d%x_max = dbuf(2)
    d%x_min_true = dbuf(3)
    d%x_max_true = dbuf(4)

```

```

    d%dx = dbuf(5)
    d%dxg = dbuf(6)
    <Insure that ubound (d%x, dim=1) == num_div 63a>
    d%x = dbuf(7:7+num_div)
    d%integral = dbuf(8+ num_div:7+2*num_div)
    d%variance = dbuf(8+2*num_div:7+3*num_div)
    ! d%efficiency = dbuf(8+3*num_div:7+4*num_div)
end subroutine unmarshal_division

68a <Declaration of divisions procedures 38a>+≡ (37a) <66c
    public :: marshal_div_history_size, marshal_div_history, unmarshal_div_history

68b <Implementation of divisions procedures 38b>+≡ (37a) <67b 68c>
    pure subroutine marshal_div_history (h, ibuf, dbuf)
        type(div_history), intent(in) :: h
        integer, dimension(:), intent(inout) :: ibuf
        real(kind=default), dimension(:), intent(inout) :: dbuf
        ibuf(1) = h%ng
        ibuf(2) = h%num_div
        if (h%stratified) then
            ibuf(3) = 1
        else
            ibuf(3) = 0
        end if
        dbuf(1) = h%x_min
        dbuf(2) = h%x_max
        dbuf(3) = h%x_min_true
        dbuf(4) = h%x_max_true
        dbuf(5) = h%spread_f_p
        dbuf(6) = h%stddev_f_p
        dbuf(7) = h%spread_p
        dbuf(8) = h%stddev_p
        dbuf(9) = h%spread_m
        dbuf(10) = h%stddev_m
    end subroutine marshal_div_history

68c <Implementation of divisions procedures 38b>+≡ (37a) <68b 68d>
    pure subroutine marshal_div_history_size (h, iwords, dwords)
        type(div_history), intent(in) :: h
        integer, intent(out) :: iwords, dwords
        iwords = 3
        dwords = 10
    end subroutine marshal_div_history_size

68d <Implementation of divisions procedures 38b>+≡ (37a) <68c 69>
    pure subroutine unmarshal_div_history (h, ibuf, dbuf)

```

```

type(div_history), intent(inout) :: h
integer, dimension(:), intent(in) :: ibuf
real(kind=default), dimension(:), intent(in) :: dbuf
h%ng = ibuf(1)
h%num_div = ibuf(2)
h%stratified = ibuf(3) /= 0
h%x_min = dbuf(1)
h%x_max = dbuf(2)
h%x_min_true = dbuf(3)
h%x_max_true = dbuf(4)
h%spread_f_p = dbuf(5)
h%stddev_f_p = dbuf(6)
h%spread_p = dbuf(7)
h%stddev_p = dbuf(8)
h%spread_m = dbuf(9)
h%stddev_m = dbuf(10)
end subroutine unmarshal_div_history

```

### 5.1.10 Boring Copying and Deleting of Objects

69 *<Implementation of divisions procedures 38b>+≡ (37a) <68d 70a>*

```

elemental subroutine copy_division (lhs, rhs)
  type(division_t), intent(inout) :: lhs
  type(division_t), intent(in) :: rhs
  if (associated (rhs%x)) then
    call copy_array_pointer (lhs%x, rhs%x, lb = 0)
  else if (associated (lhs%x)) then
    deallocate (lhs%x)
  end if
  if (associated (rhs%integral)) then
    call copy_array_pointer (lhs%integral, rhs%integral)
  else if (associated (lhs%integral)) then
    deallocate (lhs%integral)
  end if
  if (associated (rhs%variance)) then
    call copy_array_pointer (lhs%variance, rhs%variance)
  else if (associated (lhs%variance)) then
    deallocate (lhs%variance)
  end if
! if (associated (rhs%efficiency)) then
!   call copy_array_pointer (lhs%efficiency, rhs%efficiency)
! else if (associated (lhs%efficiency)) then
!   deallocate (lhs%efficiency)

```

```

! end if
  lhs%dx = rhs%dx
  lhs%dxg = rhs%dxg
  lhs%x_min = rhs%x_min
  lhs%x_max = rhs%x_max
  lhs%x_min_true = rhs%x_min_true
  lhs%x_max_true = rhs%x_max_true
  lhs%ng = rhs%ng
  lhs%stratified = rhs%stratified
end subroutine copy_division

```

70a  $\langle$ Implementation of divisions procedures 38b $\rangle + \equiv$  (37a)  $\triangleleft$ 69 70b $\triangleright$

```

elemental subroutine delete_division (d)
  type(division_t), intent(inout) :: d
  if (associated (d%x)) then
    deallocate (d%x, d%integral, d%variance)
!    deallocate (d%efficiency)
  end if
end subroutine delete_division

```

70b  $\langle$ Implementation of divisions procedures 38b $\rangle + \equiv$  (37a)  $\triangleleft$ 70a

```

elemental subroutine copy_history (lhs, rhs)
  type(div_history), intent(out) :: lhs
  type(div_history), intent(in) :: rhs
  lhs%stratified = rhs%stratified
  lhs%ng = rhs%ng
  lhs%num_div = rhs%num_div
  lhs%x_min = rhs%x_min
  lhs%x_max = rhs%x_max
  lhs%x_min_true = rhs%x_min_true
  lhs%x_max_true = rhs%x_max_true
  lhs%spread_f_p = rhs%spread_f_p
  lhs%stddev_f_p = rhs%stddev_f_p
  lhs%spread_p = rhs%spread_p
  lhs%stddev_p = rhs%stddev_p
  lhs%spread_m = rhs%spread_m
  lhs%stddev_m = rhs%stddev_m
end subroutine copy_history

```

## 5.2 The Abstract Datatype *vamp\_grid*

70c  $\langle$ vamp.f90 70c $\rangle \equiv$  71a $\triangleright$

```
! vamp.f90 --
<Copyleft notice 1>
```

⚡ NAG f95 requires this split. Check with the Fortran community, if it is really necessary, or a bug! The problem is that this split forces us to expose the components of **vamp\_grid**.

**NB:** with the introduction of **vamp\_equivalences**, this question has (probably) become academic.

```
71a <vamp.f90 70c>+≡ <70c 71b>
    module vamp_grid_type
        use kinds
        use divisions
        private
        <Declaration of vamp_grid_type types 76b>
    end module vamp_grid_type
```

⚡ By WK for WHIZARD.

```
71b <vamp.f90 70c>+≡ <71a 75b>
    module vamp_equivalences
        use kinds
        use divisions
        use vamp_grid_type !NODEP!
        implicit none
        private
        <Declaration of vamp_equivalences procedures 72d>
        <Constants in vamp_equivalences 72b>
        <Declaration of vamp_equivalences types 71c>
        character(len=*), public, parameter :: VAMP_EQUIVALENCES_RCS_ID = &
            "$Id: vamp.nw 317 2010-04-18 00:31:03Z ohl $"
    contains
        <Implementation of vamp_equivalences procedures 72c>
    end module vamp_equivalences
```

```
71c <Declaration of vamp_equivalences types 71c>≡ (71b) 72a>
    type, public :: vamp_equivalence_t
        integer :: left, right
        integer, dimension(:), allocatable :: permutation
        integer, dimension(:), allocatable :: mode
    end type vamp_equivalence_t
```



72a  $\langle$ Declaration of `vamp_equivalences` types 71c $\rangle + \equiv$  (71b)  $\triangleleft$  71c

```

type, public :: vamp_equivalences_t
  type(vamp_equivalence_t), dimension(:), allocatable :: eq
  integer :: n_eq, n_ch
  integer, dimension(:), allocatable :: pointer
  logical, dimension(:), allocatable :: independent
  integer, dimension(:), allocatable :: equivalent_to_ch
  integer, dimension(:), allocatable :: multiplicity
  integer, dimension(:), allocatable :: symmetry
  logical, dimension(:, :), allocatable :: div_is_invariant
end type vamp_equivalences_t

```

72b  $\langle$ Constants in `vamp_equivalences` 72b $\rangle \equiv$  (71b)

```

integer, parameter, public :: &
  VEQ_IDENTITY = 0, VEQ_INVERT = 1, VEQ_SYMMETRIC = 2, VEQ_INVARIANT = 3

```

72c  $\langle$ Implementation of `vamp_equivalences` procedures 72c $\rangle \equiv$  (71b) 72e $\triangleright$

```

subroutine vamp_equivalence_init (eq, n_dim)
  type(vamp_equivalence_t), intent(inout) :: eq
  integer, intent(in) :: n_dim
  allocate (eq%permutation(n_dim), eq%mode(n_dim))
end subroutine vamp_equivalence_init

```

72d  $\langle$ Declaration of `vamp_equivalences` procedures 72d $\rangle \equiv$  (71b) 73b $\triangleright$

```

public :: vamp_equivalences_init

```

72e  $\langle$ Implementation of `vamp_equivalences` procedures 72c $\rangle + \equiv$  (71b)  $\triangleleft$  72c 73a $\triangleright$

```

subroutine vamp_equivalences_init (eq, n_eq, n_ch, n_dim)
  type(vamp_equivalences_t), intent(inout) :: eq
  integer, intent(in) :: n_eq, n_ch, n_dim
  integer :: i
  eq%n_eq = n_eq
  eq%n_ch = n_ch
  allocate (eq%eq(n_eq))
  allocate (eq%pointer(n_ch+1))
  do i=1, n_eq
    call vamp_equivalence_init (eq%eq(i), n_dim)
  end do
  allocate (eq%independent(n_ch), eq%equivalent_to_ch(n_ch))
  allocate (eq%multiplicity(n_ch), eq%symmetry(n_ch))
  allocate (eq%div_is_invariant(n_ch, n_dim))
  eq%independent = .true.
  eq%equivalent_to_ch = 0
  eq%multiplicity = 0
  eq%symmetry = 0
  eq%div_is_invariant = .false.

```

```

end subroutine vamp_equivalences_init

73a <Implementation of vamp_equivalences procedures 72c>+≡ (71b) <72e 73c>
subroutine vamp_equivalence_final (eq)
  type(vamp_equivalence_t), intent(inout) :: eq
  deallocate (eq%permutation, eq%mode)
end subroutine vamp_equivalence_final

73b <Declaration of vamp_equivalences procedures 72d>+≡ (71b) <72d 73e>
public :: vamp_equivalences_final

73c <Implementation of vamp_equivalences procedures 72c>+≡ (71b) <73a 73d>
subroutine vamp_equivalences_final (eq)
  type(vamp_equivalences_t), intent(inout) :: eq
  ! integer :: i
  ! do i=1, eq%n_eq
  !   call vamp_equivalence_final (eq%eq(i))
  ! end do
  if (allocated (eq%eq)) deallocate (eq%eq)
  if (allocated (eq%pointer)) deallocate (eq%pointer)
  if (allocated (eq%multiplicity)) deallocate (eq%multiplicity)
  if (allocated (eq%symmetry)) deallocate (eq%symmetry)
  if (allocated (eq%independent)) deallocate (eq%independent)
  if (allocated (eq%equivalent_to_ch)) deallocate (eq%equivalent_to_ch)
  if (allocated (eq%div_is_invariant)) deallocate (eq%div_is_invariant)
  eq%n_eq = 0
  eq%n_ch = 0
end subroutine vamp_equivalences_final

73d <Implementation of vamp_equivalences procedures 72c>+≡ (71b) <73c 73f>
subroutine vamp_equivalence_write (eq, unit)
  integer, intent(in), optional :: unit
  integer :: u
  type(vamp_equivalence_t), intent(in) :: eq
  u = 6; if (present (unit)) u = unit
  write (u, "(3x,A,2(1x,I0))") "Equivalent channels:", eq%left, eq%right
  write (u, "(5x,A,99(1x,I0))") "Permutation:", eq%permutation
  write (u, "(5x,A,99(1x,I0))") "Mode:          ", eq%mode
end subroutine vamp_equivalence_write

73e <Declaration of vamp_equivalences procedures 72d>+≡ (71b) <73b 74a>
public :: vamp_equivalences_write

73f <Implementation of vamp_equivalences procedures 72c>+≡ (71b) <73d 74b>
subroutine vamp_equivalences_write (eq, unit)
  type(vamp_equivalences_t), intent(in) :: eq
  integer, intent(in), optional :: unit

```

```

integer :: u
integer :: ch, i
u = 6; if (present (unit)) u = unit
write (u, "(1x,A)") "Inequivalent channels:"
if (allocated (eq%independent)) then
  do ch=1, eq%n_ch
    if (eq%independent(ch)) then
      write (u, "(3x,A,1x,I0,A,4x,A,I0,4x,A,I0,4x,A,999(L1))") &
        "Channel", ch, ":", &
        "Mult. = ", eq%multiplicity(ch), &
        "Symm. = ", eq%symmetry(ch), &
        "Invar.: ", eq%div_is_invariant(ch,:)
    end if
  end do
else
  write (u, "(3x,A)") "[not allocated]"
end if
write (u, "(1x,A)") "Equivalence list:"
if (allocated (eq%eq)) then
  do i=1, size (eq%eq)
    call vamp_equivalence_write (eq%eq(i), u)
  end do
else
  write (u, "(3x,A)") "[not allocated]"
end if
end subroutine vamp_equivalences_write

```

74a  $\langle$ Declaration of vamp\_equivalences procedures 72d $\rangle + \equiv$  (71b)  $\langle$ 73e 74c $\rangle$   
 public :: vamp\_equivalence\_set

74b  $\langle$ Implementation of vamp\_equivalences procedures 72c $\rangle + \equiv$  (71b)  $\langle$ 73f 75a $\rangle$   
 subroutine vamp\_equivalence\_set (eq, i, left, right, perm, mode)  
 type(vamp\_equivalences\_t), intent(inout) :: eq  
 integer, intent(in) :: i  
 integer, intent(in) :: left, right  
 integer, dimension(:), intent(in) :: perm, mode  
 eq%eq(i)%left = left  
 eq%eq(i)%right = right  
 eq%eq(i)%permutation = perm  
 eq%eq(i)%mode = mode  
end subroutine vamp\_equivalence\_set

74c  $\langle$ Declaration of vamp\_equivalences procedures 72d $\rangle + \equiv$  (71b)  $\langle$ 74a $\rangle$   
 public :: vamp\_equivalences\_complete

75a *<Implementation of vamp\_equivalences procedures 72c>+≡*

(71b) <74b

```

subroutine vamp_equivalences_complete (eq)
  type(vamp_equivalences_t), intent(inout) :: eq
  integer :: i, ch
  ch = 0
  do i=1, eq%n_eq
    if (ch /= eq%eq(i)%left) then
      ch = eq%eq(i)%left
      eq%pointer(ch) = i
    end if
  end do
  eq%pointer(ch+1) = eq%n_eq + 1
  do ch=1, eq%n_ch
    call set_multiplicities (eq%eq(eq%pointer(ch):eq%pointer(ch+1)-1))
  end do
  ! call write (6, eq)
contains
  subroutine set_multiplicities (eq_ch)
    type(vamp_equivalence_t), dimension(:), intent(in) :: eq_ch
    integer :: i
    if (.not. all(eq_ch%left == ch) .or. eq_ch(1)%right > ch) then
      do i = 1, size (eq_ch)
        call vamp_equivalence_write (eq_ch(i))
      end do
      stop "VAMP: Equivalences: Something's wrong with equivalence ordering"
    end if
    eq%symmetry(ch) = count (eq_ch%right == ch)
    if (mod (size(eq_ch), eq%symmetry(ch)) /= 0) then
      do i = 1, size (eq_ch)
        call vamp_equivalence_write (eq_ch(i))
      end do
      stop "VAMP: Equivalences: Something's wrong with permutation count"
    end if
    eq%multiplicity(ch) = size (eq_ch) / eq%symmetry(ch)
    eq%independent(ch) = all (eq_ch%right >= ch)
    eq%equivalent_to_ch(ch) = eq_ch(1)%right
    eq%div_is_invariant(ch,:) = eq_ch(1)%mode == VEQ_INVARIANT
  end subroutine set_multiplicities
end subroutine vamp_equivalences_complete

```

75b *<vamp.f90 70c>+≡*

<71b 76a>

```

module vamp_rest
  use kinds
  use utils

```

```

    use exceptions
    use divisions
    use tao_random_numbers
    use vamp_stat
    use linalg
    use iso_fortran_env
    use vamp_grid_type !NODEP!
    use vamp_equivalences !NODEP!
    implicit none
    private
    <Declaration of vamp procedures 77a>
    <Interfaces of vamp procedures 96b>
    <Constants in vamp 153a>
    <Declaration of vamp types 77b>
    <Variables in vamp 79a>
    character(len=*), public, parameter :: VAMP_RCS_ID = &
        "$Id: vamp.nw 317 2010-04-18 00:31:03Z ohl $"
contains
    <Implementation of vamp procedures 78b>
end module vamp_rest
76a <vamp.f90 70c>+≡ <75b
    module vamp
        use vamp_grid_type !NODEP!
        use vamp_rest !NODEP!
        use vamp_equivalences !NODEP!
        public
    end module vamp

```

N.B.: In Fortran95 we will be able to give default initializations to components of the type. In particular, we can use the `null ()` intrinsic to initialize the pointers to a disassociated state. Until then, the user *must* call the initializer `vamp_create_grid` himself of herself, because we can't check for the allocation status of the pointers in Fortran90 or F.

⚡ Augment this datatype by `real(kind=default), dimension(2) :: mu_plus, mu_minus` to record positive and negative weight separately, so that we can estimate the efficiency for reweighting from indefinite weights to  $\{+1, -1\}$ . [WK 2015/11/06: done. Those values are recorded but not used inside `vamp`. They can be retrieved by the caller.]

⚡ WK 2015/11/06: `f_min` and `f_max` work with the absolute value of the matrix element, so they record the minimum and maximum absolute value.

76b <Declaration of vamp\_grid\_type types 76b>≡ (71a)

```

type, public :: vamp_grid
  ! private ! forced by use association in interface
  type(division_t), dimension(:), pointer :: div => null ()
  real(kind=default), dimension(:,:), pointer :: map => null ()
  real(kind=default), dimension(:), pointer :: mu_x => null ()
  real(kind=default), dimension(:), pointer :: sum_mu_x => null ()
  real(kind=default), dimension(:,:), pointer :: mu_xx => null ()
  real(kind=default), dimension(:,:), pointer :: sum_mu_xx => null ()
  real(kind=default), dimension(2) :: mu
  real(kind=default), dimension(2) :: mu_plus, mu_minus
  real(kind=default) :: sum_integral, sum_weights, sum_chi2
  real(kind=default) :: calls, dv2g, jacobi
  real(kind=default) :: f_min, f_max
  real(kind=default) :: mu_gi, sum_mu_gi
  integer, dimension(:), pointer :: num_div => null ()
  integer :: num_calls, calls_per_cell
  logical :: stratified = .true.
  logical :: all_stratified = .true.
  logical :: quadrupole = .false.
  logical :: independent
  integer :: equivalent_to_ch, multiplicity
end type vamp_grid

```

77a  $\langle$ Declaration of vamp procedures 77a $\rangle \equiv$  (75b) 78a $\triangleright$   
 public :: vamp\_copy\_grid, vamp\_delete\_grid

### 5.2.1 Container for application data



By WK for WHIZARD. We define an empty data type that the application can extend according to its needs. The purpose is to hold all sorts of data that are predefined and accessed during the call of the sampling function.

The actual interface for the sampling function is PURE. Nevertheless, we can implement side effects via pointer components of a `vamp_data_t` extension.

77b  $\langle$ Declaration of vamp types 77b $\rangle \equiv$  (75b) 77c $\triangleright$   
 type, public :: vamp\_data\_t  
 end type vamp\_data\_t

This is the object to be passed if we want nothing else:

77c  $\langle$ Declaration of vamp types 77b $\rangle + \equiv$  (75b)  $\langle$ 77b 106c $\rangle$   
 type(vamp\_data\_t), parameter, public :: NO\_DATA = vamp\_data\_t ()

## 5.2.2 Initialization

78a  $\langle$ Declaration of `vamp` procedures 77a $\rangle + \equiv$  (75b)  $\langle$ 77a 79b $\rangle$   
`public :: vamp_create_grid, vamp_create_empty_grid`

Create a fresh grid for the integration domain

$$\mathcal{D} = [D_{1,1}, D_{2,1}] \times [D_{1,2}, D_{2,2}] \times \dots \times [D_{1,n}, D_{2,n}] \quad (5.9)$$

dropping all accumulated results. This function *must not* be called twice on the first argument, without an intervening `vamp_delete_grid`. If the second variable is given, it will be the number of sampling points for the call to `vamp_sample_grid`.

78b  $\langle$ Implementation of `vamp` procedures 78b $\rangle \equiv$  (75b) 79c $\rangle$   
`pure subroutine vamp_create_grid &  
 (g, domain, num_calls, num_div, &  
 stratified, quadrupole, covariance, map, exc)  
 type(vamp_grid), intent(inout) :: g  
 real(kind=default), dimension(:,:), intent(in) :: domain  
 integer, intent(in) :: num_calls  
 integer, dimension(:), intent(in), optional :: num_div  
 logical, intent(in), optional :: stratified, quadrupole, covariance  
 real(kind=default), dimension(:,:), intent(in), optional :: map  
 type(exception), intent(inout), optional :: exc  
 character(len=*), parameter :: FN = "vamp_create_grid"  
 real(kind=default), dimension(size(domain,dim=2)) :: &  
 x_min, x_max, x_min_true, x_max_true  
 integer :: ndim  
 ndim = size (domain, dim=2)  
 allocate (g%div(ndim), g%num_div(ndim))  
 x_min = domain(1,:)
 x_max = domain(2,:)
 if (present (map)) then
 allocate (g%map(ndim,ndim))
 g%map = map
 x_min_true = x_min
 x_max_true = x_max
 call map_domain (g%map, x_min_true, x_max_true, x_min, x_max)
 call create_division (g%div, x_min, x_max, x_min_true, x_max_true)
 else
 nullify (g%map)
 call create_division (g%div, x_min, x_max)
 end if
 g%num_calls = num_calls`

```

if (present (num_div)) then
  g%num_div = num_div
else
  g%num_div = NUM_DIV_DEFAULT
end if
g%stratified = .true.
g%quadrupole = .false.
g%independent = .true.
g%equivalent_to_ch = 0
g%multiplicity = 1
nullify (g%mu_x, g%mu_xx, g%sum_mu_x, g%sum_mu_xx)
call vamp_discard_integral &
  (g, num_calls, num_div, stratified, quadrupole, covariance, exc)
end subroutine vamp_create_grid

```

Below, we assume that `NUM_DIV_DEFAULT`  $\geq 6$ , but we will never go that low anyway.

79a  $\langle$  Variables in `vamp` 79a  $\rangle \equiv$  (75b) 94c  $\rangle$   
 integer, private, parameter :: `NUM_DIV_DEFAULT` = 20

Given a linear map  $M$ , find a domain  $\mathcal{D}_0$  such that

$$\mathcal{D} \subset M\mathcal{D}_0 \quad (5.10)$$

79b  $\langle$  Declaration of `vamp` procedures 77a  $\rangle + \equiv$  (75b)  $\langle$  78a 80b  $\rangle$   
 private :: `map_domain`

If we can assume that  $M$  is orthogonal  $M^{-1} = M^T$ , then we just have to rotate  $\mathcal{D}$  and determine the maximal and minimal extension of the corners:

$$\mathcal{D}_0^T = \overline{\mathcal{D}^T M} \quad (5.11)$$

The corners are just the powerset of the maximal and minimal extension in each coordinate. It is determined most easily with binary counting:

79c  $\langle$  Implementation of `vamp` procedures 78b  $\rangle + \equiv$  (75b)  $\langle$  78b 80a  $\rangle$   
 pure subroutine `map_domain` (map, true\_xmin, true\_xmax, xmin, xmax)  
 real(kind=default), dimension(:, :), intent(in) :: map  
 real(kind=default), dimension(:), intent(in) :: true\_xmin, true\_xmax  
 real(kind=default), dimension(:), intent(out) :: xmin, xmax  
 real(kind=default), dimension(2\*\*size(xmin), size(xmin)) :: corners  
 integer, dimension(size(xmin)) :: zero\_to\_n  
 integer :: j, ndim, perm  
 ndim = size (xmin)  
 zero\_to\_n = (/ (j, j=0, ndim-1) /)  
 do perm = 1, 2\*\*ndim  
 corners (perm, :) = &



```

        merge (true_xmin, true_xmax, btest (perm-1, zero_to_n))
    end do
    corners = matmul (corners, map)
    xmin = minval (corners, dim=1)
    xmax = maxval (corners, dim=1)
end subroutine map_domain

80a <Implementation of vamp procedures 78b>+≡ (75b) <79c 80c>
    elemental subroutine vamp_create_empty_grid (g)
        type(vamp_grid), intent(inout) :: g
        nullify (g%div, g%num_div, g%map, g%mu_x, g%mu_xx, g%sum_mu_x, g%sum_mu_xx)
    end subroutine vamp_create_empty_grid

80b <Declaration of vamp procedures 77a>+≡ (75b) <79b 81a>
    public :: vamp_discard_integral

Keep the current optimized grid, but drop the accumulated results for the
integral (value and errors). If the second variable is given, it will be the new
number of sampling points for the next call to vamp_sample_grid.

80c <Implementation of vamp procedures 78b>+≡ (75b) <80a 81b>
    pure subroutine vamp_discard_integral &
        (g, num_calls, num_div, stratified, quadrupole, covariance, exc, &
         & independent, equivalent_to_ch, multiplicity)
    type(vamp_grid), intent(inout) :: g
    integer, intent(in), optional :: num_calls
    integer, dimension(:), intent(in), optional :: num_div
    logical, intent(in), optional :: stratified, quadrupole, covariance
    type(exception), intent(inout), optional :: exc
    logical, intent(in), optional :: independent
    integer, intent(in), optional :: equivalent_to_ch, multiplicity
    character(len=*), parameter :: FN = "vamp_discard_integral"
    g%mu = 0.0
    g%mu_plus = 0.0
    g%mu_minus = 0.0
    g%mu_gi = 0.0
    g%sum_integral = 0.0
    g%sum_weights = 0.0
    g%sum_chi2 = 0.0
    g%sum_mu_gi = 0.0
    if (associated (g%sum_mu_x)) then
        g%sum_mu_x = 0.0
        g%sum_mu_xx = 0.0
    end if
    call set_grid_options (g, num_calls, num_div, stratified, quadrupole, &
        independent, equivalent_to_ch, multiplicity)

```

```

    if ((present (num_calls)) &
        .or. (present (num_div)) &
        .or. (present (stratified)) &
        .or. (present (quadrupole)) &
        .or. (present (covariance))) then
        call vamp_reshape_grid &
            (g, g%num_calls, g%num_div, &
             g%stratified, g%quadrupole, covariance, exc)
    end if
end subroutine vamp_discard_integral
81a  <Declaration of vamp procedures 77a>+≡ (75b) <80b 83a>
    private :: set_grid_options
81b  <Implementation of vamp procedures 78b>+≡ (75b) <80c 82>
    pure subroutine set_grid_options &
        (g, num_calls, num_div, stratified, quadrupole, &
         independent, equivalent_to_ch, multiplicity)
    type(vamp_grid), intent(inout) :: g
    integer, intent(in), optional :: num_calls
    integer, dimension(:), intent(in), optional :: num_div
    logical, intent(in), optional :: stratified, quadrupole
    logical, intent(in), optional :: independent
    integer, intent(in), optional :: equivalent_to_ch, multiplicity
    if (present (num_calls)) then
        g%num_calls = num_calls
    end if
    if (present (num_div)) then
        g%num_div = num_div
    end if
    if (present (stratified)) then
        g%stratified = stratified
    end if
    if (present (quadrupole)) then
        g%quadrupole = quadrupole
    end if
    if (present (independent)) then
        g%independent = independent
    end if
    if (present (equivalent_to_ch)) then
        g%equivalent_to_ch = equivalent_to_ch
    end if
    if (present (multiplicity)) then
        g%multiplicity = multiplicity
    end if

```

```
end subroutine set_grid_options
```

### *Setting Up the Initial Grid*

Keep the current optimized grid and the accumulated results for the integral (value and errors). The second variable will be the new number of sampling points for the next call to `vamp_sample_grid`.

```
82 <Implementation of vamp procedures 78b>+≡ (75b) <81b 83b>
  pure subroutine vamp_reshape_grid_internal &
    (g, num_calls, num_div, &
     stratified, quadrupole, covariance, exc, use_variance, &
     independent, equivalent_to_ch, multiplicity)
  type(vamp_grid), intent(inout) :: g
  integer, intent(in), optional :: num_calls
  integer, dimension(:), intent(in), optional :: num_div
  logical, intent(in), optional :: stratified, quadrupole, covariance
  type(exception), intent(inout), optional :: exc
  logical, intent(in), optional :: use_variance
  logical, intent(in), optional :: independent
  integer, intent(in), optional :: equivalent_to_ch, multiplicity
  integer :: ndim, num_cells
  integer, dimension(size(g%div)) :: ng
  character(len=*), parameter :: FN = "vamp_reshape_grid_internal"
  ndim = size (g%div)
  call set_grid_options &
    (g, num_calls, num_div, stratified, quadrupole, &
     & independent, equivalent_to_ch, multiplicity)
  <Adjust grid and other state for new num_calls 84a>
  g%all_stratified = all (stratified_division (g%div))
  if (present (covariance)) then
    ndim = size (g%div)
    if (covariance .and. (.not. associated (g%mu_x))) then
      allocate (g%mu_x(ndim), g%mu_xx(ndim,ndim))
      allocate (g%sum_mu_x(ndim), g%sum_mu_xx(ndim,ndim))
      g%sum_mu_x = 0.0
      g%sum_mu_xx = 0.0
    else if ((.not. covariance) .and. (associated (g%mu_x))) then
      deallocate (g%mu_x, g%mu_xx, g%sum_mu_x, g%sum_mu_xx)
    end if
  end if
end subroutine vamp_reshape_grid_internal
```

The `use_variance` argument is too dangerous for careless users, because the variance in the divisions will contain garbage before sampling and after

reshaping. Build a fence with another routine.

83a *<Declaration of vamp procedures 77a>+≡* (75b) *<81a 84d>*  
`private :: vamp_reshape_grid_internal`  
`public :: vamp_reshape_grid`

83b *<Implementation of vamp procedures 78b>+≡* (75b) *<82 84e>*  
`pure subroutine vamp_reshape_grid &`  
`(g, num_calls, num_div, stratified, quadrupole, covariance, exc, &`  
`independent, equivalent_to_ch, multiplicity)`  
`type(vamp_grid), intent(inout) :: g`  
`integer, intent(in), optional :: num_calls`  
`integer, dimension(:), intent(in), optional :: num_div`  
`logical, intent(in), optional :: stratified, quadrupole, covariance`  
`type(exception), intent(inout), optional :: exc`  
`logical, intent(in), optional :: independent`  
`integer, intent(in), optional :: equivalent_to_ch, multiplicity`  
`call vamp_reshape_grid_internal &`  
`(g, num_calls, num_div, stratified, quadrupole, covariance, &`  
`exc, use_variance = .false., &`  
`independent=independent, equivalent_to_ch=equivalent_to_ch, &`  
`multiplicity=multiplicity)`  
`end subroutine vamp_reshape_grid`

vegas operates in three different modes, which are chosen according to explicit user requests and to the relation of the requested number of sampling points to the dimensionality of the integration domain.

The simplest case is when the user has overwritten the default of stratified sampling with the optional argument `stratified` in the call to `vamp_create_grid`. Then sample points will be chosen randomly with equal probability in each cell of the adaptive grid, as displayed in figure 5.1.

The implementation is actually shared with the stratified case described below, by pretending that there is just a single stratification cell. The number of divisions for the adaptive grid is set to a compile time maximum value.

If the user has agreed on stratified sampling then there are two cases, depending on the dimensionality of the integration region and the number of sample points. First we determine the number of divisions  $n_g$  (i. e. `ng`) of the rigid grid such that there will be two sampling points per cell.

$$N_{\text{calls}} = 2 \cdot (n_g)^{n_{\text{dim}}} \quad (5.12)$$

The additional optional argument  $\hat{n}_g$  specifies an anisotropy in the shape

$$n_{g,j} = \frac{\hat{n}_{g,j}}{\left(\prod_j \hat{n}_{g,j}\right)^{1/n_{\text{dim}}}} \left(\frac{N}{2}\right)^{1/n_{\text{dim}}} \quad (5.13)$$

NB:

$$\prod_j n_{g,j} = \frac{N}{2} \quad (5.14)$$

84a  $\langle$ Adjust grid and other state for new num.calls 84a $\rangle \equiv$  (82) 84b $\triangleright$

```

  if (g%stratified) then
    ng = (g%num_calls / 2.0 + 0.25)**(1.0/ndim)
    ! ng = ng * real (g%num_div, kind=default) &
    !       / (product (real (g%num_div, kind=default)))** (1.0/ndim)
  else
    ng = 1
  end if
  call reshape_division (g%div, g%num_div, ng, use_variance)
  call clear_integral_and_variance (g%div)
  num_cells = product (rigid_division (g%div))
  g%calls_per_cell = max (g%num_calls / num_cells, 2)
  g%calls = real (g%calls_per_cell) * real (num_cells)
  jacobi = J = Volume / N_calls

```

(5.15)

and

$$\text{dv2g} = \frac{N_{\text{calls}}^2 ((\Delta x)^{n_{\text{dim}}})^2}{N_{\text{calls/cell}}^2 (N_{\text{calls/cell}} - 1)} = \frac{\left(\frac{N_{\text{calls}}}{N_{\text{cells}}}\right)^2}{N_{\text{calls/cell}}^2 (N_{\text{calls/cell}} - 1)} \quad (5.16)$$

84b  $\langle$ Adjust grid and other state for new num.calls 84a $\rangle + \equiv$  (82)  $\triangleleft$ 84a 84c $\triangleright$

```

  g%jacobi = product (volume_division (g%div)) / g%calls
  g%dv2g = (g%calls / num_cells)**2 &
           / g%calls_per_cell / g%calls_per_cell / (g%calls_per_cell - 1.0)

```

84c  $\langle$ Adjust grid and other state for new num.calls 84a $\rangle + \equiv$  (82)  $\triangleleft$ 84b

```

  call vamp_nullify_f_limits (g)

```

When the grid is refined or reshaped, the recorded minimum and maximum of the sampling function should be nullified:

84d  $\langle$ Declaration of vamp procedures 77a $\rangle + \equiv$  (75b)  $\triangleleft$ 83a 85a $\triangleright$

```

  public :: vamp_nullify_f_limits

```

84e  $\langle$ Implementation of vamp procedures 78b $\rangle + \equiv$  (75b)  $\triangleleft$ 83b 85b $\triangleright$

```

  elemental subroutine vamp_nullify_f_limits (g)
    type(vamp_grid), intent(inout) :: g
    g%f_min = 1.0
    g%f_max = 0.0
  end subroutine vamp_nullify_f_limits

```

85a *<Declaration of vamp procedures 77a>+≡* (75b) <84d 86b>  
public :: vamp\_rigid\_divisions  
public :: vamp\_get\_covariance, vamp\_nullify\_covariance  
public :: vamp\_get\_variance, vamp\_nullify\_variance

85b *<Implementation of vamp procedures 78b>+≡* (75b) <84e 85c>  
pure function vamp\_rigid\_divisions (g) result (ng)  
type(vamp\_grid), intent(in) :: g  
integer, dimension(size(g%div)) :: ng  
ng = rigid\_division (g%div)  
end function vamp\_rigid\_divisions

85c *<Implementation of vamp procedures 78b>+≡* (75b) <85b 85d>  
pure function vamp\_get\_covariance (g) result (cov)  
type(vamp\_grid), intent(in) :: g  
real(kind=default), dimension(size(g%div),size(g%div)) :: cov  
if (associated (g%mu\_x)) then  
if (abs (g%sum\_weights) <= tiny (cov(1,1))) then  
where (g%sum\_mu\_xx == 0.0\_default)  
cov = 0.0  
elsewhere  
cov = huge (cov(1,1))  
endwhere  
else  
cov = g%sum\_mu\_xx / g%sum\_weights &  
- outer\_product (g%sum\_mu\_x, g%sum\_mu\_x) / g%sum\_weights\*\*2  
end if  
else  
cov = 0.0  
end if  
end function vamp\_get\_covariance

85d *<Implementation of vamp procedures 78b>+≡* (75b) <85c 85e>  
elemental subroutine vamp\_nullify\_covariance (g)  
type(vamp\_grid), intent(inout) :: g  
if (associated (g%mu\_x)) then  
g%sum\_mu\_x = 0  
g%sum\_mu\_xx = 0  
end if  
end subroutine vamp\_nullify\_covariance

85e *<Implementation of vamp procedures 78b>+≡* (75b) <85d 86a>  
elemental function vamp\_get\_variance (g) result (v)  
type(vamp\_grid), intent(in) :: g  
real(kind=default) :: v  
if (abs (g%sum\_weights) <= tiny (v)) then

```

        if (g%sum_mu_gi == 0.0_default) then
            v = 0.0
        else
            v = huge (v)
        end if
    else
        v = g%sum_mu_gi / g%sum_weights
    end if
end function vamp_get_variance

```

86a  $\langle$ Implementation of vamp procedures 78b $\rangle + \equiv$  (75b)  $\langle$ 85e 86c $\rangle$

```

    elemental subroutine vamp_nullify_variance (g)
        type(vamp_grid), intent(inout) :: g
        g%sum_mu_gi = 0
    end subroutine vamp_nullify_variance

```

### 5.2.3 Sampling

86b  $\langle$ Declaration of vamp procedures 77a $\rangle + \equiv$  (75b)  $\langle$ 85a 92b $\rangle$

```

    public :: vamp_sample_grid
    public :: vamp_sample_grid0
    public :: vamp_refine_grid
    public :: vamp_refine_grids

```

#### Simple Non-Adaptive Sampling: $S_0$

86c  $\langle$ Implementation of vamp procedures 78b $\rangle + \equiv$  (75b)  $\langle$ 86a 92c $\rangle$

```

    subroutine vamp_sample_grid0 &
        (rng, g, func, data, channel, weights, grids, exc, &
         negative_weights)
        type(tao_random_state), intent(inout) :: rng
        type(vamp_grid), intent(inout) :: g
        class(vamp_data_t), intent(in) :: data
        integer, intent(in), optional :: channel
        real(kind=default), dimension(:), intent(in), optional :: weights
        type(vamp_grid), dimension(:), intent(in), optional :: grids
        type(exception), intent(inout), optional :: exc
         $\langle$ Interface declaration for func 22 $\rangle$ 
        character(len=*), parameter :: FN = "vamp_sample_grid0"
        logical, intent(in), optional :: negative_weights
         $\langle$ Local variables in vamp_sample_grid0 87c $\rangle$ 
        integer :: ndim
        logical :: neg_w

```

```

    ndim = size (g%div)
    neg_w = .false.
    if (present (negative_weights)) neg_w = negative_weights
    <Check optional arguments in vamp_sample_grid0 92a>
    <Reset counters in vamp_sample_grid0 87b>
    loop_over_cells: do
        <Sample calls_per_cell points in the current cell 88b>
        <Collect integration and grid optimization data for current cell 90a>
        <Count up cell, exit if done 87a>
    end do loop_over_cells
    <Collect results of vamp_sample_grid0 90b>
end subroutine vamp_sample_grid0

```

Count cells like a  $n_g$ -ary number—i.e.  $(1, \dots, 1, 1), (1, \dots, 1, 2), \dots, (1, \dots, 1, n_g), (1, \dots, 2, 1), \dots, (n_g, \dots, n_g, n_g - 1), (n_g, \dots, n_g, n_g)$ —and terminate when all (`cell == 1`) again.

87a <Count up cell, exit if done 87a>≡ (86c)

```

    do j = ndim, 1, -1
        cell(j) = modulo (cell(j), rigid_division (g%div(j))) + 1
        if (cell(j) /= 1) then
            cycle loop_over_cells
        end if
    end do
    exit loop_over_cells

```

87b <Reset counters in vamp\_sample\_grid0 87b>≡ (86c)

```

    g%mu = 0.0
    g%mu_plus = 0.0
    g%mu_minus = 0.0
    cell = 1
    call clear_integral_and_variance (g%div)
    if (associated (g%mu_x)) then
        g%mu_x = 0.0
        g%mu_xx = 0.0
    end if
    if (present (channel)) then
        g%mu_gi = 0.0
    end if

```

87c <Local variables in vamp\_sample\_grid0 87c>≡ (86c) 88a>

```

    real(kind=default), parameter :: &
        eps = tiny (1._default) / epsilon (1._default)
    character(len=6) :: buffer

```



```

88a  <Local variables in vamp_sample_grid0 87c>+≡ (86c) <87c 89c>
      integer :: j, k
      integer, dimension(size(g%div)) :: cell

88b  <Sample calls_per_cell points in the current cell 88b>≡ (86c)
      sum_f = 0.0
      sum_f_plus = 0.0
      sum_f_minus = 0.0
      sum_f2 = 0.0
      sum_f2_plus = 0.0
      sum_f2_minus = 0.0
      do k = 1, g%calls_per_cell
        <Get x in the current cell 88c>
        <f = wgt * func (x, weights, channel), iff x inside true_domain 88d>
        <Collect integration and grid optimization data for x from f 89a>
      end do

```

We are using the generic procedure `tao_random_number` from the `tao_random_numbers` module for generating an array of uniform deviates. A better alternative would be to pass the random number generator as an argument to `vamp_sample_grid`. Unfortunately, it is not possible to pass *generic* procedures in Fortran90, Fortran95, or F. While we could export a specific procedure from `tao_random_numbers`, a more serious problem is that we have to pass the state `rng` of the random number generator as a `tao_random_state` anyway and we have to hardcode the random number generator anyway.

```

88c  <Get x in the current cell 88c>≡ (88b)
      call tao_random_number (rng, r)
      call inject_division (g%div, real (r, kind=default), &
                           cell, x, x_mid, ia, wgts)
      wgt = g%jacobi * product (wgts)
      if (associated (g%map)) then
        x = matmul (g%map, x)
      end if

```

This somewhat contorted nested if constructs allow to minimize the number of calls to `func`. This is useful, since `func` is the most expensive part of real world applications. Also `func` might be singular outside of `true_domain`.

The original `vegas` used to call `f = wgt * func (x, wgt)` below to allow `func` to use `wgt` (i.e.  $1/p(x)$ ) for integrating another function at the same time. This form of “parallelism” relies on side effects and is therefore impossible with pure functions. Consequently, it is not supported in the current implementation.

```

88d  <f = wgt * func (x, weights, channel), iff x inside true_domain 88d>≡ (88b 136a)
      if (associated (g%map)) then

```

```

        if (all (inside_division (g%div, x))) then
            f = wgt * func (x, data, weights, channel, grids)
        else
            f = 0.0
        end if
    else
        f = wgt * func (x, data, weights, channel, grids)
    end if

89a  <Collect integration and grid optimization data for x from f 89a>≡      (88b) 89b▷
        if (g%f_min > g%f_max) then
            g%f_min = abs (f) * g%calls
            g%f_max = abs (f) * g%calls
        else if (abs (f) * g%calls < g%f_min) then
            g%f_min = abs (f) * g%calls
        else if (abs (f) * g%calls > g%f_max) then
            g%f_max = abs (f) * g%calls
        end if

89b  <Collect integration and grid optimization data for x from f 89a>+≡      (88b) <89a
        f2 = f * f
        sum_f = sum_f + f
        sum_f2 = sum_f2 + f2
        if (f > 0) then
            sum_f_plus = sum_f_plus + f
            sum_f2_plus = sum_f2_plus + f * f
        else if (f < 0) then
            sum_f_minus = sum_f_minus + f
            sum_f2_minus = sum_f2_minus + f * f
        end if
        call record_integral (g%div, ia, f)
        ! call record_efficiency (g%div, ia, f/g%f_max)
        if ((associated (g%mu_x)) .and. (.not. g%all_stratified)) then
            g%mu_x = g%mu_x + x * f
            g%mu_xx = g%mu_xx + outer_product (x, x) * f
        end if
        if (present (channel)) then
            g%mu_gi = g%mu_gi + f2
        end if

89c  <Local variables in vamp_sample_grid0 87c>+≡      (86c) <88a
        real(kind=default) :: wgt, f, f2
        real(kind=default) :: sum_f, sum_f2, var_f
        real(kind=default) :: sum_f_plus, sum_f2_plus, var_f_plus
        real(kind=default) :: sum_f_minus, sum_f2_minus, var_f_minus

```

```

real(kind=default), dimension(size(g%div)):: x, x_mid, wgts
real(kind=default), dimension(size(g%div)):: r
integer, dimension(size(g%div)) :: ia

```

$$\sigma^2 \cdot N_{\text{calls/cell}}^2 (N_{\text{calls/cell}} - 1) = \text{var}(f) = N^2 \sigma^2 \left( \left\langle \frac{f^2}{p} \right\rangle - \langle f \rangle^2 \right) \quad (5.17)$$

90a *⟨Collect integration and grid optimization data for current cell 90a⟩*≡ (86c)

```

var_f = sum_f2 * g%calls_per_cell - sum_f**2
var_f_plus = sum_f2_plus * g%calls_per_cell - sum_f_plus**2
var_f_minus = sum_f2_minus * g%calls_per_cell - sum_f_minus**2
if (var_f <= 0.0) then
    var_f = tiny (1.0_default)
end if
if (sum_f_plus /= 0 .and. var_f_plus <= 0) then
    var_f_plus = tiny (1.0_default)
end if
if (sum_f_minus /= 0 .and. var_f_minus <= 0) then
    var_f_minus = tiny (1.0_default)
end if
g%mu = g%mu + (/ sum_f, var_f /)
g%mu_plus = g%mu_plus + (/ sum_f_plus, var_f_plus /)
g%mu_minus = g%mu_minus + (/ sum_f_minus, var_f_minus /)
call record_variance (g%div, ia, var_f)
if ((associated (g%mu_x)) .and. g%all_stratified) then
    if (associated (g%map)) then
        x_mid = matmul (g%map, x_mid)
    end if
    g%mu_x = g%mu_x + x_mid * var_f
    g%mu_xx = g%mu_xx + outer_product (x_mid, x_mid) * var_f
end if

```

$$\sigma^2 = \frac{\left( \frac{N_{\text{calls}}}{N_{\text{cells}}} \right)^2}{N_{\text{calls/cell}}^2 (N_{\text{calls/cell}} - 1)} \sum_{\text{cells}} \sigma_{\text{cell}}^2 \cdot N_{\text{calls/cell}}^2 (N_{\text{calls/cell}} - 1) \quad (5.18)$$

where the  $N_{\text{calls}}^2$  cancels the corresponding factor in the Jacobian and the  $N_{\text{cells}}^{-2}$  is the result of stratification. In order to avoid numerical noise for some OS when using 80bit precision, we wrap the numerical resetting into a negative weights-only if-clause.

90b *⟨Collect results of vamp\_sample\_grid0 90b⟩*≡ (86c) 91▷

```

g%mu(2) = g%mu(2) * g%dv2g
if (g%mu(2) < eps * max (g%mu(1)**2, 1._default)) then
    g%mu(2) = eps * max (g%mu(1)**2, 1._default)
end if

```

```

if (neg_w) then
  g%mu_plus(2) = g%mu_plus(2) * g%dv2g
  if (g%mu_plus(2) < eps * max (g%mu_plus(1)**2, 1._default)) then
    g%mu_plus(2) = eps * max (g%mu_plus(1)**2, 1._default)
  end if
  g%mu_minus(2) = g%mu_minus(2) * g%dv2g
  if (g%mu_minus(2) < eps * max (g%mu_minus(1)**2, 1._default)) then
    g%mu_minus(2) = eps * max (g%mu_minus(1)**2, 1._default)
  end if
end if

```

91 *<Collect results of vamp\_sample\_grid0 90b>+≡* (86c) <90b

```


if (g%mu(1)>0) then
  g%sum_integral = g%sum_integral + g%mu(1) / g%mu(2)
  g%sum_weights = g%sum_weights + 1.0 / g%mu(2)
  g%sum_chi2 = g%sum_chi2 + g%mu(1)**2 / g%mu(2)
  if (associated (g%mu_x)) then
    if (g%all_stratified) then
      g%mu_x = g%mu_x / g%mu(2)
      g%mu_xx = g%mu_xx / g%mu(2)
    else
      g%mu_x = g%mu_x / g%mu(1)
      g%mu_xx = g%mu_xx / g%mu(1)
    end if
    g%sum_mu_x = g%sum_mu_x + g%mu_x / g%mu(2)
    g%sum_mu_xx = g%sum_mu_xx + g%mu_xx / g%mu(2)
  end if
  if (present (channel)) then
    g%sum_mu_gi = g%sum_mu_gi + g%mu_gi / g%mu(2)
  end if
else if (neg_w) then
  g%sum_integral = g%sum_integral + g%mu(1) / g%mu(2)
  g%sum_weights = g%sum_weights + 1.0 / g%mu(2)
  g%sum_chi2 = g%sum_chi2 + g%mu(1)**2 / g%mu(2)
  if (associated (g%mu_x)) then
    if (g%all_stratified) then
      g%mu_x = g%mu_x / g%mu(2)
      g%mu_xx = g%mu_xx / g%mu(2)
    else
      g%mu_x = g%mu_x / g%mu(1)
      g%mu_xx = g%mu_xx / g%mu(1)
    end if
    g%sum_mu_x = g%sum_mu_x + g%mu_x / g%mu(2)
    g%sum_mu_xx = g%sum_mu_xx + g%mu_xx / g%mu(2)
  end if

```

```

end if
if (present (channel)) then
    g%sum_mu_gi = g%sum_mu_gi + g%mu_gi / g%mu(2)
end if
else
if (present(channel) .and. g%mu(1)==0) then
    write (buffer, "(I6)") channel
    call raise_exception (exc, EXC_WARN, "! vamp", &
        "Function identically zero in channel " // buffer)
else if (present(channel) .and. g%mu(1)<0) then
    write (buffer, "(I6)") channel
    call raise_exception (exc, EXC_ERROR, "! vamp", &
        "Negative integral in channel " // buffer)
end if
g%sum_integral = 0
g%sum_chi2 = 0
g%sum_weights = 0
end if
92a <Check optional arguments in vamp_sample_grid0 92a>≡ (86c)
    if (present (channel) .neqv. present (weights)) then
        call raise_exception (exc, EXC_FATAL, FN, &
            "channel and weights required together")
        return
    end if
92b <Declaration of vamp procedures 77a>+≡ (75b) <86b 96a>
    public :: vamp_probability
92c <Implementation of vamp procedures 78b>+≡ (75b) <86c 92d>
    pure function vamp_probability (g, x) result (p)
        type(vamp_grid), intent(in) :: g
        real(kind=default), dimension(:), intent(in) :: x
        real(kind=default) :: p
        p = product (probability (g%div, x))
    end function vamp_probability

```

 %variance should be private to division

```

92d <Implementation of vamp procedures 78b>+≡ (75b) <92c 94a>
    subroutine vamp_apply_equivalences (g, eq)
        type(vamp_grids), intent(inout) :: g
        type(vamp_equivalences_t), intent(in) :: eq
        integer :: n_ch, n_dim, nb, i, ch, ch_src, dim, dim_src
        integer, dimension(:,:), allocatable :: n_bin
        real(kind=default), dimension(:,:,:), allocatable :: var_tmp

```

```

n_ch = size (g%grids)
if (n_ch == 0) return
n_dim = size (g%grids(1)%div)
allocate (n_bin(n_ch, n_dim))
do ch = 1, n_ch
  do dim = 1, n_dim
    n_bin(ch, dim) = size (g%grids(ch)%div(dim)%variance)
  end do
end do
allocate (var_tmp (maxval(n_bin), n_dim, n_ch))
var_tmp = 0
do i=1, eq%n_eq
  ch = eq%eq(i)%left
  ch_src = eq%eq(i)%right
  do dim=1, n_dim
    nb = n_bin(ch_src, dim)
    dim_src = eq%eq(i)%permutation(dim)
    select case (eq%eq(i)%mode(dim))
    case (VEQ_IDENTITY)
      var_tmp(:nb,dim,ch) = var_tmp(:nb,dim,ch) &
        & + g%grids(ch_src)%div(dim_src)%variance
    case (VEQ_INVERT)
      var_tmp(:nb,dim,ch) = var_tmp(:nb,dim,ch) &
        & + g%grids(ch_src)%div(dim_src)%variance(nb:1:-1)
    case (VEQ_SYMMETRIC)
      var_tmp(:nb,dim,ch) = var_tmp(:nb,dim,ch) &
        & + g%grids(ch_src)%div(dim_src)%variance / 2 &
        & + g%grids(ch_src)%div(dim_src)%variance(nb:1:-1)/2
    case (VEQ_INVARIANT)
      var_tmp(:nb,dim,ch) = 1
    end select
  end do
end do
do ch=1, n_ch
  do dim=1, n_dim
    g%grids(ch)%div(dim)%variance = var_tmp(:n_bin(ch, dim),dim,ch)
  end do
end do
deallocate (var_tmp)
deallocate (n_bin)
end subroutine vamp_apply_equivalences

```

*Grid Refinement:  $r$*

$$n_{\text{div},j} \rightarrow \frac{Q_j n_{\text{div},j}}{\left(\prod_j Q_j\right)^{1/n_{\text{dim}}}} \quad (5.19)$$

where

$$Q_j = \left( \sqrt{\text{Var}(\{m\}_j)} \right)^\alpha \quad (5.20)$$

94a *<Implementation of vamp procedures 78b>+≡* (75b) *<92d 94b>*  

```

pure subroutine vamp_refine_grid (g, exc)
  type(vamp_grid), intent(inout) :: g
  type(exception), intent(inout), optional :: exc
  real(kind=default), dimension(size(g%div)) :: quad
  integer :: ndim
  if (g%quadrupole) then
    ndim = size (g%div)
    quad = (quadrupole_division (g%div))**QUAD_POWER
    call vamp_reshape_grid_internal &
      (g, use_variance = .true., exc = exc, &
        num_div = int (quad / product (quad)**(1.0/ndim) * g%num_div))
  else
    call refine_division (g%div)
    call vamp_nullify_f_limits (g)
  end if
end subroutine vamp_refine_grid

```

94b *<Implementation of vamp procedures 78b>+≡* (75b) *<94a 94d>*  

```

subroutine vamp_refine_grids (g)
  type(vamp_grids), intent(inout) :: g
  integer :: ch
  do ch=1, size(g%grids)
    call refine_division (g%grids(ch)%div)
    call vamp_nullify_f_limits (g%grids(ch))
  end do
end subroutine vamp_refine_grids

```

94c *<Variables in vamp 79a>+≡* (75b) *<79a 110a>*  

```

real(kind=default), private, parameter :: QUAD_POWER = 0.5_default

```

*Adaptive Sampling:  $S_n = S_0(rS_0)^n$*

94d *<Implementation of vamp procedures 78b>+≡* (75b) *<94b 95>*  

```

subroutine vamp_sample_grid &
  (rng, g, func, data, iterations, &

```

```

    integral, std_dev, avg_chi2, accuracy, &
    channel, weights, grids, exc, history)
type(tao_random_state), intent(inout) :: rng
type(vamp_grid), intent(inout) :: g
class(vamp_data_t), intent(in) :: data
integer, intent(in) :: iterations
real(kind=default), intent(out), optional :: integral, std_dev, avg_chi2
real(kind=default), intent(in), optional :: accuracy
integer, intent(in), optional :: channel
real(kind=default), dimension(:), intent(in), optional :: weights
type(vamp_grid), dimension(:), intent(in), optional :: grids
type(exception), intent(inout), optional :: exc
type(vamp_history), dimension(:), intent(inout), optional :: history
<Interface declaration for func 22>
character(len=*), parameter :: FN = "vamp_sample_grid"
real(kind=default) :: local_integral, local_std_dev, local_avg_chi2
integer :: iteration, ndim
ndim = size (g%div)
iterate: do iteration = 1, iterations
    call vamp_sample_grid0 &
        (rng, g, func, data, channel, weights, grids, exc)
    call vamp_average_iterations &
        (g, iteration, local_integral, local_std_dev, local_avg_chi2)
    <Trace results of vamp_sample_grid 107a>
    <Exit iterate if accuracy has been reached 97a>
    if (iteration < iterations) call vamp_refine_grid (g)
end do iterate
<Copy results of vamp_sample_grid to dummy variables 96c>
end subroutine vamp_sample_grid

```

Assuming that the iterations have been statistically independent, we can combine them with the usual formulae.

$$\bar{I} = \sigma_I^2 \sum_i \frac{I_i}{\sigma_i^2} \quad (5.21a)$$

$$\frac{1}{\sigma_I^2} = \sum_i \frac{1}{\sigma_i^2} \quad (5.21b)$$

$$\chi^2 = \sum_i \frac{(I_i - \bar{I})^2}{\sigma_i^2} = \sum_i \frac{I_i^2}{\sigma_i^2} - \bar{I} \sum_i \frac{I_i}{\sigma_i^2} \quad (5.21c)$$

95    <Implementation of vamp procedures 78b>+≡ (75b) <94d 97d>  
 elemental subroutine vamp\_average\_iterations\_grid &  
 (g, iteration, integral, std\_dev, avg\_chi2)



```

type(vamp_grid), intent(in) :: g
integer, intent(in) :: iteration
real(kind=default), intent(out) :: integral, std_dev, avg_chi2
real(kind=default), parameter :: eps = 1000 * epsilon (1._default)
if (g%sum_weights>0) then
    integral = g%sum_integral / g%sum_weights
    std_dev = sqrt (1.0 / g%sum_weights)
    avg_chi2 = &
        max ((g%sum_chi2 - g%sum_integral * integral) / (iteration-0.99), &
            0.0_default)
    if (avg_chi2 < eps * g%sum_chi2) avg_chi2 = 0
else
    integral = 0
    std_dev = 0
    avg_chi2 = 0
end if
end subroutine vamp_average_iterations_grid

```

96a  $\langle$ Declaration of vamp procedures 77a $\rangle \equiv$  (75b)  $\langle$ 92b 97b $\rangle$

```

public :: vamp_average_iterations
private :: vamp_average_iterations_grid

```

96b  $\langle$ Interfaces of vamp procedures 96b $\rangle \equiv$  (75b) 97c $\rangle$

```

interface vamp_average_iterations
    module procedure vamp_average_iterations_grid
end interface

```

Lepage suggests [1] to reweight the contributions as in the following improved formulae, which we might implement as an option later.

$$\bar{I} = \frac{1}{\left(\sum_i \frac{I_i^2}{\sigma_i^2}\right)^2} \sum_i I_i \frac{I_i^2}{\sigma_i^2} \quad (5.22a)$$

$$\frac{1}{\sigma_I^2} = \frac{1}{(\bar{I})^2} \sum_i \frac{I_i^2}{\sigma_i^2} \quad (5.22b)$$

$$\chi^2 = \sum_i \frac{(I_i - \bar{I})^2}{(\bar{I})^2} \frac{I_i^2}{\sigma_i^2} \quad (5.22c)$$

Iff possible, copy the result to the caller's variables:

96c  $\langle$ Copy results of vamp\_sample\_grid to dummy variables 96c $\rangle \equiv$  (94d 104 120b)

```

if (present (integral)) then
    integral = local_integral
end if
if (present (std_dev)) then

```

```

        std_dev = local_std_dev
    end if
    if (present (avg_chi2)) then
        avg_chi2 = local_avg_chi2
    end if
97a <Exit iterate if accuracy has been reached 97a>≡ (94d 104 120b)
    if (present (accuracy)) then
        if (local_std_dev <= accuracy * local_integral) then
            call raise_exception (exc, EXC_INFO, FN, &
                "requested accuracy reached")
            exit iterate
        end if
    end if
end if

```

## 5.2.4 Forking and Joining

```

97b <Declaration of vamp procedures 77a>+≡ (75b) <96a 102b>
    public :: vamp_fork_grid
    private :: vamp_fork_grid_single, vamp_fork_grid_multi
    public :: vamp_join_grid
    private :: vamp_join_grid_single, vamp_join_grid_multi

97c <Interfaces of vamp procedures 96b>+≡ (75b) <96b 107c>
    interface vamp_fork_grid
        module procedure vamp_fork_grid_single, vamp_fork_grid_multi
    end interface
    interface vamp_join_grid
        module procedure vamp_join_grid_single, vamp_join_grid_multi
    end interface

```

Caveat emptor: splitting divisions can lead to `num_div` < 3 an the application must not try to refine such grids before merging them again! `d == 0` is special.

```

97d <Implementation of vamp procedures 78b>+≡ (75b) <95 100c>
    pure subroutine vamp_fork_grid_single (g, gs, d, exc)
        type(vamp_grid), intent(in) :: g
        type(vamp_grid), dimension(:), intent(inout) :: gs
        integer, intent(in) :: d
        type(exception), intent(inout), optional :: exc
        character(len=*), parameter :: FN = "vamp_fork_grid_single"
        type(division_t), dimension(:), allocatable :: d_tmp
        integer :: i, j, num_grids, num_div, ndim, num_cells
        num_grids = size (gs)

```

```

    ndim = size (g%div)
    <Allocate or resize the divisions 100b>
    do j = 1, ndim
        if (j == d) then
            <call fork_division (g%div(j), gs%div(j), g%calls_per_cell, ...) 99c>
        else
            <call copy_division (gs%div(j), g%div(j)) 100a>
        end if
    end do
    if (d == 0) then
        <Handle g%calls_per_cell for d == 0 98a>
    end if
    <Copy the rest of g to the gs 98b>
end subroutine vamp_fork_grid_single

Divide the sampling points among identical grids
98a <Handle g%calls_per_cell for d == 0 98a>≡ (97d)
    if (any (stratified_division (g%div))) then
        call raise_exception (exc, EXC_FATAL, FN, &
            "d == 0 incompatible w/ stratification")
    else
        gs(2:)%calls_per_cell = ceiling (real (g%calls_per_cell) / num_grids)
        gs(1)%calls_per_cell = g%calls_per_cell - sum (gs(2:)%calls_per_cell)
    end if

98b <Copy the rest of g to the gs 98b>≡ (97d) 98c>
    do i = 1, num_grids
        call copy_array_pointer (gs(i)%num_div, g%num_div)
        if (associated (g%map)) then
            call copy_array_pointer (gs(i)%map, g%map)
        end if
        if (associated (g%mu_x)) then
            call create_array_pointer (gs(i)%mu_x, ndim)
            call create_array_pointer (gs(i)%sum_mu_x, ndim)
            call create_array_pointer (gs(i)%mu_xx, (/ ndim, ndim /))
            call create_array_pointer (gs(i)%sum_mu_xx, (/ ndim, ndim /))
        end if
    end do

Reset results
98c <Copy the rest of g to the gs 98b>+≡ (97d) <98b 99a>
    gs%mu(1) = 0.0
    gs%mu(2) = 0.0
    gs%mu_plus(1) = 0.0
    gs%mu_plus(2) = 0.0

```

```

gs%mu_minus(1) = 0.0
gs%mu_minus(2) = 0.0
gs%sum_integral = 0.0
gs%sum_weights = 0.0
gs%sum_chi2 = 0.0
gs%mu_gi = 0.0
gs%sum_mu_gi = 0.0

99a <Copy the rest of g to the gs 98b>+≡ (97d) <98c 99b>
gs%stratified = g%stratified
gs%all_stratified = g%all_stratified
gs%quadrupole = g%quadrupole

99b <Copy the rest of g to the gs 98b>+≡ (97d) <99a
do i = 1, num_grids
    num_cells = product (rigid_division (gs(i)%div))
    gs(i)%calls = gs(i)%calls_per_cell * num_cells
    gs(i)%num_calls = gs(i)%calls
    gs(i)%jacobi = product (volume_division (gs(i)%div)) / gs(i)%calls
    gs(i)%dv2g = (gs(i)%calls / num_cells)**2 &
        / gs(i)%calls_per_cell / gs(i)%calls_per_cell / (gs(i)%calls_per_cell - 1.0)
end do
gs%f_min = g%f_min * (gs%jacobi * gs%calls) / (g%jacobi * g%calls)
gs%f_max = g%f_max * (gs%jacobi * gs%calls) / (g%jacobi * g%calls)
This could be self-explaining, if the standard would allow .... Note that we
can get away with copying just the pointers, because fork_division does
the dirty work for the memory management.

99c <call fork_division (g%div(j), gs%div(j), g%calls_per_cell, ...) 99c>≡ (97d)
allocate (d_tmp(num_grids))
do i = 1, num_grids
    d_tmp(i) = gs(i)%div(j)
end do
call fork_division (g%div(j), d_tmp, g%calls_per_cell, gs%calls_per_cell, exc)
do i = 1, num_grids
    gs(i)%div(j) = d_tmp(i)
end do
deallocate (d_tmp)
<Bail out if exception exc raised 99d>

99d <Bail out if exception exc raised 99d>≡ (99c 100d 104 140c 142c)
if (present (exc)) then
    if (exc%level > EXC_WARN) then
        return
    end if
end if

```

We have to do a deep copy ( $gs(i)\%div(j) = g\%div(j)$  does not suffice), because `copy_division` handles the memory management.

```
100a <call copy_division (gs%div(j), g%div(j)) 100a>≡ (97d)
      do i = 1, num_grids
        call copy_division (gs(i)%div(j), g%div(j))
      end do
```

```
100b <Allocate or resize the divisions 100b>≡ (97d)
      num_div = size (g%div)
      do i = 1, size (gs)
        if (associated (gs(i)%div)) then
          if (size (gs(i)%div) /= num_div) then
            allocate (gs(i)%div(num_div))
            call create_empty_division (gs(i)%div)
          end if
        else
          allocate (gs(i)%div(num_div))
          call create_empty_division (gs(i)%div)
        end if
      end do
```

```
100c <Implementation of vamp procedures 78b>+≡ (75b) <97d 102a>
      pure subroutine vamp_join_grid_single (g, gs, d, exc)
        type(vamp_grid), intent(inout) :: g
        type(vamp_grid), dimension(:), intent(inout) :: gs
        integer, intent(in) :: d
        type(exception), intent(inout), optional :: exc
        type(division_t), dimension(:), allocatable :: d_tmp
        integer :: i, j, num_grids
        num_grids = size (gs)
        do j = 1, size (g%div)
          if (j == d) then
            <call join_division (g%div(j), gs%div(j)) 100d>
          else
            <call sum_division (g%div(j), gs%div(j)) 101a>
          end if
        end do
        <Combine the rest of gs onto g 101b>
      end subroutine vamp_join_grid_single
```

```
100d <call join_division (g%div(j), gs%div(j)) 100d>≡ (100c)
      allocate (d_tmp(num_grids))
      do i = 1, num_grids
        d_tmp(i) = gs(i)%div(j)
      end do
```

```

    call join_division (g%div(j), d_tmp, exc)
    deallocate (d_tmp)
    <Bail out if exception exc raised 99d>

101a <call sum_division (g%div(j), gs%div(j)) 101a>≡ (100c)
    allocate (d_tmp(num_grids))
    do i = 1, num_grids
        d_tmp(i) = gs(i)%div(j)
    end do
    call sum_division (g%div(j), d_tmp)
    deallocate (d_tmp)

101b <Combine the rest of gs onto g 101b>≡ (100c)
    g%f_min = minval (gs%f_min * (g%jacobi * g%calls) / (gs%jacobi * gs%calls))
    g%f_max = maxval (gs%f_max * (g%jacobi * g%calls) / (gs%jacobi * gs%calls))
    g%mu(1) = sum (gs%mu(1))
    g%mu(2) = sum (gs%mu(2))
    g%mu_plus(1) = sum (gs%mu_plus(1))
    g%mu_plus(2) = sum (gs%mu_plus(2))
    g%mu_minus(1) = sum (gs%mu_minus(1))
    g%mu_minus(2) = sum (gs%mu_minus(2))
    g%mu_gi = sum (gs%mu_gi)
    g%sum_mu_gi = g%sum_mu_gi + g%mu_gi / g%mu(2)
    g%sum_integral = g%sum_integral + g%mu(1) / g%mu(2)
    g%sum_chi2 = g%sum_chi2 + g%mu(1)**2 / g%mu(2)
    g%sum_weights = g%sum_weights + 1.0 / g%mu(2)
    if (associated (g%mu_x)) then
        do i = 1, num_grids
            g%mu_x = g%mu_x + gs(i)%mu_x
            g%mu_xx = g%mu_xx + gs(i)%mu_xx
        end do
        g%sum_mu_x = g%sum_mu_x + g%mu_x / g%mu(2)
        g%sum_mu_xx = g%sum_mu_xx + g%mu_xx / g%mu(2)
    end if

```

The following is made a little bit hairy by the fact that `vamp_fork_grid` can't join grids onto a non-existing grid<sup>2</sup> therefore we have to keep a tree of joints. Maybe it would be the right thing to handle this tree of joints as a tree with pointers, but since we need the leaves flattened anyway (as food for multiple `vamp_sample_grid`) we use a similar storage layout for the joints.

```

101c <Idioms 101c>≡ 250▷
    type(vamp_grid), dimension(:), allocatable :: gx

```

---

<sup>2</sup>It would be possible to make it possible by changing many things under the hood, but it doesn't really make sense, anyway.

