# PSBLAS 3.0-beta User's guide

A reference guide for the Parallel Sparse BLAS library

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# 1 Introduction

The PSBLAS library, developed with the aim to facilitate the parallelization of computationally intensive scientific applications, is designed to address parallel implementation of iterative solvers for sparse linear systems through the distributed memory paradigm. It includes routines for multiplying sparse matrices by dense matrices, solving block diagonal systems with triangular diagonal entries, preprocessing sparse matrices, and contains additional routines for dense matrix operations. The current implementation of PSBLAS addresses a distributed memory execution model operating with message passing.

The PSBLAS library is internally implemented in the Fortran 95 [14] programming language, with reuse and/or adaptation of some existing Fortran 77 software, and a handful of C routines. A similar approach has been advocated by a number of authors, e.g. [13]. Moreover, the Fortran 95 facilities for dynamic memory management and interface overloading greatly enhance the usability of the PSBLAS subroutines. In this way, the library can take care of runtime memory requirements that are quite difficult or even impossible to predict at implementation or compilation time. In the current release we rely on the availability of the so-called allocatable extensions, specified in TR 15581. Strictly speaking they are outside the Fortran 95 standard; however they have been included in the Fortran 2003 language standard, and are available in practically all Fortran 95 compilers on the market, including the GNU Fortran compiler from the Free Software Foundation (as of version 4.2). The presentation of the PSBLAS library follows the general structure of the proposal for serial Sparse BLAS [7, 8], which in its turn is based on the proposal for BLAS on dense matrices [12, 4, 5].

The applicability of sparse iterative solvers to many different areas causes some terminology problems because the same concept may be denoted through different names depending on the application area. The PSBLAS features presented in this document will be discussed referring to a finite difference discretization of a Partial Differential Equation (PDE). However, the scope of the library is wider than that: for example, it can be applied to finite element discretizations of PDEs, and even to different classes of problems such as nonlinear optimization, for example in optimal control problems.

The design of a solver for sparse linear systems is driven by many conflicting objectives, such as limiting occupation of storage resources, exploiting regularities in the input data, exploiting hardware characteristics of the parallel platform. To achieve an optimal communication to computation ratio on distributed memory machines it is essential to keep the *data locality* as high as possible; this can be done through an appropriate data allocation strategy. The choice of the preconditioner is another very important factor that affects efficiency of the implemented application. Optimal data distribution requirements for a given preconditioner may conflict with distribution requirements of the rest of the solver. Finding the optimal trade-off may be very difficult because it is application dependent. Possible solutions to these problems and other important inputs to the development of the PSBLAS software package have come from an established experience in applying the PSBLAS solvers to computational fluid dynamics applications.

# 2 General overview

The PSBLAS library is designed to handle the implementation of iterative solvers for sparse linear systems on distributed memory parallel computers. The system coefficient matrix A must be square; it may be real or complex, nonsymmetric, and its sparsity pattern needs not to be symmetric. The serial computation parts are based on the serial sparse BLAS, so that any extension made to the data structures of the serial kernels is available to the parallel version. The overall design and parallelization strategy have been influenced by the structure of the ScaLAPACK parallel library. The layered structure of the PSBLAS library is shown in figure 1; lower layers of the library indicate an encapsulation relationship with upper layers. The ongoing discussion focuses on the Fortran 95 layer immediately below the application layer. The serial parts of the computation on each process are executed through calls to the serial sparse BLAS subroutines. In a similar way, the inter-process message exchanges are implemented through the Basic Linear Algebra Communication Subroutines (BLACS) library [6] that guarantees a portable and efficient communication layer. The Message Passing Interface code is encapsulated within the BLACS layer. However, in some cases, MPI routines are directly used either to improve efficiency or to implement communication patterns for which the BLACS package doesn't provide any method.

In any case we provide wrappers around the BLACS routines so that the user does not need to delve into their details (see Sec. 7).

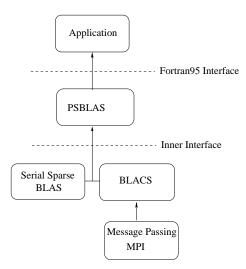


Figure 1: PSBLAS library components hierarchy.

The type of linear system matrices that we address typically arise in the numerical solution of PDEs; in such a context, it is necessary to pay special attention to the structure of the problem from which the application originates. The nonzero pattern of a matrix arising from the discretization of a PDE is influenced by various factors, such as the shape of the domain, the discretization strategy, and the equation/unknown ordering. The matrix itself can be interpreted as the adjacency matrix of the graph associated with the discretization

mesh.

The distribution of the coefficient matrix for the linear system is based on the "owner computes" rule: the variable associated to each mesh point is assigned to a process that will own the corresponding row in the coefficient matrix and will carry out all related computations. This allocation strategy is equivalent to a partition of the discretization mesh into *sub-domains*. Our library supports any distribution that keeps together the coefficients of each matrix row; there are no other constraints on the variable assignment. This choice is consistent with data distributions commonly used in Scalapack such as Cyclic(N) and Block, as well as completely arbitrary assignments of equation indices to processes. In particular it is consistent with the usage of graph partitioning tools commonly available in the literature, e.g. METIS [11]. Dense vectors conform to sparse matrices, that is, the entries of a vector follow the same distribution of the matrix rows.

We assume that the sparse matrix is built in parallel, where each process generates its own portion. We never require that the entire matrix be available on a single node. However, it is possible to hold the entire matrix in one process and distribute it explicitly<sup>1</sup>, even though the resulting bottleneck would make this option unattractive in most cases.

#### 2.1 Basic Nomenclature

Our computational model implies that the data allocation on the parallel distributed memory machine is guided by the structure of the physical model, and specifically by the discretization mesh of the PDE.

Each point of the discretization mesh will have (at least) one associated equation/variable, and therefore one index. We say that point i depends on point j if the equation for a variable associated with i contains a term in j, or equivalently if  $a_{ij} \neq 0$ . After the partition of the discretization mesh into sub-domains assigned to the parallel processes, we classify the points of a given sub-domain as following.

**Internal.** An internal point of a given domain *depends* only on points of the same domain. If all points of a domain are assigned to one process, then a computational step (e.g., a matrix-vector product) of the equations associated with the internal points requires no data items from other domains and no communications.

**Boundary.** A point of a given domain is a boundary point if it *depends* on points belonging to other domains.

Halo. A halo point for a given domain is a point belonging to another domain such that there is a boundary point which depends on it. Whenever performing a computational step, such as a matrix-vector product, the values associated with halo points are requested from other domains. A boundary point of a given domain is usually a halo point for some other domain<sup>2</sup>; therefore the cardinality of the boundary points set denotes the

<sup>&</sup>lt;sup>1</sup>In our prototype implementation we provide sample scatter/gather routines.

<sup>&</sup>lt;sup>2</sup>This is the normal situation when the pattern of the sparse matrix is symmetric, which is equivalent to say that the interaction between two variables is reciprocal. If the matrix pattern is non-symmetric we may have one-way interactions, and these could cause a situation in which a boundary point is not a halo point for its neighbour.

amount of data sent to other domains.

**Overlap.** An overlap point is a boundary point assigned to multiple domains. Any operation that involves an overlap point has to be replicated for each assignment.

Overlap points do not usually exist in the basic data distributions; however they are a feature of Domain Decomposition Schwarz preconditioners which are the subject of related research work [3, 2].

We denote the sets of internal, boundary and halo points for a given subdomain by  $\mathcal{I}$ ,  $\mathcal{B}$  and  $\mathcal{H}$ . Each subdomain is assigned to one process; each process usually owns one subdomain, although the user may choose to assign more than one subdomain to a process. If each process i owns one subdomain, the number of rows in the local sparse matrix is  $|\mathcal{I}_i| + |\mathcal{B}_i|$ , and the number of local columns (i.e. those for which there exists at least one non-zero entry in the local rows) is  $|\mathcal{I}_i| + |\mathcal{B}_i| + |\mathcal{H}_i|$ .

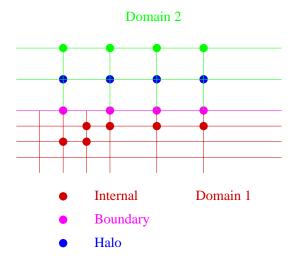


Figure 2: Point classification.

This classification of mesh points guides the naming scheme that we adopted in the library internals and in the data structures. We explicitly note that "Halo" points are also often called "ghost" points in the literature.

# 2.2 Library contents

The PSBLAS library consists of various classes of subroutines:

#### Computational routines comprising:

- Sparse matrix by dense matrix product;
- Sparse triangular systems solution for block diagonal matrices;
- Vector and matrix norms;
- Dense matrix sums;
- Dot products.

Communication routines handling halo and overlap communications;

Data management and auxiliary routines including:

- Parallel environment management
- Communication descriptors allocation;
- Dense and sparse matrix allocation;
- Dense and sparse matrix build and update;
- Sparse matrix and data distribution preprocessing.

#### Preconditioner routines

Iterative methods a subset of Krylov subspace iterative methods

The following naming scheme has been adopted for all the symbols internally defined in the PSBLAS software package:

- all the symbols (i.e. subroutine names, data types...) are prefixed by psb\_
- all the data type names are suffixed by \_type
- all the constant values are suffixed by \_
- all the subroutine names follow the rule psb\_xxname where xx can be either:
  - ge: the routine is related to dense data,
  - sp: the routine is related to sparse data,
  - cd: the routine is related to communication descriptor (see 3).

For example the psb\_geins, psb\_spins and psb\_cdins perform the same action (see 6) on dense matrices, sparse matrices and communication descriptors respectively. Interface overloading allows the usage of the same subroutine interfaces for both real and complex data.

In the description of the subroutines, arguments or argument entries are classified as:

**global** For input arguments, the value must be the same on all processes participating in the subroutine call; for output arguments the value is guaranteed to be the same.

**local** Each process has its own value(s) independently.

# 2.3 Application structure

The main underlying principle of the PSBLAS library is that the library objects are created and exist with reference to a discretized space to which there corresponds an index space and a matrix sparsity pattern. As an example, consider a cell-centered finite-volume discretization of the Navier-Stokes equations on a simulation domain; the index space  $1 \dots n$  is isomorphic to the set of cell centers, whereas the pattern of the associated linear system matrix is isomorphic

to the adjacency graph imposed on the discretization mesh by the discretization stencil.

Thus the first order of business is to establish an index space, and this is done with a call to  $psb\_cdall$  in which we specify the size of the index space n and the allocation of the elements of the index space to the various processes making up the MPI (virtual) parallel machine.

The index space is partitioned among processes, and this creates a mapping from the "global" numbering  $1 \dots n$  to a numbering "local" to each process; each process i will own a certain subset  $1 \dots n_{\text{TOW}i}$ , each element of which corresponds to a certain element of  $1 \dots n$ . The user does not set explicitly this mapping; when the application needs to indicate to which element of the index space a certain item is related, such as the row and column index of a matrix coefficient, it does so in the "global" numbering, and the library will translate into the appropriate "local" numbering.

For a given index space  $1\dots n$  there are many possible associated topologies, i.e. many different discretization stencils; thus the description of the index space is not completed until the user has defined a sparsity pattern, either explicitly through psb\_cdins or implicitly through psb\_spins. The descriptor is finalized with a call to psb\_cdasb and a sparse matrix with a call to psb\_spasb. After psb\_cdasb each process i will have defined a set of "halo" (or "ghost") indices  $n_{\text{ToW}_i} + 1\dots n_{\text{col}_i}$ , denoting elements of the index space that are not assigned to process i; however the variables associated with them are needed to complete computations associated with the sparse matrix A, and thus they have to be fetched from (neighbouring) processes. The descriptor of the index space is built exactly for the purpose of properly sequencing the communication steps required to achieve this objective.

A simple application structure will walk through the index space allocation, matrix/vector creation and linear system solution as follows:

- 1. Initialize parallel environment with psb\_init
- 2. Initialize index space with psb\_cdall
- 3. Allocate sparse matrix and dense vectors with psb\_spall and psb\_geall
- 4. Loop over all local rows, generate matrix and vector entries, and insert them with psb\_spins and psb\_geins
- 5. Assemble the various entities:
  - (a) psb\_cdasb
  - (b) psb\_spasb
  - (c) psb\_geasb
- Choose the preconditioner to be used with psb\_precset and build it with psb\_precbld
- 7. Call the iterative method of choice, e.g. psb\_bicgstab

This is the structure of the sample program test/pargen/ppde90.f90.

For a simulation in which the same discretization mesh is used over multiple time steps, the following structure may be more appropriate:

- 1. Initialize parallel environment with psb\_init
- 2. Initialize index space with psb\_cdall
- 3. Loop over the topology of the discretization mesh and build the descriptor with psb\_cdins
- 4. Assemble the descriptor with psb\_cdasb
- 5. Allocate the sparse matrices and dense vectors with psb\_spall and psb\_geall
- 6. Loop over the time steps:
  - (a) If after first time step, reinitialize the sparse matrix with psb\_sprn; also zero out the dense vectors;
  - (b) Loop over the mesh, generate the coefficients and insert/update them with psb\_spins and psb\_geins
  - (c) Assemble with psb\_spasb and psb\_geasb
  - (d) Choose and build preconditioner with psb\_precset and psb\_precbld
  - (e) Call the iterative method of choice, e.g. psb\_bicgstab

The insertion routines will be called as many times as needed; they only need to be called on the data that is actually allocated to the current process, i.e. each process generates its own data.

In principle there is no specific order in the calls to psb\_spins, nor is there a requirement to build a matrix row in its entirety before calling the routine; this allows the application programmer to walk through the discretization mesh element by element, generating the main part of a given matrix row but also contributions to the rows corresponding to neighbouring elements.

From a functional point of view it is even possible to execute one call for each nonzero coefficient; however this would have a substantial computational overhead. It is therefore advisable to pack a certain amount of data into each call to the insertion routine, say touching on a few tens of rows; the best performing value would depend on both the architecture of the computer being used and on the problem structure. At the opposite extreme, it would be possible to generate the entire part of a coefficient matrix residing on a process and pass it in a single call to psb\_spins; this, however, would entail a doubling of memory occupation, and thus would be almost always far from optimal.

#### 2.4 Programming model

The PSBLAS librarary is based on the Single Program Multiple Data (SPMD) programming model: each process participating in the computation performs the same actions on a chunk of data. Parallelism is thus data-driven.

Because of this structure, many subroutines coordinate their action across the various processes, thus providing an implicit synchronization point, and therefore *must* be called simultaneously by all processes participating in the computation. This is certainly true for the data allocation and assembly routines, for all the computational routines and for some of the tools routines.

However there are many cases where no synchronization, and indeed no communication among processes, is implied; for instance, all the routines in

sec. 3.4 are only acting on the local data structures, and thus may be called independently. The most important case is that of the coefficient insertion routines: since the number of coefficients in the sparse and dense matrices varies among the processors, and since the user is free to choose an arbitrary order in building the matrix entries, these routines cannot imply a synchronization.

Throughout this user's guide each subroutine will be clearly indicated as:

**Synchronous:** must be called simultaneously by all the processes in the relevant communication context;

**Asynchronous:** may be called in a totally independent manner.

# 3 Data Structures

In this chapter we illustrate the data structures used for definition of routines interfaces. They include data structures for sparse matrices, communication descriptors and preconditioners.