```

integer, dimension(:,:), allocatable :: dim
...
allocate (gx(vamp_fork_grid_joints (dim)))
call vamp_fork_grid (g, gs, gx, dim, exc)
...
call vamp_join_grid (g, gs, gx, dim, exc)

```

102a  $\langle$ Implementation of vamp procedures 78b $\rangle + \equiv$  (75b)  $\triangleleft$ 100c 102c $\triangleright$

```

pure recursive subroutine vamp_fork_grid_multi (g, gs, gx, d, exc)
  type(vamp_grid), intent(in) :: g
  type(vamp_grid), dimension(:), intent(inout) :: gs, gx
  integer, dimension(:,:), intent(in) :: d
  type(exception), intent(inout), optional :: exc
  character(len=*), parameter :: FN = "vamp_fork_grid_multi"
  integer :: i, offset, stride, joints_offset, joints_stride
  select case (size (d, dim=2))
    case (0)
      return
    case (1)
      call vamp_fork_grid_single (g, gs, d(1,1), exc)
    case default
      offset = 1
      stride = product (d(2,2:))
      joints_offset = 1 + d(2,1)
      joints_stride = vamp_fork_grid_joints (d(:,2:))
      call vamp_create_empty_grid (gx(1:d(2,1)))
      call vamp_fork_grid_single (g, gx(1:d(2,1)), d(1,1), exc)
      do i = 1, d(2,1)
        call vamp_fork_grid_multi &
          (gx(i), gs(offset:offset+stride-1), &
           gx(joints_offset:joints_offset+joints_stride-1), &
           d(:,2:), exc)
        offset = offset + stride
        joints_offset = joints_offset + joints_stride
      end do
    end select
  end subroutine vamp_fork_grid_multi

```

102b  $\langle$ Declaration of vamp procedures 77a $\rangle + \equiv$  (75b)  $\triangleleft$ 97b 103b $\triangleright$

```

public :: vamp_fork_grid_joints

```

$$\sum_{n=1}^{N-1} \prod_{i_n=1}^n d_{i_n} = d_1(1 + d_2(1 + d_3(1 + \dots(1 + d_{N-1}) \dots))) \quad (5.23)$$

102c  $\langle$ Implementation of vamp procedures 78b $\rangle + \equiv$  (75b)  $\triangleleft$ 102a 103a $\triangleright$

```

pure function vamp_fork_grid_joints (d) result (s)
  integer, dimension(:,:), intent(in) :: d
  integer :: s
  integer :: i
  s = 0
  do i = size (d, dim=2) - 1, 1, -1
    s = (s + 1) * d(2,i)
  end do
end function vamp_fork_grid_joints

```

103a  $\langle$ Implementation of vamp procedures 78b $\rangle + \equiv$  (75b)  $\langle$ 102c 104 $\rangle$

```

pure recursive subroutine vamp_join_grid_multi (g, gs, gx, d, exc)
  type(vamp_grid), intent(inout) :: g
  type(vamp_grid), dimension(:), intent(inout) :: gs, gx
  integer, dimension(:,:), intent(in) :: d
  type(exception), intent(inout), optional :: exc
  character(len=*), parameter :: FN = "vamp_join_grid_multi"
  integer :: i, offset, stride, joints_offset, joints_stride
  select case (size (d, dim=2))
    case (0)
      return
    case (1)
      call vamp_join_grid_single (g, gs, d(1,1), exc)
    case default
      offset = 1
      stride = product (d(2,2:))
      joints_offset = 1 + d(2,1)
      joints_stride = vamp_fork_grid_joints (d(:,2:))
      do i = 1, d(2,1)
        call vamp_join_grid_multi &
          (gx(i), gs(offset:offset+stride-1), &
           gx(joints_offset:joints_offset+joints_stride-1), &
           d(:,2:), exc)
        offset = offset + stride
        joints_offset = joints_offset + joints_stride
      end do
      call vamp_join_grid_single (g, gx(1:d(2,1)), d(1,1), exc)
      call vamp_delete_grid (gx(1:d(2,1)))
    end select
end subroutine vamp_join_grid_multi

```

### 5.2.5 Parallel Execution

103b  $\langle$ Declaration of vamp procedures 77a $\rangle + \equiv$  (75b)  $\langle$ 102b 107b $\rangle$



```

public :: vamp_sample_grid_parallel
public :: vamp_distribute_work

```

HPF [10, 11, 15]:

```

104 <Implementation of vamp procedures 78b>+≡ (75b) <103a 105b>
subroutine vamp_sample_grid_parallel &
    (rng, g, func, data, iterations, &
     integral, std_dev, avg_chi2, accuracy, &
     channel, weights, grids, exc, history)
type(tao_random_state), dimension(:), intent(inout) :: rng
type(vamp_grid), intent(inout) :: g
class(vamp_data_t), intent(in) :: data
integer, intent(in) :: iterations
real(kind=default), intent(out), optional :: integral, std_dev, avg_chi2
real(kind=default), intent(in), optional :: accuracy
integer, intent(in), optional :: channel
real(kind=default), dimension(:), intent(in), optional :: weights
type(vamp_grid), dimension(:), intent(in), optional :: grids
type(exception), intent(inout), optional :: exc
type(vamp_history), dimension(:), intent(inout), optional :: history
<Interface declaration for func 22>
character(len=*), parameter :: FN = "vamp_sample_grid_parallel"
real(kind=default) :: local_integral, local_std_dev, local_avg_chi2
type(exception), dimension(size(rng)) :: excs
type(vamp_grid), dimension(:), allocatable :: gs, gx
!hpf$ processors p(number_of_processors())
!hpf$ distribute gs(cyclic(1)) onto p
integer, dimension(:,:), pointer :: d
integer :: iteration, i
integer :: num_workers
nullify (d)
call clear_exception (excs)
iterate: do iteration = 1, iterations
    call vamp_distribute_work (size (rng), vamp_rigid_divisions (g), d)
    num_workers = max (1, product (d(2,:)))
    if (num_workers > 1) then
        allocate (gs(num_workers), gx(vamp_fork_grid_joints (d)))
        call vamp_create_empty_grid (gs)
        ! vamp_fork_grid is certainly not local. Speed freaks might
        ! want to tune it to the processor topology, but the gain will be small.
        call vamp_fork_grid (g, gs, gx, d, exc)
        !hpf$ independent
        do i = 1, num_workers
            call vamp_sample_grid0 &

```

```

        (rng(i), gs(i), func, data, &
         channel, weights, grids, exc)
    end do
    <Gather exceptions in vamp_sample_grid_parallel 105a>
    call vamp_join_grid (g, gs, gx, d, exc)
    call vamp_delete_grid (gs)
    deallocate (gs, gx)
else
    call vamp_sample_grid0 &
        (rng(1), g, func, data, channel, weights, grids, exc)
end if
<Bail out if exception exc raised 99d>
call vamp_average_iterations &
    (g, iteration, local_integral, local_std_dev, local_avg_chi2)
<Trace results of vamp_sample_grid 107a>
<Exit iterate if accuracy has been reached 97a>
if (iteration < iterations) call vamp_refine_grid (g)
end do iterate
deallocate (d)
<Copy results of vamp_sample_grid to dummy variables 96c>
end subroutine vamp_sample_grid_parallel
105a <Gather exceptions in vamp_sample_grid_parallel 105a>≡ (104)
    if ((present (exc)) .and. (any (excs(1:num_workers)%level > 0))) then
        call gather_exceptions (exc, excs(1:num_workers))
    end if

```

We could sort  $d$  such that (5.23) is minimized

$$d_1 \leq d_2 \leq \dots \leq d_N \quad (5.24)$$

but the gain will be negligible.

```

105b <Implementation of vamp procedures 78b>+≡ (75b) <104 107d>
pure subroutine vamp_distribute_work (num_workers, ng, d)
    integer, intent(in) :: num_workers
    integer, dimension(:), intent(in) :: ng
    integer, dimension(:,:), pointer :: d
    integer, dimension(32) :: factors
    integer :: n, num_factors, i, j
    integer, dimension(size(ng)) :: num_forks
    integer :: nfork
    try: do n = num_workers, 1, -1
        call factorize (n, factors, num_factors)
        num_forks = 1
        do i = num_factors, 1, -1

```

```

        j = sum (maxloc (ng / num_forks))
        nfork = num_forks(j) * factors(i)
        if (nfork <= ng(j)) then
            num_forks(j) = nfork
        else
            cycle try
        end if
    end do
    <Accept distribution among n workers 106a>
end do try
end subroutine vamp_distribute_work
106a <Accept distribution among n workers 106a>≡ (105b) 106b>
    j = count (num_forks > 1)
    if (associated (d)) then
        if (size (d, dim = 2) /= j) then
            deallocate (d)
            allocate (d(2,j))
        end if
    else
        allocate (d(2,j))
    end if
106b <Accept distribution among n workers 106a>+≡ (105b) <106a
    j = 1
    do i = 1, size (ng)
        if (num_forks(i) > 1) then
            d(:,j) = (/ i, num_forks(i) /)
            j = j + 1
        end if
    end do
    return

```

### 5.2.6 Diagnostics

```

106c <Declaration of vamp types 77b>+≡ (75b) <77c 113a>
    type, public :: vamp_history
    private
    real(kind=default) :: &
        integral, std_dev, avg_integral, avg_std_dev, avg_chi2, f_min, f_max
    integer :: calls
    logical :: stratified
    logical :: verbose
    type(div_history), dimension(:), pointer :: div => null ()

```

```

end type vamp_history

107a <Trace results of vamp_sample_grid 107a>≡ (94d 104)
  if (present (history)) then
    if (iteration <= size (history)) then
      call vamp_get_history &
        (history(iteration), g, local_integral, local_std_dev, &
         local_avg_chi2)
    else
      call raise_exception (exc, EXC_WARN, FN, "history too short")
    end if
    call vamp_terminate_history (history(iteration+1:))
  end if

107b <Declaration of vamp procedures 77a>+≡ (75b) <103b 108c>
  public :: vamp_create_history, vamp_copy_history, vamp_delete_history
  public :: vamp_terminate_history
  public :: vamp_get_history, vamp_get_history_single

107c <Interfaces of vamp procedures 96b>+≡ (75b) <97c 108d>
  interface vamp_get_history
    module procedure vamp_get_history_single
  end interface

107d <Implementation of vamp procedures 78b>+≡ (75b) <105b 107e>
  elemental subroutine vamp_create_history (h, ndim, verbose)
    type(vamp_history), intent(out) :: h
    integer, intent(in), optional :: ndim
    logical, intent(in), optional :: verbose
    if (present (verbose)) then
      h%verbose = verbose
    else
      h%verbose = .false.
    end if
    h%calls = 0.0
    if (h%verbose .and. (present (ndim))) then
      if (associated (h%div)) then
        deallocate (h%div)
      end if
      allocate (h%div(ndim))
    end if
  end subroutine vamp_create_history

107e <Implementation of vamp procedures 78b>+≡ (75b) <107d 108a>
  elemental subroutine vamp_terminate_history (h)
    type(vamp_history), intent(inout) :: h

```

```

        h%calls = 0.0
    end subroutine vamp_terminate_history

108a  <Implementation of vamp procedures 78b>+≡ (75b) <107e 109>
    pure subroutine vamp_get_history_single (h, g, integral, std_dev, avg_chi2)
        type(vamp_history), intent(inout) :: h
        type(vamp_grid), intent(in) :: g
        real(kind=default), intent(in) :: integral, std_dev, avg_chi2
        h%calls = g%calls
        h%stratified = g%all_stratified
        h%integral = g%mu(1)
        h%std_dev = sqrt (g%mu(2))
        h%avg_integral = integral
        h%avg_std_dev = std_dev
        h%avg_chi2 = avg_chi2
        h%f_min = g%f_min
        h%f_max = g%f_max
        if (h%verbose) then
            <Adjust h%div iff necessary 108b>
            call copy_history (h%div, summarize_division (g%div))
        end if
    end subroutine vamp_get_history_single

108b  <Adjust h%div iff necessary 108b>≡ (108a)
    if (associated (h%div)) then
        if (size (h%div) /= size (g%div)) then
            deallocate (h%div)
            allocate (h%div(size(g%div)))
        end if
    else
        allocate (h%div(size(g%div)))
    end if

108c  <Declaration of vamp procedures 77a>+≡ (75b) <107b 113b>
    public :: vamp_print_history, vamp_write_history
    private :: vamp_print_one_history, vamp_print_histories
    ! private :: vamp_write_one_history, vamp_write_histories

108d  <Interfaces of vamp procedures 96b>+≡ (75b) <107c 124d>
    interface vamp_print_history
        module procedure vamp_print_one_history, vamp_print_histories
    end interface
    interface vamp_write_history
        module procedure vamp_write_one_history_unit, vamp_write_histories_unit
    end interface

```

109 *<Implementation of vamp procedures 78b>+≡* (75b) *<108a 110b>*

```

subroutine vamp_print_one_history (h, tag)
  type(vamp_history), dimension(:), intent(in) :: h
  character(len=*), intent(in), optional :: tag
  type(div_history), dimension(:), allocatable :: h_tmp
  character(len=BUFFER_SIZE) :: pfx
  character(len=1) :: s
  integer :: i, imax, j
  if (present (tag)) then
    pfx = tag
  else
    pfx = "[vamp]"
  end if
  print "(1X,A78)", repeat("-", 78)
  print "(1X,A8,1X,A2,A9,A1,1X,A11,1X,8X,1X," &
    // "1X,A13,1X,8X,1X,A5,1X,A5)", &
    pfx, "it", "#calls", "", "integral", "average", "chi2", "eff."
  imax = size (h)
  iterations: do i = 1, imax
    if (h(i)%calls <= 0) then
      imax = i - 1
      exit iterations
    end if
    ! *JR: Skip zero channel
    if (h(i)%f_max==0) cycle
    if (h(i)%stratified) then
      s = "*"
    else
      s = ""
    end if
    print "(1X,A8,1X,I2,I9,A1,1X,E11.4,A1,E8.2,A1," &
      // "1X,E13.6,A1,E8.2,A1,F5.1,1X,F5.3)", pfx, &
      i, h(i)%calls, s, h(i)%integral, "(", h(i)%std_dev, ")", &
      h(i)%avg_integral, "(", h(i)%avg_std_dev, ")", h(i)%avg_chi2, &
      h(i)%integral / h(i)%f_max
  end do iterations
  print "(1X,A78)", repeat("-", 78)
  if (all (h%verbose) .and. (imax >= 1)) then
    if (associated (h(1)%div)) then
      allocate (h_tmp(imax))
      dimensions: do j = 1, size (h(1)%div)
        do i = 1, imax
          call copy_history (h_tmp(i), h(i)%div(j))
        end do
      end do
    end if
  end if
end subroutine vamp_print_one_history

```

```

        end do
        if (present (tag)) then
            write (unit = pfx, fmt = "(A,A1,I2.2)") &
                trim (tag(1:min(len_trim(tag),8))), "#", j
        else
            write (unit = pfx, fmt = "(A,A1,I2.2)") "[vamp]", "#", j
        end if
        call print_history (h_tmp, tag = pfx)
        print "(1X,A78)", repeat ("-", 78)
    end do dimensions
    deallocate (h_tmp)
end if
end if
flush (output_unit)
end subroutine vamp_print_one_history
110a <Variables in vamp 79a>+≡ (75b) <94c 146a>
    integer, private, parameter :: BUFFER_SIZE = 50
110b <Implementation of vamp procedures 78b>+≡ (75b) <109 110c>
    subroutine vamp_print_histories (h, tag)
        type(vamp_history), dimension(:,,:), intent(in) :: h
        character(len=*), intent(in), optional :: tag
        character(len=BUFFER_SIZE) :: pfx
        integer :: i
        print "(1X,A78)", repeat ("=", 78)
        channels: do i = 1, size (h, dim=2)
            if (present (tag)) then
                write (unit = pfx, fmt = "(A4,A1,I3.3)") tag, "#", i
            else
                write (unit = pfx, fmt = "(A4,A1,I3.3)") "chan", "#", i
            end if
            call vamp_print_one_history (h(:,i), pfx)
        end do channels
        print "(1X,A78)", repeat ("=", 78)
        flush (output_unit)
    end subroutine vamp_print_histories

```



WK

```

110c <Implementation of vamp procedures 78b>+≡ (75b) <110b 113c>
    subroutine vamp_write_one_history_unit (u, h, tag)
        integer, intent(in) :: u
        type(vamp_history), dimension(:), intent(in) :: h
        character(len=*), intent(in), optional :: tag
    end subroutine vamp_write_one_history_unit

```

```

type(div_history), dimension(:), allocatable :: h_tmp
character(len=BUFFER_SIZE) :: pfx
character(len=1) :: s
integer :: i, imax, j
if (present (tag)) then
    pfx = tag
else
    pfx = "[vamp]"
end if
write (u, "(1X,A78)") repeat ("-", 78)
write (u, "(1X,A8,1X,A2,A9,A1,1X,A11,1X,8X,1X," &
    // "1X,A13,1X,8X,1X,A5,1X,A5)") &
    pfx, "it", "#calls", "", "integral", "average", "chi2", "eff."
imax = size (h)
iterations: do i = 1, imax
    if (h(i)%calls <= 0) then
        imax = i - 1
        exit iterations
    end if
    ! *WK: Skip zero channel
    if (h(i)%f_max==0) cycle
    if (h(i)%stratified) then
        s = "*"
    else
        s = ""
    end if
    write (u, "(1X,A8,1X,I2,I9,A1,1X,ES11.4,A1,ES8.2,A1," &
        // "1X,ES13.6,A1,ES8.2,A1,F5.1,1X,F5.3)") pfx, &
        i, h(i)%calls, s, h(i)%integral, "(", h(i)%std_dev, ")", &
        h(i)%avg_integral, "(", h(i)%avg_std_dev, ")", h(i)%avg_chi2, &
        h(i)%integral / h(i)%f_max
end do iterations
write (u, "(1X,A78)") repeat ("-", 78)
if (all (h%verbose) .and. (imax >= 1)) then
    if (associated (h(1)%div)) then
        allocate (h_tmp(imax))
        dimensions: do j = 1, size (h(1)%div)
            do i = 1, imax
                call copy_history (h_tmp(i), h(i)%div(j))
            end do
            if (present (tag)) then
                write (unit = pfx, fmt = "(A,A1,I2.2)") &
                    trim (tag(1:min(len_trim(tag),8))), "#", j
            end if
        end do
    end if
end if

```



```

        else
            write (unit = pfx, fmt = "(A,A1,I2.2)") "[vamp]", "#", j
        end if
        call write_history (u, h_tmp, tag = pfx)
        print "(1X,A78)", repeat ("-", 78)
    end do dimensions
    deallocate (h_tmp)
end if
end if
flush (u)
end subroutine vamp_write_one_history_unit
subroutine vamp_write_histories_unit (u, h, tag)
    integer, intent(in) :: u
    type(vamp_history), dimension(:, :), intent(in) :: h
    character(len=*), intent(in), optional :: tag
    character(len=BUFFER_SIZE) :: pfx
    integer :: i
    write (u, "(1X,A78)") repeat ("=", 78)
    channels: do i = 1, size (h, dim=2)
        if (present (tag)) then
            write (unit = pfx, fmt = "(A4,A1,I3.3)") tag, "#", i
        else
            write (unit = pfx, fmt = "(A4,A1,I3.3)") "chan", "#", i
        end if
        call vamp_write_one_history_unit (u, h(:, i), pfx)
    end do channels
    write (u, "(1X,A78)") repeat ("=", 78)
    flush (u)
end subroutine vamp_write_histories_unit

```

### 5.2.7 Multi Channel

[23]

$$g(x) = \sum_i \alpha_i g_i(x) \quad (5.25a)$$

$$w(x) = \frac{f(x)}{g(x)} \quad (5.25b)$$

We want to minimize the variance  $W(\alpha)$  with the subsidiary condition  $\sum_i \alpha_i = 1$ . We introduce a Lagrange multiplier  $\lambda$ :

$$\tilde{W}(\alpha) = W(\alpha) + \lambda \left( \sum_i \alpha_i - 1 \right) \quad (5.26)$$

Therefore...

$$W_i(\alpha) = -\frac{\partial}{\partial \alpha_i} W(\alpha) = \int dx g_i(x) (w(x))^2 \approx \left\langle \frac{g_i(x)}{g(x)} (w(x))^2 \right\rangle \quad (5.27)$$

⚡ Here it *really* hurts that Fortran has no *first-class* functions. The following can be expressed much more elegantly in a functional programming language with *first-class* functions, currying and closures. Fortran makes it extra painful since not even procedure pointers are supported. This puts extra burden on the users of this library.

Note that the components of **vamp\_grids** are not protected. However, this is not a license for application programs to access it. Only Other libraries (e.g. for parallel processing, like **vampi**) should do so.

113a  $\langle$ Declaration of **vamp** types 77b $\rangle + \equiv$  (75b)  $\triangleleft$ 106c

```

type, public :: vamp_grids
  !!! private ! used by vampi
  real(kind=default), dimension(:), pointer :: weights => null ()
  type(vamp_grid), dimension(:), pointer :: grids => null ()
  integer, dimension(:), pointer :: num_calls => null ()
  real(kind=default) :: sum_chi2, sum_integral, sum_weights
end type vamp_grids

```

$$g \circ \phi_i = \left| \frac{\partial \phi_i}{\partial x} \right|^{-1} \left( \alpha_i g_i + \sum_{\substack{j=1 \\ j \neq i}}^{N_c} \alpha_j (g_j \circ \pi_{ij}) \left| \frac{\partial \pi_{ij}}{\partial x} \right| \right). \quad (5.28)$$

113b  $\langle$ Declaration of **vamp** procedures 77a $\rangle + \equiv$  (75b)  $\triangleleft$ 108c 114b $\rangle$

```

public :: vamp_multi_channel, vamp_multi_channel0

```

113c  $\langle$ Implementation of **vamp** procedures 78b $\rangle + \equiv$  (75b)  $\triangleleft$ 110c 114a $\rangle$

```

function vamp_multi_channel &
  (func, data, phi, ihp, jacobian, x, weights, channel, grids) result (w_x)
  class(vamp_data_t), intent(in) :: data
  real(kind=default), dimension(:), intent(in) :: x
  real(kind=default), dimension(:), intent(in) :: weights
  integer, intent(in) :: channel
  type(vamp_grid), dimension(:), intent(in) :: grids
   $\langle$ Interface declaration for func 22 $\rangle$ 
   $\langle$ Interface declaration for phi 31a $\rangle$ 
   $\langle$ Interface declaration for ihp 31b $\rangle$ 
   $\langle$ Interface declaration for jacobian 31c $\rangle$ 
  real(kind=default) :: w_x
  integer :: i

```

```

real(kind=default), dimension(size(x)) :: phi_x
real(kind=default), dimension(size(weights)) :: g_phi_x, g_pi_x
phi_x = phi (x, channel)
do i = 1, size (weights)
  if (i == channel) then
    g_pi_x(i) = vamp_probability (grids(i), x)
  else
    g_pi_x(i) = vamp_probability (grids(i), ihp (phi_x, i))
  end if
end do
do i = 1, size (weights)
  g_phi_x(i) = g_pi_x(i) / g_pi_x(channel) * jacobian (phi_x, data, i)
end do
w_x = func (phi_x, data, weights, channel, grids) &
      / dot_product (weights, g_phi_x)
end function vamp_multi_channel

```

114a *<Implementation of vamp procedures 78b>+≡* (75b) <113c 114c>

```

function vamp_multi_channel0 &
  (func, data, phi, jacobian, x, weights, channel) result (w_x)
class(vamp_data_t), intent(in) :: data
real(kind=default), dimension(:), intent(in) :: x
real(kind=default), dimension(:), intent(in) :: weights
integer, intent(in) :: channel
<Interface declaration for func 22>
<Interface declaration for phi 31a>
<Interface declaration for jacobian 31c>
real(kind=default) :: w_x
real(kind=default), dimension(size(x)) :: x_prime
real(kind=default), dimension(size(weights)) :: g_phi_x
integer :: i
x_prime = phi (x, channel)
do i = 1, size (weights)
  g_phi_x(i) = jacobian (x_prime, data, i)
end do
w_x = func (x_prime, data) / dot_product (weights, g_phi_x)
end function vamp_multi_channel0

```



WK

114b *<Declaration of vamp procedures 77a>+≡* (75b) <113b 117a>  
 public :: vamp\_jacobian, vamp\_check\_jacobian

114c *<Implementation of vamp procedures 78b>+≡* (75b) <114a 115>  
 pure subroutine vamp\_jacobian (phi, channel, x, region, jacobian, delta\_x)

```

integer, intent(in) :: channel
real(kind=default), dimension(:), intent(in) :: x
real(kind=default), dimension(:, :), intent(in) :: region
real(kind=default), intent(out) :: jacobian
real(kind=default), intent(in), optional :: delta_x
interface
  pure function phi (xi, channel) result (x)
    use kinds
    real(kind=default), dimension(:), intent(in) :: xi
    integer, intent(in) :: channel
    real(kind=default), dimension(size(xi)) :: x
  end function phi
end interface
real(kind=default), dimension(size(x)) :: x_min, x_max
real(kind=default), dimension(size(x)) :: x_plus, x_minus
real(kind=default), dimension(size(x), size(x)) :: d_phi
real(kind=default), parameter :: &
  dx_default = 10.0_default**(-precision(jacobian)/3)
real(kind=default) :: dx
integer :: j
if (present (delta_x)) then
  dx = delta_x
else
  dx = dx_default
end if
x_min = region(1,:)
x_max = region(2,:)
x_minus = max (x_min, x)
x_plus = min (x_max, x)
do j = 1, size (x)
  x_minus(j) = max (x_min(j), x(j) - dx)
  x_plus(j) = min (x_max(j), x(j) + dx)
  d_phi(:,j) = (phi (x_plus, channel) - phi (x_minus, channel)) &
    / (x_plus(j) - x_minus(j))
  x_minus(j) = max (x_min(j), x(j))
  x_plus(j) = min (x_max(j), x(j))
end do
call determinant (d_phi, jacobian)
jacobian = abs (jacobian)
end subroutine vamp_jacobian

```

$$g(\phi(x)) = \frac{1}{\left| \frac{\partial \phi}{\partial x} \right| (x)} \quad (5.29)$$

115  $\langle$ Implementation of vamp procedures 78b $\rangle + \equiv$

(75b)  $\langle$ 114c 117b $\rangle$

```

subroutine vamp_check_jacobian &
    (rng, n, func, data, phi, channel, region, delta, x_delta)
type(tao_random_state), intent(inout) :: rng
integer, intent(in) :: n
class(vamp_data_t), intent(in) :: data
integer, intent(in) :: channel
real(kind=default), dimension(:, :), intent(in) :: region
real(kind=default), intent(out) :: delta
real(kind=default), dimension(:), intent(out), optional :: x_delta
<Interface declaration for func 22>
<Interface declaration for phi 31a>
real(kind=default), dimension(size(region,dim=2)) :: x, r
real(kind=default) :: jac, d
real(kind=default), dimension(0) :: wgts
integer :: i
delta = 0.0
do i = 1, max (1, n)
    call tao_random_number (rng, r)
    x = region(1,:) + (region(2,:) - region(1,:)) * r
    call vamp_jacobian (phi, channel, x, region, jac)
    d = func (phi (x, channel), data, wgts, channel) * jac &
        - 1.0_default
    if (abs (d) >= abs (delta)) then
        delta = d
        if (present (x_delta)) then
            x_delta = x
        end if
    end if
end do
end subroutine vamp_check_jacobian

```

This is a subroutine to comply with F's rules, otherwise, we would code it as a function.

116a <Declaration of vamp procedures (removed from WHIZARD) 116a>≡  
 private :: numeric\_jacobian

116b <Implementation of vamp procedures (removed from WHIZARD) 116b>≡  
 pure subroutine numeric\_jacobian (phi, channel, x, region, jacobian, delta\_x)  
 integer, intent(in) :: channel  
 real(kind=default), dimension(:), intent(in) :: x  
 real(kind=default), dimension(:, :), intent(in) :: region  
 real(kind=default), intent(out) :: jacobian  
 real(kind=default), intent(in), optional :: delta\_x  
 <Interface declaration for phi 31a>

```

real(kind=default), dimension(size(x)) :: x_min, x_max
real(kind=default), dimension(size(x)) :: x_plus, x_minus
real(kind=default), dimension(size(x),size(x)) :: d_phi
real(kind=default), parameter :: &
    dx_default = 10.0_default**(-precision(jacobian)/3)
real(kind=default) :: dx
integer :: j
if (present (delta_x)) then
    dx = delta_x
else
    dx = dx_default
end if
x_min = region(1,:)
x_max = region(2,:)
x_minus = max (x_min, x)
x_plus = min (x_max, x)
do j = 1, size (x)
    x_minus(j) = max (x_min(j), x(j) - dx)
    x_plus(j) = min (x_max(j), x(j) + dx)
    d_phi(:,j) = (phi (x_plus, channel) - phi (x_minus, channel)) &
        / (x_plus(j) - x_minus(j))
    x_minus(j) = max (x_min(j), x(j))
    x_plus(j) = min (x_max(j), x(j))
end do
call determinant (d_phi, jacobian)
jacobian = abs (jacobian)
end subroutine numeric_jacobian

```

117a *<Declaration of vamp procedures 77a>+≡* (75b) <114b 118b>  
 public :: vamp\_create\_grids, vamp\_create\_empty\_grids  
 public :: vamp\_copy\_grids, vamp\_delete\_grids

The rules for optional arguments forces us to handle special cases, because we can't just pass a array section of an optional array as an actual argument (cf. 12.4.1.5(4) in [9]) even if the dummy argument is optional itself.

117b *<Implementation of vamp procedures 78b>+≡* (75b) <115 118a>  
 pure subroutine vamp\_create\_grids &  
 (g, domain, num\_calls, weights, maps, num\_div, &  
 stratified, quadrupole, exc)  
 type(vamp\_grids), intent(inout) :: g  
 real(kind=default), dimension(:,,:), intent(in) :: domain  
 integer, intent(in) :: num\_calls  
 real(kind=default), dimension(:), intent(in) :: weights  
 real(kind=default), dimension(:, :, :), intent(in), optional :: maps

```

integer, dimension(:), intent(in), optional :: num_div
logical, intent(in), optional :: stratified, quadrupole
type(exception), intent(inout), optional :: exc
character(len=*), parameter :: FN = "vamp_create_grids"
integer :: ch, nch
nch = size (weights)
allocate (g%grids(nch), g%weights(nch), g%num_calls(nch))
g%weights = weights / sum (weights)
g%num_calls = g%weights * num_calls
do ch = 1, size (g%grids)
  if (present (maps)) then
    call vamp_create_grid &
      (g%grids(ch), domain, g%num_calls(ch), num_div, &
       stratified, quadrupole, map = maps(:, :, ch), exc = exc)
  else
    call vamp_create_grid &
      (g%grids(ch), domain, g%num_calls(ch), num_div, &
       stratified, quadrupole, exc = exc)
  end if
end do
g%sum_integral = 0.0
g%sum_chi2 = 0.0
g%sum_weights = 0.0
end subroutine vamp_create_grids

```

118a *<Implementation of vamp procedures 78b>+≡* (75b) *<117b 118c>*

```

pure subroutine vamp_create_empty_grids (g)
  type(vamp_grids), intent(inout) :: g
  nullify (g%grids, g%weights, g%num_calls)
end subroutine vamp_create_empty_grids

```

118b *<Declaration of vamp procedures 77a>+≡* (75b) *<117a 119a>*

```

public :: vamp_discard_integrals

```

118c *<Implementation of vamp procedures 78b>+≡* (75b) *<118a 119b>*

```

pure subroutine vamp_discard_integrals &
  (g, num_calls, num_div, stratified, quadrupole, exc, eq)
type(vamp_grids), intent(inout) :: g
integer, intent(in), optional :: num_calls
integer, dimension(:), intent(in), optional :: num_div
logical, intent(in), optional :: stratified, quadrupole
type(exception), intent(inout), optional :: exc
type(vamp_equivalences_t), intent(in), optional :: eq
integer :: ch
character(len=*), parameter :: FN = "vamp_discard_integrals"

```

```

    g%sum_integral = 0.0
    g%sum_weights = 0.0
    g%sum_chi2 = 0.0
    do ch = 1, size (g%grids)
        call vamp_discard_integral (g%grids(ch))
    end do
    if (present (num_calls)) then
        call vamp_reshape_grids &
            (g, num_calls, num_div, stratified, quadrupole, exc, eq)
    end if
end subroutine vamp_discard_integrals

```

119a *<Declaration of vamp procedures 77a>+≡* (75b) <118b 119c>  
 public :: vamp\_update\_weights

We must discard the accumulated integrals, because the weight function  $w = f / \sum_i \alpha_i g_i$  changes:

119b *<Implementation of vamp procedures 78b>+≡* (75b) <118c 119d>  
 pure subroutine vamp\_update\_weights &  
 (g, weights, num\_calls, num\_div, stratified, quadrupole, exc)  
 type(vamp\_grids), intent(inout) :: g  
 real(kind=default), dimension(:), intent(in) :: weights  
 integer, intent(in), optional :: num\_calls  
 integer, dimension(:), intent(in), optional :: num\_div  
 logical, intent(in), optional :: stratified, quadrupole  
 type(exception), intent(inout), optional :: exc  
 character(len=\*), parameter :: FN = "vamp\_update\_weights"  
 if (sum (weights) > 0) then  
 g%weights = weights / sum (weights)  
 else  
 g%weights = 1.\_default / size(g%weights)  
 end if  
 if (present (num\_calls)) then  
 call vamp\_discard\_integrals (g, num\_calls, num\_div, &  
 stratified, quadrupole, exc)  
 else  
 call vamp\_discard\_integrals (g, sum (g%num\_calls), num\_div, &  
 stratified, quadrupole, exc)  
 end if  
end subroutine vamp\_update\_weights

119c *<Declaration of vamp procedures 77a>+≡* (75b) <119a 120a>  
 public :: vamp\_reshape\_grids

119d *<Implementation of vamp procedures 78b>+≡* (75b) <119b 120b>  
 pure subroutine vamp\_reshape\_grids &



```

    (g, num_calls, num_div, stratified, quadrupole, exc, eq)
type(vamp_grids), intent(inout) :: g
integer, intent(in) :: num_calls
integer, dimension(:), intent(in), optional :: num_div
logical, intent(in), optional :: stratified, quadrupole
type(exception), intent(inout), optional :: exc
type(vamp_equivalences_t), intent(in), optional :: eq
integer, dimension(size(g%grids(1)%num_div)) :: num_div_new
integer :: ch
character(len=*), parameter :: FN = "vamp_reshape_grids"
g%num_calls = g%weights * num_calls
do ch = 1, size(g%grids)
    if (g%num_calls(ch) >= 2) then
        if (present(eq)) then
            if (present(num_div)) then
                num_div_new = num_div
            else
                num_div_new = g%grids(ch)%num_div
            end if
            where (eq%div_is_invariant(ch,:))
                num_div_new = 1
            end where
            call vamp_reshape_grid (g%grids(ch), g%num_calls(ch), &
                num_div_new, stratified, quadrupole, exc = exc, &
                independent = eq%independent(ch), &
                equivalent_to_ch = eq%equivalent_to_ch(ch), &
                multiplicity = eq%multiplicity(ch))
        else
            call vamp_reshape_grid (g%grids(ch), g%num_calls(ch), &
                num_div, stratified, quadrupole, exc = exc)
        end if
    else
        g%num_calls(ch) = 0
    end if
end do
end subroutine vamp_reshape_grids

```

120a  $\langle$ Declaration of vamp procedures 77a $\rangle + \equiv$  (75b)  $\langle$ 119c 123a $\rangle$   
 public :: vamp\_sample\_grids

Even if `g%num_calls` is derived from `g%weights`, we must *not* use the latter, allow for integer arithmetic in `g%num_calls`.

120b  $\langle$ Implementation of vamp procedures 78b $\rangle + \equiv$  (75b)  $\langle$ 119d 123b $\rangle$   
 subroutine vamp\_sample\_grids &

```

    (rng, g, func, data, iterations, integral, std_dev, avg_chi2, &
      accuracy, history, histories, exc, eq, warn_error, negative_weights)
type(tao_random_state), intent(inout) :: rng
type(vamp_grids), intent(inout) :: g
class(vamp_data_t), intent(in) :: data
integer, intent(in) :: iterations
real(kind=default), intent(out), optional :: integral, std_dev, avg_chi2
real(kind=default), intent(in), optional :: accuracy
type(vamp_history), dimension(:), intent(inout), optional :: history
type(vamp_history), dimension(:, :), intent(inout), optional :: histories
type(exception), intent(inout), optional :: exc
type(vamp_equivalences_t), intent(in), optional :: eq
logical, intent(in), optional :: warn_error, negative_weights
<Interface declaration for func 22>
integer :: ch, iteration
logical :: neg_w
type(exception), dimension(size(g%grids)) :: excs
logical, dimension(size(g%grids)) :: active
real(kind=default), dimension(size(g%grids)) :: weights, integrals, std_devs
real(kind=default) :: local_integral, local_std_dev, local_avg_chi2
character(len=*), parameter :: FN = "vamp_sample_grids"
integrals = 0
std_devs = 0
neg_w = .false.
if (present (negative_weights)) neg_w = negative_weights
active = (g%num_calls >= 2)
where (active)
    weights = g%num_calls
elsewhere
    weights = 0.0
endwhere
if (sum (weights) /= 0) weights = weights / sum (weights)
call clear_exception (excs)
iterate: do iteration = 1, iterations
    do ch = 1, size (g%grids)
        if (active(ch)) then
            call vamp_discard_integral (g%grids(ch))
            <Sample the grid g%grids(ch) 122>
        else
            call vamp_nullify_variance (g%grids(ch))
            call vamp_nullify_covariance (g%grids(ch))
        end if
    end do
end do

```

```

    if (present(eq)) call vamp_apply_equivalences (g, eq)
    if (iteration < iterations) then
      do ch = 1, size (g%grids)
        active(ch) = (integrals(ch) /= 0)
        if (active(ch)) then
          call vamp_refine_grid (g%grids(ch))
        end if
      end do
    end if
    if (present (exc) .and. (any (excs%level > 0))) then
      call gather_exceptions (exc, excs)
!      return
    end if
    call vamp_reduce_channels (g, integrals, std_devs, active)
    call vamp_average_iterations &
      (g, iteration, local_integral, local_std_dev, local_avg_chi2)
    <Trace results of vamp_sample_grids 125a>
    <Exit iterate if accuracy has been reached 97a>
  end do iterate
  <Copy results of vamp_sample_grid to dummy variables 96c>
end subroutine vamp_sample_grids

```

We must refine the grids after *all* grids have been sampled, therefore we use `vamp_sample_grid0` instead of `vamp_sample_grid`:

```

122 <Sample the grid g%grids(ch) 122>≡ (120b)
    call vamp_sample_grid0 &
      (rng, g%grids(ch), func, data, &
        ch, weights, g%grids, excs(ch), neg_w)
    if (present (exc) .and. present (warn_error)) then
      if (warn_error) call handle_exception (excs(ch))
    end if
    call vamp_average_iterations &
      (g%grids(ch), iteration, integrals(ch), std_devs(ch), local_avg_chi2)
    if (present (histories)) then
      if (iteration <= ubound (histories, dim=1)) then
        call vamp_get_history &
          (histories(iteration,ch), g%grids(ch), &
            integrals(ch), std_devs(ch), local_avg_chi2)
      else
        call raise_exception (exc, EXC_WARN, FN, "history too short")
      end if
      call vamp_terminate_history (histories(iteration+1:,ch))
    end if

```

123a  $\langle$ Declaration of `vamp` procedures 77a $\rangle + \equiv$  (75b)  $\langle$ 120a 124a $\rangle$   
`public :: vamp_reduce_channels`

$$I = \frac{1}{N} \sum_c N_c I_c \quad (5.30a)$$

$$\sigma^2 = \frac{1}{N^2} \sum_c N_c^2 \sigma_c^2 \quad (5.30b)$$

$$N = \sum_c N_c \quad (5.30c)$$

where (5.30b) is actually

$$\sigma^2 = \frac{1}{N} (\mu_2 - \mu_1) = \frac{1}{N} \left( \frac{1}{N} \sum_c N_c \mu_{2,c} - I^2 \right) = \frac{1}{N} \left( \frac{1}{N} \sum_c (N_c^2 \sigma_c^2 + N_c I_c^2) - I^2 \right)$$

but the latter form suffers from numerical instability and (5.30b) is thus preferred.

123b  $\langle$ Implementation of `vamp` procedures 78b $\rangle + \equiv$  (75b)  $\langle$ 120b 124b $\rangle$   
`pure subroutine vamp_reduce_channels (g, integrals, std_devs, active)`  
`type(vamp_grids), intent(inout) :: g`  
`real(kind=default), dimension(:), intent(in) :: integrals, std_devs`  
`logical, dimension(:), intent(in) :: active`  
`real(kind=default) :: this_integral, this_weight, total_calls`  
`real(kind=default) :: total_variance`  
`if (.not.any(active)) return`  
`total_calls = sum (g%num_calls, mask=active)`  
`if (total_calls > 0) then`  
`this_integral = sum (g%num_calls * integrals, mask=active) / total_calls`  
`else`  
`this_integral = 0`  
`end if`  
`total_variance = sum ((g%num_calls*std_devs)**2, mask=active)`  
`if (total_variance > 0) then`  
`this_weight = total_calls**2 / total_variance`  
`else`  
`this_weight = 0`  
`end if`  
`g%sum_weights = g%sum_weights + this_weight`  
`g%sum_integral = g%sum_integral + this_weight * this_integral`  
`g%sum_chi2 = g%sum_chi2 + this_weight * this_integral**2`  
`end subroutine vamp_reduce_channels`

124a  $\langle$ Declaration of vamp procedures 77a $\rangle + \equiv$  (75b)  $\langle$ 123a 124c $\rangle$   
public :: vamp\_refine\_weights

124b  $\langle$ Implementation of vamp procedures 78b $\rangle + \equiv$  (75b)  $\langle$ 123b 124e $\rangle$   
elemental subroutine vamp\_average\_iterations\_grids &  
(g, iteration, integral, std\_dev, avg\_chi2)  
type(vamp\_grids), intent(in) :: g  
integer, intent(in) :: iteration  
real(kind=default), intent(out) :: integral, std\_dev, avg\_chi2  
real(kind=default), parameter :: eps = 1000 \* epsilon (1.\_default)  
if (g%sum\_weights>0) then  
integral = g%sum\_integral / g%sum\_weights  
std\_dev = sqrt (1.0 / g%sum\_weights)  
avg\_chi2 = &  
max ((g%sum\_chi2 - g%sum\_integral \* integral) / (iteration-0.99), &  
0.0\_default)  
if (avg\_chi2 < eps \* g%sum\_chi2) avg\_chi2 = 0  
else  
integral = 0  
std\_dev = 0  
avg\_chi2 = 0  
end if  
end subroutine vamp\_average\_iterations\_grids

124c  $\langle$ Declaration of vamp procedures 77a $\rangle + \equiv$  (75b)  $\langle$ 124a 125b $\rangle$   
private :: vamp\_average\_iterations\_grids

124d  $\langle$ Interfaces of vamp procedures 96b $\rangle + \equiv$  (75b)  $\langle$ 108d 125c $\rangle$   
interface vamp\_average\_iterations  
module procedure vamp\_average\_iterations\_grids  
end interface

$$\alpha_i \rightarrow \alpha_i \sqrt{V_i} \quad (5.31)$$

124e  $\langle$ Implementation of vamp procedures 78b $\rangle + \equiv$  (75b)  $\langle$ 124b 125d $\rangle$   
pure subroutine vamp\_refine\_weights (g, power)  
type(vamp\_grids), intent(inout) :: g  
real(kind=default), intent(in), optional :: power  
real(kind=default) :: local\_power  
real(kind=default), parameter :: DEFAULT\_POWER = 0.5\_default  
if (present (power)) then  
local\_power = power  
else  
local\_power = DEFAULT\_POWER  
end if  
call vamp\_update\_weights &

```

        (g, g%weights * vamp_get_variance (g%grids) ** local_power)
    end subroutine vamp_refine_weights
125a <Trace results of vamp_sample_grids 125a>≡ (120b)
    if (present (history)) then
        if (iteration <= size (history)) then
            call vamp_get_history &
                (history(iteration), g, local_integral, local_std_dev, &
                 local_avg_chi2)
        else
            call raise_exception (exc, EXC_WARN, FN, "history too short")
        end if
        call vamp_terminate_history (history(iteration+1:))
    end if
125b <Declaration of vamp procedures 77a>+≡ (75b) <124c 126a>
    private :: vamp_get_history_multi
125c <Interfaces of vamp procedures 96b>+≡ (75b) <124d 131b>
    interface vamp_get_history
        module procedure vamp_get_history_multi
    end interface
125d <Implementation of vamp procedures 78b>+≡ (75b) <124e 126b>
    pure subroutine vamp_get_history_multi (h, g, integral, std_dev, avg_chi2)
        type(vamp_history), intent(inout) :: h
        type(vamp_grids), intent(in) :: g
        real(kind=default), intent(in) :: integral, std_dev, avg_chi2
        h%calls = sum (g%grids%calls)
        h%stratified = all (g%grids%all_stratified)
        h%integral = 0.0
        h%std_dev = 0.0
        h%avg_integral = integral
        h%avg_std_dev = std_dev
        h%avg_chi2 = avg_chi2
        h%f_min = 0.0
        h%f_max = huge (h%f_max)
        if (h%verbose) then
            h%verbose = .false.
            if (associated (h%div)) then
                deallocate (h%div)
            end if
        end if
    end subroutine vamp_get_history_multi

```



126a  $\langle$ Declaration of `vamp` procedures 77a $\rangle + \equiv$  (75b)  $\langle$ 125b 127a $\rangle$   
`public :: vamp_sum_channels`

126b  $\langle$ Implementation of `vamp` procedures 78b $\rangle + \equiv$  (75b)  $\langle$ 125d 127c $\rangle$   
`function vamp_sum_channels (x, weights, func, data, grids) result (g)`  
`real(kind=default), dimension(:), intent(in) :: x, weights`  
`class(vamp_data_t), intent(in) :: data`  
`type(vamp_grid), dimension(:), intent(in), optional :: grids`  
`interface`  
`function func (xi, data, weights, channel, grids) result (f)`  
`use kinds`  
`use vamp_grid_type !NODEP!`  
`import vamp_data_t`  
`real(kind=default), dimension(:), intent(in) :: xi`  
`class(vamp_data_t), intent(in) :: data`  
`real(kind=default), dimension(:), intent(in), optional :: weights`  
`integer, intent(in), optional :: channel`  
`type(vamp_grid), dimension(:), intent(in), optional :: grids`  
`real(kind=default) :: f`  
`end function func`  
`end interface`  
`real(kind=default) :: g`  
`integer :: ch`  
`g = 0.0`  
`do ch = 1, size (weights)`  
`g = g + weights(ch) * func (x, data, weights, ch, grids)`  
`end do`  
`end function vamp_sum_channels`

### 5.2.8 Mapping

 This section is still under construction. The basic algorithm is in place, but the heuristics have not been developed yet.

The most naive approach is to use the rotation matrix  $R$  that diagonalizes the covariance  $C$ :

$$R_{ij} = (v_j)_i \quad (5.32)$$

where

$$Cv_j = \lambda_j v_j \quad (5.33)$$

with the eigenvalues  $\{\lambda_j\}$  and eigenvectors  $\{v_j\}$ . Then

$$R^T C R = \text{diag}(\lambda_1, \dots) \quad (5.34)$$

After call `diagonalize_real_symmetric (cov, evals, evecs)`, we have  $\text{evals}(j) = \lambda_j$  and  $\text{evecs}(:, j) = v_j$ . This is equivalent with  $\text{evecs}(i, j) = R_{ij}$ .

This approach will not work in high dimensions, however. In general,  $R$  will *not* leave most of the axes invariant, even if the covariance matrix is almost isotropic in these directions. In this case the benefit from the rotation is rather small and offset by the negative effects from the misalignment of the integration region.

A better strategy is to find the axis of the original coordinate system around which a rotation is most beneficial. There are two extreme cases:

- “pancake”: one eigenvalue much smaller than the others
- “cigar”: one eigenvalue much larger than the others

Actually, instead of rotating around a specific axis, we can as well diagonalize in a subspace. Empirically, rotation around an axis is better than diagonalizing in a two-dimensional subspace, but diagonalizing in a three-dimensional subspace can be even better.

```

127a <Declaration of vamp procedures 77a>+≡ (75b) <126a 128a>
    public :: select_rotation_axis
    public :: select_rotation_subspace

127b <Set iv to the index of the optimal eigenvector 127b>≡ (129d 130c)
    if (num_pancake > 0) then
        print *, "FORCED PANCAKE: ", num_pancake
        iv = sum (minloc (evals))
    else if (num_cigar > 0) then
        print *, "FORCED CIGAR: ", num_cigar
        iv = sum (maxloc (evals))
    else
        call more_pancake_than_cigar (evals, like_pancake)
        if (like_pancake) then
            iv = sum (minloc (evals))
        else
            iv = sum (maxloc (evals))
        end if
    end if

127c <Implementation of vamp procedures 78b>+≡ (75b) <126b 129d>
    subroutine more_pancake_than_cigar (eval, yes_or_no)
        real(kind=default), dimension(:), intent(in) :: eval
        logical, intent(out) :: yes_or_no
        integer, parameter :: N_CL = 2

```



```

real(kind=default), dimension(size(eval)) :: evals
real(kind=default), dimension(N_CL) :: cluster_pos
integer, dimension(N_CL,2) :: clusters
evals = eval
call sort (evals)
call condense (evals, cluster_pos, clusters)
print *, clusters(1,2) - clusters(1,1) + 1, "small EVs: ", &
    evals(clusters(1,1):clusters(1,2))
print *, clusters(2,2) - clusters(2,1) + 1, "large EVs: ", &
    evals(clusters(2,1):clusters(2,2))
if ((clusters(1,2) - clusters(1,1)) &
    < (clusters(2,2) - clusters(2,1))) then
    print *, " => PANCAKE!"
    yes_or_no = .true.
else
    print *, " => CIGAR!"
    yes_or_no = .false.
end if
end subroutine more_pancake_than_cigar

```

128a  $\langle$ Declaration of `vamp` procedures 77a $\rangle + \equiv$  (75b)  $\langle$ 127a 131c $\rangle$   
 private :: more\_pancake\_than\_cigar

In both cases, we can rotate in the plane  $P_{ij}$  closest to eigenvector corresponding to the the singled out eigenvalue. This plane is given by

$$\max_{i \neq i'} \sqrt{(v_j)_i^2 + (v_j)_{i'}^2} \quad (5.35)$$

which is simply found by looking for the two largest  $|(v_j)_i|$ :<sup>3</sup>

128b  $\langle$ Set `i(1)`, `i(2)` to the axes of the optimal plane 128b $\rangle \equiv$  (129d) 129a $\rangle$   
`abs_evec = abs (evecs(:,iv))`  
`i(1) = sum (maxloc (abs_evec))`  
`abs_evec(i(1)) = -1.0`  
`i(2) = sum (maxloc (abs_evec))`

The following is cute, but unfortunately broken, since it fails for degenerate eigenvalues:

128c  $\langle$ Set `i(1)`, `i(2)` to the axes of the optimal plane (broken!) 128c $\rangle \equiv$   
`abs_evec = abs (evecs(:,iv))`  
`i(1) = sum (maxloc (abs_evec))`  
`i(2) = sum (maxloc (abs_evec, mask = abs_evec < abs_evec(i(1))))`

---

<sup>3</sup>The `sum` intrinsic is a convenient Fortran90 trick for turning the rank-one array with one element returned by `maxloc` into its value. It has no semantic significance.

129a  $\langle$ Set  $i(1)$ ,  $i(2)$  to the axes of the optimal plane 128b $\rangle + \equiv$  (129d)  $\triangleleft$  128b

```
print *, iv, evals(iv), " => ", evcs(:,iv)
print *, i(1), abs_evec(i(1)), ", ", i(2), abs_evec(i(2))
print *, i(1), evcs(i(1),iv), ", ", i(2), evcs(i(2),iv)
```

129b  $\langle$ Get  $\cos \theta$  and  $\sin \theta$  from evcs 129b $\rangle \equiv$  (129d)

```
cos_theta = evcs(i(1),iv)
sin_theta = evcs(i(2),iv)
norm = 1.0 / sqrt (cos_theta**2 + sin_theta**2)
cos_theta = cos_theta * norm
sin_theta = sin_theta * norm
```

$$\hat{R}(\theta; i, j) = \begin{pmatrix} 1 & & & & & \\ & \ddots & & & & \\ & & \cos \theta & \cdots & -\sin \theta & \\ & & \vdots & 1 & \vdots & \\ & & \sin \theta & \cdots & \cos \theta & \\ & & & & & \ddots & \\ & & & & & & 1 \end{pmatrix} \quad (5.36)$$

129c  $\langle$ Construct  $\hat{R}(\theta; i, j)$  129c $\rangle \equiv$  (129d)

```
call unit (r)
r(i(1),i) = (/ cos_theta, - sin_theta /)
r(i(2),i) = (/ sin_theta, cos_theta /)
```

129d  $\langle$ Implementation of vamp procedures 78b $\rangle + \equiv$  (75b)  $\triangleleft$  127c 130b $\rangle$

```
subroutine select_rotation_axis (cov, r, pancake, cigar)
  real(kind=default), dimension(:, :), intent(in) :: cov
  real(kind=default), dimension(:, :), intent(out) :: r
  integer, intent(in), optional :: pancake, cigar
  integer :: num_pancake, num_cigar
  logical :: like_pancake
  real(kind=default), dimension(size(cov,dim=1),size(cov,dim=2)) :: evcs
  real(kind=default), dimension(size(cov,dim=1)) :: evals, abs_evec
  integer :: iv
  integer, dimension(2) :: i
  real(kind=default) :: cos_theta, sin_theta, norm
   $\langle$ Handle optional pancake and cigar 130a $\rangle$ 
  call diagonalize_real_symmetric (cov, evals, evcs)
   $\langle$ Set iv to the index of the optimal eigenvector 127b $\rangle$ 
   $\langle$ Set  $i(1)$ ,  $i(2)$  to the axes of the optimal plane 128b $\rangle$ 
   $\langle$ Get  $\cos \theta$  and  $\sin \theta$  from evcs 129b $\rangle$ 
   $\langle$ Construct  $\hat{R}(\theta; i, j)$  129c $\rangle$ 
end subroutine select_rotation_axis
```

130a *<Handle optional pancake and cigar 130a>*≡ (129d 130c)

```

    if (present (pancake)) then
        num_pancake = pancake
    else
        num_pancake = -1
    endif
    if (present (cigar)) then
        num_cigar = cigar
    else
        num_cigar = -1
    endif

```

Here's a less efficient version that can be easily generalized to more than two dimension, however:

130b *<Implementation of vamp procedures 78b>*+≡ (75b) <129d 130c>

```

subroutine select_subspace_explicit (cov, r, subspace)
    real(kind=default), dimension(:,,:), intent(in) :: cov
    real(kind=default), dimension(:,,:), intent(out) :: r
    integer, dimension(:), intent(in) :: subspace
    real(kind=default), dimension(size(subspace)) :: eval_sub
    real(kind=default), dimension(size(subspace),size(subspace)) :: &
        cov_sub, evec_sub
    cov_sub = cov(subspace,subspace)
    call diagonalize_real_symmetric (cov_sub, eval_sub, evec_sub)
    call unit (r)
    r(subspace,subspace) = evec_sub
end subroutine select_subspace_explicit

```

130c *<Implementation of vamp procedures 78b>*+≡ (75b) <130b 131e>

```

subroutine select_subspace_guess (cov, r, ndim, pancake, cigar)
    real(kind=default), dimension(:,,:), intent(in) :: cov
    real(kind=default), dimension(:,,:), intent(out) :: r
    integer, intent(in) :: ndim
    integer, intent(in), optional :: pancake, cigar
    integer :: num_pancake, num_cigar
    logical :: like_pancake
    real(kind=default), dimension(size(cov,dim=1),size(cov,dim=2)) :: evecs
    real(kind=default), dimension(size(cov,dim=1)) :: evals, abs_evec
    integer :: iv, i
    integer, dimension(ndim) :: subspace
    <Handle optional pancake and cigar 130a>
    call diagonalize_real_symmetric (cov, evals, evecs)
    <Set iv to the index of the optimal eigenvector 127b>
    <Set subspace to the axes of the optimal plane 131a>

```

```

        call select_subspace_explicit (cov, r, subspace)
    end subroutine select_subspace_guess

131a  <Set subspace to the axes of the optimal plane 131a>≡ (130c)
    abs_evec = abs (evecs(:,iv))
    subspace(1) = sum (maxloc (abs_evec))
    do i = 2, ndim
        abs_evec(subspace(i-1)) = -1.0
        subspace(i) = sum (maxloc (abs_evec))
    end do

131b  <Interfaces of vamp procedures 96b>+≡ (75b) <125c 135b>
    interface select_rotation_subspace
        module procedure select_subspace_explicit, select_subspace_guess
    end interface

131c  <Declaration of vamp procedures 77a>+≡ (75b) <128a 131d>
    private :: select_subspace_explicit
    private :: select_subspace_guess

131d  <Declaration of vamp procedures 77a>+≡ (75b) <131c 132a>
    public :: vamp_print_covariance

131e  <Implementation of vamp procedures 78b>+≡ (75b) <130c 133c>
    subroutine vamp_print_covariance (cov)
        real(kind=default), dimension(:,,:), intent(in) :: cov
        real(kind=default), dimension(size(cov,dim=1)) :: &
            evals, abs_evals, tmp
        real(kind=default), dimension(size(cov,dim=1),size(cov,dim=2)) :: &
            evecs, abs_evecs
        integer, dimension(size(cov,dim=1)) :: idx
        integer :: i, i_max, j
        i_max = size (evals)
        call diagonalize_real_symmetric (cov, evals, evecs)
        call sort (evals, evecs)
        abs_evals = abs (evals)
        abs_evecs = abs (evecs)
        print "(1X,A78)", repeat ("-", 78)
        print "(1X,A)", "Eigenvalues and eigenvectors:"
        print "(1X,A78)", repeat ("-", 78)
        do i = 1, i_max
            print "(1X,I2,A1,1X,E11.4,1X,A1,10(10(1X,F5.2)/,18X))", &
                i, ":", evals(i), "|", evecs(:,i)
        end do
        print "(1X,A78)", repeat ("-", 78)
        print "(1X,A)", "Approximate subspaces:"

```

```

print "(1X,A78)", repeat ("-", 78)
do i = 1, i_max
  idx = (/ (j, j=1,i_max) /)
  tmp = abs_evecs(:,i)
  call sort (tmp, idx, reverse = .true.)
  print "(1X,I2,A1,1X,E11.4,1X,A1,10(1X,I5))", &
    i, ":", evals(i), "|", idx(1:min(10,size(idx)))
  print "(17X,A1,10(1X,F5.2))", &
    "|", evecs(idx(1:min(10,size(idx))),i)
end do
print "(1X,A78)", repeat ("-", 78)
end subroutine vamp_print_covariance

```

### Condensing Eigenvalues

In order to decide whether we have a “pancake” or a “cigar”, we have to classify the eigenvalues of the covariance matrix. We do this by condensing the  $n_{\text{dim}}$  eigenvalues into  $n_{\text{cl}} \ll n_{\text{dim}}$  clusters.


132a  $\langle$ Declaration of `vamp` procedures 77a $\rangle \equiv$  (75b)  $\langle$ 131d 134a $\rangle$

```

! private :: condense
public :: condense

```

The rough description is as follows: in each step, combine the nearest neighbours (according to an appropriate metric) to form a smaller set. This is an extremely simplified, discretized modeling of molecules condensing under the influence of some potential.

 If there’s not a clean separation, this algorithm is certainly chaotic and we need to apply some form of damping!

132b  $\langle$ Initialize clusters 132b $\rangle \equiv$  (133c)

```

cl_pos = x
cl_num = size (cl_pos)
cl = spread ((/ (i, i=1,cl_num) /), dim = 2, ncopies = 2)

```

It appears that the logarithmic metric

$$d_0(x, y) = \left| \log \left( \frac{x}{y} \right) \right| \quad (5.37a)$$

performs better than the linear metric

$$d_1(x, y) = |x - y| \quad (5.37b)$$

since the latter won't separate very small eigenvalues from the bulk. Another option is

$$d_\alpha(x, y) = |x^\alpha - y^\alpha| \quad (5.37c)$$

with  $\alpha \neq 1$ , in particular  $\alpha \approx -1$ . I haven't studied it yet, though.

⚡ but I should perform more empirical studies to determine whether the logarithmic or the linear metric is more appropriate in realistic cases.

```

133a  <Join closest clusters 133a>≡ (133c) 133b>
      if (linear_metric) then
        gap = sum (minloc (cl_pos(2:cl_num) - cl_pos(1:cl_num-1)))
      else
        gap = sum (minloc (cl_pos(2:cl_num) / cl_pos(1:cl_num-1)))
      end if
      wgt0 = cl(gap,2) - cl(gap,1) + 1
      wgt1 = cl(gap+1,2) - cl(gap+1,1) + 1
      cl_pos(gap) = (wgt0 * cl_pos(gap) + wgt1 * cl_pos(gap+1)) / (wgt0 + wgt1)
      cl(gap,2) = cl(gap+1,2)

133b  <Join closest clusters 133a>+≡ (133c) <133a
      cl_pos(gap+1:cl_num-1) = cl_pos(gap+2:cl_num)
      cl(gap+1:cl_num-1,:) = cl(gap+2:cl_num,:)

133c  <Implementation of vamp procedures 78b>+≡ (75b) <131e 134b>
      subroutine condense (x, cluster_pos, clusters, linear)
        real(kind=default), dimension(:), intent(in) :: x
        real(kind=default), dimension(:), intent(out) :: cluster_pos
        integer, dimension(:,:), intent(out) :: clusters
        logical, intent(in), optional :: linear
        logical :: linear_metric
        real(kind=default), dimension(size(x)) :: cl_pos
        real(kind=default) :: wgt0, wgt1
        integer :: cl_num
        integer, dimension(size(x),2) :: cl
        integer :: i, gap
        linear_metric = .false.
        if (present (linear)) then
          linear_metric = linear
        end if
        <Initialize clusters 132b>
        do cl_num = size (cl_pos), size (cluster_pos) + 1, -1
          <Join closest clusters 133a>
          print *, cl_num, ": action = ", condense_action (x, cl)
        end do
      end subroutine

```

```

        end do
        cluster_pos = cl_pos(1:cl_num)
        clusters = cl(1:cl_num,:)
    end subroutine condense
134a  <Declaration of vamp procedures 77a>+≡ (75b) <132a 135a>
    ! private :: condense_action
    public :: condense_action

```

$$S = \sum_{c \in \text{clusters}} \text{var}^{\frac{\alpha}{2}}(c) \quad (5.38)$$

```

134b  <Implementation of vamp procedures 78b>+≡ (75b) <133c 135d>
    function condense_action (positions, clusters) result (s)
        real(kind=default), dimension(:), intent(in) :: positions
        integer, dimension(:,:), intent(in) :: clusters
        real(kind=default) :: s
        integer :: i
        integer, parameter :: POWER = 2
        s = 0
        do i = 1, size (clusters, dim = 1)
            s = s + standard_deviation (positions(clusters(i,1) &
                                                    :clusters(i,2))) ** POWER
        end do
    end function condense_action
134c  <ctest.f90 134c>≡
    program ctest
        use kinds
        use utils
        use vamp_stat
        use tao_random_numbers
        use vamp
        implicit none
        integer, parameter :: N = 16, NC = 2
        real(kind=default), dimension(N) :: eval
        real(kind=default), dimension(NC) :: cluster_pos
        integer, dimension(NC,2) :: clusters
        integer :: i
        call tao_random_number (eval)
        call sort (eval)
        print *, eval
        eval(1:N/2) = 0.95*eval(1:N/2)
        eval(N/2+1:N) = 1.0 - 0.95*(1.0 - eval(N/2+1:N))
        print *, eval
        call condense (eval, cluster_pos, clusters, linear=.true.)

```

```

do i = 1, NC
  print "(I2,A,F5.2,A,I2,A,I2,A,A,F5.2,A,F5.2,A,32F5.2)", &
    i, ":", cluster_pos(i), &
    " [", clusters(i,1), "-", clusters(i,2), "]", &
    " [", eval(clusters(i,1)), " - ", eval(clusters(i,2)), "]", &
    eval(clusters(i,1)+1:clusters(i,2)) &
    - eval(clusters(i,1):clusters(i,2)-1)
  print *, average (eval(clusters(i,1):clusters(i,2))), "+/-", &
    standard_deviation (eval(clusters(i,1):clusters(i,2)))
end do
end program ctest

```

### 5.2.9 Event Generation

Automagically adaptive tools are not always appropriate for unweighted event generation, but we can give it a try.

135a *<Declaration of vamp procedures 77a>+≡* (75b) <134a 135c>  
 public :: vamp\_next\_event

135b *<Interfaces of vamp procedures 96b>+≡* (75b) <131b 140b>  
 interface vamp\_next\_event  
 module procedure vamp\_next\_event\_single, vamp\_next\_event\_multi  
 end interface

135c *<Declaration of vamp procedures 77a>+≡* (75b) <135a 139a>  
 private :: vamp\_next\_event\_single, vamp\_next\_event\_multi

Both event generation routines operate in two modes, depending on whether the optional argument `weight` is present.

135d *<Implementation of vamp procedures 78b>+≡* (75b) <134b 137>  
 subroutine vamp\_next\_event\_single &  
 (x, rng, g, func, data, &  
 weight, channel, weights, grids, exc)  
 real(kind=default), dimension(:), intent(out) :: x  
 type(tao\_random\_state), intent(inout) :: rng  
 type(vamp\_grid), intent(inout) :: g  
 real(kind=default), intent(out), optional :: weight  
 class(vamp\_data\_t), intent(in) :: data  
 integer, intent(in), optional :: channel  
 real(kind=default), dimension(:), intent(in), optional :: weights  
 type(vamp\_grid), dimension(:), intent(in), optional :: grids  
 type(exception), intent(inout), optional :: exc  
*<Interface declaration for func 22>*  
 character(len=\*), parameter :: FN = "vamp\_next\_event\_single"



```

real(kind=default), dimension(size(g%div)):: wgts
real(kind=default), dimension(size(g%div)):: r
integer, dimension(size(g%div)):: ia
real(kind=default) :: f, wgt
real(kind=default) :: r0
rejection: do
  <Choose a x and calculate f(x) 136a>
  if (present (weight)) then
    <Unconditionally accept weighted event 136b>
  else
    <Maybe accept unweighted event 136c>
  end if
end do rejection
end subroutine vamp_next_event_single
136a <Choose a x and calculate f(x) 136a>≡ (135d)
call tao_random_number (rng, r)
call inject_division_short (g%div, real(r, kind=default), x, ia, wgts)
wgt = g%jacobi * product (wgts)
wgt = g%calls * wgt ! the calling procedure will divide by #calls
if (associated (g%map)) then
  x = matmul (g%map, x)
end if
<f = wgt * func (x, weights, channel), iff x inside true.domain 88d>
! call record_efficiency (g%div, ia, f/g%f_max)
136b <Unconditionally accept weighted event 136b>≡ (135d)
weight = f
exit rejection
136c <Maybe accept unweighted event 136c>≡ (135d)
if (f > g%f_max) then
  g%f_max = f
  call raise_exception (exc, EXC_WARN, FN, "weight > 1")
  exit rejection
end if
call tao_random_number (rng, r0)
if (r0 * g%f_max <= f) then
  exit rejection
end if

```

We know that `g%weights` are normalized: `sum (g%weights) == 1.0`. The basic formula for multi channel sampling is

$$f(x) = \sum_i \alpha_i g_i(x) w(x) \quad (5.39)$$

with  $w(x) = f(x)/g(x) = f(x)/\sum_i \alpha_i g_i(x)$  and  $\sum_i \alpha_i = 1$ . The non-trivial problem is that the adaptive grid is different in each channel, so we can't just reject on  $w(x)$ .

137  $\langle$ Implementation of vamp procedures 78b $\rangle + \equiv$  (75b)  $\triangleleft$ 135d 139b $\triangleright$

```

subroutine vamp_next_event_multi &
  (x, rng, g, func, data, phi, weight, excess, positive, exc)
  real(kind=default), dimension(:), intent(out) :: x
  type(tao_random_state), intent(inout) :: rng
  type(vamp_grids), intent(inout) :: g
  class(vamp_data_t), intent(in) :: data
  real(kind=default), intent(out), optional :: weight
  real(kind=default), intent(out), optional :: excess
  logical, intent(out), optional :: positive
  type(exception), intent(inout), optional :: exc
   $\langle$ Interface declaration for func 22 $\rangle$ 
   $\langle$ Interface declaration for phi 31a $\rangle$ 
  character(len=*), parameter :: FN = "vamp_next_event_multi"
  real(kind=default), dimension(size(x)) :: xi
  real(kind=default) :: r, wgt
  real(kind=default), dimension(size(g%weights)) :: weights
  integer :: channel
   $\langle$ weights:  $\alpha_i \rightarrow w_{\max,i} \alpha_i$  138a $\rangle$ 
  rejection: do
     $\langle$ Select channel from weights 138b $\rangle$ 
    call vamp_next_event_single &
      (xi, rng, g%grids(channel), func, data, wgt, &
       channel, g%weights, g%grids, exc)
    if (present (weight)) then
       $\langle$ Unconditionally accept weighted multi channel event 138c $\rangle$ 
    else
       $\langle$ Maybe accept unweighted multi channel event 138d $\rangle$ 
    end if
  end do rejection
  x = phi (xi, channel)
end subroutine vamp_next_event_multi

```

We can either reject with the weights

$$\frac{w_i(x)}{\max_i \max_x w_i(x)} \quad (5.40)$$

after using the apriori weights  $\alpha_i$  to select a channel  $i$  or we can reject with the weights

$$\frac{w_i(x)}{\max_x w_i(x)} \quad (5.41)$$

after using the apriori weights  $\alpha_i(\max_x w_i(x))/(\max_i \max_x w_i(x))$ . The latter method is more efficient if the  $\max_x w_i(x)$  have a wide spread.

- 138a  $\langle \text{weights: } \alpha_i \rightarrow w_{\max,i} \alpha_i \text{ 138a} \rangle \equiv$  (137 138e)
- ```

    if (any (g%grids%f_max > 0)) then
        weights = g%weights * g%grids%f_max
    else
        weights = g%weights
    end if
    weights = weights / sum (weights)

```
- 138b  $\langle \text{Select channel from weights 138b} \rangle \equiv$  (137)
- ```

    call tao_random_number (rng, r)
    select_channel: do channel = 1, size (g%weights)
        r = r - weights(channel)
        if (r <= 0.0) then
            exit select_channel
        end if
    end do select_channel
    channel = min (channel, size (g%weights)) ! for r = 1 and rounding errors

```
- 138c  $\langle \text{Unconditionally accept weighted multi channel event 138c} \rangle \equiv$  (137)
- ```

    weight = wgt * g%weights(channel) / weights(channel)
    exit rejection

```
- 138d  $\langle \text{Maybe accept unweighted multi channel event 138d} \rangle \equiv$  (137)
- ```

    if (abs (wgt) > g%grids(channel)%f_max) then
        if (present(excess)) then
            excess = abs (wgt) / g%grids(channel)%f_max - 1
        else
            call raise_exception (exc, EXC_WARN, FN, "weight > 1")
            !      print *, "weight > 1 (", wgt/g%grids(channel)%f_max, &
            !          & ") in channel ", channel

            end if
        ! exit rejection
    else
        if (present(excess)) excess = 0
    end if
    call tao_random_number (rng, r)
    if (r * g%grids(channel)%f_max <= abs (wgt)) then
        if (present (positive)) positive = wgt >= 0
        exit rejection
    end if

```
- 138e  $\langle \text{Maybe accept unweighted multi channel event (old version) 138e} \rangle \equiv$

```

if (wgt > g%grids(channel)%f_max) then
  g%grids(channel)%f_max = wgt
   $\langle \text{weights: } \alpha_i \rightarrow w_{\max,i} \alpha_i \text{ 138a} \rangle$ 
  call raise_exception (exc, EXC_WARN, FN, "weight > 1")
  exit rejection
end if
call tao_random_number (rng, r)
if (r * g%grids(channel)%f_max <= wgt) then
  exit rejection
end if

```

Using `vamp_sample_grid (g, ...)` to warm up the grid `g` has a somewhat subtle problem: the minimum and maximum weights `g%f_min` and `g%f_max` refer to the grid *before* the final refinement. One could require an additional `vamp_sample_grid0 (g, ...)`, but users are likely to forget such technical details. A better solution is a wrapper `vamp_warmup_grid (g, ...)` that drops the final refinement transparently.

139a  $\langle \text{Declaration of vamp procedures 77a} \rangle + \equiv$  (75b)  $\langle 135c \ 140a \rangle$   
 public :: vamp\_warmup\_grid, vamp\_warmup\_grids

139b  $\langle \text{Implementation of vamp procedures 78b} \rangle + \equiv$  (75b)  $\langle 137 \ 139c \rangle$   
 subroutine vamp\_warmup\_grid &  
   (rng, g, func, data, iterations, exc, history)  
   type(tao\_random\_state), intent(inout) :: rng  
   type(vamp\_grid), intent(inout) :: g  
   class(vamp\_data\_t), intent(in) :: data  
   integer, intent(in) :: iterations  
   type(exception), intent(inout), optional :: exc  
   type(vamp\_history), dimension(:), intent(inout), optional :: history  
    $\langle \text{Interface declaration for func 22} \rangle$   
   call vamp\_sample\_grid &  
     (rng, g, func, data, &  
       iterations - 1, exc = exc, history = history)  
   call vamp\_sample\_grid0 (rng, g, func, data, exc = exc)  
 end subroutine vamp\_warmup\_grid



WHERE ... END WHERE alert!

139c  $\langle \text{Implementation of vamp procedures 78b} \rangle + \equiv$  (75b)  $\langle 139b \ 140c \rangle$

```

subroutine vamp_warmup_grids &
  (rng, g, func, data, iterations, history, histories, exc)
  type(tao_random_state), intent(inout) :: rng
  type(vamp_grids), intent(inout) :: g
  class(vamp_data_t), intent(in) :: data
  integer, intent(in) :: iterations

```

```

type(vamp_history), dimension(:), intent(inout), optional :: history
type(vamp_history), dimension(:, :), intent(inout), optional :: histories
type(exception), intent(inout), optional :: exc
<Interface declaration for func 22>
integer :: ch
logical, dimension(size(g%grids)) :: active
real(kind=default), dimension(size(g%grids)) :: weights
active = (g%num_calls >= 2)
where (active)
    weights = g%num_calls
elsewhere
    weights = 0.0
end where
weights = weights / sum(weights)
call vamp_sample_grids (rng, g, func, data, iterations - 1, &
                        exc = exc, history = history, histories = histories)
do ch = 1, size(g%grids)
    if (g%grids(ch)%num_calls >= 2) then
        call vamp_sample_grid0 &
            (rng, g%grids(ch), func, data, &
             ch, weights, g%grids, exc = exc)
    end if
end do
end subroutine vamp_warmup_grids

```

### 5.2.10 Convenience Routines

- 140a <Declaration of vamp procedures 77a>+≡ (75b) <139a 142a>  
 public :: vamp\_integrate  
 private :: vamp\_integrate\_grid, vamp\_integrate\_region
- 140b <Interfaces of vamp procedures 96b>+≡ (75b) <135b 142b>  
 interface vamp\_integrate  
 module procedure vamp\_integrate\_grid, vamp\_integrate\_region  
 end interface
- 140c <Implementation of vamp procedures 78b>+≡ (75b) <139c 141>  
 subroutine vamp\_integrate\_grid &  
 (rng, g, func, data, calls, integral, std\_dev, avg\_chi2, num\_div, &  
 stratified, quadrupole, accuracy, exc, history)  
 type(tao\_random\_state), intent(inout) :: rng  
 type(vamp\_grid), intent(inout) :: g  
 class(vamp\_data\_t), intent(in) :: data  
 integer, dimension(:, :), intent(in) :: calls

```

real(kind=default), intent(out), optional :: integral, std_dev, avg_chi2
integer, dimension(:), intent(in), optional :: num_div
logical, intent(in), optional :: stratified, quadrupole
real(kind=default), intent(in), optional :: accuracy
type(exception), intent(inout), optional :: exc
type(vamp_history), dimension(:), intent(inout), optional :: history
<Interface declaration for func 22>
character(len=*), parameter :: FN = "vamp_integrate_grid"
integer :: step, last_step, it
last_step = size (calls, dim = 2)
it = 1
do step = 1, last_step - 1
    call vamp_discard_integral (g, calls(2,step), num_div, &
                                stratified, quadrupole, exc = exc)
    call vamp_sample_grid (rng, g, func, data, calls(1,step), &
                           exc = exc, history = history(it:))
    <Bail out if exception exc raised 99d>
    it = it + calls(1,step)
end do
call vamp_discard_integral (g, calls(2,last_step), exc = exc)
call vamp_sample_grid (rng, g, func, data, calls(1,last_step), &
                        integral, std_dev, avg_chi2, accuracy, exc = exc, &
                        history = history(it:))
end subroutine vamp_integrate_grid
141 <Implementation of vamp procedures 78b>+≡ (75b) <140c 142c>
subroutine vamp_integrate_region &
    (rng, region, func, data, calls, &
     integral, std_dev, avg_chi2, num_div, &
     stratified, quadrupole, accuracy, map, covariance, exc, history)
type(tao_random_state), intent(inout) :: rng
real(kind=default), dimension(:,:), intent(in) :: region
class(vamp_data_t), intent(in) :: data
integer, dimension(:,:), intent(in) :: calls
real(kind=default), intent(out), optional :: integral, std_dev, avg_chi2
integer, dimension(:), intent(in), optional :: num_div
logical, intent(in), optional :: stratified, quadrupole
real(kind=default), intent(in), optional :: accuracy
real(kind=default), dimension(:,:), intent(in), optional :: map
real(kind=default), dimension(:,:), intent(out), optional :: covariance
type(exception), intent(inout), optional :: exc
type(vamp_history), dimension(:), intent(inout), optional :: history
<Interface declaration for func 22>
character(len=*), parameter :: FN = "vamp_integrate_region"

```

```

type(vamp_grid) :: g
call vamp_create_grid &
    (g, region, calls(2,1), num_div, &
     stratified, quadrupole, present (covariance), map, exc)
call vamp_integrate_grid &
    (rng, g, func, data, calls, &
     integral, std_dev, avg_chi2, num_div, &
     accuracy = accuracy, exc = exc, history = history)
if (present (covariance)) then
    covariance = vamp_get_covariance (g)
end if
call vamp_delete_grid (g)
end subroutine vamp_integrate_region

142a <Declaration of vamp procedures 77a>+≡ (75b) <140a 143>
public :: vamp_integratex
private :: vamp_integratex_region

142b <Interfaces of vamp procedures 96b>+≡ (75b) <140b 144b>
interface vamp_integratex
    module procedure vamp_integratex_region
end interface

142c <Implementation of vamp procedures 78b>+≡ (75b) <141 144d>
subroutine vamp_integratex_region &
    (rng, region, func, data, calls, integral, std_dev, avg_chi2, &
     num_div, stratified, quadrupole, accuracy, pancake, cigar, &
     exc, history)
type(tao_random_state), intent(inout) :: rng
real(kind=default), dimension(:,,:), intent(in) :: region
class(vamp_data_t), intent(in) :: data
integer, dimension(:,:,:), intent(in) :: calls
real(kind=default), intent(out), optional :: integral, std_dev, avg_chi2
integer, dimension(:), intent(in), optional :: num_div
logical, intent(in), optional :: stratified, quadrupole
real(kind=default), intent(in), optional :: accuracy
integer, intent(in), optional :: pancake, cigar
type(exception), intent(inout), optional :: exc
type(vamp_history), dimension(:), intent(inout), optional :: history
<Interface declaration for func 22>
real(kind=default), dimension(size(region,dim=2)) :: eval
real(kind=default), dimension(size(region,dim=2),size(region,dim=2)) :: evec
type(vamp_grid) :: g
integer :: step, last_step, it
it = 1

```

```

call vamp_create_grid &
  (g, region, calls(2,1,1), num_div, &
   stratified, quadrupole, covariance = .true., exc = exc)
call vamp_integrate_grid &
  (rng, g, func, data, calls(:, :, 1), num_div = num_div, &
   exc = exc, history = history(it:))
<Bail out if exception exc raised 99d>
it = it + sum (calls(1, :, 1))
last_step = size (calls, dim = 3)
do step = 2, last_step - 1
  call diagonalize_real_symmetric (vamp_get_covariance(g), eval, evec)
  call sort (eval, evec)
  call select_rotation_axis (vamp_get_covariance(g), evec, pancake, cigar)
  call vamp_delete_grid (g)
  call vamp_create_grid &
    (g, region, calls(2,1,step), num_div, stratified, quadrupole, &
     covariance = .true., map = evec, exc = exc)
  call vamp_integrate_grid &
    (rng, g, func, data, calls(:, :, step), num_div = num_div, &
     exc = exc, history = history(it:))
  <Bail out if exception exc raised 99d>
  it = it + sum (calls(1, :, step))
end do
call diagonalize_real_symmetric (vamp_get_covariance(g), eval, evec)
call sort (eval, evec)
call select_rotation_axis (vamp_get_covariance(g), evec, pancake, cigar)
call vamp_delete_grid (g)
call vamp_create_grid &
  (g, region, calls(2,1,last_step), num_div, stratified, quadrupole, &
   covariance = .true., map = evec, exc = exc)
call vamp_integrate_grid &
  (rng, g, func, data, calls(:, :, last_step), &
   integral, std_dev, avg_chi2, &
   num_div = num_div, exc = exc, history = history(it:))
call vamp_delete_grid (g)
end subroutine vamp_integratex_region

```

### 5.2.11 I/O

143 *<Declaration of vamp procedures 77a>*+≡ (75b) *<142a 144a>*

```

public :: vamp_write_grid
private :: write_grid_unit, write_grid_name
public :: vamp_read_grid

```



```

private :: read_grid_unit, read_grid_name
public :: vamp_write_grids
private :: write_grids_unit, write_grids_name
public :: vamp_read_grids
private :: read_grids_unit, read_grids_name

144a <Declaration of vamp procedures 77a>+≡ (75b) <143 158a>
  public :: vamp_read_grids_raw
  private :: read_grids_raw_unit, read_grids_raw_name
  public :: vamp_read_grid_raw
  private :: read_grid_raw_unit, read_grid_raw_name
  public :: vamp_write_grids_raw
  private :: write_grids_raw_unit, write_grids_raw_name
  public :: vamp_write_grid_raw
  private :: write_grid_raw_unit, write_grid_raw_name

144b <Interfaces of vamp procedures 96b>+≡ (75b) <142b 144c>
  interface vamp_write_grid
    module procedure write_grid_unit, write_grid_name
  end interface
  interface vamp_read_grid
    module procedure read_grid_unit, read_grid_name
  end interface
  interface vamp_write_grids
    module procedure write_grids_unit, write_grids_name
  end interface
  interface vamp_read_grids
    module procedure read_grids_unit, read_grids_name
  end interface

144c <Interfaces of vamp procedures 96b>+≡ (75b) <144b
  interface vamp_write_grid_raw
    module procedure write_grid_raw_unit, write_grid_raw_name
  end interface
  interface vamp_read_grid_raw
    module procedure read_grid_raw_unit, read_grid_raw_name
  end interface
  interface vamp_write_grids_raw
    module procedure write_grids_raw_unit, write_grids_raw_name
  end interface
  interface vamp_read_grids_raw
    module procedure read_grids_raw_unit, read_grids_raw_name
  end interface

144d <Implementation of vamp procedures 78b>+≡ (75b) <142c 146b>
  subroutine write_grid_unit (g, unit, write_integrals)

```

```

type(vamp_grid), intent(in) :: g
integer, intent(in) :: unit
logical, intent(in), optional :: write_integrals
integer :: i, j
write (unit = unit, fmt = descr_fmt) "begin type(vamp_grid) :: g"
write (unit = unit, fmt = integer_fmt) "size (g%div) = ", size (g%div)
write (unit = unit, fmt = integer_fmt) "num_calls = ", g%num_calls
write (unit = unit, fmt = integer_fmt) "calls_per_cell = ", g%calls_per_cell
write (unit = unit, fmt = logical_fmt) "stratified = ", g%stratified
write (unit = unit, fmt = logical_fmt) "all_stratified = ", g%all_stratified
write (unit = unit, fmt = logical_fmt) "quadrupole = ", g%quadrupole
write (unit = unit, fmt = double_fmt) "mu(1) = ", g%mu(1)
write (unit = unit, fmt = double_fmt) "mu(2) = ", g%mu(2)
write (unit = unit, fmt = double_fmt) "mu_plus(1) = ", g%mu_plus(1)
write (unit = unit, fmt = double_fmt) "mu_plus(2) = ", g%mu_plus(2)
write (unit = unit, fmt = double_fmt) "mu_minus(1) = ", g%mu_minus(1)
write (unit = unit, fmt = double_fmt) "mu_minus(2) = ", g%mu_minus(2)
write (unit = unit, fmt = double_fmt) "sum_integral = ", g%sum_integral
write (unit = unit, fmt = double_fmt) "sum_weights = ", g%sum_weights
write (unit = unit, fmt = double_fmt) "sum_chi2 = ", g%sum_chi2
write (unit = unit, fmt = double_fmt) "calls = ", g%calls
write (unit = unit, fmt = double_fmt) "dv2g = ", g%dv2g
write (unit = unit, fmt = double_fmt) "jacobi = ", g%jacobi
write (unit = unit, fmt = double_fmt) "f_min = ", g%f_min
write (unit = unit, fmt = double_fmt) "f_max = ", g%f_max
write (unit = unit, fmt = double_fmt) "mu_gi = ", g%mu_gi
write (unit = unit, fmt = double_fmt) "sum_mu_gi = ", g%sum_mu_gi
write (unit = unit, fmt = descr_fmt) "begin g%num_div"
do i = 1, size (g%div)
    write (unit = unit, fmt = integer_array_fmt) i, g%num_div(i)
end do
write (unit = unit, fmt = descr_fmt) "end g%num_div"
write (unit = unit, fmt = descr_fmt) "begin g%div"
do i = 1, size (g%div)
    call write_division (g%div(i), unit, write_integrals)
end do
write (unit = unit, fmt = descr_fmt) "end g%div"
if (associated (g%map)) then
    write (unit = unit, fmt = descr_fmt) "begin g%map"
    do i = 1, size (g%div)
        do j = 1, size (g%div)
            write (unit = unit, fmt = double_array2_fmt) i, j, g%map(i,j)
        end do
    end do
end if

```

```

        end do
        write (unit = unit, fmt = descr_fmt) "end g%map"
    else
        write (unit = unit, fmt = descr_fmt) "empty g%map"
    end if
    if (associated (g%mu_x)) then
        write (unit = unit, fmt = descr_fmt) "begin g%mu_x"
        do i = 1, size (g%div)
            write (unit = unit, fmt = double_array_fmt) i, g%mu_x(i)
            write (unit = unit, fmt = double_array_fmt) i, g%sum_mu_x(i)
            do j = 1, size (g%div)
                write (unit = unit, fmt = double_array2_fmt) i, j, g%mu_xx(i,j)
                write (unit = unit, fmt = double_array2_fmt) i, j, g%sum_mu_xx(i,j)
            end do
        end do
        write (unit = unit, fmt = descr_fmt) "end g%mu_x"
    else
        write (unit = unit, fmt = descr_fmt) "empty g%mu_x"
    end if
    write (unit = unit, fmt = descr_fmt) "end type(vamp_grid)"
end subroutine write_grid_unit

```

146a *<Variables in vamp 79a>+≡* (75b) <110a

```

character(len=*), parameter, private :: &
    descr_fmt = "(1x,a)", &
    integer_fmt = "(1x,a17,1x,i15)", &
    integer_array_fmt = "(1x,i17,1x,i15)", &
    logical_fmt = "(1x,a17,1x,l1)", &
    double_fmt = "(1x,a17,1x,e30.22e4)", &
    double_array_fmt = "(1x,i17,1x,e30.22e4)", &
    double_array2_fmt = "(2(1x,i8),1x,e30.22e4)"

```

146b *<Implementation of vamp procedures 78b>+≡* (75b) <144d 149a>

```

subroutine read_grid_unit (g, unit, read_integrals)
    type(vamp_grid), intent(inout) :: g
    integer, intent(in) :: unit
    logical, intent(in), optional :: read_integrals
    character(len=*), parameter :: FN = "vamp_read_grid"
    character(len=80) :: chdum
    integer :: ndim, i, j, idum, jdum
    read (unit = unit, fmt = descr_fmt) chdum
    read (unit = unit, fmt = integer_fmt) chdum, ndim
    <Insure that size (g%div) == ndim 148a>
    call create_array_pointer (g%num_div, ndim)
    read (unit = unit, fmt = integer_fmt) chdum, g%num_calls

```

```

read (unit = unit, fmt = integer_fmt) chdum, g%calls_per_cell
read (unit = unit, fmt = logical_fmt) chdum, g%stratified
read (unit = unit, fmt = logical_fmt) chdum, g%all_stratified
read (unit = unit, fmt = logical_fmt) chdum, g%quadrupole
read (unit = unit, fmt = double_fmt) chdum, g%mu(1)
read (unit = unit, fmt = double_fmt) chdum, g%mu(2)
read (unit = unit, fmt = double_fmt) chdum, g%mu_plus(1)
read (unit = unit, fmt = double_fmt) chdum, g%mu_plus(2)
read (unit = unit, fmt = double_fmt) chdum, g%mu_minus(1)
read (unit = unit, fmt = double_fmt) chdum, g%mu_minus(2)
read (unit = unit, fmt = double_fmt) chdum, g%sum_integral
read (unit = unit, fmt = double_fmt) chdum, g%sum_weights
read (unit = unit, fmt = double_fmt) chdum, g%sum_chi2
read (unit = unit, fmt = double_fmt) chdum, g%calls
read (unit = unit, fmt = double_fmt) chdum, g%dv2g
read (unit = unit, fmt = double_fmt) chdum, g%jacobi
read (unit = unit, fmt = double_fmt) chdum, g%f_min
read (unit = unit, fmt = double_fmt) chdum, g%f_max
read (unit = unit, fmt = double_fmt) chdum, g%mu_gi
read (unit = unit, fmt = double_fmt) chdum, g%sum_mu_gi
read (unit = unit, fmt = descr_fmt) chdum
do i = 1, size (g%div)
  read (unit = unit, fmt = integer_array_fmt) idum, g%num_div(i)
end do
read (unit = unit, fmt = descr_fmt) chdum
read (unit = unit, fmt = descr_fmt) chdum
do i = 1, size (g%div)
  call read_division (g%div(i), unit, read_integrals)
end do
read (unit = unit, fmt = descr_fmt) chdum
read (unit = unit, fmt = descr_fmt) chdum
if (chdum == "begin g%map") then
  call create_array_pointer (g%map, (/ ndim, ndim /))
  do i = 1, size (g%div)
    do j = 1, size (g%div)
      read (unit = unit, fmt = double_array2_fmt) idum, jdum, g%map(i,j)
    end do
  end do
  read (unit = unit, fmt = descr_fmt) chdum
else
  ⟨Insure that associated (g%map) == .false. 148b⟩
end if
read (unit = unit, fmt = descr_fmt) chdum

```

```

if (chdum == "begin g%mu_x") then
  call create_array_pointer (g%mu_x, ndim )
  call create_array_pointer (g%sum_mu_x, ndim)
  call create_array_pointer (g%mu_xx, (/ ndim, ndim /))
  call create_array_pointer (g%sum_mu_xx, (/ ndim, ndim /))
  do i = 1, size (g%div)
    read (unit = unit, fmt = double_array_fmt) idum, jdum, g%mu_x(i)
    read (unit = unit, fmt = double_array_fmt) idum, jdum, g%sum_mu_x(i)
    do j = 1, size (g%div)
      read (unit = unit, fmt = double_array2_fmt) &
        idum, jdum, g%mu_xx(i,j)
      read (unit = unit, fmt = double_array2_fmt) &
        idum, jdum, g%sum_mu_xx(i,j)
    end do
  end do
  read (unit = unit, fmt = descr_fmt) chdum
else
  <Insure that associated (g%mu_x) == .false. 148c>
end if
read (unit = unit, fmt = descr_fmt) chdum
end subroutine read_grid_unit

148a <Insure that size (g%div) == ndim 148a>≡ (146b 153b 160b)
if (associated (g%div)) then
  if (size (g%div) /= ndim) then
    call delete_division (g%div)
    deallocate (g%div)
    allocate (g%div(ndim))
    call create_empty_division (g%div)
  end if
else
  allocate (g%div(ndim))
  call create_empty_division (g%div)
end if

148b <Insure that associated (g%map) == .false. 148b>≡ (146b 153b 160b)
if (associated (g%map)) then
  deallocate (g%map)
end if

148c <Insure that associated (g%mu_x) == .false. 148c>≡ (146b 153b 160b)
if (associated (g%mu_x)) then
  deallocate (g%mu_x)
end if
if (associated (g%mu_xx)) then

```

```

        deallocate (g%mu_xx)
    end if
    if (associated (g%sum_mu_x)) then
        deallocate (g%sum_mu_x)
    end if
    if (associated (g%sum_mu_xx)) then
        deallocate (g%sum_mu_xx)
    end if

149a  <Implementation of vamp procedures 78b>+≡ (75b) <146b 149b>
    subroutine write_grid_name (g, name, write_integrals)
        type(vamp_grid), intent(inout) :: g
        character(len=*), intent(in) :: name
        logical, intent(in), optional :: write_integrals
        integer :: unit
        call find_free_unit (unit)
        open (unit = unit, action = "write", status = "replace", file = name)
        call write_grid_unit (g, unit, write_integrals)
        close (unit = unit)
    end subroutine write_grid_name

149b  <Implementation of vamp procedures 78b>+≡ (75b) <149a 149c>
    subroutine read_grid_name (g, name, read_integrals)
        type(vamp_grid), intent(inout) :: g
        character(len=*), intent(in) :: name
        logical, intent(in), optional :: read_integrals
        integer :: unit
        call find_free_unit (unit)
        open (unit = unit, action = "read", status = "old", file = name)
        call read_grid_unit (g, unit, read_integrals)
        close (unit = unit)
    end subroutine read_grid_name

149c  <Implementation of vamp procedures 78b>+≡ (75b) <149b 150>
    subroutine write_grids_unit (g, unit, write_integrals)
        type(vamp_grids), intent(in) :: g
        integer, intent(in) :: unit
        logical, intent(in), optional :: write_integrals
        integer :: i
        write (unit = unit, fmt = descr_fmt) "begin type(vamp_grids) :: g"
        write (unit = unit, fmt = integer_fmt) "size (g%grids) = ", size (g%grids)
        write (unit = unit, fmt = double_fmt) "sum_integral = ", g%sum_integral
        write (unit = unit, fmt = double_fmt) "sum_weights = ", g%sum_weights
        write (unit = unit, fmt = double_fmt) "sum_chi2 = ", g%sum_chi2
        write (unit = unit, fmt = descr_fmt) "begin g%weights"

```

```

do i = 1, size (g%grids)
  write (unit = unit, fmt = double_array_fmt) i, g%weights(i)
end do
write (unit = unit, fmt = descr_fmt) "end g%weights"
write (unit = unit, fmt = descr_fmt) "begin g%num_calls"
do i = 1, size (g%grids)
  write (unit = unit, fmt = integer_array_fmt) i, g%num_calls(i)
end do
write (unit = unit, fmt = descr_fmt) "end g%num_calls"
write (unit = unit, fmt = descr_fmt) "begin g%grids"
do i = 1, size (g%grids)
  call write_grid_unit (g%grids(i), unit, write_integrals)
end do
write (unit = unit, fmt = descr_fmt) "end g%grids"
write (unit = unit, fmt = descr_fmt) "end type(vamp_grids)"
end subroutine write_grids_unit

```

150 *<Implementation of vamp procedures 78b>+≡* (75b) *<149c 151a>*

```

subroutine read_grids_unit (g, unit, read_integrals)
  type(vamp_grids), intent(inout) :: g
  integer, intent(in) :: unit
  logical, intent(in), optional :: read_integrals
  character(len=*), parameter :: FN = "vamp_read_grids"
  character(len=80) :: chdum
  integer :: i, nch, idum
  read (unit = unit, fmt = descr_fmt) chdum
  read (unit = unit, fmt = integer_fmt) chdum, nch
  if (associated (g%grids)) then
    if (size (g%grids) /= nch) then
      call vamp_delete_grid (g%grids)
      deallocate (g%grids, g%weights, g%num_calls)
      allocate (g%grids(nch), g%weights(nch), g%num_calls(nch))
      call vamp_create_empty_grid (g%grids)
    end if
  else
    allocate (g%grids(nch), g%weights(nch), g%num_calls(nch))
    call vamp_create_empty_grid (g%grids)
  end if
  read (unit = unit, fmt = double_fmt) chdum, g%sum_integral
  read (unit = unit, fmt = double_fmt) chdum, g%sum_weights
  read (unit = unit, fmt = double_fmt) chdum, g%sum_chi2
  read (unit = unit, fmt = descr_fmt) chdum
  do i = 1, nch
    read (unit = unit, fmt = double_array_fmt) idum, g%weights(i)
  end do

```

```

end do
read (unit = unit, fmt = descr_fmt) chdum
read (unit = unit, fmt = descr_fmt) chdum
do i = 1, nch
    read (unit = unit, fmt = integer_array_fmt) idum, g%num_calls(i)
end do
read (unit = unit, fmt = descr_fmt) chdum
read (unit = unit, fmt = descr_fmt) chdum
do i = 1, nch
    call read_grid_unit (g%grids(i), unit, read_integrals)
end do
read (unit = unit, fmt = descr_fmt) chdum
read (unit = unit, fmt = descr_fmt) chdum
end subroutine read_grids_unit

```

151a *<Implementation of vamp procedures 78b>+≡* (75b) <150 151b>

```

subroutine write_grids_name (g, name, write_integrals)
    type(vamp_grids), intent(inout) :: g
    character(len=*), intent(in) :: name
    logical, intent(in), optional :: write_integrals
    integer :: unit
    call find_free_unit (unit)
    open (unit = unit, action = "write", status = "replace", file = name)
    call write_grids_unit (g, unit, write_integrals)
    close (unit = unit)
end subroutine write_grids_name

```

151b *<Implementation of vamp procedures 78b>+≡* (75b) <151a 151c>

```

subroutine read_grids_name (g, name, read_integrals)
    type(vamp_grids), intent(inout) :: g
    character(len=*), intent(in) :: name
    logical, intent(in), optional :: read_integrals
    integer :: unit
    call find_free_unit (unit)
    open (unit = unit, action = "read", status = "old", file = name)
    call read_grids_unit (g, unit, read_integrals)
    close (unit = unit)
end subroutine read_grids_name

```

151c *<Implementation of vamp procedures 78b>+≡* (75b) <151b 153b>

```

subroutine write_grid_raw_unit (g, unit, write_integrals)
    type(vamp_grid), intent(in) :: g
    integer, intent(in) :: unit
    logical, intent(in), optional :: write_integrals
    integer :: i, j

```



```

write (unit = unit) MAGIC_GRID_BEGIN
write (unit = unit) size (g%div)
write (unit = unit) g%num_calls
write (unit = unit) g%calls_per_cell
write (unit = unit) g%stratified
write (unit = unit) g%all_stratified
write (unit = unit) g%quadrupole
write (unit = unit) g%mu(1)
write (unit = unit) g%mu(2)
write (unit = unit) g%mu_plus(1)
write (unit = unit) g%mu_plus(2)
write (unit = unit) g%mu_minus(1)
write (unit = unit) g%mu_minus(2)
write (unit = unit) g%sum_integral
write (unit = unit) g%sum_weights
write (unit = unit) g%sum_chi2
write (unit = unit) g%calls
write (unit = unit) g%dv2g
write (unit = unit) g%jacobi
write (unit = unit) g%f_min
write (unit = unit) g%f_max
write (unit = unit) g%mu_gi
write (unit = unit) g%sum_mu_gi
do i = 1, size (g%div)
    write (unit = unit) g%num_div(i)
end do
do i = 1, size (g%div)
    call write_division_raw (g%div(i), unit, write_integrals)
end do
if (associated (g%map)) then
    write (unit = unit) MAGIC_GRID_MAP
    do i = 1, size (g%div)
        do j = 1, size (g%div)
            write (unit = unit) g%map(i,j)
        end do
    end do
else
    write (unit = unit) MAGIC_GRID_EMPTY
end if
if (associated (g%mu_x)) then
    write (unit = unit) MAGIC_GRID_MU_X
    do i = 1, size (g%div)
        write (unit = unit) g%mu_x(i)
    end do
end if

```

```

        write (unit = unit) g%sum_mu_x(i)
        do j = 1, size (g%div)
            write (unit = unit) g%mu_xx(i,j)
            write (unit = unit) g%sum_mu_xx(i,j)
        end do
    end do
else
    write (unit = unit) MAGIC_GRID_EMPTY
end if
write (unit = unit) MAGIC_GRID_END
end subroutine write_grid_raw_unit

```

153a *<Constants in vamp 153a>*≡ (75b) 156b>

```

integer, parameter, private :: MAGIC_GRID = 22222222
integer, parameter, private :: MAGIC_GRID_BEGIN = MAGIC_GRID + 1
integer, parameter, private :: MAGIC_GRID_END = MAGIC_GRID + 2
integer, parameter, private :: MAGIC_GRID_EMPTY = MAGIC_GRID + 3
integer, parameter, private :: MAGIC_GRID_MAP = MAGIC_GRID + 4
integer, parameter, private :: MAGIC_GRID_MU_X = MAGIC_GRID + 5

```

153b *<Implementation of vamp procedures 78b>*+≡ (75b) <151c 155a>

```

subroutine read_grid_raw_unit (g, unit, read_integrals)
    type(vamp_grid), intent(inout) :: g
    integer, intent(in) :: unit
    logical, intent(in), optional :: read_integrals
    character(len=*), parameter :: FN = "vamp_read_raw_grid"
    integer :: ndim, i, j, magic
    read (unit = unit) magic
    if (magic /= MAGIC_GRID_BEGIN) then
        print *, FN, " fatal: expecting magic ", MAGIC_GRID_BEGIN, &
            ", found ", magic
        stop
    end if
    read (unit = unit) ndim
    <Insure that size (g%div) == ndim 148a>
    call create_array_pointer (g%num_div, ndim)
    read (unit = unit) g%num_calls
    read (unit = unit) g%calls_per_cell
    read (unit = unit) g%stratified
    read (unit = unit) g%all_stratified
    read (unit = unit) g%quadrupole
    read (unit = unit) g%mu(1)
    read (unit = unit) g%mu(2)
    read (unit = unit) g%mu_plus(1)
    read (unit = unit) g%mu_plus(2)

```

```

read (unit = unit) g%mu_minus(1)
read (unit = unit) g%mu_minus(2)
read (unit = unit) g%sum_integral
read (unit = unit) g%sum_weights
read (unit = unit) g%sum_chi2
read (unit = unit) g%calls
read (unit = unit) g%dv2g
read (unit = unit) g%jacobi
read (unit = unit) g%f_min
read (unit = unit) g%f_max
read (unit = unit) g%mu_gi
read (unit = unit) g%sum_mu_gi
do i = 1, size (g%div)
    read (unit = unit) g%num_div(i)
end do
do i = 1, size (g%div)
    call read_division_raw (g%div(i), unit, read_integrals)
end do
read (unit = unit) magic
if (magic == MAGIC_GRID_MAP) then
    call create_array_pointer (g%map, (/ ndim, ndim /))
    do i = 1, size (g%div)
        do j = 1, size (g%div)
            read (unit = unit) g%map(i,j)
        end do
    end do
else if (magic == MAGIC_GRID_EMPTY) then
    <Insure that associated (g%map) == .false. 148b>
else
    print *, FN, " fatal: expecting magic ", MAGIC_GRID_EMPTY, &
        " or ", MAGIC_GRID_MAP, ", found ", magic
    stop
end if
read (unit = unit) magic
if (magic == MAGIC_GRID_MU_X) then
    call create_array_pointer (g%mu_x, ndim )
    call create_array_pointer (g%sum_mu_x, ndim)
    call create_array_pointer (g%mu_xx, (/ ndim, ndim /))
    call create_array_pointer (g%sum_mu_xx, (/ ndim, ndim /))
    do i = 1, size (g%div)
        read (unit = unit) g%mu_x(i)
        read (unit = unit) g%sum_mu_x(i)
        do j = 1, size (g%div)

```

```

        read (unit = unit) g%mu_xx(i,j)
        read (unit = unit) g%sum_mu_xx(i,j)
    end do
end do
else if (magic == MAGIC_GRID_EMPTY) then
    <Insure that associated (g%mu_x) == .false. 148c>
else
    print *, FN, " fatal: expecting magic ", MAGIC_GRID_EMPTY, &
        " or ", MAGIC_GRID_MU_X, " found ", magic
    stop
end if
read (unit = unit) magic
if (magic /= MAGIC_GRID_END) then
    print *, FN, " fatal: expecting magic ", MAGIC_GRID_END, &
        " found ", magic
    stop
end if
end subroutine read_grid_raw_unit
155a <Implementation of vamp procedures 78b>+≡ (75b) <153b 155b>
subroutine write_grid_raw_name (g, name, write_integrals)
    type(vamp_grid), intent(inout) :: g
    character(len=*), intent(in) :: name
    logical, intent(in), optional :: write_integrals
    integer :: unit
    call find_free_unit (unit)
    open (unit = unit, action = "write", status = "replace", &
        form = "unformatted", file = name)
    call write_grid_raw_unit (g, unit, write_integrals)
    close (unit = unit)
end subroutine write_grid_raw_name
155b <Implementation of vamp procedures 78b>+≡ (75b) <155a 156a>
subroutine read_grid_raw_name (g, name, read_integrals)
    type(vamp_grid), intent(inout) :: g
    character(len=*), intent(in) :: name
    logical, intent(in), optional :: read_integrals
    integer :: unit
    call find_free_unit (unit)
    open (unit = unit, action = "read", status = "old", &
        form = "unformatted", file = name)
    call read_grid_raw_unit (g, unit, read_integrals)
    close (unit = unit)
end subroutine read_grid_raw_name

```

```

156a <Implementation of vamp procedures 78b>+≡ (75b) <155b 156c>
subroutine write_grids_raw_unit (g, unit, write_integrals)
  type(vamp_grids), intent(in) :: g
  integer, intent(in) :: unit
  logical, intent(in), optional :: write_integrals
  integer :: i
  write (unit = unit) MAGIC_GRIDS_BEGIN
  write (unit = unit) size (g%grids)
  write (unit = unit) g%sum_integral
  write (unit = unit) g%sum_weights
  write (unit = unit) g%sum_chi2
  do i = 1, size (g%grids)
    write (unit = unit) g%weights(i)
  end do
  do i = 1, size (g%grids)
    write (unit = unit) g%num_calls(i)
  end do
  do i = 1, size (g%grids)
    call write_grid_raw_unit (g%grids(i), unit, write_integrals)
  end do
  write (unit = unit) MAGIC_GRIDS_END
end subroutine write_grids_raw_unit

156b <Constants in vamp 153a>+≡ (75b) <153a>
integer, parameter, private :: MAGIC_GRIDS = 33333333
integer, parameter, private :: MAGIC_GRIDS_BEGIN = MAGIC_GRIDS + 1
integer, parameter, private :: MAGIC_GRIDS_END = MAGIC_GRIDS + 2

156c <Implementation of vamp procedures 78b>+≡ (75b) <156a 157a>
subroutine read_grids_raw_unit (g, unit, read_integrals)
  type(vamp_grids), intent(inout) :: g
  integer, intent(in) :: unit
  logical, intent(in), optional :: read_integrals
  character(len=*), parameter :: FN = "vamp_read_grids_raw"
  integer :: i, nch, magic
  read (unit = unit) magic
  if (magic /= MAGIC_GRIDS_BEGIN) then
    print *, FN, " fatal: expecting magic ", MAGIC_GRIDS_BEGIN, &
      " found ", magic
    stop
  end if
  read (unit = unit) nch
  if (associated (g%grids)) then
    if (size (g%grids) /= nch) then
      call vamp_delete_grid (g%grids)

```

```

        deallocate (g%grids, g%weights, g%num_calls)
        allocate (g%grids(nch), g%weights(nch), g%num_calls(nch))
        call vamp_create_empty_grid (g%grids)
    end if
else
    allocate (g%grids(nch), g%weights(nch), g%num_calls(nch))
    call vamp_create_empty_grid (g%grids)
end if
read (unit = unit) g%sum_integral
read (unit = unit) g%sum_weights
read (unit = unit) g%sum_chi2
do i = 1, nch
    read (unit = unit) g%weights(i)
end do
do i = 1, nch
    read (unit = unit) g%num_calls(i)
end do
do i = 1, nch
    call read_grid_raw_unit (g%grids(i), unit, read_integrals)
end do
read (unit = unit) magic
if (magic /= MAGIC_GRIDS_END) then
    print *, FN, " fatal: expecting magic ", MAGIC_GRIDS_END, &
        " found ", magic
    stop
end if
end subroutine read_grids_raw_unit
157a <Implementation of vamp procedures 78b>+≡ (75b) <156c 157b>
subroutine write_grids_raw_name (g, name, write_integrals)
    type(vamp_grids), intent(inout) :: g
    character(len=*), intent(in) :: name
    logical, intent(in), optional :: write_integrals
    integer :: unit
    call find_free_unit (unit)
    open (unit = unit, action = "write", status = "replace", &
        form = "unformatted", file = name)
    call write_grids_raw_unit (g, unit, write_integrals)
    close (unit = unit)
end subroutine write_grids_raw_name
157b <Implementation of vamp procedures 78b>+≡ (75b) <157a 158b>
subroutine read_grids_raw_name (g, name, read_integrals)
    type(vamp_grids), intent(inout) :: g
    character(len=*), intent(in) :: name

```

```

logical, intent(in), optional :: read_integrals
integer :: unit
call find_free_unit (unit)
open (unit = unit, action = "read", status = "old", &
      form = "unformatted", file = name)
call read_grids_raw_unit (g, unit, read_integrals)
close (unit = unit)
end subroutine read_grids_raw_name

```

### 5.2.12 Marshaling

[WK] Note: mu\_plus and mu\_minus not transferred (hard-coded buffer indices)!

```

158a <Declaration of vamp procedures 77a>+≡ (75b) <144a 161>
      public :: vamp_marshall_grid_size, vamp_marshall_grid, vamp_unmarshal_grid

158b <Implementation of vamp procedures 78b>+≡ (75b) <157b 160a>
      pure subroutine vamp_marshall_grid (g, ibuf, dbuf)
        type(vamp_grid), intent(in) :: g
        integer, dimension(:), intent(inout) :: ibuf
        real(kind=default), dimension(:), intent(inout) :: dbuf
        integer :: i, iwords, dwords, iidx, didx, ndim
        ndim = size (g%div)
        ibuf(1) = g%num_calls
        ibuf(2) = g%calls_per_cell
        ibuf(3) = ndim
        if (g%stratified) then
          ibuf(4) = 1
        else
          ibuf(4) = 0
        end if
        if (g%all_stratified) then
          ibuf(5) = 1
        else
          ibuf(5) = 0
        end if
        if (g%quadrupole) then
          ibuf(6) = 1
        else
          ibuf(6) = 0
        end if
        dbuf(1:2) = g%mu
        dbuf(3) = g%sum_integral

```

```

dbuf(4) = g%sum_weights
dbuf(5) = g%sum_chi2
dbuf(6) = g%calls
dbuf(7) = g%dv2g
dbuf(8) = g%jacobi
dbuf(9) = g%f_min
dbuf(10) = g%f_max
dbuf(11) = g%mu_gi
dbuf(12) = g%sum_mu_gi
ibuf(7:6+ndim) = g%num_div
iidx = 7 + ndim
didx = 13
do i = 1, ndim
  call marshal_division_size (g%div(i), iwords, dwords)
  ibuf(iidx) = iwords
  ibuf(iidx+1) = dwords
  iidx = iidx + 2
  call marshal_division (g%div(i), ibuf(iidx:iidx-1+iwords), &
                        dbuf(didx:didx-1+dwords))

  iidx = iidx + iwords
  didx = didx + dwords
end do
if (associated (g%map)) then
  ibuf(iidx) = 1
  dbuf(didx:didx-1+ndim**2) = reshape (g%map, (/ ndim**2 /))
  didx = didx + ndim**2
else
  ibuf(iidx) = 0
end if
iidx = iidx + 1
if (associated (g%mu_x)) then
  ibuf(iidx) = 1
  dbuf(didx:didx-1+ndim) = g%mu_x
  didx = didx + ndim
  dbuf(didx:didx-1+ndim) = g%sum_mu_x
  didx = didx + ndim
  dbuf(didx:didx-1+ndim**2) = reshape (g%mu_xx, (/ ndim**2 /))
  didx = didx + ndim**2
  dbuf(didx:didx-1+ndim**2) = reshape (g%sum_mu_xx, (/ ndim**2 /))
  didx = didx + ndim**2
else
  ibuf(iidx) = 0
end if

```



```

        iidx = iidx + 1
    end subroutine vamp_marshall_grid
160a  <Implementation of vamp procedures 78b>+≡ (75b) <158b 160b>
    pure subroutine vamp_marshall_grid_size (g, iwords, dwords)
        type(vamp_grid), intent(in) :: g
        integer, intent(out) :: iwords, dwords
        integer :: i, ndim, iw, dw
        ndim = size (g%div)
        iwords = 6 + ndim
        dwords = 12
        do i = 1, ndim
            call marshal_division_size (g%div(i), iw, dw)
            iwords = iwords + 2 + iw
            dwords = dwords + dw
        end do
        iwords = iwords + 1
        if (associated (g%map)) then
            dwords = dwords + ndim**2
        end if
        iwords = iwords + 1
        if (associated (g%mu_x)) then
            dwords = dwords + 2 * (ndim + ndim**2)
        end if
    end subroutine vamp_marshall_grid_size
160b  <Implementation of vamp procedures 78b>+≡ (75b) <160a 162a>
    pure subroutine vamp_unmarshal_grid (g, ibuf, dbuf)
        type(vamp_grid), intent(inout) :: g
        integer, dimension(:), intent(in) :: ibuf
        real(kind=default), dimension(:), intent(in) :: dbuf
        integer :: i, iwords, dwords, iidx, didx, ndim
        g%num_calls = ibuf(1)
        g%calls_per_cell = ibuf(2)
        ndim = ibuf(3)
        g%stratified = ibuf(4) /= 0
        g%all_stratified = ibuf(5) /= 0
        g%quadrupole = ibuf(6) /= 0
        g%mu = dbuf(1:2)
        g%sum_integral = dbuf(3)
        g%sum_weights = dbuf(4)
        g%sum_chi2 = dbuf(5)
        g%calls = dbuf(6)
        g%dv2g = dbuf(7)
        g%jacobi = dbuf(8)

```

```

g%f_min = dbuf(9)
g%f_max = dbuf(10)
g%mu_gi = dbuf(11)
g%sum_mu_gi = dbuf(12)
call copy_array_pointer (g%num_div, ibuf(7:6+ndim))
<Insure that size (g%div) == ndim 148a>
iidx = 7 + ndim
didx = 13
do i = 1, ndim
  iwords = ibuf(iidx)
  dwords = ibuf(iidx+1)
  iidx = iidx + 2
  call unmarshal_division (g%div(i), ibuf(iidx:iidx-1+iwords), &
                           dbuf(didx:didx-1+dwords))

  iidx = iidx + iwords
  didx = didx + dwords
end do
if (ibuf(iidx) > 0) then
  call copy_array_pointer &
    (g%map, reshape (dbuf(didx:didx-1+ibuf(iidx)), (/ ndim, ndim /)))
  didx = didx + ibuf(iidx)
else
  <Insure that associated (g%map) == .false. 148b>
end if
iidx = iidx + 1
if (ibuf(iidx) > 0) then
  call copy_array_pointer (g%mu_x, dbuf(didx:didx-1+ndim))
  didx = didx + ndim
  call copy_array_pointer (g%sum_mu_x, dbuf(didx:didx-1+ndim))
  didx = didx + ndim
  call copy_array_pointer &
    (g%mu_xx, reshape (dbuf(didx:didx-1+ndim**2), (/ ndim, ndim /)))
  didx = didx + ndim**2
  call copy_array_pointer &
    (g%sum_mu_xx, reshape (dbuf(didx:didx-1+ndim**2), (/ ndim, ndim /)))
  didx = didx + ndim**2
else
  <Insure that associated (g%mu_x) == .false. 148c>
end if
iidx = iidx + 1
end subroutine vamp_unmarshal_grid

```

161 <Declaration of vamp procedures 77a>+≡ (75b) <158a  
public :: vamp\_marshal\_history\_size, vamp\_marshal\_history

```

public :: vamp_unmarshal_history

162a <Implementation of vamp procedures 78b>+≡ (75b) <160b 162b>
pure subroutine vamp_marshall_history (h, ibuf, dbuf)
  type(vamp_history), intent(in) :: h
  integer, dimension(:), intent(inout) :: ibuf
  real(kind=default), dimension(:), intent(inout) :: dbuf
  integer :: j, ndim, iidx, didx, iwords, dwords
  if (h%verbose .and. (associated (h%div))) then
    ndim = size (h%div)
  else
    ndim = 0
  end if
  ibuf(1) = ndim
  ibuf(2) = h%calls
  if (h%stratified) then
    ibuf(3) = 1
  else
    ibuf(3) = 0
  end if
  dbuf(1) = h%integral
  dbuf(2) = h%std_dev
  dbuf(3) = h%avg_integral
  dbuf(4) = h%avg_std_dev
  dbuf(5) = h%avg_chi2
  dbuf(6) = h%f_min
  dbuf(7) = h%f_max
  iidx = 4
  didx = 8
  do j = 1, ndim
    call marshal_div_history_size (h%div(j), iwords, dwords)
    ibuf(iidx) = iwords
    ibuf(iidx+1) = dwords
    iidx = iidx + 2
    call marshal_div_history (h%div(j), ibuf(iidx:iidx-1+iwords), &
                             dbuf(didx:didx-1+dwords))

    iidx = iidx + iwords
    didx = didx + dwords
  end do
end subroutine vamp_marshall_history

162b <Implementation of vamp procedures 78b>+≡ (75b) <162a 163>
pure subroutine vamp_marshall_history_size (h, iwords, dwords)
  type(vamp_history), intent(in) :: h
  integer, intent(out) :: iwords, dwords

```

```

integer :: i, ndim, iw, dw
if (h%verbose .and. (associated (h%div))) then
    ndim = size (h%div)
else
    ndim = 0
end if
iwords = 3
dwords = 7
do i = 1, ndim
    call marshal_div_history_size (h%div(i), iw, dw)
    iwords = iwords + 2 + iw
    dwords = dwords + dw
end do
end subroutine vamp_marshal_history_size

```

163 *<Implementation of vamp procedures 78b>+≡ (75b) <162b 164>*

```

pure subroutine vamp_unmarshal_history (h, ibuf, dbuf)
type(vamp_history), intent(inout) :: h
integer, dimension(:), intent(in) :: ibuf
real(kind=default), dimension(:), intent(in) :: dbuf
integer :: j, ndim, iidx, didx, iwords, dwords
ndim = ibuf(1)
h%calls = ibuf(2)
h%stratified = ibuf(3) /= 0
h%integral = dbuf(1)
h%std_dev = dbuf(2)
h%avg_integral = dbuf(3)
h%avg_std_dev = dbuf(4)
h%avg_chi2 = dbuf(5)
h%f_min = dbuf(6)
h%f_max = dbuf(7)
if (ndim > 0) then
    if (associated (h%div)) then
        if (size (h%div) /= ndim) then
            deallocate (h%div)
            allocate (h%div(ndim))
        end if
    else
        allocate (h%div(ndim))
    end if
    iidx = 4
    didx = 8
    do j = 1, ndim
        iwords = ibuf(iidx)

```

```

        dwords = ibuf(iidx+1)
        iidx = iidx + 2
        call unmarshal_div_history (h%div(j), ibuf(iidx:iidx-1+iwords), &
                                   dbuf(didx:didx-1+dwords))

        iidx = iidx + iwords
        didx = didx + dwords
    end do
end if
end subroutine vamp_unmarshal_history

```

### 5.2.13 Boring Copying and Deleting of Objects

164  $\langle$ Implementation of `vamp` procedures 78b $\rangle + \equiv$  (75b)  $\langle$ 163 165a $\rangle$

```

elemental subroutine vamp_copy_grid (lhs, rhs)
    type(vamp_grid), intent(inout) :: lhs
    type(vamp_grid), intent(in) :: rhs
    integer :: ndim
    ndim = size (rhs%div)
    lhs%mu = rhs%mu
    lhs%mu_plus = rhs%mu_plus
    lhs%mu_minus = rhs%mu_minus
    lhs%sum_integral = rhs%sum_integral
    lhs%sum_weights = rhs%sum_weights
    lhs%sum_chi2 = rhs%sum_chi2
    lhs%calls = rhs%calls
    lhs%num_calls = rhs%num_calls
    call copy_array_pointer (lhs%num_div, rhs%num_div)
    lhs%dv2g = rhs%dv2g
    lhs%jacobi = rhs%jacobi
    lhs%f_min = rhs%f_min
    lhs%f_max = rhs%f_max
    lhs%mu_gi = rhs%mu_gi
    lhs%sum_mu_gi = rhs%sum_mu_gi
    lhs%calls_per_cell = rhs%calls_per_cell
    lhs%stratified = rhs%stratified
    lhs%all_stratified = rhs%all_stratified
    lhs%quadrupole = rhs%quadrupole
    if (associated (lhs%div)) then
        if (size (lhs%div) /= ndim) then
            call delete_division (lhs%div)
            deallocate (lhs%div)
            allocate (lhs%div(ndim))
        end if
    end if

```

```

else
    allocate (lhs%div(ndim))
end if
call copy_division (lhs%div, rhs%div)
if (associated (rhs%map)) then
    call copy_array_pointer (lhs%map, rhs%map)
else if (associated (lhs%map)) then
    deallocate (lhs%map)
end if
if (associated (rhs%mu_x)) then
    call copy_array_pointer (lhs%mu_x, rhs%mu_x)
    call copy_array_pointer (lhs%mu_xx, rhs%mu_xx)
    call copy_array_pointer (lhs%sum_mu_x, rhs%sum_mu_x)
    call copy_array_pointer (lhs%sum_mu_xx, rhs%sum_mu_xx)
else if (associated (lhs%mu_x)) then
    deallocate (lhs%mu_x, lhs%mu_xx, lhs%sum_mu_x, lhs%sum_mu_xx)
end if
end subroutine vamp_copy_grid

```

165a *<Implementation of vamp procedures 78b>+≡* (75b) *<164 165b>*

```

elemental subroutine vamp_delete_grid (g)
    type(vamp_grid), intent(inout) :: g
    if (associated (g%div)) then
        call delete_division (g%div)
        deallocate (g%div, g%num_div)
    end if
    if (associated (g%map)) then
        deallocate (g%map)
    end if
    if (associated (g%mu_x)) then
        deallocate (g%mu_x, g%mu_xx, g%sum_mu_x, g%sum_mu_xx)
    end if
end subroutine vamp_delete_grid

```

165b *<Implementation of vamp procedures 78b>+≡* (75b) *<165a 166a>*

```

elemental subroutine vamp_copy_grids (lhs, rhs)
    type(vamp_grids), intent(inout) :: lhs
    type(vamp_grids), intent(in) :: rhs
    integer :: nch
    nch = size (rhs%grids)
    lhs%sum_integral = rhs%sum_integral
    lhs%sum_chi2 = rhs%sum_chi2
    lhs%sum_weights = rhs%sum_weights
    if (associated (lhs%grids)) then

```

```

        if (size (lhs%grids) /= nch) then
            deallocate (lhs%grids)
            allocate (lhs%grids(nch))
            call vamp_create_empty_grid (lhs%grids(nch))
        end if
    else
        allocate (lhs%grids(nch))
        call vamp_create_empty_grid (lhs%grids(nch))
    end if
    call vamp_copy_grid (lhs%grids, rhs%grids)
    call copy_array_pointer (lhs%weights, rhs%weights)
    call copy_array_pointer (lhs%num_calls, rhs%num_calls)
end subroutine vamp_copy_grids

```

166a *<Implementation of vamp procedures 78b>+≡* (75b) *<165b 166b>*

```

    elemental subroutine vamp_delete_grids (g)
        type(vamp_grids), intent(inout) :: g
        if (associated (g%grids)) then
            call vamp_delete_grid (g%grids)
            deallocate (g%weights, g%grids, g%num_calls)
        end if
    end subroutine vamp_delete_grids

```

166b *<Implementation of vamp procedures 78b>+≡* (75b) *<166a 167a>*

```

    elemental subroutine vamp_copy_history (lhs, rhs)
        type(vamp_history), intent(inout) :: lhs
        type(vamp_history), intent(in) :: rhs
        lhs%calls = rhs%calls
        lhs%stratified = rhs%stratified
        lhs%verbose = rhs%verbose
        lhs%integral = rhs%integral
        lhs%std_dev = rhs%std_dev
        lhs%avg_integral = rhs%avg_integral
        lhs%avg_std_dev = rhs%avg_std_dev
        lhs%avg_chi2 = rhs%avg_chi2
        lhs%f_min = rhs%f_min
        lhs%f_max = rhs%f_max
        if (rhs%verbose) then
            if (associated (lhs%div)) then
                if (size (lhs%div) /= size (rhs%div)) then
                    deallocate (lhs%div)
                    allocate (lhs%div(size(rhs%div)))
                end if
            else
                allocate (lhs%div(size(rhs%div)))
            end if
        end if
    end subroutine vamp_copy_history

```

```

        end if
        call copy_history (lhs%div, rhs%div)
    end if
end subroutine vamp_copy_history

```

167a  $\langle$ Implementation of **vamp** procedures 78b $\rangle + \equiv$  (75b)  $\triangleleft$  166b

```

    elemental subroutine vamp_delete_history (h)
        type(vamp_history), intent(inout) :: h
        if (associated (h%div)) then
            deallocate (h%div)
        end if
    end subroutine vamp_delete_history

```

### 5.3 Interface to MPI

The module **vamp** makes no specific assumptions about the hardware and software supporting parallel execution. In this section, we present a specific example of a parallel implementation of multi channel sampling using the message passing paradigm.

The modules **vamp\_serial\_mpi** and **vamp\_parallel\_mpi** are not intended to be used directly by application programs. For this purpose, the module **vampi** is provided. **vamp\_serial\_mpi** is identical to **vamp**, but some types, procedures and variables are renamed so that **vamp\_parallel\_mpi** can redefine them:

167b  $\langle$ vampi.f90 167b $\rangle \equiv$  167c $\triangleright$

```

! vampi.f90 --
 $\langle$ Copyleft notice 1 $\rangle$ 
module vamp_serial_mpi
    use vamp, &
         $\langle$ vamp0_* => vamp_* 168c $\rangle$ 
        VAMPO_RCS_ID => VAMP_RCS_ID
    public
end module vamp_serial_mpi

```

**vamp\_parallel\_mpi** contains the non trivial MPI code and will be discussed in detail below.

167c  $\langle$ vampi.f90 167b $\rangle + \equiv$   $\triangleleft$  167b 168a $\triangleright$

```

module vamp_parallel_mpi
    use kinds
    use utils

```



```

use tao_random_numbers
use exceptions
use mpi90
use divisions
use vamp_serial_mpi !NODEP!
use iso_fortran_env
implicit none
private
<Declaration of vampi procedures 168b>
<Interfaces of vampi procedures 173a>
<Parameters in vampi 169b>
<Declaration of vampi types 173d>
character(len=*), public, parameter :: VAMPI_RCS_ID = &
    "$Id: vampi.nw 314 2010-04-17 20:32:33Z ohl $"
contains
    <Implementation of vampi procedures 169a>
end module vamp_parallel_mpi

```

**vampi** is now a plug-in replacement for **vamp** and *must not* be used together with **vamp**:

```

168a <vampi.f90 167b>+≡ <167c>
    module vampi
        use vamp_serial_mpi !NODEP!
        use vamp_parallel_mpi !NODEP!
        public
    end module vampi

```

### 5.3.1 Parallel Execution

#### Single Channel

```

168b <Declaration of vampi procedures 168b>≡ (167c) 172b>
    public :: vamp_create_grid
    public :: vamp_discard_integral
    public :: vamp_reshape_grid
    public :: vamp_sample_grid
    public :: vamp_delete_grid

168c <vamp0.* => vamp.* 168c>≡ (167b) 172c>
    vamp0_create_grid => vamp_create_grid, &
    vamp0_discard_integral => vamp_discard_integral, &
    vamp0_reshape_grid => vamp_reshape_grid, &
    vamp0_sample_grid => vamp_sample_grid, &

```

```

vamp0_delete_grid => vamp_delete_grid, &
169a <Implementation of vampi procedures 169a>≡ (167c) 169c>
subroutine vamp_create_grid &
  (g, domain, num_calls, num_div, &
   stratified, quadrupole, covariance, map, exc)
type(vamp_grid), intent(inout) :: g
real(kind=default), dimension(:,:), intent(in) :: domain
integer, intent(in) :: num_calls
integer, dimension(:), intent(in), optional :: num_div
logical, intent(in), optional :: stratified, quadrupole, covariance
real(kind=default), dimension(:,:), intent(in), optional :: map
type(exception), intent(inout), optional :: exc
integer :: proc_id
call mpi90_rank (proc_id)
if (proc_id == VAMP_ROOT) then
  call vamp0_create_grid &
    (g, domain, num_calls, num_div, &
     stratified, quadrupole, covariance, map, exc)
else
  call vamp_create_empty_grid (g)
end if
end subroutine vamp_create_grid
169b <Parameters in vampi 169b>≡ (167c) 177a>
integer, public, parameter :: VAMP_ROOT = 0
169c <Implementation of vampi procedures 169a>+≡ (167c) <169a 169d>
subroutine vamp_discard_integral &
  (g, num_calls, num_div, stratified, quadrupole, covariance, exc)
type(vamp_grid), intent(inout) :: g
integer, intent(in), optional :: num_calls
integer, dimension(:), intent(in), optional :: num_div
logical, intent(in), optional :: stratified, quadrupole, covariance
type(exception), intent(inout), optional :: exc
integer :: proc_id
call mpi90_rank (proc_id)
if (proc_id == VAMP_ROOT) then
  call vamp0_discard_integral &
    (g, num_calls, num_div, stratified, quadrupole, covariance, exc)
end if
end subroutine vamp_discard_integral
169d <Implementation of vampi procedures 169a>+≡ (167c) <169c 170>
subroutine vamp_reshape_grid &
  (g, num_calls, num_div, stratified, quadrupole, covariance, exc)

```

```

type(vamp_grid), intent(inout) :: g
integer, intent(in), optional :: num_calls
integer, dimension(:), intent(in), optional :: num_div
logical, intent(in), optional :: stratified, quadrupole, covariance
type(exception), intent(inout), optional :: exc
integer :: proc_id
call mpi90_rank (proc_id)
if (proc_id == VAMP_ROOT) then
    call vamp0_reshape_grid &
        (g, num_calls, num_div, stratified, quadrupole, covariance, exc)
end if
end subroutine vamp_reshape_grid

```

NB: grids has to have intent(inout) because we will call vamp\_broadcast\_grid on it.

170 *<Implementation of vampi procedures 169a>+≡ (167c) <169d 172a>*

```

subroutine vamp_sample_grid &
    (rng, g, func, iterations, integral, std_dev, avg_chi2, accuracy, &
    channel, weights, grids, exc, history)
type(tao_random_state), intent(inout) :: rng
type(vamp_grid), intent(inout) :: g
integer, intent(in) :: iterations
real(kind=default), intent(out), optional :: integral, std_dev, avg_chi2
real(kind=default), intent(in), optional :: accuracy
integer, intent(in), optional :: channel
real(kind=default), dimension(:), intent(in), optional :: weights
type(vamp_grid), dimension(:), intent(inout), optional :: grids
type(exception), intent(inout), optional :: exc
type(vamp_history), dimension(:), intent(inout), optional :: history
<Interface declaration for func 22>
character(len=*), parameter :: FN = "vamp_sample_grid"
real(kind=default) :: local_integral, local_std_dev, local_avg_chi2
type(vamp_grid), dimension(:), allocatable :: gs, gx
integer, dimension(:,:), pointer :: d
integer :: iteration, i
integer :: num_proc, proc_id, num_workers
nullify (d)
call mpi90_size (num_proc)
call mpi90_rank (proc_id)
iterate: do iteration = 1, iterations
    if (proc_id == VAMP_ROOT) then
        call vamp_distribute_work (num_proc, vamp_rigid_divisions (g), d)
        num_workers = max (1, product (d(2,:)))
    end if
end if

```

```

call mpi90_broadcast (num_workers, VAMP_ROOT)
if ((present (grids)) .and. (num_workers > 1)) then
    call vamp_broadcast_grid (grids, VAMP_ROOT)
end if
if (proc_id == VAMP_ROOT) then
    allocate (gs(num_workers), gx(vamp_fork_grid_joints (d)))
    call vamp_create_empty_grid (gs)
    call vamp_fork_grid (g, gs, gx, d, exc)
    do i = 2, num_workers
        call vamp_send_grid (gs(i), i-1, 0)
    end do
else if (proc_id < num_workers) then
    call vamp_receive_grid (g, VAMP_ROOT, 0)
end if
if (proc_id == VAMP_ROOT) then
    if (num_workers > 1) then
        call vamp_sample_grid0 &
            (rng, gs(1), func, channel, weights, grids, exc)
    else
        call vamp_sample_grid0 &
            (rng, g, func, channel, weights, grids, exc)
    end if
else if (proc_id < num_workers) then
    call vamp_sample_grid0 &
        (rng, g, func, channel, weights, grids, exc)
end if
if (proc_id == VAMP_ROOT) then
    do i = 2, num_workers
        call vamp_receive_grid (gs(i), i-1, 0)
    end do
    call vamp_join_grid (g, gs, gx, d, exc)
    call vamp0_delete_grid (gs)
    deallocate (gs, gx)
    call vamp_refine_grid (g)
    call vamp_average_iterations &
        (g, iteration, local_integral, local_std_dev, local_avg_chi2)
    if (present (history)) then
        if (iteration <= size (history)) then
            call vamp_get_history &
                (history(iteration), g, &
                    local_integral, local_std_dev, local_avg_chi2)
        else
            call raise_exception (exc, EXC_WARN, FN, "history too short")
        end if
    end if
end if

```

```

        end if
        call vamp_terminate_history (history(iteration+1:))
    end if
    if (present (accuracy)) then
        if (local_std_dev <= accuracy * local_integral) then
            call raise_exception (exc, EXC_INFO, FN, &
                "requested accuracy reached")
            exit iterate
        end if
    end if
    else if (proc_id < num_workers) then
        call vamp_send_grid (g, VAMP_ROOT, 0)
    end if
end do iterate
if (proc_id == VAMP_ROOT) then
    deallocate (d)
    if (present (integral)) then
        integral = local_integral
    end if
    if (present (std_dev)) then
        std_dev = local_std_dev
    end if
    if (present (avg_chi2)) then
        avg_chi2 = local_avg_chi2
    end if
end if
end subroutine vamp_sample_grid
172a <Implementation of vampi procedures 169a>+≡ (167c) <170 173b>
subroutine vamp_delete_grid (g)
    type(vamp_grid), intent(inout) :: g
    integer :: proc_id
    call mpi90_rank (proc_id)
    if (proc_id == VAMP_ROOT) then
        call vamp0_reshape_grid (g)
    end if
end subroutine vamp_delete_grid
172b <Declaration of vampi procedures 168b>+≡ (167c) <168b 173f>
public :: vamp_print_history
private :: vamp_print_one_history, vamp_print_histories
172c <vamp0.* => vamp.* 168c>+≡ (167b) <168c 173e>
vamp0_print_history => vamp_print_history, &

```

173a  $\langle$ Interfaces of `vampi` procedures 173a $\rangle \equiv$  (167c) 182c $\triangleright$   

```

interface vamp_print_history
  module procedure vamp_print_one_history, vamp_print_histories
end interface

```

173b  $\langle$ Implementation of `vampi` procedures 169a $\rangle + \equiv$  (167c)  $\triangleleft$ 172a 173c $\triangleright$   

```

subroutine vamp_print_one_history (h, tag)
  type(vamp_history), dimension(:), intent(in) :: h
  character(len=*), intent(in), optional :: tag
  integer :: proc_id
  call mpi90_rank (proc_id)
  if (proc_id == VAMP_ROOT) then
    call vamp0_print_history (h, tag)
  end if
end subroutine vamp_print_one_history

```

173c  $\langle$ Implementation of `vampi` procedures 169a $\rangle + \equiv$  (167c)  $\triangleleft$ 173b 174b $\triangleright$   

```

subroutine vamp_print_histories (h, tag)
  type(vamp_history), dimension(:, :), intent(in) :: h
  character(len=*), intent(in), optional :: tag
  integer :: proc_id
  call mpi90_rank (proc_id)
  if (proc_id == VAMP_ROOT) then
    call vamp0_print_history (h, tag)
  end if
end subroutine vamp_print_histories

```

### *Multi Channel*

173d  $\langle$ Declaration of `vampi` types 173d $\rangle \equiv$  (167c)  

```

type, public :: vamp_grids
  !!! private
  type(vamp0_grids) :: g0
  logical, dimension(:), pointer :: active
  integer, dimension(:), pointer :: proc
  real(kind=default), dimension(:), pointer :: integrals, std_devs
end type vamp_grids

```

173e  $\langle$ vamp0.\* => vamp.\* 168c $\rangle + \equiv$  (167b)  $\triangleleft$ 172c 174a $\triangleright$   
 vamp0\_grids => vamp\_grids, &  
 Partially duplicate the API of `vamp`:

173f  $\langle$ Declaration of `vampi` procedures 168b $\rangle + \equiv$  (167c)  $\triangleleft$ 172b 179c $\triangleright$   

```

public :: vamp_create_grids
public :: vamp_discard_integrals

```

```

public :: vamp_update_weights
public :: vamp_refine_weights
public :: vamp_delete_grids
public :: vamp_sample_grids

```

174a  $\langle \text{vamp0\_} * \Rightarrow \text{vamp\_} * \text{ 168c} \rangle + \equiv$  (167b)  $\langle \text{173e 182b} \rangle$

```

vamp0_create_grids => vamp_create_grids, &
vamp0_discard_integrals => vamp_discard_integrals, &
vamp0_update_weights => vamp_update_weights, &
vamp0_refine_weights => vamp_refine_weights, &
vamp0_delete_grids => vamp_delete_grids, &
vamp0_sample_grids => vamp_sample_grids, &

```

Call **vamp\_create\_grids** just like the serial version. It will create the actual grids on the root processor and create stubs on the other processors

174b  $\langle \text{Implementation of vampi procedures 169a} \rangle + \equiv$  (167c)  $\langle \text{173c 174c} \rangle$

```

subroutine vamp_create_grids (g, domain, num_calls, weights, maps, &
                             num_div, stratified, quadrupole, exc)
    type(vamp_grids), intent(inout) :: g
    real(kind=default), dimension(:, :), intent(in) :: domain
    integer, intent(in) :: num_calls
    real(kind=default), dimension(:), intent(in) :: weights
    real(kind=default), dimension(:, :, :), intent(in), optional :: maps
    integer, dimension(:), intent(in), optional :: num_div
    logical, intent(in), optional :: stratified, quadrupole
    type(exception), intent(inout), optional :: exc
    integer :: proc_id, nch
    call mpi90_rank (proc_id)
    nch = size (weights)
    allocate (g%active(nch), g%proc(nch), g%integrals(nch), g%std_devs(nch))
    if (proc_id == VAMP_ROOT) then
        call vamp0_create_grids (g%g0, domain, num_calls, weights, maps, &
                                num_div, stratified, quadrupole, exc)
    else
        allocate (g%g0%grids(nch), g%g0%weights(nch), g%g0%num_calls(nch))
        call vamp_create_empty_grid (g%g0%grids)
    end if
end subroutine vamp_create_grids

```

174c  $\langle \text{Implementation of vampi procedures 169a} \rangle + \equiv$  (167c)  $\langle \text{174b 175a} \rangle$

```

subroutine vamp_discard_integrals &
    (g, num_calls, num_div, stratified, quadrupole, exc)
    type(vamp_grids), intent(inout) :: g
    integer, intent(in), optional :: num_calls
    integer, dimension(:), intent(in), optional :: num_div

```

```

logical, intent(in), optional :: stratified, quadrupole
type(exception), intent(inout), optional :: exc
integer :: proc_id
call mpi90_rank (proc_id)
if (proc_id == VAMP_ROOT) then
    call vamp0_discard_integrals &
        (g%g0, num_calls, num_div, stratified, quadrupole, exc)
end if
end subroutine vamp_discard_integrals
175a <Implementation of vampi procedures 169a>+≡ (167c) <174c 175b>
subroutine vamp_update_weights &
    (g, weights, num_calls, num_div, stratified, quadrupole, exc)
type(vamp_grids), intent(inout) :: g
real(kind=default), dimension(:), intent(in) :: weights
integer, intent(in), optional :: num_calls
integer, dimension(:), intent(in), optional :: num_div
logical, intent(in), optional :: stratified, quadrupole
type(exception), intent(inout), optional :: exc
integer :: proc_id
call mpi90_rank (proc_id)
if (proc_id == VAMP_ROOT) then
    call vamp0_update_weights &
        (g%g0, weights, num_calls, num_div, stratified, quadrupole, exc)
end if
end subroutine vamp_update_weights
175b <Implementation of vampi procedures 169a>+≡ (167c) <175a 175c>
subroutine vamp_refine_weights (g, power)
type(vamp_grids), intent(inout) :: g
real(kind=default), intent(in), optional :: power
integer :: proc_id
call mpi90_rank (proc_id)
if (proc_id == VAMP_ROOT) then
    call vamp0_refine_weights (g%g0, power)
end if
end subroutine vamp_refine_weights
175c <Implementation of vampi procedures 169a>+≡ (167c) <175b 176>
subroutine vamp_delete_grids (g)
type(vamp_grids), intent(inout) :: g
character(len=*), parameter :: FN = "vamp_delete_grids"
deallocate (g%active, g%proc, g%integrals, g%std_devs)
call vamp0_delete_grids (g%g0)
end subroutine vamp_delete_grids

```



Call `vamp_sample_grids` just like `vamp0_sample_grids`.