All the data types and the basic subroutine interfaces are defined in the module psb\_base\_mod; this will have to be included by every user subroutine that makes use of the library.

Real and complex data types are parametrized with a kind type defined in the library as follows:

psb\_spk\_ Kind parameter for short precision real and complex data; corresponds to a REAL declaration and is normally 4 bytes.

psb\_dpk\_ Kind parameter for long precision real and complex data; corresponds to a DOUBLE PRECISION declaration and is normally 8 bytes.

Moreover, the library defines a long integer kind psb\_long\_int\_k\_ which normally corresponds to 64-bit integers; it is only used for the psb\_sizeof utility.

# 3.1 Descriptor data structure

All the general matrix informations and elements to be exchanged among processes are stored within a data structure of the type psb\_desc\_type. Every structure of this type is associated to a sparse matrix, it contains data about general matrix informations and elements to be exchanged among processes.

It is not necessary for the user to know the internal structure of psb\_desc\_type, it is set in a transparent mode by the tools routines of Sec. 6, and its fields may be accessed if necessary via the routines of sec. 3.4; nevertheless we include a description for the curious reader:

matrix\_data includes general information about matrix and process grid, such as the communication context, the size of the global matrix, the size of the portion of matrix stored on the current process, and so on. Specified as: an allocatable integer array of dimension psb\_mdata\_size\_.

halo\_index A list of the halo and boundary elements for the current process to be exchanged with other processes; for each processes with which it is necessary to communicate:

- 1. Process identifier;
- 2. Number of points to be received;
- 3. Indices of points to be received;
- 4. Number of points to be sent;
- 5. Indices of points to be sent;

The list may contain an arbitrary number of groups; its end is marked by a -1.

Specified as: an allocatable integer array of rank one.

ext\_index A list of element indices to be exchanged to implement the mapping between a base descriptor and a descriptor with overlap.

**ovrlap\_index** A list of the overlap elements for the current process, organized in groups like the previous vector:

- 1. Process identifier;
- 2. Number of points to be received;
- 3. Indices of points to be received;
- 4. Number of points to be sent;
- 5. Indices of points to be sent;

The list may contain an arbitrary number of groups; its end is marked by a -1.

Specified as: an allocatable integer array of rank one.

**ovr\_mst\_idx** A list to retrieve the value of each overlap element from the respective master process.

Specified as: an allocatable integer array of rank one.

ovrlap\_elem For all overlap points belonging to the current process:

- 1. Overlap point index;
- 2. Number of processes sharing that overlap points;
- 3. Index of a "master" process:

Specified as: an allocatable integer array of rank two.

 $\mathbf{loc\_to\_glob}$  each element i of this array contains global identifier of the local variable i.

Specified as: an allocatable integer array of rank one.

glob\_to\_loc, glb\_lc, hashv Contain a mapping from global to local indices.

The Fortran 95 definition for psb\_desc\_type structures is as follows:

```
type psb_desc_type
  integer, allocatable :: matrix_data(:), halo_index(:)
  integer, allocatable :: ext_index(:)
  integer, allocatable :: ovrlap_elem(:,:)
  integer, allocatable :: ovrlap_index(:)
  integer, allocatable :: ovr_mst_idx(:)
  integer, allocatable :: loc_to_glob(:), glob_to_loc(:)
  integer, allocatable :: hashv(:), glb_lc(:,:)
  end type psb_desc_type
```

Figure 3: The PSBLAS defined data type that contains the communication descriptor.

A communication descriptor associated with a sparse matrix has a state, which can take the following values:

**Build:** State entered after the first allocation, and before the first assembly; in this state it is possible to add communication requirements among different processes.

**Assembled:** State entered after the assembly; computations using the associated sparse matrix, such as matrix-vector products, are only possible in this state.

The global to local index mapping may be stored in two different formats: the first is simpler but more expensive, as it requires on each process an amount of memory proportional to the global size of the index space; the second is more complex, but only requires memory proportional to the local index space size. The choice is made at the time of the initialization according to a threshold; this threshold may be queried and set using the functions in sec. 3.4.

#### 3.1.1 Named Constants

psb\_none\_ Generic no-op;

psb\_nohalo\_ Do not fetch halo elements;

psb\_halo\_ Fetch halo elements from neighbouring processes;

 $psb\_sum\_$  Sum overlapped elements

psb\_avg\_ Average overlapped elements

psb\_comm\_halo\_ Exchange data based on the halo\_index list;

psb\_comm\_ext\_ Exchange data based on the ext\_index list;

psb\_comm\_ovr\_ Exchange data based on the ovrlap\_index list;

psb\_comm\_mov\_ Exchange data based on the ovr\_mst\_idx list;

# 3.2 Sparse Matrix data structure

The psb\_spmat\_type data structure contains all information about local portion of the sparse matrix and its storage mode. Most of these fields are set by the tools routines when inserting a new sparse matrix; the user needs only choose, if he/she so whishes, a specific matrix storage mode.

- aspk Contains values of the local distributed sparse matrix.
  Specified as: an allocatable array of rank one of type corresponding to matrix entries type.
- ia1 Holds integer information on distributed sparse matrix. Actual information will depend on data format used.
   Specified as: an allocatable integer array of rank one.
- ia2 Holds integer information on distributed sparse matrix. Actual information will depend on data format used.Specified as: an allocatable integer array of rank one.

infoa On entry can hold auxiliary information on distributed sparse matrix. Actual information will depend on data format used. Specified as: an integer array of length psb\_ifasize\_.

**fida** Defines the format of the distributed sparse matrix. Specified as: a string of length 5

**descra** Describe the characteristic of the distributed sparse matrix. Specified as: array of character of length 9.

- pl Specifies the local row permutation of distributed sparse matrix. If pl(1) is equal to 0, then there isn't row permutation. Specified as: an allocatable integer array of dimension equal to number of local row (matrix\_data[psb\_n\_row\_])
- pr Specifies the local column permutation of distributed sparse matrix. If PR(1) is equal to 0, then there isn't columnm permutation. Specified as: an allocatable integer array of dimension equal to number of local row (matrix\_data[psb\_n\_col\_])
- m Number of rows; if row indices are stored explicitly, as in Coordinate Storage, should be greater than or equal to the maximum row index actually present in the sparse matrix. Specified as: integer variable.
- **k** Number of columns; if column indices are stored explicitly, as in Coordinate Storage or Compressed Sparse Rows, should be greater than or equal to the maximum column index actually present in the sparse matrix. Specified as: integer variable.

The Fortran 95 interface for distributed sparse matrices containing double precision real entries is defined as shown in figure 4. The definitions for single precision and complex data are identical except for the real declaration and for the kind type parameter.

The following two cases are among the most commonly used:

fida="CSR" Compressed storage by rows. In this case the following should hold:

- 1. ia2(i) contains the index of the first element of row i; the last element of the sparse matrix is thus stored at index ia2(m+1)-1. It should contain m+1 entries in nondecreasing order (strictly increasing, if there are no empty rows).
- 2. ia1(j) contains the column index and aspk(j) contains the corresponding coefficient value, for all  $ia2(1) \le j \le ia2(m+1) 1$ .

fida="COO" Coordinate storage. In this case the following should hold:

- 1. infoa(1) contains the number of nonzero elements in the matrix;
- 2. For all  $1 \le j \le infoa(1)$ , the coefficient, row index and column index are stored into apsk(j), ia1(j) and ia2(j) respectively.

A sparse matrix has an associated state, which can take the following values:

```
type psb_sspmat_type
  integer :: m, k
  character :: fida(5)
  character :: descra(10)
  integer :: infoa(psb_ifa_size_)
  real(psb_spk_), allocatable :: aspk(:)
  integer, allocatable :: ia1(:), ia2(:)
  integer, allocatable :: pr(:), pl(:)
end type psb_sspmat_type
type psb_dspmat_type
  integer :: m, k
  character :: fida(5)
  character :: descra(10)
  integer
             :: infoa(psb_ifa_size_)
  real(psb_dpk_), allocatable :: aspk(:)
  integer, allocatable :: ia1(:), ia2(:)
  integer, allocatable :: pr(:), pl(:)
end type psb_dspmat_type
type psb_cspmat_type
  integer :: m, k
character :: fida
              :: fida(5)
  character :: descra(10)
  integer :: infoa(psb_ifa_size_)
  complex(psb_spk_), allocatable :: aspk(:)
  integer, allocatable :: ia1(:), ia2(:)
  integer, allocatable :: pr(:), pl(:)
end type psb_cspmat_type
type psb_zspmat_type
  integer :: m, k
  character :: fida(5)
  character :: descra(10)
  integer :: infoa(psb_ifa_size_)
  complex(psb_dpk_), allocatable :: aspk(:)
  integer, allocatable :: ia1(:), ia2(:)
  integer, allocatable :: pr(:), pl(:)
end type psb_zspmat_type
```

Figure 4: The PSBLAS defined data type that contains a sparse matrix.

**Build:** State entered after the first allocation, and before the first assembly; in this state it is possible to add nonzero entries.

**Assembled:** State entered after the assembly; computations using the sparse

matrix, such as matrix-vector products, are only possible in this state;

**Update:** State entered after a reinitalization; this is used to handle applications in which the same sparsity pattern is used multiple times with different coefficients. In this state it is only possible to enter coefficients for already existing nonzero entries.

# 3.2.1 Named Constants

psb\_dupl\_ovwrt\_ Duplicate coefficients should be overwritten (i.e. ignore duplications)

psb\_dupl\_add\_ Duplicate coefficients should be added;

psb\_dupl\_err\_ Duplicate coefficients should trigger an error conditino

psb\_upd\_dflt\_ Default update strategy for matrix coefficients;

psb\_upd\_srch\_ Update strategy based on search into the data structure;

**psb\_upd\_perm**\_ Update strategy based on additional permutation data (see tools routine description).

#### 3.3 Preconditioner data structure

Our base library offers support for simple well known preconditioners like Diagonal Scaling or Block Jacobi with incomplete factorization ILU(0).

A preconditioner is held in the psb\_prec\_type data structure reported in figure 5. The psb\_prec\_type data type may contain a simple preconditioning matrix with the associated communication descriptor. The values contained in the iprcparm and rprcparm define tha type of preconditioner along with all the parameters related to it; thus, iprcparm and rprcparm define how the other records have to be interpreted. This data structure is the basis of more complex preconditioning strategies, which are the subject of further research.

# 3.4 Data structure query routines

psb\_cd\_get\_local\_rows — Get number of local rows

nr = psb\_cd\_get\_local\_rows(desc)

Type: Asynchronous.

On Entry

desc the communication descriptor.

Scope: local.
Type: required.
Intent: in.

Specified as: a structured data of type psb\_desc\_type.

#### On Return

**Function value** The number of local rows, i.e. the number of rows owned by the current process; as explained in 1, it is equal to  $|\mathcal{I}_i| + |\mathcal{B}_i|$ . The returned value is specific to the calling process.

```
type psb_sprec_type
  type(psb_sspmat_type), allocatable :: av(:)
 real(psb_spk_), allocatable

type(psb_desc_type) :: desc_data

integer, allocatable :: iprcparm(:)

real(psb_spk_), allocatable :: rprcparm(:)

integer, allocatable :: perm(:), invperm(:)

:: prec, base_prec
  real(psb_spk_), allocatable :: d(:)
end type psb_sprec_type
type psb_dprec_type
  type(psb_dspmat_type), allocatable :: av(:)
 real(psb_dpk_), allocatable :: d(:)

type(psb_desc_type) :: desc_data

integer, allocatable :: iprcparm(:)

real(psb_dpk_), allocatable :: rprcparm(:)

integer, allocatable :: perm(:), invperm(:)

integer :: prec, base_prec
end type psb_dprec_type
type psb_cprec_type
  type(psb_cspmat_type), allocatable :: av(:)
  complex(psb_spk_), allocatable :: d(:)
 integer
                                            :: prec, base_prec
end type psb_cprec_type
type psb_zprec_type
 type(psb_zspmat_type), allocatable :: av(:)
  complex(psb\_dpk\_), allocatable :: d(:)
 integer
                                           :: prec, base_prec
end type psb_zprec_type
```

Figure 5: The PSBLAS defined data type that contains a preconditioner.

```
psb_cd_get_local_cols — Get number of local cols
nc = psb_cd_get_local_cols(desc)
On Entry
```

 $\mathbf{Type:}\ \mathrm{Asynchronous}.$ 

```
desc the communication descriptor.
```

Scope: local.
Type: required.
Intent: in.

Specified as: a structured data of type psb\_desc\_type.

#### On Return

**Function value** The number of local cols, i.e. the number of indices used by the current process, including both local and halo indices; as explained in 1, it is equal to  $|\mathcal{I}_i| + |\mathcal{B}_i| + |\mathcal{H}_i|$ . The returned value is specific to the calling process.

```
psb\_cd\_get\_global\_rows --- Get\ number\ of\ global\ rows
```

```
nr = psb_cd_get_global_rows(desc)
```

#### On Entry

Type: Asynchronous.

desc the communication descriptor.

Scope: local.
Type: required.
Intent: in.

Specified as: a structured data of type psb\_desc\_type.

#### On Return

Function value The number of global rows in the mesh

```
psb\_cd\_get\_global\_cols — Get number of global cols
```

```
nr = psb_cd_get_global_cols(desc)
```

Type: Asynchronous.

#### On Entry

desc the communication descriptor.

Scope: **local**. Type: **required**. Intent: **in**.

Specified as: a structured data of type psb\_desc\_type.

#### On Return

Function value The number of global cols in the mesh

# 

```
ictxt = psb_cd_get_context(desc)
```

**Type:** Asynchronous.

#### On Entry

desc the communication descriptor.

Scope: local. Type: required. Intent: in.

Specified as: a structured data of type psb\_desc\_type.

#### On Return

Function value The communication context.

 $psb\_cd\_get\_large\_threshold --- Get\ threshold\ for\ index\ mapping\ switch$ 

```
ith = psb_cd_get_large_threshold()
```

Type: Asynchronous.

#### On Return

Function value The current value for the size threshold.

psb\_cd\_set\_large\_threshold — Set threshold for index mapping switch

```
call psb_cd_set_large_threshold(ith)
```

**Type:** Asynchronous.

#### On Entry

ith the new threshold for communication descriptors.

Scope: global. Type: required. Intent: in.

Specified as: an integer value greater than zero.

Note: the threshold value is only queried by the library at the time a call to psb\_cdall is executed, therefore changing the threshold has no effect on communication descriptors that have already been initialized.

```
psb_sp_get_nrows — Get number of rows in a sparse matrix
nr = psb_sp_get_nrows(a)
Type: Asynchronous.
On Entry
a the sparse matrix
     Scope: local
     Type: required
     Intent: in.
     Specified as: a structured data of type psb_spmat_type.
On Return
Function value The number of rows of sparse matrix a.
psb_sp_get_ncols — Get number of columns in a sparse matrix
nr = psb_sp_get_ncols(a)
Type: Asynchronous.
On Entry
a the sparse matrix
     Scope: local
     Type: required
     Intent: in.
     Specified as: a structured data of type psb_spmat_type.
On Return
Function value The number of columns of sparse matrix a.
psb_sp_get_nnzeros — Get number of nonzero elements in a sparse
matrix
nr = psb_sp_get_nnzeros(a)
Type: Asynchronous.
On Entry
a the sparse matrix
     Scope: local
     Type: required
     Intent: in.
     Specified as: a structured data of type psb_spmat_type.
```

#### On Return

Function value The number of nonzero elements stored in sparse matrix a.