```

176  <Implementation of vampi procedures 169a>+≡ (167c) <175c 179d>
      subroutine vamp_sample_grids &
         (rng, g, func, iterations, integral, std_dev, avg_chi2, &
          accuracy, history, histories, exc)
      type(tao_random_state), intent(inout) :: rng
      type(vamp_grids), intent(inout) :: g
      integer, intent(in) :: iterations
      real(kind=default), intent(out), optional :: integral, std_dev, avg_chi2
      real(kind=default), intent(in), optional :: accuracy
      type(vamp_history), dimension(:), intent(inout), optional :: history
      type(vamp_history), dimension(:, :), intent(inout), optional :: histories
      type(exception), intent(inout), optional :: exc
      <Interface declaration for func 22>
      character(len=*), parameter :: FN = "vamp_sample_grids"
      integer :: num_proc, proc_id, nch, ch, iteration
      real(kind=default), dimension(size(g%g0%weights)) :: weights
      real(kind=default) :: local_integral, local_std_dev, local_avg_chi2
      real(kind=default) :: current_accuracy, waste
      logical :: distribute_complete_grids
      call mpi90_size (num_proc)
      call mpi90_rank (proc_id)
      nch = size (g%g0%weights)
      if (proc_id == VAMP_ROOT) then
         g%active = (g%g0%num_calls >= 2)
         where (g%active)
            weights = g%g0%num_calls
         elsewhere
            weights = 0.0
         endwhere
         weights = weights / sum (weights)
         call schedule (weights, num_proc, g%proc, waste)
         distribute_complete_grids = (waste <= VAMP_MAX_WASTE)
      end if
      call mpi90_broadcast (weights, VAMP_ROOT)
      call mpi90_broadcast (g%active, VAMP_ROOT)
      call mpi90_broadcast (distribute_complete_grids, VAMP_ROOT)
      if (distribute_complete_grids) then
         call mpi90_broadcast (g%proc, VAMP_ROOT)
      end if
      iterate: do iteration = 1, iterations
         if (distribute_complete_grids) then
            call vamp_broadcast_grid (g%g0%grids, VAMP_ROOT)

```

```

        <Distribute complete grids among processes 177b>
    else
        <Distribute each grid among processes 181b>
    end if
    <Exit iterate if accuracy has been reached (MPI) 180a>
end do iterate
<Copy results of vamp_sample_grids to dummy variables 179f>
end subroutine vamp_sample_grids

```

Setting `VAMP_MAX_WASTE` to 1 disables the splitting of grids, which doesn't work yet.

```

177a <Parameters in vampi 169b>+≡ (167c) <169b 179e>
    real(kind=default), private, parameter :: VAMP_MAX_WASTE = 1.0
    ! real(kind=default), private, parameter :: VAMP_MAX_WASTE = 0.3

177b <Distribute complete grids among processes 177b>≡ (176) 177c>
    do ch = 1, nch
        if (g%active(ch)) then
            if (proc_id == g%proc(ch)) then
                call vamp0_discard_integral (g%g0%grids(ch))
                <Sample g%g0%grids(ch) 177d>
            end if
        else
            call vamp_nullify_variance (g%g0%grids(ch))
            call vamp_nullify_covariance (g%g0%grids(ch))
        end if
    end do

```

Refine the grids after *all* grids have been sampled:

```

177c <Distribute complete grids among processes 177b>+≡ (176) <177b 178a>
    do ch = 1, nch
        if (g%active(ch) .and. (proc_id == g%proc(ch))) then
            call vamp_refine_grid (g%g0%grids(ch))
            if (proc_id /= VAMP_ROOT) then
                <Ship the result for channel #ch back to the root 179a>
            end if
        end if
    end do

```

therefore we use `vamp_sample_grid0` instead of `vamp0_sample_grid`:

```

177d <Sample g%g0%grids(ch) 177d>≡ (177b)
    call vamp_sample_grid0 &
        (rng, g%g0%grids(ch), func, ch, weights, g%g0%grids, exc)
    call vamp_average_iterations &
        (g%g0%grids(ch), iteration, g%integrals(ch), g%std_devs(ch), local_avg_chi2)

```

```

if (present (histories)) then
  if (iteration <= ubound (histories, dim=1)) then
    call vamp_get_history &
      (histories(iteration,ch), g%g0%grids(ch), &
       g%integrals(ch), g%std_devs(ch), local_avg_chi2)
  else
    call raise_exception (exc, EXC_WARN, FN, "history too short")
  end if
  call vamp_terminate_history (histories(iteration+1:,ch))
end if

178a <Distribute complete grids among processes 177b>+≡ (176) <177c
if (proc_id == VAMP_ROOT) then
  do ch = 1, nch
    if (g%active(ch) .and. (g%proc(ch) /= proc_id)) then
      <Receive the result for channel #ch at the root 179b>
    end if
  end do
  call vamp_reduce_channels (g%g0, g%integrals, g%std_devs, g%active)
  call vamp_average_iterations &
    (g%g0, iteration, local_integral, local_std_dev, local_avg_chi2)
  if (present (history)) then
    if (iteration <= size (history)) then
      call vamp_get_history &
        (history(iteration), g%g0, local_integral, local_std_dev, &
         local_avg_chi2)
    else
      call raise_exception (exc, EXC_WARN, FN, "history too short")
    end if
    call vamp_terminate_history (history(iteration+1:))
  end if
end if

```

This would be cheaper than `vamp.broadcast_grid`, but we need the latter to support the adaptive multi channel sampling:

```

178b <Ship g%g0%grids from the root to the assigned processor 178b>≡
do ch = 1, nch
  if (g%active(ch) .and. (g%proc(ch) /= VAMP_ROOT)) then
    if (proc_id == VAMP_ROOT) then
      call vamp_send_grid &
        (g%g0%grids(ch), g%proc(ch), object (ch, TAG_GRID))
    else if (proc_id == g%proc(ch)) then
      call vamp_receive_grid &
        (g%g0%grids(ch), VAMP_ROOT, object (ch, TAG_GRID))
    end if
  end if
end do

```

```

        end if
    end if
end do

179a  <Ship the result for channel #ch back to the root 179a>≡ (177c)
    call mpi90_send (g%integrals(ch), VAMP_ROOT, object (ch, TAG_INTEGRAL))
    call mpi90_send (g%std_devs(ch), VAMP_ROOT, object (ch, TAG_STD_DEV))
    call vamp_send_grid (g%g0%grids(ch), VAMP_ROOT, object (ch, TAG_GRID))
    if (present (histories)) then
        call vamp_send_history &
            (histories(iteration,ch), VAMP_ROOT, object (ch, TAG_HISTORY))
    end if

179b  <Receive the result for channel #ch at the root 179b>≡ (178a)
    call mpi90_receive (g%integrals(ch), g%proc(ch), object (ch, TAG_INTEGRAL))
    call mpi90_receive (g%std_devs(ch), g%proc(ch), object (ch, TAG_STD_DEV))
    call vamp_receive_grid (g%g0%grids(ch), g%proc(ch), object (ch, TAG_GRID))
    if (present (histories)) then
        call vamp_receive_history &
            (histories(iteration,ch), g%proc(ch), object (ch, TAG_HISTORY))
    end if

179c  <Declaration of vampi procedures 168b>+≡ (167c) <173f 180b>
    private :: object

179d  <Implementation of vampi procedures 169a>+≡ (167c) <176 180c>
    pure function object (ch, obj) result (tag)
        integer, intent(in) :: ch, obj
        integer :: tag
        tag = 100 * ch + obj
    end function object

179e  <Parameters in vampi 169b>+≡ (167c) <177a
    integer, public, parameter :: &
        TAG_INTEGRAL = 1, &
        TAG_STD_DEV = 2, &
        TAG_GRID = 3, &
        TAG_HISTORY = 6, &
        TAG_NEXT_FREE = 9

179f  <Copy results of vamp_sample_grids to dummy variables 179f>≡ (176)
    if (present (integral)) then
        call mpi90_broadcast (local_integral, VAMP_ROOT)
        integral = local_integral
    end if
    if (present (std_dev)) then
        call mpi90_broadcast (local_std_dev, VAMP_ROOT)

```

```

        std_dev = local_std_dev
    end if
    if (present (avg_chi2)) then
        call mpi90_broadcast (local_avg_chi2, VAMP_ROOT)
        avg_chi2 = local_avg_chi2
    end if

```

180a *<Exit iterate if accuracy has been reached (MPI) 180a>≡* (176)

```

    if (present (accuracy)) then
        if (proc_id == VAMP_ROOT) then
            current_accuracy = local_std_dev / local_integral
        end if
        call mpi90_broadcast (current_accuracy, VAMP_ROOT)
        if (current_accuracy <= accuracy) then
            call raise_exception (exc, EXC_INFO, FN, &
                "requested accuracy reached")
            exit iterate
        end if
    end if

```

A very simple minded scheduler: maximizes processor utilization and, does not pay attention to communication costs.

180b *<Declaration of vampi procedures 168b>+≡* (167c) <179c 182a>  
 private :: **schedule**

We disfavor the root process a little bit (by starting up with a fake filling ratio of 10%) so that it is likely to be ready to answer all communication requests.

180c *<Implementation of vampi procedures 169a>+≡* (167c) <179d 182d>

```

    pure subroutine schedule (jobs, num_procs, assign, waste)
        real(kind=default), dimension(:), intent(in) :: jobs
        integer, intent(in) :: num_procs
        integer, dimension(:), intent(out) :: assign
        real(kind=default), intent(out), optional :: waste
        integer, dimension(size(jobs)) :: idx
        real(kind=default), dimension(size(jobs)) :: sjobs
        real(kind=default), dimension(num_procs) :: fill
        integer :: job, proc
        sjobs = jobs / sum (jobs) * num_procs
        idx = (/ (job, job = 1, size(jobs)) /)
        call sort (sjobs, idx, reverse = .true.)
        fill = 0.0
        fill(VAMP_ROOT+1) = 0.1
        do job = 1, size (sjobs)
            proc = sum (minloc (fill))

```

```

        fill(proc) = fill(proc) + sjobs(job)
        assign(idx(job)) = proc - 1
    end do
    <Estimate waste of processor time 181a>
end subroutine schedule

```

Assuming equivalent processors and uniform computation costs, the waste is given by the fraction of the time that it spent by the other processors waiting for the processor with the biggest assignment:

181a *<Estimate waste of processor time 181a>*≡ (180c)

```

    if (present (waste)) then
        waste = 1.0 - sum (fill) / (num_procs * maxval (fill))
    end if

```

Accordingly, if the waste caused by distributing only complete grids, we switch to splitting the grids, just like in single channel sampling. This is *not* the default, because the communication costs are measurably higher for many grids and many processors.



This version is broken!

181b *<Distribute each grid among processes 181b>*≡ (176)

```

    do ch = 1, size (g%g0%grids)
        if (g%active(ch)) then
            call vamp_discard_integral (g%g0%grids(ch))
            if (present (histories)) then
                call vamp_sample_grid &
                    (rng, g%g0%grids(ch), func, 1, g%integrals(ch), g%std_devs(ch), &
                     channel = ch, weights = weights, grids = g%g0%grids, &
                     history = histories(iteration:iteration,ch))
            else
                call vamp_sample_grid &
                    (rng, g%g0%grids(ch), func, 1, g%integrals(ch), g%std_devs(ch), &
                     channel = ch, weights = weights, grids = g%g0%grids)
            end if
        else
            if (proc_id == VAMP_ROOT) then
                call vamp_nullify_variance (g%g0%grids(ch))
                call vamp_nullify_covariance (g%g0%grids(ch))
            end if
        end if
    end do
    if (proc_id == VAMP_ROOT) then
        call vamp_reduce_channels (g%g0, g%integrals, g%std_devs, g%active)
        call vamp_average_iterations &

```

```

        (g%g0, iteration, local_integral, local_std_dev, local_avg_chi2)
    if (present (history)) then
        if (iteration <= size (history)) then
            call vamp_get_history &
                (history(iteration), g%g0, local_integral, local_std_dev, &
                 local_avg_chi2)
        else
            call raise_exception (exc, EXC_WARN, FN, "history too short")
        end if
        call vamp_terminate_history (history(iteration+1:))
    end if
end if

```

### 5.3.2 Event Generation

This is currently only a syntactical translation ...

- 182a *<Declaration of vampi procedures 168b>+≡* (167c) <180b 184a>  
 public :: vamp\_warmup\_grid  
 public :: vamp\_warmup\_grids  
 public :: vamp\_next\_event  
 private :: vamp\_next\_event\_single, vamp\_next\_event\_multi
- 182b *<vamp0.\* => vamp.\* 168c>+≡* (167b) <174a 184b>  
 vamp0\_warmup\_grid => vamp\_warmup\_grid, &  
 vamp0\_warmup\_grids => vamp\_warmup\_grids, &  
 vamp0\_next\_event => vamp\_next\_event, &
- 182c *<Interfaces of vampi procedures 173a>+≡* (167c) <173a 184c>  
 interface vamp\_next\_event  
 module procedure vamp\_next\_event\_single, vamp\_next\_event\_multi  
 end interface
- 182d *<Implementation of vampi procedures 169a>+≡* (167c) <180c 183a>  
 subroutine vamp\_next\_event\_single &  
 (x, rng, g, func, weight, channel, weights, grids, exc)  
 real(kind=default), dimension(:), intent(out) :: x  
 type(tao\_random\_state), intent(inout) :: rng  
 type(vamp\_grid), intent(inout) :: g  
 real(kind=default), intent(out), optional :: weight  
 integer, intent(in), optional :: channel  
 real(kind=default), dimension(:), intent(in), optional :: weights  
 type(vamp\_grid), dimension(:), intent(in), optional :: grids  
 type(exception), intent(inout), optional :: exc  
*<Interface declaration for func 22>*

```

integer :: proc_id
call mpi90_rank (proc_id)
if (proc_id == VAMP_ROOT) then
    call vamp0_next_event &
        (x, rng, g, func, weight, channel, weights, grids, exc)
end if
end subroutine vamp_next_event_single
183a <Implementation of vampi procedures 169a>+≡ (167c) <182d 183b>
subroutine vamp_next_event_multi (x, rng, g, func, phi, weight, exc)
    real(kind=default), dimension(:), intent(out) :: x
    type(tao_random_state), intent(inout) :: rng
    type(vamp_grids), intent(inout) :: g
    real(kind=default), intent(out), optional :: weight
    type(exception), intent(inout), optional :: exc
    <Interface declaration for func 22>
    <Interface declaration for phi 31a>
    integer :: proc_id
    call mpi90_rank (proc_id)
    if (proc_id == VAMP_ROOT) then
        call vamp0_next_event (x, rng, g%g0, func, phi, weight, exc)
    end if
end subroutine vamp_next_event_multi
183b <Implementation of vampi procedures 169a>+≡ (167c) <183a 183c>
subroutine vamp_warmup_grid (rng, g, func, iterations, exc, history)
    type(tao_random_state), intent(inout) :: rng
    type(vamp_grid), intent(inout) :: g
    integer, intent(in) :: iterations
    type(exception), intent(inout), optional :: exc
    type(vamp_history), dimension(:), intent(inout), optional :: history
    <Interface declaration for func 22>
    call vamp_sample_grid &
        (rng, g, func, iterations - 1, exc = exc, history = history)
    call vamp_sample_grid0 (rng, g, func, exc = exc)
end subroutine vamp_warmup_grid
183c <Implementation of vampi procedures 169a>+≡ (167c) <183b 184d>
subroutine vamp_warmup_grids &
    (rng, g, func, iterations, history, histories, exc)
    type(tao_random_state), intent(inout) :: rng
    type(vamp_grids), intent(inout) :: g
    integer, intent(in) :: iterations
    type(vamp_history), dimension(:), intent(inout), optional :: history
    type(vamp_history), dimension(:, :), intent(inout), optional :: histories

```



```

type(exception), intent(inout), optional :: exc
<Interface declaration for func 22>
integer :: ch
call vamp0_sample_grids (rng, g%g0, func, iterations - 1, exc = exc, &
                        history = history, histories = histories)
do ch = 1, size (g%g0%grids)
  ! if (g%g0%grids(ch)%num_calls >= 2) then
    call vamp_sample_grid0 (rng, g%g0%grids(ch), func, exc = exc)
  ! end if
end do
end subroutine vamp_warmup_grids

```

### 5.3.3 I/O

- 184a <Declaration of vampi procedures 168b>+≡ (167c) <182a 185c>  
 public :: vamp\_write\_grid, vamp\_read\_grid  
 private :: write\_grid\_unit, write\_grid\_name  
 private :: read\_grid\_unit, read\_grid\_name
- 184b <vamp0.\* => vamp.\* 168c>+≡ (167b) <182b 185d>  
 vamp0\_write\_grid => vamp\_write\_grid, &  
 vamp0\_read\_grid => vamp\_read\_grid, &
- 184c <Interfaces of vampi procedures 173a>+≡ (167c) <182c 185e>  
 interface vamp\_write\_grid  
 module procedure write\_grid\_unit, write\_grid\_name  
 end interface  
 interface vamp\_read\_grid  
 module procedure read\_grid\_unit, read\_grid\_name  
 end interface
- 184d <Implementation of vampi procedures 169a>+≡ (167c) <183c 184e>  
 subroutine write\_grid\_unit (g, unit)  
 type(vamp\_grid), intent(in) :: g  
 integer, intent(in) :: unit  
 integer :: proc\_id  
 call mpi90\_rank (proc\_id)  
 if (proc\_id == VAMP\_ROOT) then  
 call vamp0\_write\_grid (g, unit)  
 end if  
 end subroutine write\_grid\_unit
- 184e <Implementation of vampi procedures 169a>+≡ (167c) <184d 185a>  
 subroutine read\_grid\_unit (g, unit)  
 type(vamp\_grid), intent(inout) :: g

```

integer, intent(in) :: unit
integer :: proc_id
call mpi90_rank (proc_id)
if (proc_id == VAMP_ROOT) then
    call vamp0_read_grid (g, unit)
end if
end subroutine read_grid_unit
185a <Implementation of vampi procedures 169a>+≡ (167c) <184e 185b>
subroutine write_grid_name (g, name)
    type(vamp_grid), intent(inout) :: g
    character(len=*), intent(in) :: name
    integer :: proc_id
    call mpi90_rank (proc_id)
    if (proc_id == VAMP_ROOT) then
        call vamp0_write_grid (g, name)
    end if
end subroutine write_grid_name
185b <Implementation of vampi procedures 169a>+≡ (167c) <185a 186a>
subroutine read_grid_name (g, name)
    type(vamp_grid), intent(inout) :: g
    character(len=*), intent(in) :: name
    integer :: proc_id
    call mpi90_rank (proc_id)
    if (proc_id == VAMP_ROOT) then
        call vamp0_read_grid (g, name)
    end if
end subroutine read_grid_name
185c <Declaration of vampi procedures 168b>+≡ (167c) <184a 187a>
public :: vamp_write_grids, vamp_read_grids
private :: write_grids_unit, write_grids_name
private :: read_grids_unit, read_grids_name
185d <vamp0.* => vamp.* 168c>+≡ (167b) <184b>
vamp0_write_grids => vamp_write_grids, &
vamp0_read_grids => vamp_read_grids, &
185e <Interfaces of vampi procedures 173a>+≡ (167c) <184c 189a>
interface vamp_write_grids
    module procedure write_grids_unit, write_grids_name
end interface
interface vamp_read_grids
    module procedure read_grids_unit, read_grids_name
end interface

```

186a *<Implementation of vampi procedures 169a>+≡* (167c) <185b 186b>

```

subroutine write_grids_unit (g, unit)
  type(vamp_grids), intent(in) :: g
  integer, intent(in) :: unit
  integer :: proc_id
  call mpi90_rank (proc_id)
  if (proc_id == VAMP_ROOT) then
    call vamp0_write_grids (g%g0, unit)
  end if
end subroutine write_grids_unit

```

186b *<Implementation of vampi procedures 169a>+≡* (167c) <186a 186c>

```

subroutine read_grids_unit (g, unit)
  type(vamp_grids), intent(inout) :: g
  integer, intent(in) :: unit
  integer :: proc_id
  call mpi90_rank (proc_id)
  if (proc_id == VAMP_ROOT) then
    call vamp0_read_grids (g%g0, unit)
  end if
end subroutine read_grids_unit

```

186c *<Implementation of vampi procedures 169a>+≡* (167c) <186b 186d>

```

subroutine write_grids_name (g, name)
  type(vamp_grids), intent(inout) :: g
  character(len=*), intent(in) :: name
  integer :: proc_id
  call mpi90_rank (proc_id)
  if (proc_id == VAMP_ROOT) then
    call vamp0_write_grids (g%g0, name)
  end if
end subroutine write_grids_name

```

186d *<Implementation of vampi procedures 169a>+≡* (167c) <186c 187b>

```

subroutine read_grids_name (g, name)
  type(vamp_grids), intent(inout) :: g
  character(len=*), intent(in) :: name
  integer :: proc_id
  call mpi90_rank (proc_id)
  if (proc_id == VAMP_ROOT) then
    call vamp0_read_grids (g%g0, name)
  end if

```

```
end subroutine read_grids_name
```

### 5.3.4 Communicating Grids

187a  $\langle$ Declaration of vampi procedures 168b $\rangle + \equiv$  (167c)  $\langle$ 185c 191a $\rangle$

```
public :: vamp_send_grid
public :: vamp_receive_grid
public :: vamp_broadcast_grid
public :: vamp_broadcast_grids
```



The next two are still kludged. Nicer implementations with one message less per call below, but MPICH does funny things during `mpi_get_count`, which is called by `mpi90_receive_pointer`.

Caveat: this `vamp_send_grid` uses *three* tags: `tag`, `tag+1` and `tag+2`:

187b  $\langle$ Implementation of vampi procedures 169a $\rangle + \equiv$  (167c)  $\langle$ 186d 187c $\rangle$

```
subroutine vamp_send_grid (g, target, tag, domain, error)
  type(vamp_grid), intent(in) :: g
  integer, intent(in) :: target, tag
  integer, intent(in), optional :: domain
  integer, intent(out), optional :: error
  integer, dimension(2) :: words
  integer, dimension(:), allocatable :: ibuf
  real(kind=default), dimension(:), allocatable :: dbuf
  call vamp_marshall_grid_size (g, words(1), words(2))
  allocate (ibuf(words(1)), dbuf(words(2)))
  call vamp_marshall_grid (g, ibuf, dbuf)
  call mpi90_send (words, target, tag, domain, error)
  call mpi90_send (ibuf, target, tag+1, domain, error)
  call mpi90_send (dbuf, target, tag+2, domain, error)
  deallocate (ibuf, dbuf)
end subroutine vamp_send_grid
```

187c  $\langle$ Implementation of vampi procedures 169a $\rangle + \equiv$  (167c)  $\langle$ 187b 189b $\rangle$

```
subroutine vamp_receive_grid (g, source, tag, domain, status, error)
  type(vamp_grid), intent(inout) :: g
  integer, intent(in) :: source, tag
  integer, intent(in), optional :: domain
  type(mpi90_status), intent(out), optional :: status
  integer, intent(out), optional :: error
  integer, dimension(2) :: words
  integer, dimension(:), allocatable :: ibuf
```

```

real(kind=default), dimension(:), allocatable :: dbuf
call mpi90_receive (words, source, tag, domain, status, error)
allocate (ibuf(words(1)), dbuf(words(2)))
call mpi90_receive (ibuf, source, tag+1, domain, status, error)
call mpi90_receive (dbuf, source, tag+2, domain, status, error)
call vamp_unmarshal_grid (g, ibuf, dbuf)
deallocate (ibuf, dbuf)
end subroutine vamp_receive_grid

```


Caveat: the real `vamp_send_grid` uses *two* tags: `tag` and `tag+1`:

188a *<Implementation of vampi procedures (doesn't work with MPICH yet) 188a>≡* 188b*>*

```

subroutine vamp_send_grid (g, target, tag, domain, error)
  type(vamp_grid), intent(in) :: g
  integer, intent(in) :: target, tag
  integer, intent(in), optional :: domain
  integer, intent(out), optional :: error
  integer :: iwords, dwords
  integer, dimension(:), allocatable :: ibuf
  real(kind=default), dimension(:), allocatable :: dbuf
  call vamp_marshall_grid_size (g, iwords, dwords)
  allocate (ibuf(iwords), dbuf(dwords))
  call vamp_marshall_grid (g, ibuf, dbuf)
  call mpi90_send (ibuf, target, tag, domain, error)
  call mpi90_send (dbuf, target, tag+1, domain, error)
  deallocate (ibuf, dbuf)
end subroutine vamp_send_grid

```

 There's something wrong with MPICH: if I call `mpi90_receive_pointer` in the opposite order, the low level call to `mpi_get_count` bombs for no apparent reason!

 There are also funky things going on with tag: `mpi90_receive_pointer` should leave it alone, but ...

188b *<Implementation of vampi procedures (doesn't work with MPICH yet) 188a>+≡* <188a

```

subroutine vamp_receive_grid (g, source, tag, domain, status, error)
  type(vamp_grid), intent(inout) :: g
  integer, intent(in) :: source, tag
  integer, intent(in), optional :: domain
  type(mpi90_status), intent(out), optional :: status
  integer, intent(out), optional :: error
  integer, dimension(:), pointer :: ibuf

```

```

real(kind=default), dimension(:), pointer :: dbuf
nullify (ibuf, dbuf)
call mpi90_receive_pointer (dbuf, source, tag+1, domain, status, error)
call mpi90_receive_pointer (ibuf, source, tag, domain, status, error)
call vamp_unmarshal_grid (g, ibuf, dbuf)
deallocate (ibuf, dbuf)
end subroutine vamp_receive_grid

```

This is not a good idea, with respect to communication costs. For SMP machines, it appears to be negligible however.

189a *<Interfaces of vampi procedures 173a>+≡* (167c) <185e

```

interface vamp_broadcast_grid
  module procedure &
    vamp_broadcast_one_grid, vamp_broadcast_many_grids
end interface

```

189b *<Implementation of vampi procedures 169a>+≡* (167c) <187c 189c>

```

subroutine vamp_broadcast_one_grid (g, root, domain, error)
  type(vamp_grid), intent(inout) :: g
  integer, intent(in) :: root
  integer, intent(in), optional :: domain
  integer, intent(out), optional :: error
  integer, dimension(:), allocatable :: ibuf
  real(kind=default), dimension(:), allocatable :: dbuf
  integer :: iwords, dwords, me
  call mpi90_rank (me)
  if (me == root) then
    call vamp_marshall_grid_size (g, iwords, dwords)
  end if
  call mpi90_broadcast (iwords, root, domain, error)
  call mpi90_broadcast (dwords, root, domain, error)
  allocate (ibuf(iwords), dbuf(dwords))
  if (me == root) then
    call vamp_marshall_grid (g, ibuf, dbuf)
  end if
  call mpi90_broadcast (ibuf, root, domain, error)
  call mpi90_broadcast (dbuf, root, domain, error)
  if (me /= root) then
    call vamp_unmarshal_grid (g, ibuf, dbuf)
  end if
  deallocate (ibuf, dbuf)
end subroutine vamp_broadcast_one_grid

```

189c *<Implementation of vampi procedures 169a>+≡* (167c) <189b 190>

```

subroutine vamp_broadcast_many_grids (g, root, domain, error)
  type(vamp_grid), dimension(:), intent(inout) :: g
  integer, intent(in) :: root
  integer, intent(in), optional :: domain
  integer, intent(out), optional :: error
  integer :: i
  do i = 1, size(g)
    call vamp_broadcast_one_grid (g(i), root, domain, error)
  end do
end subroutine vamp_broadcast_many_grids

```

190 *<Implementation of vampi procedures 169a>+≡ (167c) <189c 191b>*

```

subroutine vamp_broadcast_grids (g, root, domain, error)
  type(vamp0_grids), intent(inout) :: g
  integer, intent(in) :: root
  integer, intent(in), optional :: domain
  integer, intent(out), optional :: error
  integer :: nch, me
  call mpi90_broadcast (g%sum_chi2, root, domain, error)
  call mpi90_broadcast (g%sum_integral, root, domain, error)
  call mpi90_broadcast (g%sum_weights, root, domain, error)
  call mpi90_rank (me)
  if (me == root) then
    nch = size (g%grids)
  end if
  call mpi90_broadcast (nch, root, domain, error)
  if (me /= root) then
    if (associated (g%grids)) then
      if (size (g%grids) /= nch) then
        call vamp0_delete_grid (g%grids)
        deallocate (g%grids, g%weights, g%num_calls)
        allocate (g%grids(nch), g%weights(nch), g%num_calls(nch))
        call vamp_create_empty_grid (g%grids)
      end if
    else
      allocate (g%grids(nch), g%weights(nch), g%num_calls(nch))
      call vamp_create_empty_grid (g%grids)
    end if
  end if
  call vamp_broadcast_grid (g%grids, root, domain, error)
  call mpi90_broadcast (g%weights, root, domain, error)
  call mpi90_broadcast (g%num_calls, root, domain, error)
end subroutine vamp_broadcast_grids

```

191a *<Declaration of vampi procedures 168b>+≡* (167c) <187a  
 public :: vamp\_send\_history  
 public :: vamp\_receive\_history

191b *<Implementation of vampi procedures 169a>+≡* (167c) <190 191c>  
 subroutine vamp\_send\_history (g, target, tag, domain, error)  
   type(vamp\_history), intent(in) :: g  
   integer, intent(in) :: target, tag  
   integer, intent(in), optional :: domain  
   integer, intent(out), optional :: error  
   integer, dimension(2) :: words  
   integer, dimension(:), allocatable :: ibuf  
   real(kind=default), dimension(:), allocatable :: dbuf  
   call vamp\_marshall\_history\_size (g, words(1), words(2))  
   allocate (ibuf(words(1)), dbuf(words(2)))  
   call vamp\_marshall\_history (g, ibuf, dbuf)  
   call mpi90\_send (words, target, tag, domain, error)  
   call mpi90\_send (ibuf, target, tag+1, domain, error)  
   call mpi90\_send (dbuf, target, tag+2, domain, error)  
   deallocate (ibuf, dbuf)  
end subroutine vamp\_send\_history

191c *<Implementation of vampi procedures 169a>+≡* (167c) <191b  
 subroutine vamp\_receive\_history (g, source, tag, domain, status, error)  
   type(vamp\_history), intent(inout) :: g  
   integer, intent(in) :: source, tag  
   integer, intent(in), optional :: domain  
   type(mpi90\_status), intent(out), optional :: status  
   integer, intent(out), optional :: error  
   integer, dimension(2) :: words  
   integer, dimension(:), allocatable :: ibuf  
   real(kind=default), dimension(:), allocatable :: dbuf  
   call mpi90\_receive (words, source, tag, domain, status, error)  
   allocate (ibuf(words(1)), dbuf(words(2)))  
   call mpi90\_receive (ibuf, source, tag+1, domain, status, error)  
   call mpi90\_receive (dbuf, source, tag+2, domain, status, error)  
   call vamp\_unmarshall\_history (g, ibuf, dbuf)  
   deallocate (ibuf, dbuf)  
end subroutine vamp\_receive\_history



# —6—

## SELF TEST

### 6.1 No Mapping Mode

In this chapter we perform a test of the major features of Vamp. A function with many peaks is integrated with the traditional Vegas algorithm, using a multi-channel approach and in parallel. The function is constructed to have a known analytical integral (which is chosen to be one) in order to be able to gauge the accuracy of the result and error estimate.

#### 6.1.1 Serial Test

```

192a <vamp_test.f90 192a>≡
! vamp_test.f90 --
<Copyleft notice 1>
<Module vamp_test_functions 192b>
<Module vamp_tests 196b>
200c>

192b <Module vamp_test_functions 192b>≡ (192a 202a)
module vamp_test_functions
  use kinds
  use constants, only: PI
  use coordinates
  use vamp, only: vamp_grid, vamp_multi_channel
  use vamp, only: vamp_data_t
  implicit none
  private
  public :: f, j, phi, ihp, w
  public :: lorentzian
  private :: lorentzian_normalized
  real(kind=default), public :: width
contains
  <Implementation of vamp_test_functions procedures 193a>

```

```
end module vamp_test_functions
```

$$\int_{x_1}^{x_2} dx \frac{1}{(x - x_0)^2 + a^2} = \frac{1}{a} \left( \operatorname{atan} \left( \frac{x_2 - x_0}{a} \right) - \operatorname{atan} \left( \frac{x_1 - x_0}{a} \right) \right) = N(x_0, x_1, x_2, a) \quad (6.1)$$

193a  $\langle$ Implementation of vamp\_test\_functions procedures 193a $\rangle \equiv$  (192b) 193b $\rangle$

```
pure function lorentzian_normalized (x, x0, x1, x2, a) result (f)
  real(kind=default), intent(in) :: x, x0, x1, x2, a
  real(kind=default) :: f
  if (x1 <= x .and. x <= x2) then
    f = 1 / ((x - x0)**2 + a**2) &
      * a / (atan2 (x2 - x0, a) - atan2 (x1 - x0, a))
  else
    f = 0
  end if
end function lorentzian_normalized
```

$$\int d^n x f(x) = \int d\Omega_n r^{n-1} dr f(x) = 1 \quad (6.2)$$

193b  $\langle$ Implementation of vamp\_test\_functions procedures 193a $\rangle + \equiv$  (192b)  $\langle$ 193a 193c $\rangle$

```
pure function lorentzian (x, x0, x1, x2, r0, a) result (f)
  real(kind=default), dimension(:), intent(in) :: x, x0, x1, x2
  real(kind=default), intent(in) :: r0, a
  real(kind=default) :: f
  real(kind=default) :: r, r1, r2
  integer :: n
  n = size (x)
  if (n > 1) then
    r = sqrt (dot_product (x-x0, x-x0))
    r1 = 0.4_default
    r2 = min (minval (x2-x0), minval (x0-x1))
    if (r1 <= r .and. r <= r2) then
      f = lorentzian_normalized (r, r0, r1, r2, a) * r**(1-n) / surface (n)
    else
      f = 0
    end if
  else
    f = lorentzian_normalized (x(1), x0(1), x1(1), x2(1), a)
  endif
end function lorentzian
```

193c  $\langle$ Implementation of vamp\_test\_functions procedures 193a $\rangle + \equiv$  (192b)  $\langle$ 193b 194 $\rangle$

```
pure function f (x, data, weights, channel, grids) result (f_x)
  real(kind=default), dimension(:), intent(in) :: x
  class(vamp_data_t), intent(in) :: data
```

```

real(kind=default), dimension(:), intent(in), optional :: weights
integer, intent(in), optional :: channel
type(vamp_grid), dimension(:), intent(in), optional :: grids
real(kind=default) :: f_x
real(kind=default), dimension(size(x)) :: minus_one, plus_one, zero, w_i, f_i
integer :: n, i
n = size(x)
minus_one = -1
zero = 0
plus_one = 1
w_i = 1
do i = 1, n
  if (all (abs (x(i+1:)) <= 1)) then
    f_i = lorentzian (x(1:i), zero(1:i), minus_one(1:i), plus_one(1:i), &
      0.7_default, width) &
      / 2.0_default**(n-i)
  else
    f_i = 0
  end if
end do
f_x = dot_product (w_i, f_i) / sum (w_i)
end function f

```

194  $\langle$ Implementation of vamp\_test functions procedures 193a $\rangle + \equiv$  (192b)  $\langle$ 193c 195a $\rangle$

```

pure function phi (xi, channel) result (x)
real(kind=default), dimension(:), intent(in) :: xi
integer, intent(in) :: channel
real(kind=default), dimension(size(xi)) :: x
real(kind=default) :: r
real(kind=default), dimension(0) :: dummy
integer :: n
n = size(x)
if (channel == 1) then
  x = xi
else if (channel == 2) then
  r = (xi(1) + 1) / 2 * sqrt (2.0_default)
  x(1:2) = spherical_cos_to_cartesian (r, PI * xi(2), dummy)
  x(3:) = xi(3:)
else if (channel < n) then
  r = (xi(1) + 1) / 2 * sqrt (real (channel, kind=default))
  x(1:channel) = spherical_cos_to_cartesian (r, PI * xi(2), xi(3:channel))
  x(channel+1:) = xi(channel+1:)
else if (channel == n) then
  r = (xi(1) + 1) / 2 * sqrt (real (channel, kind=default))

```

```

        x = spherical_cos_to_cartesian (r, PI * xi(2), xi(3:))
    else
        x = 0
    end if
end function phi
195a <Implementation of vamp_test_functions procedures 193a>+≡ (192b) <194 195b>
pure function ihp (x, channel) result (xi)
    real(kind=default), dimension(:), intent(in) :: x
    integer, intent(in) :: channel
    real(kind=default), dimension(size(x)) :: xi
    real(kind=default) :: r, phi
    integer :: n
    n = size(x)
    if (channel == 1) then
        xi = x
    else if (channel == 2) then
        call cartesian_to_spherical_cos (x(1:2), r, phi)
        xi(1) = 2 * r / sqrt (2.0_default) - 1
        xi(2) = phi / PI
        xi(3:) = x(3:)
    else if (channel < n) then
        call cartesian_to_spherical_cos (x(1:channel), r, phi, xi(3:channel))
        xi(1) = 2 * r / sqrt (real (channel, kind=default)) - 1
        xi(2) = phi / PI
        xi(channel+1:) = x(channel+1:)
    else if (channel == n) then
        call cartesian_to_spherical_cos (x, r, phi, xi(3:))
        xi(1) = 2 * r / sqrt (real (channel, kind=default)) - 1
        xi(2) = phi / PI
    else
        xi = 0
    end if
end function ihp
195b <Implementation of vamp_test_functions procedures 193a>+≡ (192b) <195a 196a>
pure function j (x, data, channel) result (j_x)
    real(kind=default), dimension(:), intent(in) :: x
    class(vamp_data_t), intent(in) :: data
    integer, intent(in) :: channel
    real(kind=default) :: j_x
    if (channel == 1) then
        j_x = 1
    else if (channel > 1) then
        j_x = 2 / sqrt (real (channel, kind=default)) ! 1/|dr/dξ1|
    end if
end function j

```

```

        j_x = j_x / PI ! 1/|dφ/dξ2|
        j_x = j_x * cartesian_to_spherical_cos_j (x(1:channel))
    else
        j_x = 0
    end if
end function j

```

196a  $\langle$ Implementation of `vamp_test_functions` procedures 193a $\rangle \equiv$  (192b)  $\triangleleft$  195b

```

function w (x, data, weights, channel, grids) result (w_x)
    real(kind=default), dimension(:), intent(in) :: x
    class(vamp_data_t), intent(in) :: data
    real(kind=default), dimension(:), intent(in), optional :: weights
    integer, intent(in), optional :: channel
    type(vamp_grid), dimension(:), intent(in), optional :: grids
    real(kind=default) :: w_x
    w_x = vamp_multi_channel (f, data, phi, ihp, j, x, weights, channel, grids)
end function w

```

196b  $\langle$ Module `vamp_tests` 196b $\rangle \equiv$  (192a)

```

module vamp_tests
    use kinds
    use exceptions
    use histograms
    use tao_random_numbers
    use coordinates
    use vamp
    use vamp_test_functions !NODEP!
    implicit none
    private
     $\langle$ Declaration of procedures in vamp_tests 196c $\rangle$ 
contains
     $\langle$ Implementation of procedures in vamp_tests 197a $\rangle$ 
end module vamp_tests

```

### Verification

196c  $\langle$ Declaration of procedures in `vamp_tests` 196c $\rangle \equiv$  (196b 202b) 198a $\triangleright$

```

! public :: check_jacobians, check_inverses, check_inverses3
public :: check_inverses, check_inverses3

```

196d  $\langle$ Implementation of procedures in `vamp_tests` (broken?) 196d $\rangle \equiv$

```

subroutine check_jacobians (rng, region, weights, samples)
    type( tao_random_state ), intent(inout) :: rng
    real(kind=default), dimension(:, :), intent(in) :: region
    real(kind=default), dimension(:), intent(in) :: weights

```

```

integer, intent(in) :: samples
real(kind=default), dimension(size(region,dim=2)) :: x
real(kind=default) :: d
integer :: ch
do ch = 1, size(weights)
    call vamp_check_jacobian (rng, samples, j, NO_DATA, phi, ch, region, d, x)
    print *, "channel", ch, ": delta(j)/j=", real(d), ", @x=", real (x)
end do
end subroutine check_jacobians

```

197a  $\langle$ Implementation of procedures in vamp\_tests 197a $\rangle \equiv$  (196b 202b) 197b $\triangleright$

```

subroutine check_inverses (rng, region, weights, samples)
    type(tao_random_state), intent(inout) :: rng
    real(kind=default), dimension(:,,:), intent(in) :: region
    real(kind=default), dimension(:), intent(in) :: weights
    integer, intent(in) :: samples
    real(kind=default), dimension(size(region,dim=2)) :: x1, x2, x_dx
    real(kind=default) :: dx, dx_max
    integer :: ch, i
    dx_max = 0
    x_dx = 0
    do ch = 1, size(weights)
        do i = 1, samples
            call tao_random_number (rng, x1)
            x2 = ihp (phi (x1, ch), ch)
            dx = sqrt (dot_product (x1-x2, x1-x2))
            if (dx > dx_max) then
                dx_max = dx
                x_dx = x1
            end if
        end do
        print *, "channel", ch, ": |x-x|=", real(dx), ", @x=", real (x_dx)
    end do
end subroutine check_inverses

```

197b  $\langle$ Implementation of procedures in vamp\_tests 197a $\rangle + \equiv$  (196b 202b)  $\triangleleft$ 197a 198b $\triangleright$

```

subroutine check_inverses3 (rng, region, samples)
    type(tao_random_state), intent(inout) :: rng
    real(kind=default), dimension(:,,:), intent(in) :: region
    integer, intent(in) :: samples
    real(kind=default), dimension(size(region,dim=2)) :: x1, x2, x_dx, x_dj
    real(kind=default) :: r, phi, jac, caj, dx, dx_max, dj, dj_max
    real(kind=default), dimension(size(x1)-2) :: cos_theta
    integer :: i
    dx_max = 0

```

```

x_dx = 0
dj_max = 0
x_dj = 0
do i = 1, samples
  call tao_random_number (rng, x1)
  call cartesian_to_spherical_cos_2 (x1, r, phi, cos_theta, jac)
  call spherical_cos_to_cartesian_2 (r, phi, cos_theta, x2, caj)
  dx = sqrt (dot_product (x1-x2, x1-x2))
  dj = jac*caj - 1
  if (dx > dx_max) then
    dx_max = dx
    x_dx = x1
  end if
  if (dj > dj_max) then
    dj_max = dj
    x_dj = x1
  end if
end do
print *, "channel 3 : j*j-1=", real(dj), ", @x=", real (x_dj)
print *, "channel 3 : |x-x|=", real(dx), ", @x=", real (x_dx)
end subroutine check_inverses3

```

### Integration

198a *<Declaration of procedures in vamp\_tests 196c>+≡ (196b 202b) <196c 200a>*  
 public :: single\_channel, multi\_channel

198b *<Implementation of procedures in vamp\_tests 197a>+≡ (196b 202b) <197b 199a>*  
 subroutine single\_channel (rng, region, samples, iterations, &  
 integral, standard\_dev, chi\_squared)  
 type(tao\_random\_state), intent(inout) :: rng  
 real(kind=default), dimension(:,:), intent(in) :: region  
 integer, dimension(:), intent(in) :: samples, iterations  
 real(kind=default), intent(out) :: integral, standard\_dev, chi\_squared  
 type(vamp\_grid) :: gr  
 type(vamp\_history), dimension(iterations(1)+iterations(2)) :: history  
 call vamp\_create\_history (history)  
 call vamp\_create\_grid (gr, region, samples(1))  
 call vamp\_sample\_grid (rng, gr, f, NO\_DATA, iterations(1), history = history)  
 call vamp\_discard\_integral (gr, samples(2))  
 call vamp\_sample\_grid &  
 (rng, gr, f, NO\_DATA, iterations(2), &  
 integral, standard\_dev, chi\_squared, &  
 history = history(iterations(1)+1:))

```

    call vamp_write_grid (gr, "vamp_test.grid")
    call vamp_delete_grid (gr)
    call vamp_print_history (history, "single")
    call vamp_delete_history (history)
end subroutine single_channel
199a <Implementation of procedures in vamp_tests 197a>+≡ (196b 202b) <198b 200b>
subroutine multi_channel (rng, region, weights, samples, iterations, powers, &
    integral, standard_dev, chi_squared)
    type(tao_random_state), intent(inout) :: rng
    real(kind=default), dimension(:,:), intent(in) :: region
    real(kind=default), dimension(:), intent(inout) :: weights
    integer, dimension(:), intent(in) :: samples, iterations
    real(kind=default), dimension(:), intent(in) :: powers
    real(kind=default), intent(out) :: integral, standard_dev, chi_squared
    type(vamp_grids) :: grs
    <Body of multi_channel 199b>
end subroutine multi_channel
199b <Body of multi_channel 199b>≡ (199a 213a) 213b>
    type(vamp_history), dimension(iterations(1)+iterations(2)+size(powers)-1) :: &
        history
    type(vamp_history), dimension(size(history),size(weights)) :: histories
    integer :: it, nit
    nit = size (powers)
    call vamp_create_history (history)
    call vamp_create_history (histories)
    call vamp_create_grids (grs, region, samples(1), weights)
    call vamp_sample_grids (rng, grs, w, NO_DATA, iterations(1) - 1, &
        history = history, histories = histories)
    call vamp_print_history (history, "multi")
    call vamp_print_history (histories, "multi")
    do it = 1, nit
        call vamp_sample_grids (rng, grs, w, NO_DATA, 1, &
            history = history(iterations(1)+it-1:), &
            histories = histories(iterations(1)+it-1:,:))
        call vamp_print_history (history(iterations(1)+it-1:), "multi")
        call vamp_print_history (histories(iterations(1)+it-1:,:), "multi")
        call vamp_refine_weights (grs, powers(it))
    end do
    call vamp_discard_integrals (grs, samples(2))
    call vamp_sample_grids &
        (rng, grs, w, NO_DATA, iterations(2), &
            integral, standard_dev, chi_squared, &
            history = history(iterations(1)+nit:), &

```



```

        histories = histories(iterations(1)+nit:,:)
call vamp_print_history (history(iterations(1)+nit:), "multi")
call vamp_print_history (histories(iterations(1)+nit:,:), "multi")
call vamp_write_grids (grs, "vamp_test.grids")
call vamp_delete_grids (grs)
call vamp_print_history (history, "multi")
call vamp_print_history (histories, "multi")
call vamp_delete_history (history)
call vamp_delete_history (histories)

```

### *Input/Output*

- 200a *<Declaration of procedures in vamp\_tests 196c>+≡ (196b 202b) <198a*  
public :: print\_results
- 200b *<Implementation of procedures in vamp\_tests 197a>+≡ (196b 202b) <199a*  
subroutine print\_results (prefix, prev\_ticks, &  
integral, std\_dev, chi2, acceptable, failures)  
character(len=\*), intent(in) :: prefix  
integer, intent(in) :: prev\_ticks  
real(kind=default), intent(in) :: integral, std\_dev, chi2, acceptable  
integer, intent(inout) :: failures  
integer :: ticks, ticks\_per\_second  
real(kind=default) :: pull  
call system\_clock (ticks, ticks\_per\_second)  
pull = (integral - 1) / std\_dev  
print "(1X,A,A,F6.2,A)", prefix, &  
": time = ", real (ticks - prev\_ticks) / ticks\_per\_second, " secs"  
print \*, prefix, ": int, err, chi2: ", &  
real (integral), real (std\_dev), real (chi2)  
if (abs (pull) > acceptable) then  
failures = failures + 1  
print \*, prefix, ": unacceptable pull:", real (pull)  
else  
print \*, prefix, ": acceptable pull:", real (pull)  
end if  
end subroutine print\_results

### *Main Program*

- 200c *<vamp\_test.f90 192a>+≡ <192a*  
program vamp\_test  
use kinds  
use tao\_random\_numbers

```

use coordinates
use divisions, only: DIVISIONS_RCS_ID
use vamp
use vamp_test_functions !NODEP!
use vamp_tests !NODEP!
implicit none
integer :: start_ticks, status
integer, dimension(2) :: iterations, samples
real(kind=default), dimension(2,5) :: region
real(kind=default), dimension(5) :: weight_vector
real(kind=default), dimension(10) :: powers
real(kind=default) :: single_integral, single_standard_dev, single_chi_squared
real(kind=default) :: multi_integral, multi_standard_dev, multi_chi_squared
type(tao_random_state) :: rng
real(kind=default), parameter :: ACCEPTABLE = 4
integer :: failures
failures = 0
call tao_random_create (rng, 0)
call get_environment_variable (name="VAMP_RANDOM_TESTS", status=status)
if (status == 0) then
    call system_clock (start_ticks)
else
    start_ticks = 42
end if
call tao_random_seed (rng, start_ticks)
iterations = (/ 4, 3 /)
samples = (/ 20000, 200000 /)
region(1,:) = -1.0
region(2,:) = 1.0
width = 0.0001
print *, "Starting VAMP 1.0 self test..."
print *, "serial code"
print *, VAMP_RCS_ID
print *, DIVISIONS_RCS_ID
call system_clock (start_ticks)
call single_channel (rng, region, samples, iterations, &
    single_integral, single_standard_dev, single_chi_squared)
call print_results ("SINGLE", start_ticks, &
    single_integral, single_standard_dev, single_chi_squared, &
    10*ACCEPTABLE, failures)
weight_vector = 1
powers = 0.25_default
call system_clock (start_ticks)

```

```

call multi_channel (rng, region, weight_vector, samples, iterations, &
    powers, multi_integral, multi_standard_dev, multi_chi_squared)
call print_results ("MULTI", start_ticks, &
    multi_integral, multi_standard_dev, multi_chi_squared, &
    ACCEPTABLE, failures)
call system_clock (start_ticks)
! call check_jacobians (rng, region, weight_vector, samples(1))
call check_inverses (rng, region, weight_vector, samples(1))
call check_inverses3 (rng, region, samples(1))
if (failures == 0) then
    stop 0
else if (failures == 1) then
    stop 1
else
    stop 2
end if
end program vamp_test

```

### 6.1.2 Parallel Test

202a  $\langle$ vampi\_test.f90 202a $\rangle \equiv$  202b  $\triangleright$

```

! vampi_test.f90 --
<Copyleft notice 1>
<Module vamp_test_functions 192b>

```

The following is identical to **vamp\_tests**, except for use **vampi**:

202b  $\langle$ vampi\_test.f90 202a $\rangle + \equiv$   $\triangleleft$ 202a 202c $\triangleright$

```

module vampi_tests
    use kinds
    use exceptions
    use histograms
    use tao_random_numbers
    use coordinates
    use vampi
    use vamp_test_functions !NODEP!
    implicit none
    private
    <Declaration of procedures in vamp_tests 196c>
contains
    <Implementation of procedures in vamp_tests 197a>
end module vampi_tests

```

202c  $\langle$ vampi\_test.f90 202a $\rangle + \equiv$   $\triangleleft$ 202b

```

program vampi_test

```

```

use kinds
use tao_random_numbers
use coordinates
use divisions, only: DIVISIONS_RCS_ID
use vamp, only: VAMP_RCS_ID
use vampi
use mpi90
use vamp_test_functions !NODEP!
use vampi_tests !NODEP!
implicit none
integer :: num_proc, proc_id, start_ticks
logical :: perform_io
integer, dimension(2) :: iterations, samples
real(kind=default), dimension(2,5) :: region
real(kind=default), dimension(5) :: weight_vector
real(kind=default), dimension(10) :: powers
real(kind=default) :: single_integral, single_standard_dev, single_chi_squared
real(kind=default) :: multi_integral, multi_standard_dev, multi_chi_squared
type( tao_random_state ) :: rng
integer :: iostat, command
character(len=72) :: command_line
integer, parameter :: &
    CMD_ERROR = -1, CMD_END = 0, &
    CMD_NOP = 1, CMD_SINGLE = 2, CMD_MULTI = 3, CMD_CHECK = 4
call tao_random_create (rng, 0)
call mpi90_init ()
call mpi90_size (num_proc)
call mpi90_rank (proc_id)
perform_io = (proc_id == 0)
call system_clock (start_ticks)
call tao_random_seed (rng, start_ticks + proc_id)
iterations = (/ 4, 3 /)
samples = (/ 20000, 200000 /)
samples = (/ 200000, 2000000 /)
region(1,:) = -1.0
region(2,:) = 1.0
width = 0.0001
if (perform_io) then
    print *, "Starting VAMP 1.0 self test..."
    if (num_proc > 1) then
        print *, "parallel code running on ", num_proc, " processors"
    else
        print *, "parallel code running serially"
    end if
end if

```

```

        end if
        print *, VAMP_RCS_ID
        print *, VAMPI_RCS_ID
        print *, DIVISIONS_RCS_ID
    end if
    command_loop: do
        <Parse the commandline in vamp_test and set command (never defined)>
        call mpi90_broadcast (command, 0)
        call system_clock (start_ticks)
        select case (command)
        <Execute command in vamp_test (never defined)>
        case (CMD_END)
            exit command_loop
        case (CMD_NOP)
            ! do nothing
        case (CMD_ERROR)
            ! do nothing
        end select
    end do command_loop
    call mpi90_finalize ()
end program vampi_test

```

### 6.1.3 Output

204a *<vamp\_test.out 204a>*≡

## 6.2 Mapped Mode

In this chapter we perform a test of the major features of Vamp. A function with many peaks is integrated with the traditional Vegas algorithm, using a multi-channel approach and in parallel. The function is constructed to have a known analytical integral (which is chosen to be one) in order to be able to gauge the accuracy of the result and error estimate.

### 6.2.1 Serial Test

204b *<vamp\_test0.f90 204b>*≡ 211a>  
 ! vamp\_test0.f90 --  
*<Copyright notice 1>*  
*<Module vamp\_test0\_functions 205>*

### Single Channel

The functions to be integrated are shared by the serial and the parallel incarnation of the code.