Notes

1. The function value is specific to the storage format of matrix a; some storage formats employ padding, thus the returned value for the same matrix may be different for different storage choices.

4 Computational routines

# psb\_geaxpby — General Dense Matrix Sum

This subroutine is an interface to the computational kernel for dense matrix sum:

$$y \leftarrow \alpha \ x + \beta y$$

call psb\_geaxpby(alpha, x, beta, y, desc\_a, info)

$x, y, \alpha, \beta$	Subroutine
Short Precision Real	psb_geaxpby
Long Precision Real	$psb\_geaxpby$
Short Precision Complex	$psb\_geaxpby$
Long Precision Complex	$psb\_geaxpby$

Table 1: Data types

Type: Synchronous.

#### On Entry

**alpha** the scalar  $\alpha$ .

Scope: **global**Type: **required**Intent: **in**.

Specified as: a number of the data type indicated in Table 1.

 $\mathbf{x}$  the local portion of global dense matrix x.

Scope: local
Type: required
Intent: in.

Specified as: a rank one or two array containing numbers of type specified in Table 1. The rank of x must be the same of y.

**beta** the scalar  $\beta$ .

Scope: **global**Type: **required**Intent: **in**.

Specified as: a number of the data type indicated in Table 1.

 $\mathbf{y}$  the local portion of the global dense matrix y.

Scope: local Type: required Intent: inout.

Specified as: a rank one or two array containing numbers of the type indicated in Table 1. The rank of y must be the same of x.

desc\_a contains data structures for communications.

Scope: local
Type: required
Intent: in.

Specified as: a structured data of type psb\_desc\_type.

# On Return

 $\mathbf{y}$  the local portion of result submatrix y.

Scope: local
Type: required
Intent: inout.

Specified as: a rank one or two array containing numbers of the type

indicated in Table 1.

info Error code.

Scope: local
Type: required
Intent: out.

# psb\_gedot — Dot Product

This function computes dot product between two vectors x and y. If x and y are real vectors it computes dot-product as:

$$dot \leftarrow x^T y$$

Else if x and y are complex vectors then it computes dot-product as:

$$dot \leftarrow x^H y$$

psb\_gedot(x, y, desc\_a, info)

dot, x, y	Function
Short Precision Real	$psb\_gedot$
Long Precision Real	$psb\_gedot$
Short Precision Complex	$psb\_gedot$
Long Precision Complex	$psb\_gedot$

Table 2: Data types

Type: Synchronous.

#### On Entry

 $\mathbf{x}$  the local portion of global dense matrix x.

Scope: local
Type: required
Intent: in.

Specified as: an array of rank one or two containing numbers of type specified in Table 2. The rank of x must be the same of y.

 $\mathbf{y}$  the local portion of global dense matrix y.

Scope: local
Type: required
Intent: in.

Specified as: an array of rank one or two containing numbers of type specified in Table 2. The rank of y must be the same of x.

 $\mathbf{desc\_a}$  contains data structures for communications.

Scope: local
Type: required
Intent: in.

Specified as: a structured data of type psb\_desc\_type.

#### On Return

Function value is the dot product of subvectors x and y.

Scope: global

Specified as: a number of the data type indicated in Table 2.

 $\mathbf{info} \ \, \mathrm{Error} \,\, \mathrm{code}.$ 

Scope: local Type: required Intent: out.

# psb\_gedots — Generalized Dot Product

This subroutine computes a series of dot products among the columns of two dense matrices x and y:

 $res(i) \leftarrow x(:,i)^T y(:,i)$ 

If the matrices are complex, then the usual convention applies, i.e. the conjugate transpose of x is used. If x and y are of rank one, then res is a scalar, else it is a rank one array.

call psb\_gedots(res, x, y, desc\_a, info)

res, x, y	Subroutine
Short Precision Real	$psb\_gedots$
Long Precision Real	$psb\_gedots$
Short Precision Complex	$psb\_gedots$
Long Precision Complex	$psb\_gedots$

Table 3: Data types

Type: Synchronous.

#### On Entry

 $\mathbf{x}$  the local portion of global dense matrix x.

Scope: local
Type: required
Intent: in.

Specified as: an array of rank one or two containing numbers of type specified in Table 3. The rank of x must be the same of y.

 $\mathbf{y}$  the local portion of global dense matrix y.

Scope: local
Type: required
Intent: in.

Specified as: an array of rank one or two containing numbers of type specified in Table 3. The rank of y must be the same of x.

 $\mathbf{desc}_{-\mathbf{a}}$  contains data structures for communications.

Scope: local Type: required Intent: in.

Specified as: a structured data of type psb\_desc\_type.

#### On Return

**res** is the dot product of subvectors x and y.

Scope: **global** Intent: **out**.

Specified as: a number or a rank-one array of the data type indicated in Table 2.

 $\mathbf{info} \ \, \mathrm{Error} \,\, \mathrm{code}.$ 

Scope: local Type: required Intent: out.

# psb\_geamax — Infinity-Norm of Vector

This function computes the infinity-norm of a vector x. If x is a real vector it computes infinity norm as:

$$amax \leftarrow \max_{i} |x_i|$$

else if x is a complex vector then it computes infinity-norm as:

$$amax \leftarrow \max_{i} (|re(x_i)| + |im(x_i)|)$$

psb\_geamax(x, desc\_a, info)

amax	x	Function
Short Precision Real	Short Precision Real	psb_geamax
Long Precision Real	Long Precision Real	$psb\_geamax$
Short Precision Real	Short Precision Complex	$psb\_geamax$
Long Precision Real	Long Precision Complex	$psb\_geamax$

Table 4: Data types

Type: Synchronous.

# On Entry

 $\mathbf{x}$  the local portion of global dense matrix x.

Scope: local
Type: required
Intent: in.

Specified as: a rank one or two array containing numbers of type specified

in Table 4.

desc\_a contains data structures for communications.

Scope: local
Type: required
Intent: in.

Specified as: a structured data of type psb\_desc\_type.

# On Return

Function value is the infinity norm of subvector x.

Scope: global

Specified as: a long precision real number.

info Error code.

Scope: local
Type: required
Intent: out.

# psb\_geamaxs — Generalized Infinity Norm

This subroutine computes a series of infinity norms on the columns of a dense matrix x:

$$res(i) \leftarrow \max_{k} |x(k,i)|$$

call psb\_geamaxs(res, x, desc\_a, info)

res	x	Subroutine
Short Precision Real	Short Precision Real	$psb\_geamaxs$
Long Precision Real	Long Precision Real	$psb\_geamaxs$
Short Precision Real	Short Precision Complex	$psb\_geamaxs$
Long Precision Real	Long Precision Complex	$psb\_geamaxs$

Table 5: Data types

Type: Synchronous.

# On Entry

 $\mathbf{x}$  the local portion of global dense matrix x.

Scope: local
Type: required
Intent: in.

Specified as: a rank one or two array containing numbers of type specified

in Table 5.

desc\_a contains data structures for communications.

Scope: **local**Type: **required**Intent: **in**.

Specified as: a structured data of type psb\_desc\_type.

#### On Return

**res** is the infinity norm of the columns of x.

Scope: **global** Intent: **out**.

Specified as: a number or a rank-one array of long precision real numbers.

info Error code.

Scope: local
Type: required
Intent: out.

# psb\_geasum — 1-Norm of Vector

This function computes the 1-norm of a vector x. If x is a real vector it computes 1-norm as:

$$asum \leftarrow ||x_i||$$

else if x is a vector then it computes 1-norm as:

$$asum \leftarrow ||re(x)||_1 + ||im(x)||_1$$

psb\_geasum(x, desc\_a, info)

asum	x	Function
Short Precision Real	Short Precision Real	psb_geasum
Long Precision Real	Long Precision Real	$psb\_geasum$
Short Precision Real	Short Precision Complex	$psb\_geasum$
Long Precision Real	Long Precision Complex	$psb\_geasum$

Table 6: Data types

Type: Synchronous.

#### On Entry

 $\mathbf{x}$  the local portion of global dense matrix x.

Scope: local
Type: required
Intent: in.

Specified as: a rank one or two array containing numbers of type specified

in Table 6.

desc\_a contains data structures for communications.

Scope: local
Type: required
Intent: in.

Specified as: a structured data of type psb\_desc\_type.

#### On Return

Function value is the 1-norm of vector x.

 ${\bf Scope:\ global}$ 

Specified as: a long precision real number.

info Error code.

Scope: local
Type: required
Intent: out.

# psb\_geasums — Generalized 1-Norm of Vector

This subroutine computes a series of 1-norms on the columns of a dense matrix x:

$$res(i) \leftarrow \max_{k} |x(k, i)|$$

This function computes the 1-norm of a vector x. If x is a real vector it computes 1-norm as:

$$res(i) \leftarrow \|x_i\|$$

else if x is a complex vector then it computes 1-norm as:

$$res(i) \leftarrow ||re(x)||_1 + ||im(x)||_1$$

call psb\_geasums(res, x, desc\_a, info)

res	x	Subroutine
Short Precision Real	Short Precision Real	$psb\_geasums$
Long Precision Real	Long Precision Real	$psb\_geasums$
Short Precision Real	Short Precision Complex	$psb\_geasums$
Long Precision Real	Long Precision Complex	$psb\_geasums$

Table 7: Data types

Type: Synchronous.

# On Entry

 $\mathbf{x}$  the local portion of global dense matrix x.

Scope: local
Type: required
Intent: in.

Specified as: a rank one or two array containing numbers of type specified

in Table 7.

 $\mathbf{desc\_a}$  contains data structures for communications.

Scope: **local**Type: **required**Intent: **in**.

Specified as: a structured data of type psb\_desc\_type.

#### On Return

**res** contains the 1-norm of (the columns of) x.

Scope: **global** Intent: **out**.

Short as: a long precision real number. Specified as: a long precision real

number.

info Error code.

Scope: local Type: required Intent: out.

# psb\_genrm2—2-Norm of Vector

This function computes the 2-norm of a vector x. If x is a double precision real vector it computes 2-norm as:

$$nrm2 \leftarrow \sqrt{x^T x}$$

else if x is double precision complex vector then it computes 2-norm as:

$$nrm2 \leftarrow \sqrt{x^H x}$$

nrm2	x	Function
Short Precision Real	Short Precision Real	$psb\_genrm2$
Long Precision Real	Long Precision Real	$psb\_genrm2$
Short Precision Real	Short Precision Complex	$psb\_genrm2$
Long Precision Real	Long Precision Complex	$psb\_genrm2$

Table 8: Data types

psb\_genrm2(x, desc\_a, info)

Type: Synchronous.

#### On Entry

 $\mathbf{x}$  the local portion of global dense matrix x.

Scope: local
Type: required
Intent: in.

Specified as: a rank one or two array containing numbers of type specified

in Table 8.

 $\mathbf{desc}_{-\mathbf{a}}$  contains data structures for communications.

Scope: local
Type: required
Intent: in.

Specified as: a structured data of type psb\_desc\_type.

#### On Return

Function Value is the 2-norm of subvector x.

Scope: **global**Type: **required** 

Specified as: a long precision real number.

info Error code.

Scope: local
Type: required
Intent: out.

## psb\_genrm2s — Generalized 1-Norm of Vector

This subroutine computes a series of 1-norms on the columns of a dense matrix x:

$$res(i) \leftarrow \max_{k} |x(k, i)|$$

This function computes the 1-norm of a vector x. If x is a real vector it computes 1-norm as:

$$res(i) \leftarrow \sqrt{x^T x}$$

else if x is a complex vector then it computes 1-norm as:

$$res(i) \leftarrow \sqrt{x^H x}$$

call psb\_genrm2s(res, x, desc\_a, info)

res	x	Subroutine
Short Precision Real	Short Precision Real	psb_genrm2s
Long Precision Real	Long Precision Real	$psb\_genrm2s$
Short Precision Real	Short Precision Complex	$psb\_genrm2s$
Long Precision Real	Long Precision Complex	$psb\_genrm2s$

Table 9: Data types

Type: Synchronous.

#### On Entry

 $\mathbf{x}$  the local portion of global dense matrix x.

Scope: local
Type: required
Intent: in.

Specified as: a rank one or two array containing numbers of type specified

in Table 9.

 $\mathbf{desc}_{-\mathbf{a}}$  contains data structures for communications.

Scope: local
Type: required
Intent: in.

Specified as: a structured data of type psb\_desc\_type.

## On Return

**res** contains the 1-norm of (the columns of) x.

Scope: **global** Intent: **out**.

Specified as: a long precision real number.

info Error code.

Scope: local Type: required Intent: out.

## psb\_spnrmi — Infinity Norm of Sparse Matrix

This function computes the infinity-norm of a matrix A:

 $nrmi \leftarrow ||A||_{\infty}$ 

where:

A represents the global matrix A

$\overline{A}$	Function
Short Precision Real	psb_spnrmi
Long Precision Real	$psb\_spnrmi$
Short Precision Complex	$psb\_spnrmi$
Long Precision Complex	$psb\_spnrmi$

Table 10: Data types

psb\_spnrmi(A, desc\_a, info)

Type: Synchronous.

On Entry

 $\mathbf{a}$  the local portion of the global sparse matrix A.

Scope: **local**Type: **required**Intent: **in**.

Specified as: a structured data of type psb\_spmat\_type.

desc\_a contains data structures for communications.

Scope: local
Type: required
Intent: in.

Specified as: a structured data of type psb\_desc\_type.

On Return

**Function value** is the infinity-norm of sparse submatrix A.

Scope: **global** 

Specified as: a long precision real number.

info Error code.

Scope: local
Type: required
Intent: out.

## psb\_spmm — Sparse Matrix by Dense Matrix Product

This subroutine computes the Sparse Matrix by Dense Matrix Product:

$$y \leftarrow \alpha P_r A P_c x + \beta y \tag{1}$$

$$y \leftarrow \alpha P_r A^T P_c x + \beta y \tag{2}$$

$$y \leftarrow \alpha P_r A^H P_c x + \beta y \tag{3}$$

where:

x is the global dense submatrix  $x_{:,:}$ 

y is the global dense submatrix  $y_{:,:}$ 

A is the global sparse submatrix A

 $P_r, P_c$  are the permutation matrices.

$A, x, y, \alpha, \beta$	Subroutine
Short Precision Real	$psb\_spmm$
Long Precision Real	$psb\_spmm$
Short Precision Complex	$psb\_spmm$
Long Precision Complex	$psb\_spmm$

Table 11: Data types

Type: Synchronous.

## On Entry

**alpha** the scalar  $\alpha$ .

Scope: **global**Type: **required**Intent: **in**.

Specified as: a number of the data type indicated in Table 11.

 ${f a}$  the local portion of the sparse matrix A.

Scope: local Type: required Intent: in.

Specified as: a structured data of type psb\_spmat\_type.

 $\mathbf{x}$  the local portion of global dense matrix x.

Scope: **local**Type: **required**Intent: **in**.