```

205  <Module vamp_test0_functions 205>≡ (204b 220b)
      module vamp_test0_functions
        use kinds
        use vamp, only: vamp_grid, vamp_multi_channel0
        use vamp, only: vamp_data_t
        implicit none
        private
        public :: f, g, phi, w
        public :: create_sample, delete_sample
        private :: f0, psi, g0, f_norm
        real(kind=default), dimension(:), allocatable, private :: c, x_min, x_max
        real(kind=default), dimension(:, :, :), allocatable, public :: x0, gamma
        contains
        <Implementation of vamp_test0_functions procedures 206a>
      end module vamp_test0_functions

```

We start from a model of  $n_p$  interfering resonances in one variable (cf. section ??)

$$f_0(x|x_{\min}, x_{\max}, x_0, \gamma) = \frac{1}{N(x_{\min}, x_{\max}, x_0, \gamma)} \left| \sum_{p=1}^{n_p} \frac{1}{x - x_{0,p} + i\gamma_p} \right|^2 \quad (6.3)$$

where

$$N(x_{\min}, x_{\max}, x_0, \gamma) = \int_{x_{\min}}^{x_{\max}} dx \left| \sum_{p=1}^{n_p} \frac{1}{x - x_{0,p} + i\gamma_p} \right|^2 \quad (6.4)$$

such that

$$\int_{x_{\min}}^{x_{\max}} dx f_0(x|x_{\min}, x_{\max}, x_0, \gamma) = 1 \quad (6.5)$$

NB: the  $N(x_{\min}, x_{\max}, x_0, \gamma)$  should be calculated once and tabulated to save processing time, but we are lazy here.

$$\begin{aligned}
N(x_{\min}, x_{\max}, x_0, \gamma) &= \sum_{p=1}^{n_p} \int_{x_{\min}}^{x_{\max}} dx \left| \frac{1}{x - x_{0,p} + i\gamma_p} \right|^2 \\
&+ 2 \operatorname{Re} \sum_{p=1}^{n_p} \sum_{q=1}^{n_p} \int_{x_{\min}}^{x_{\max}} dx \frac{1}{x - x_{0,p} + i\gamma_p} \frac{1}{x - x_{0,q} - i\gamma_q} \quad (6.6)
\end{aligned}$$

206a  $\langle$ Implementation of vamp\_test0\_functions procedures 206a $\rangle \equiv$  (205) 206b $\triangleright$

```

pure function f0 (x, x_min, x_max, x0, g) result (f_x)
  real(kind=default), intent(in) :: x, x_min, x_max
  real(kind=default), dimension(:), intent(in) :: x0, g
  real(kind=default) :: f_x
  complex(kind=default) :: amp
  real(kind=default) :: norm
  integer :: i, j
  amp = sum (1.0 / cmplx (x - x0, g, kind=default))
  norm = 0
  do i = 1, size (x0)
    norm = norm + f_norm (x_min, x_max, x0(i), g(i), x0(i), g(i))
    do j = i + 1, size (x0)
      norm = norm + 2 * f_norm (x_min, x_max, x0(i), g(i), x0(j), g(j))
    end do
  end do
  f_x = amp * conjg (amp) / norm
end function f0

```

$$\int_{x_{\min}}^{x_{\max}} dx \frac{1}{x - x_{0,p} + i\gamma_p} \frac{1}{x - x_{0,q} - i\gamma_q} = \frac{1}{x_{0,p} - x_{0,q} - i\gamma_p - i\gamma_q} \left( \ln \left( \frac{x_{\max} - x_{0,p} + i\gamma_p}{x_{\min} - x_{0,p} + i\gamma_p} \right) - \ln \left( \frac{x_{\max} - x_{0,q} - i\gamma_q}{x_{\min} - x_{0,q} - i\gamma_q} \right) \right) \quad (6.7)$$

Don't even think of merging the logarithms: it will screw up the Riemann sheet.

206b  $\langle$ Implementation of vamp\_test0\_functions procedures 206a $\rangle + \equiv$  (205)  $\triangleleft$ 206a 207a $\triangleright$

```

pure function f_norm (x_min, x_max, x0p, gp, x0q, gq) &
  result (norm)
  real(kind=default), intent(in) :: x_min, x_max, x0p, gp, x0q, gq
  real(kind=default) :: norm
  norm = real (( log ( cmplx (x_max - x0p, gp, kind=default) &
    / cmplx (x_min - x0p, gp, kind=default)) &
    - log ( cmplx (x_max - x0q, - gq, kind=default) &
    / cmplx (x_min - x0q, - gq, kind=default))) &
    / cmplx (x0p - x0q, - gp - gq, kind=default), &
    kind=default)
end function f_norm

```

Since we want to be able to do the integral of  $f$  analytically, it is most

convenient to take a weighted sum of products:

$$f(x_1, \dots, x_{n_d} | x_{\min}, x_{\max}, x_0, \gamma) = \frac{1}{\sum_{i=1}^{n_c} c_i} \sum_{i=1}^{n_c} c_i \prod_{j=1}^{n_d} f_0(x_j | x_{\min,j}, x_{\max,j}, x_{0,ij}, \gamma_{ij}) \quad (6.8)$$

Each summand is factorized and therefore very easily integrated by Vegas. A non-trivial sum is more realistic in this respect.

207a  $\langle$ Implementation of `vamp_test0.functions` procedures 206a $\rangle + \equiv$  (205)  $\langle$ 206b 207b $\rangle$

```
pure function f (x, data, weights, channel, grids) result (f_x)
  real(kind=default), dimension(:), intent(in) :: x
  class(vamp_data_t), intent(in) :: data
  real(kind=default), dimension(:), intent(in), optional :: weights
  integer, intent(in), optional :: channel
  type(vamp_grid), dimension(:), intent(in), optional :: grids
  real(kind=default) :: f_x
  real(kind=default) :: fi_x
  integer :: i, j
  f_x = 0.0
  do i = 1, size (c)
    fi_x = 1.0
    do j = 1, size (x)
      if (all (gamma(:,i,j) > 0)) then
        fi_x = fi_x * f0 (x(j), x_min(j), x_max(j), &
                        x0(:,i,j), gamma(:,i,j))
      else
        fi_x = fi_x / (x_max(j) - x_min(j))
      end if
    end do
    f_x = f_x + c(i) * fi_x
  end do
  f_x = f_x / sum (c)
end function f
```

207b  $\langle$ Implementation of `vamp_test0.functions` procedures 206a $\rangle + \equiv$  (205)  $\langle$ 207a 207c $\rangle$

```
subroutine delete_sample ()
  deallocate (c, x_min, x_max, x0, gamma)
end subroutine delete_sample
```

207c  $\langle$ Implementation of `vamp_test0.functions` procedures 206a $\rangle + \equiv$  (205)  $\langle$ 207b 208 $\rangle$

```
subroutine create_sample (num_poles, weights, region)
  integer, intent(in) :: num_poles
  real(kind=default), dimension(:), intent(in) :: weights
```



```

real(kind=default), dimension(:,,:), intent(in) :: region
integer :: nd, nc
nd = size (region, dim=2)
nc = size (weights)
allocate (c(nc), x_min(nd), x_max(nd))
allocate (x0(num_poles,nc,nd), gamma(num_poles,nc,nd))
x_min = region(1,:)
x_max = region(2,:)
c = weights
end subroutine create_sample

```

### Multi Channel

We start from the usual mapping for Lorentzian peaks

$$\begin{aligned} \psi(x_{\min}, x_{\max}, x_0, \gamma) : [x_{\min}, x_{\max}] &\rightarrow [x_{\min}, x_{\max}] \\ \xi \mapsto x = \psi(\xi|x_{\min}, x_{\max}, x_0, \gamma) \end{aligned} \quad (6.9)$$

where

$$\begin{aligned} \psi(\xi|x_{\min}, x_{\max}, x_0, \gamma) = x_0 + \\ \gamma \cdot \tan \left( \frac{\xi - x_{\min}}{x_{\max} - x_{\min}} \cdot \operatorname{atan} \frac{x_{\max} - x_0}{\gamma} - \frac{x_{\max} - \xi}{x_{\max} - x_{\min}} \cdot \operatorname{atan} \frac{x_0 - x_{\min}}{\gamma} \right) \end{aligned} \quad (6.10)$$

208  $\langle$ Implementation of `vamp_test0` functions procedures 206a $\rangle + \equiv$  (205)  $\triangleleft$ 207c 209a $\triangleright$

```

pure function psi (xi, x_min, x_max, x0, gamma) result (x)
  real(kind=default), intent(in) :: xi, x_min, x_max, x0, gamma
  real(kind=default) :: x
  x = x0 + gamma &
    * tan (((xi - x_min) * atan ((x_max - x0) / gamma) &
      - (x_max - xi) * atan ((x0 - x_min) / gamma)) &
      / (x_max - x_min))
end function psi

```

The inverse mapping is

$$\begin{aligned} \psi^{-1}(x_{\min}, x_{\max}, x_0, \gamma) : [x_{\min}, x_{\max}] &\rightarrow [x_{\min}, x_{\max}] \\ x \mapsto \xi = \psi^{-1}(x|x_{\min}, x_{\max}, x_0, \gamma) \end{aligned} \quad (6.11)$$

with

$$\begin{aligned} \psi^{-1}(x|x_{\min}, x_{\max}, x_0, \gamma) = \\ \frac{x_{\max}(\operatorname{atan} \frac{x_0 - x_{\min}}{\gamma} + \operatorname{atan} \frac{x - x_0}{\gamma}) + x_{\min}(\operatorname{atan} \frac{x_{\max} - x_0}{\gamma} + \operatorname{atan} \frac{x_0 - x}{\gamma})}{\operatorname{atan} \frac{x_{\max} - x_0}{\gamma} + \operatorname{atan} \frac{x_0 - x_{\min}}{\gamma}} \end{aligned} \quad (6.12)$$

with Jacobian

$$\frac{d(\psi^{-1}(x|x_{\min}, x_{\max}, x_0, \gamma))}{dx} = \frac{x_{\max} - x_{\min}}{\operatorname{atan} \frac{x_{\max} - x_0}{\gamma} + \operatorname{atan} \frac{x_0 - x_{\min}}{\gamma}} \frac{\gamma}{(x - x_0)^2 + \gamma^2} \quad (6.13)$$

209a *<Implementation of vamp\_test0\_functions procedures 206a>+≡ (205) <208 209c>*  

```

pure function g0 (x, x_min, x_max, x0, gamma) result (g_x)
  real(kind=default), intent(in) :: x, x_min, x_max, x0, gamma
  real(kind=default) :: g_x
  g_x = gamma / (atan ((x_max - x0) / gamma) - atan ((x_min - x0) / gamma)) &
    * (x_max - x_min) / ((x - x0)**2 + gamma**2)
end function g0

```

The function  $f$  has  $n_c n_p^{n_d}$  peaks and we need a channel for each one, plus a constant function for the background. We encode the position on the grid linearly:

209b *<Decode channel into ch and p(:) 209b>≡ (209c 210a)*  

```

ch = channel - 1
do j = 1, size (x)
  p(j) = 1 + modulo (ch, np)
  ch = ch / np
end do
ch = ch + 1

```

The map  $\phi$  is the direct product of  $\psi$ s:

209c *<Implementation of vamp\_test0\_functions procedures 206a>+≡ (205) <209a 210a>*  

```

pure function phi (xi, channel) result (x)
  real(kind=default), dimension(:), intent(in) :: xi
  integer, intent(in) :: channel
  real(kind=default), dimension(size(xi)) :: x
  integer, dimension(size(xi)) :: p
  integer :: j, ch, np, nch, nd, channels
  np = size (x0, dim = 1)
  nch = size (x0, dim = 2)
  nd = size (x0, dim = 3)
  channels = nch * np**nd
  if (channel >= 1 .and. channel <= channels) then
    <Decode channel into ch and p(:) 209b>
    do j = 1, size (xi)
      if (all (gamma(:,ch,j) > 0)) then
        x(j) = psi (xi(j), x_min(j), x_max(j), &
          x0(p(j),ch,j), gamma(p(j),ch,j))
      else
        x = xi

```

```

        end if
    end do
    else if (channel == channels + 1) then
        x = xi
    else
        x = 0
    end if
end function phi

```

similarly for the Jacobians:

210a  $\langle$ Implementation of `vamp_test0.functions.procedures 206a` $\rangle + \equiv$  (205)  $\triangleleft$ 209c 210b $\triangleright$

```

pure recursive function g (x, data, channel) result (g_x)
    real(kind=default), dimension(:), intent(in) :: x
    class(vamp_data_t), intent(in) :: data
    integer, intent(in) :: channel
    real(kind=default) :: g_x
    integer, dimension(size(x)) :: p
    integer :: j, ch, np, nch, nd, channels
    np = size (x0, dim = 1)
    nch = size (x0, dim = 2)
    nd = size (x0, dim = 3)
    channels = nch * np**nd
    if (channel >= 1 .and. channel <= channels) then
         $\langle$ Decode channel into ch and p(:) 209b $\rangle$ 
        g_x = 1.0
        do j = 1, size (x)
            if (all (gamma(:,ch,j) > 0)) then
                g_x = g_x * g0 (x(j), x_min(j), x_max(j), &
                    x0(p(j),ch,j), gamma(p(j),ch,j))
            end if
        end do
    else if (channel == channels + 1) then
        g_x = 1.0
    else
        g_x = 0
    end if
end function g

```

210b  $\langle$ Implementation of `vamp_test0.functions.procedures 206a` $\rangle + \equiv$  (205)  $\triangleleft$ 210a

```

function w (x, data, weights, channel, grids) result (w_x)
    real(kind=default), dimension(:), intent(in) :: x
    class(vamp_data_t), intent(in) :: data
    real(kind=default), dimension(:), intent(in), optional :: weights
    integer, intent(in), optional :: channel

```

```

    type(vamp_grid), dimension(:), intent(in), optional :: grids
    real(kind=default) :: w_x
    w_x = vamp_multi_channel0 (f, data, phi, g, x, weights, channel)
end function w

```

### Driver Routines

```

211a <vamp_test0.f90 204b>+≡ <204b 217>
    module vamp_tests0
        <Modules used by vamp_tests0 211b>
        use vamp
        implicit none
        private
        <Declaration of procedures in vamp_tests0 212a>
    contains
        <Implementation of procedures in vamp_tests0 212b>
    end module vamp_tests0

211b <Modules used by vamp_tests0 211b>≡ (211a 220b)
    use kinds
    use exceptions
    use histograms
    use tao_random_numbers
    use vamp_test0_functions !NODEP!

```

### Verification

```

211c <Declaration of procedures in vamp_tests0 (broken?) 211c>≡
    public :: check_jacobians

211d <Implementation of procedures in vamp_tests0 (broken?) 211d>≡
    subroutine check_jacobians (do_print, region, samples, rng)
        logical, intent(in) :: do_print
        real(kind=default), dimension(:,:), intent(in) :: region
        integer, dimension(:), intent(in) :: samples
        type( tao_random_state ), intent(inout) :: rng
        real(kind=default), dimension(size(region,dim=2)) :: x
        real(kind=default) :: d
        integer :: ch
        do ch = 1, size(x0,dim=2) * size(x0,dim=1)**size(x0,dim=3) + 1
            call vamp_check_jacobian (rng, samples(1), g, phi, ch, region, d, x)
            if (do_print) then
                print *, ch, ": ", d, ", x = ", real (x)
            end if
        end do
    end subroutine

```

```

    end do
end subroutine check_jacobians

```

### Integration

```

212a <Declaration of procedures in vamp_tests0 212a>≡ (211a 220b) 214a>
    public :: single_channel, multi_channel

212b <Implementation of procedures in vamp_tests0 212b>≡ (211a 220b) 213a>
    subroutine single_channel (do_print, region, iterations, samples, rng, &
        acceptable, failures)
        logical, intent(in) :: do_print
        real(kind=default), dimension(:,:), intent(in) :: region
        integer, dimension(:), intent(in) :: iterations, samples
        type(tao_random_state), intent(inout) :: rng
        real(kind=default), intent(in) :: acceptable
        integer, intent(inout) :: failures
        type(vamp_grid) :: gr
        type(vamp_history), dimension(iterations(1)+iterations(2)) :: history
        real(kind=default) :: integral, standard_dev, chi_squared, pull
        call vamp_create_history (history)
        call vamp_create_grid (gr, region, samples(1))
        call vamp_sample_grid (rng, gr, f, NO_DATA, iterations(1), history = history)
        call vamp_discard_integral (gr, samples(2))
        call vamp_sample_grid &
            (rng, gr, f, NO_DATA, iterations(2), &
             integral, standard_dev, chi_squared, &
             history = history(iterations(1)+1:))
        call vamp_write_grid (gr, "vamp_test0.grid")
        call vamp_delete_grid (gr)
        call vamp_print_history (history, "single")
        call vamp_delete_history (history)
        pull = (integral - 1) / standard_dev
        if (do_print) then
            print *, "    int, err, chi2:", integral, standard_dev, chi_squared
        end if
        if (abs (pull) > acceptable) then
            failures = failures + 1
            print *, " unacceptable pull:", pull
        else
            print *, "    acceptable pull:", pull
        end if
    end subroutine single_channel

```

213a *<Implementation of procedures in vamp\_tests0 212b>+≡ (211a 220b) <212b 214b>*  
`subroutine multi_channel (do_print, region, iterations, samples, rng, &  
acceptable, failures)  
logical, intent(in) :: do_print  
real(kind=default), dimension(:,:), intent(in) :: region  
integer, dimension(:), intent(in) :: iterations, samples  
type(tao_random_state), intent(inout) :: rng  
real(kind=default), intent(in) :: acceptable  
type(vamp_grids) :: grs  
integer, intent(inout) :: failures  
<Body of multi_channel 199b>  
end subroutine multi_channel`

213b *<Body of multi\_channel 199b>+≡ (199a 213a) <199b*  
`real(kind=default), &  
dimension(size(x0,dim=2)*size(x0,dim=1)**size(x0,dim=3)+1) :: &  
weight_vector  
type(vamp_history), dimension(iterations(1)+iterations(2)+4) :: history  
type(vamp_history), dimension(size(history),size(weight_vector)) :: histories  
real(kind=default) :: integral, standard_dev, chi_squared, pull  
integer :: it  
weight_vector = 1.0  
call vamp_create_history (history)  
call vamp_create_history (histories)  
call vamp_create_grids (grs, region, samples(1), weight_vector)  
call vamp_sample_grids (rng, grs, w, NO_DATA, iterations(1) - 1, &  
history = history, histories = histories)  
do it = 1, 5  
call vamp_sample_grids (rng, grs, w, NO_DATA, 1, &  
history = history(iterations(1)+it-1:), &  
histories = histories(iterations(1)+it-1:,:))  
call vamp_refine_weights (grs)  
end do  
call vamp_discard_integrals (grs, samples(2))  
call vamp_sample_grids &  
(rng, grs, w, NO_DATA, iterations(2), &  
integral, standard_dev, chi_squared, &  
history = history(iterations(1)+5:), &  
histories = histories(iterations(1)+5:,:))  
call vamp_write_grids (grs, "vamp_test0.grids")  
call vamp_delete_grids (grs)  
call vamp_print_history (history, "multi")  
call vamp_print_history (histories, "multi")  
call vamp_delete_history (history)`

```

call vamp_delete_history (histories)
if (do_print) then
  print *, integral, standard_dev, chi_squared
end if
pull = (integral - 1) / standard_dev
if (abs (pull) > acceptable) then
  failures = failures + 1
  print *, " unacceptable pull:", pull
else
  print *, "   acceptable pull:", pull
end if

```

### Event Generation

214a *<Declaration of procedures in vamp\_tests0 212a>+≡ (211a 220b) <212a*  
 public :: single\_channel\_generator, multi\_channel\_generator

214b *<Implementation of procedures in vamp\_tests0 212b>+≡ (211a 220b) <213a 215>*  
 subroutine single\_channel\_generator (do\_print, region, iterations, samples, rng)  
 logical, intent(in) :: do\_print  
 real(kind=default), dimension(:,:), intent(in) :: region  
 integer, dimension(:), intent(in) :: iterations, samples  
 type(tao\_random\_state), intent(inout) :: rng  
 type(vamp\_grid) :: gr  
 type(vamp\_history), dimension(iterations(1)+iterations(2)) :: history  
 type(histogram) :: unweighted, reweighted, weighted, weights  
 type(exception) :: exc  
 real(kind=default) :: weight, integral, standard\_dev  
 integer :: i  
 real(kind=default), dimension(size(region,dim=2)) :: x  
 call vamp\_create\_grid (gr, region, samples(1))  
 call vamp\_sample\_grid (rng, gr, f, NO\_DATA, iterations(1), history = history)  
 call vamp\_discard\_integral (gr, samples(2))  
 call vamp\_warmup\_grid &  
 (rng, gr, f, NO\_DATA, iterations(2), history = history(iterations(1)+1:))  
 call vamp\_print\_history (history, "single")  
 call vamp\_delete\_history (history)  
 call create\_histogram (unweighted, region(1,1), region(2,1), 100)  
 call create\_histogram (reweighted, region(1,1), region(2,1), 100)  
 call create\_histogram (weighted, region(1,1), region(2,1), 100)  
 call create\_histogram (weights, 0.0\_default, 10.0\_default, 100)  
 ! do i = 1, 1000000  
 do i = 1, 100  
 call clear\_exception (exc)

```

    call vamp_next_event (x, rng, gr, f, NO_DATA, exc = exc)
    call handle_exception (exc)
    call fill_histogram (unweighted, x(1))
    call fill_histogram (reweighted, x(1), 1.0_default / f (x, NO_DATA))
end do
integral = 0.0
standard_dev = 0.0
do i = 1, 10000
    call clear_exception (exc)
    call vamp_next_event (x, rng, gr, f, NO_DATA, weight, exc = exc)
    call handle_exception (exc)
    call fill_histogram (weighted, x(1), weight / f (x, NO_DATA))
    call fill_histogram (weights, x(1), weight)
    integral = integral + weight
    standard_dev = standard_dev + weight**2
end do
if (do_print) then
    print *, integral / (i-1), sqrt (standard_dev) / (i-1)
    call write_histogram (unweighted, "u_s.d")
    call write_histogram (reweighted, "r_s.d")
    call write_histogram (weighted, "w_s.d")
    call write_histogram (weights, "ws_s.d")
end if
call delete_histogram (unweighted)
call delete_histogram (reweighted)
call delete_histogram (weighted)
call delete_histogram (weights)
call vamp_delete_grid (gr)
end subroutine single_channel_generator

```

215 *<Implementation of procedures in vamp\_tests0 212b>+≡ (211a 220b) <214b*

```

subroutine multi_channel_generator (do_print, region, iterations, samples, rng)
    logical, intent(in) :: do_print
    real(kind=default), dimension(:,:), intent(in) :: region
    integer, dimension(:), intent(in) :: iterations, samples
    type(tao_random_state), intent(inout) :: rng
    type(vamp_grids) :: grs
    real(kind=default), &
        dimension(size(x0,dim=2)*size(x0,dim=1)**size(x0,dim=3)+1) :: &
        weight_vector
    type(vamp_history), dimension(iterations(1)+iterations(2)+4) :: history
    type(vamp_history), dimension(size(history),size(weight_vector)) :: histories
    type(histogram) :: unweighted, reweighted, weighted, weights
    type(exception) :: exc

```



```

real(kind=default) :: weight, integral, standard_dev
real(kind=default), dimension(size(region,dim=2)) :: x
character(len=5) :: pfx
integer :: it, i, j
weight_vector = 1.0
call vamp_create_history (history)
call vamp_create_history (histories)
call vamp_create_grids (grs, region, samples(1), weight_vector)
call vamp_sample_grids (rng, grs, w, NO_DATA, iterations(1) - 1, &
                        history = history, histories = histories)
do it = 1, 5
    call vamp_sample_grids (rng, grs, w, NO_DATA, 1, &
                            history = history(iterations(1)+it-1:), &
                            histories = histories(iterations(1)+it-1:,:))
    call vamp_refine_weights (grs)
end do
call vamp_discard_integrals (grs, samples(2))
call vamp_warmup_grids &
    (rng, grs, w, NO_DATA, iterations(2), &
     history = history(iterations(1)+5:), &
     histories = histories(iterations(1)+5:,:))
call vamp_print_history (history, "multi")
call vamp_print_history (histories, "multi")
call vamp_delete_history (history)
call vamp_delete_history (histories)
!!! do i = 1, size (grs%grids)
!!!     do j = 1, size (grs%grids(i)%div)
!!!         write (pfx, "(I2.2,'/',I2.2)") i, j
!!!         call dump_division (grs%grids(i)%div(j), pfx)
!!!     end do
!!! end do
call create_histogram (unweighted, region(1,1), region(2,1), 100)
call create_histogram (reweighted, region(1,1), region(2,1), 100)
call create_histogram (weighted, region(1,1), region(2,1), 100)
call create_histogram (weights, 0.0_default, 10.0_default, 100)
! do i = 1, 1000000
do i = 1, 100
    call clear_exception (exc)
    call vamp_next_event (x, rng, grs, f, NO_DATA, phi, exc = exc)
    call handle_exception (exc)
    call fill_histogram (unweighted, x(1))
    call fill_histogram (reweighted, x(1), 1.0_default / f (x, NO_DATA))
end do

```

```

integral = 0.0
standard_dev = 0.0
do i = 1, 10000
  call clear_exception (exc)
  call vamp_next_event (x, rng, grs, f, NO_DATA, phi, weight, exc = exc)
  call handle_exception (exc)
  call fill_histogram (weighted, x(1), weight / f (x, NO_DATA))
  call fill_histogram (weights, x(1), weight)
  integral = integral + weight
  standard_dev = standard_dev + weight**2
end do
if (do_print) then
  print *, integral / (i-1), sqrt (standard_dev) / (i-1)
  call write_histogram (unweighted, "u_m.d")
  call write_histogram (reweighted, "r_m.d")
  call write_histogram (weighted, "w_m.d")
  call write_histogram (weights, "ws_m.d")
end if
call delete_histogram (unweighted)
call delete_histogram (reweighted)
call delete_histogram (weighted)
call delete_histogram (weights)
call vamp_delete_grids (grs)
end subroutine multi_channel_generator

```

### *Main Program*

```

217  <vamp_test0.f90 204b>+≡ <211a
  program vamp_test0
    <Modules used by vamp_test0 219d>
    implicit none
    <Variables in vamp_test0 219b>
    do_print = .true.
    print *, "Starting VAMP 1.0 self test..."
    print *, "serial code"
    print *, VAMP_RCS_ID
    print *, DIVISIONS_RCS_ID
    call tao_random_create (rng, 0)
    call get_environment_variable (name="VAMP_RANDOM_TESTS", status=status)
    if (status == 0) then
      call system_clock (ticks0)
    else
      ticks0 = 42
    end if
  end program

```

```

end if
call tao_random_seed (rng, ticks0)
<Set up integrand and region in vamp_test0 219f>
<Execute tests in vamp_test0 218a>
<Cleanup in vamp_test0 220a>
if (failures == 0) then
    stop 0
else if (failures == 1) then
    stop 1
else
    stop 2
end if
end program vamp_test0

218a <Execute tests in vamp_test0 218a>≡ (217) 218b>
failures = 0
call system_clock (ticks0)
call single_channel (do_print, region, iterations, samples, rng, 10*ACCEPTABLE, failures)
call system_clock (ticks, ticks_per_second)
print "(1X,A,F6.2,A)", &
    "time = ", real (ticks - ticks0) / ticks_per_second, " secs"

218b <Execute tests in vamp_test0 218a>+≡ (217) <218a 218c>
call system_clock (ticks0)
call single_channel_generator &
    (do_print, region, iterations, samples, rng)
call system_clock (ticks, ticks_per_second)
print "(1X,A,F6.2,A)", &
    "time = ", real (ticks - ticks0) / ticks_per_second, " secs"

218c <Execute tests in vamp_test0 218a>+≡ (217) <218b 218d>
call system_clock (ticks0)
call multi_channel (do_print, region, iterations, samples, rng, ACCEPTABLE, failures)
call system_clock (ticks, ticks_per_second)
print "(1X,A,F6.2,A)", &
    "time = ", real (ticks - ticks0) / ticks_per_second, " secs"

218d <Execute tests in vamp_test0 218a>+≡ (217) <218c 219a>
call system_clock (ticks0)
call multi_channel_generator &
    (do_print, region, iterations, samples, rng)
call system_clock (ticks, ticks_per_second)
print "(1X,A,F6.2,A)", &
    "time = ", real (ticks - ticks0) / ticks_per_second, " secs"

```

```

219a <Execute tests in vamp_test0 218a>+≡ (217) <218d
      call system_clock (ticks0)
      ! call check_jacobians (do_print, region, samples, rng)
      call system_clock (ticks, ticks_per_second)
      print "(1X,A,F6.2,A)", &
            "time = ", real (ticks - ticks0) / ticks_per_second, " secs"

219b <Variables in vamp_test0 219b>≡ (217 220c) 219e>
      logical :: do_print

219c <Execute command 219c>≡ (220c)

219d <Modules used by vamp_test0 219d>≡ (217 220c)
      use kinds
      use tao_random_numbers
      use divisions, only: DIVISIONS_RCS_ID
      use vamp, only: VAMP_RCS_ID
      use vamp_test0_functions !NODEP!
      use vamp_tests0 !NODEP!

219e <Variables in vamp_test0 219b>+≡ (217 220c) <219b
      integer :: i, j, ticks, ticks_per_second, ticks0, status
      integer, dimension(2) :: iterations, samples
      real(kind=default), dimension(:,,:), allocatable :: region
      type(tao_random_state) :: rng
      real(kind=default), parameter :: ACCEPTABLE = 4
      integer :: failures

219f <Set up integrand and region in vamp_test0 219f>≡ (217 220c)
      iterations = (/ 4, 3 /)
      samples = (/ 10000, 50000 /)
      allocate (region(2,2))
      region(1,:) = -1.0
      region(2,:) = 2.0
      call create_sample &
            (num_poles = 2, weights = (/ 1.0_default, 2.0_default /), region = region)
      do i = 1, size (x0, dim=2)
        do j = 1, size (x0, dim=3)
          call tao_random_number (rng, x0(:,i,j))
        end do
      end do
      gamma = 0.001
      x0(1, :, :) = 0.2
      x0(2, :, :) = 0.8

```

220a *<Cleanup in vamp\_test0 220a>*≡ (217 220c)  
 call delete\_sample ()  
 deallocate (region)

## 6.2.2 Parallel Test

220b *<vampi\_test0.f90 220b>*≡ 220c>  
 ! vampi\_test0.f90 --  
*<Copyleft notice 1>*  
*<Module vamp\_test0\_functions 205>*  
 module vamp\_tests0  
*<Modules used by vamp\_tests0 211b>*  
 use vampi  
 use mpi90  
 implicit none  
 private  
*<Declaration of procedures in vamp\_tests0 212a>*  
 contains  
*<Implementation of procedures in vamp\_tests0 212b>*  
 end module vamp\_tests0

220c *<vampi\_test0.f90 220b>*+≡ <220b  
 program vampi\_test0  
*<Modules used by vamp\_test0 219d>*  
 use mpi90  
 use vampi, only: VAMPI\_RCS\_ID  
 implicit none  
*<Variables in vamp\_test0 219b>*  
 integer :: num\_proc, proc\_id  
 call mpi90\_init ()  
 call mpi90\_size (num\_proc)  
 call mpi90\_rank (proc\_id)  
 if (proc\_id == 0) then  
 do\_print = .true.  
 print \*, "Starting VAMP 1.0 self test..."  
 if (num\_proc > 1) then  
 print \*, "parallel code running on ", num\_proc, " processors"  
 else  
 print \*, "parallel code running serially"  
 end if  
 print \*, VAMP\_RCS\_ID  
 print \*, VAMPI\_RCS\_ID  
 print \*, DIVISIONS\_RCS\_ID

```

else
    do_print = .false.
end if
call tao_random_create (rng, 0)
call system_clock (ticks0)
call tao_random_seed (rng, ticks0 + proc_id)
<Set up integrand and region in vamp_test0 219f>
call mpi90_broadcast (x0, 0)
call mpi90_broadcast (gamma, 0)
command_loop: do
    if (proc_id == 0) then
        <Read command line and decode it as command (never defined)>
    end if
    call mpi90_broadcast (command, 0)
    call system_clock (ticks0)
    <Execute command 219c>
    call system_clock (ticks, ticks_per_second)
    if (proc_id == 0) then
        print "(1X,A,F6.2,A)", &
            "time = ", real (ticks - ticks0) / ticks_per_second, " secs"
    end if
end do command_loop
<Cleanup in vamp_test0 220a>
call mpi90_finalize ()
if (proc_id == 0) then
    print *, "bye."
end if
end program vampi_test0

```

### 6.2.3 Output

221 *<vamp\_test0.out 221>*≡

# —7—

## APPLICATION

### 7.1 Cross section

```
222a <application.f90 222a>≡ 239▷
! application.f90 --
<Copyleft notice 1>
module cross_section
  use kinds
  use constants
  use utils
  use kinematics
  use tao_random_numbers
  use products, only: dot
  use helicity
  use vamp, only: vamp_grid, vamp_probability
  implicit none
  private
  <Declaration of cross_section procedures 223d>
  <Types in cross_section 228c>
  <Variables in cross_section 222b>
contains
  <Implementation of cross_section procedures 224a>
end module cross_section

222b <Variables in cross_section 222b>≡ (222a) 223c▷
  real(kind=default), private, parameter :: &
    MA_0 = 0.0, &
    MB_0 = 0.0, &
    M1_0 = 0.0, &
    M2_0 = 0.0, &
    M3_0 = 0.0, &
```

```
S_0 = 200.0 ** 2
```

223a  $\langle$ XXX Variables in cross\_section 223a $\rangle \equiv$  223b $\triangleright$

```
real(kind=default), private, parameter :: &
  MA_0 = 0.01, &
  MB_0 = 0.01, &
  M1_0 = 0.01, &
  M2_0 = 0.01, &
  M3_0 = 0.01, &
  S_0 = 200.0 ** 2
```

223b  $\langle$ XXX Variables in cross\_section 223a $\rangle + \equiv$   $\triangleleft$  223a

```
real(kind=default), private, parameter :: &
  S1_MIN_0 = 0.0 ** 2, &
  S2_MIN_0 = 0.0 ** 2, &
  S3_MIN_0 = 0.0 ** 2, &
  T1_MIN_0 = 0.0 ** 2, &
  T2_MIN_0 = 0.0 ** 2
```

223c  $\langle$ Variables in cross\_section 222b $\rangle + \equiv$  (222a)  $\triangleleft$  222b 223f $\triangleright$

```
real(kind=default), private, parameter :: &
  S1_MIN_0 = 1.0 ** 2, &
  S2_MIN_0 = 1.0 ** 2, &
  S3_MIN_0 = 1.0 ** 2, &
  T1_MIN_0 = 10.0 ** 2, &
  T2_MIN_0 = 10.0 ** 2
```

223d  $\langle$ Declaration of cross\_section procedures 223d $\rangle \equiv$  (222a) 225a $\triangleright$

```
private :: cuts
```

223e  $\langle$ XXX Implementation of cross\_section procedures 223e $\rangle \equiv$

```
pure function cuts (k1, k2, p1, p2, q) result (inside)
  real(kind=default), dimension(0:), intent(in) :: k1, k2, p1, p2, q
  logical :: inside
  inside = (abs (dot (k1 - q, k1 - q)) >= T1_MIN_0) &
    .and. (abs (dot (k2 - q, k2 - q)) >= T2_MIN_0) &
    .and. (abs (dot (p1 + q, p1 + q)) >= S1_MIN_0) &
    .and. (abs (dot (p2 + q, p2 + q)) >= S2_MIN_0) &
    .and. (abs (dot (p1 + p2, p1 + p2)) >= S3_MIN_0)
end function cuts
```

223f  $\langle$ Variables in cross\_section 222b $\rangle + \equiv$  (222a)  $\triangleleft$  223c

```
real(kind=default), private, parameter :: &
```



```

E_MIN = 1.0, &
COSTH_SEP_MAX = 0.99, &
COSTH_BEAM_MAX = 0.99

```

**224a** *⟨Implementation of cross\_section procedures 224a⟩*≡ (222a) 224b>

```

pure function cuts (k1, k2, p1, p2, q) result (inside)
  real(kind=default), dimension(0:), intent(in) :: k1, k2, p1, p2, q
  logical :: inside
  real(kind=default), dimension(3) :: p1n, p2n, qn
  inside = .false.
  if ((p1(0) < E_MIN) .or. (p2(0) < E_MIN) .or. (q(0) < E_MIN)) then
    return
  end if
  p1n = p1(1:3) / sqrt (dot_product (p1(1:3), p1(1:3)))
  p2n = p2(1:3) / sqrt (dot_product (p2(1:3), p2(1:3)))
  qn = q(1:3) / sqrt (dot_product (q(1:3), q(1:3)))
  if ((abs (qn(3)) > COSTH_BEAM_MAX) &
      .or. (abs (p1n(3)) > COSTH_BEAM_MAX)&
      .or. (abs (p2n(3)) > COSTH_BEAM_MAX)) then
    return
  end if
  if (dot_product (p1n, qn) > COSTH_SEP_MAX) then
    return
  end if
  if (dot_product (p2n, qn) > COSTH_SEP_MAX) then
    return
  end if
  if (dot_product (p1n, p2n) > COSTH_SEP_MAX) then
    return
  end if
  inside = .true.
end function cuts

```

**224b** *⟨Implementation of cross\_section procedures 224a⟩*+≡ (222a) <224a 226b>

```

function xsect (k1, k2, p1, p2, q) result (xs)
  real(kind=default), dimension(0:), intent(in) :: k1, k2, p1, p2, q
  real(kind=default) :: xs
  complex(kind=default), dimension(-1:1,-1:1,-1:1,-1:1,-1:1) :: amp
  !!! xs = 1.0_double / phase_space_volume (3, k1(0) + k2(0))
  !!! xs = 1.0_double / dot (p1 + q, p1 + q) &
  !!!      + 1.0_double / dot (p2 + q, p2 + q)
  !!! return
  amp = nneeg (k1, k2, p1, p2, q)

```

```

xs = sum (amp(-1:1:2,-1:1:2,-1:1:2,-1:1:2,-1:1:2) &
          * conjg (amp(-1:1:2,-1:1:2,-1:1:2,-1:1:2,-1:1:2)))
end function xsect

```

225a  $\langle$ Declaration of cross\_section procedures 223d $\rangle + \equiv$  (222a)  $\langle$ 223d 227b $\rangle$

private :: xsect  
 $\phi : [0, 1]^{\otimes 5} \rightarrow [(m_2 + m_3)^2, (\sqrt{s} - m_1)^2] \otimes [t_1^{\min}(s_2), t_1^{\max}(s_2)]$   
 $\otimes [0, 2\pi] \otimes [-1, 1] \otimes [0, 2\pi]$   
 $(x_1, \dots, x_5) \mapsto (s_2, t_1, \phi, \cos \theta_3, \phi_3)$   
 $= (s_2(x_1), x_2 t_1^{\max}(s_2) + (1 - x_2) t_1^{\min}(s_2), 2\pi x_3, 2x_4 - 1, 2\pi x_5)$   
(7.1)

where

$$t_1^{\max/\min}(s_2)$$

$$= m_a^2 + m_1^2 - \frac{(s + m_a^2 - m_b^2)(s - s_2 + m_1^2) \mp \sqrt{\lambda(s, m_a^2, m_b^2)\lambda(s, s_2, m_1^2)}}{2s}$$
(7.2)

225b  $\langle$ Set  $(s_2, t_1, \phi, \cos \theta_3, \phi_3)$  from  $(x_1, \dots, x_5)$  225b $\rangle \equiv$  (226b)

```

! s2_min = S1_MIN_0
s2_min = (m2 + m3)**2
s2_max = (sqrt(s) - m1)**2
s2 = s2_max * x(1) + s2_min * (1 - x(1))
t1_min = ma**2 + m1**2 - ((s + ma**2 - mb**2) * (s - s2 + m1**2) &
+ sqrt(lambda(s, ma**2, mb**2) * lambda(s, s2, m1**2))) / (2*s)
t1_max = ma**2 + m1**2 - ((s + ma**2 - mb**2) * (s - s2 + m1**2) &
- sqrt(lambda(s, ma**2, mb**2) * lambda(s, s2, m1**2))) / (2*s)
t1 = t1_max * x(2) + t1_min * (1 - x(2))
phi = 2*PI * x(3)
cos_theta3 = 2 * x(4) - 1
phi3 = 2*PI * x(5)

```

225c  $\langle$ Set  $(s_2, t_1, \phi, \cos \theta_3, \phi_3)$  from  $(x_1, \dots, x_5)$  (massless case) 225c $\rangle \equiv$  (228b)

```

! s2_min = S1_MIN_0
s2_min = 0
s2_max = s
s2 = s2_max * x(1) + s2_min * (1 - x(1))
t1_min = - (s - s2)
t1_max = 0
t1 = t1_max * x(2) + t1_min * (1 - x(2))
phi = 2*PI * x(3)
cos_theta3 = 2 * x(4) - 1
phi3 = 2*PI * x(5)

```

$$J_\phi(x_1, \dots, x_5) = \left| \begin{array}{cc} \frac{\partial s_2}{\partial x_1} & \frac{\partial t_1}{\partial x_1} \\ \frac{\partial s_2}{\partial x_2} & \frac{\partial t_1}{\partial x_2} \end{array} \right| \cdot 8\pi^2 \quad (7.3)$$

i.e.

$$J_\phi(x_1, \dots, x_5) = 8\pi^2 \cdot \left| \frac{ds_2}{dx_1} \right| \cdot (t_1^{\max}(s_2) - t_1^{\min}(s_2)) \quad (7.4)$$

226a  $\langle \text{Adjust Jacobian 226a} \rangle \equiv$  (226b 228b)

```
p%jacobian = p%jacobian &
* (8.0 * PI**2 * (s2_max - s2_min) * (t1_max - t1_min))
```

226b  $\langle \text{Implementation of cross\_section procedures 224a} \rangle + \equiv$  (222a)  $\langle 224b \ 227c \rangle$

```
pure function phase_space(x, channel) result(p)
  real(kind=default), dimension(:), intent(in) :: x
  integer, intent(in) :: channel
  type(LIPS3) :: p
  real(kind=default) :: &
    ma, mb, m1, m2, m3, s, t1, s2, phi, cos_theta3, phi3
  real(kind=default) :: s2_min, s2_max, t1_min, t1_max
  s = S_0
   $\langle m_a \leftrightarrow m_b, m_1 \leftrightarrow m_2 \text{ for channel \#1 226c} \rangle$ 
   $\langle \text{Set } (s_2, t_1, \phi, \cos \theta_3, \phi_3) \text{ from } (x_1, \dots, x_5) \text{ 225b} \rangle$ 
  p = two_to_three(s, t1, s2, phi, cos_theta3, phi3, ma, mb, m1, m2, m3)
   $\langle \text{Adjust Jacobian 226a} \rangle$ 
   $\langle p_1 \leftrightarrow p_2 \text{ for channel \#2 227a} \rangle$ 
end function phase_space
```

226c  $\langle m_a \leftrightarrow m_b, m_1 \leftrightarrow m_2 \text{ for channel \#1 226c} \rangle \equiv$  (226b)

```
select case (channel)
case (1)
  ma = MA_0
  mb = MB_0
  m1 = M1_0
  m2 = M2_0
  m3 = M3_0
case (2)
  ma = MB_0
  mb = MA_0
  m1 = M2_0
  m2 = M1_0
  m3 = M3_0
case (3)
  ma = MA_0
  mb = MB_0
  m1 = M3_0
```

```

        m2 = M2_0
        m3 = M1_0
    case default
        ma = MA_0
        mb = MB_0
        m1 = M1_0
        m2 = M2_0
        m3 = M3_0
    end select

```

227a  $\langle p_1 \leftrightarrow p_2 \text{ for channel \#2 227a} \rangle \equiv$  (226b 228b)

```

    select case (channel)
    case (1)
        ! OK
    case (2)
        call swap (p%p(1,:), p%p(2,:))
    case (3)
        call swap (p%p(1,:), p%p(3,:))
    case default
        ! OK
    end select

```

227b  $\langle \text{Declaration of cross\_section procedures 223d} \rangle + \equiv$  (222a)  $\langle$ 225a 228a $\rangle$   
 private :: jacobian

227c  $\langle \text{Implementation of cross\_section procedures 224a} \rangle + \equiv$  (222a)  $\langle$ 226b 228b $\rangle$

```

pure function jacobian (k1, k2, p1, p2, q) result (jac)
    real(kind=default), dimension(0:), intent(in) :: k1, k2, p1, p2, q
    real(kind=default) :: jac
    real(kind=default) :: ma_2, mb_2, m1_2, m2_2, m3_2
    real(kind=default) :: s, s2, s2_min, s2_max, t1_min, t1_max
    ma_2 = max (dot (k1, k1), 0.0_double)
    mb_2 = max (dot (k2, k2), 0.0_double)
    m1_2 = max (dot (p1, p1), 0.0_double)
    m2_2 = max (dot (p2, p2), 0.0_double)
    m3_2 = max (dot (q, q), 0.0_double)
    s = dot (k1 + k2, k1 + k2)
    s2 = dot (p2 + q, p2 + q)
    ! s2_min = S1_MIN_0
    s2_min = (sqrt (m2_2) + sqrt (m3_2))**2
    s2_max = (sqrt (s) - sqrt (m1_2))**2
    t1_min = ma_2 + m1_2 - ((s + ma_2 - mb_2) * (s - s2 + m1_2) &
        + sqrt (lambda (s, ma_2, mb_2) * lambda (s, s2, m1_2))) / (2*s)
    t1_max = ma_2 + m1_2 - ((s + ma_2 - mb_2) * (s - s2 + m1_2) &
        - sqrt (lambda (s, ma_2, mb_2) * lambda (s, s2, m1_2))) / (2*s)

```

```

    jac = 1.0 / ((2*PI)**5 * 32 * s2) &
        * sqrt (lambda (s2, m2_2, m3_2) / lambda (s, ma_2, mb_2)) &
        * (8.0 * PI**2 * (s2_max - s2_min) * (t1_max - t1_min))
end function jacobian

```

228a *<Declaration of cross\_section procedures 223d>+≡ (222a) <227b 228e>*  
 private :: phase\_space, phase\_space\_massless

228b *<Implementation of cross\_section procedures 224a>+≡ (222a) <227c 228f>*  
 pure function phase\_space\_massless (x, channel) result (p)  
 real(kind=default), dimension(:), intent(in) :: x  
 integer, intent(in) :: channel  
 type(LIPS3) :: p  
 real(kind=default) :: s, t1, s2, phi, cos\_theta3, phi3  
 real(kind=default) :: s2\_min, s2\_max, t1\_min, t1\_max  
 s = S\_0  
*<Set (s2, t1, φ, cos θ3, φ3) from (x1, ..., x5) (massless case) 225c>*  
 p = two\_to\_three (s, t1, s2, phi, cos\_theta3, phi3)  
*<Adjust Jacobian 226a>*  
*<p1 ↔ p2 for channel #2 227a>*  
 end function phase\_space\_massless

228c *<Types in cross\_section 228c>≡ (222a) 228d>*  
 type, public :: LIPS3\_m5i2a3  
 ! private  
 real(kind=default) :: ma, mb, m1, m2, m3  
 real(kind=default) :: s, s2, t1  
 real(kind=default) :: phi, cos\_theta3, phi3  
 real(kind=default) :: jacobian  
 end type LIPS3\_m5i2a3

228d *<Types in cross\_section 228c>+≡ (222a) <228c>*  
 type, public :: x5  
 ! private  
 real(kind=default), dimension(5) :: x  
 real(kind=default) :: jacobian  
 end type x5

228e *<Declaration of cross\_section procedures 223d>+≡ (222a) <228a 231a>*  
 private :: invariants\_from\_p, invariants\_to\_p  
 private :: invariants\_from\_x, invariants\_to\_x

228f *<Implementation of cross\_section procedures 224a>+≡ (222a) <228b 229a>*  
 pure function invariants\_from\_p (p, k1, k2) result (q)  
 type(LIPS3), intent(in) :: p

```

real(kind=default), dimension(0:), intent(in) :: k1, k2
type(LIPS3_m5i2a3) :: q
real(kind=default) :: ma_2, mb_2, m1_2, m2_2, m3_2
real(kind=default), dimension(0:3) :: k1k2, p2p3, k1p1, p3_23
k1k2 = k1 + k2
k1p1 = - k1 + p%p(1,:)
p2p3 = p%p(2,:) + p%p(3,:)
ma_2 = max (dot (k1, k1), 0.0_double)
mb_2 = max (dot (k2, k2), 0.0_double)
m1_2 = max (dot (p%p(1,:), p%p(1:)), 0.0_double)
m2_2 = max (dot (p%p(2,:), p%p(2:)), 0.0_double)
m3_2 = max (dot (p%p(3,:), p%p(3:)), 0.0_double)
q%ma = sqrt (ma_2)
q%mb = sqrt (mb_2)
q%m1 = sqrt (m1_2)
q%m2 = sqrt (m2_2)
q%m3 = sqrt (m3_2)
q%s = dot (k1k2, k1k2)
q%s2 = dot (p2p3, p2p3)
q%t1 = dot (k1p1, k1p1)
q%phi = atan2 (p%p(1,2), p%p(1,1))
if (q%phi < 0) then
    q%phi = q%phi + 2*PI
end if
p3_23 = boost_momentum (p%p(3,:), p2p3)
q%cos_theta3 = p3_23(3) / sqrt (dot_product (p3_23(1:3), p3_23(1:3)))
q%phi3 = atan2 (p3_23(2), p3_23(1))
if (q%phi3 < 0) then
    q%phi3 = q%phi3 + 2*PI
end if
q%jacobian = 1.0 / ((2*PI)**5 * 32 * q%s2) &
    * sqrt (lambda (q%s2, m2_2, m3_2) / lambda (q%s, ma_2, mb_2))
end function invariants_from_p

```

229a  $\langle$ Implementation of cross\_section procedures 224a $\rangle + \equiv$  (222a)  $\langle$ 228f 229b $\rangle$

```

pure function invariants_to_p (p) result (q)
type(LIPS3_m5i2a3), intent(in) :: p
type(LIPS3) :: q
q = two_to_three (p%s, p%t1, p%s2, p%phi, p%cos_theta3, p%phi3)
q%jacobian = q%jacobian * p%jacobian
end function invariants_to_p

```

229b  $\langle$ Implementation of cross\_section procedures 224a $\rangle + \equiv$  (222a)  $\langle$ 229a 230 $\rangle$

```

pure function invariants_from_x (x, s, ma, mb, m1, m2, m3) result (p)
  real(kind=default), dimension(:), intent(in) :: x
  real(kind=default), intent(in) :: s, ma, mb, m1, m2, m3
  type(LIPS3_m5i2a3) :: p
  real(kind=default) :: s2_min, s2_max, t1_min, t1_max
  p%ma = ma
  p%mb = mb
  p%m1 = m1
  p%m2 = m2
  p%m3 = m3
  p%s = s
  s2_min = (p%m2 + p%m3)**2
  s2_max = (sqrt (p%s) - p%m1)**2
  p%s2 = s2_max * x(1) + s2_min * (1 - x(1))
  t1_min = p%ma**2 + p%m1**2 &
    - ((p%s + p%ma**2 - p%mb**2) * (p%s - p%s2 + p%m1**2) &
      + sqrt (lambda (p%s, p%ma**2, p%mb**2) &
        * lambda (p%s, p%s2, p%m1**2))) / (2*p%s)
  t1_max = p%ma**2 + p%m1**2 &
    - ((p%s + p%ma**2 - p%mb**2) * (p%s - p%s2 + p%m1**2) &
      - sqrt (lambda (p%s, p%ma**2, p%mb**2) &
        * lambda (p%s, p%s2, p%m1**2))) / (2*p%s)
  p%t1 = t1_max * x(2) + t1_min * (1 - x(2))
  p%phi = 2*PI * x(3)
  p%cos_theta3 = 2 * x(4) - 1
  p%phi3 = 2*PI * x(5)
  p%jacobian = 8*PI**2 * (s2_max - s2_min) * (t1_max - t1_min)
end function invariants_from_x

```

230  $\langle$ Implementation of cross-section procedures 224a $\rangle + \equiv$  (222a)  $\langle$ 229b 231b $\rangle$

```

pure function invariants_to_x (p) result (x)
  type(LIPS3_m5i2a3), intent(in) :: p
  type(x5) :: x
  real(kind=default) :: s2_min, s2_max, t1_min, t1_max
  s2_min = (p%m2 + p%m3)**2
  s2_max = (sqrt (p%s) - p%m1)**2
  t1_min = p%ma**2 + p%m1**2 &
    - ((p%s + p%ma**2 - p%mb**2) * (p%s - p%s2 + p%m1**2) &
      + sqrt (lambda (p%s, p%ma**2, p%mb**2) &
        * lambda (p%s, p%s2, p%m1**2))) / (2*p%s)
  t1_max = p%ma**2 + p%m1**2 &
    - ((p%s + p%ma**2 - p%mb**2) * (p%s - p%s2 + p%m1**2) &
      - sqrt (lambda (p%s, p%ma**2, p%mb**2) &

```

```

        * lambda (p%s, p%s2, p%m1**2))) / (2*p%s)
x%x(1) = (p%s2 - s2_min) / (s2_max - s2_min)
x%x(2) = (p%t1 - t1_min) / (t1_max - t1_min)
x%x(3) = p%phi / (2*PI)
x%x(4) = (p%cos_theta3 + 1) / 2
x%x(5) = p%phi3 / (2*PI)
x%jacobian = p%jacobian * 8*PI**2 * (s2_max - s2_min) * (t1_max - t1_min)
end function invariants_to_x

```

231a *<Declaration of cross\_section procedures 223d>+≡ (222a) <228e 232b>*  
public :: sigma, sigma\_raw, sigma\_massless

231b *<Implementation of cross\_section procedures 224a>+≡ (222a) <230 231c>*  
function sigma (x, weights, channel, grids) result (xs)
 real(kind=default), dimension(:), intent(in) :: x
 real(kind=default), dimension(:), intent(in), optional :: weights
 integer, intent(in), optional :: channel
 type(vamp\_grid), dimension(:), intent(in), optional :: grids
 real(kind=default) :: xs
 real(kind=default), dimension(2,0:3) :: k
 type(LIPS3) :: p
 k(1,:) = (/ 100.0\_double, 0.0\_double, 0.0\_double, 100.0\_double /)
 k(2,:) = (/ 100.0\_double, 0.0\_double, 0.0\_double, -100.0\_double /)
 if (present (channel)) then
 p = phase\_space (x, channel)
 else
 p = phase\_space (x, 0)
 end if
 if (cuts (k(1,:), k(2,:), p%p(1,:), p%p(2,:), p%p(3,:))) then
 xs = xsect (k(1,:), k(2,:), p%p(1,:), p%p(2,:), p%p(3,:)) &
 \* jacobian (k(1,:), k(2,:), p%p(1,:), p%p(2,:), p%p(3,:))
 !!! \* p%jacobian
 else
 xs = 0.0
 end if
end function sigma

231c *<Implementation of cross\_section procedures 224a>+≡ (222a) <231b 232a>*  
function sigma\_raw (k1, k2, p1, p2, q) result (xs)
 real(kind=default), dimension(0:), intent(in) :: k1, k2, p1, p2, q
 real(kind=default) :: xs
 if (cuts (k1, k2, p1, p2, q)) then
 xs = xsect (k1, k2, p1, p2, q)
 end if
end function sigma\_raw



```

else
  xs = 0.0
end if
end function sigma_raw

```

232a  $\langle$ Implementation of cross\_section procedures 224a $\rangle + \equiv$  (222a)  $\langle$ 231c 232c $\rangle$

```

function sigma_massless (x, weights, channel, grids) result (xs)
  real(kind=default), dimension(:), intent(in) :: x
  real(kind=default), dimension(:), intent(in), optional :: weights
  integer, intent(in), optional :: channel
  type(vamp_grid), dimension(:), intent(in), optional :: grids
  real(kind=default) :: xs
  real(kind=default), dimension(2,0:3) :: k
  type(LIPS3) :: p
  k(1,:) = (/ 100.0_double, 0.0_double, 0.0_double, 100.0_double /)
  k(2,:) = (/ 100.0_double, 0.0_double, 0.0_double, -100.0_double /)
  p = phase_space_massless (x, 0)
  if (cuts (k(1,:), k(2,:), p%p(1,:), p%p(2,:), p%p(3,:))) then
    xs = xsect (k(1,:), k(2,:), p%p(1,:), p%p(2,:), p%p(3,:)) &
      * p%jacobian
  else
    xs = 0.0
  end if
end function sigma_massless

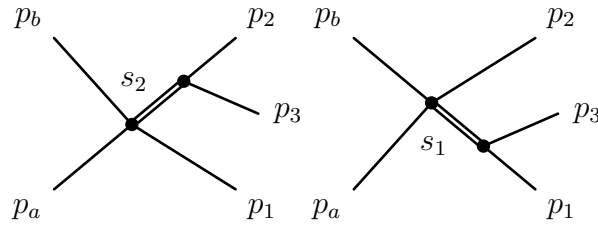
```

232b  $\langle$ Declaration of cross\_section procedures 223d $\rangle + \equiv$  (222a)  $\langle$ 231a 234a $\rangle$

```

public :: w

```



232c  $\langle$ Implementation of cross\_section procedures 224a $\rangle + \equiv$  (222a)  $\langle$ 232a 233 $\rangle$

```

function w (x, weights, channel, grids) result (w_x)
  real(kind=default), dimension(:), intent(in) :: x
  real(kind=default), dimension(:), intent(in), optional :: weights
  integer, intent(in), optional :: channel
  type(vamp_grid), dimension(:), intent(in), optional :: grids
  real(kind=default) :: w_x
  real(kind=default), dimension(size(weights)) :: g_x

```

```

real(kind=default), dimension(2,0:3) :: k
type(LIPS3) :: p
integer :: ch
if (present (channel)) then
    ch = channel
else
    ch = 0
end if
k(1,:) = (/ 100.0_double, 0.0_double, 0.0_double, 100.0_double /)
k(2,:) = (/ 100.0_double, 0.0_double, 0.0_double, -100.0_double /)
p = phase_space (x, abs (ch))
g_x(1) = 1.0_double / jacobian (k(1,:), k(2,:), p%p(1,:), p%p(2,:), p%p(3,:))
g_x(2) = 1.0_double / jacobian (k(1,:), k(2,:), p%p(2,:), p%p(1,:), p%p(3,:))
g_x(3) = 1.0_double / jacobian (k(1,:), k(2,:), p%p(3,:), p%p(2,:), p%p(1,:))
if (ch > 0) then
    w_x = sigma_raw (k(1,:), k(2,:), p%p(1,:), p%p(2,:), p%p(3,:)) &
        / sum (weights * g_x)
else if (ch < 0) then
    w_x = g_x(-ch) / sum (weights * g_x)
else
    w_x = -1
end if
end function w

```

233  $\langle$ Implementation of cross-section procedures 224a $\rangle + \equiv$  (222a)  $\langle$ 232c 234c $\rangle$

```

function sigma_rambo (x, weights, channel, grids) result (xs)
    real(kind=default), dimension(:), intent(in) :: x
    real(kind=default), dimension(:), intent(in), optional :: weights
    integer, intent(in), optional :: channel
    type(vamp_grid), dimension(:), intent(in), optional :: grids
    real(kind=default) :: xs
    real(kind=default), dimension(2,0:3) :: k
    real(kind=default), dimension(3,0:3) :: p
    k(1,:) = (/ 100.0_double, 0.0_double, 0.0_double, 100.0_double /)
    k(2,:) = (/ 100.0_double, 0.0_double, 0.0_double, -100.0_double /)
    p = massless_isotropic_decay (sum (k(:,0)), reshape (x, (/ 3, 4 /)))
    if (cuts (k(1,:), k(2,:), p(1,:), p(2,:), p(3,:))) then
        xs = xsect (k(1,:), k(2,:), p(1,:), p(2,:), p(3,:)) &
            * phase_space_volume (size (p, dim = 1), sum (k(:,0)))
    else
        xs = 0.0
    end if
end function sigma_rambo

```

234a *<Declaration of cross\_section procedures 223d>+≡ (222a) <232b 234b>*  
public :: sigma\_rambo

234b *<Declaration of cross\_section procedures 223d>+≡ (222a) <234a 235a>*  
public :: check\_kinematics  
private :: print\_LIPS3\_m5i2a3

234c *<Implementation of cross\_section procedures 224a>+≡ (222a) <233 234d>*  
subroutine check\_kinematics (rng)  
type(tao\_random\_state), intent(inout) :: rng  
real(kind=default), dimension(5) :: x  
real(kind=default), dimension(0:3) :: k1, k2  
type(x5) :: x1, x2  
type(LIPS3) :: p1, p2  
type(LIPS3\_m5i2a3) :: q, q1, q2  
k1 = (/ 100.0\_double, 0.0\_double, 0.0\_double, 100.0\_double /)  
k2 = (/ 100.0\_double, 0.0\_double, 0.0\_double, -100.0\_double /)  
call tao\_random\_number (rng, x)  
q = invariants\_from\_x (x, S\_0, MA\_0, MB\_0, M1\_0, M2\_0, M3\_0)  
p1 = invariants\_to\_p (q)  
q1 = invariants\_from\_p (p1, k1, k2)  
p2 = phase\_space (x, 1)  
q2 = invariants\_from\_p (p2, k1, k2)  
x1 = invariants\_to\_x (q1)  
x2 = invariants\_to\_x (q2)  
print \*, p1%jacobian, p2%jacobian, x1%jacobian, x2%jacobian  
call print\_lips3\_m5i2a3 (q)  
call print\_lips3\_m5i2a3 (q1)  
call print\_lips3\_m5i2a3 (q2)  
end subroutine check\_kinematics

234d *<Implementation of cross\_section procedures 224a>+≡ (222a) <234c 235b>*  
subroutine print\_LIPS3\_m5i2a3 (p)  
type(LIPS3\_m5i2a3), intent(in) :: p  
print "(1x,5('m',a1,'=',e9.2,' '))", &  
'a', p%ma, 'b', p%mb, '1', p%m1, '2', p%m2, '3', p%m3  
print "(1x,'s=',e9.2,' s2=',e9.2,' t1=',e9.2)", &  
p%s, p%s2, p%t1  
print "(1x,'phi=',e9.2,' cos(th3)=',e9.2,' phi2=',e9.2)", &  
p%phi, p%cos\_theta3, p%phi3  
print "(1x,'j=',e9.2)", &  
p%jacobian  
end subroutine print\_LIPS3\_m5i2a3

235a *<Declaration of cross\_section procedures 223d>+≡ (222a) <234b 238a>*

```

public :: phi12, phi21, phi1, phi2
public :: g12, g21, g1, g2

```

235b *<Implementation of cross\_section procedures 224a>+≡ (222a) <234d 235c>*

```

pure function phi12 (x1, dummy) result (x2)
  real(kind=default), dimension(:), intent(in) :: x1
  integer, intent(in) :: dummy
  real(kind=default), dimension(size(x1)) :: x2
  type(LIPS3) :: p1, p2
  type(LIPS3_m5i2a3) :: q1, q2
  type(x5) :: x52
  real(kind=default), dimension(0:3) :: k1, k2
  k1 = (/ 100.0_double, 0.0_double, 0.0_double, 100.0_double /)
  k2 = (/ 100.0_double, 0.0_double, 0.0_double, -100.0_double /)
  q1 = invariants_from_x (x1, S_0, MA_0, MB_0, M1_0, M2_0, M3_0)
  p1 = invariants_to_p (q1)
  p2%p(1,:) = p1%p(2,:)
  p2%p(2,:) = p1%p(1,:)
  p2%p(3,:) = p1%p(3,:)
  if (dummy < 0) then
    q2 = invariants_from_p (p2, k2, k1)
  else
    q2 = invariants_from_p (p2, k1, k2)
  end if
  x52 = invariants_to_x (q2)
  x2 = x52%x
end function phi12

```

235c *<Implementation of cross\_section procedures 224a>+≡ (222a) <235b 236a>*

```

pure function phi21 (x2, dummy) result (x1)
  real(kind=default), dimension(:), intent(in) :: x2
  integer, intent(in) :: dummy
  real(kind=default), dimension(size(x2)) :: x1
  type(LIPS3) :: p1, p2
  type(LIPS3_m5i2a3) :: q1, q2
  type(x5) :: x51
  real(kind=default), dimension(0:3) :: k1, k2
  k1 = (/ 100.0_double, 0.0_double, 0.0_double, 100.0_double /)
  k2 = (/ 100.0_double, 0.0_double, 0.0_double, -100.0_double /)
  q2 = invariants_from_x (x2, S_0, MA_0, MB_0, M2_0, M1_0, M3_0)
  p2 = invariants_to_p (q2)
  p1%p(1,:) = p2%p(2,:)
  p1%p(2,:) = p2%p(1,:)

```

```

p1%p(3,:) = p2%p(3,:)
if (dummy < 0) then
    q1 = invariants_from_p (p1, k2, k1)
else
    q1 = invariants_from_p (p1, k1, k2)
end if
x51 = invariants_to_x (q1)
x1 = x51%x
end function phi21

```

236a  $\langle$ Implementation of cross\_section procedures 224a $\rangle + \equiv$  (222a)  $\langle$ 235c 236b $\rangle$

```

pure function phi1 (x1) result (p1)
    real(kind=default), dimension(:), intent(in) :: x1
    type(LIPS3) :: p1
    type(LIPS3_m5i2a3) :: q1
    q1 = invariants_from_x (x1, S_0, MA_0, MB_0, M1_0, M2_0, M3_0)
    p1 = invariants_to_p (q1)
end function phi1

```

236b  $\langle$ Implementation of cross\_section procedures 224a $\rangle + \equiv$  (222a)  $\langle$ 236a 236c $\rangle$

```

pure function phi2 (x2) result (p2)
    real(kind=default), dimension(:), intent(in) :: x2
    type(LIPS3) :: p2
    type(LIPS3_m5i2a3) :: q2
    q2 = invariants_from_x (x2, S_0, MA_0, MB_0, M2_0, M1_0, M3_0)
    p2 = invariants_to_p (q2)
end function phi2

```

236c  $\langle$ Implementation of cross\_section procedures 224a $\rangle + \equiv$  (222a)  $\langle$ 236b 237a $\rangle$

```

pure function g12 (x1) result (g)
    real(kind=default), dimension(:), intent(in) :: x1
    real(kind=default) :: g
    type(LIPS3) :: p1, p2
    type(LIPS3_m5i2a3) :: q1, q2
    type(x5) :: x52
    real(kind=default), dimension(0:3) :: k1, k2
    k1 = (/ 100.0_double, 0.0_double, 0.0_double, 100.0_double /)
    k2 = (/ 100.0_double, 0.0_double, 0.0_double, -100.0_double /)
    q1 = invariants_from_x (x1, S_0, MA_0, MB_0, M1_0, M2_0, M3_0)
    p1 = invariants_to_p (q1)
    p2%p(1,:) = p1%p(2,:)
    p2%p(2,:) = p1%p(1,:)

```

```

p2%p(3,:) = p1%p(3,:)
q2 = invariants_from_p (p2, k2, k1)
x52 = invariants_to_x (q2)
g = x52%jacobian / p1%jacobian
end function g12

```

237a *<Implementation of cross\_section procedures 224a>+≡ (222a) <236c 237b>*

```

pure function g21 (x2) result (g)
  real(kind=default), dimension(:), intent(in) :: x2
  real(kind=default) :: g
  type(LIPS3) :: p1, p2
  type(LIPS3_m5i2a3) :: q1, q2
  type(x5) :: x51
  real(kind=default), dimension(0:3) :: k1, k2
  k1 = (/ 100.0_double, 0.0_double, 0.0_double, 100.0_double /)
  k2 = (/ 100.0_double, 0.0_double, 0.0_double, -100.0_double /)
  q2 = invariants_from_x (x2, S_0, MA_0, MB_0, M2_0, M1_0, M3_0)
  p2 = invariants_to_p (q2)
  p1%p(1,:) = p2%p(2,:)
  p1%p(2,:) = p2%p(1,:)
  p1%p(3,:) = p2%p(3,:)
  q1 = invariants_from_p (p1, k2, k1)
  x51 = invariants_to_x (q1)
  g = x51%jacobian / p2%jacobian
end function g21

```

237b *<Implementation of cross\_section procedures 224a>+≡ (222a) <237a 237c>*

```

pure function g1 (x1) result (g)
  real(kind=default), dimension(:), intent(in) :: x1
  real(kind=default) :: g
  type(LIPS3) :: p1
  type(LIPS3_m5i2a3) :: q1
  q1 = invariants_from_x (x1, S_0, MA_0, MB_0, M1_0, M2_0, M3_0)
  p1 = invariants_to_p (q1)
  g = 1 / p1%jacobian
end function g1

```

237c *<Implementation of cross\_section procedures 224a>+≡ (222a) <237b 238b>*

```

pure function g2 (x2) result (g)
  real(kind=default), dimension(:), intent(in) :: x2
  real(kind=default) :: g
  type(LIPS3) :: p2

```

```

type(LIPS3_m5i2a3) :: q2
q2 = invariants_from_x (x2, S_0, MA_0, MB_0, M2_0, M1_0, M3_0)
p2 = invariants_to_p (q2)
g = 1 / p2%jacobian
end function g2

```

238a *<Declaration of cross\_section procedures 223d>+≡ (222a) <235a*  
public :: wx

238b *<Implementation of cross\_section procedures 224a>+≡ (222a) <237c*  
function wx (x, weights, channel, grids) result (w\_x)  
  real(kind=default), dimension(:), intent(in) :: x  
  real(kind=default), dimension(:), intent(in) :: weights  
  integer, intent(in) :: channel  
  type(vamp\_grid), dimension(:), intent(in) :: grids  
  real(kind=default) :: w\_x  
  real(kind=default), dimension(size(weights)) :: g\_x, p\_q  
  real(kind=default), dimension(size(x)) :: x1, x2  
  real(kind=default), dimension(2,0:3) :: k  
  type(LIPS3) :: q  
  k(1,:) = (/ 100.0\_double, 0.0\_double, 0.0\_double, 100.0\_double /)  
  k(2,:) = (/ 100.0\_double, 0.0\_double, 0.0\_double, -100.0\_double /)  
  select case (abs (channel))  
  case (1)  
    x1 = x  
    x2 = phi12 (x, 0)  
    q = phi1 (x1)  
  case (2)  
    x1 = phi21 (x, 0)  
    x2 = x  
    q = phi2 (x2)  
  end select  
  p\_q(1) = vamp\_probability (grids(1), x1)  
  p\_q(2) = vamp\_probability (grids(2), x2)  
  g\_x(1) = p\_q(1) \* g1 (x1)  
  g\_x(2) = p\_q(2) \* g2 (x2)  
  g\_x = g\_x / p\_q(abs(channel))  
  if (channel > 0) then  
    w\_x = sigma\_raw (k(1,:), k(2,:), q%p(1,:), q%p(2,:), q%p(3,:)) &  
      / dot\_product (weights, g\_x)  
  else if (channel < 0) then  
    w\_x = vamp\_probability (grids(-channel), x) / dot\_product (weights, g\_x)  
  else  
    w\_x = 0  
  end if  
end function wx

```

        end if
    end function wx

```

```

239  <application.f90 222a>+≡                                     <222a
    program application
        use kinds
        use utils
        use vampi
        use mpi90
        use linalg
        use exceptions
        use kinematics, only: phase_space_volume
        use cross_section !NODEP!
        use tao_random_numbers
        implicit none
        type(vamp_grid) :: gr
        type(vamp_grids) :: grs
        real(kind=default), dimension(:,:), allocatable :: region
        real(kind=default) :: integral, standard_dev, chi_squared
        real(kind=default) :: &
            single_integral, single_standard_dev, &
            rambo_integral, rambo_standard_dev
        real(kind=default), dimension(2) :: weight_vector
        integer, dimension(2) :: calls, iterations
        type(vamp_history), dimension(100) :: history
        type(vamp_history), dimension(100,size(weight_vector)) :: histories
        type(exception) :: exc
        type( tao_random_state ) :: rng
        real(kind=default), dimension(5) :: x
        real(kind=default) :: jac
        integer :: i
        integer :: num_proc, proc_id, ticks, ticks0, ticks_per_second, command
        character(len=72) :: command_line
        integer, parameter :: &
            CMD_SINGLE = 1, &
            CMD_MULTI = 2, &
            CMD_ROTATING = 3, &
            CMD_RAMBO = 4, &
            CMD_COMPARE = 5, &
            CMD_MASSLESS = 6, &
            CMD_ERROR = 0
        call mpi90_init ()
        call mpi90_size (num_proc)

```



```

call mpi90_rank (proc_id)
call system_clock (ticks0)
call tao_random_create (rng, 0)
call tao_random_seed (rng, ticks0 + proc_id)
!!! call tao_random_seed (rng, proc_id)
call vamp_create_history (history, verbose = .true.)
call vamp_create_history (histories, verbose = .true.)
iterations = (/ 3, 4 /)
calls = (/ 10000, 100000 /)
if (proc_id == 0) then
  read *, command_line
  if (command_line == "single") then
    command = CMD_SINGLE
  else if (command_line == "multi") then
    command = CMD_MULTI
  else if (command_line == "rotating") then
    command = CMD_ROTATING
  else if (command_line == "rambo") then
    command = CMD_RAMBO
  else if (command_line == "compare") then
    command = CMD_COMPARE
  else if (command_line == "massless") then
    command = CMD_MASSLESS
  else
    command = CMD_ERROR
  end if
end if
call mpi90_broadcast (command, 0)
call system_clock (ticks0)
select case (command)
case (CMD_SINGLE)
  Application in single channel mode 242a
case (CMD_MASSLESS)
  Application in massless single channel mode 242b
case (CMD_MULTI)
  Application in multi channel mode 243
case (CMD_ROTATING)
  allocate (region(2,5))
  region(1,:) = 0.0
  region(2,:) = 1.0
  if (proc_id == 0) then
    print *, "rotating N/A yet ..."
  end if

```

```

case (CMD_RAMBO)
  <Application in Rambo mode 244>
case (CMD_COMPARE)
  <Application in single channel mode 242a>
  single_integral = integral
  single_standard_dev = standard_dev
  <Application in Rambo mode 244>
  if (proc_id == 0) then
    rambo_integral = integral
    rambo_standard_dev = standard_dev
    integral = &
      (single_integral / single_standard_dev**2 &
       + rambo_integral / rambo_standard_dev**2) &
      / (1.0_double / single_standard_dev**2 &
       + 1.0_double / rambo_standard_dev**2)
    standard_dev = 1.0_double &
      / sqrt (1.0_double / single_standard_dev**2 &
       + 1.0_double / rambo_standard_dev**2)
    chi_squared = &
      ((single_integral - integral)**2 / single_standard_dev**2) &
      + ((rambo_integral - integral)**2 / rambo_standard_dev**2)
    print *, "S&R:   ", integral, standard_dev, chi_squared
  end if
case default
  if (proc_id == 0) then
    print *, "???: ", command
    !!! TO BE REMOVED !!!
    call check_kinematics (rng)
    allocate (region(2,5))
    region(1,:) = 0
    region(2,:) = 1
    do i = 1, 10
      call tao_random_number (rng, x)
      call vamp_jacobian (phi12, 0, x, region, jac)
      print *, "12:  ", jac, 1 / g12 (x), jac * g12 (x) - 1
      call vamp_jacobian (phi21, 0, x, region, jac)
      print *, "21:  ", jac, 1 / g21 (x), jac * g21 (x) - 1
      print *, "1:   ", real(x)
      print *, "2:   ", real(phi12(phi21(x,0),0))
      print *, "2':  ", real(phi12(phi21(x,-1),-1))
      print *, "3:   ", real(phi21(phi12(x,0),0))
      print *, "3':  ", real(phi21(phi12(x,-1),-1))
      print *, "2-1: ", real(phi12(phi21(x,0),0) - x)
    end do
  end if
end

```

```

        print *, "3-1: ", real(phi21(phi12(x,0),0) - x)
        print *, "a:   ", real(phi12(x,0))
        print *, "a':  ", real(phi12(x,-1))
        print *, "b:   ", real(phi21(x,0))
        print *, "b':  ", real(phi21(x,-1))
    end do
    deallocate (region)
    ! do i = 2, 5
    !     print *, i, phase_space_volume (i, 200.0_double)
    ! end do
end if
end select
if (proc_id == 0) then
    call system_clock (ticks, ticks_per_second)
    print "(1X,A,F8.2,A)", &
        "time = ", real (ticks - ticks0) / ticks_per_second, " secs"
end if
call mpi90_finalize ()
end program application
242a  <Application in single channel mode 242a>≡ (239)
    allocate (region(2,5))
    region(1,:) = 0.0
    region(2,:) = 1.0
    call vamp_create_grid (gr, region, calls(1))
    call clear_exception (exc)
    call vamp_sample_grid &
        (rng, gr, sigma, iterations(1), history = history, exc = exc)
    call handle_exception (exc)
    call vamp_discard_integral (gr, calls(2))
    call vamp_sample_grid &
        (rng, gr, sigma, iterations(2), &
            integral, standard_dev, chi_squared, &
            history = history(iterations(1)+1:), exc = exc)
    call handle_exception (exc)
    call vamp_print_history (history, "single")
    if (proc_id == 0) then
        print *, "SINGLE: ", integral, standard_dev, chi_squared
    end if
    call vamp_write_grid (gr, "application.grid")
    call vamp_delete_grid (gr)
    deallocate (region)
242b  <Application in massless single channel mode 242b>≡ (239)
    allocate (region(2,5))

```

```

region(1,:) = 0.0
region(2,:) = 1.0
call vamp_create_grid (gr, region, calls(1))
call clear_exception (exc)
call vamp_sample_grid &
    (rng, gr, sigma_massless, iterations(1), history = history, exc = exc)
call handle_exception (exc)
call vamp_discard_integral (gr, calls(2))
call vamp_sample_grid &
    (rng, gr, sigma_massless, iterations(2), &
     integral, standard_dev, chi_squared, &
     history = history(iterations(1)+1:), exc = exc)
call handle_exception (exc)
call vamp_print_history (history, "single")
if (proc_id == 0) then
    print *, "M=0:   ", integral, standard_dev, chi_squared
end if
call vamp_write_grid (gr, "application.grid")
call vamp_delete_grid (gr)
deallocate (region)

```

243    *Application in multi channel mode 243* ≡ (239)

```

allocate (region(2,5))
region(1,:) = 0.0
region(2,:) = 1.0
weight_vector = 1.0
if (proc_id == 0) then
    read *, weight_vector
end if
call mpi90_broadcast (weight_vector, 0)
weight_vector = weight_vector / sum (weight_vector)
call vamp_create_grids (grs, region, calls(1), weight_vector)
do i = 1, 3
    call clear_exception (exc)
    call vamp_sample_grids &
        (rng, grs, wx, iterations(1), &
         history = history(1+(i-1)*iterations(1):), &
         histories = histories(1+(i-1)*iterations(1):,:), exc = exc)
    call handle_exception (exc)
    call vamp_refine_weights (grs)
end do
call vamp_discard_integrals (grs, calls(2))
call vamp_sample_grids &
    (rng, grs, wx, iterations(2), &

```

```

        integral, standard_dev, chi_squared, &
        history = history(3*iterations(1)+1:), &
        histories = histories(3*iterations(1)+1:,:), exc = exc)
call handle_exception (exc)
call vamp_print_history (history, "multi")
call vamp_print_history (histories, "multi")
if (proc_id == 0) then
    print *, "MULTI: ", integral, standard_dev, chi_squared
end if
call vamp_write_grids (grs, "application.grids")
call vamp_delete_grids (grs)
deallocate (region)

```

244 *Application in Rambo mode 244*≡

(239)

```

allocate (region(2,12))
region(1,:) = 0.0
region(2,:) = 1.0
call vamp_create_grid (gr, region, calls(1))
call clear_exception (exc)
call vamp_sample_grid &
    (rng, gr, sigma_rambo, iterations(1), history = history, exc = exc)
call handle_exception (exc)
call vamp_discard_integral (gr, calls(2))
call vamp_sample_grid &
    (rng, gr, sigma_rambo, iterations(2), &
    integral, standard_dev, chi_squared, &
    history = history(iterations(1)+1:), exc = exc)
call handle_exception (exc)
call vamp_print_history (history, "rambo")
if (proc_id == 0) then
    print *, "RAMBO: ", integral, standard_dev, chi_squared
end if
call vamp_delete_grid (gr)
deallocate (region)

```

# —A—

## CONSTANTS

### *A.1 Kinds*

This borders on overkill, but it is the most portable way to get double precision in standard Fortran without relying on `kind (1.0D0)`. Currently, it is possible to change `double` to any other supported real kind. The MPI interface is a potential trouble source for such things, however.