Specified as: a rank one or two array containing numbers of type specified

in Table 11. The rank of x must be the same of y.

```
beta the scalar \beta.
     Scope: global
     Type: required
     Intent: in.
     Specified as: a number of the data type indicated in Table 11.
\mathbf{y} the local portion of global dense matrix y.
     Scope: local
     Type: required
     Intent: inout.
     Specified as: a rank one or two array containing numbers of type specified
     in Table 11. The rank of y must be the same of x.
desc_a contains data structures for communications.
     Scope: local
     Type: required
     Intent: in.
     Specified as: a structured data of type psb_desc_type.
trans indicate what kind of operation to perform.
     trans = N the operation is specified by equation 1
     trans = T the operation is specified by equation 2
     trans = C the operation is specified by equation 3
     Scope: global
     Type: optional
     Intent: in.
     Default: trans = N
     Specified as: a character variable.
work work array.
     Scope: local
     Type: optional
     Intent: inout.
     Specified as: a rank one array of the same type of x and y with the
     TARGET attribute.
On Return
\mathbf{y} the local portion of result submatrix y.
     Scope: local
     Type: required
     Intent: inout.
     Specified as: an array of rank one or two containing numbers of type
     specified in Table 11.
info Error code.
     Scope: local
     Type: required
     Intent: out.
     An integer value; 0 means no error has been detected.
```

## psb\_spsm — Triangular System Solve

This subroutine computes the Triangular System Solve:

$$\begin{array}{lcl} y & \leftarrow & \alpha P_r T^{-1} P_c x + \beta y \\ y & \leftarrow & \alpha D P_r T^{-1} P_c x + \beta y \\ y & \leftarrow & \alpha P_r T^{-1} P_c D x + \beta y \\ y & \leftarrow & \alpha P_r T^{-T} P_c x + \beta y \\ y & \leftarrow & \alpha D P_r T^{-T} P_c x + \beta y \\ y & \leftarrow & \alpha P_r T^{-T} P_c D x + \beta y \\ y & \leftarrow & \alpha P_r T^{-H} P_c x + \beta y \\ y & \leftarrow & \alpha D P_r T^{-H} P_c x + \beta y \\ y & \leftarrow & \alpha P_r T^{-H} P_c x + \beta y \\ y & \leftarrow & \alpha P_r T^{-H} P_c D x + \beta y \end{array}$$

where:

x is the global dense submatrix  $x_{:,:}$ 

y is the global dense submatrix  $y_{:,:}$ 

T is the global sparse block triangular submatrix T

D is the scaling diagonal matrix.

 $P_r, P_c$  are the permutation matrices.

$T, x, y, D, \alpha, \beta$	Subroutine
Short Precision Real	psb_spsm
Long Precision Real	$psb\_spsm$
Short Precision Complex	$psb\_spsm$
Long Precision Complex	$psb\_spsm$

Table 12: Data types

Type: Synchronous.

## On Entry

**alpha** the scalar  $\alpha$ .

Scope: **global**Type: **required**Intent: **in**.

Specified as: a number of the data type indicated in Table 12.

```
Scope: local
     Type: required
     Intent: in.
     Specified as: a structured data type specified in § 3.
\mathbf{x} the local portion of global dense matrix x.
     Scope: local
     Type: required
     Intent: in.
     Specified as: a rank one or two array containing numbers of type specified
     in Table 12. The rank of x must be the same of y.
beta the scalar \beta.
     Scope: global
     Type: required
     Intent: in.
     Specified as: a number of the data type indicated in Table 12.
\mathbf{y} the local portion of global dense matrix y.
     Scope: local
     Type: required
     Intent: inout.
     Specified as: a rank one or two array containing numbers of type specified
     in Table 12. The rank of y must be the same of x.
desc_a contains data structures for communications.
     Scope: local
     Type: required
     Intent: in.
     Specified as: a structured data of type psb_desc_type.
trans specify with unitd the operation to perform.
     trans = 'N' the operation is with no transposed matrix
     trans = 'T' the operation is with transposed matrix.
     trans = 'C' the operation is with conjugate transposed matrix.
     Scope: global
     Type: optional
     Intent: in.
     Default: trans = N
     Specified as: a character variable.
unitd specify with trans the operation to perform.
     unitd = 'U' the operation is with no scaling
     unitd = 'L' the operation is with left scaling
     unitd = 'R' the operation is with right scaling.
```

 $\mathbf{t}$  the global portion of the sparse matrix T.

```
Scope: global
     Type: optional
     Intent: in.
     Default: unitd = U
     Specified as: a character variable.
choice specifies the update of overlap elements to be performed on exit:
      psb_none_
      psb_sum_
      psb_avg_
      psb_square_root_
     Scope: global
     Type: optional
     Intent: in.
     Default: psb_avg_
     Specified as: an integer variable.
diag the diagonal scaling matrix.
     Scope: local
     Type: optional
     Intent: in.
     Default: diag(1) = 1(noscaling)
     Specified as: a rank one array containing numbers of the type indicated
     in Table 12.
work a work array.
     Scope: local
     Type: optional
     Intent: inout.
     Specified as: a rank one array of the same type of x with the TARGET
     attribute.
On Return
\mathbf{y} the local portion of global dense matrix y.
     Scope: local
     Type: required
     Intent: inout.
     Specified as: an array of rank one or two containing numbers of type
     specified in Table 12.
info Error code.
     Scope: local
```

An integer value; 0 means no error has been detected.

Type: required Intent: out.

# 5 Communication routines

The routines in this chapter implement various global communication operators on vectors associated with a discretization mesh. For auxiliary communication routines not tied to a discretization space see 6.

## psb\_halo — Halo Data Communication

These subroutines gathers the values of the halo elements, and (optionally) scale the result:

 $x \leftarrow \alpha x$ 

where:

x is a global dense submatrix.

$\alpha, x$	Subroutine
Integer	psb_halo
Short Precision Real	$psb\_halo$
Long Precision Real	$psb\_halo$
Short Precision Complex	$psb\_halo$
Long Precision Complex	psb_halo

Table 13: Data types

```
call psb_halo(x, desc_a, info)
call psb_halo(x, desc_a, info, alpha, work, data)
```

Type: Synchronous.

#### On Entry

 $\mathbf{x}$  global dense matrix x.

Scope: local
Type: required
Intent: inout.

Specified as: a rank one or two array with the TARGET attribute con-

taining numbers of type specified in Table 13.

desc\_a contains data structures for communications.

Scope: local Type: required Intent: in.

Specified as: a structured data of type psb\_desc\_type.

**alpha** the scalar  $\alpha$ .

Scope: global
Type: optional
Intent: in.

Default: alpha = 1

Specified as: a number of the data type indicated in Table 13.

work the work array.

Scope: local
Type: optional
Intent: inout.

Specified as: a rank one array of the same type of x with the POINTER

attribute.

data index list selector.

Scope: **global** Type: **optional** 

Specified as: an integer. Values:psb\_comm\_halo\_,psb\_comm\_mov\_, psb\_comm\_ext\_,

default: psb\_comm\_halo\_. Chooses the index list on which to base the

data exchange.

#### On Return

 $\mathbf{x}$  global dense result matrix x.

Scope: local Type: required Intent: inout.

Returned as: a rank one or two array containing numbers of type specified

in Table 13.

**info** the local portion of result submatrix y.

Scope: local
Type: required
Intent: out.

An integer value that contains an error code.

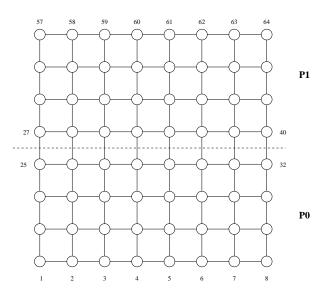


Figure 6: Sample discretization mesh.

Usage Example Consider the discretization mesh depicted in fig. 6, partitioned among two processes as shown by the dashed line; the data distribution is such that each process will own 32 entries in the index space, with a halo made of 8 entries placed at local indices 33 through 40. If process 0 assigns an initial value of 1 to its entries in the x vector, and process 1 assigns a value of 2, then after a call to psb\_halo the contents of the local vectors will be the following:

	Proce	ss 0		Process	1
I	GLOB(I)	X(I)	I	GLOB(I)	X(I)
1	1	1.0	1	33	2.0
2	2	1.0	2	34	2.0
3	3	1.0	3	35	2.0
4	4	1.0	4	36	2.0
5	5	1.0	5	37	2.0
6	6	1.0	6	38	2.0
7	7	1.0	7	39	2.0
8	8	1.0	8	40	2.0
9	9	1.0	9	41	2.0
10	10	1.0	10	42	2.0
11	11	1.0	11	43	2.0
12	12	1.0	12	44	2.0
13	13	1.0	13	45	2.0
14	14	1.0	14	46	2.0
15	15	1.0	15	47	2.0
16	16	1.0	16	48	2.0
17	17	1.0	17	49	2.0
18	18	1.0	18	50	2.0
19	19	1.0	19	51	2.0
20	20	1.0	20	52	2.0
21	21	1.0	21	53	2.0
22	22	1.0	22	54	2.0
23	23	1.0	23	55	2.0
24	24	1.0	24	56	2.0
25	25	1.0	25	57	2.0
26	26	1.0	26	58	2.0
27	27	1.0	27	59	2.0
28	28	1.0	28	60	2.0
29	29	1.0	29	61	2.0
30	30	1.0	30	62	2.0
31	31	1.0	31	63	2.0
32	32	1.0	32	64	2.0
33	33	2.0	33	25	1.0
34	34	2.0	34	26	1.0
35	35	2.0	35	27	1.0
36	36	2.0	36	28	1.0
37	37	2.0	37	29	1.0
38	38	2.0	38	30	1.0
39	39	2.0	39	31	1.0
40	40	2.0	40	32	1.0

## psb\_ovrl — Overlap Update

These subroutines applies an overlap operator to the input vector:

$$x \leftarrow Qx$$

where:

x is the global dense submatrix x

Q is the overlap operator; it is the composition of two operators  $P_a$  and  $P^T$ .

$\overline{x}$	Subroutine
Short Precision Real	psb_ovrl
Long Precision Real	psb_ovrl
Short Precision Complex	psb_ovrl
Long Precision Complex	psb_ovrl

Table 14: Data types

```
call psb_ovrl(x, desc_a, info)
call psb_ovrl(x, desc_a, info, update=update_type, work=work)
```

Type: Synchronous.

#### On Entry

 $\mathbf{x}$  global dense matrix x.

Scope: local Type: required Intent: inout.

Specified as: a rank one or two array containing numbers of type specified

in Table 14.

 $\mathbf{desc}_{-\mathbf{a}}$  contains data structures for communications.

Scope: **local**Type: **required**Intent: **in**.

Specified as: a structured data of type  $psb\_desc\_type$ .

update Update operator.

```
\mathbf{update} = \mathbf{psb\_none}_{-} Do nothing;

\mathbf{update} = \mathbf{psb\_add}_{-} Sum overlap entries, i.e. apply P^T;

\mathbf{update} = \mathbf{psb\_avg}_{-} Average overlap entries, i.e. apply P_aP^T;
```

Scope: **global** Intent: **in**.

Default:  $update\_type = psb\_avg\_$ 

Scope: global

Specified as: a integer variable.

work the work array.

Scope: local
Type: optional
Intent: inout.

Specified as: a one dimensional array of the same type of x.

#### On Return

 $\mathbf{x}$  global dense result matrix x.

Scope: local Type: required Intent: inout.

Specified as: an array of rank one or two containing numbers of type

specified in Table 14.

info Error code.

Scope: **local**Type: **required**Intent: **out**.

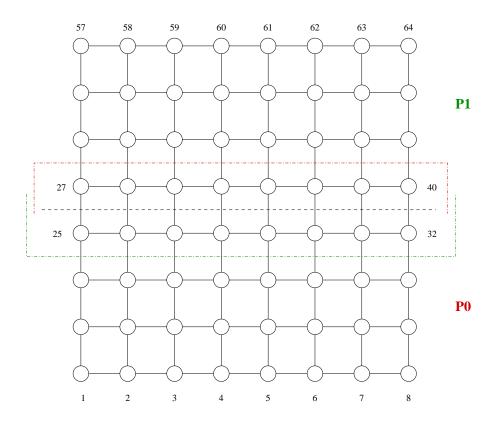
An integer value; 0 means no error has been detected.

#### Notes

- 1. If there is no overlap in the data distribution associated with the descriptor, no operations are performed;
- 2. The operator  $P^T$  performs the reduction sum of overlap elements; it is a "prolongation" operator  $P^T$  that replicates overlap elements, accounting for the physical replication of data;
- 3. The operator  $P_a$  performs a scaling on the overlap elements by the amount of replication; thus, when combined with the reduction operator, it implements the average of replicated elements over all of their instances.

**Example of use** Consider the discretization mesh depicted in fig. 7, partitioned among two processes as shown by the dashed lines, with an overlap of 1 extra layer with respect to the partition of fig. 6; the data distribution is such that each process will own 40 entries in the index space, with an overlap of 16 entries placed at local indices 25 through 40; the halo will run from local index 41 through local index 48.. If process 0 assigns an initial value of 1 to its entries in the x vector, and process 1 assigns a value of 2, then after a call to psb\_ovrl with psb\_avg\_ and a call to psb\_halo\_ the contents of the local vectors will be the following (showing a transition among the two subdomains)

	Proces	ss 0		Process 1	L
I	GLOB(I)	X(I)	I	GLOB(I)	X(I)
1	ĺ	1.0	1	33	$\hat{1.5}$
2	2	1.0	2	34	1.5
3	3	1.0	3	35	1.5
4	4	1.0	4	36	1.5
5	5	1.0	5	37	1.5
6	6	1.0	6	38	1.5
7	7	1.0	7	39	1.5
8	8	1.0	8	40	1.5
9	9	1.0	9	41	2.0
10	10	1.0	10	42	2.0
11	11	1.0	11	43	2.0
12	12	1.0	12	44	2.0
13	13	1.0	13	45	2.0
14	14	1.0	14	46	2.0
15	15	1.0	15	47	2.0
16	16	1.0	16	48	2.0
17	17	1.0	17	49	2.0
18	18	1.0	18	50	2.0
19	19	1.0	19	51	2.0
20	20	1.0	20	52	2.0
21	21	1.0	21	53	2.0
22	22	1.0	22	54	2.0
23	23	1.0	23	55	2.0
24	24	1.0	24	56	2.0
25	25	1.5	25	57	2.0
26	26	1.5	26	58	2.0
27	27	1.5	27	59	2.0
28	28	1.5	28	60	2.0
29	29	1.5	29	61	2.0
30	30	1.5	30	62	2.0
31	31	1.5	31	63	2.0
32	32	1.5	32	64	2.0
33	33	1.5	33	25	1.5
34	34	1.5	34	26	1.5
35	35	1.5	35	27	1.5
36	36	1.5	36	28	1.5
37	37	1.5	37	29	1.5
38	38 39	$\frac{1.5}{1.5}$	38 39	30 31	1.5
39	59 40	1.5	40	32	$1.5 \\ 1.5$
$\frac{40}{41}$	40	$\frac{1.5}{2.0}$	40	32 17	1.0
$\frac{41}{42}$	41	$\frac{2.0}{2.0}$	$\frac{41}{42}$	18	1.0
42	42	$\frac{2.0}{2.0}$	42	18 19	1.0
43 44	45 44	$\frac{2.0}{2.0}$	43	20	1.0
$\frac{44}{45}$	44 45	$\frac{2.0}{2.0}$	$\frac{44}{45}$	20 21	1.0
46	46	$\frac{2.0}{2.0}$	46	21 22	1.0
$\frac{40}{47}$	46 47	$\frac{2.0}{2.0}$	40 47	23	1.0
48	48	$\frac{2.0}{2.0}$	48	$\frac{23}{24}$	1.0
40	40	۵.0	40	44	1.0



 $Figure \ 7: \ Sample \ discretization \ mesh.$ 

## psb\_gather — Gather Global Dense Matrix

These subroutines collect the portions of global dense matrix distributed over all process into one single array stored on one process.

$$glob\_x \leftarrow collect(loc\_x_i)$$

where:

 $glob\_x$  is the global submatrix  $glob\_x_{1:m,1:n}$ 

 $loc\_x_i$  is the local portion of global dense matrix on process i.

collect is the collect function.

$x_i, y$	Subroutine
Integer	$psb\_gather$
Short Precision Real	$psb\_gather$
Long Precision Real	$psb\_gather$
Short Precision Complex	$psb\_gather$
Long Precision Complex	$psb\_gather$

Table 15: Data types

```
call psb_gather(glob_x, loc_x, desc_a, info, root)
call psb_gather(glob_x, loc_x, desc_a, info, root)
```

Type: Synchronous.

## On Entry

 $loc_x$  the local portion of global dense matrix  $glob_x$ .

Scope: local Type: required Intent: in.

Specified as: a rank one or two array containing numbers of the type indicated in Table 15.

desc\_a contains data structures for communications.

Scope: local Type: required Intent: in.

Specified as: a structured data of type psb\_desc\_type.

**root** The process that holds the global copy. If root = -1 all the processes will have a copy of the global vector.

Scope: global Type: optional

Intent: in.

Specified as: an integer variable  $-1 \le root \le np - 1$ , default -1.

#### On Return

 ${\bf glob\_x}$  The array where the local parts must be gathered.

Scope: **global**Type: **required**Intent: **out**.

Specified as: a rank one or two array.

info Error code.

Scope: local
Type: required
Intent: out.

## psb\_scatter — Scatter Global Dense Matrix

These subroutines scatters the portions of global dense matrix owned by a process to all the processes in the processes grid.

 $loc\_x_i \leftarrow scatter(glob\_x)$ 

where:

 $glob\_x$  is the global matrix  $glob\_x_{1:m,1:n}$ 

 $loc_{-}x_{i}$  is the local portion of global dense matrix on process i.

scatter is the scatter function.

$x_i, y$	Subroutine
Integer	$psb\_scatter$
Short Precision Real	$psb\_scatter$
Long Precision Real	$psb\_scatter$
Short Precision Complex	$psb\_scatter$
Long Precision Complex	$psb\_scatter$

Table 16: Data types

```
call psb_scatter(glob_x, loc_x, desc_a, info, root)
call psb_scatter(glob_x, loc_x, desc_a, info, root)
```

Type: Synchronous.

## On Entry

 $\mathbf{glob}_{-}\mathbf{x}$  The array that must be scattered into local pieces.

Scope: **global**Type: **required**Intent: **in**.

Specified as: a rank one or two array.

desc\_a contains data structures for communications.

Scope: local
Type: required
Intent: in.

Specified as: a structured data of type psb\_desc\_type.

**root** The process that holds the global copy. If root = -1 all the processes have a copy of the global vector.

Scope: **global**Type: **optional** 

Intent: in.

Specified as: an integer variable  $-1 \le root \le np - 1$ , default -1.

#### On Return

 $\mathbf{loc}_{-}\mathbf{x} \ \text{ the local portion of global dense matrix } glob_{-}x.$ 

Scope: local
Type: required
Intent: out.

Specified as: a rank one or two array containing numbers of the type

indicated in Table 16.

info Error code.

Scope: local
Type: required
Intent: out.

# 6 Data management routines

## psb\_cdall — Allocates a communication descriptor

```
call psb_cdall(icontxt, desc_a, info,mg=mg,parts=parts)
call psb_cdall(icontxt, desc_a, info,vg=vg,flag=flag)
call psb_cdall(icontxt, desc_a, info,vl=vl,nl=nl,globalcheck=.true.)
call psb_cdall(icontxt, desc_a, info,nl=nl)
call psb_cdall(icontxt, desc_a, info,mg=mg,repl=.true.)
```

This subroutine initializes the communication descriptor associated with an index space. One of the optional arguments parts, vg, vl, nl or repl must be specified, thereby choosing the specific initialization strategy.

## On Entry

```
Type: Synchronous.
```

icontxt the communication context.

Scope:global.

Type:required.

Intent: in.

Specified as: an integer value.

**vg** Data allocation: each index  $i \in \{1 \dots mg\}$  is allocated to process vg(i).

Scope:global.

Type:optional.

Intent: in.

Specified as: an integer array.

flag Specifies whether entries in vg are zero- or one-based.

Scope:global.

Type:optional.

Intent: in.

Specified as: an integer value 0, 1, default 0.

mg the (global) number of rows of the problem.

Scope:global.

Type:optional.

Intent: in.

Specified as: an integer value. It is required if parts or repl is specified, it is optional if vg is specified.

parts the subroutine that defines the partitioning scheme.

Scope:global.

Type:required.

Specified as: a subroutine.

vl Data allocation: the set of global indices belonging to the calling process.

Scope:local.

Type:optional.

Intent: in.

Specified as: an integer array.

**nl** Data allocation: in a generalized block-row distribution the number of indices belonging to the current process.

Scope:local.

Type:optional.

Intent: in.

Specified as: an integer value. May be specified together with vl.

**repl** Data allocation: build a replicated index space (i.e. all processes own all indices).

Scope:global.

 ${\bf Type:} {\bf optional.}$ 

Intent: in.

Specified as: the logical value .true.

globalcheck Data allocation: do global checks on the local index lists vl

Scope:**global**. Type:**optional**.

Intent: in.

Specified as: a logical value, default: .true.

#### On Return

 $\mathbf{desc}_{-\mathbf{a}}$  the communication descriptor.

Scope:local.

Type:required.

Intent: out.

Specified as: a structured data of type psb\_desc\_type.

info Error code.

Scope: local Type: required Intent: out.

An integer value; 0 means no error has been detected.

## Notes

1. One of the optional arguments parts, vg, vl, nl or repl must be specified, thereby choosing the initialization strategy as follows:

parts In this case we have a subroutine specifying the mapping between global indices and process/local index pairs. If this optional argument is specified, then it is mandatory to specify the argument mg as well. The subroutine must conform to the following interface:

```
interface
   subroutine psb_parts(glob_index,mg,np,pv,nv)
   integer, intent (in) :: glob_index,np,mg
   integer, intent (out) :: nv, pv(*)
   end subroutine psb_parts
end interface
```

The input arguments are:

**glob\_index** The global index to be mapped;

- **np** The number of processes in the mapping;
- mg The total number of global rows in the mapping;

The output arguments are:

- nv The number of entries in pv;
- **pv** A vector containing the indices of the processes to which the global index should be assigned; each entry must satisfy  $0 \le pv(i) < np$ ; if nv > 1 we have an index assigned to multiple processes, i.e. we have an overlap among the subdomains.
- vg In this case the association between an index and a process is specified via an integer vector; the size of the index space is equal to the size of vg, and each index i is assigned to the process vg(i). The vector vg must be identical on all calling processes; its entries may have the ranges  $(0 \dots np-1)$  or  $(1 \dots np)$  according to the value of flag. Optionally, the user may specify mg, in which case the portion vg(1:mg) is used.
- vl In this case we are specifying the list of indices assigned to the current process; thus, the global problem size mg is given by the range of the aggregate of the individual vectors vl specified in the calling processes. If globalcheck=.true. the subroutine will check how many times each entry in the global index space  $(1 \dots mg)$  is specified in the input lists vl, thus allowing for the presence of overlap in the input, and checking for "orphan" indices. If globalcheck=.false., the subroutine will not check for overlap, and may be substantially faster, but the user is implicitly guaranteeing that there are neither orphan nor overlap indices. Optionally, the user may specify nl, in which case the portion vl(1:nl) is used.
- **nl** In this case we are implying a generalized row-block distribution in which each process I gets assigned a consecutive chunk of  $N_I = nl$  global indices.
- **repl** In this case we are asking to replicate all indices on all processes. This is a special purpose data allocation that is useful in the construction of some multilevel preconditioners.
- 2. On exit from this routine the descriptor is in the build state

#### Notes

- 1. On exit from this routine the descriptor is in the build state.
- 2. Calling the routine with vg or parts implies that every process will scan the entire index space to figure out the local indices.
- 3. Overlapped indices are possible with both parts and vl invocations.
- 4. When the subroutine is invoked with vl in conjunction with globalcheck=.true., it will perform a scan of the index space to search for overlap or orphan indices.
- 5. When the subroutine is invoked with vl in conjunction with globalcheck=.false., no index space scan will take place. Thus it is the responsibility of the user to make sure that the indices specified in vl have neither orphans nor overlaps; if this assumption fails, results will be unpredictable.

6.	Orphan and overlap indices are impossible by construction when the subroutine is invoked with nl (alone), or vg.

## psb\_cdins — Communication descriptor insert routine

```
call psb_cdins(nz, ia, ja, desc_a, info)
```

This subroutine examines the edges of the graph associated with the discretization mesh (and isomorphic to the sparsity pattern of a linear system coefficient matrix), storing them as necessary into the communication descriptor.

Type: Asynchronous.

#### On Entry

nz the number of points being inserted.

Scope: local.
Type: required.
Intent: in.

Specified as: an integer value.

ia the indices of the starting vertex of the edges being inserted.

Scope: local.
Type: required.
Intent: in.

Specified as: an integer array of length nz.

**ja** the indices of the end vertex of the edges being inserted.

Scope: local. Type: required. Intent: in.

Specified as: an integer array of length nz.

#### On Return

**desc\_a** the updated communication descriptor.

Scope:local.
Type:required.
Intent: inout.

Specified as: a structured data of type psb\_desc\_type.

info Error code.

Scope: local
Type: required
Intent: out.

An integer value; 0 means no error has been detected.

#### Notes

- 1. This routine may only be called if the descriptor is in the build state;
- 2. This routine automatically ignores edges that do not insist on the current process, i.e. edges for which neither the starting nor the end vertex belong to the current process.

## psb\_cdasb — Communication descriptor assembly routine

```
call psb_cdasb(desc_a, info)
```

Type: Synchronous.

## On Entry

 $\mathbf{desc}\_\mathbf{a}$  the communication descriptor.

Scope:local.
Type:required.
Intent: inout.

Specified as: a structured data of type psb\_desc\_type.

## On Return

 $\mathbf{desc}_{-\mathbf{a}}$  the communication descriptor.

Scope:local.
Type:required.
Intent: inout.

Specified as: a structured data of type psb\_desc\_type.

info Error code.

Scope: local Type: required Intent: out.

An integer value; 0 means no error has been detected.

## Notes

1. On exit from this routine the descriptor is in the assembled state.

## psb\_cdcpy — Copies a communication descriptor

call psb\_cdcpy(desc\_in, desc\_out, info)

Type: Asynchronous.

## On Entry

 $\mathbf{desc\_in}\;\;\mathbf{the}\;\mathbf{communication}\;\mathbf{descriptor}.$ 

Scope:local.
Type:required.

Intent: in.

Specified as: a structured data of type psb\_desc\_type.

## On Return

 $\mathbf{desc\_out}$  the communication descriptor copy.

Scope:local.
Type:required.
Intent: out.

Specified as: a structured data of type psb\_desc\_type.

info Error code.

Scope: local
Type: required
Intent: out.

## psb\_cdfree — Frees a communication descriptor

call psb\_cdfree(desc\_a, info)

Type: Synchronous.

## On Entry

 $\mathbf{desc\_a}$  the communication descriptor to be freed.

Scope:local.
Type:required.
Intent: inout.

Specified as: a structured data of type psb\_desc\_type.

## On Return

info Error code.

Scope: local
Type: required
Intent: out.

# $psb\_cdbldext$ — Build an extended communication descriptor

```
call psb_cdbldext(a,desc_a,nl,desc_out, info, extype)
```

This subroutine builds an extended communication descriptor, based on the input descriptor desc\_a and on the stencil specified through the input sparse matrix a.

Type: Synchronous.

#### On Entry

a A sparse matrix Scope:local.

Type:required.

Intent: in.

Specified as: a structured data type.

 $\mathbf{desc}_{-}\mathbf{a}$  the communication descriptor.

Scope:local.

Type:required.

Intent: in.

Specified as: a structured data of type psb\_spmat\_type.

nl the number of additional layers desired.

Scope:global.

Type:required.

Intent: in.

Specified as: an integer value  $nl \geq 0$ .

**extype** the kind of estension required.

Scope:global.

Type:optional.

Intent: in.

Specified as: an integer value psb\_ovt\_xhal\_, psb\_ovt\_asov\_, default:

psb\_ovt\_xhal\_

#### On Return

 $\mathbf{desc\_out}$  the extended communication descriptor.

Scope:local.

Type:required.

Intent: inout.

Specified as: a structured data of type psb\_desc\_type.

info Error code.

Scope: local
Type: required
Intent: out.

An integer value; 0 means no error has been detected.

#### Notes

- 1. Specifying psb\_ovt\_xhal\_ for the extype argument the user will obtain a descriptor for a domain partition in which the additional layers are fetched as part of an (extended) halo; however the index-to-process mapping is identical to that of the base descriptor;
- 2. Specifying psb\_ovt\_asov\_ for the extype argument the user will obtain a descriptor with an overlapped decomposition: the additional layer is aggregated to the local subdomain (and thus is an overlap), and a new halo extending beyond the last additional layer is formed.

## psb\_spall — Allocates a sparse matrix

call psb\_spall(a, desc\_a, info, nnz)

Type: Synchronous.

## On Entry

desc\_a the communication descriptor.

Scope:local.
Type:required.
Intent: in.

Specified as: a structured data of type psb\_desc\_type.

nnz An estimate of the number of nonzeroes in the local part of the assembled matrix.

Scope: global.
Type: optional.
Intent: in.

Specified as: an integer value.

#### On Return

a the matrix to be allocated.

Scope:local
Type:required
Intent: out.

Specified as: a structured data of type psb\_spmat\_type.

info Error code.

Scope: local Type: required Intent: out.

An integer value; 0 means no error has been detected.

## Notes

- 1. On exit from this routine the sparse matrix is in the build state.
- 2. The descriptor may be in either the build or assembled state.
- 3. Providing a good estimate for the number of nonzeroes nnz in the assembled matrix may substantially improve performance in the matrix build phase, as it will reduce or eliminate the need for (potentially multiple) data reallocations.

## psb\_spins — Insert a cloud of elements into a sparse matrix

```
call psb_spins(nz, ia, ja, val, a, desc_a, info)
```

**Type:** Asynchronous.

#### On Entry

**nz** the number of elements to be inserted.

Scope:local.

 ${\bf Type:} {\bf required}.$ 

Intent: in.

Specified as: an integer scalar.

ia the row indices of the elements to be inserted.

Scope:local.

Type:required.

Intent: in.

Specified as: an integer array of size nz.

ja the column indices of the elements to be inserted.

Scope:local.

Type:required.

Intent: in.

Specified as: an integer array of size nz.

val the elements to be inserted.