```
245a <vamp_kinds.f90 245a>≡
! vamp_kinds.f90 --
<Copyleft notice 1>
module kinds
  implicit none
  integer, parameter, private :: single = &
    & selected_real_kind (precision(1.0), range(1.0))
  integer, parameter, private :: double = &
    & selected_real_kind (precision(1.0_single) + 1, range(1.0_single) + 1)
  integer, parameter, private :: extended = &
    & selected_real_kind (precision (1.0_double) + 1, range (1.0_double))
  integer, parameter, public :: default = double
  character(len=*), public, parameter :: KINDS_RCS_ID = &
    "$Id: kinds.nw 314 2010-04-17 20:32:33Z ohl $"
end module kinds
```

### *A.2 Mathematical and Physical Constants*

```
245b <constants.f90 245b>≡
! constants.f90 --
<Copyleft notice 1>
```

```
module constants
  use kinds
  implicit none
  private
  real(kind=default), public, parameter :: &
    PI = 3.1415926535897932384626433832795028841972_default
  character(len=*), public, parameter :: CONSTANTS_RCS_ID = &
    "$Id: constants.nw 314 2010-04-17 20:32:33Z ohl $"
end module constants
```

# —B—

## ERRORS AND EXCEPTIONS

Fortran95 does not allow *any* I/O in pure and elemental procedures, not even output to the unit \*. A stop statement is verboten as well. Therefore we have to use condition codes

```

247a <exceptions.f90 247a>≡
      ! exceptions.f90 --
      <Copyleft notice 1>
      module exceptions
        use kinds
        implicit none
        private
        <Declaration of exceptions procedures 248b>
        <Interfaces of exceptions procedures (never defined)>
        <Variables in exceptions 247c>
        <Declaration of exceptions types 247b>
        character(len=*, public, parameter :: EXCEPTIONS_RCS_ID = &
          "$Id: exceptions.nw 314 2010-04-17 20:32:33Z ohl $"
        contains
          <Implementation of exceptions procedures 248c>
        end module exceptions

247b <Declaration of exceptions types 247b>≡ (247a)
      type, public :: exception
        integer :: level = EXC_NONE
        character(len=NAME_LENGTH) :: message = ""
        character(len=NAME_LENGTH) :: origin = ""
      end type exception

247c <Variables in exceptions 247c>≡ (247a) 248a>
      integer, public, parameter :: &
        EXC_NONE = 0, &
        EXC_INFO = 1, &
        EXC_WARN = 2, &

```



```

    EXC_ERROR = 3, &
    EXC_FATAL = 4

```

248a *<Variables in exceptions 247c>+≡* (247a) <247c  
 integer, private, parameter :: EXC\_DEFAULT = EXC\_ERROR  
 integer, private, parameter :: NAME\_LENGTH = 64

248b *<Declaration of exceptions procedures 248b>≡* (247a) 248d>  
 public :: handle\_exception

248c *<Implementation of exceptions procedures 248c>≡* (247a) 248e>  
 subroutine handle\_exception (exc)  
   type(exception), intent(inout) :: exc  
   character(len=10) :: name  
   if (exc%level > 0) then  
     select case (exc%level)  
       case (EXC\_NONE)  
         name = "(none)"  
       case (EXC\_INFO)  
         name = "info"  
       case (EXC\_WARN)  
         name = "warning"  
       case (EXC\_ERROR)  
         name = "error"  
       case (EXC\_FATAL)  
         name = "fatal"  
       case default  
         name = "invalid"  
     end select  
     print \*, trim (exc%origin), ": ", trim(name), ": ", trim (exc%message)  
     if (exc%level >= EXC\_FATAL) then  
       print \*, "terminated."  
       stop  
     end if  
   end if  
end subroutine handle\_exception

248d *<Declaration of exceptions procedures 248b>+≡* (247a) <248b  
 public :: raise\_exception, clear\_exception, gather\_exceptions

Raise an exception, but don't overwrite the messages in exc if it holds a more severe exception. This way we can accumulate error codes across procedure calls. We have exc optional to simplify life for the cslling procedures, which might have it optional themselves.

248e *<Implementation of exceptions procedures 248c>+≡* (247a) <248c 249a>  
 elemental subroutine raise\_exception (exc, level, origin, message)

```

type(exception), intent(inout), optional :: exc
integer, intent(in), optional :: level
character(len=*), intent(in), optional :: origin, message
integer :: local_level
if (present (exc)) then
  if (present (level)) then
    local_level = level
  else
    local_level = EXC_DEFAULT
  end if
  if (exc%level < local_level) then
    exc%level = local_level
    if (present (origin)) then
      exc%origin = origin
    else
      exc%origin = "[vamp]"
    end if
    if (present (message)) then
      exc%message = message
    else
      exc%message = "[vamp]"
    end if
  end if
end if
end subroutine raise_exception

```

249a *⟨Implementation of exceptions procedures 248c⟩+≡ (247a) <248e 249b>*

```

elemental subroutine clear_exception (exc)
  type(exception), intent(inout) :: exc
  exc%level = 0
  exc%message = ""
  exc%origin = ""
end subroutine clear_exception

```

249b *⟨Implementation of exceptions procedures 248c⟩+≡ (247a) <249a*

```

pure subroutine gather_exceptions (exc, excs)
  type(exception), intent(inout) :: exc
  type(exception), dimension(:), intent(in) :: excs
  integer :: i
  i = sum (maxloc (excs%level))
  if (exc%level < excs(i)%level) then
    call raise_exception (exc, excs(i)%level, excs(i)%origin, &
                        excs(i)%message)
  end if
end subroutine gather_exceptions

```

Here's how to use `gather_exceptions`. `elemental_procedure`

250 *<Idioms 101c>+≡*

*<101c*

```
call clear_exception (excs)
call elemental_procedure_1 (y, x, excs)
call elemental_procedure_2 (b, a, excs)
if (any (excs%level > 0)) then
  call gather_exceptions (exc, excs)
  return
end if
```

# —C—

## THE ART OF RANDOM NUMBERS

Volume two of Donald E. Knuth’ *The Art of Computer Programming* [16] has always been celebrated as a prime reference for random number generation. Recently, the third edition has been published and it contains a gem of a *portable* random number generator. It generates 30-bit integers with the following desirable properties

- they pass all the tests from George Marsaglia’s “diehard” suite of tests for random number generators [24] (but see [16] for a caveat regarding the “birthday-spacing” test)
- they can be generated with portable signed 32-bit arithmetic (Fortran can’t do unsigned arithmetic)
- it is faster than other lagged Fibonacci generators
- it can create at least  $2^{30} - 2$  independent sequences

We implement the improved versions available as FORTRAN77 code from

<http://www-cs-faculty.stanford.edu/~uno/programs.html#rng>

that contain a streamlined seeding algorithm with better independence of substreams.

### *C.1 Application Program Interface*

A function returning single reals and integers. Note that the static version without the `tao_random_state` argument does not require initialization. It will behave as if call `tao_random_seed(0)` had been executed. On the other hand, the parallelizable version with the explicit `tao_random_state` will fail

if none of the `tao_random_create` have been called for the state. (This is a deficiency of Fortran90 that can be fixed in Fortran95).

252a *<API documentation 252a>*≡ 252b>  
       call `tao_random_number` (`r`)  
       call `tao_random_number` (`s`, `r`)

The state of the random number generator comes in two varieties: buffered and raw. The former is much more efficient, but it can be beneficial to flush the buffers and to pass only the raw state in order to save of interprocess communication (IPC) costs.

252b *<API documentation 252a>*+≡ <252a 252c>  
       type(`tao_random_state`) :: `s`  
       type(`tao_random_raw_state`) :: `rs`

Subroutines filling arrays of reals and integers:

252c *<API documentation 252a>*+≡ <252b 252d>  
       call `tao_random_number` (`a`, `num` = `n`)  
       call `tao_random_number` (`s`, `a`, `num` = `n`)

Subroutine for changing the seed:

252d *<API documentation 252a>*+≡ <252c 252e>  
       call `tao_random_seed` (`seed` = `seed`)  
       call `tao_random_seed` (`s`, `seed` = `seed`)

Subroutine for changing the luxury. Per default, use all random numbers:

252e *<API documentation 252a>*+≡ <252d 252f>  
       call `tao_random_luxury` (`)`  
       call `tao_random_luxury` (`s`)

With an integer argument, use the first `n` of each fill of the buffer:

252f *<API documentation 252a>*+≡ <252e 252g>  
       call `tao_random_luxury` (`n`)  
       call `tao_random_luxury` (`s`, `n`)

With a floating point argument, use that fraction of each fill of the buffer:

252g *<API documentation 252a>*+≡ <252f 252h>  
       call `tao_random_luxury` (`x`)  
       call `tao_random_luxury` (`s`, `x`)

Create a `tao_random_state`

252h *<API documentation 252a>*+≡ <252g 253a>  
       call `tao_random_create` (`s`, `seed`, `buffer_size` = `buffer_size`)  
       call `tao_random_create` (`s`, `raw_state`, `buffer_size` = `buffer_size`)  
       call `tao_random_create` (`s`, `state`)

Create a `tao_random_raw_state`

253a *<API documentation 252a>+≡* <252h 253b>  
    call `tao_random_create` (rs, seed)  
    call `tao_random_create` (rs, raw\_state)  
    call `tao_random_create` (rs, state)

Destroy a `tao_random_state` or `tao_random_raw_state`

253b *<API documentation 252a>+≡* <253a 253c>  
    call `tao_random_destroy` (s)

Copy `tao_random_state` and `tao_random_raw_state` in all four combinations

253c *<API documentation 252a>+≡* <253b 253d>  
    call `tao_random_copy` (lhs, rhs)  
    lhs = rhs

253d *<API documentation 252a>+≡* <253c 253e>  
    call `tao_random_flush` (s)

253e *<API documentation 252a>+≡* <253d 253f>  
    call `tao_random_read` (s, unit)  
    call `tao_random_write` (s, unit)

253f *<API documentation 252a>+≡* <253e 253g>  
    call `tao_random_test` (name = name)

Here is a sample application of random number states:

253g *<API documentation 252a>+≡* <253f 253h>  
    **subroutine** threads (args, y, state)  
        real, dimension(:), intent(in) :: args  
        real, dimension(:), intent(out) :: y  
        type(`tao_random_state`) :: state  
        integer :: seed  
        type(`tao_random_raw_state`), dimension(size(y)) :: states  
        integer :: s  
        call `tao_random_number` (state, seed)  
        call `tao_random_create` (states, (/ (s, s=seed,size(y)-1) /))  
        y = thread (args, states)  
    **end function** thread

In this example, we could equivalently pass an integer seed, instead of `raw_state`. But in more complicated cases it can be beneficial to have the option of reusing `raw_state` in the calling routine.

253h *<API documentation 252a>+≡* <253g  
    **elemental function** thread (arg, raw\_state) result (y)  
        real, dimension, intent(in) :: arg  
        type(`tao_random_raw_state`) :: raw\_state  
        real :: y

```

type(tao_random_state) :: state
real :: r
call tao_random_create (state, raw_state)
do
  ...
  call tao_random_number (state, r)
  ...
end do
end function thread

```

## C.2 Low Level Routines

Here the low level routines are *much* more interesting than the high level routines. The latter contain a lot of duplication (made necessary by Fortran's lack of parametric polymorphism) and consist mostly of bookkeeping. We wil therefore start with the former.

### C.2.1 Generation of 30-bit Random Numbers

The generator is a subtractive lagged Fibonacci

$$X_j = (X_{j-K} - X_{j-L}) \mod 2^{30} \quad (\text{C.1})$$

with lags  $K = 100$  and  $L = 37$ .

254a  $\langle$ Parameters in tao\_random\_numbers 254a $\rangle \equiv$  (273d 274a) 255a $\triangleright$

```
integer, parameter, private :: K = 100, L = 37
```

Other good choices for  $K$  and  $L$  are (cf. [16], table 1 in section 3.2.2, p. 29)

254b  $\langle$ Parameters in tao\_random\_numbers (alternatives) 254b $\rangle \equiv$

```

integer, parameter, private :: K = 55, L = 24
integer, parameter, private :: K = 89, L = 38
integer, parameter, private :: K = 100, L = 37
integer, parameter, private :: K = 127, L = 30
integer, parameter, private :: K = 258, L = 83
integer, parameter, private :: K = 378, L = 107
integer, parameter, private :: K = 607, L = 273

```

A modulus of  $2^{30}$  is the largest we can handle in *portable* (i.e. *signed*) 32-bit arithmetic

254c  $\langle$ Variables in 30-bit tao\_random\_numbers 254c $\rangle \equiv$  (273d) 256b $\triangleright$

```
integer(kind=tao_i32), parameter, private :: M = 2**30
```

**generate** fills the array  $a_1, \dots, a_n$  with random integers  $0 \leq a_i < 2^{30}$ . We *must* have at least  $n \geq K$ . Higher values don't change the results, but make **generate** more efficient (about a factor of two, asymptotically). For  $K = 100$ , DEK recommends  $n \geq 1000$ . Best results are obtained using the first 100 random numbers out of 1009. Let's therefore use 1009 as a default buffer size. The user can call **tao\_random\_luxury** (100) him/herself:

255a  $\langle$ Parameters in **tao\_random\_numbers** 254a $\rangle + \equiv$  (273d 274a)  $\triangleleft$ 254a  
integer, parameter, private :: **DEFAULT\_BUFFER\_SIZE** = 1009

Since users are not expected to call **generate** directly, we do *not* check for  $n \geq K$  and assume that the caller knows what (s)he's doing ...

255b  $\langle$ Implementation of 30-bit **tao\_random\_numbers** 255b $\rangle \equiv$  (273d) 255e $\triangleright$   
pure subroutine **generate** (a, state)  
integer(kind=tao\_i32), dimension(:), intent(inout) :: a, state  
integer :: j, n  
n = size (a)  
 $\langle$ Load a and refresh state 255d $\rangle$   
end subroutine **generate**

255c  $\langle$ Declaration of **tao\_random\_numbers** 255c $\rangle \equiv$  (273d 274a) 259b $\triangleright$   
private :: **generate**

**state(1:K)** is already set up properly:

255d  $\langle$ Load a and refresh state 255d $\rangle \equiv$  (255b) 255e $\triangleright$   
**a(1:K)** = **state(1:K)**

The remaining  $n - K$  random numbers can be gotten directly from the recursion (C.1). Note that Fortran90's **modulo** intrinsic does the right thing, since it guarantees (unlike Fortran77's **mod**) that  $0 \leq \text{modulo}(a, m) < a$  if  $m > 0$ ).

255e  $\langle$ Load a and refresh state 255d $\rangle + \equiv$  (255b)  $\triangleleft$ 255d 255f $\triangleright$   
do j = K+1, n  
**a(j)** = **modulo** (**a(j-K)** - **a(j-L)**, **M**)  
end do

Do the recursion (C.1)  $K$  more times to prepare **state(1:K)** for the next invocation of **generate**.

255f  $\langle$ Load a and refresh state 255d $\rangle + \equiv$  (255b)  $\triangleleft$ 255e  
**state(1:L)** = **modulo** (**a(n+1-K:n+L-K)** - **a(n+1-L:n)**, **M**)  
do j = L+1, K  
**state(j)** = **modulo** (**a(n+j-K)** - **state(j-L)**, **M**)  
end do



## C.2.2 Initialization of 30-bit Random Numbers

The non-trivial and most beautiful part is the algorithm to initialize the random number generator state `state` with the first  $K$  numbers. I haven't studied algebra over finite fields in sufficient depth to consider the mathematics behind it straightforward. The commentary below is rather verbose and reflects my understanding of DEK's rather terse remarks (solution to exercise 3.6-9 [16]).

256a *<Implementation of tao\_random\_numbers 256a>*≡ (273d 274a) 256c>  
`subroutine seed_static (seed)`  
`integer, optional, intent(in) :: seed`  
`call seed_stateless (s_state, seed)`  
`s_virginal = .false.`  
`s_last = size (s_buffer)`  
`end subroutine seed_static`

The static version of `tao_random_raw_state`:

256b *<Variables in 30-bit tao\_random\_numbers 254c>*+≡ (273d) <254c 275c>  
`integer(kind=tao_i32), dimension(K), save, private :: s_state`  
`logical, save, private :: s_virginal = .true.`

256c *<Implementation of tao\_random\_numbers 256a>*+≡ (273d 274a) <256a 256d>  
`elemental subroutine seed_raw_state (s, seed)`  
`type(tao_random_raw_state), intent(inout) :: s`  
`integer, optional, intent(in) :: seed`  
`call seed_stateless (s%x, seed)`  
`end subroutine seed_raw_state`

256d *<Implementation of tao\_random\_numbers 256a>*+≡ (273d 274a) <256c 262d>  
`elemental subroutine seed_state (s, seed)`  
`type(tao_random_state), intent(inout) :: s`  
`integer, optional, intent(in) :: seed`  
`call seed_raw_state (s%state, seed)`  
`s%last = size (s%buffer)`  
`end subroutine seed_state`

This incarnation of the procedure is pure.

256e *<Implementation of 30-bit tao\_random\_numbers 255b>*+≡ (273d) <255b 267c>  
`pure subroutine seed_stateless (state, seed)`  
`integer(kind=tao_i32), dimension(:), intent(out) :: state`  
`integer, optional, intent(in) :: seed`  
*<Parameters local to tao\_random\_seed 257a>*  
`integer :: seed_value, j, s, t`  
`integer(kind=tao_i32), dimension(2*K-1) :: x`  
*<Set up seed\_value from seed or DEFAULT\_SEED 257c>*

```

    <Bootstrap the x buffer 257d>
    <Set up s and t 257f>
    do
        <p(z) → p(z)2 (modulo zK + zL + 1) 258a>
        <p(z) → zp(z) (modulo zK + zL + 1) 258c>
        <Shift s or t and exit if t ≤ 0 258d>
    end do
    <Fill state from x 258e>
    <Warm up state 258f>
    end subroutine seed_stateless

```

Any default will do

```

257a <Parameters local to tao_random_seed 257a>≡ (256e 260a) 257b>
    integer, parameter :: DEFAULT_SEED = 0

```

These must not be changed:

```

257b <Parameters local to tao_random_seed 257a>+≡ (256e 260a) <257a
    integer, parameter :: MAX_SEED = 2**30 - 3
    integer, parameter :: TT = 70

```

```

257c <Set up seed_value from seed or DEFAULT_SEED 257c>≡ (256e 260a)
    if (present (seed)) then
        seed_value = modulo (seed, MAX_SEED + 1)
    else
        seed_value = DEFAULT_SEED
    end if

```

Fill the array  $x_1, \dots, x_K$  with even integers, shifted cyclically by 29 bits.

```

257d <Bootstrap the x buffer 257d>≡ (256e) 257e>
    s = seed_value - modulo (seed_value, 2) + 2
    do j = 1, K
        x(j) = s
        s = 2*s
        if (s >= M) then
            s = s - M + 2
        end if
    end do
    x(K+1:2*K-1) = 0

```

Make  $x_2$  (and only  $x_2$ ) odd:

```

257e <Bootstrap the x buffer 257d>+≡ (256e) <257d
    x(2) = x(2) + 1

```

```

257f <Set up s and t 257f>≡ (256e 260a)
    s = seed_value
    t = TT - 1

```

Consider the polynomial

$$p(z) = \sum_{n=1}^K x_n z^{n-1} = x_K z^{K-1} + \dots + x_2 z + x_1 \quad (\text{C.2})$$

We have  $p(z)^2 = p(z^2) \pmod{2}$  because cross terms have an even coefficient and  $x_n^2 = x_n \pmod{2}$ . Therefore we can square the polynomial by shifting the coefficients. The coefficients for  $n > K$  will be reduced.

258a  $\langle p(z) \rightarrow p(z)^2 \pmod{z^K + z^L + 1} \text{ 258a} \rangle \equiv$  (256e) 258b  $\triangleright$   
 $\mathbf{x}(3:2*K-1:2) = \mathbf{x}(2:K)$   
 $\mathbf{x}(2:2*K-2:2) = 0$

Let's return to the coefficients for  $n > K$  generated by the shifting above. Subtract  $z^n(z^K + z^L + 1) = z^n z^K (1 + z^{-(K-L)} + z^{-K})$ . The coefficient of  $z^n z^K$  is left alone, because it doesn't belong to  $p(z)$  anyway.

258b  $\langle p(z) \rightarrow p(z)^2 \pmod{z^K + z^L + 1} \text{ 258a} \rangle + \equiv$  (256e)  $\triangleleft$  258a  
do  $\mathbf{j} = 2*K-1, K+1, -1$   
 $\mathbf{x}(\mathbf{j}-(K-L)) = \text{modulo } (\mathbf{x}(\mathbf{j}-(K-L))-\mathbf{x}(\mathbf{j}), \mathbf{M})$   
 $\mathbf{x}(\mathbf{j}-K) = \text{modulo } (\mathbf{x}(\mathbf{j}-K)-\mathbf{x}(\mathbf{j}), \mathbf{M})$   
end do

258c  $\langle p(z) \rightarrow zp(z) \pmod{z^K + z^L + 1} \text{ 258c} \rangle \equiv$  (256e)  
if (modulo (s, 2) == 1) then  
 $\mathbf{x}(2:K+1) = \mathbf{x}(1:K)$   
 $\mathbf{x}(1) = \mathbf{x}(K+1)$   
 $\mathbf{x}(L+1) = \text{modulo } (\mathbf{x}(L+1) - \mathbf{x}(K+1), \mathbf{M})$   
end if

258d  $\langle \text{Shift s or t and exit if } t \leq 0 \text{ 258d} \rangle \equiv$  (256e 260a)  
if (s /= 0) then  
 $\mathbf{s} = \mathbf{s} / 2$   
else  
 $\mathbf{t} = \mathbf{t} - 1$   
end if  
if (t <= 0) then  
exit  
end if

258e  $\langle \text{Fill state from x 258e} \rangle \equiv$  (256e 260a)  
 $\text{state}(1:K-L) = \mathbf{x}(L+1:K)$   
 $\text{state}(K-L+1:K) = \mathbf{x}(1:L)$

258f  $\langle \text{Warm up state 258f} \rangle \equiv$  (256e 260a)  
do  $\mathbf{j} = 1, 10$   
call generate (x, state)  
end do

259a *<Interfaces of tao\_random\_numbers 259a>*≡ (273d 274a) 262a>  
 interface **tao\_random\_seed**  
   module procedure *<Specific procedures for tao\_random\_seed 259c>*  
 end interface

259b *<Declaration of tao\_random\_numbers 255c>*+≡ (273d 274a) <255c 260b>  
 private :: *<Specific procedures for tao\_random\_seed 259c>*

259c *<Specific procedures for tao\_random\_seed 259c>*≡ (259)  
**seed\_static, seed\_state, seed\_raw\_state**

### C.2.3 Generation of 52-bit Random Numbers

$$X_j = (X_{j-K} + X_{j-L}) \mod 1 \quad (\text{C.3})$$

259d *<Variables in 52-bit tao\_random\_numbers 259d>*≡ (274a) 259e>  
 real(kind=tao\_r64), parameter, private :: **M = 1.0\_tao\_r64**

The state of the internal routines

259e *<Variables in 52-bit tao\_random\_numbers 259d>*+≡ (274a) <259d 276b>  
 real(kind=tao\_r64), dimension(**K**), save, private :: **s\_state**  
 logical, save, private :: **s\_virginal = .true.**

259f *<Implementation of 52-bit tao\_random\_numbers 259f>*≡ (274a) 260a>  
 pure **subroutine generate** (a, state)  
   real(kind=tao\_r64), dimension(:), intent(inout) :: a  
   real(kind=tao\_r64), dimension(:), intent(inout) :: state  
   integer :: **j, n**  
   **n = size (a)**  
   *<Load 52-bit a and refresh state 259g>*  
 end **subroutine generate**

That's almost identical to the 30-bit version, except that the relative sign is flipped:

259g *<Load 52-bit a and refresh state 259g>*≡ (259f)  
 a(1:**K**) = state(1:**K**)  
 do **j = K+1, n**  
   a(**j**) = modulo (a(**j-K**) + a(**j-L**), **M**)  
 end do  
 state(1:**L**) = modulo (a(n+1-**K**:n+**L-K**) + a(n+1-**L**:n), **M**)  
 do **j = L+1, K**  
   state(**j**) = modulo (a(n+**j-K**) + state(**j-L**), **M**)  
 end do

## C.2.4 Initialization of 52-bit Random Numbers

This incarnation of the procedure is pure.

```

260a  <Implementation of 52-bit tao_random_numbers 259f>+≡      (274a) <259f 268a>
      pure subroutine seed_stateless (state, seed)
        real(kind=tao_r64), dimension(:), intent(out) :: state
        integer, optional, intent(in) :: seed
        <Parameters local to tao_random_seed 257a>
        <Variables local to 52-bit tao_random_seed 260c>
        <Set up seed_value from seed or DEFAULT_SEED 257c>
        <Bootstrap the 52-bit x buffer 260e>
        <Set up s and t 257f>
        do
          <52-bit  $p(z) \rightarrow p(z)^2$  (modulo  $z^K + z^L + 1$ ) 261a>
          <52-bit  $p(z) \rightarrow zp(z)$  (modulo  $z^K + z^L + 1$ ) 261c>
          <Shift s or t and exit if  $t \leq 0$  258d>
        end do
        <Fill state from x 258e>
        <Warm up state 258f>
      end subroutine seed_stateless

260b  <Declaration of tao_random_numbers 255c>+≡      (273d 274a) <259b 262b>
      private :: seed_stateless

260c  <Variables local to 52-bit tao_random_seed 260c>≡      (260a) 260d>
      real(kind=tao_r64), parameter :: ULP = 2.0_tao_r64**(-52)

260d  <Variables local to 52-bit tao_random_seed 260c>+≡      (260a) <260c
      real(kind=tao_r64), dimension(2*K-1) :: x
      real(kind=tao_r64) :: ss
      integer :: seed_value, t, s, j

260e  <Bootstrap the 52-bit x buffer 260e>≡      (260a) 260f>
      ss = 2*ULP * (seed_value + 2)
      do j = 1, K
        x(j) = ss
        ss = 2*ss
        if (ss >= 1) then
          ss = ss - 1 + 2*ULP
        end if
      end do
      x(K+1:2*K-1) = 0.0

260f  <Bootstrap the 52-bit x buffer 260e>+≡      (260a) <260e
      x(2) = x(2) + ULP

```

261a  $\langle 52\text{-bit } p(z) \rightarrow p(z)^2 \text{ (modulo } z^K + z^L + 1) \text{ 261a)} \equiv$  (260a) 261b $\triangleright$

$x(3:2*K-1:2) = x(2:K)$   
 $x(2:2*K-2:2) = 0$

This works because  $2*K-1$  is odd

261b  $\langle 52\text{-bit } p(z) \rightarrow p(z)^2 \text{ (modulo } z^K + z^L + 1) \text{ 261a)} + \equiv$  (260a)  $\triangleleft$  261a

do  $j = 2*K-1, K+1, -1$   
 $x(j-(K-L)) = \text{modulo } (x(j-(K-L)) + x(j), M)$   
 $x(j-K) = \text{modulo } (x(j-K) + x(j), M)$   
end do

261c  $\langle 52\text{-bit } p(z) \rightarrow zp(z) \text{ (modulo } z^K + z^L + 1) \text{ 261c)} \equiv$  (260a)

if (modulo (s, 2) == 1) THEN  
 $x(2:K+1) = x(1:K)$   
 $x(1) = x(K+1)$   
 $x(L+1) = \text{modulo } (x(L+1) + x(K+1), M)$   
end if

### C.3 The State

261d  $\langle \text{Declaration of 30-bit tao\_random\_numbers types 261d)} \equiv$  (273d) 261e $\triangleright$

type, public :: tao\_random\_raw\_state  
private  
integer(kind=tao\_i32), dimension(K) :: x  
end type tao\_random\_raw\_state

261e  $\langle \text{Declaration of 30-bit tao\_random\_numbers types 261d)} + \equiv$  (273d)  $\triangleleft$  261d

type, public :: tao\_random\_state  
private  
type(tao\_random\_raw\_state) :: state  
integer(kind=tao\_i32), dimension(:), pointer :: buffer => null ()  
integer :: buffer\_end, last  
end type tao\_random\_state

261f  $\langle \text{Declaration of 52-bit tao\_random\_numbers types 261f)} \equiv$  (274a) 261g $\triangleright$

type, public :: tao\_random\_raw\_state  
private  
real(kind=tao\_r64), dimension(K) :: x  
end type tao\_random\_raw\_state

261g  $\langle \text{Declaration of 52-bit tao\_random\_numbers types 261f)} + \equiv$  (274a)  $\triangleleft$  261f

type, public :: tao\_random\_state  
private  
type(tao\_random\_raw\_state) :: state  
real(kind=tao\_r64), dimension(:), pointer :: buffer => null ()

```

        integer :: buffer_end, last
    end type tao_random_state

```

### C.3.1 Creation

- 262a *<Interfaces of tao\_random\_numbers 259a>+≡ (273d 274a) <259a 263e>*  

```

    interface tao_random_create
        module procedure <Specific procedures for tao_random_create 262c>
    end interface

```
- 262b *<Declaration of tao\_random\_numbers 255c>+≡ (273d 274a) <260b 264a>*  

```

    private :: <Specific procedures for tao_random_create 262c>

```
- 262c *<Specific procedures for tao\_random\_create 262c>≡ (262)*  

```

    create_state_from_seed, create_raw_state_from_seed, &
    create_state_from_state, create_raw_state_from_state, &
    create_state_from_raw_state, create_raw_state_from_raw_st

```

There are no procedures for copying the state of the static generator to or from an explicit `tao_random_state`. Users needing this functionality can be expected to handle explicit states anyway. Since the direction of the copying can not be obvious from the type of the argument, such functions would spoil the simplicity of the generic procedure interface.

- 262d *<Implementation of tao\_random\_numbers 256a>+≡ (273d 274a) <256d 262e>*  

```

    elemental subroutine create_state_from_seed (s, seed, buffer_size)
        type(tao_random_state), intent(out) :: s
        integer, intent(in) :: seed
        integer, intent(in), optional :: buffer_size
        call create_raw_state_from_seed (s%state, seed)
        if (present (buffer_size)) then
            s%buffer_end = max (buffer_size, K)
        else
            s%buffer_end = DEFAULT_BUFFER_SIZE
        end if
        allocate (s%buffer(s%buffer_end))
        call tao_random_flush (s)
    end subroutine create_state_from_seed

```
- 262e *<Implementation of tao\_random\_numbers 256a>+≡ (273d 274a) <262d 263a>*  

```

    elemental subroutine create_state_from_state (s, state)
        type(tao_random_state), intent(out) :: s
        type(tao_random_state), intent(in) :: state
        call create_raw_state_from_raw_st (s%state, state%state)
        allocate (s%buffer(size(state%buffer)))
        call tao_random_copy (s, state)

```

```

end subroutine create_state_from_state
263a <Implementation of tao_random_numbers 256a>+≡ (273d 274a) <262e 263b>
elemental subroutine create_state_from_raw_state &
    (s, raw_state, buffer_size)
    type(tao_random_state), intent(out) :: s
    type(tao_random_raw_state), intent(in) :: raw_state
    integer, intent(in), optional :: buffer_size
    call create_raw_state_from_raw_st (s%state, raw_state)
    if (present (buffer_size)) then
        s%buffer_end = max (buffer_size, K)
    else
        s%buffer_end = DEFAULT_BUFFER_SIZE
    end if
    allocate (s%buffer(s%buffer_end))
    call tao_random_flush (s)
end subroutine create_state_from_raw_state
263b <Implementation of tao_random_numbers 256a>+≡ (273d 274a) <263a 263c>
elemental subroutine create_raw_state_from_seed (s, seed)
    type(tao_random_raw_state), intent(out) :: s
    integer, intent(in) :: seed
    call seed_raw_state (s, seed)
end subroutine create_raw_state_from_seed
263c <Implementation of tao_random_numbers 256a>+≡ (273d 274a) <263b 263d>
elemental subroutine create_raw_state_from_state (s, state)
    type(tao_random_raw_state), intent(out) :: s
    type(tao_random_state), intent(in) :: state
    call copy_state_to_raw_state (s, state)
end subroutine create_raw_state_from_state
263d <Implementation of tao_random_numbers 256a>+≡ (273d 274a) <263c 264b>
elemental subroutine create_raw_state_from_raw_st (s, raw_state)
    type(tao_random_raw_state), intent(out) :: s
    type(tao_random_raw_state), intent(in) :: raw_state
    call copy_raw_state (s, raw_state)
end subroutine create_raw_state_from_raw_st

```

### C.3.2 Destruction

```

263e <Interfaces of tao_random_numbers 259a>+≡ (273d 274a) <262a 264d>
interface tao_random_destroy
    module procedure destroy_state, destroy_raw_state
end interface

```



264a *<Declaration of tao\_random\_numbers 255c>+≡* (273d 274a) *<262b 264f>*  
`private :: destroy_state, destroy_raw_state`

264b *<Implementation of tao\_random\_numbers 256a>+≡* (273d 274a) *<263d 264c>*  
`elemental subroutine destroy_state (s)  
type(tao_random_state), intent(inout) :: s  
deallocate (s%buffer)  
end subroutine destroy_state`

Currently, this is a no-op, but we might need a non-trivial destruction method in the future

264c *<Implementation of tao\_random\_numbers 256a>+≡* (273d 274a) *<264b 264h>*  
`elemental subroutine destroy_raw_state (s)  
type(tao_random_raw_state), intent(inout) :: s  
end subroutine destroy_raw_state`

### C.3.3 Copying

264d *<Interfaces of tao\_random\_numbers 259a>+≡* (273d 274a) *<263e 264e>*  
`interface tao_random_copy  
module procedure <Specific procedures for tao_random_copy 264g>  
end interface`

264e *<Interfaces of tao\_random\_numbers 259a>+≡* (273d 274a) *<264d 265e>*  
`interface assignment(=)  
module procedure <Specific procedures for tao_random_copy 264g>  
end interface`

264f *<Declaration of tao\_random\_numbers 255c>+≡* (273d 274a) *<264a 266a>*  
`public :: assignment(=)  
private :: <Specific procedures for tao_random_copy 264g>`

264g *<Specific procedures for tao\_random\_copy 264g>≡* (264)  
`copy_state, copy_raw_state, &  
copy_raw_state_to_state, copy_state_to_raw_state`

264h *<Implementation of tao\_random\_numbers 256a>+≡* (273d 274a) *<264c 265a>*  
`elemental subroutine copy_state (lhs, rhs)  
type(tao_random_state), intent(inout) :: lhs  
type(tao_random_state), intent(in) :: rhs  
call copy_raw_state (lhs%state, rhs%state)  
if (size (lhs%buffer) /= size (rhs%buffer)) then  
deallocate (lhs%buffer)  
allocate (lhs%buffer(size(rhs%buffer)))  
end if  
lhs%buffer = rhs%buffer`

```

    lhs%buffer_end = rhs%buffer_end
    lhs%last = rhs%last
end subroutine copy_state
265a <Implementation of tao_random_numbers 256a>+≡ (273d 274a) <264h 265b>
    elemental subroutine copy_raw_state (lhs, rhs)
        type(tao_random_raw_state), intent(out) :: lhs
        type(tao_random_raw_state), intent(in) :: rhs
        lhs%x = rhs%x
    end subroutine copy_raw_state
265b <Implementation of tao_random_numbers 256a>+≡ (273d 274a) <265a 265c>
    elemental subroutine copy_raw_state_to_state (lhs, rhs)
        type(tao_random_state), intent(inout) :: lhs
        type(tao_random_raw_state), intent(in) :: rhs
        call copy_raw_state (lhs%state, rhs)
        call tao_random_flush (lhs)
    end subroutine copy_raw_state_to_state
265c <Implementation of tao_random_numbers 256a>+≡ (273d 274a) <265b 265d>
    elemental subroutine copy_state_to_raw_state (lhs, rhs)
        type(tao_random_raw_state), intent(out) :: lhs
        type(tao_random_state), intent(in) :: rhs
        call copy_raw_state (lhs, rhs%state)
    end subroutine copy_state_to_raw_state

```

### C.3.4 Flushing

```

265d <Implementation of tao_random_numbers 256a>+≡ (273d 274a) <265c 266d>
    elemental subroutine tao_random_flush (s)
        type(tao_random_state), intent(inout) :: s
        s%last = size (s%buffer)
    end subroutine tao_random_flush

```

### C.3.5 Input and Output

```

265e <Interfaces of tao_random_numbers 259a>+≡ (273d 274a) <264e 266b>
    interface tao_random_write
        module procedure &
            write_state_unit, write_state_name, &
            write_raw_state_unit, write_raw_state_name
    end interface

```

```

266a  <Declaration of tao_random_numbers 255c>+≡ (273d 274a) <264f 266c>
      private :: write_state_unit, write_state_name
      private :: write_raw_state_unit, write_raw_state_name

266b  <Interfaces of tao_random_numbers 259a>+≡ (273d 274a) <265e 270b>
      interface tao_random_read
        module procedure &
          read_state_unit, read_state_name, &
          read_raw_state_unit, read_raw_state_name
      end interface

266c  <Declaration of tao_random_numbers 255c>+≡ (273d 274a) <266a 269b>
      private :: read_state_unit, read_state_name
      private :: read_raw_state_unit, read_raw_state_name

266d  <Implementation of tao_random_numbers 256a>+≡ (273d 274a) <265d 266e>
      subroutine write_state_unit (s, unit)
        type(tao_random_state), intent(in) :: s
        integer, intent(in) :: unit
        write (unit = unit, fmt = *) "BEGIN TAO_RANDOM_STATE"
        call write_raw_state_unit (s%state, unit)
        write (unit = unit, fmt = "(2(1x,a16,1x,i10/),1x,a16,1x,i10)") &
          "BUFFER_SIZE", size (s%buffer), &
          "BUFFER_END", s%buffer_end, &
          "LAST", s%last
        write (unit = unit, fmt = *) "BEGIN BUFFER"
        call write_state_array (s%buffer, unit)
        write (unit = unit, fmt = *) "END BUFFER"
        write (unit = unit, fmt = *) "END TAO_RANDOM_STATE"
      end subroutine write_state_unit

266e  <Implementation of tao_random_numbers 256a>+≡ (273d 274a) <266d 267a>
      subroutine read_state_unit (s, unit)
        type(tao_random_state), intent(inout) :: s
        integer, intent(in) :: unit
        integer :: buffer_size
        read (unit = unit, fmt = *)
        call read_raw_state_unit (s%state, unit)
        read (unit = unit, fmt = "(2(1x,16x,1x,i10/),1x,16x,1x,i10)") &
          buffer_size, s%buffer_end, s%last
        read (unit = unit, fmt = *)
        if (buffer_size /= size (s%buffer)) then
          deallocate (s%buffer)
          allocate (s%buffer(buffer_size))
        end if
        call read_state_array (s%buffer, unit)

```

```

        read (unit = unit, fmt = *)
        read (unit = unit, fmt = *)
    end subroutine read_state_unit
267a <Implementation of tao_random_numbers 256a>+≡ (273d 274a) <266e 267b>
    subroutine write_raw_state_unit (s, unit)
        type(tao_random_raw_state), intent(in) :: s
        integer, intent(in) :: unit
        write (unit = unit, fmt = *) "BEGIN TAO_RANDOM_RAW_STATE"
        call write_state_array (s%x, unit)
        write (unit = unit, fmt = *) "END TAO_RANDOM_RAW_STATE"
    end subroutine write_raw_state_unit
267b <Implementation of tao_random_numbers 256a>+≡ (273d 274a) <267a 268e>
    subroutine read_raw_state_unit (s, unit)
        type(tao_random_raw_state), intent(inout) :: s
        integer, intent(in) :: unit
        read (unit = unit, fmt = *)
        call read_state_array (s%x, unit)
        read (unit = unit, fmt = *)
    end subroutine read_raw_state_unit
267c <Implementation of 30-bit tao_random_numbers 255b>+≡ (273d) <256e 267e>
    subroutine write_state_array (a, unit)
        integer(kind=tao_i32), dimension(:), intent(in) :: a
        integer, intent(in) :: unit
        integer :: i
        do i = 1, size (a)
            write (unit = unit, fmt = "(1x,i10,1x,i10)") i, a(i)
        end do
    end subroutine write_state_array
267d <Declaration of 30-bit tao_random_numbers 267d>≡ (273d) 267f>
    private :: write_state_array
267e <Implementation of 30-bit tao_random_numbers 255b>+≡ (273d) <267c 270d>
    subroutine read_state_array (a, unit)
        integer(kind=tao_i32), dimension(:), intent(inout) :: a
        integer, intent(in) :: unit
        integer :: i, idum
        do i = 1, size (a)
            read (unit = unit, fmt = *) idum, a(i)
        end do
    end subroutine read_state_array
267f <Declaration of 30-bit tao_random_numbers 267d>+≡ (273d) <267d 281c>
    private :: read_state_array

```

Reading and writing 52-bit floating point numbers accurately is beyond most Fortran runtime libraries. Their job is simplified considerably if we rescale by  $2^{52}$  before writing. Then the temptation to truncate will not be as overwhelming as before ...

- 268a  $\langle$ Implementation of 52-bit tao\_random\_numbers 259f $\rangle + \equiv$  (274a)  $\langle$ 260a 268c $\rangle$   

```

subroutine write_state_array (a, unit)
  real(kind=tao_r64), dimension(:), intent(in) :: a
  integer, intent(in) :: unit
  integer :: i
  do i = 1, size (a)
    write (unit = unit, fmt = "(1x,i10,1x,f30.0)") i, 2.0_tao_r64**52 * a(i)
  end do
end subroutine write_state_array

```

268b  $\langle$ Declaration of 52-bit tao\_random\_numbers 268b $\rangle \equiv$  (274a) 268d $\rangle$   

```

private :: write_state_array

```

268c  $\langle$ Implementation of 52-bit tao\_random\_numbers 259f $\rangle + \equiv$  (274a)  $\langle$ 268a 272b $\rangle$   

```

subroutine read_state_array (a, unit)
  real(kind=tao_r64), dimension(:), intent(inout) :: a
  integer, intent(in) :: unit
  real(kind=tao_r64) :: x
  integer :: i, idum
  do i = 1, size (a)
    read (unit = unit, fmt = *) idum, x
    a(i) = 2.0_tao_r64**(-52) * x
  end do
end subroutine read_state_array

```

268d  $\langle$ Declaration of 52-bit tao\_random\_numbers 268b $\rangle + \equiv$  (274a)  $\langle$ 268b 281g $\rangle$   

```

private :: read_state_array

```

268e  $\langle$ Implementation of tao\_random\_numbers 256a $\rangle + \equiv$  (273d 274a)  $\langle$ 267b 269c $\rangle$   

```

subroutine find_free_unit (u, iostat)
  integer, intent(out) :: u
  integer, intent(out), optional :: iostat
  logical :: exists, is_open
  integer :: i, status
  do i = MIN_UNIT, MAX_UNIT
    inquire (unit = i, exist = exists, opened = is_open, &
      iostat = iostat)
    if (status == 0) then
      if (exists .and. .not. is_open) then
        u = i
        if (present (iostat)) then

```

```

        iostat = 0
    end if
    return
end if
end do
if (present (iostat)) then
    iostat = -1
end if
u = -1
end subroutine find_free_unit

```

269a *<Variables in tao\_random\_numbers 269a>*≡ (273d 274a)

```
integer, parameter, private :: MIN_UNIT = 11, MAX_UNIT = 99
```

269b *<Declaration of tao\_random\_numbers 255c>*+≡ (273d 274a) <266c 270c>

```
private :: find_free_unit
```

269c *<Implementation of tao\_random\_numbers 256a>*+≡ (273d 274a) <268e 269d>

```

subroutine write_state_name (s, name)
    type(tao_random_state), intent(in) :: s
    character(len=*), intent(in) :: name
    integer :: unit
    call find_free_unit (unit)
    open (unit = unit, action = "write", status = "replace", file = name)
    call write_state_unit (s, unit)
    close (unit = unit)
end subroutine write_state_name

```

269d *<Implementation of tao\_random\_numbers 256a>*+≡ (273d 274a) <269c 269e>

```

subroutine write_raw_state_name (s, name)
    type(tao_random_raw_state), intent(in) :: s
    character(len=*), intent(in) :: name
    integer :: unit
    call find_free_unit (unit)
    open (unit = unit, action = "write", status = "replace", file = name)
    call write_raw_state_unit (s, unit)
    close (unit = unit)
end subroutine write_raw_state_name

```

269e *<Implementation of tao\_random\_numbers 256a>*+≡ (273d 274a) <269d 270a>

```

subroutine read_state_name (s, name)
    type(tao_random_state), intent(inout) :: s
    character(len=*), intent(in) :: name
    integer :: unit

```

```

        call find_free_unit (unit)
        open (unit = unit, action = "read", status = "old", file = name)
        call read_state_unit (s, unit)
        close (unit = unit)
    end subroutine read_state_name
270a <Implementation of tao_random_numbers 256a>+≡ (273d 274a) <269e 281i>
    subroutine read_raw_state_name (s, name)
        type(tao_random_raw_state), intent(inout) :: s
        character(len=*), intent(in) :: name
        integer :: unit
        call find_free_unit (unit)
        open (unit = unit, action = "read", status = "old", file = name)
        call read_raw_state_unit (s, unit)
        close (unit = unit)
    end subroutine read_raw_state_name

```

### C.3.6 Marshaling and Unmarshaling

Note that we can not use the transfer intrinsic function for marshalling types that contain pointers that substitute for allocatable array components. transfer will copy the pointers in this case and not where they point to!

```

270b <Interfaces of tao_random_numbers 259a>+≡ (273d 274a) <266b>
    interface tao_random_marshall_size
        module procedure marshal_state_size, marshal_raw_state_size
    end interface
    interface tao_random_marshall
        module procedure marshal_state, marshal_raw_state
    end interface
    interface tao_random_unmarshal
        module procedure unmarshal_state, unmarshal_raw_state
    end interface
270c <Declaration of tao_random_numbers 255c>+≡ (273d 274a) <269b 274b>
    public :: tao_random_marshall
    private :: marshal_state, marshal_raw_state
    public :: tao_random_marshall_size
    private :: marshal_state_size, marshal_raw_state_size
    public :: tao_random_unmarshal
    private :: unmarshal_state, unmarshal_raw_state
270d <Implementation of 30-bit tao_random_numbers 255b>+≡ (273d) <267e 271a>
    pure subroutine marshal_state (s, ibuf, dbuf)
        type(tao_random_state), intent(in) :: s

```

```

integer, dimension(:), intent(inout) :: ibuf
real(kind=tao_r64), dimension(:), intent(inout) :: dbuf
integer :: buf_size
buf_size = size (s%buffer)
ibuf(1) = s%buffer_end
ibuf(2) = s%last
ibuf(3) = buf_size
ibuf(4:3+buf_size) = s%buffer
call marshal_raw_state (s%state, ibuf(4+buf_size:), dbuf)
end subroutine marshal_state
271a <Implementation of 30-bit tao_random_numbers 255b>+≡ (273d) <270d 271b>
pure subroutine marshal_state_size (s, iwords, dwords)
type(tao_random_state), intent(in) :: s
integer, intent(out) :: iwords, dwords
call marshal_raw_state_size (s%state, iwords, dwords)
iwords = iwords + 3 + size (s%buffer)
end subroutine marshal_state_size
271b <Implementation of 30-bit tao_random_numbers 255b>+≡ (273d) <271a 271c>
pure subroutine unmarshal_state (s, ibuf, dbuf)
type(tao_random_state), intent(inout) :: s
integer, dimension(:), intent(in) :: ibuf
real(kind=tao_r64), dimension(:), intent(in) :: dbuf
integer :: buf_size
s%buffer_end = ibuf(1)
s%last = ibuf(2)
buf_size = ibuf(3)
s%buffer = ibuf(4:3+buf_size)
call unmarshal_raw_state (s%state, ibuf(4+buf_size:), dbuf)
end subroutine unmarshal_state
271c <Implementation of 30-bit tao_random_numbers 255b>+≡ (273d) <271b 271d>
pure subroutine marshal_raw_state (s, ibuf, dbuf)
type(tao_random_raw_state), intent(in) :: s
integer, dimension(:), intent(inout) :: ibuf
real(kind=tao_r64), dimension(:), intent(inout) :: dbuf
ibuf(1) = size (s%x)
ibuf(2:1+size(s%x)) = s%x
end subroutine marshal_raw_state
271d <Implementation of 30-bit tao_random_numbers 255b>+≡ (273d) <271c 272a>
pure subroutine marshal_raw_state_size (s, iwords, dwords)
type(tao_random_raw_state), intent(in) :: s
integer, intent(out) :: iwords, dwords
iwords = 1 + size (s%x)

```



```

        dwords = 0
    end subroutine marshal_raw_state_size
272a  <Implementation of 30-bit tao_random_numbers 255b>+≡      (273d) <271d 275a>
    pure subroutine unmarshal_raw_state (s, ibuf, dbuf)
        type(tao_random_raw_state), intent(inout) :: s
        integer, dimension(:), intent(in) :: ibuf
        real(kind=tao_r64), dimension(:), intent(in) :: dbuf
        integer :: buf_size
        buf_size = ibuf(1)
        s%x = ibuf(2:1+buf_size)
    end subroutine unmarshal_raw_state

272b  <Implementation of 52-bit tao_random_numbers 259f>+≡      (274a) <268c 272c>
    pure subroutine marshal_state (s, ibuf, dbuf)
        type(tao_random_state), intent(in) :: s
        integer, dimension(:), intent(inout) :: ibuf
        real(kind=tao_r64), dimension(:), intent(inout) :: dbuf
        integer :: buf_size
        buf_size = size (s%buffer)
        ibuf(1) = s%buffer_end
        ibuf(2) = s%last
        ibuf(3) = buf_size
        dbuf(1:buf_size) = s%buffer
        call marshal_raw_state (s%state, ibuf(4:), dbuf(buf_size+1:))
    end subroutine marshal_state

272c  <Implementation of 52-bit tao_random_numbers 259f>+≡      (274a) <272b 272d>
    pure subroutine marshal_state_size (s, iwords, dwords)
        type(tao_random_state), intent(in) :: s
        integer, intent(out) :: iwords, dwords
        call marshal_raw_state_size (s%state, iwords, dwords)
        iwords = iwords + 3
        dwords = dwords + size(s%buffer)
    end subroutine marshal_state_size

272d  <Implementation of 52-bit tao_random_numbers 259f>+≡      (274a) <272c 273a>
    pure subroutine unmarshal_state (s, ibuf, dbuf)
        type(tao_random_state), intent(inout) :: s
        integer, dimension(:), intent(in) :: ibuf
        real(kind=tao_r64), dimension(:), intent(in) :: dbuf
        integer :: buf_size
        s%buffer_end = ibuf(1)
        s%last = ibuf(2)
        buf_size = ibuf(3)
        s%buffer = dbuf(1:buf_size)

```

```

        call unmarshal_raw_state (s%state, ibuf(4:), dbuf(buf_size+1:))
    end subroutine unmarshal_state
273a  <Implementation of 52-bit tao_random_numbers 259f>+≡      (274a) <272d 273b>
    pure subroutine marshal_raw_state (s, ibuf, dbuf)
        type(tao_random_raw_state), intent(in) :: s
        integer, dimension(:), intent(inout) :: ibuf
        real(kind=tao_r64), dimension(:), intent(inout) :: dbuf
        ibuf(1) = size (s%x)
        dbuf(1:size(s%x)) = s%x
    end subroutine marshal_raw_state
273b  <Implementation of 52-bit tao_random_numbers 259f>+≡      (274a) <273a 273c>
    pure subroutine marshal_raw_state_size (s, iwords, dwords)
        type(tao_random_raw_state), intent(in) :: s
        integer, intent(out) :: iwords, dwords
        iwords = 1
        dwords = size (s%x)
    end subroutine marshal_raw_state_size
273c  <Implementation of 52-bit tao_random_numbers 259f>+≡      (274a) <273b 276a>
    pure subroutine unmarshal_raw_state (s, ibuf, dbuf)
        type(tao_random_raw_state), intent(inout) :: s
        integer, dimension(:), intent(in) :: ibuf
        real(kind=tao_r64), dimension(:), intent(in) :: dbuf
        integer :: buf_size
        buf_size = ibuf(1)
        s%x = dbuf(1:buf_size)
    end subroutine unmarshal_raw_state

```

## C.4 High Level Routines

```

273d  <tao_random_numbers.f90 273d>≡
    ! tao_random_numbers.f90 --
    <Copyleft notice 1>
    module tao_random_numbers
        use kinds
        implicit none
        integer, parameter, private :: tao_i32 = selected_int_kind (9)
        integer, parameter, private :: tao_r64 = selected_real_kind (15)
        <Declaration of tao_random_numbers 255c>
        <Declaration of 30-bit tao_random_numbers 267d>
        <Interfaces of tao_random_numbers 259a>
        <Interfaces of 30-bit tao_random_numbers 281a>
    end module tao_random_numbers

```

```

    <Parameters in tao_random_numbers 254a>
    <Variables in tao_random_numbers 269a>
    <Variables in 30-bit tao_random_numbers 254c>
    <Declaration of 30-bit tao_random_numbers types 261d>
    character(len=*), public, parameter :: TAO_RANDOM_NUMBERS_RCS_ID = &
        "$Id: tao_random_numbers.nw 314 2010-04-17 20:32:33Z ohl $"
contains
    <Implementation of tao_random_numbers 256a>
    <Implementation of 30-bit tao_random_numbers 255b>
end module tao_random_numbers

274a <tao52_random_numbers.f90 274a>≡
    ! tao52_random_numbers.f90 --
    <Copyleft notice 1>
    module tao52_random_numbers
        use kinds
        implicit none
        integer, parameter, private :: tao_i32 = selected_int_kind (9)
        integer, parameter, private :: tao_r64 = selected_real_kind (15)
        <Declaration of tao_random_numbers 255c>
        <Declaration of 52-bit tao_random_numbers 268b>
        <Interfaces of tao_random_numbers 259a>
        <Interfaces of 52-bit tao_random_numbers 281e>
        <Parameters in tao_random_numbers 254a>
        <Variables in tao_random_numbers 269a>
        <Variables in 52-bit tao_random_numbers 259d>
        <Declaration of 52-bit tao_random_numbers types 261f>
        character(len=*), public, parameter :: TAO52_RANDOM_NUMBERS_RCS_ID = &
            "$Id: tao_random_numbers.nw 314 2010-04-17 20:32:33Z ohl $"
contains
    <Implementation of tao_random_numbers 256a>
    <Implementation of 52-bit tao_random_numbers 259f>
end module tao52_random_numbers

Ten functions are exported

274b <Declaration of tao_random_numbers 255c>+≡
    public :: tao_random_number
    public :: tao_random_seed
    public :: tao_random_create
    public :: tao_random_destroy
    public :: tao_random_copy
    public :: tao_random_read
    public :: tao_random_write
    public :: tao_random_flush

```

(273d 274a) <270c

```
! public :: tao_random_luxury
public :: tao_random_test
```

### C.4.1 Single Random Numbers

A random integer  $r$  with  $0 \leq r < 2^{30} = 1073741824$ :

```
275a <Implementation of 30-bit tao_random_numbers 255b>+≡      (273d) <272a 275e>
  pure subroutine integer_stateless &
    (state, buffer, buffer_end, last, r)
    integer(kind=tao_i32), dimension(:), intent(inout) :: state, buffer
    integer, intent(in) :: buffer_end
    integer, intent(inout) :: last
    integer, intent(out) :: r
    integer, parameter :: NORM = 1
    <Body of tao_random.* 275b>
  end subroutine integer_stateless

275b <Body of tao_random.* 275b>≡      (275 276a)
  <Step last and reload buffer iff necessary 275d>
  r = NORM * buffer(last)
```

The low level routine `generate` will fill an array  $a_1, \dots, a_n$ , which will be consumed and refilled like an input buffer. We need at least  $n \geq K$  for the call to `generate`.

```
275c <Variables in 30-bit tao_random_numbers 254c>+≡      (273d) <256b>
  integer(kind=tao_i32), dimension(DEFAULT_BUFFER_SIZE), save, private :: s_buffer
  integer, save, private :: s_buffer_end = size(s_buffer)
  integer, save, private :: s_last = size(s_buffer)
```

Increment the index `last` and reload the array `buffer`, iff this buffer is exhausted. Throughout these routines, `last` will point to random number that has just been consumed. For the array filling routines below, this is simpler than pointing to the next waiting number.

```
275d <Step last and reload buffer iff necessary 275d>≡      (275b)
  last = last + 1
  if (last > buffer_end) then
    call generate(buffer, state)
    last = 1
  end if
```

A random real  $r \in [0, 1)$ . This is almost identical to `tao_random_integer`, but we duplicate the code to avoid the function call overhead for speed.

```
275e <Implementation of 30-bit tao_random_numbers 255b>+≡      (273d) <275a 276c>
  pure subroutine real_stateless(state, buffer, buffer_end, last, r)
```

```

integer(kind=tao_i32), dimension(:), intent(inout) :: state, buffer
integer, intent(in) :: buffer_end
integer, intent(inout) :: last
real(kind=default), intent(out) :: r
real(kind=default), parameter :: NORM = 1.0_default / M
  <Body of tao_random.* 275b>
end subroutine real_stateless

```

A random real  $r \in [0, 1)$ .

276a *<Implementation of 52-bit tao\_random\_numbers 259f>+≡ (274a) <273c 278b>*  
 pure **subroutine real\_stateless** (state, buffer, **buffer\_end**, **last**, **r**)  
   real(kind=tao\_r64), dimension(:), intent(inout) :: state, buffer  
   integer, intent(in) :: **buffer\_end**  
   integer, intent(inout) :: **last**  
   real(kind=default), intent(out) :: **r**  
   integer, parameter :: NORM = 1  
   *<Body of tao\_random.\* 275b>*  
end **subroutine real\_stateless**

The low level routine **generate** will fill an array  $a_1, \dots, a_N$ , which will be consumed and refilled like an input buffer.

276b *<Variables in 52-bit tao\_random\_numbers 259d>+≡ (274a) <259e*  
   real(kind=tao\_r64), dimension(DEFAULT\_BUFFER\_SIZE), save, private :: **s\_buffer**  
   integer, save, private :: **s\_buffer\_end** = size (**s\_buffer**)  
   integer, save, private :: **s\_last** = size (**s\_buffer**)

### C.4.2 Arrays of Random Numbers

Fill the array  $j_1, \dots, j_\nu$  with random integers  $0 \leq j_i < 2^{30} = 1073741824$ . This has to be done such that the underlying array length in **generate** is transparent to the user. At the same time we want to avoid the overhead of calling **tao\_random\_real**  $\nu$  times.

276c *<Implementation of 30-bit tao\_random\_numbers 255b>+≡ (273d) <275e 278a>*  
 pure **subroutine integer\_array\_stateless** &  
   (state, buffer, **buffer\_end**, **last**, v, num)  
   integer(kind=tao\_i32), dimension(:), intent(inout) :: state, buffer  
   integer, intent(in) :: **buffer\_end**  
   integer, intent(inout) :: **last**  
   integer, dimension(:), intent(out) :: v  
   integer, optional, intent(in) :: num  
   integer, parameter :: NORM = 1  
   *<Body of tao\_random.\*\_array 277a>*  
end **subroutine integer\_array\_stateless**

277a *⟨Body of tao\_random\*\_array 277a⟩≡* (276c 278)

```

integer :: nu, done, todo, chunk
⟨Set nu to num or size(v) 277b⟩
⟨Prepare array buffer and done, todo, chunk 277c⟩
v(1:chunk) = NORM * buffer(last+1:last+chunk)
do
  ⟨Update last, done and todo and set new chunk 277d⟩
  ⟨Reload buffer or exit 277e⟩
  v(done+1:done+chunk) = NORM * buffer(1:chunk)
end do

```

277b *⟨Set nu to num or size(v) 277b⟩≡* (277a)

```

if (present (num)) then
  nu = num
else
  nu = size (v)
end if

```

`last` is used as an offset into the buffer `buffer`, as usual. `done` is an offset into the target. We still have to process all `nu` numbers. The first chunk can only use what's left in the buffer.

277c *⟨Prepare array buffer and done, todo, chunk 277c⟩≡* (277a)

```

if (last >= buffer_end) then
  call generate (buffer, state)
  last = 0
end if
done = 0
todo = nu
chunk = min (todo, buffer_end - last)

```

This logic is a bit weird, but after the first chunk, `todo` will either vanish (in which case we're done) or we have consumed all of the buffer and must reload. In any case we can pretend that the next chunk can use the whole buffer.

277d *⟨Update last, done and todo and set new chunk 277d⟩≡* (277a)

```

last = last + chunk
done = done + chunk
todo = todo - chunk
chunk = min (todo, buffer_end)

```

277e *⟨Reload buffer or exit 277e⟩≡* (277a)

```

if (chunk <= 0) then
  exit
end if
call generate (buffer, state)
last = 0

```

278a  $\langle$ Implementation of 30-bit tao\_random\_numbers 255b $\rangle + \equiv$  (273d)  $\triangleleft$ 276c 278c $\triangleright$   
 pure subroutine real\_array\_stateless &  
   (state, buffer, buffer\_end, last, v, num)  
   integer(kind=tao\_i32), dimension(:), intent(inout) :: state, buffer  
   integer, intent(in) :: buffer\_end  
   integer, intent(inout) :: last  
   real(kind=default), dimension(:), intent(out) :: v  
   integer, optional, intent(in) :: num  
   real(kind=default), parameter :: NORM = 1.0\_default / M  
    $\langle$ Body of tao\_random\*\_array 277a $\rangle$   
 end subroutine real\_array\_stateless

Fill the array  $v_1, \dots, v_\nu$  with uniform deviates  $v_i \in [0, 1)$ .

278b  $\langle$ Implementation of 52-bit tao\_random\_numbers 259f $\rangle + \equiv$  (274a)  $\triangleleft$ 276a 279a $\triangleright$   
 pure subroutine real\_array\_stateless &  
   (state, buffer, buffer\_end, last, v, num)  
   real(kind=tao\_r64), dimension(:), intent(inout) :: state, buffer  
   integer, intent(in) :: buffer\_end  
   integer, intent(inout) :: last  
   real(kind=default), dimension(:), intent(out) :: v  
   integer, optional, intent(in) :: num  
   integer, parameter :: NORM = 1  
    $\langle$ Body of tao\_random\*\_array 277a $\rangle$   
 end subroutine real\_array\_stateless

### C.4.3 Procedures With Explicit tao\_random\_state

Unfortunately, this is very boring, but Fortran's lack of parametric polymorphism forces this duplication on us:

278c  $\langle$ Implementation of 30-bit tao\_random\_numbers 255b $\rangle + \equiv$  (273d)  $\triangleleft$ 278a 278d $\triangleright$   
 elemental subroutine integer\_state (s, r)  
   type(tao\_random\_state), intent(inout) :: s  
   integer, intent(out) :: r  
   call integer\_stateless (s%state%x, s%buffer, s%buffer\_end, s%last, r)  
 end subroutine integer\_state

278d  $\langle$ Implementation of 30-bit tao\_random\_numbers 255b $\rangle + \equiv$  (273d)  $\triangleleft$ 278c 279b $\triangleright$   
 elemental subroutine real\_state (s, r)  
   type(tao\_random\_state), intent(inout) :: s  
   real(kind=default), intent(out) :: r  
   call real\_stateless (s%state%x, s%buffer, s%buffer\_end, s%last, r)  
 end subroutine real\_state

279a *Implementation of 52-bit tao\_random\_numbers 259f*+≡ (274a) <278b 279d>  
 elemental subroutine real\_state (s, r)  
   type(tao\_random\_state), intent(inout) :: s  
   real(kind=default), intent(out) :: r  
   call real\_stateless (s%state%x, s%buffer, s%buffer\_end, s%last, r)  
 end subroutine real\_state

279b *Implementation of 30-bit tao\_random\_numbers 255b*+≡ (273d) <278d 279c>  
 pure subroutine integer\_array\_state (s, v, num)  
   type(tao\_random\_state), intent(inout) :: s  
   integer, dimension(:), intent(out) :: v  
   integer, optional, intent(in) :: num  
   call integer\_array\_stateless &  
     (s%state%x, s%buffer, s%buffer\_end, s%last, v, num)  
 end subroutine integer\_array\_state

279c *Implementation of 30-bit tao\_random\_numbers 255b*+≡ (273d) <279b 280a>  
 pure subroutine real\_array\_state (s, v, num)  
   type(tao\_random\_state), intent(inout) :: s  
   real(kind=default), dimension(:), intent(out) :: v  
   integer, optional, intent(in) :: num  
   call real\_array\_stateless &  
     (s%state%x, s%buffer, s%buffer\_end, s%last, v, num)  
 end subroutine real\_array\_state

279d *Implementation of 52-bit tao\_random\_numbers 259f*+≡ (274a) <279a 280c>  
 pure subroutine real\_array\_state (s, v, num)  
   type(tao\_random\_state), intent(inout) :: s  
   real(kind=default), dimension(:), intent(out) :: v  
   integer, optional, intent(in) :: num  
   call real\_array\_stateless &  
     (s%state%x, s%buffer, s%buffer\_end, s%last, v, num)  
 end subroutine real\_array\_state

#### C.4.4 Static Procedures

First make sure that `tao_random_seed` has been called to initialize the generator state:

279e *Initialize a virginal random number generator 279e*≡ (280 282)  
 if (s\_virginal) then  
   call tao\_random\_seed ()  
 end if



280a *<Implementation of 30-bit tao\_random\_numbers 255b>+≡ (273d) <279c 280b>*  
**subroutine integer\_static (r)**  
integer, intent(out) :: r  
*<Initialize a virginal random number generator 279e>*  
call **integer\_stateless (s\_state, s\_buffer, s\_buffer\_end, s\_last, r)**  
**end subroutine integer\_static**

280b *<Implementation of 30-bit tao\_random\_numbers 255b>+≡ (273d) <280a 280d>*  
**subroutine real\_static (r)**  
real(kind=default), intent(out) :: r  
*<Initialize a virginal random number generator 279e>*  
call **real\_stateless (s\_state, s\_buffer, s\_buffer\_end, s\_last, r)**  
**end subroutine real\_static**

280c *<Implementation of 52-bit tao\_random\_numbers 259f>+≡ (274a) <279d 280f>*  
**subroutine real\_static (r)**  
real(kind=default), intent(out) :: r  
*<Initialize a virginal random number generator 279e>*  
call **real\_stateless (s\_state, s\_buffer, s\_buffer\_end, s\_last, r)**  
**end subroutine real\_static**

280d *<Implementation of 30-bit tao\_random\_numbers 255b>+≡ (273d) <280b 280e>*  
**subroutine integer\_array\_static (v, num)**  
integer, dimension(:), intent(out) :: v  
integer, optional, intent(in) :: num  
*<Initialize a virginal random number generator 279e>*  
call **integer\_array\_stateless &**  
**(s\_state, s\_buffer, s\_buffer\_end, s\_last, v, num)**  
**end subroutine integer\_array\_static**

280e *<Implementation of 30-bit tao\_random\_numbers 255b>+≡ (273d) <280d 283e>*  
**subroutine real\_array\_static (v, num)**  
real(kind=default), dimension(:), intent(out) :: v  
integer, optional, intent(in) :: num  
*<Initialize a virginal random number generator 279e>*  
call **real\_array\_stateless &**  
**(s\_state, s\_buffer, s\_buffer\_end, s\_last, v, num)**  
**end subroutine real\_array\_static**

280f *<Implementation of 52-bit tao\_random\_numbers 259f>+≡ (274a) <280c 286a>*  
**subroutine real\_array\_static (v, num)**  
real(kind=default), dimension(:), intent(out) :: v  
integer, optional, intent(in) :: num  
*<Initialize a virginal random number generator 279e>*  
call **real\_array\_stateless &**  
**(s\_state, s\_buffer, s\_buffer\_end, s\_last, v, num)**  
**end subroutine real\_array\_static**

### C.4.5 Generic Procedures

281a *<Interfaces of 30-bit tao\_random\_numbers 281a>*≡ (273d)

```
interface tao_random_number
  module procedure <Specific procedures for 30-bit tao_random_number 281b>
end interface
```

281b *<Specific procedures for 30-bit tao\_random\_number 281b>*≡ (281)

```
integer_static, integer_state, &
integer_array_static, integer_array_state, &
real_static, real_state, real_array_static, real_array_state
```

These are not exported

281c *<Declaration of 30-bit tao\_random\_numbers 267d>*+≡ (273d) *<267f 281d>*

```
private :: &
  integer_stateless, integer_array_stateless, &
  real_stateless, real_array_stateless
```

281d *<Declaration of 30-bit tao\_random\_numbers 267d>*+≡ (273d) *<281c>*

```
private :: <Specific procedures for 30-bit tao_random_number 281b>
```

281e *<Interfaces of 52-bit tao\_random\_numbers 281e>*≡ (274a)

```
interface tao_random_number
  module procedure <Specific procedures for 52-bit tao_random_number 281f>
end interface
```

281f *<Specific procedures for 52-bit tao\_random\_number 281f>*≡ (281)

```
real_static, real_state, real_array_static, real_array_state
```

Thes are not exported

281g *<Declaration of 52-bit tao\_random\_numbers 268b>*+≡ (274a) *<268d 281h>*

```
private :: real_stateless, real_array_stateless
```

281h *<Declaration of 52-bit tao\_random\_numbers 268b>*+≡ (274a) *<281g>*

```
private :: <Specific procedures for 52-bit tao_random_number 281f>
```

### C.4.6 Luxury

281i *<Implementation of tao\_random\_numbers 256a>*+≡ (273d 274a) *<270a 282a>*

```
pure subroutine luxury_stateless &
  (buffer_size, buffer_end, last, consumption)
  integer, intent(in) :: buffer_size
  integer, intent(inout) :: buffer_end
  integer, intent(inout) :: last
  integer, intent(in) :: consumption
  if (consumption >= 1 .and. consumption <= buffer_size) then
    buffer_end = consumption
```

```

        last = min (last, buffer_end)
    else
        !!! print *, "tao_random_luxury: ", "invalid consumption ", &
        !!!      consumption, ", not in [ 1, ", buffer_size, "]"
        buffer_end = buffer_size
    end if
end subroutine luxury_stateless

282a  <Implementation of tao_random_numbers 256a>+≡      (273d 274a) <281i 282b>
      elemental subroutine luxury_state (s)
        type(tao_random_state), intent(inout) :: s
        call luxury_state_integer (s, size (s%buffer))
      end subroutine luxury_state

282b  <Implementation of tao_random_numbers 256a>+≡      (273d 274a) <282a 282c>
      elemental subroutine luxury_state_integer (s, consumption)
        type(tao_random_state), intent(inout) :: s
        integer, intent(in) :: consumption
        call luxury_stateless (size (s%buffer), s%buffer_end, s%last, consumption)
      end subroutine luxury_state_integer

282c  <Implementation of tao_random_numbers 256a>+≡      (273d 274a) <282b 282d>
      elemental subroutine luxury_state_real (s, consumption)
        type(tao_random_state), intent(inout) :: s
        real(kind=default), intent(in) :: consumption
        call luxury_state_integer (s, int (consumption * size (s%buffer)))
      end subroutine luxury_state_real

282d  <Implementation of tao_random_numbers 256a>+≡      (273d 274a) <282c 282e>
      subroutine luxury_static ()
        <Initialize a virginal random number generator 279e>
        call luxury_static_integer (size (s_buffer))
      end subroutine luxury_static

282e  <Implementation of tao_random_numbers 256a>+≡      (273d 274a) <282d 282f>
      subroutine luxury_static_integer (consumption)
        integer, intent(in) :: consumption
        <Initialize a virginal random number generator 279e>
        call luxury_stateless (size (s_buffer), s_buffer_end, s_last, consumption)
      end subroutine luxury_static_integer

282f  <Implementation of tao_random_numbers 256a>+≡      (273d 274a) <282e
      subroutine luxury_static_real (consumption)
        real(kind=default), intent(in) :: consumption
        <Initialize a virginal random number generator 279e>
        call luxury_static_integer (int (consumption * size (s_buffer)))
      end subroutine luxury_static_real

```

283a *<Interfaces of tao\_random\_numbers (unused luxury) 283a>*≡  
 interface **tao\_random\_luxury**  
 module procedure *<Specific procedures for tao\_random\_luxury 283d>*  
 end interface

283b *<Declaration of tao\_random\_numbers (unused luxury) 283b>*≡ 283c▷  
 private :: **luxury\_stateless**

283c *<Declaration of tao\_random\_numbers (unused luxury) 283b>*+≡ ◁283b  
 private :: *<Specific procedures for tao\_random\_luxury 283d>*

283d *<Specific procedures for tao\_random\_luxury 283d>*≡ (283)  
**luxury\_static**, **luxury\_state**, &  
**luxury\_static\_integer**, **luxury\_state\_integer**, &  
**luxury\_static\_real**, **luxury\_state\_real**

## C.5 Testing

### C.5.1 30-bit

283e *<Implementation of 30-bit tao\_random\_numbers 255b>*+≡ (273d) ◁280e  
**subroutine tao\_random\_test** (name)  
 character(len=\*), optional, intent(in) :: name  
 character (len = \*), parameter :: &  
 OK = "(1x,i10,' is ok. ')", &  
 NOT\_OK = "(1x,i10,' is not ok, (expected ',i10,')!')"  
*<Parameters in tao\_random\_test 283f>*  
 integer, parameter :: &  
 A\_2027082 = 995235265  
 integer, dimension(N) :: a  
 type(**tao\_random\_state**) :: s, t  
 integer, dimension(:), allocatable :: ibuf  
 real(kind=tao\_r64), dimension(:), allocatable :: dbuf  
 integer :: **i**, ibuf\_size, dbuf\_size  
 print \*, TAO\_RANDOM\_NUMBERS\_RCS\_ID  
 print \*, "testing the 30-bit **tao\_random\_numbers** ..."  
*<Perform simple tests of tao\_random\_numbers 284a>*  
*<Perform more tests of tao\_random\_numbers 284d>*  
 end **subroutine tao\_random\_test**

283f *<Parameters in tao\_random\_test 283f>*≡ (283e 286a)  
 integer, parameter :: &  
 SEED = 310952, &

```

N = 2009, M = 1009, &
N_SHORT = 1984

```

DEK's "official" test expects  $a_{1009 \cdot 2009 + 1} = a_{2027082} = 995235265$ :

```

284a <Perform simple tests of tao_random_numbers 284a>≡ (283e 286a) 284c>
! call tao_random_luxury ()
call tao_random_seed (SEED)
do i = 1, N+1
  call tao_random_number (a, M)
end do
<Test a(1) = A_2027082 284b>
284b <Test a(1) = A_2027082 284b>≡ (284 285)
if (a(1) == A_2027082) then
  print OK, a(1)
else
  print NOT_OK, a(1), A_2027082
  stop 1
end if

```

Deja vu all over again, but 2027081 is factored the other way around this time

```

284c <Perform simple tests of tao_random_numbers 284a>+≡ (283e 286a) <284a
call tao_random_seed (SEED)
do i = 1, M+1
  call tao_random_number (a)
end do
<Test a(1) = A_2027082 284b>

```

Now checkpoint the random number generator after  $N_{\text{short}} \cdot M$  numbers

```

284d <Perform more tests of tao_random_numbers 284d>≡ (283e 286a) 284e>
print *, "testing the stateless stuff ..."
call tao_random_create (s, SEED)
do i = 1, N_SHORT
  call tao_random_number (s, a, M)
end do
call tao_random_create (t, s)
do i = 1, N+1 - N_SHORT
  call tao_random_number (s, a, M)
end do
<Test a(1) = A_2027082 284b>

```

and restart the saved generator

```

284e <Perform more tests of tao_random_numbers 284d>+≡ (283e 286a) <284d 285a>
do i = 1, N+1 - N_SHORT
  call tao_random_number (t, a, M)

```

```

end do
<Test a(1) = A_2027082 284b>

```

The same story again, but this time saving the copy to a file

```

285a <Perform more tests of tao_random_numbers 284d>+≡      (283e 286a) <284e 285b>
  if (present (name)) then
    print *, "testing I/O ..."
    call tao_random_seed (s, SEED)
    do i = 1, N_SHORT
      call tao_random_number (s, a, M)
    end do
    call tao_random_write (s, name)
    do i = 1, N+1 - N_SHORT
      call tao_random_number (s, a, M)
    end do
    <Test a(1) = A_2027082 284b>
    call tao_random_read (s, name)
    do i = 1, N+1 - N_SHORT
      call tao_random_number (s, a, M)
    end do
    <Test a(1) = A_2027082 284b>
  end if

```

And finally using marshaling/unmarshaling:

```

285b <Perform more tests of tao_random_numbers 284d>+≡      (283e 286a) <285a
  print *, "testing marshaling/unmarshaling ..."
  call tao_random_seed (s, SEED)
  do i = 1, N_SHORT
    call tao_random_number (s, a, M)
  end do
  call tao_random_marshal_size (s, ibuf_size, dbuf_size)
  allocate (ibuf(ibuf_size), dbuf(dbuf_size))
  call tao_random_marshal (s, ibuf, dbuf)
  do i = 1, N+1 - N_SHORT
    call tao_random_number (s, a, M)
  end do
  <Test a(1) = A_2027082 284b>
  call tao_random_unmarshal (s, ibuf, dbuf)
  do i = 1, N+1 - N_SHORT
    call tao_random_number (s, a, M)
  end do
  <Test a(1) = A_2027082 284b>

```

### C.5.2 52-bit

DEK's "official" test expects  $x_{1009 \cdot 2009 + 1} = x_{2027082} = 0.36410514377569680455$ :

286a  $\langle$ Implementation of 52-bit tao\_random\_numbers 259f $\rangle + \equiv$  (274a)  $\triangleleft$  280f

```

subroutine tao_random_test (name)
  character(len=*), optional, intent(in) :: name
  character(len=*), parameter :: &
    OK = "(1x,f22.20,' is ok. ')", &
    NOT_OK = "(1x,f22.20,' is not ok, (A_2027082 ',f22.20,')!')'"
   $\langle$ Parameters in tao_random_test 283f $\rangle$ 
  real(kind=default), parameter :: &
    A_2027082 = 0.36410514377569680455_tao_r64
  real(kind=default), dimension(N) :: a
  type(tao_random_state) :: s, t
  integer, dimension(:), allocatable :: ibuf
  real(kind=tao_r64), dimension(:), allocatable :: dbuf
  integer :: i, ibuf_size, dbuf_size
  print *, TAO52_RANDOM_NUMBERS_RCS_ID
  print *, "testing the 52-bit tao_random_numbers ..."
   $\langle$ Perform simple tests of tao_random_numbers 284a $\rangle$ 
   $\langle$ Perform more tests of tao_random_numbers 284d $\rangle$ 
end subroutine tao_random_test

```

### C.5.3 Test Program

286b  $\langle$ tao\_test.f90 286b $\rangle \equiv$

```

program tao_test
  use tao_random_numbers, only: test30 => tao_random_test
  use tao52_random_numbers, only: test52 => tao_random_test
  implicit none
  call test30 ("tmp.tao")
  call test52 ("tmp.tao")
  stop 0
end program tao_test

```

# —D—

## SPECIAL FUNCTIONS

```

287a  <specfun.f90 287a>≡
      ! specfun.f90 --
      <Copyleft notice 1>
      module specfun
        use kinds
        ! use constants
        implicit none
        private
        <Declaration of specfun procedures 287b>
        character(len=*), public, parameter :: SPECFUN_RCS_ID = &
          "$Id: specfun.nw 314 2010-04-17 20:32:33Z ohl $"
        !WK:
        real(kind=default), public, parameter :: &
          PI = 3.1415926535897932384626433832795028841972_default
        contains
        <Implementation of specfun procedures 288c>
      end module specfun

```

The algorithm is stolen from the FORTRAN version in routine C303 of the CERN library [25]. It has an accuracy which is approximately one digit less than machine precision.

```

287b  <Declaration of specfun procedures 287b>≡ (287a)
      public :: gamma

```

The so-called reflection formula is used for negative arguments:

$$\Gamma(x)\Gamma(1-x) = \frac{\pi}{\sin \pi x} \quad (\text{D.1})$$

Here's the identity transformation that pulls the argument of  $\Gamma$  into [3, 4]:

$$\Gamma(u) = \begin{cases} (u-1)\Gamma(u-1) & \text{for } u > 4 \\ \frac{1}{u}\Gamma(u+1) & \text{for } u < 3 \end{cases} \quad (\text{D.2})$$



288a  $\langle$  Pull  $u$  into the intervall  $[3, 4]$  288a  $\rangle \equiv$  (288c)

```

f = 1
if (u < 3) then
  do i = 1, int (4 - u)
    f = f / u
    u = u + 1
  end do
else
  do i = 1, int (u - 3)
    u = u - 1
    f = f * u
  end do
end if

```

A Chebyshev approximation for  $\Gamma(x)$  is used after mapping  $x \in [3, 4]$  linearly to  $h \in [-1, 1]$ . The series is evaluted by Clenshaw's recurrence formula:

$$\begin{aligned}
 d_m &= d_{m+1} = 0 \\
 d_j &= 2xd_{j+1} - d_{j+2} + c_j \text{ for } 0 < j < m - 1 \\
 f(x) &= d_0 = xd_1 - d_2 + \frac{1}{2}c_0
 \end{aligned}
 \tag{D.3}$$

288b  $\langle$  Clenshaw's recurrence formula 288b  $\rangle \equiv$  (288c)

```

alpha = 2*g
b1 = 0
b2 = 0
do i = 15, 0, -1
  b0 = c(i) + alpha * b1 - b2
  b2 = b1
  b1 = b0
end do
g = f * (b0 - g * b2)

```

Note that we're assuming that  $c(0)$  is in fact  $c_0/2$ . This is for compatibility with the CERN library routines.

288c  $\langle$  Implementation of specfun procedures 288c  $\rangle \equiv$  (287a)

```

pure function gamma (x) result (g)
  real(kind=default), intent(in) :: x
  real(kind=default) :: g
  integer :: i
  real(kind=default) :: u, f, alpha, b0, b1, b2
  real(kind=default), dimension(0:15), parameter :: &
    c =  $\langle c_0/2, c_1, c_2, \dots, c_{15}$  for  $\Gamma(x)$  289a  $\rangle$ 
  u = x
  if (u <= 0.0) then

```

```

        if (u == int (u)) then
            g = huge (g)
            return
        else
            u = 1 - u
        end if
    endif
    <Pull u into the intervall [3,4] 288a>
    g = 2*u - 7
    <Clenshaw's recurrence formula 288b>
    if (x < 0) then
        g = PI / (sin (PI * x) * g)
    end if
end function gamma
289a <c0/2, c1, c2, ..., c15 for  $\Gamma(x)$  289a>≡ (288c)
    (/ 3.65738772508338244_default, &
       1.95754345666126827_default, &
       0.33829711382616039_default, &
       0.04208951276557549_default, &
       0.00428765048212909_default, &
       0.00036521216929462_default, &
       0.00002740064222642_default, &
       0.00000181240233365_default, &
       0.00000010965775866_default, &
       0.00000000598718405_default, &
       0.00000000030769081_default, &
       0.00000000001431793_default, &
       0.00000000000065109_default, &
       0.0000000000002596_default, &
       0.0000000000000111_default, &
       0.0000000000000004_default /)

```

## D.1 Test

```

289b <stest.f90 289b>≡ (290c)
    ! stest.f90 --
    <Copyleft notice 1>
    module stest_functions
        use kinds
        use constants
        use specfun

```

```

private
  <Declaration of stest_functions procedures 290a>
contains
  <Implementation of stest_functions procedures 290b>
end module stest_functions

```

290a <Declaration of stest\_functions procedures 290a>≡ (289b)

```

public :: gauss_multiplication

```

Gauss' multiplication fomula can serve as a non-trivial test

$$\Gamma(nx) = (2\pi)^{(1-n)/2} n^{nx-1/2} \prod_{k=0}^{n-1} \Gamma(x + k/n) \quad (\text{D.4})$$

290b <Implementation of stest\_functions procedures 290b>≡ (289b)

```

pure function gauss_multiplication (x, n) result (delta)
  real(kind=default), intent(in) :: x
  integer, intent(in) :: n
  real(kind=default) :: delta
  real(kind=default) :: gxn
  integer :: k
  gxn = (2*PI)**(0.5_double*(1-n)) * n**(n*x-0.5_double)
  do k = 0, n - 1
    gxn = gxn * gamma (x + real (k, kind=default) / n)
  end do
  delta = abs ((gamma (n*x) - gxn) / gamma (n*x))
end function gauss_multiplication

```

290c <stest.f90 289b>+≡ <289b

```

program stest
  use kinds
  use specfun
  use stest_functions !NODEP!
  implicit none
  integer :: i, steps
  real(kind=default) :: x, g, xmin, xmax
  xmin = -4.5
  xmax = 4.5
  steps = 100 ! 9
  do i = 0, steps
    x = xmin + ((xmax - xmin) / real (steps)) * i
    print "(f6.3,4(1x,e9.2))", x, &
      gauss_multiplication (x, 2), &
      gauss_multiplication (x, 3), &
      gauss_multiplication (x, 4), &

```

```
        gauss_multiplication (x, 5)
    end do
end program stest
```

# —E—

## STATISTICS

292a  $\langle \text{vamp\_stat.f90 292a} \rangle \equiv$   
`! vamp_stat.f90 --`  
 $\langle \text{Copyleft notice 1} \rangle$   
`module vamp_stat`  
`use kinds`  
`implicit none`  
`private`  
 $\langle \text{Declaration of vamp\_stat procedures 292b} \rangle$   
`character(len=*), public, parameter :: VAMP_STAT_RCS_ID = &`  
`"$Id: vamp_stat.nw 314 2010-04-17 20:32:33Z ohl $"`  
`contains`  
 $\langle \text{Implementation of vamp\_stat procedures 292c} \rangle$   
`end module vamp_stat`

292b  $\langle \text{Declaration of vamp\_stat procedures 292b} \rangle \equiv$  (292a) 293c  $\triangleright$   
`public :: average, standard_deviation, value_spread`

$$\text{avg}(X) = \frac{1}{|X|} \sum_{x \in X} x \quad (\text{E.1})$$

292c  $\langle \text{Implementation of vamp\_stat procedures 292c} \rangle \equiv$  (292a) 293a  $\triangleright$   
`pure function average (x) result (a)`  
`real(kind=default), dimension(:), intent(in) :: x`  
`real(kind=default) :: a`  
`integer :: n`  
`n = size (x)`  
`if (n == 0) then`  
`a = 0.0`  
`else`  
`a = sum (x) / n`  
`end if`  
`end function average`

$$\text{stddev}(X) = \frac{1}{|X| - 1} \sum_{x \in X} (x - \text{avg}(X))^2 = \frac{1}{|X| - 1} \left( \frac{1}{|X|} \sum_{x \in X} x^2 - (\text{avg}(X))^2 \right) \quad (\text{E.2})$$

293a *⟨Implementation of vamp\_stat procedures 292c⟩*+≡ (292a) <292c 293b>

```

pure function standard_deviation (x) result (s)
  real(kind=default), dimension(:), intent(in) :: x
  real(kind=default) :: s
  integer :: n
  n = size (x)
  if (n < 2) then
    s = huge (s)
  else
    s = sqrt (max ((sum (x**2) / n - (average (x))**2) / (n - 1), &
                  0.0_default))
  end if
end function standard_deviation

```

$$\text{spread}(X) = \max_{x \in X}(x) - \min_{x \in X}(x) \quad (\text{E.3})$$

293b *⟨Implementation of vamp\_stat procedures 292c⟩*+≡ (292a) <293a 293d>

```

pure function value_spread (x) result (s)
  real(kind=default), dimension(:), intent(in) :: x
  real(kind=default) :: s
  s = maxval(x) - minval(x)
end function value_spread

```

293c *⟨Declaration of vamp\_stat procedures 292b⟩*+≡ (292a) <292b>

```

public :: standard_deviation_percent, value_spread_percent

```

293d *⟨Implementation of vamp\_stat procedures 292c⟩*+≡ (292a) <293b 293e>

```

pure function standard_deviation_percent (x) result (s)
  real(kind=default), dimension(:), intent(in) :: x
  real(kind=default) :: s
  real(kind=default) :: abs_avg
  abs_avg = abs (average (x))
  if (abs_avg <= tiny (abs_avg)) then
    s = huge (s)
  else
    s = 100.0 * standard_deviation (x) / abs_avg
  end if
end function standard_deviation_percent

```

293e *⟨Implementation of vamp\_stat procedures 292c⟩*+≡ (292a) <293d>

```

pure function value_spread_percent (x) result (s)
  real(kind=default), dimension(:), intent(in) :: x

```

```

real(kind=default) :: s
real(kind=default) :: abs_avg
abs_avg = abs (average (x))
if (abs_avg <= tiny (abs_avg)) then
    s = huge (s)
else
    s = 100.0 * value_spread (x) / abs_avg
end if
end function value_spread_percent

```

# —F—

## HISTOGRAMMING

⚡ Merged WK's improvements for WHIZARD. TODO *after* merging:

1. bins3 is a bad undescriptive name
2. bins3 should be added to `histogram2`
3. `write_histogram2_unit` for symmetry.

⚡ There's almost no sanity checking. If you call one of these functions on a histogram that has not been initialized, you loose. — *Big time.*

```

295a <histograms.f90 295a>≡
    ! histograms.f90 --
    <Copyleft notice 1>
    module histograms
        use kinds
        use utils, only: find_free_unit
        implicit none
        private
        <Declaration of histograms procedures 296b>
        <Interfaces of histograms procedures 296c>
        <Variables in histograms 296e>
        <Declaration of histograms types 295b>
        character(len=*), public, parameter :: HISTOGRAMS_RCS_ID = &
            "$Id: histograms.nw 314 2010-04-17 20:32:33Z ohl $"
    contains
        <Implementation of histograms procedures 296f>
    end module histograms

295b <Declaration of histograms types 295b>≡                                     (295a) 296a>
    type, public :: histogram
        private
        integer :: n_bins
        real(kind=default) :: x_min, x_max

```



```

        real(kind=default), dimension(:), pointer :: bins => null ()
        real(kind=default), dimension(:), pointer :: bins2 => null ()
        real(kind=default), dimension(:), pointer :: bins3 => null ()
    end type histogram

296a  <Declaration of histograms types 295b>+≡ (295a) <295b
    type, public :: histogram2
    private
    integer, dimension(2) :: n_bins
    real(kind=default), dimension(2) :: x_min, x_max
    real(kind=default), dimension(:,:), pointer :: bins => null ()
    real(kind=default), dimension(:,:), pointer :: bins2 => null ()
    end type histogram2

296b  <Declaration of histograms procedures 296b>≡ (295a) 296d>
    public :: create_histogram
    public :: fill_histogram
    public :: delete_histogram
    public :: write_histogram

296c  <Interfaces of histograms procedures 296c>≡ (295a) 301b>
    interface create_histogram
        module procedure create_histogram1, create_histogram2
    end interface
    interface fill_histogram
        module procedure fill_histogram1, fill_histogram2s, fill_histogram2v
    end interface
    interface delete_histogram
        module procedure delete_histogram1, delete_histogram2
    end interface
    interface write_histogram
        module procedure write_histogram1, write_histogram2
        module procedure write_histogram1_unit
    end interface

296d  <Declaration of histograms procedures 296b>+≡ (295a) <296b 300a>
    private :: create_histogram1, create_histogram2
    private :: fill_histogram1, fill_histogram2s, fill_histogram2v
    private :: delete_histogram1, delete_histogram2
    private :: write_histogram1, write_histogram2

296e  <Variables in histograms 296e>≡ (295a)
    integer, parameter, private :: N_BINS_DEFAULT = 10

296f  <Implementation of histograms procedures 296f>≡ (295a) 297a>
    elemental subroutine create_histogram1 (h, x_min, x_max, nb)
    type(histogram), intent(out) :: h

```

```

real(kind=default), intent(in) :: x_min, x_max
integer, intent(in), optional :: nb
if (present (nb)) then
    h%n_bins = nb
else
    h%n_bins = N_BINS_DEFAULT
end if
h%x_min = x_min
h%x_max = x_max
allocate (h%bins(0:h%n_bins+1), h%bins2(0:h%n_bins+1))
h%bins = 0
h%bins2 = 0
allocate (h%bins3(0:h%n_bins+1))
h%bins3 = 0
end subroutine create_histogram1

```

297a *<Implementation of histograms procedures 296f>+≡ (295a) <296f 297b>*

```

pure subroutine create_histogram2 (h, x_min, x_max, nb)
type(histogram2), intent(out) :: h
real(kind=default), dimension(:), intent(in) :: x_min, x_max
integer, intent(in), dimension(:), optional :: nb
if (present (nb)) then
    h%n_bins = nb
else
    h%n_bins = N_BINS_DEFAULT
end if
h%x_min = x_min
h%x_max = x_max
allocate (h%bins(0:h%n_bins(1)+1,0:h%n_bins(1)+1), &
          h%bins2(0:h%n_bins(2)+1,0:h%n_bins(2)+1))
h%bins = 0
h%bins2 = 0
end subroutine create_histogram2

```

297b *<Implementation of histograms procedures 296f>+≡ (295a) <297a 298a>*

```

elemental subroutine fill_histogram1 (h, x, weight, excess)
type(histogram), intent(inout) :: h
real(kind=default), intent(in) :: x
real(kind=default), intent(in), optional :: weight
real(kind=default), intent(in), optional :: excess
integer :: i
if (x < h%x_min) then
    i = 0
else if (x > h%x_max) then
    i = h%n_bins + 1

```

```

else
    i = 1 + h%n_bins * (x - h%x_min) / (h%x_max - h%x_min)
!WK! i = min (max (i, 0), h%n_bins + 1)
end if
if (present (weight)) then
    h%bins(i) = h%bins(i) + weight
    h%bins2(i) = h%bins2(i) + weight*weight
else
    h%bins(i) = h%bins(i) + 1
    h%bins2(i) = h%bins2(i) + 1
end if
if (present (excess)) h%bins3(i) = h%bins3(i) + excess
end subroutine fill_histogram1

```

298a *<Implementation of histograms procedures 296f>+≡ (295a) <297b 298b>*  
 elemental subroutine fill\_histogram2s (h, x1, x2, weight)  
 type(histogram2), intent(inout) :: h  
 real(kind=default), intent(in) :: x1, x2  
 real(kind=default), intent(in), optional :: weight  
 call fill\_histogram2v (h, (/ x1, x2 /), weight)  
 end subroutine fill\_histogram2s

298b *<Implementation of histograms procedures 296f>+≡ (295a) <298a 298c>*  
 pure subroutine fill\_histogram2v (h, x, weight)  
 type(histogram2), intent(inout) :: h  
 real(kind=default), dimension(:), intent(in) :: x  
 real(kind=default), intent(in), optional :: weight  
 integer, dimension(2) :: i  
 i = 1 + h%n\_bins \* (x - h%x\_min) / (h%x\_max - h%x\_min)  
 i = min (max (i, 0), h%n\_bins + 1)  
 if (present (weight)) then  
 h%bins(i(1),i(2)) = h%bins(i(1),i(2)) + weight  
 h%bins2(i(1),i(2)) = h%bins2(i(1),i(2)) + weight\*weight  
 else  
 h%bins(i(1),i(2)) = h%bins(i(1),i(2)) + 1  
 h%bins2(i(1),i(2)) = h%bins2(i(1),i(2)) + 1  
 end if  
 end subroutine fill\_histogram2v

298c *<Implementation of histograms procedures 296f>+≡ (295a) <298b 299a>*  
 elemental subroutine delete\_histogram1 (h)  
 type(histogram), intent(inout) :: h  
 deallocate (h%bins, h%bins2)  
 deallocate (h%bins3)  
 end subroutine delete\_histogram1

```

299a  <Implementation of histograms procedures 296f>+≡ (295a) <298c 299b>
      elemental subroutine delete_histogram2 (h)
        type(histogram2), intent(inout) :: h
        deallocate (h%bins, h%bins2)
      end subroutine delete_histogram2

299b  <Implementation of histograms procedures 296f>+≡ (295a) <299a 300b>
      subroutine write_histogram1 (h, name, over)
        type(histogram), intent(in) :: h
        character(len=*), intent(in), optional :: name
        logical, intent(in), optional :: over
        integer :: i, iounit
        if (present (name)) then
          call find_free_unit (iounit)
          if (iounit > 0) then
            open (unit = iounit, action = "write", status = "replace", &
                  file = name)
            if (present (over)) then
              if (over) then
                write (unit = iounit, fmt = *) &
                  "underflow", h%bins(0), sqrt (h%bins2(0))
              end if
            end if
            do i = 1, h%n_bins
              write (unit = iounit, fmt = *) &
                midpoint (h, i), h%bins(i), sqrt (h%bins2(i))
            end do
            if (present (over)) then
              if (over) then
                write (unit = iounit, fmt = *) &
                  "overflow", h%bins(h%n_bins+1), &
                  sqrt (h%bins2(h%n_bins+1))
              end if
            end if
            close (unit = iounit)
          else
            print *, "write_histogram: Can't find a free unit!"
          end if
        else
          if (present (over)) then
            if (over) then
              print *, "underflow", h%bins(0), sqrt (h%bins2(0))
            end if
          end if
        end if
      end if

```

```

do i = 1, h%n_bins
  print *, midpoint (h, i), h%bins(i), sqrt (h%bins2(i))
end do
if (present (over)) then
  if (over) then
    print *, "overflow", h%bins(h%n_bins+1), &
      sqrt (h%bins2(h%n_bins+1))
  end if
end if
end if
end subroutine write_histogram1

```

300a *<Declaration of histograms procedures 296b>+≡ (295a) <296d 301a>*  
 !WK! public :: write\_histogram1\_unit



I don't like the format statement with the line number. Use a character constant instead (after we have merged with WHIZARD's branch).

300b *<Implementation of histograms procedures 296f>+≡ (295a) <299b 301d>*  
 subroutine write\_histogram1\_unit (h, iounit, over, show\_excess)  
 type(histogram), intent(in) :: h  
 integer, intent(in) :: iounit  
 logical, intent(in), optional :: over, show\_excess  
 integer :: i  
 logical :: show\_exc  
 show\_exc = .false.; if (present(show\_excess)) show\_exc = show\_excess  
 if (present (over)) then  
 if (over) then  
 if (show\_exc) then  
 write (unit = iounit, fmt = 1) &  
 "underflow", h%bins(0), sqrt (h%bins2(0)), h%bins3(0)  
 else  
 write (unit = iounit, fmt = 1) &  
 "underflow", h%bins(0), sqrt (h%bins2(0))  
 end if  
 end if  
 end if  
 do i = 1, h%n\_bins  
 if (show\_exc) then  
 write (unit = iounit, fmt = 1) &  
 midpoint (h, i), h%bins(i), sqrt (h%bins2(i)), h%bins3(i)  
 else  
 write (unit = iounit, fmt = 1) &  
 midpoint (h, i), h%bins(i), sqrt (h%bins2(i))  
 end if  
 end do

```

        end if
    end do
    if (present (over)) then
        if (over) then
            if (show_exc) then
                write (unit = iounit, fmt = 1) &
                    "overflow", h%bins(h%n_bins+1), &
                    sqrt (h%bins2(h%n_bins+1)), &
                    h%bins3(h%n_bins+1)
            else
                write (unit = iounit, fmt = 1) &
                    "overflow", h%bins(h%n_bins+1), &
                    sqrt (h%bins2(h%n_bins+1))
            end if
        end if
    end if
    1 format (1x,4(G16.9,2x))
end subroutine write_histogram1_unit

```

- 301a *<Declaration of histograms procedures 296b>+≡ (295a) <300a 301c>*  
 private :: midpoint
- 301b *<Interfaces of histograms procedures 296c>+≡ (295a) <296c*  
 interface midpoint  
     module procedure midpoint1, midpoint2  
end interface
- 301c *<Declaration of histograms procedures 296b>+≡ (295a) <301a*  
 private :: midpoint1, midpoint2
- 301d *<Implementation of histograms procedures 296f>+≡ (295a) <300b 301e>*  
 elemental function midpoint1 (h, bin) result (x)  
     type(histogram), intent(in) :: h  
     integer, intent(in) :: bin  
     real(kind=default) :: x  
     x = h%x\_min + (h%x\_max - h%x\_min) \* (bin - 0.5) / h%n\_bins  
end function midpoint1
- 301e *<Implementation of histograms procedures 296f>+≡ (295a) <301d 302>*  
 elemental function midpoint2 (h, bin, d) result (x)  
     type(histogram2), intent(in) :: h  
     integer, intent(in) :: bin, d  
     real(kind=default) :: x  
     x = h%x\_min(d) + (h%x\_max(d) - h%x\_min(d)) \* (bin - 0.5) / h%n\_bins(d)  
end function midpoint2

302 *<Implementation of histograms procedures 296f>+≡* (295a) <301e

```

subroutine write_histogram2 (h, name, over)
  type(histogram2), intent(in) :: h
  character(len=*), intent(in), optional :: name
  logical, intent(in), optional :: over
  integer :: i1, i2, iounit
  if (present (name)) then
    call find_free_unit (iounit)
    if (iounit > 0) then
      open (unit = iounit, action = "write", status = "replace", &
           file = name)
      if (present (over)) then
        if (over) then
          write (unit = iounit, fmt = *) &
            "double underflow", h%bins(0,0), sqrt (h%bins2(0,0))
          do i2 = 1, h%n_bins(2)
            write (unit = iounit, fmt = *) &
              "x1 underflow", midpoint (h, i2, 2), &
              h%bins(0,i2), sqrt (h%bins2(0,i2))
          end do
          do i1 = 1, h%n_bins(1)
            write (unit = iounit, fmt = *) &
              "x2 underflow", midpoint (h, i1, 1), &
              h%bins(i1,0), sqrt (h%bins2(i1,0))
          end do
        end if
      end if
      do i1 = 1, h%n_bins(1)
        do i2 = 1, h%n_bins(2)
          write (unit = iounit, fmt = *) &
            midpoint (h, i1, 1), midpoint (h, i2, 2), &
            h%bins(i1,i2), sqrt (h%bins2(i1,i2))
        end do
      end do
      if (present (over)) then
        if (over) then
          do i2 = 1, h%n_bins(2)
            write (unit = iounit, fmt = *) &
              "x1 overflow", midpoint (h, i2, 2), &
              h%bins(h%n_bins(1)+1,i2), &
              sqrt (h%bins2(h%n_bins(1)+1,i2))
          end do
          do i1 = 1, h%n_bins(1)

```

```

        write (unit = iounit, fmt = *) &
            "x2 overflow", midpoint (h, i1, 1), &
            h%bins(i1,h%n_bins(2)+1), &
            sqrt (h%bins2(i1,h%n_bins(2)+1))
    end do
    write (unit = iounit, fmt = *) "double overflow", &
        h%bins(h%n_bins(1)+1,h%n_bins(2)+1), &
        sqrt (h%bins2(h%n_bins(1)+1,h%n_bins(2)+1))
    end if
end if
close (unit = iounit)
else
    print *, "write_histogram: Can't find a free unit!"
end if
else
    if (present (over)) then
        if (over) then
            print *, "double underflow", h%bins(0,0), sqrt (h%bins2(0,0))
            do i2 = 1, h%n_bins(2)
                print *, "x1 underflow", midpoint (h, i2, 2), &
                    h%bins(0,i2), sqrt (h%bins2(0,i2))
            end do
            do i1 = 1, h%n_bins(1)
                print *, "x2 underflow", midpoint (h, i1, 1), &
                    h%bins(i1,0), sqrt (h%bins2(i1,0))
            end do
        end if
    end if
    do i1 = 1, h%n_bins(1)
        do i2 = 1, h%n_bins(2)
            print *, midpoint (h, i1, 1), midpoint (h, i2, 2), &
                h%bins(i1,i2), sqrt (h%bins2(i1,i2))
        end do
    end do
    if (present (over)) then
        if (over) then
            do i2 = 1, h%n_bins(2)
                print *, "x1 overflow", midpoint (h, i2, 2), &
                    h%bins(h%n_bins(1)+1,i2), &
                    sqrt (h%bins2(h%n_bins(1)+1,i2))
            end do
            do i1 = 1, h%n_bins(1)
                print *, "x2 overflow", midpoint (h, i1, 1), &

```



```

        h%bins(i1,h%n_bins(2)+1), &
        sqrt (h%bins2(i1,h%n_bins(2)+1))
    end do
    print *, "double overflow", &
        h%bins(h%n_bins(1)+1,h%n_bins(2)+1), &
        sqrt (h%bins2(h%n_bins(1)+1,h%n_bins(2)+1))
    end if
end if
end if
end subroutine write_histogram2

```

# —G—

## MISCELLANEOUS UTILITIES

```

305a  <utils.f90 305a>≡
      ! utils.f90 --
      <Copyleft notice 1>
      module utils
        use kinds
        implicit none
        private
        <Declaration of utils procedures 305b>
        <Parameters in utils 312c>
        <Variables in utils 313b>
        <Interfaces of utils procedures 305c>
        character(len=*), public, parameter :: UTILS_RCS_ID = &
          "$Id: utils.nw 314 2010-04-17 20:32:33Z ohl $"
      contains
        <Implementation of utils procedures 306c>
      end module utils

```

### *G.1 Memory Management*

```

305b  <Declaration of utils procedures 305b>≡                                     (305a) 307d>
      public :: create_array_pointer
      private :: create_integer_array_pointer
      private :: create_real_array_pointer
      private :: create_integer_array2_pointer
      private :: create_real_array2_pointer

305c  <Interfaces of utils procedures 305c>≡                                     (305a) 307e>
      interface create_array_pointer
        module procedure &
          create_integer_array_pointer, &
          create_real_array_pointer, &

```

```

        create_integer_array2_pointer, &
        create_real_array2_pointer
    end interface
306a  <Body of create_*_array_pointer 306a>≡ (306c 307a)
    if (associated (lhs)) then
        if (size (lhs) /= n) then
            deallocate (lhs)
            if (present (lb)) then
                allocate (lhs(lb:n+lb-1))
            else
                allocate (lhs(n))
            end if
        end if
    else
        if (present (lb)) then
            allocate (lhs(lb:n+lb-1))
        else
            allocate (lhs(n))
        end if
    end if
    lhs = 0
306b  <Body of create_*_array2_pointer 306b>≡ (307)
    if (associated (lhs)) then
        if (any (ubound (lhs) /= n)) then
            deallocate (lhs)
            if (present (lb)) then
                allocate (lhs(lb(1):n(1)+lb(1)-1,lb(2):n(2)+lb(2)-1))
            else
                allocate (lhs(n(1),n(2)))
            end if
        end if
    else
        if (present (lb)) then
            allocate (lhs(lb(1):n(1)+lb(1)-1,lb(2):n(2)+lb(2)-1))
        else
            allocate (lhs(n(1),n(2)))
        end if
    end if
    lhs = 0
306c  <Implementation of utils procedures 306c>≡ (305a) 307a>
    pure subroutine create_integer_array_pointer (lhs, n, lb)
        integer, dimension(:), pointer :: lhs

```

```

integer, intent(in) :: n
integer, intent(in), optional :: lb
<Body of create_*.array_pointer 306a>
end subroutine create_integer_array_pointer

307a <Implementation of utils procedures 306c>+≡ (305a) <306c 307b>
pure subroutine create_real_array_pointer (lhs, n, lb)
real(kind=default), dimension(:), pointer :: lhs
integer, intent(in) :: n
integer, intent(in), optional :: lb
<Body of create_*.array_pointer 306a>
end subroutine create_real_array_pointer

307b <Implementation of utils procedures 306c>+≡ (305a) <307a 307c>
pure subroutine create_integer_array2_pointer (lhs, n, lb)
integer, dimension(:,:), pointer :: lhs
integer, dimension(:), intent(in) :: n
integer, dimension(:), intent(in), optional :: lb
<Body of create_*.array2_pointer 306b>
end subroutine create_integer_array2_pointer

307c <Implementation of utils procedures 306c>+≡ (305a) <307b 308a>
pure subroutine create_real_array2_pointer (lhs, n, lb)
real(kind=default), dimension(:,:), pointer :: lhs
integer, dimension(:), intent(in) :: n
integer, dimension(:), intent(in), optional :: lb
<Body of create_*.array2_pointer 306b>
end subroutine create_real_array2_pointer

Copy an allocatable array component of a derived type, reshaping the target
if necessary. The target can be disassociated, but its association must not
be undefined.

307d <Declaration of utils procedures 305b>+≡ (305a) <305b 308e>
public :: copy_array_pointer
private :: copy_integer_array_pointer
private :: copy_real_array_pointer
private :: copy_integer_array2_pointer
private :: copy_real_array2_pointer

307e <Interfaces of utils procedures 305c>+≡ (305a) <305c 309a>
interface copy_array_pointer
module procedure &
    copy_integer_array_pointer, &
    copy_real_array_pointer, &
    copy_integer_array2_pointer, &
    copy_real_array2_pointer

```

```

end interface

308a <Implementation of utils procedures 306c>+≡ (305a) <307c 308b>
pure subroutine copy_integer_array_pointer (lhs, rhs, lb)
  integer, dimension(:), pointer :: lhs
  integer, dimension(:), intent(in) :: rhs
  integer, intent(in), optional :: lb
  call create_integer_array_pointer (lhs, size (rhs), lb)
  lhs = rhs
end subroutine copy_integer_array_pointer

308b <Implementation of utils procedures 306c>+≡ (305a) <308a 308c>
pure subroutine copy_real_array_pointer (lhs, rhs, lb)
  real(kind=default), dimension(:), pointer :: lhs
  real(kind=default), dimension(:), intent(in) :: rhs
  integer, intent(in), optional :: lb
  call create_real_array_pointer (lhs, size (rhs), lb)
  lhs = rhs
end subroutine copy_real_array_pointer

308c <Implementation of utils procedures 306c>+≡ (305a) <308b 308d>
pure subroutine copy_integer_array2_pointer (lhs, rhs, lb)
  integer, dimension(:, :), pointer :: lhs
  integer, dimension(:, :), intent(in) :: rhs
  integer, dimension(:), intent(in), optional :: lb
  call create_integer_array2_pointer &
    (lhs, (/ size (rhs, dim=1), size (rhs, dim=2) /), lb)
  lhs = rhs
end subroutine copy_integer_array2_pointer

308d <Implementation of utils procedures 306c>+≡ (305a) <308c 309b>
pure subroutine copy_real_array2_pointer (lhs, rhs, lb)
  real(kind=default), dimension(:, :), pointer :: lhs
  real(kind=default), dimension(:, :), intent(in) :: rhs
  integer, dimension(:), intent(in), optional :: lb
  call create_real_array2_pointer &
    (lhs, (/ size (rhs, dim=1), size (rhs, dim=2) /), lb)
  lhs = rhs
end subroutine copy_real_array2_pointer

```

## G.2 Sorting

```

308e <Declaration of utils procedures 305b>+≡ (305a) <307d 310d>
public :: swap
private :: swap_integer, swap_real

```

309a *<Interfaces of utils procedures 305c>+≡* (305a) <307e 311a>

```
interface swap
  module procedure swap_integer, swap_real
end interface
```

309b *<Implementation of utils procedures 306c>+≡* (305a) <308d 309c>

```
elemental subroutine swap_integer (a, b)
  integer, intent(inout) :: a, b
  integer :: tmp
  tmp = a
  a = b
  b = tmp
end subroutine swap_integer
```

309c *<Implementation of utils procedures 306c>+≡* (305a) <309b 309d>

```
elemental subroutine swap_real (a, b)
  real(kind=default), intent(inout) :: a, b
  real(kind=default) :: tmp
  tmp = a
  a = b
  b = tmp
end subroutine swap_real
```

Straight insertion:

309d *<Implementation of utils procedures 306c>+≡* (305a) <309c 310b>

```
pure subroutine sort_real (key, reverse)
  real(kind=default), dimension(:), intent(inout) :: key
  logical, intent(in), optional :: reverse
  logical :: rev
  integer :: i, j
  <Set rev to reverse or .false. 309e>
  do i = 1, size (key) - 1
    <Set j to minloc(key) 310a>
    if (j /= i) then
      call swap (key(i), key(j))
    end if
  end do
end subroutine sort_real
```

309e *<Set rev to reverse or .false. 309e>≡* (309 310)

```
if (present (reverse)) then
  rev = reverse
else
  rev = .false.
end if
```

```

310a  <Set j to minloc(key) 310a>≡ (309 310)
      if (rev) then
        j = sum (maxloc (key(i:))) + i - 1
      else
        j = sum (minloc (key(i:))) + i - 1
      end if

310b  <Implementation of utils procedures 306c>+≡ (305a) <309d 310c>
      pure subroutine sort_real_and_real_array (key, table, reverse)
        real(kind=default), dimension(:), intent(inout) :: key
        real(kind=default), dimension(:, :), intent(inout) :: table
        logical, intent(in), optional :: reverse
        logical :: rev
        integer :: i, j
        <Set rev to reverse or .false. 309e>
        do i = 1, size (key) - 1
          <Set j to minloc(key) 310a>
          if (j /= i) then
            call swap (key(i), key(j))
            call swap (table(:, i), table(:, j))
          end if
        end do
      end subroutine sort_real_and_real_array

310c  <Implementation of utils procedures 306c>+≡ (305a) <310b 311c>
      pure subroutine sort_real_and_integer (key, table, reverse)
        real(kind=default), dimension(:), intent(inout) :: key
        integer, dimension(:), intent(inout) :: table
        logical, intent(in), optional :: reverse
        logical :: rev
        integer :: i, j
        <Set rev to reverse or .false. 309e>
        do i = 1, size (key) - 1
          <Set j to minloc(key) 310a>
          if (j /= i) then
            call swap (key(i), key(j))
            call swap (table(i), table(j))
          end if
        end do
      end subroutine sort_real_and_integer

310d  <Declaration of utils procedures 305b>+≡ (305a) <308e 311b>
      public :: sort
      private :: sort_real, sort_real_and_real_array, sort_real_and_integer

```

311a  $\langle$ Interfaces of utils procedures 305c $\rangle + \equiv$  (305a)  $\triangleleft$ 309a $\triangleright$

```

interface sort
  module procedure &
    sort_real, sort_real_and_real_array, &
    sort_real_and_integer
end interface

```

### G.3 Mathematics

311b  $\langle$ Declaration of utils procedures 305b $\rangle + \equiv$  (305a)  $\triangleleft$ 310d 311d $\triangleright$

```

public :: outer_product

```

Admittedly, one has to get used to this notation for the tensor product:

311c  $\langle$ Implementation of utils procedures 306c $\rangle + \equiv$  (305a)  $\triangleleft$ 310c 311e $\triangleright$

```

pure function outer_product (x, y) result (xy)
  real(kind=default), dimension(:), intent(in) :: x, y
  real(kind=default), dimension(size(x),size(y)) :: xy
  xy = spread (x, dim=2, ncopies=size(y)) &
    * spread (y, dim=1, ncopies=size(x))
end function outer_product

```

Greatest common divisor and least common multiple

311d  $\langle$ Declaration of utils procedures 305b $\rangle + \equiv$  (305a)  $\triangleleft$ 311b 313a $\triangleright$

```

public :: factorize, gcd, lcm
private :: gcd_internal

```

For our purposes, a straightforward implementation of Euclid's algorithm suffices:

311e  $\langle$ Implementation of utils procedures 306c $\rangle + \equiv$  (305a)  $\triangleleft$ 311c 311f $\triangleright$

```

pure recursive function gcd_internal (m, n) result (gcd_m_n)
  integer, intent(in) :: m, n
  integer :: gcd_m_n
  if (n <= 0) then
    gcd_m_n = m
  else
    gcd_m_n = gcd_internal (n, modulo (m, n))
  end if
end function gcd_internal

```

Wrap an elemental procedure around the recursive procedure:

311f  $\langle$ Implementation of utils procedures 306c $\rangle + \equiv$  (305a)  $\triangleleft$ 311e 312a $\triangleright$

```

elemental function gcd (m, n) result (gcd_m_n)
  integer, intent(in) :: m, n
  integer :: gcd_m_n

```



```

gcd_m_n = gcd_internal (m, n)
end function gcd

```

As long as  $m \cdot n$  does not overflow, we can use  $\text{gcd}(m, n) \text{lcm}(m, n) = mn$ :

312a *<Implementation of utils procedures 306c>+≡ (305a) <311f 312b>*

```

elemental function lcm (m, n) result (lcm_m_n)
  integer, intent(in) :: m, n
  integer :: lcm_m_n
  lcm_m_n = (m * n) / gcd (m, n)
end function lcm

```

A very simple minded factorization procedure, that is not fool proof at all. It maintains  $n == \text{product}(\text{factors}(1:i))$ , however, and will work in all cases of practical relevance.

312b *<Implementation of utils procedures 306c>+≡ (305a) <312a 313c>*

```

pure subroutine factorize (n, factors, i)
  integer, intent(in) :: n
  integer, dimension(:), intent(out) :: factors
  integer, intent(out) :: i
  integer :: nn, p
  nn = n
  i = 0
  do p = 1, size (PRIMES)
    try: do
      if (modulo (nn, PRIMES(p)) == 0) then
        i = i + 1
        factors(i) = PRIMES(p)
        nn = nn / PRIMES(p)
        if (i >= size (factors)) then
          factors(i) = nn
          return
        end if
      else
        exit try
      end if
    end do try
    if (nn == 1) then
      return
    end if
  end do
end subroutine factorize

```

312c *<Parameters in utils 312c>≡ (305a)*

```

integer, dimension(13), parameter, private :: &
  PRIMES = (/ 2, 3, 5, 7, 11, 13, 17, 19, 23, 29, 31, 37, 41 /)

```

## G.4 I/O

313a *<Declaration of utils procedures 305b>+≡* (305a) <311d  
       public :: **find\_free\_unit**

313b *<Variables in utils 313b>≡* (305a)  
       integer, parameter, private :: **MIN\_UNIT** = 11, **MAX\_UNIT** = 99

313c *<Implementation of utils procedures 306c>+≡* (305a) <312b  
       **subroutine find\_free\_unit** (u, iostat)  
         integer, intent(out) :: u  
         integer, intent(out), optional :: iostat  
         logical :: exists, is\_open  
         integer :: **i**, status  
         do **i** = **MIN\_UNIT**, **MAX\_UNIT**  
           inquire (**unit** = **i**, exist = exists, opened = is\_open, &  
                   iostat = status)  
           if (status == 0) then  
             if (exists .and. .not. is\_open) then  
               u = **i**  
               if (present (iostat)) then  
                 iostat = 0  
               end if  
               return  
             end if  
           end if  
         end do  
         if (present (iostat)) then  
           iostat = -1  
         end if  
         u = -1  
       end **subroutine find\_free\_unit**

# —H— LINEAR ALGEBRA

```

314a <linalg.f90 314a>≡
! linalg.f90 --
<Coyleft notice 1>
module linalg
  use kinds
  use utils
  implicit none
  private
  <Declaration of linalg procedures 314b>
  character(len=*), public, parameter :: LINALG_RCS_ID = &
    "$Id: linalg.nw 314 2010-04-17 20:32:33Z ohl $"
  contains
    <Implementation of linalg procedures 315>
end module linalg

```

## *H.1 LU Decomposition*

```

314b <Declaration of linalg procedures 314b>≡ (314a) 317a>
  public :: lu_decompose

```

$$A = LU \tag{H.1a}$$

In more detail

$$\begin{pmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ a_{n1} & a_{n2} & \dots & a_{nn} \end{pmatrix} = \begin{pmatrix} 1 & 0 & \dots & 0 \\ l_{21} & 1 & \dots & 0 \\ \vdots & \vdots & \vdots & \vdots \\ l_{n1} & l_{n2} & \dots & 1 \end{pmatrix} \begin{pmatrix} u_{11} & u_{12} & \dots & u_{1n} \\ 0 & u_{22} & \dots & u_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & \dots & u_{nn} \end{pmatrix} \tag{H.1b}$$

Rewriting (H.1) in block matrix notation

$$\begin{pmatrix} a_{11} & a_{1\cdot} \\ a_{\cdot 1} & A \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ l_{\cdot 1} & L \end{pmatrix} \begin{pmatrix} u_{11} & u_{1\cdot} \\ 0 & U \end{pmatrix} = \begin{pmatrix} u_{11} & u_{1\cdot} \\ l_{\cdot 1} u_{11} & l_{\cdot 1} \otimes u_{1\cdot} + LU \end{pmatrix} \quad (\text{H.2})$$

we can solve it easily

$$u_{11} = a_{11} \quad (\text{H.3a})$$

$$u_{1\cdot} = a_{1\cdot} \quad (\text{H.3b})$$

$$l_{\cdot 1} = \frac{a_{\cdot 1}}{a_{11}} \quad (\text{H.3c})$$

$$LU = A - \frac{a_{\cdot 1} \otimes a_{1\cdot}}{a_{11}} \quad (\text{H.3d})$$

and (H.3c) and (H.3d) define a simple iterative algorithm if we work from the outside in. It just remains to add pivoting.

315 *<Implementation of linalg procedures 315>* (314a) 317b>  
 pure subroutine lu\_decompose (a, pivots, eps, l, u)  
 real(kind=default), dimension(:,:), intent(inout) :: a  
 integer, dimension(:), intent(out), optional :: pivots  
 real(kind=default), intent(out), optional :: eps  
 real(kind=default), dimension(:,:), intent(out), optional :: l, u  
 real(kind=default), dimension(size(a,dim=1)) :: vv  
 integer, dimension(size(a,dim=1)) :: p  
 integer :: j, pivot  
*<eps = 1 316a>*  
 vv = maxval (abs (a), dim=2)  
 if (any (vv == 0.0)) then  
 a = 0.0  
*<pivots = 0 and eps = 0 316c>*  
 return  
 end if  
 vv = 1.0 / vv  
 do j = 1, size (a, dim=1)  
 pivot = j - 1 + sum (maxloc (vv(j:) \* abs (a(j:,j))))  
 if (j /= pivot) then  
 call swap (a(pivot,:), a(j,:))  
*<eps = - eps 316b>*  
 vv(pivot) = vv(j)  
 end if  
 p(j) = pivot  
 if (a(j,j) == 0.0) then  
 a(j,j) = tiny (a(j,j))

```

        end if
        a(j+1:,j) = a(j+1:,j) / a(j,j)
        a(j+1:,j+1:) &
            = a(j+1:,j+1:) - outer_product (a(j+1:,j), a(j,j+1:))
    end do
    <Return optional arguments in lu_decompose 316d>
end subroutine lu_decompose

316a <eps = 1 316a>≡ (315)
    if (present (eps)) then
        eps = 1.0
    end if

316b <eps = - eps 316b>≡ (315)
    if (present (eps)) then
        eps = - eps
    end if

316c <pivots = 0 and eps = 0 316c>≡ (315)
    if (present (pivots)) then
        pivots = 0
    end if
    if (present (eps)) then
        eps = 0
    end if

316d <Return optional arguments in lu_decompose 316d>≡ (315)
    if (present (pivots)) then
        pivots = p
    end if
    if (present (l)) then
        do j = 1, size (a, dim=1)
            l(1:j-1,j) = 0.0
            l(j,j) = 1.0
            l(j+1:,j) = a(j+1:,j)
        end do
        do j = size (a, dim=1), 1, -1
            call swap (l(j,:), l(p(j),:))
        end do
    end if
    if (present (u)) then
        do j = 1, size (a, dim=1)
            u(1:j,j) = a(1:j,j)
            u(j+1:,j) = 0.0
        end do
    end if
end if

```

## H.2 Determinant

317a  $\langle$ Declaration of `linalg` procedures 314b $\rangle + \equiv$  (314a)  $\langle$ 314b 318a $\rangle$   
`public :: determinant`

This is a subroutine to comply with F's rules, otherwise, we would code it as a function.

317b  $\langle$ Implementation of `linalg` procedures 315 $\rangle + \equiv$  (314a)  $\langle$ 315 318b $\rangle$   
`pure subroutine determinant (a, det)`  
`real(kind=default), dimension(:, :), intent(in) :: a`  
`real(kind=default), intent(out) :: det`  
`real(kind=default), dimension(size(a,dim=1),size(a,dim=2)) :: lu`  
`integer :: i`  
`lu = a`  
`call lu_decompose (lu, eps = det)`  
`do i = 1, size (a, dim = 1)`  
`det = det * lu(i,i)`  
`end do`  
`end subroutine determinant`

## H.3 Diagonalization

The code is an implementation of the algorithm presented in [17, 18], but independent from the code presented in [19] to avoid legal problems.

A Jacobi rotation around the angle  $\phi$  in row  $p$  and column  $q$

$$P(\phi; p, q) = \begin{pmatrix} 1 & & & & \\ & \ddots & & & \\ & & \cos \phi & \cdots & \sin \phi \\ & & \vdots & 1 & \vdots \\ & & -\sin \phi & \cdots & \cos \phi \\ & & & & \ddots \\ & & & & & 1 \end{pmatrix} \quad (\text{H.4})$$

results in

$$A' = P^T(\phi; p, q) \cdot A \cdot P(\phi; p, q) = \begin{pmatrix} & A'_{1p} & A'_{1q} & & \\ & \vdots & \vdots & & \\ A'_{p1} & \cdots & A'_{pq} & \cdots & A'_{pn} \\ & \vdots & \vdots & & \\ A'_{q1} & \cdots & A'_{qp} & \cdots & A'_{qn} \\ & \vdots & \vdots & & \\ & A'_{np} & A'_{nq} & & \end{pmatrix} \quad (\text{H.5})$$

318a  $\langle$ Declaration of linalg procedures 314b $\rangle + \equiv$  (314a)  $\langle$ 317a 321c $\rangle$   
public :: diagonalize\_real\_symmetric

318b  $\langle$ Implementation of linalg procedures 315 $\rangle + \equiv$  (314a)  $\langle$ 317b 321b $\rangle$   
pure subroutine diagonalize\_real\_symmetric (a, eval, evec, num\_rot)  
  real(kind=default), dimension(:, :), intent(in) :: a  
  real(kind=default), dimension(:), intent(out) :: eval  
  real(kind=default), dimension(:, :), intent(out) :: evec  
  integer, intent(out), optional :: num\_rot  
  real(kind=default), dimension(size(a,dim=1),size(a,dim=2)) :: aa  
  real(kind=default) :: off\_diagonal\_norm, threshold, &  
    c, g, h, s, t, tau, cot\_2phi  
  logical, dimension(size(eval),size(eval)) :: upper\_triangle  
  integer, dimension(size(eval)) :: one\_to\_ndim  
  integer :: p, q, ndim, j, sweep  
  integer, parameter :: MAX\_SWEEPS = 50  
  ndim = size (eval)  
  one\_to\_ndim = (/ (j, j=1,ndim) /)  
  upper\_triangle = &  
    spread (one\_to\_ndim, dim=1, ncopies=ndim) &  
    > spread (one\_to\_ndim, dim=2, ncopies=ndim)  
  aa = a  
  call unit (evec)  
 $\langle$ Initialize num\_rot 321e $\rangle$   
  sweeps: do sweep = 1, MAX\_SWEEPS  
    off\_diagonal\_norm = sum (abs (aa), mask=upper\_triangle)  
    if (off\_diagonal\_norm == 0.0) then  
      eval = diag (aa)  
      return  
    end if  
    if (sweep < 4) then  
      threshold = 0.2 \* off\_diagonal\_norm / ndim\*\*2  
    else

```

        threshold = 0.0
    end if
    do p = 1, ndim - 1
        do q = p + 1, ndim
            ⟨Perform the Jacobi rotation resulting in  $A'_{pq} = 0$  319⟩
        end do
    end do
end do sweeps
if (present (num_rot)) then
    num_rot = -1
end if
!!! print *, "linalg::diagonalize_real_symmetric: exceeded sweep count"
end subroutine diagonalize_real_symmetric
319 ⟨Perform the Jacobi rotation resulting in  $A'_{pq} = 0$  319⟩ ≡ (318b)
    g = 100 * abs (aa (p,q))
    if ((sweep > 4) &
        .and. (g <= min (spacing (aa(p,p)), spacing (aa(q,q))))) then
        aa(p,q) = 0.0
    else if (abs (aa(p,q)) > threshold) then
        ⟨Determine  $\phi$  for the Jacobi rotation  $P(\phi; p, q)$  with  $A'_{pq} = 0$  320a⟩
        ⟨ $A' = P^T(\phi; p, q) \cdot A \cdot P(\phi; p, q)$  320c⟩
        ⟨ $V' = V \cdot P(\phi; p, q)$  321d⟩
        ⟨Update num_rot 321f⟩
    end if

```

We want

$$A'_{pq} = (c^2 - s^2)A_{pq} + sc(A_{pp} - A_{qq}) = 0 \quad (\text{H.6})$$

and therefore

$$\cot 2\phi = \frac{1 - \tan^2 \phi}{2 \tan \phi} = \frac{\cos^2 \phi - \sin^2 \phi}{2 \sin \phi \cos \phi} = \frac{A_{pp} - A_{qq}}{2A_{pq}} \quad (\text{H.7})$$

i.e. with  $t = \tan \phi = s/c$

$$t^2 + 2t \cot 2\phi - 1 = 0 \quad (\text{H.8})$$

This quadratic equation has the roots

$$t = -\cot 2\phi \pm \sqrt{1 + \cot^2 2\phi} = \frac{\epsilon(\cot 2\phi)}{|\cot 2\phi| \pm \epsilon(\cot 2\phi)\sqrt{1 + \cot^2 2\phi}} \quad (\text{H.9})$$

and the smaller in magnitude of these is

$$t = \frac{\epsilon(\cot 2\phi)}{|\cot 2\phi| + \sqrt{1 + \cot^2 2\phi}} \quad (\text{H.10})$$



and since  $|t| \leq 1$ , it corresponds to  $|\phi| \leq \pi/4$ . For very large  $\cot 2\phi$  we will use

$$t = \frac{1}{2 \cot 2\phi} = \frac{A_{pq}}{A_{pp} - A_{qq}} \quad (\text{H.11})$$

$$h = A_{qq} - A_{pp} \quad (\text{H.12})$$

**320a**  $\langle \text{Determine } \phi \text{ for the Jacobi rotation } P(\phi; p, q) \text{ with } A'_{pq} = 0 \text{ } \mathbf{320a} \rangle \equiv \quad (\mathbf{319}) \quad \mathbf{320b} \triangleright$

```

h = aa(q,q) - aa(p,p)
if (g <= spacing (h)) then
  t = aa(p,q) / h
else
  cot_2phi = 0.5 * h / aa(p,q)
  t = sign (1.0_default, cot_2phi) &
    / (abs (cot_2phi) + sqrt (1.0 + cot_2phi**2))
end if

```

Trivia

$$\cos^2 \phi = \frac{\cos^2 \phi}{\cos^2 \phi + \sin^2 \phi} = \frac{1}{1 + \tan^2 \phi} \quad (\text{H.13a})$$

$$\sin \phi = \tan \phi \cos \phi \quad (\text{H.13b})$$

$$\tau \sin \phi = \frac{\sin^2}{1 + \cos \phi} = \frac{1 - \cos^2}{1 + \cos \phi} = 1 - \cos \phi \quad (\text{H.13c})$$

**320b**  $\langle \text{Determine } \phi \text{ for the Jacobi rotation } P(\phi; p, q) \text{ with } A'_{pq} = 0 \text{ } \mathbf{320a} \rangle + \equiv \quad (\mathbf{319}) \quad \triangleleft \mathbf{320a}$

```

c = 1.0 / sqrt (1.0 + t**2)
s = t * c
tau = s / (1.0 + c)

```

$$\begin{aligned}
A'_{pp} &= c^2 A_{pp} + s^2 A_{qq} - 2sc A_{pq} = A_{pp} - t A_{pq} \\
A'_{qq} &= s^2 A_{pp} + c^2 A_{qq} + 2sc A_{pq} = A_{qq} + t A_{pq} \\
A'_{pq} &= (c^2 - s^2) A_{pq} + sc (A_{pp} - A_{qq})
\end{aligned} \quad (\text{H.14})$$

**320c**  $\langle A' = P^T(\phi; p, q) \cdot A \cdot P(\phi; p, q) \text{ } \mathbf{320c} \rangle \equiv \quad (\mathbf{319}) \quad \mathbf{321a} \triangleright$

```

aa(p,p) = aa(p,p) - t * aa(p,q)
aa(q,q) = aa(q,q) + t * aa(p,q)
aa(p,q) = 0.0

```

$$\begin{aligned}
r \neq p < q \neq r : A'_{rp} &= c A_{rp} - s A_{rq} \\
A'_{rq} &= s A_{rp} + c A_{rq}
\end{aligned} \quad (\text{H.15})$$

Here's how we cover the upper triangular region using array notation:

$$\begin{pmatrix} & a(1:p-1,p) & & a(1:p-1,q) & \\ \cdots & A_{pq} & a(p,p+1:q-1) & A_{pq} & a(p,q+1:\text{ndim}) \\ & \vdots & & a(p+1:q-1,q) & \\ \cdots & A_{qp} & \cdots & A_{qq} & a(q,q+1:\text{ndim}) \\ & \vdots & & \vdots & \end{pmatrix} \quad (\text{H.16})$$

321a  $\langle A' = P^T(\phi; p, q) \cdot A \cdot P(\phi; p, q) \text{ 320c} \rangle + \equiv$  (319)  $\langle \text{320c}$   
`call jacobi_rotation (s, tau, aa(1:p-1,p), aa(1:p-1,q))`  
`call jacobi_rotation (s, tau, aa(p,p+1:q-1), aa(p+1:q-1,q))`  
`call jacobi_rotation (s, tau, aa(p,q+1:ndim), aa(q,q+1:ndim))`

Using (H.13c), we can write the rotation as a perturbation:

$$\begin{aligned} V'_p &= cV_p - sV_q = V_p - s(V_q + \tau V_p) \\ V'_q &= sV_p + cV_q = V_q + s(V_p - \tau V_q) \end{aligned} \quad (\text{H.17})$$

321b  $\langle \text{Implementation of linalg procedures 315} \rangle + \equiv$  (314a)  $\langle \text{318b 322a} \rangle$   
`pure subroutine jacobi_rotation (s, tau, vp, vq)`  
`real(kind=default), intent(in) :: s, tau`  
`real(kind=default), dimension(:), intent(inout) :: vp, vq`  
`real(kind=default), dimension(size(vp)) :: vp_tmp`  
`vp_tmp = vp`  
`vp = vp - s * (vq + tau * vp)`  
`vq = vq + s * (vp_tmp - tau * vq)`  
`end subroutine jacobi_rotation`

321c  $\langle \text{Declaration of linalg procedures 314b} \rangle + \equiv$  (314a)  $\langle \text{318a 322c} \rangle$   
`private :: jacobi_rotation`

321d  $\langle V' = V \cdot P(\phi; p, q) \text{ 321d} \rangle \equiv$  (319)  
`call jacobi_rotation (s, tau, evec(:,p), evec(:,q))`

321e  $\langle \text{Initialize num_rot 321e} \rangle \equiv$  (318b)  
`if (present (num_rot)) then`  
`num_rot = 0`  
`end if`

321f  $\langle \text{Update num_rot 321f} \rangle \equiv$  (319)  
`if (present (num_rot)) then`  
`num_rot = num_rot + 1`  
`end if`

322a *<Implementation of linalg procedures 315>+≡* (314a) <321b 322b>  

```

pure subroutine unit (u)
  real(kind=default), dimension(:,,:), intent(out) :: u
  integer :: i
  u = 0.0
  do i = 1, min (size (u, dim = 1), size (u, dim = 2))
    u(i,i) = 1.0
  end do
end subroutine unit

```

322b *<Implementation of linalg procedures 315>+≡* (314a) <322a  

```

pure function diag (a) result (d)
  real(kind=default), dimension(:,,:), intent(in) :: a
  real(kind=default), dimension(min(size(a,dim=1),size(a,dim=2))) :: d
  integer :: i
  do i = 1, min (size (a, dim = 1), size (a, dim = 2))
    d(i) = a(i,i)
  end do
end function diag

```

322c *<Declaration of linalg procedures 314b>+≡* (314a) <321c  

```

public :: unit, diag

```

## H.4 Test

322d *<la\_sample.f90 322d>≡*  

```

! la_sample.f90 --
<Copyleft notice 1>
program la_sample
  use kinds
  use utils
  use tao_random_numbers
  use linalg
  implicit none
  integer, parameter :: N = 200
  real(kind=default), dimension(N,N) :: a, evec, a0, l, u, NAG_bug
  real(kind=default), dimension(N) :: b, eval
  real(kind=default) :: d
  integer :: i
  call system_clock (i)
  call tao_random_seed (i)
  print *, i
  do i = 1, N

```