Scope:local.

 ${\bf Type:} {\bf required}.$ 

Intent: in.

Specified as: an array of size nz. Must be of the same type and kind of the aspk component of the sparse matrix a.

 $\mathbf{desc}_{-\mathbf{a}}$  The communication descriptor.

Scope: local.
Type: required.
Intent: inout.

Specified as: a variable of type psb\_desc\_type.

## On Return

a the matrix into which elements will be inserted.

Scope:local
Type:required
Intent: inout.

Specified as: a structured data of type psb\_spmat\_type.

 $\mathbf{desc}_{-\mathbf{a}}$  The communication descriptor.

Scope: local.
Type: required.
Intent: inout.

Specified as: a variable of type psb\_desc\_type.

info Error code.

Scope: local Type: required Intent: out.

An integer value; 0 means no error has been detected.

#### Notes

1. On entry to this routine the descriptor may be in either the build or assembled state.

- 2. On entry to this routine the sparse matrix may be in either the build or update state.
- 3. If the descriptor is in the build state, then the sparse matrix must also be in the build state; the action of the routine is to (implicitly) call psb\_cdins to add entries to the sparsity pattern; each sparse matrix entry implicitly defines a graph edge, that is passed to the descriptor routine for the appropriate processing.
- 4. Any coefficients from matrix rows not assigned to the calling process are silently ignored;
- 5. If the descriptor is in the assembled state, then any entries in the sparse matrix that would generate additional communication requirements will be ignored;
- 6. If the matrix is in the update state, any entries in positions that were not present in the original matrix will be ignored.

```
psb_spasb — Sparse matrix assembly routine call psb_spasb(a, desc_a, info, afmt, upd, dupl)

Type: Synchronous.

On Entry
```

 $\mathbf{desc}_{-}\mathbf{a}$  the communication descriptor.

Scope:local.
Type:required.

Intent: in.

Specified as: a structured data of type psb\_desc\_type.

afmt the storage format for the sparse matrix.

Scope: **global**. Type: **optional**. Intent: **in**.

Specified as: an array of characters. Defalt: 'CSR'.

upd Provide for updates to the matrix coefficients.

Scope: **global**. Type: **optional**. Intent: **in**.

Specified as: integer, possible values: psb\_upd\_srch\_, psb\_upd\_perm\_

dupl How to handle duplicate coefficients.

Scope: **global**. Type: **optional**. Intent: **in**.

Specified as: integer, possible values: psb\_dupl\_ovwrt\_, psb\_dupl\_add\_,

psb\_dupl\_err\_.

#### On Return

**a** the matrix to be assembled.

Scope:local
Type:required
Intent: inout.

Specified as: a structured data of type  $psb\_spmat\_type$ .

info Error code.

Scope: local Type: required Intent: out.

An integer value; 0 means no error has been detected.

#### Notes

- 1. On entry to this routine the descriptor must be in the assembled state, i.e. psb\_cdasb must already have been called.
- 2. The sparse matrix may be in either the build or update state;

- 3. Duplicate entries are detected and handled in both build and update state, with the exception of the error action that is only taken in the build state, i.e. on the first assembly;
- 4. If the update choice is psb\_upd\_perm\_, then subsequent calls to psb\_spins to update the matrix must be arranged in such a way as to produce exactly the same sequence of coefficient values as encountered at the first assembly;
- 5. On exit from this routine the matrix is in the assembled state, and thus is suitable for the computational routines.

# psb\_spfree — Frees a sparse matrix

```
call psb_spfree(a, desc_a, info)
```

Type: Synchronous.

# On Entry

a the matrix to be freed.

Scope:local
Type:required
Intent: inout.

Specified as: a structured data of type psb\_spmat\_type.

 $\mathbf{desc}_{-\mathbf{a}}$  the communication descriptor.

Scope:local.
Type:required.
Intent: in.

Specified as: a structured data of type psb\_desc\_type.

## On Return

info Error code.

Scope: local
Type: required
Intent: out.

# psb\_sprn — Reinit sparse matrix structure for psblas routines.

```
call psb_sprn(a, decsc_a, info, clear)
```

Type: Synchronous.

## On Entry

a the matrix to be reinitialized.

Scope:local
Type:required
Intent: inout.

Specified as: a structured data of type psb\_spmat\_type.

 $\mathbf{desc}\_\mathbf{a}$  the communication descriptor.

Scope:local.
Type:required.
Intent: in.

Specified as: a structured data of type psb\_desc\_type.

clear Choose whether to zero out matrix coefficients

Scope:**local**. Type:**optional**. Intent: **in**. Default: true.

## On Return

info Error code.

Scope: local
Type: required
Intent: out.

An integer value; 0 means no error has been detected.

# Notes

1. On exit from this routine the sparse matrix is in the update state.

# psb\_geall — Allocates a dense matrix

call psb\_geall(x, desc\_a, info, n, lb)

Type: Synchronous.

# On Entry

 $\mathbf{desc}_{-\mathbf{a}}$  The communication descriptor.

Scope: local
Type: required
Intent: in.

Specified as: a variable of type psb\_desc\_type.

n The number of columns of the dense matrix to be allocated.

Scope: local
Type: optional
Intent: in.

Specified as: Integer scalar, default 1. It is not a valid argument if x is a

rank-1 array.

**lb** The lower bound for the column index range of the dense matrix to be allocated.

Scope: local
Type: optional
Intent: in.

Specified as: Integer scalar, default 1. It is not a valid argument if x is a

rank-1 array.

## On Return

 $\mathbf{x}$  The dense matrix to be allocated.

Scope: local
Type: required
Intent: out.

Specified as: a rank one or two array with the ALLOCATABLE attribute,  $\,$ 

of type real, complex or integer.

info Error code.

Scope: local Type: required Intent: out.

# psb\_geins — Dense matrix insertion routine

call psb\_geins(m, irw, val, x, desc\_a, info,dupl)

Type: Asynchronous.

## On Entry

**m** Number of rows in *val* to be inserted.

Scope:local.
Type:required.
Intent: in.

Specified as: an integer value.

**irw** Indices of the rows to be inserted. Specifically, row i of val will be inserted into the local row corresponding to the global row index irw(i).

Scope:local. Type:required.

Intent: in.

Specified as: an integer array.

val the dense submatrix to be inserted.

Scope:local.
Type:required.

Intent: in.

Specified as: a rank 1 or 2 array. Specified as: an integer value.

desc\_a the communication descriptor.

Scope:**local**.
Type:**required**.

Intent: in.

Specified as: a structured data of type psb\_desc\_type.

dupl How to handle duplicate coefficients.

Scope: **global**. Type: **optional**. Intent: **in**.

Specified as: integer, possible values: psb\_dupl\_ovwrt\_, psb\_dupl\_add\_.

#### On Return

 $\mathbf{x}$  the output dense matrix.

Scope: local
Type: required
Intent: inout.

Specified as: a rank one or two array with the ALLOCATABLE attribute,

of type real, complex or integer.

info Error code.

Scope: **local**Type: **required**Intent: **out**.

- 1. Dense vectors/matrices do not have an associated state;
- $2.\,$  Duplicate entries are either overwritten or added, there is no provision for raising an error condition.

# psb\_geasb — Assembly a dense matrix

call psb\_geasb(x, desc\_a, info)

Type: Synchronous.

# On Entry

 $\mathbf{desc\_a}$  The communication descriptor.

Scope: local
Type: required
Intent: in.

Specified as: a variable of type psb\_desc\_type.

## On Return

 $\mathbf{x}$  The dense matrix to be assembled.

Scope: local
Type: required
Intent: inout.

Specified as: a rank one or two array with the ALLOCATABLE attribute,  $\,$ 

of type real, complex or integer.

## info Error code.

Scope: local
Type: required
Intent: out.

# $psb\_gefree$ — Frees a dense matrix

call psb\_gefree(x, desc\_a, info)

Type: Synchronous.

# On Entry

 $\mathbf{x}$  The dense matrix to be freed.

Scope: local Type: required Intent: inout.

Specified as: a rank one or two array with the ALLOCATABLE attribute,

of type real, complex or integer.

 $\mathbf{desc}_{-}\mathbf{a}$  The communication descriptor.

Scope: local
Type: required
Intent: in.

Specified as: a variable of type psb\_desc\_type.

## On Return

info Error code.

Scope: local Type: required Intent: out.

# psb\_gelp — Applies a left permutation to a dense matrix

call psb\_gelp(trans, iperm, x, info)

**Type:** Asynchronous.

# On Entry

**trans** A character that specifies whether to permute A or  $A^T$ .

Scope: local
Type: required
Intent: in.

Specified as: a single character with value 'N' for A or 'T' for  $A^T$ .

iperm An integer array containing permutation information.

Scope: local
Type: required
Intent: in.

Specified as: an integer one-dimensional array.

 $\mathbf{x}$  The dense matrix to be permuted.

Scope: local Type: required Intent: inout.

Specified as: a one or two dimensional array.

# On Return

info Error code.

Scope: local
Type: required
Intent: out.

# psb\_glob\_to\_loc — Global to local indices convertion

call psb\_glob\_to\_loc(x, y, desc\_a, info, iact,owned)
call psb\_glob\_to\_loc(x, desc\_a, info, iact,owned)

**Type:** Asynchronous.

## On Entry

 $\mathbf{x}$  An integer vector of indices to be converted.

Scope: local
Type: required
Intent: in, inout.

Specified as: a rank one integer array.

**desc\_a** the communication descriptor.

Scope:local.
Type:required.

Intent: in.

Specified as: a structured data of type psb\_desc\_type.

iact specifies action to be taken in case of range errors. Scope: global

Type: **optional** Intent: **in**.

Specified as: a character variable Ignore, Warning or Abort, default Ignore.

owned Specfies valid range of input Scope: global

Type: **optional** Intent: **in**.

If true, then only indices strictly owned by the current process are considered valid, if false then halo indices are also accepted. Default: false.

#### On Return

 $\mathbf{x}$  If y is not present, then x is overwritten with the translated integer indices.

Scope: **global**Type: **required**Intent: **inout**.

Specified as: a rank one integer array.

y If y is present, then y is overwritten with the translated integer indices, and

x is left unchanged. Scope: **global** 

Type: **optional** Intent: **out**.

Specified as: a rank one integer array.

info Error code.

Scope: local Type: required Intent: out.

An integer value; 0 means no error has been detected.

- 1. If an input index is out of range, then the corresponding output index is set to a negative number;
- 2. The default Ignore means that the negative output is the only action taken on an out-of-range input.

# psb\_loc\_to\_glob — Local to global indices conversion

```
call psb_loc_to_glob(x, y, desc_a, info, iact)
call psb_loc_to_glob(x, desc_a, info, iact)
```

Type: Asynchronous.

#### On Entry

 $\mathbf{x}$  An integer vector of indices to be converted.

Scope: local
Type: required
Intent: in, inout.

Specified as: a rank one integer array.

 $\mathbf{desc}_{-\mathbf{a}}$  the communication descriptor.

Scope:local.
Type:required.
Intent: in.

Specified as: a structured data of type psb\_desc\_type.

iact specifies action to be taken in case of range errors. Scope: global

Type: **optional** Intent: **in**.

Specified as: a character variable Ignore, Warning or Abort, default Ignore.

# On Return

 $\mathbf{x}$  If y is not present, then x is overwritten with the translated integer indices.

Scope: **global**Type: **required**Intent: **inout**.

Specified as: a rank one integer array.

 $\mathbf{y}$  If y is not present, then y is overwritten with the translated integer indices,

and x is left unchanged. Scope: **global** 

Type: **optional** Intent: **out**.

Specified as: a rank one integer array.

info Error code.

Scope: local
Type: required
Intent: out.

# $psb\_is\_owned$

```
call psb_is_owned(x, desc_a)
```

**Type:** Asynchronous.

# On Entry

 $\mathbf{x}$  Integer index.

Scope: local
Type: required
Intent: in.

Specified as: a scalar integer.

 $\mathbf{desc}_{-\mathbf{a}}$  the communication descriptor.

Scope:local.
Type:required.

Intent: in.

Specified as: a structured data of type psb\_desc\_type.

## On Return

Function value A logical mask which is true if x is owned by the current pro-

cess Scope: local Type: required Intent: out.

# Notes

1. This routine returns a .true. value for an index that is strictly owned by the current process, excluding the halo indices

# $psb\_owned\_index$

```
call psb_owned_index(y, x, desc_a, info)
```

**Type:** Asynchronous.

## On Entry

 $\mathbf{x}$  Integer indices.

Scope: local
Type: required
Intent: in, inout.

Specified as: a scalar or a rank one integer array.

 $\mathbf{desc}_{-\mathbf{a}}$  the communication descriptor.

Scope:local.
Type:required.

Intent: in.

Specified as: a structured data of type psb\_desc\_type.

iact specifies action to be taken in case of range errors. Scope: global

Type: **optional** Intent: **in**.

Specified as: a character variable Ignore, Warning or Abort, default Ignore.

# On Return

 $\mathbf{y}$  A logical mask which is true for all corresponding entries of x that are owned

by the current process Scope: local

Type: **required** Intent: **out**.

Specified as: a scalar or rank one logical array.

info Error code.

Scope: local Type: required Intent: out.

An integer value; 0 means no error has been detected.

# Notes

1. This routine returns a .true. value for those indices that are strictly owned by the current process, excluding the halo indices

# psb\_is\_local

```
call psb_is_local(x, desc_a)
```

**Type:** Asynchronous.

# On Entry

 $\mathbf{x}$  Integer index.

Scope: local
Type: required
Intent: in.

Specified as: a scalar integer.

 $\mathbf{desc\_a}$  the communication descriptor.

Scope:local.
Type:required.
Intent: in.

Specified as: a structured data of type psb\_desc\_type.

## On Return

Function value A logical mask which is true if x is local to the current process

Scope: local Type: required Intent: out.

# Notes

1. This routine returns a .true. value for an index that is local to the current process, including the halo indices

# psb\_local\_index

```
call psb_local_index(y, x, desc_a, info)
```

**Type:** Asynchronous.

## On Entry

 $\mathbf{x}$  Integer indices.

Scope: local
Type: required
Intent: in, inout.

Specified as: a scalar or a rank one integer array.

 $\mathbf{desc}_{-\mathbf{a}}$  the communication descriptor.

Scope:local.
Type:required.

Intent: in.

Specified as: a structured data of type psb\_desc\_type.

iact specifies action to be taken in case of range errors. Scope: global

Type: **optional** Intent: **in**.

Specified as: a character variable Ignore, Warning or Abort, default Ignore.

#### On Return

y A logical mask which is true for all corresponding entries of x that are local

to the current process Scope: local

Type: **required** Intent: **out**.

Specified as: a scalar or rank one logical array.

info Error code.

Scope: local
Type: required
Intent: out.

An integer value; 0 means no error has been detected.

# Notes

1. This routine returns a .true. value for those indices that are local to the current process, including the halo indices.

# psb\_get\_boundary — Extract list of boundary elements

call psb\_get\_boundary(bndel, desc, info)

**Type:** Asynchronous.

# On Entry

desc the communication descriptor.

Scope:local.
Type:required.
Intent: in.

Specified as: a structured data of type psb\_desc\_type.

#### On Return

bndel The list of boundary elements on the calling process, in local numbering.

Scope: local
Type: required
Intent: out.

Specified as: a rank one array with the ALLOCATABLE attribute, of

type integer.

info Error code.

Scope: **local**Type: **required**Intent: **out**.

An integer value; 0 means no error has been detected.

- 1. If there are no boundary elements (i.e., if the local part of the connectivity graph is self-contained) the output vector is set to the "not allocated" state.
- 2. Otherwise the size of bndel will be exactly equal to the number of boundary elements.

# psb\_get\_overlap — Extract list of overlap elements

call psb\_get\_overlap(ovrel, desc, info)

**Type:** Asynchronous.

## On Entry

desc the communication descriptor.

Scope:local.
Type:required.
Intent: in.

Specified as: a structured data of type psb\_desc\_type.

# On Return

ovrel The list of overlap elements on the calling process, in local numbering.

Scope: local
Type: required
Intent: out.

Specified as: a rank one array with the ALLOCATABLE attribute, of

type integer.

info Error code.

Scope: local
Type: required
Intent: out.

An integer value; 0 means no error has been detected.

- 1. If there are no overlap elements the output vector is set to the "not allocated" state.
- 2. Otherwise the size of ovrel will be exactly equal to the number of overlap elements.

```
psb_sp_getrow — Extract row(s) from a sparse matrix
```

Type: Asynchronous.

# On Entry

row The (first) row to be extracted.

Scope:local Type:required

Intent: in.

Specified as: an integer > 0.

**a** the matrix from which to get rows.

Scope:local

 ${\bf Type:} {\bf required}$ 

Intent: in.

Specified as: a structured data of type psb\_spmat\_type.

append Whether to append or overwrite existing output.

Scope:local

Type:optional

Intent: in.

Specified as: a logical value default: false (overwrite).

nzin Input size to be appended to.

Scope:local

 ${\bf Type:} {\bf optional}$ 

Intent: in.

Specified as: an integer > 0. When append is true, specifies how many entries in the output vectors are already filled.

**lrw** The last row to be extracted.

Scope:local

Type:optional

Intent: in.

Specified as: an integer > 0, default: row.

# On Return

nz the number of elements returned by this call.

Scope:local.

 ${\bf Type:} {\bf required}.$ 

Intent: out.

Returned as: an integer scalar.

ia the row indices.

Scope:local.

Type:required.

Intent: inout.

Specified as: an integer array with the ALLOCATABLE attribute.

**ja** the column indices of the elements to be inserted.

Scope:local.
Type:required.
Intent: inout.

Specified as: an integer array with the ALLOCATABLE attribute.

val the elements to be inserted.

Scope:local.
Type:required.
Intent: inout.

Specified as: a real array with the ALLOCATABLE attribute.

info Error code.

Scope: local Type: required Intent: out.

An integer value; 0 means no error has been detected.

- The output nz is always the size of the output generated by the current call; thus, if append=.true., the total output size will be nzin+nz, with the newly extracted coefficients stored in entries nzin+1:nzin+nz of the array arguments;
- 2. When append=.true. the output arrays are reallocated as necessary;
- 3. The row and column indices are returned in the local numbering scheme; if the global numbering is desired, the user may employ the psb\_loc\_to\_glob routine on the output.

# psb\_sizeof — Memory occupation

This function computes the memory occupation of a PSBLAS object.

```
isz = psb_sizeof(a)
isz = psb_sizeof(desc_a)
isz = psb_sizeof(prec)
```

**Type:** Asynchronous.

## On Entry

**a** A sparse matrix A. Scope: local Type: required Intent: in.

Specified as: a structured data of type psb\_spmat\_type.

 $\mathbf{desc\_a}$  Communication descriptor.

Scope: local Type: required Intent: in.

Specified as: a structured data of type psb\_desc\_type.

prec Scope: local Type: required

Intent: in.

Specified as: a preconditioner data structure psb\_prec\_type.

# On Return

Function value The memory occupation of the object specified in the calling

sequence, in bytes. Scope: local

Returned as: an integer(psb\_long\_int\_k\_) number.

# Sorting utilities

```
psb_msort — Sorting by the Merge-sort algorithm
psb_qsort — Sorting by the Quicksort algorithm
psb_hsort — Sorting by the Heapsort algorithm

call psb_msort(x,ix,dir,flag)
call psb_qsort(x,ix,dir,flag)
call psb_hsort(x,ix,dir,flag)
```

These serial routines sort a sequence X into ascending or descending order. The argument meaning is identical for the three calls; the only difference is the algorithm used to accomplish the task (see Usage Notes below).

**Type:** Asynchronous.

#### On Entry

 $\mathbf{x}$  The sequence to be sorted.

Type:required.

Specified as: an integer, real or complex array of rank 1.

ix A vector of indices.

Type:optional.

Specified as: an integer array of (at least) the same size as X.

dir The desired ordering.

Type:optional.

Specified as: an integer value:

```
Integer and real data: psb_sort_up_, psb_sort_down_, psb_asort_up_,
    psb_asort_down_; default psb_sort_up_.
```

flag Whether to keep the original values in IX.

Type:**optional**.

Specified as: an integer value psb\_sort\_ovw\_idx\_ or psb\_sort\_keep\_idx\_; default psb\_sort\_ovw\_idx\_.

#### On Return

**x** The sequence of values, in the chosen ordering.

Type:required.

Specified as: an integer, real or complex array of rank 1.

ix A vector of indices.

Type: Optional

An integer array of rank 1, whose entries are moved to the same position as the corresponding entries in x.

- 1. For integer or real data the sorting can be performed in the up/down direction, on the natural or absolute values;
- 2. For complex data the sorting can be done in a lexicographic order (i.e.: sort on the real part with ties broken according to the imaginary part) or on the absolute values;
- 3. The routines return the items in the chosen ordering; the output difference is the handling of ties (i.e. items with an equal value) in the original input. With the merge-sort algorithm ties are preserved in the same relative order as they had in the original sequence, while this is not guaranteed for quicksort or heapsort;
- 4. If  $flag = psb\_sort\_ovw\_idx\_$  then the entries in ix(1:n) where n is the size of x are initialized to  $ix(i) \leftarrow i$ ; thus, upon return from the subroutine, for each index i we have in ix(i) the position that the item x(i) occupied in the original data sequence;
- 5. If  $flag = psb\_sort\_keep\_idx$  the routine will assume that the entries in ix(:) have already been initialized by the user;
- 6. The three sorting algorithms have a similar  $O(n \log n)$  expected running time; in the average case quicksort will be the fastest and merge-sort the slowest. However note that:
  - (a) The worst case running time for quicksort is  $O(n^2)$ ; the algorithm implemented here follows the well-known median-of-three heuristics, but the worst case may still apply;
  - (b) The worst case running time for merge-sort and heap-sort is  $O(n \log n)$  as the average case;
  - (c) The merge-sort algorithm is implemented to take advantage of subsequences that may be already in the desired ordering prior to the subroutine call; this situation is relatively common when dealing with groups of indices of sparse matrix entries, thus merge-sort is often the preferred choice when a sorting is needed by other routines in the library.

7 Parallel environment routines

## psb\_init — Initializes PSBLAS parallel environment

```
call psb_init(icontxt, np, basectxt, ids)
```

This subroutine initializes the PSBLAS parallel environment, defining a virtual parallel machine.

Type: Synchronous.

## On Entry

**np** Number of processes in the PSBLAS virtual parallel machine.

Scope: **global**. Type: **optional**. Intent: **in**.

Specified as: an integer value. Default: use all available processes.

**basectxt** the initial communication context. The new context will be defined from the processes participating in the initial one.

Scope: **global**. Type: **optional**. Intent: **in**.

Specified as: an integer value. Default: use MPI\_COMM\_WORLD.

ids Identities of the processes to use for the new context; the argument is ignored when np is not specified. This allows the processes in the new environment to be in an order different from the original one.

Scope: global.
Type: optional.

Intent: in.

Specified as: an integer array. Default: use the indices  $(0 \dots np - 1)$ .

# On Return

icontxt the communication context identifying the virtual parallel machine. Note that this is always a duplicate of basectxt, so that library communications are completely separated from other communication operations.

Scope: **global**. Type: **required**. Intent: **out**.

Specified as: an integer variable.

- 1. A call to this routine must precede any other PSBLAS call.
- 2. It is an error to specify a value for np greater than the number of processes available in the underlying base parallel environment.

# $psb\_info$ — Return information about PSBLAS parallel environment

```
call psb_info(icontxt, iam, np)
```

This subroutine returns information about the PSBLAS parallel environment, defining a virtual parallel machine.

**Type:** Asynchronous.

#### On Entry

**icontxt** the communication context identifying the virtual parallel machine.

Scope: **global**. Type: **required**. Intent: **in**.

Specified as: an integer variable.

#### On Return

iam Identifier of current process in the PSBLAS virtual parallel machine.

Scope: local.
Type: required.
Intent: out.

Specified as: an integer value.  $-1 \le iam \le np - 1$ 

**np** Number of processes in the PSBLAS virtual parallel machine.

Scope: **global**. Type: **required**. Intent: **out**.

Specified as: an integer variable.

- 1. For processes in the virtual parallel machine the identifier will satisfy  $0 \le iam \le np-1$ ;
- 2. If the user has requested on  $psb_i$  a number of processes less than the total available in the parallel execution environment, the remaining processes will have on return iam = -1; the only call involving icontxt that any such process may execute is to  $psb_e$ .

# psb\_exit — Exit from PSBLAS parallel environment

```
call psb_exit(icontxt)
call psb_exit(icontxt,close)
```

This subroutine exits from the PSBLAS parallel virtual machine.

Type: Synchronous.

## On Entry

icontxt the communication context identifying the virtual parallel machine.

Scope: **global**. Type: **required**. Intent: **in**.

Specified as: an integer variable.

**close** Whether to close all data structures related to the virtual parallel machine, besides those associated with icontxt.

Scope: global.
Type: optional.
Intent: in.

Specified as: a logical variable, default value: true.

- 1. This routine may be called even if a previous call to  $psb_info$  has returned with iam = -1; indeed, it it is the only routine that may be called with argument icontxt in this situation.
- 2. A call to this routine with close=.true. implies a call to MPI\_Finalize, after which no parallel routine may be called.
- 3. If the user whishes to use multiple communication contexts in the same program, or to enter and exit multiple times into the parallel environment, this routine may be called to selectively close the contexts with close=.false., while on the last call it should be called with close=.true. to shutdown in a clean way the entire parallel environment.

# $psb\_get\_mpicomm$ — Get the MPI communicator

call psb\_get\_mpicomm(icontxt, icomm)

This subroutine returns the MPI communicator associated with a PSBLAS context  $\,$ 

Type: Asynchronous.

# On Entry

 ${\bf icontxt}$  the communication context identifying the virtual parallel machine.

Scope: **global**. Type: **required**. Intent: **in**.

Specified as: an integer variable.

#### On Return

 ${\bf icomm}$  The MPI communicator associated with the PSBLAS virtual parallel machine.

Scope: **global**. Type: **required**. Intent: **out**.

# $psb\_get\_rank$ — Get the MPI rank

```
call psb_get_rank(rank, icontxt, id)
```

This subroutine returns the MPI rank of the PSBLAS process id

Type: Asynchronous.

## On Entry

icontxt the communication context identifying the virtual parallel machine.

Scope: global.
Type: required.

Intent: in.

Specified as: an integer variable.

id Identifier of a process in the PSBLAS virtual parallel machine.

Scope: local.
Type: required.

Intent: in.

Specified as: an integer value.  $0 \le id \le np - 1$ 

## On Return

rank The MPI rank associated with the PSBLAS process id.

Scope: local.
Type: required.
Intent: out.

# $psb\_wtime - Wall clock timing$

time = psb\_wtime()

This function returns a wall clock timer. The resolution of the timer is dependent on the underlying parallel environment implementation.

Type: Asynchronous.

On Exit

Function value the elapsed time in seconds.

Returned as: a real(psb\_dpk\_) variable.

# psb\_barrier — Sinchronization point parallel environment

call psb\_barrier(icontxt)

This subroutine acts as an explicit synchronization point for the PSBLAS parallel virtual machine.

Type: Synchronous.

# On Entry

 ${\bf icontxt}$  the communication context identifying the virtual parallel machine.

Scope: **global**.

Type: **required**.

Intent: in.

Specified as: an integer variable.

# psb\_abort — Abort a computation

call psb\_abort(icontxt)

This subroutine aborts computation on the parallel virtual machine.

Type: Asynchronous.

# On Entry

 ${\bf icontxt}$  the communication context identifying the virtual parallel machine.

Scope: **global**. Type: **required**. Intent: **in**.

Specified as: an integer variable.

## psb\_bcast — Broadcast data

call psb\_bcast(icontxt, dat, root)

This subroutine implements a broadcast operation based on the underlying communication library.

Type: Synchronous.

## On Entry

icontxt the communication context identifying the virtual parallel machine.

Scope: **global**. Type: **required**. Intent: **in**.

Specified as: an integer variable.

dat On the root process, the data to be broadcast.

Scope: **global**. Type: **required**. Intent: **inout**.

Specified as: an integer, real or complex variable, which may be a scalar, or a rank 1 or 2 array, or a character or logical variable, which may be a scalar or rank 1 array. Type, kind, rank and size must agree on all processes.

root Root process holding data to be broadcast.

Scope: **global**. Type: **optional**. Intent: **in**.

Specified as: an integer value  $0 \le root \le np - 1$ , default 0

# On Return

dat On processes other than root, the data to be broadcast.

Scope: **global**. Type: **required**. Intent: **inout**.

Specified as: an integer, real or complex variable, which may be a scalar, or a rank 1 or 2 array, or a character or logical scalar. Type, kind, rank and size must agree on all processes.

# psb\_sum — Global sum

```
call psb_sum(icontxt, dat, root)
```

This subroutine implements a sum reduction operation based on the underlying communication library.

Type: Synchronous.

## On Entry

icontxt the communication context identifying the virtual parallel machine.

Scope: **global**. Type: **required**.

Intent: in.

Specified as: an integer variable.

dat The local contribution to the global sum.

Scope: **global**. Type: **required**. Intent: **inout**.

Specified as: an integer, real or complex variable, which may be a scalar, or a rank 1 or 2 array. Type, kind, rank and size must agree on all processes.

**root** Process to hold the final sum, or -1 to make it available on all processes.

Scope: **global**. Type: **optional**.

Intent: in.

Specified as: an integer value  $-1 \le root \le np - 1$ , default -1.

#### On Return

dat On destination process(es), the result of the sum operation.

Scope: **global**. Type: **required**. Intent: **inout**.

Specified as: an integer, real or complex variable, which may be a scalar,

or a rank 1 or 2 array.

Type, kind, rank and size must agree on all processes.

- 1. The dat argument is both input and output, and its value may be changed even on processes different from the final result destination.
- 2. The dat argument may also be a long integer scalar.

# $psb_max - Global maximum$

```
call psb_max(icontxt, dat, root)
```

This subroutine implements a maximum valuereduction operation based on the underlying communication library.

Type: Synchronous.

# On Entry

icontxt the communication context identifying the virtual parallel machine.

Scope: **global**. Type: **required**.

Intent: in.

Specified as: an integer variable.

dat The local contribution to the global maximum.

Scope: local.
Type: required.
Intent: inout.

Specified as: an integer or real variable, which may be a scalar, or a rank 1 or 2 array. Type, kind, rank and size must agree on all processes.