```

        call tao_random_number (a(:,i))
    end do
    NAG_bug = (a + transpose (a)) / 2
    a = NAG_bug
    a0 = a
    call lu_decompose (a, l=l, u=u)
    a = matmul (l, u)
    print *, maxval (abs(a-a0))
    call determinant (a, d)
    print *, d
    call diagonalize_real_symmetric (a, eval, evec)
    print *, product (eval)
    stop
    call sort (eval, evec)
    do i = 1, N
        b = matmul (a, evec(:,i)) - eval(i) * evec(:,i)
        write (unit = *, fmt = "(A,I3, 2(A,E11.4))") &
            "eval #", i, " = ", eval(i), ", |(A-lambda)V|_infty = ", &
            maxval (abs(b)) / maxval (abs(evec(:,i)))
    end do
end program la_sample

```

# —I—

## PRODUCTS

```
324 <products.f90 324>≡
! products.f90 --
<Copyleft notice 1>
module products
  use kinds
  implicit none
  private
  public :: dot, sp, spc
  character(len=*), public, parameter :: PRODUCTS_RCS_ID = &
    "$Id: products.nw 314 2010-04-17 20:32:33Z ohl $"
contains
  pure function dot (p, q) result (pq)
    real(kind=default), dimension(0:), intent(in) :: p, q
    real(kind=default) :: pq
    pq = p(0)*q(0) - dot_product (p(1:), q(1:))
  end function dot
  pure function sp (p, q) result (sppq)
    real(kind=default), dimension(0:), intent(in) :: p, q
    complex(kind=default) :: sppq
    sppq = cmplx (p(2), p(3), kind=default) * sqrt ((q(0)-q(1))/(p(0)-p(1))) &
      - cmplx (q(2), q(3), kind=default) * sqrt ((p(0)-p(1))/(q(0)-q(1)))
  end function sp
  pure function spc (p, q) result (spcpq)
    real(kind=default), dimension(0:), intent(in) :: p, q
    complex(kind=default) :: spcpq
    spcpq = conjg (sp (p, q))
  end function spc
end module products
```

# —J—

## KINEMATICS

```

325a  <kinematics.f90 325a>≡                                     330d>
      ! kinematics.f90 --
      <Copleft notice 1>
      module kinematics
        use kinds
        use constants
        use products, only: dot
        use specfun, only: gamma
        implicit none
        private
        <Declaration of kinematics procedures 325b>
        <Interfaces of kinematics procedures 325c>
        <Declaration of kinematics types 327g>
        character(len=*), public, parameter :: KINEMATICS_RCS_ID = &
            "$Id: kinematics.nw 314 2010-04-17 20:32:33Z ohl $"
        contains
        <Implementation of kinematics procedures 326a>
      end module kinematics

```

### *J.1 Lorentz Transformations*

```

325b  <Declaration of kinematics procedures 325b>≡                (325a) 327d>
      public :: boost_velocity
      private :: boost_one_velocity, boost_many_velocity
      public :: boost_momentum
      private :: boost_one_momentum, boost_many_momentum

325c  <Interfaces of kinematics procedures 325c>≡                (325a) 327f>
      interface boost_velocity
        module procedure boost_one_velocity, boost_many_velocity
      end interface

```

```

interface boost_momentum
  module procedure boost_one_momentum, boost_many_momentum
end interface

```

Boost a four vector  $p$  to the inertial frame moving with the velocity  $\beta$ :

$$p'_0 = \gamma (p_0 - \vec{\beta} \vec{p}) \quad (\text{J.1a})$$

$$\vec{p}' = \gamma (\vec{p}_{\parallel} - \vec{\beta} p_0) + \vec{p}_{\perp} \quad (\text{J.1b})$$

with  $\gamma = 1/\sqrt{1 - \vec{\beta}^2}$ ,  $\vec{p}_{\parallel} = \vec{\beta}(\vec{\beta} \vec{p})/\vec{\beta}^2$  and  $\vec{p}_{\perp} = \vec{p} - \vec{p}_{\parallel}$ . Using  $1/\vec{\beta}^2 = \gamma^2/(\gamma + 1) \cdot 1/(\gamma - 1)$  and  $\vec{b} = \gamma \vec{\beta}$  this can be rewritten as

$$p'_0 = \gamma p_0 - \vec{b} \vec{p} \quad (\text{J.2a})$$

$$\vec{p}' = \vec{p} + \left( \frac{\vec{b} \vec{p}}{\gamma + 1} - p_0 \right) \vec{b} \quad (\text{J.2b})$$

326a  $\langle$ Implementation of kinematics procedures 326a $\rangle \equiv$  (325a) 326b $\rangle$

```

pure function boost_one_velocity (p, beta) result (p_prime)
  real(kind=default), dimension(0:), intent(in) :: p
  real(kind=default), dimension(1:), intent(in) :: beta
  real(kind=default), dimension(0:3) :: p_prime
  real(kind=default), dimension(1:3) :: b
  real(kind=default) :: gamma, b_dot_p
  gamma = 1.0 / sqrt (1.0 - dot_product (beta, beta))
  b = gamma * beta
  b_dot_p = dot_product (b, p(1:3))
  p_prime(0) = gamma * p(0) - b_dot_p
  p_prime(1:3) = p(1:3) + (b_dot_p / (1.0 + gamma) - p(0)) * b
end function boost_one_velocity

```

326b  $\langle$ Implementation of kinematics procedures 326a $\rangle + \equiv$  (325a)  $\langle$ 326a 327a $\rangle$

```

pure function boost_many_velocity (p, beta) result (p_prime)
  real(kind=default), dimension(:,0:), intent(in) :: p
  real(kind=default), dimension(1:), intent(in) :: beta
  real(kind=default), dimension(size(p,dim=1),0:3) :: p_prime
  integer :: i
  do i = 1, size (p, dim=1)
    p_prime(i,:) = boost_one_velocity (p(i,:), beta)
  end do
end function boost_many_velocity

```

Boost a four vector  $p$  to the rest frame of the four vector  $q$ . The velocity is  $\vec{\beta} = \vec{q}/|q_0|$ :

327a  $\langle$ Implementation of kinematics procedures 326a $\rangle + \equiv$  (325a)  $\langle$ 326b 327b $\rangle$   
 pure function **boost\_one\_momentum** (p, q) result (p\_prime)  
   real(kind=default), dimension(0:), intent(in) :: p, q  
   real(kind=default), dimension(0:3) :: p\_prime  
   p\_prime = **boost\_velocity** (p, q(1:3) / abs (q(0)))  
 end function **boost\_one\_momentum**

327b  $\langle$ Implementation of kinematics procedures 326a $\rangle + \equiv$  (325a)  $\langle$ 327a 327c $\rangle$   
 pure function **boost\_many\_momentum** (p, q) result (p\_prime)  
   real(kind=default), dimension(:,0:), intent(in) :: p  
   real(kind=default), dimension(0:), intent(in) :: q  
   real(kind=default), dimension(size(p,dim=1),0:3) :: p\_prime  
   p\_prime = **boost\_many\_velocity** (p, q(1:3) / abs (q(0)))  
 end function **boost\_many\_momentum**

## J.2 Massive Phase Space

$$\lambda(a, b, c) = a^2 + b^2 + c^2 - 2ab - 2bc - 2ca = (a - b - c)^2 - 4bc \quad (\text{J.3})$$

and permutations

327c  $\langle$ Implementation of kinematics procedures 326a $\rangle + \equiv$  (325a)  $\langle$ 327b 328a $\rangle$   
 pure function **lambda** (a, b, c) result (lam)  
   real(kind=default), intent(in) :: a, b, c  
   real(kind=default) :: lam  
   lam = a\*\*2 + b\*\*2 + c\*\*2 - 2\*(a\*b + b\*c + c\*a)  
 end function **lambda**

327d  $\langle$ Declaration of kinematics procedures 325b $\rangle + \equiv$  (325a)  $\langle$ 325b 327e $\rangle$   
 public :: **lambda**

327e  $\langle$ Declaration of kinematics procedures 325b $\rangle + \equiv$  (325a)  $\langle$ 327d 329a $\rangle$   
 public :: two\_to\_three  
 private :: two\_to\_three\_massive, **two\_to\_three\_massless**

327f  $\langle$ Interfaces of kinematics procedures 325c $\rangle + \equiv$  (325a)  $\langle$ 325c 329b $\rangle$   
 interface two\_to\_three  
   module procedure two\_to\_three\_massive, **two\_to\_three\_massless**  
 end interface

327g  $\langle$ Declaration of kinematics types 327g $\rangle \equiv$  (325a)  
 type, public :: **LIPS3**  
   real(kind=default), dimension(3,0:3) :: p  
   real(kind=default) :: **jacobian**  
 end type **LIPS3**



$$dLIPS_3 = \int \frac{d^3\vec{p}_1}{(2\pi)^3 2E_1} \frac{d^3\vec{p}_2}{(2\pi)^3 2E_2} \frac{d^3\vec{p}_3}{(2\pi)^3 2E_3} (2\pi)^4 \delta^4(p_1 + p_2 + p_3 - p_a - p_b) \quad (J.4)$$

The jacobian is given by

$$dLIPS_3 = \frac{1}{(2\pi)^5} \int d\phi dt_1 ds_2 d\Omega_3^{[23]} \frac{1}{32\sqrt{ss_2}} \frac{|p_3^{[23]}|}{|p_a^{[ab]}|} \quad (J.5)$$

where  $\vec{p}_i^{[jk]}$  denotes the momentum of particle  $i$  in the center of mass system of particles  $j$  and  $k$ .

328a  $\langle$ Implementation of kinematics procedures 326a $\rangle + \equiv$  (325a)  $\langle$ 327c 328b $\rangle$

```

pure function two_to_three_massive &
  (s, t1, s2, phi, cos_theta3, phi3, ma, mb, m1, m2, m3) result (p)
  real(kind=default), intent(in) :: &
    s, t1, s2, phi, cos_theta3, phi3, ma, mb, m1, m2, m3
  type(LIPS3) :: p
  real(kind=default), dimension(0:3) :: p23
  real(kind=default) :: Ea, pa_abs, E1, p1_abs, p3_abs, cos_theta
  pa_abs = sqrt (lambda (s, ma**2, mb**2) / (4 * s))
  Ea = sqrt (ma**2 + pa_abs**2)
  p1_abs = sqrt (lambda (s, m1**2, s2) / (4 * s))
  E1 = sqrt (m1**2 + p1_abs**2)
  p3_abs = sqrt (lambda (s2, m2**2, m3**2) / (4 * s2))
  p%jacobian = &
    1.0 / (2*PI)**5 * (p3_abs / pa_abs) / (32 * sqrt (s * s2))
  cos_theta = (t1 - ma**2 - m1**2 + 2*Ea*E1) / (2*pa_abs*p1_abs)
  p%p(1,1:3) = polar_to_cartesian (p1_abs, cos_theta, phi)
  p%p(1,0) = on_shell (p%p(1,:), m1)
  p23(1:3) = - p%p(1,1:3)
  p23(0) = on_shell (p23, sqrt (s2))
  p%p(3:2:-1,:) = one_to_two (p23, cos_theta3, phi3, m3, m2)
end function two_to_three_massive

```

A specialized version for massless particles can be faster, because the kinematics is simpler:

328b  $\langle$ Implementation of kinematics procedures 326a $\rangle + \equiv$  (325a)  $\langle$ 328a 329c $\rangle$

```

pure function two_to_three_massless (s, t1, s2, phi, cos_theta3, phi3) &
  result (p)
  real(kind=default), intent(in) :: s, t1, s2, phi, cos_theta3, phi3
  type(LIPS3) :: p
  real(kind=default), dimension(0:3) :: p23
  real(kind=default) :: pa_abs, p1_abs, p3_abs, cos_theta
  pa_abs = sqrt (s) / 2
  p1_abs = (s - s2) / (2 * sqrt (s))

```

```

    p3_abs = sqrt (s2) / 2
    p%jacobian = 1.0 / ((2*PI)**5 * 32 * s)
    cos_theta = 1 + t1 / (2*pa_abs*p1_abs)
    p%p(1,0) = p1_abs
    p%p(1,1:3) = polar_to_cartesian (p1_abs, cos_theta, phi)
    p23(1:3) = - p%p(1,1:3)
    p23(0) = on_shell (p23, sqrt (s2))
    p%p(3:2:-1,:) = one_to_two (p23, cos_theta3, phi3)
end function two_to_three_massless

329a <Declaration of kinematics procedures 325b>+≡ (325a) <327e 330a>
    public :: one_to_two
    private :: one_to_two_massive, one_to_two_massless

329b <Interfaces of kinematics procedures 325c>+≡ (325a) <327f
    interface one_to_two
        module procedure one_to_two_massive, one_to_two_massless
    end interface

329c <Implementation of kinematics procedures 326a>+≡ (325a) <328b 329d>
    pure function one_to_two_massive (p12, cos_theta, phi, m1, m2) result (p)
        real(kind=default), dimension(0:), intent(in) :: p12
        real(kind=default), intent(in) :: cos_theta, phi, m1, m2
        real(kind=default), dimension(2,0:3) :: p
        real(kind=default) :: s, p1_abs
        s = dot (p12, p12)
        p1_abs = sqrt (lambda (s, m1**2, m2**2) / (4 * s))
        p(1,1:3) = polar_to_cartesian (p1_abs, cos_theta, phi)
        p(2,1:3) = - p(1,1:3)
        p(1,0) = on_shell (p(1,:), m1)
        p(2,0) = on_shell (p(2,:), m2)
        p = boost_momentum (p, - p12)
    end function one_to_two_massive

329d <Implementation of kinematics procedures 326a>+≡ (325a) <329c 330b>
    pure function one_to_two_massless (p12, cos_theta, phi) result (p)
        real(kind=default), dimension(0:), intent(in) :: p12
        real(kind=default), intent(in) :: cos_theta, phi
        real(kind=default), dimension(2,0:3) :: p
        real(kind=default) :: p1_abs
        p1_abs = sqrt (dot (p12, p12)) / 2
        p(1,0) = p1_abs
        p(1,1:3) = polar_to_cartesian (p1_abs, cos_theta, phi)
        p(2,0) = p1_abs
        p(2,1:3) = - p(1,1:3)
        p = boost_momentum (p, - p12)

```

```

end function one_to_two_massless

330a <Declaration of kinematics procedures 325b>+≡ (325a) <329a 333c>
public :: polar_to_cartesian, on_shell

330b <Implementation of kinematics procedures 326a>+≡ (325a) <329d 330c>
pure function polar_to_cartesian (v_abs, cos_theta, phi) result (v)
  real(kind=default), intent(in) :: v_abs, cos_theta, phi
  real(kind=default), dimension(3) :: v
  real(kind=default) :: sin_phi, cos_phi, sin_theta
  sin_theta = sqrt (1.0 - cos_theta**2)
  cos_phi = cos (phi)
  sin_phi = sin (phi)
  v = (/ sin_theta * cos_phi, sin_theta * sin_phi, cos_theta /) * v_abs
end function polar_to_cartesian

330c <Implementation of kinematics procedures 326a>+≡ (325a) <330b 333d>
pure function on_shell (p, m) result (E)
  real(kind=default), dimension(0:), intent(in) :: p
  real(kind=default), intent(in) :: m
  real(kind=default) :: E
  E = sqrt (m**2 + dot_product (p(1:3), p(1:3)))
end function on_shell

```

### J.3 Massive 3-Particle Phase Space Revisited

$$\begin{array}{ccccc}
U_1 & \xrightarrow{\xi_1} & P_1 & \xrightarrow{\phi_1} & M \\
\pi_U \downarrow & & \downarrow \pi_P & & \parallel \\
U_2 & \xrightarrow{\xi_2} & P_2 & \xrightarrow{\phi_2} & M
\end{array} \tag{J.6}$$

$$\begin{array}{ccccc}
U_1 & \xrightarrow{\xi} & P_1 & \xrightarrow{\phi} & M \\
\pi_U \downarrow & & \downarrow \pi_P & & \downarrow \pi \\
U_2 & \xrightarrow{\xi} & P_2 & \xrightarrow{\phi} & M
\end{array} \tag{J.7}$$

```

330d <kinematics.f90 325a>+≡ <325a>
module phase_space
  use kinds
  use constants
  use kinematics !NODEP!
  use tao_random_numbers
  implicit none
  private

```

```

    <Declaration of phase_space procedures 332b>
    <Interfaces of phase_space procedures 332c>
    <Declaration of phase_space types 331a>
    character(len=*), public, parameter :: PHASE_SPACE_RCS_ID = &
        "$Id: kinematics.nw 314 2010-04-17 20:32:33Z ohl $"
contains
    <Implementation of phase_space procedures 332d>
end module phase_space

LIPS3_unit : [0, 1]5 (J.8)

331a <Declaration of phase_space types 331a>≡ (330d) 331b>
type, public :: LIPS3_unit
    real(kind=default), dimension(5) :: x
    real(kind=default) :: s
    real(kind=default), dimension(2) :: mass_in
    real(kind=default), dimension(3) :: mass_out
    real(kind=default) :: jacobian
end type LIPS3_unit

331b <Declaration of phase_space types 331a>+≡ (330d) <331a 331c>
type, public :: LIPS3_unit_massless
    real(kind=default), dimension(5) :: x
    real(kind=default) :: s
    real(kind=default) :: jacobian
end type LIPS3_unit_massless

LIPS3_s2_t1_angles : (s2, t1, φ, cos θ3, φ3) (J.9)

331c <Declaration of phase_space types 331a>+≡ (330d) <331b 331d>
type, public :: LIPS3_s2_t1_angles
    real(kind=default) :: s2, t1, phi, cos_theta3, phi3
    real(kind=default) :: s
    real(kind=default), dimension(2) :: mass_in
    real(kind=default), dimension(3) :: mass_out
    real(kind=default) :: jacobian
end type LIPS3_s2_t1_angles

331d <Declaration of phase_space types 331a>+≡ (330d) <331c 331e>
type, public :: LIPS3_s2_t1_angles_massless
    real(kind=default) :: s2, t1, phi, cos_theta3, phi3
    real(kind=default) :: s
    real(kind=default) :: jacobian
end type LIPS3_s2_t1_angles_massless

LIPS3_momenta : (p1, p2, p3) (J.10)

331e <Declaration of phase_space types 331a>+≡ (330d) <331d 332a>

```

```

type, public :: LIPS3_momenta
  real(kind=default), dimension(0:3,3) :: p
  real(kind=default) :: s
  real(kind=default), dimension(2) :: mass_in
  real(kind=default), dimension(3) :: mass_out
  real(kind=default) :: jacobian
end type LIPS3_momenta

332a <Declaration of phase_space types 331a>+≡ (330d) <331e>
type, public :: LIPS3_momenta_massless
  real(kind=default), dimension(0:3,3) :: p
  real(kind=default) :: s
  real(kind=default) :: jacobian
end type LIPS3_momenta_massless

332b <Declaration of phase_space procedures 332b>≡ (330d) 332f>
public :: random_LIPS3
private :: random_LIPS3_unit, random_LIPS3_unit_massless

332c <Interfaces of phase_space procedures 332c>≡ (330d)
interface random_LIPS3
  module procedure random_LIPS3_unit, random_LIPS3_unit_massless
end interface

332d <Implementation of phase_space procedures 332d>≡ (330d) 332e>
pure subroutine random_LIPS3_unit (rng, lips)
  type(tao_random_state), intent(inout) :: rng
  type(LIPS3_unit), intent(inout) :: lips
  call tao_random_number (rng, lips%x)
  lips%jacobian = 1
end subroutine random_LIPS3_unit

332e <Implementation of phase_space procedures 332d>+≡ (330d) <332d 333a>
pure subroutine random_LIPS3_unit_massless (rng, lips)
  type(tao_random_state), intent(inout) :: rng
  type(LIPS3_unit_massless), intent(inout) :: lips
  call tao_random_number (rng, lips%x)
  lips%jacobian = 1
end subroutine random_LIPS3_unit_massless

332f <Declaration of phase_space procedures 332b>+≡ (330d) <332b>
private :: LIPS3_unit_to_s2_t1_angles, LIPS3_unit_to_s2_t1_angles_m0

332g <(Unused) Interfaces of phase_space procedures 332g>≡
interface assignment(=)
  module procedure &
    LIPS3_unit_to_s2_t1_angles, LIPS3_unit_to_s2_t1_angles_m0
end interface

```

333a  $\langle$ Implementation of phase\_space procedures 332d $\rangle + \equiv$  (330d)  $\langle$ 332e 333b $\rangle$   
 pure subroutine LIPS3\_unit\_to\_s2\_t1\_angles (s2\_t1\_angles, unit)  
   type(LIPS3\_s2\_t1\_angles), intent(out) :: s2\_t1\_angles  
   type(LIPS3\_unit), intent(in) :: unit  
 end subroutine LIPS3\_unit\_to\_s2\_t1\_angles

333b  $\langle$ Implementation of phase\_space procedures 332d $\rangle + \equiv$  (330d)  $\langle$ 333a  
 pure subroutine LIPS3\_unit\_to\_s2\_t1\_angles\_m0 (s2\_t1\_angles, unit)  
   type(LIPS3\_s2\_t1\_angles\_massless), intent(out) :: s2\_t1\_angles  
   type(LIPS3\_unit\_massless), intent(in) :: unit  
 end subroutine LIPS3\_unit\_to\_s2\_t1\_angles\_m0

## J.4 Massless $n$ -Particle Phase Space: RAMBO

333c  $\langle$ Declaration of kinematics procedures 325b $\rangle + \equiv$  (325a)  $\langle$ 330a 334b $\rangle$   
 public :: massless\_isotropic\_decay

The massless RAMBO algorithm [26]:

333d  $\langle$ Implementation of kinematics procedures 326a $\rangle + \equiv$  (325a)  $\langle$ 330c 334c $\rangle$   
 pure function massless\_isotropic\_decay (roots, ran) result (p)  
   real (kind=default), intent(in) :: roots  
   real (kind=default), dimension(:, :), intent(in) :: ran  
   real (kind=default), dimension(size(ran, dim=1), 0:3) :: p  
   real (kind=default), dimension(size(ran, dim=1), 0:3) :: q  
   real (kind=default), dimension(0:3) :: qsum  
   real (kind=default) :: cos\_theta, sin\_theta, phi, qabs, x, r, z  
   integer :: k  
    $\langle$ Generate isotropic null vectors 333e $\rangle$   
    $\langle$ Boost and rescale the vectors 334a $\rangle$   
 end function massless\_isotropic\_decay

Generate a  $xe^{-x}$  distribution for  $q(\mathbf{k}, 0)$

333e  $\langle$ Generate isotropic null vectors 333e $\rangle \equiv$  (333d)  
 do k = 1, size (p, dim = 1)  
   q(k, 0) = - log (ran(k, 1) \* ran(k, 2))  
   cos\_theta = 2 \* ran(k, 3) - 1  
   sin\_theta = sqrt (1 - cos\_theta\*\*2)  
   phi = 2 \* PI \* ran(k, 4)  
   q(k, 1) = q(k, 0) \* sin\_theta \* cos (phi)  
   q(k, 2) = q(k, 0) \* sin\_theta \* sin (phi)  
   q(k, 3) = q(k, 0) \* cos\_theta  
 enddo

The proof that the Jacobian of the transformation vanishes can be found in [26]. The transformation is really a Lorentz boost (as can be seen easily).

334a  $\langle$ Boost and rescale the vectors 334a $\rangle \equiv$  (333d)

```
qsum = sum (q, dim = 1)
qabs = sqrt (dot (qsum, qsum))
x = roots / qabs
do k = 1, size (p, dim = 1)
  r = dot (q(k,:), qsum) / qabs
  z = (q(k,0) + r) / (qsum(0) + qabs)
  p(k,1:3) = x * (q(k,1:3) - qsum(1:3) * z)
  p(k,0) = x * r
enddo
```

334b  $\langle$ Declaration of kinematics procedures 325b $\rangle + \equiv$  (325a)  $\triangleleft$  333c

```
public :: phase_space_volume
```

$$V_n(s) = \frac{1}{8\pi} \frac{n-1}{(\Gamma(n))^2} \left( \frac{s}{16\pi^2} \right)^{n-2} \quad (\text{J.11})$$

334c  $\langle$ Implementation of kinematics procedures 326a $\rangle + \equiv$  (325a)  $\triangleleft$  333d

```
pure function phase_space_volume (n, roots) result (volume)
  integer, intent(in) :: n
  real (kind=default), intent(in) :: roots
  real (kind=default) :: volume
  real (kind=default) :: nd
  nd = n
  volume = (nd - 1) / (8*PI * (gamma (nd))**2) * (roots / (4*PI))**(2*n-4)
end function phase_space_volume
```

## J.5 Tests

334d  $\langle$ ktest.f90 334d $\rangle \equiv$

```
program ktest
  use kinds
  use constants
  use products
  use kinematics
  use tao_random_numbers
  implicit none
  real(kind=default) :: &
    ma, mb, m1, m2, m3, s, t1, s2, phi, cos_theta3, phi3
  real(kind=default) :: t1_min, t1_max
  real(kind=default), dimension(5) :: r
  type(LIPS3) :: p
```

```

integer :: i
character(len=*), parameter :: fmt = "(A,4(1X,E12.5))"
ma = 1.0
mb = 1.0
m1 = 10.0
m2 = 20.0
m3 = 30.0
s = 100.0 ** 2
do i = 1, 10
  call tao_random_number (r)
  s2 = (r(1) * (sqrt (s) - m1) + (1 - r(1)) * (m2 + m3)) ** 2
  t1_max = ma**2 + m1**2 - ((s + ma**2 - mb**2) * (s - s2 + m1**2) &
    + sqrt (lambda (s, ma**2, mb**2) * lambda (s, s2, m1**2))) / (2*s)
  t1_min = ma**2 + m1**2 - ((s + ma**2 - mb**2) * (s - s2 + m1**2) &
    - sqrt (lambda (s, ma**2, mb**2) * lambda (s, s2, m1**2))) / (2*s)
  t1 = r(2) * t1_max + (1 - r(2)) * t1_min
  phi = 2*PI * r(3)
  cos_theta3 = 2 * r(4) - 1
  phi3 = 2*PI * r(5)
  p = two_to_three (s, t1, s2, phi, cos_theta3, phi3, ma, mb, m1, m2, m3)
  print fmt, "p1      = ", p%p(1,:)
  print fmt, "p2      = ", p%p(2,:)
  print fmt, "p3      = ", p%p(3,:)
  print fmt, "p1,2,3^2 = ", dot (p%p(1,:), p%p(1,)), &
    dot (p%p(2,:), p%p(2,)), dot (p%p(3,:), p%p(3,))
  print fmt, "sum(p)   = ", p%p(1,:) + p%p(2,:) + p%p(3,:)
  print fmt, "|J|     = ", p%jacobian
end do
end program ktest

```



Trivial check for typos, should be removed from the finalized program!

335  $\langle$ Trivial ktest.f90 335 $\rangle \equiv$

```

program ktest
  use kinds
  use constants
  use products
  use kinematics
  use tao_random_numbers
  implicit none
  real(kind=default), dimension(0:3) :: p, q, p_prime, p0
  real(kind=default) :: m
  character(len=*), parameter :: fmt = "(A,4(1X,E12.5))"
  integer :: i

```



```

do i = 1, 5
  if (i == 1) then
    p = (/ 1.0_double, 0.0_double, 0.0_double, 0.0_double /)
    m = 1.0
  else
    call tao_random_number (p)
    m = sqrt (PI)
  end if
  call tao_random_number (q(1:3))
  q(0) = sqrt (m**2 + dot_product (q(1:3), q(1:3)))
  p_prime = boost_momentum (p, q)
  print fmt, "p    = ", p
  print fmt, "q    = ", q
  print fmt, "p'   = ", p_prime
  print fmt, "p^2  = ", dot (p, p)
  print fmt, "p'^2 = ", dot (p_prime, p_prime)
  if (dot (p, p) > 0.0) then
    p0 = boost_momentum (p, p)
    print fmt, "p0   = ", p0
    print fmt, "p0^2 = ", dot (p0, p0)
  end if
end do
end program ktest

```

# —K—

## COORDINATES

```

337  <coordinates.f90 337>≡
      ! coordinates.f90 --
      <Copyleft notice 1>
      module coordinates
        use kinds
        use constants, only: PI
        use specfun, only: gamma
        implicit none
        private
        <Declaration of coordinates procedures 338a>
      contains
        <Implementation of coordinates procedures 338b>
      end module coordinates

```

### *K.1 Angular Spherical Coordinates*

$$\begin{aligned}
 x_n &= r \cos \theta_{n-2} \\
 x_{n-1} &= r \sin \theta_{n-2} \cos \theta_{n-3} \\
 &\dots \\
 x_3 &= r \sin \theta_{n-2} \sin \theta_{n-3} \cdots \cos \theta_1 \\
 x_2 &= r \sin \theta_{n-2} \sin \theta_{n-3} \cdots \sin \theta_1 \cos \phi \\
 x_1 &= r \sin \theta_{n-2} \sin \theta_{n-3} \cdots \sin \theta_1 \sin \phi
 \end{aligned} \tag{K.1}$$

and

$$J = r^{n-1} \prod_{i=1}^{n-2} (\sin \theta_i)^i \tag{K.2}$$

We can minimize the number of multiplications by computing the products

$$P_j = \prod_{i=j}^{n-2} \sin \theta_i \quad (\text{K.3})$$

Then

$$\begin{aligned} x_n &= r \cos \theta_{n-2} \\ x_{n-1} &= r P_{n-2} \cos \theta_{n-3} \\ &\dots \\ x_3 &= r P_2 \cos \theta_1 \\ x_2 &= r P_1 \cos \phi \\ x_1 &= r P_1 \sin \phi \end{aligned} \quad (\text{K.4})$$

and

$$J = r^{n-1} \prod_{i=1}^{n-2} P_i \quad (\text{K.5})$$

Note that  $\theta_i \in [0, \pi]$  and  $\phi \in [0, 2\pi]$  or  $\phi \in [-\pi, \pi]$ . Therefore  $\sin \theta_i \geq 0$  and

$$\sin \theta_i = \sqrt{1 - \cos^2 \theta_i} \quad (\text{K.6})$$

which is not true for  $\phi$ . Since `sqrt` is typically much faster than `sin` and `cos`, we use (K.6) where ever possible.

```

338a <Declaration of coordinates procedures 338a>≡ (337) 339c>
      public :: spherical_to_cartesian_2, &
                spherical_to_cartesian, spherical_to_cartesian_j

338b <Implementation of coordinates procedures 338b>≡ (337) 339a>
      pure subroutine spherical_to_cartesian_2 (r, phi, theta, x, jacobian)
        real(kind=default), intent(in) :: r, phi
        real(kind=default), dimension(:), intent(in) :: theta
        real(kind=default), dimension(:), intent(out), optional :: x
        real(kind=default), intent(out), optional :: jacobian
        real(kind=default), dimension(size(theta)) :: cos_theta
        real(kind=default), dimension(size(theta)+1) :: product_sin_theta
        integer :: n, i
        n = size (theta) + 2
        cos_theta = cos (theta)
        product_sin_theta(n-1) = 1.0_default
        do i = n - 2, 1, -1
          product_sin_theta(i) = &
            product_sin_theta(i+1) * sqrt (1 - cos_theta(i)**2)
        end do

```

```

if (present (x)) then
  x(1) = r * product_sin_theta(1) * sin (phi)
  x(2) = r * product_sin_theta(1) * cos (phi)
  x(3:) = r * product_sin_theta(2:n-1) * cos_theta
end if
if (present (jacobian)) then
  jacobian = r**(n-1) * product (product_sin_theta)
end if
end subroutine spherical_to_cartesian_2

```



Note that call inside of a function breaks F-compatibility. Here it would be easy to fix, but the inverse can not be coded as a function, unless a type for spherical coordinates is introduced, where `theta` could not be assumed shape ...

- 339a *<Implementation of coordinates procedures 338b>+≡ (337) <338b 339b>*  
 pure function `spherical_to_cartesian` (r, phi, theta) result (x)  
   real(kind=default), intent(in) :: r, phi  
   real(kind=default), dimension(:), intent(in) :: theta  
   real(kind=default), dimension(size(theta)+2) :: x  
   call `spherical_to_cartesian_2` (r, phi, theta, x = x)  
 end function `spherical_to_cartesian`
- 339b *<Implementation of coordinates procedures 338b>+≡ (337) <339a 339d>*  
 pure function `spherical_to_cartesian_j` (r, phi, theta) &  
   result (jacobian)  
   real(kind=default), intent(in) :: r, phi  
   real(kind=default), dimension(:), intent(in) :: theta  
   real(kind=default) :: jacobian  
   call `spherical_to_cartesian_2` (r, phi, theta, jacobian = jacobian)  
 end function `spherical_to_cartesian_j`
- 339c *<Declaration of coordinates procedures 338a>+≡ (337) <338a 341c>*  
 public :: `cartesian_to_spherical_2`, &  
   `cartesian_to_spherical`, `cartesian_to_spherical_j`
- 339d *<Implementation of coordinates procedures 338b>+≡ (337) <339b 341a>*  
 pure subroutine `cartesian_to_spherical_2` (x, r, phi, theta, jacobian)  
   real(kind=default), dimension(:), intent(in) :: x  
   real(kind=default), intent(out), optional :: r, phi  
   real(kind=default), dimension(:), intent(out), optional :: theta  
   real(kind=default), intent(out), optional :: jacobian  
   real(kind=default) :: local\_r  
   real(kind=default), dimension(size(x)-2) :: cos\_theta  
   real(kind=default), dimension(size(x)-1) :: product\_sin\_theta

```

integer :: n, i
n = size (x)
local_r = sqrt (dot_product (x, x))
if (local_r == 0) then
  if (present (r)) then
    r = 0
  end if
  if (present (phi)) then
    phi = 0
  end if
  if (present (theta)) then
    theta = 0
  end if
  if (present (jacobian)) then
    jacobian = 1
  end if
else
  product_sin_theta(n-1) = 1
  do i = n, 3, -1
    if (product_sin_theta(i-1) == 0) then
      cos_theta(i-2) = 0
    else
      cos_theta(i-2) = x(i) / product_sin_theta(i-1) / local_r
    end if
    product_sin_theta(i-2) = &
      product_sin_theta(i-1) * sqrt (1 - cos_theta(i-2)**2)
  end do
  if (present (r)) then
    r = local_r
  end if
  if (present (phi)) then
    ! Set phi = 0 for vanishing vector
    if (x(1) == 0 .and. x(2)==0) then
      phi = 0
    else
      phi = atan2 (x(1), x(2))
    end if
  end if
  if (present (theta)) then
    theta = acos (cos_theta)
  end if
  if (present (jacobian)) then
    jacobian = local_r**(1-n) / product (product_sin_theta)
  end if
end if

```

```

        end if
    end if
end subroutine cartesian_to_spherical_2
341a  <Implementation of coordinates procedures 338b>+≡ (337) <339d 341b>
pure subroutine cartesian_to_spherical (x, r, phi, theta)
    real(kind=default), dimension(:), intent(in) :: x
    real(kind=default), intent(out) :: r, phi
    real(kind=default), dimension(:), intent(out) :: theta
    call cartesian_to_spherical_2 (x, r, phi, theta)
end subroutine cartesian_to_spherical
341b  <Implementation of coordinates procedures 338b>+≡ (337) <341a 341d>
pure function cartesian_to_spherical_j (x) result (jacobian)
    real(kind=default), dimension(:), intent(in) :: x
    real(kind=default) :: jacobian
    call cartesian_to_spherical_2 (x, jacobian = jacobian)
end function cartesian_to_spherical_j

```

## K.2 Trigonometric Spherical Coordinates

```

341c  <Declaration of coordinates procedures 338a>+≡ (337) <339c 342c>
public :: spherical_cos_to_cartesian_2, &
        spherical_cos_to_cartesian, spherical_cos_to_cartesian_j

```

Using the cosine, we have to drop  $P_1$  from the Jacobian

```

341d  <Implementation of coordinates procedures 338b>+≡ (337) <341b 342a>
pure subroutine spherical_cos_to_cartesian_2 (r, phi, cos_theta, x, jacobian)
    real(kind=default), intent(in) :: r, phi
    real(kind=default), dimension(:), intent(in) :: cos_theta
    real(kind=default), dimension(:), intent(out), optional :: x
    real(kind=default), intent(out), optional :: jacobian
    real(kind=default), dimension(size(cos_theta)+1) :: product_sin_theta
    integer :: n, i
    n = size (cos_theta) + 2
    product_sin_theta(n-1) = 1.0_default
    do i = n - 2, 1, -1
        product_sin_theta(i) = &
            product_sin_theta(i+1) * sqrt (1 - cos_theta(i)**2)
    end do
    if (present (x)) then
        x(1) = r * product_sin_theta(1) * sin (phi)
        x(2) = r * product_sin_theta(1) * cos (phi)
        x(3:) = r * product_sin_theta(2:n-1) * cos_theta
    end if
end subroutine spherical_cos_to_cartesian_2

```

```

        end if
        if (present (jacobian)) then
            jacobian = r**(n-1) * product (product_sin_theta(2:))
        end if
    end subroutine spherical_cos_to_cartesian_2
342a  <Implementation of coordinates procedures 338b>+≡ (337) <341d 342b>
    pure function spherical_cos_to_cartesian (r, phi, theta) result (x)
        real(kind=default), intent(in) :: r, phi
        real(kind=default), dimension(:), intent(in) :: theta
        real(kind=default), dimension(size(theta)+2) :: x
        call spherical_cos_to_cartesian_2 (r, phi, theta, x = x)
    end function spherical_cos_to_cartesian
342b  <Implementation of coordinates procedures 338b>+≡ (337) <342a 342d>
    pure function spherical_cos_to_cartesian_j (r, phi, theta) &
        result (jacobian)
        real(kind=default), intent(in) :: r, phi
        real(kind=default), dimension(:), intent(in) :: theta
        real(kind=default) :: jacobian
        call spherical_cos_to_cartesian_2 (r, phi, theta, jacobian = jacobian)
    end function spherical_cos_to_cartesian_j
342c  <Declaration of coordinates procedures 338a>+≡ (337) <341c 344b>
    public :: cartesian_to_spherical_cos_2, &
        cartesian_to_spherical_cos, cartesian_to_spherical_cos_j
342d  <Implementation of coordinates procedures 338b>+≡ (337) <342b 343>
    pure subroutine cartesian_to_spherical_cos_2 (x, r, phi, cos_theta, jacobian)
        real(kind=default), dimension(:), intent(in) :: x
        real(kind=default), intent(out), optional :: r, phi
        real(kind=default), dimension(:), intent(out), optional :: cos_theta
        real(kind=default), intent(out), optional :: jacobian
        real(kind=default) :: local_r
        real(kind=default), dimension(size(x)-2) :: local_cos_theta
        real(kind=default), dimension(size(x)-1) :: product_sin_theta
        integer :: n, i
        n = size (x)
        local_r = sqrt (dot_product (x, x))
        if (local_r == 0) then
            if (present (r)) then
                r = 0
            end if
            if (present (phi)) then
                phi = 0
            end if

```

```

    if (present (cos_theta)) then
        cos_theta = 0
    end if
    if (present (jacobian)) then
        jacobian = 1
    end if
else
    product_sin_theta(n-1) = 1
    do i = n, 3, -1
        if (product_sin_theta(i-1) == 0) then
            local_cos_theta(i-2) = 0
        else
            local_cos_theta(i-2) = x(i) / product_sin_theta(i-1) / local_r
        end if
        product_sin_theta(i-2) = &
            product_sin_theta(i-1) * sqrt (1 - local_cos_theta(i-2)**2)
    end do
    if (present (r)) then
        r = local_r
    end if
    if (present (phi)) then
        ! Set phi = 0 for vanishing vector
        if (x(1) == 0 .and. x(2)==0) then
            phi = 0
        else
            phi = atan2 (x(1), x(2))
        end if
    end if
    if (present (cos_theta)) then
        cos_theta = local_cos_theta
    end if
    if (present (jacobian)) then
        jacobian = local_r**(1-n) / product (product_sin_theta(2:))
    end if
end if
end subroutine cartesian_to_spherical_cos_2
343  <Implementation of coordinates procedures 338b>+≡ (337) <342d 344a>
pure subroutine cartesian_to_spherical_cos (x, r, phi, cos_theta)
    real(kind=default), dimension(:), intent(in) :: x
    real(kind=default), intent(out) :: r, phi
    real(kind=default), dimension(:), intent(out), optional :: cos_theta
    call cartesian_to_spherical_cos_2 (x, r, phi, cos_theta)
end subroutine cartesian_to_spherical_cos

```



344a  $\langle$ Implementation of coordinates procedures 338b $\rangle + \equiv$  (337)  $\triangleleft$ 343 344c $\triangleright$

```

pure function cartesian_to_spherical_cos_j (x) result (jacobian)
  real(kind=default), dimension(:), intent(in) :: x
  real(kind=default) :: jacobian
  call cartesian_to_spherical_cos_2 (x, jacobian = jacobian)
end function cartesian_to_spherical_cos_j

```

### K.3 Surface of a Sphere

344b  $\langle$ Declaration of coordinates procedures 338a $\rangle + \equiv$  (337)  $\triangleleft$ 342c

```

public :: surface

```

$$\int d\Omega_n = \frac{2\pi^{n/2}}{\Gamma(n/2)} = S_n \quad (\text{K.7})$$

344c  $\langle$ Implementation of coordinates procedures 338b $\rangle + \equiv$  (337)  $\triangleleft$ 344a

```

pure function surface (n) result (vol)
  integer, intent(in) :: n
  real(kind=default) :: vol
  real(kind=default) :: n_by_2
  n_by_2 = 0.5_default * n
  vol = 2 * PI**n_by_2 / gamma (n_by_2)
end function surface

```

# —L—

## IDIOMATIC FORTRAN90 INTERFACE FOR MPI

```
345a <mpi90.f90 345a>≡
      ! mpi90.f90 --
      <Copyleft notice 1>
      module mpi90
        use kinds
        use mpi
        implicit none
        private
        <Declaration of mpi90 procedures 345b>
        <Interfaces of mpi90 procedures 348c>
        <Parameters in mpi90 (never defined)>
        <Variables in mpi90 (never defined)>
        <Declaration of mpi90 types 350b>
        character(len=*), public, parameter :: MPI90_RCS_ID = &
          "$Id: mpi90.nw 314 2010-04-17 20:32:33Z ohl $"
      contains
        <Implementation of mpi90 procedures 346a>
      end module mpi90
```

### *L.1 Basics*

```
345b <Declaration of mpi90 procedures 345b>≡ (345a) 348b▷
      public :: mpi90_init
      public :: mpi90_finalize
      public :: mpi90_abort
      public :: mpi90_print_error
      public :: mpi90_size
      public :: mpi90_rank
```

```

346a  <Implementation of mpi90 procedures 346a>≡ (345a) 346d>
      subroutine mpi90_init (error)
        integer, intent(out), optional :: error
        integer :: local_error
        character(len=*), parameter :: FN = "mpi90_init"
        external mpi_init
        call mpi_init (local_error)
        <Handle local_error (no mpi90_abort) 346b>
      end subroutine mpi90_init

346b  <Handle local_error (no mpi90_abort) 346b>≡ (346)
      if (present (error)) then
        error = local_error
      else
        if (local_error /= MPI_SUCCESS) then
          call mpi90_print_error (local_error, FN)
          stop
        end if
      end if

346c  <Handle local_error 346c>≡ (346-49 351c 353d 354b 356a)
      if (present (error)) then
        error = local_error
      else
        if (local_error /= MPI_SUCCESS) then
          call mpi90_print_error (local_error, FN)
          call mpi90_abort (local_error)
          stop
        end if
      end if

346d  <Implementation of mpi90 procedures 346a>+≡ (345a) <346a 346e>
      subroutine mpi90_finalize (error)
        integer, intent(out), optional :: error
        integer :: local_error
        character(len=*), parameter :: FN = "mpi90_finalize"
        external mpi_finalize
        call mpi_finalize (local_error)
        <Handle local_error 346c>
      end subroutine mpi90_finalize

346e  <Implementation of mpi90 procedures 346a>+≡ (345a) <346d 347a>
      subroutine mpi90_abort (code, domain, error)
        integer, intent(in), optional :: code, domain
        integer, intent(out), optional :: error
        character(len=*), parameter :: FN = "mpi90_abort"

```

```

integer :: local_domain, local_code, local_error
external mpi_abort
if (present (code)) then
    local_code = code
else
    local_code = MPI_ERR_UNKNOWN
end if
<Set default for domain 347b>
call mpi_abort (local_domain, local_code, local_error)
<Handle local_error (no mpi90_abort) 346b>
end subroutine mpi90_abort
347a <Implementation of mpi90 procedures 346a>+≡ (345a) <346e 347c>
subroutine mpi90_print_error (error, msg)
integer, intent(in) :: error
character(len=*), optional :: msg
character(len=*), parameter :: FN = "mpi90_print_error"
integer :: msg_len, local_error
external mpi_error_string
call mpi_error_string (error, msg, msg_len, local_error)
if (local_error /= MPI_SUCCESS) then
    print *, "PANIC: even MPI_ERROR_STRING() failed!!!"
    call mpi90_abort (local_error)
else if (present (msg)) then
    print *, trim (msg), ": ", trim (msg(msg_len+1:))
else
    print *, "mpi90: ", trim (msg(msg_len+1:))
end if
end subroutine mpi90_print_error
347b <Set default for domain 347b>≡ (346-50 356a) 354f>
if (present (domain)) then
    local_domain = domain
else
    local_domain = MPI_COMM_WORLD
end if
347c <Implementation of mpi90 procedures 346a>+≡ (345a) <347a 348a>
subroutine mpi90_size (sz, domain, error)
integer, intent(out) :: sz
integer, intent(in), optional :: domain
integer, intent(out), optional :: error
character(len=*), parameter :: FN = "mpi90_size"
integer :: local_domain, local_error
external mpi_comm_size

```

```

    <Set default for domain 347b>
    call mpi_comm_size (local_domain, sz, local_error)
    <Handle local_error 346c>
end subroutine mpi90_size
348a <Implementation of mpi90 procedures 346a>+≡ (345a) <347c 348d>
    subroutine mpi90_rank (rank, domain, error)
        integer, intent(out) :: rank
        integer, intent(in), optional :: domain
        integer, intent(out), optional :: error
        character(len=*), parameter :: FN = "mpi90_rank"
        integer :: local_domain, local_error
        external mpi_comm_rank
        <Set default for domain 347b>
        call mpi_comm_rank (local_domain, rank, local_error)
        <Handle local_error 346c>
    end subroutine mpi90_rank

```

## *L.2 Point to Point*

```

348b <Declaration of mpi90 procedures 345b>+≡ (345a) <345b 351d>
    public :: mpi90_send
    public :: mpi90_receive
    public :: mpi90_receive_pointer

348c <Interfaces of mpi90 procedures 348c>≡ (345a) 350d>
    interface mpi90_send
        module procedure &
            mpi90_send_integer, mpi90_send_double, &
            mpi90_send_integer_array, mpi90_send_double_array, &
            mpi90_send_integer_array2, mpi90_send_double_array2
    end interface

348d <Implementation of mpi90 procedures 346a>+≡ (345a) <348a 348e>
    subroutine mpi90_send_integer (value, target, tag, domain, error)
        integer, intent(in) :: value
        integer, intent(in) :: target, tag
        integer, intent(in), optional :: domain
        integer, intent(out), optional :: error
        call mpi90_send_integer_array ((/ value /), target, tag, domain, error)
    end subroutine mpi90_send_integer

348e <Implementation of mpi90 procedures 346a>+≡ (345a) <348d 349a>
    subroutine mpi90_send_double (value, target, tag, domain, error)

```

```

    real(kind=default), intent(in) :: value
    integer, intent(in) :: target, tag
    integer, intent(in), optional :: domain
    integer, intent(out), optional :: error
    call mpi90_send_double_array ((/ value /), target, tag, domain, error)
end subroutine mpi90_send_double

349a  <Implementation of mpi90 procedures 346a>+≡ (345a) <348e 349c>
    subroutine mpi90_send_integer_array (buffer, target, tag, domain, error)
        integer, dimension(:), intent(in) :: buffer
        integer, intent(in) :: target, tag
        integer, intent(in), optional :: domain
        integer, intent(out), optional :: error
        character(len=*), parameter :: FN = "mpi90_send_integer_array"
        integer, parameter :: datatype = MPI_INTEGER
        <Body of mpi90_send.*_array 349b>
    end subroutine mpi90_send_integer_array

349b  <Body of mpi90_send.*_array 349b>≡ (349)
    integer :: local_domain, local_error
    external mpi_send
    <Set default for domain 347b>
    call mpi_send (buffer, size (buffer), datatype, target, tag, &
        local_domain, local_error)
    <Handle local_error 346c>

349c  <Implementation of mpi90 procedures 346a>+≡ (345a) <349a 349d>
    subroutine mpi90_send_double_array (buffer, target, tag, domain, error)
        real(kind=default), dimension(:), intent(in) :: buffer
        integer, intent(in) :: target, tag
        integer, intent(in), optional :: domain
        integer, intent(out), optional :: error
        character(len=*), parameter :: FN = "mpi90_send_double_array"
        integer, parameter :: datatype = MPI_DOUBLE_PRECISION
        <Body of mpi90_send.*_array 349b>
    end subroutine mpi90_send_double_array

349d  <Implementation of mpi90 procedures 346a>+≡ (345a) <349c 350a>
    subroutine mpi90_send_integer_array2 (value, target, tag, domain, error)
        integer, dimension(:, :), intent(in) :: value
        integer, intent(in) :: target, tag
        integer, intent(in), optional :: domain
        integer, intent(out), optional :: error
        integer, dimension(size(value)) :: buffer
        buffer = reshape (value, shape(buffer))
        call mpi90_send_integer_array (buffer, target, tag, domain, error)

```

```

        end subroutine mpi90_send_integer_array2

350a  <Implementation of mpi90 procedures 346a>+≡ (345a) <349d 350c>
        subroutine mpi90_send_double_array2 (value, target, tag, domain, error)
            real(kind=default), dimension(:,,:), intent(in) :: value
            integer, intent(in) :: target, tag
            integer, intent(in), optional :: domain
            integer, intent(out), optional :: error
            real(kind=default), dimension(size(value)) :: buffer
            buffer = reshape (value, shape(buffer))
            call mpi90_send_double_array (buffer, target, tag, domain, error)
        end subroutine mpi90_send_double_array2

350b  <Declaration of mpi90 types 350b>≡ (345a)
        type, public :: mpi90_status
            integer :: count, source, tag, error
        end type mpi90_status

350c  <Implementation of mpi90 procedures 346a>+≡ (345a) <350a 351a>
        subroutine mpi90_receive_integer (value, source, tag, domain, status, error)
            integer, intent(out) :: value
            integer, intent(in), optional :: source, tag, domain
            type(mpi90_status), intent(out), optional :: status
            integer, intent(out), optional :: error
            integer, dimension(1) :: buffer
            call mpi90_receive_integer_array (buffer, source, tag, domain, status, error)
            value = buffer(1)
        end subroutine mpi90_receive_integer

350d  <Interfaces of mpi90 procedures 348c>+≡ (345a) <348c 353a>
        interface mpi90_receive
            module procedure &
                mpi90_receive_integer, mpi90_receive_double, &
                mpi90_receive_integer_array, mpi90_receive_double_array, &
                mpi90_receive_integer_array2, mpi90_receive_double_array2
        end interface

350e  <Set defaults for source, tag and domain 350e>≡ (351c 353c)
        if (present (source)) then
            local_source = source
        else
            local_source = MPI_ANY_SOURCE
        end if
        if (present (tag)) then
            local_tag = tag
        else

```

```

        local_tag = MPI_ANY_TAG
    end if
    <Set default for domain 347b>
351a <Implementation of mpi90 procedures 346a>+≡ (345a) <350c 351b>
    subroutine mpi90_receive_double (value, source, tag, domain, status, error)
        real(kind=default), intent(out) :: value
        integer, intent(in), optional :: source, tag, domain
        type(mpi90_status), intent(out), optional :: status
        integer, intent(out), optional :: error
        real(kind=default), dimension(1) :: buffer
        call mpi90_receive_double_array (buffer, source, tag, domain, status, error)
        value = buffer(1)
    end subroutine mpi90_receive_double
351b <Implementation of mpi90 procedures 346a>+≡ (345a) <351a 351e>
    subroutine mpi90_receive_integer_array &
        (buffer, source, tag, domain, status, error)
        integer, dimension(:), intent(out) :: buffer
        integer, intent(in), optional :: source, tag, domain
        type(mpi90_status), intent(out), optional :: status
        integer, intent(out), optional :: error
        character(len=*), parameter :: FN = "mpi90_receive_integer_array"
        integer, parameter :: datatype = MPI_INTEGER
        <Body of mpi90_receive.*_array 351c>
    end subroutine mpi90_receive_integer_array
351c <Body of mpi90_receive.*_array 351c>≡ (351b 352a)
    integer :: local_source, local_tag, local_domain, local_error
    integer, dimension(MPI_STATUS_SIZE) :: local_status
    external mpi_receive, mpi_get_count
    <Set defaults for source, tag and domain 350e>
    call mpi_recv (buffer, size (buffer), datatype, local_source, local_tag, &
        local_domain, local_status, local_error)
    <Handle local_error 346c>
    if (present (status)) then
        call decode_status (status, local_status, datatype)
    end if
351d <Declaration of mpi90 procedures 345b>+≡ (345a) <348b 354d>
    private :: decode_status

```



Can we ignore ierror???

```

351e <Implementation of mpi90 procedures 346a>+≡ (345a) <351b 352a>
    subroutine decode_status (status, mpi_status, datatype)

```



```

type(mpi90_status), intent(out) :: status
integer, dimension(:), intent(in) :: mpi_status
integer, intent(in), optional :: datatype
integer :: ierror
if (present (datatype)) then
    call mpi_get_count (mpi_status, datatype, status%count, ierror)
else
    status%count = 0
end if
status%source = mpi_status(MPI_SOURCE)
status%tag = mpi_status(MPI_TAG)
status%error = mpi_status(MPI_ERROR)
end subroutine decode_status

```

352a *<Implementation of mpi90 procedures 346a>+≡* (345a) <351e 352b>

```

subroutine mpi90_receive_double_array &
    (buffer, source, tag, domain, status, error)
real(kind=default), dimension(:), intent(out) :: buffer
integer, intent(in), optional :: source, tag, domain
type(mpi90_status), intent(out), optional :: status
integer, intent(out), optional :: error
character(len=*), parameter :: FN = "mpi90_receive_double_array"
integer, parameter :: datatype = MPI_DOUBLE_PRECISION
<Body of mpi90_receive.*_array 351c>
end subroutine mpi90_receive_double_array

```

352b *<Implementation of mpi90 procedures 346a>+≡* (345a) <352a 352c>

```

subroutine mpi90_receive_integer_array2 &
    (value, source, tag, domain, status, error)
integer, dimension(:,:), intent(out) :: value
integer, intent(in), optional :: source, tag, domain
type(mpi90_status), intent(out), optional :: status
integer, intent(out), optional :: error
integer, dimension(size(value)) :: buffer
call mpi90_receive_integer_array &
    (buffer, source, tag, domain, status, error)
value = reshape (buffer, shape(value))
end subroutine mpi90_receive_integer_array2

```

352c *<Implementation of mpi90 procedures 346a>+≡* (345a) <352b 353b>

```

subroutine mpi90_receive_double_array2 &
    (value, source, tag, domain, status, error)
real(kind=default), dimension(:,:), intent(out) :: value
integer, intent(in), optional :: source, tag, domain
type(mpi90_status), intent(out), optional :: status

```

```

integer, intent(out), optional :: error
real(kind=default), dimension(size(value)) :: buffer
call mpi90_receive_double_array &
    (buffer, source, tag, domain, status, error)
value = reshape (buffer, shape(value))
end subroutine mpi90_receive_double_array2
353a <Interfaces of mpi90 procedures 348c>+≡ (345a) <350d 354e>
interface mpi90_receive_pointer
    module procedure &
        mpi90_receive_integer_pointer, mpi90_receive_double_pointer
end interface
353b <Implementation of mpi90 procedures 346a>+≡ (345a) <352c 354c>
subroutine mpi90_receive_integer_pointer &
    (buffer, source, tag, domain, status, error)
integer, dimension(:), pointer :: buffer
integer, intent(in), optional :: source, tag, domain
type(mpi90_status), intent(out), optional :: status
integer, intent(out), optional :: error
character(len=*), parameter :: FN = "mpi90_receive_integer_pointer"
integer, parameter :: datatype = MPI_INTEGER
<Body of mpi90_receive_*.pointer 353c>
end subroutine mpi90_receive_integer_pointer
353c <Body of mpi90_receive_*.pointer 353c>≡ (353b 354c) 353d>
integer :: local_source, local_tag, local_domain, local_error, buffer_size
integer, dimension(MPI_STATUS_SIZE) :: local_status
integer :: ierror
external mpi_receive, mpi_get_count
<Set defaults for source, tag and domain 350e>
353d <Body of mpi90_receive_*.pointer 353c>+≡ (353b 354c) <353c 353e>
call mpi_probe (local_source, local_tag, local_domain, &
    local_status, local_error)
<Handle local_error 346c>

```



Can we ignore ierror???

```

353e <Body of mpi90_receive_*.pointer 353c>+≡ (353b 354c) <353d 354a>
call mpi_get_count (local_status, datatype, buffer_size, ierror)
if (associated (buffer)) then
    if (size (buffer) /= buffer_size) then
        deallocate (buffer)
        allocate (buffer(buffer_size))
    end if

```

```

else
    allocate (buffer(buffer_size))
end if

354a  <Body of mpi90_receive_*_pointer 353c>+≡ (353b 354c) <353e 354b>
    call mpi_recv (buffer, size (buffer), datatype, local_source, local_tag, &
        local_domain, local_status, local_error)

354b  <Body of mpi90_receive_*_pointer 353c>+≡ (353b 354c) <354a>
    <Handle local_error 346c>
    if (present (status)) then
        call decode_status (status, local_status, datatype)
    end if

354c  <Implementation of mpi90 procedures 346a>+≡ (345a) <353b 355a>
    subroutine mpi90_receive_double_pointer &
        (buffer, source, tag, domain, status, error)
        real(kind=default), dimension(:), pointer :: buffer
        integer, intent(in), optional :: source, tag, domain
        type(mpi90_status), intent(out), optional :: status
        integer, intent(out), optional :: error
        character(len=*), parameter :: FN = "mpi90_receive_double_pointer"
        integer, parameter :: datatype = MPI_DOUBLE_PRECISION
    <Body of mpi90_receive_*_pointer 353c>
end subroutine mpi90_receive_double_pointer

```

### L.3 Collective Communication

```

354d  <Declaration of mpi90 procedures 345b>+≡ (345a) <351d>
    public :: mpi90_broadcast

354e  <Interfaces of mpi90 procedures 348c>+≡ (345a) <353a>
    interface mpi90_broadcast
        module procedure &
            mpi90_broadcast_integer, mpi90_broadcast_integer_array, &
            mpi90_broadcast_integer_array2, mpi90_broadcast_integer_array3, &
            mpi90_broadcast_double, mpi90_broadcast_double_array, &
            mpi90_broadcast_double_array2, mpi90_broadcast_double_array3, &
            mpi90_broadcast_logical, mpi90_broadcast_logical_array, &
            mpi90_broadcast_logical_array2, mpi90_broadcast_logical_array3
    end interface

354f  <Set default for domain 347b>+≡ (346-50 356a) <347b>
    if (present (domain)) then
        local_domain = domain
    end if

```

```

else
    local_domain = MPI_COMM_WORLD
end if

355a  <Implementation of mpi90 procedures 346a>+≡ (345a) <354c 355b>
    subroutine mpi90_broadcast_integer (value, root, domain, error)
        integer, intent(inout) :: value
        integer, intent(in) :: root
        integer, intent(in), optional :: domain
        integer, intent(out), optional :: error
        integer, dimension(1) :: buffer
        buffer(1) = value
        call mpi90_broadcast_integer_array (buffer, root, domain, error)
        value = buffer(1)
    end subroutine mpi90_broadcast_integer

355b  <Implementation of mpi90 procedures 346a>+≡ (345a) <355a 355c>
    subroutine mpi90_broadcast_double (value, root, domain, error)
        real(kind=default), intent(inout) :: value
        integer, intent(in) :: root
        integer, intent(in), optional :: domain
        integer, intent(out), optional :: error
        real(kind=default), dimension(1) :: buffer
        buffer(1) = value
        call mpi90_broadcast_double_array (buffer, root, domain, error)
        value = buffer(1)
    end subroutine mpi90_broadcast_double

355c  <Implementation of mpi90 procedures 346a>+≡ (345a) <355b 355d>
    subroutine mpi90_broadcast_logical (value, root, domain, error)
        logical, intent(inout) :: value
        integer, intent(in) :: root
        integer, intent(in), optional :: domain
        integer, intent(out), optional :: error
        logical, dimension(1) :: buffer
        buffer(1) = value
        call mpi90_broadcast_logical_array (buffer, root, domain, error)
        value = buffer(1)
    end subroutine mpi90_broadcast_logical

355d  <Implementation of mpi90 procedures 346a>+≡ (345a) <355c 356b>
    subroutine mpi90_broadcast_integer_array (buffer, root, domain, error)
        integer, dimension(:), intent(inout) :: buffer
        integer, intent(in) :: root
        integer, intent(in), optional :: domain
        integer, intent(out), optional :: error

```

```

        character(len=*), parameter :: FN = "mpi90_broadcast_integer_array"
        integer, parameter :: datatype = MPI_INTEGER
        <Body of mpi90_broadcast_*_array 356a>
    end subroutine mpi90_broadcast_integer_array

356a <Body of mpi90_broadcast_*_array 356a>≡ (355 356)
    integer :: local_domain, local_error
    external mpi_bcast
    <Set default for domain 347b>
    call mpi_bcast (buffer, size (buffer), datatype, root, &
                    local_domain, local_error)
    <Handle local_error 346c>

356b <Implementation of mpi90 procedures 346a>+≡ (345a) <355d 356c>
    subroutine mpi90_broadcast_double_array (buffer, root, domain, error)
        real(kind=default), dimension(:), intent(inout) :: buffer
        integer, intent(in) :: root
        integer, intent(in), optional :: domain
        integer, intent(out), optional :: error
        integer, parameter :: datatype = MPI_DOUBLE_PRECISION
        character(len=*), parameter :: FN = "mpi90_broadcast_double_array"
        <Body of mpi90_broadcast_*_array 356a>
    end subroutine mpi90_broadcast_double_array

356c <Implementation of mpi90 procedures 346a>+≡ (345a) <356b 356d>
    subroutine mpi90_broadcast_logical_array (buffer, root, domain, error)
        logical, dimension(:), intent(inout) :: buffer
        integer, intent(in) :: root
        integer, intent(in), optional :: domain
        integer, intent(out), optional :: error
        integer, parameter :: datatype = MPI_LOGICAL
        character(len=*), parameter :: FN = "mpi90_broadcast_logical_array"
        <Body of mpi90_broadcast_*_array 356a>
    end subroutine mpi90_broadcast_logical_array

356d <Implementation of mpi90 procedures 346a>+≡ (345a) <356c 357a>
    subroutine mpi90_broadcast_integer_array2 (value, root, domain, error)
        integer, dimension(:,:), intent(inout) :: value
        integer, intent(in) :: root
        integer, intent(in), optional :: domain
        integer, intent(out), optional :: error
        integer, dimension(size(value)) :: buffer
        buffer = reshape (value, shape(buffer))
        call mpi90_broadcast_integer_array (buffer, root, domain, error)
        value = reshape (buffer, shape(value))
    end subroutine mpi90_broadcast_integer_array2

```

357a *<Implementation of mpi90 procedures 346a>+≡* (345a) <356d 357b>  
`subroutine mpi90_broadcast_double_array2 (value, root, domain, error)`  
`real(kind=default), dimension(:,,:), intent(inout) :: value`  
`integer, intent(in) :: root`  
`integer, intent(in), optional :: domain`  
`integer, intent(out), optional :: error`  
`real(kind=default), dimension(size(value)) :: buffer`  
`buffer = reshape (value, shape(buffer))`  
`call mpi90_broadcast_double_array (buffer, root, domain, error)`  
`value = reshape (buffer, shape(value))`  
`end subroutine mpi90_broadcast_double_array2`

357b *<Implementation of mpi90 procedures 346a>+≡* (345a) <357a 357c>  
`subroutine mpi90_broadcast_logical_array2 (value, root, domain, error)`  
`logical, dimension(:,,:), intent(inout) :: value`  
`integer, intent(in) :: root`  
`integer, intent(in), optional :: domain`  
`integer, intent(out), optional :: error`  
`logical, dimension(size(value)) :: buffer`  
`buffer = reshape (value, shape(buffer))`  
`call mpi90_broadcast_logical_array (buffer, root, domain, error)`  
`value = reshape (buffer, shape(value))`  
`end subroutine mpi90_broadcast_logical_array2`

357c *<Implementation of mpi90 procedures 346a>+≡* (345a) <357b 357d>  
`subroutine mpi90_broadcast_integer_array3 (value, root, domain, error)`  
`integer, dimension(:,:,:), intent(inout) :: value`  
`integer, intent(in) :: root`  
`integer, intent(in), optional :: domain`  
`integer, intent(out), optional :: error`  
`integer, dimension(size(value)) :: buffer`  
`buffer = reshape (value, shape(buffer))`  
`call mpi90_broadcast_integer_array (buffer, root, domain, error)`  
`value = reshape (buffer, shape(value))`  
`end subroutine mpi90_broadcast_integer_array3`

357d *<Implementation of mpi90 procedures 346a>+≡* (345a) <357c 358>  
`subroutine mpi90_broadcast_double_array3 (value, root, domain, error)`  
`real(kind=default), dimension(:,:,:), intent(inout) :: value`  
`integer, intent(in) :: root`  
`integer, intent(in), optional :: domain`  
`integer, intent(out), optional :: error`  
`real(kind=default), dimension(size(value)) :: buffer`  
`buffer = reshape (value, shape(buffer))`  
`call mpi90_broadcast_double_array (buffer, root, domain, error)`

```

        value = reshape (buffer, shape(value))
    end subroutine mpi90_broadcast_double_array3
358  <Implementation of mpi90 procedures 346a>+≡ (345a) <357d
    subroutine mpi90_broadcast_logical_array3 (value, root, domain, error)
        logical, dimension(:,:,:), intent(inout) :: value
        integer, intent(in) :: root
        integer, intent(in), optional :: domain
        integer, intent(out), optional :: error
        logical, dimension(size(value)) :: buffer
        buffer = reshape (value, shape(buffer))
        call mpi90_broadcast_logical_array (buffer, root, domain, error)
        value = reshape (buffer, shape(value))
    end subroutine mpi90_broadcast_logical_array3

```

# —M— IDEAS

## *M.1 Toolbox for Interactive Optimization*

*Idea:* Provide a OpenGL interface to visualize the grid optimization.

*Motivation:* Would help multi channel developers.

*Implementation:* Coding is straightforward, but interface design is hard.

## *M.2 Partially Non-Factorized Importance Sampling*

*Idea:* Allow non-factorized grid optimization in two- or three-dimensional subspaces.

*Motivation:* Handle nastiest subspaces. Non-factorized approaches are impossible in higher than three dimensions (and probably only realistic in two dimensions), but there are cases that are best handled by including non-factorized optimization in two dimensions.

*Implementation:* The problem is that the present `vamp_sample_grid0` can't accomodate this, because other auxiliary information has to be collected, but a generalization is straightforward. Work has to start from an extended `divisions` module.

## *M.3 Correlated Importance Sampling (?)*

*Idea:* Is it possible to include *some* correlations in a mainly factorized context?



*Motivation:* Would be nice ...

*Implementation:* First, I have to think about the maths ...

## *M.4 Align Coordinate System (i.e. the grid) with Singularities (or the hot region)*

*Idea:* Solve **vegas**' nastiest problem by finding the direction(s) along which singularities are aligned.

*Motivation:* Automatically choose proper coordinate system in generator generators and separate wild and smooth directions.

*Implementation:* Diagonalize the covariance matrix  $\text{cov}(x_i x_j)$  to find better axes. Caveats:

- damp rotations (rotate only if eigenvalues are spread out sufficiently).
- be careful about blow up of the integration volume, which is  $V' = V d^{d/2}$  in the worst case for hypercubes and can be even worse for stretched cubes. (An adaptive grid can help, since we will have more smooth directions!)

*Maybe* try non-linear transformations as well.

## *M.5 Automagic Multi Channel*

*Idea:* Find and extract one singularity after the other.

*Motivation:* Obvious.

*Implementation:* Either use multiple of **vegas**'  $p(x)$  for importance sampling. Or find hot region(s) and split the integration region (à la signal/background).

# —N—

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## *Acknowledgements*

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