**root** Process to hold the final maximum, or -1 to make it available on all pro-

cesses.

Scope: **global**. Type: **optional**. Intent: **in**.

Specified as: an integer value  $-1 \le root \le np - 1$ , default -1.

## On Return

dat On destination process(es), the result of the maximum operation.

Scope: **global**. Type: **required**.

Intent: in.

Specified as: an integer or real variable, which may be a scalar, or a rank 1 or 2 array. Type, kind, rank and size must agree on all processes.

- 1. The dat argument is both input and output, and its value may be changed even on processes different from the final result destination.
- 2. The dat argument may also be a long integer scalar.

# psb\_min — Global minimum

```
call psb_min(icontxt, dat, root)
```

This subroutine implements a minimum value reduction operation based on the underlying communication library.

Type: Synchronous.

## On Entry

icontxt the communication context identifying the virtual parallel machine.

Scope: **global**.

Type: **required**.

Intent: in.

Specified as: an integer variable.

dat The local contribution to the global minimum.

Scope: **local**. Type: **required**. Intent: **inout**.

Specified as: an integer or real variable, which may be a scalar, or a rank 1 or 2 array. Type, kind, rank and size must agree on all processes.

 ${f root}$  Process to hold the final value, or -1 to make it available on all processes.

Scope: global.
Type: optional.

Intent: in.

Specified as: an integer value  $-1 \le root \le np - 1$ , default -1.

#### On Return

dat On destination process(es), the result of the minimum operation.

Scope: **global**. Type: **required**. Intent: **inout**.

Specified as: an integer or real variable, which may be a scalar, or a rank

1 or 2 array.

Type, kind, rank and size must agree on all processes.

- 1. The dat argument is both input and output, and its value may be changed even on processes different from the final result destination.
- 2. The dat argument may also be a long integer scalar.

## psb\_amx — Global maximum absolute value

```
call psb_amx(icontxt, dat, root)
```

This subroutine implements a maximum absolute value reduction operation based on the underlying communication library.

Type: Synchronous.

## On Entry

icontxt the communication context identifying the virtual parallel machine.

Scope: global. Type: required.

Intent: in.

Specified as: an integer variable.

dat The local contribution to the global maximum.

Scope: local. Type: required. Intent: inout.

Specified as: an integer, real or complex variable, which may be a scalar, or a rank 1 or 2 array. Type, kind, rank and size must agree on all processes.

**root** Process to hold the final value, or -1 to make it available on all processes.

Scope: global. Type: optional. Intent: in.

Specified as: an integer value  $-1 \le root \le np - 1$ , default -1.

## On Return

dat On destination process(es), the result of the maximum operation.

Scope: global. Type: required. Intent: inout.

Specified as: an integer, real or complex variable, which may be a scalar, or a rank 1 or 2 array. Type, kind, rank and size must agree on all processes.

- 1. The dat argument is both input and output, and its value may be changed even on processes different from the final result destination.
- 2. The dat argument may also be a long integer scalar.

#### psb\_amn — Global minimum absolute value

call psb\_amn(icontxt, dat, root)

This subroutine implements a minimum absolute value reduction operation based on the underlying communication library.

Type: Synchronous.

#### On Entry

icontxt the communication context identifying the virtual parallel machine.

Scope: global. Type: required.

Intent: in.

Specified as: an integer variable.

dat The local contribution to the global minimum.

Scope: local. Type: required. Intent: inout.

Specified as: an integer, real or complex variable, which may be a scalar, Type, kind, rank and size must agree on all or a rank 1 or 2 array.

processes.

 ${f root}$  Process to hold the final value, or -1 to make it available on all processes.

Scope: global. Type: optional.

Intent: in.

Specified as: an integer value  $-1 \le root \le np - 1$ , default -1.

#### On Return

dat On destination process(es), the result of the minimum operation.

Scope: global. Type: required. Intent: inout.

Specified as: an integer, real or complex variable, which may be a scalar,

or a rank 1 or 2 array.

Type, kind, rank and size must agree on all processes.

### Notes

- 1. The dat argument is both input and output, and its value may be changed even on processes different from the final result destination.
- 2. The dat argument may also be a long integer scalar.

### psb\_snd — Send data

```
call psb_snd(icontxt, dat, dst, m)
```

This subroutine sends a packet of data to a destination.

Type: Synchronous: see usage notes.

### On Entry

**icontxt** the communication context identifying the virtual parallel machine.

Scope: **global**. Type: **required**. Intent: **in**.

Specified as: an integer variable.

dat The data to be sent.

Scope: local.
Type: required.
Intent: in.

Specified as: an integer, real or complex variable, which may be a scalar, or a rank 1 or 2 array, or a character or logical scalar. Type, kind and rank must agree on sender and receiver process; if m is not specified, size must agree as well.

dst Destination process.

Scope: **global**. Type: **required**. Intent: **in**.

Specified as: an integer value  $0 \le dst \le np - 1$ .

m Number of rows.

Scope: **global**. Type: **Optional**. Intent: **in**.

Specified as: an integer value  $0 \le m \le size(dat, 1)$ .

When dat is a rank 2 array, specifies the number of rows to be sent independently of the leading dimension size(dat, 1); must have the same value on sending and receiving processes.

#### On Return

#### Notes

1. This subroutine implies a synchronization, but only between the calling process and the destination process dst.

## psb\_rcv — Receive data

```
call psb_rcv(icontxt, dat, src, m)
```

This subroutine receives a packet of data to a destination.

Type: Synchronous: see usage notes.

#### On Entry

icontxt the communication context identifying the virtual parallel machine.

Scope: **global**. Type: **required**. Intent: **in**.

Specified as: an integer variable.

src Source process.

Scope: **global**. Type: **required**. Intent: **in**.

Specified as: an integer value  $0 \le src \le np - 1$ .

m Number of rows.

Scope: **global**.
Type: **Optional**.

Intent: in.

Specified as: an integer value  $0 \le m \le size(dat, 1)$ .

When dat is a rank 2 array, specifies the number of rows to be sent independently of the leading dimension size(dat, 1); must have the same value on sending and receiving processes.

#### On Return

dat The data to be received.

Scope: local.
Type: required.
Intent: inout.

Specified as: an integer, real or complex variable, which may be a scalar, or a rank 1 or 2 array, or a character or logical scalar. Type, kind and rank must agree on sender and receiver process; if m is not specified, size must agree as well.

#### Notes

1. This subroutine implies a synchronization, but only between the calling process and the source process src.

# 8 Error handling

The PSBLAS library error handling policy has been completely rewritten in version 2.0. The idea behind the design of this new error handling strategy is to keep error messages on a stack allowing the user to trace back up to the point where the first error message has been generated. Every routine in the PSBLAS-2.0 library has, as last non-optional argument, an integer info variable; whenever, inside the routine, an error is detected, this variable is set to a value corresponding to a specific error code. Then this error code is also pushed on the error stack and then either control is returned to the caller routine or the execution is aborted, depending on the users choice. At the time when the execution is aborted, an error message is printed on standard output with a level of verbosity than can be chosen by the user. If the execution is not aborted, then, the caller routine checks the value returned in the info variable and, if not zero, an error condition is raised. This process continues on all the levels of nested calls until the level where the user decides to abort the program execution.

Figure 8 shows the layout of a generic psb\_foo routine with respect to the PSBLAS-2.0 error handling policy. It is possible to see how, whenever an error condition is detected, the info variable is set to the corresponding error code which is, then, pushed on top of the stack by means of the psb\_errpush. An error condition may be directly detected inside a routine or indirectly checking the error code returned returned by a called routine. Whenever an error is encountered, after it has been pushed on stack, the program execution skips to a point where the error condition is handled; the error condition is handled either by returning control to the caller routine or by calling the psb\\_error routine which prints the content of the error stack and aborts the program execution, according to the choice made by the user with psb\_set\_erraction. The default is to print the error and terminate the program, but the user may choose to handle the error explicitly.

Figure 9 reports a sample error message generated by the PSBLAS-2.0 library. This error has been generated by the fact that the user has chosen the invalid "FOO" storage format to represent the sparse matrix. From this error message it is possible to see that the error has been detected inside the psb\_cest subroutine called by psb\_spasb ... by process 0 (i.e. the root process).

```
subroutine psb_foo(some args, info)
  if(error detected) then
      info=errcode1
      call psb_errpush('psb_foo', errcode1)
     goto 9999
  end if
  call psb_bar(some args, info)
  if(info .ne. zero) then
      info=errcode2
      call psb_errpush('psb_foo', errcode2)
      goto 9999
   end if
9999 continue
  if (err_act .eq. act_abort) then
    call psb_error(icontxt)
    return
   else
     return
   end if
end subroutine psb_foo
```

Figure 8: The layout of a generic psb\_foo routine with respect to PSBLAS-2.0 error handling policy.

Figure 9: A sample PSBLAS-2.0 error message. Process 0 detected an error condition inside the psb\_cest subroutine

# psb\_errpush — Pushes an error code onto the error stack

```
call psb_errpush(err_c, r_name, i_err, a_err)
```

**Type:** Asynchronous.

### On Entry

 $\mathbf{err}_{\mathbf{c}}$  the error code

Scope: local
Type: required
Intent: in.

Specified as: an integer.

r\_name the soutine where the error has been caught.

Scope: local
Type: required
Intent: in.

Specified as: a string.

 $i\_err$  addional info for error code

Scope: **local**Type: **optional** 

Specified as: an integer array

 $\mathbf{a}$ \_err addional info for error code

Scope: **local**Type: **optional**Specified as: a string.

# $psb\_error$ — Prints the error stack content and aborts execution

call psb\_error(icontxt)

Type: Asynchronous.

# On Entry

 ${\bf icontxt}$  the communication context.

Scope: **global**Type: **optional**Intent: **in**.

Specified as: an integer.

# $psb\_set\_errverbosity$ — Sets the verbosity of error messages.

call psb\_set\_errverbosity(v)

Type: Asynchronous.

# On Entry

v the verbosity levelScope: globalType: required

Intent: in.

Specified as: an integer.

# $psb\_set\_erraction$ — Set the type of action to be taken upon error condition.

# 9 Utilities

We have some utilities available for input and output of sparsematrices; the interfaces to these routines are available in the module psb\_util\_mod.

# hb\_read — Read a sparse matrix from a file in the Harwell–Boeing format

call hb\_read(a, iret, iunit, filename, b, mtitle)

Type: Asynchronous.

#### On Entry

filename The name of the file to be read.

Type:optional.

Specified as: a character variable containing a valid file name, or -, in which case the default input unit 5 (i.e. standard input in Unix jargon) is used. Default: -.

iunit The Fortran file unit number.

Type:optional.

Specified as: an integer value. Only meaningful if filename is not -.

#### On Return

a the sparse matrix read from file.

Type:required.

Specified as: a structured data of type psb\_spmat\_type.

**b** Rigth hand side(s).

Type: Optional

An array of type real or complex, rank 2 and having the ALLOCATABLE attribute; will be allocated and filled in if the input file contains a right hand side, otherwise will be left in the UNALLOCATED state.

mtitle Matrix title.

Type: Optional

A charachter variable of length 72 holding a copy of the matrix title as specified by the Harwell-Boeing format and contained in the input file.

iret Error code.

Type: required

# hb\_write — Write a sparse matrix to a file in the Harwell–Boeing format

call hb\_write(a, iret, iunit, filename, key, rhs, mtitle)

Type: Asynchronous.

#### On Entry

a the sparse matrix to be written.

Type:required.

Specified as: a structured data of type psb\_spmat\_type.

**b** Rigth hand side.

Type: Optional

An array of type real or complex, rank 1 and having the ALLOCATABLE attribute; will be allocated and filled in if the input file contains a right hand side.

filename The name of the file to be written to.

Type:**optional**.

Specified as: a character variable containing a valid file name, or -, in which case the default output unit 6 (i.e. standard output in Unix jargon) is used. Default: -.

iunit The Fortran file unit number.

Type:optional.

Specified as: an integer value. Only meaningful if filename is not -.

key Matrix key.

Type: Optional

A charachter variable of length 8 holding the matrix key as specified by the Harwell-Boeing format and to be written to file.

mtitle Matrix title.

Type: Optional

A charachter variable of length 72 holding the matrix title as specified by the Harwell-Boeing format and to be written to file.

#### On Return

iret Error code.

Type: required

# mm\_mat\_read — Read a sparse matrix from a file in the MatrixMarket format

call mm\_mat\_read(a, iret, iunit, filename)

**Type:** Asynchronous.

#### On Entry

filename The name of the file to be read.

Type:optional.

Specified as: a character variable containing a valid file name, or  $\neg$ , in which case the default input unit 5 (i.e. standard input in Unix jargon) is used. Default:  $\neg$ .

iunit The Fortran file unit number.

Type:optional.

Specified as: an integer value. Only meaningful if filename is not -.

#### On Return

a the sparse matrix read from file.

Type:required.

Specified as: a structured data of type psb\_spmat\_type.

iret Error code.

Type: required

# mm\_vet\_read — Read a dense vector from a file in the MatrixMarket format

call mm\_vet\_read(b, iret, iunit, filename)

Type: Asynchronous.

#### On Entry

filename The name of the file to be read.

Type:optional.

Specified as: a character variable containing a valid file name, or  $\neg$ , in which case the default input unit 5 (i.e. standard input in Unix jargon) is used. Default:  $\neg$ .

iunit The Fortran file unit number.

Type:optional.

Specified as: an integer value. Only meaningful if filename is not -.

#### On Return

**b** Rigth hand side(s).

Type: required

An array of type real or complex, rank 2 and having the ALLOCATABLE attribute; will be allocated and filled in if the input file contains a right hand side, otherwise will be left in the UNALLOCATED state.

iret Error code.

Type: required

# mm\_mat\_write — Write a sparse matrix to a file in the MatrixMarket format

call mm\_mat\_write(a, mtitle, iret, iunit, filename)

**Type:** Asynchronous.

#### On Entry

a the sparse matrix to be written.

Type:required.

Specified as: a structured data of type psb\_spmat\_type.

#### mtitle Matrix title.

Type: required

A charachter variable holding a descriptive title for the matrix to be written to file.

filename The name of the file to be written to.

Type:optional.

Specified as: a character variable containing a valid file name, or -, in which case the default output unit 6 (i.e. standard output in Unix jargon) is used. Default: -.

iunit The Fortran file unit number.

Type:optional.

Specified as: an integer value. Only meaningful if filename is not -.

## On Return

iret Error code.

Type: required

# 10 Preconditioner routines

- Diagonal Scaling
- $\bullet$  Block Jacobi with ILU(0) factorization

The supporting data type and subroutine interfaces are defined in the module  ${\tt psb\_prec\_mod}$ .

# psb\_precinit — Initialize a preconditioner

call psb\_precinit(prec, ptype, info)

**Type:** Asynchronous.

### On Entry

ptype the type of preconditioner. Scope: global

Type: **required** Intent: **in**.

Specified as: a character string, see usage notes.

#### On Exit

prec Scope: local
Type: required
Intent: inout.

Specified as: a preconditioner data structure psb\_prec\_type.

info Scope: global
Type: required
Intent: out.

Error code: if no error, 0 is returned.

**Notes** Legal inputs to this subroutine are interpreted depending on the *ptype* string as follows<sup>3</sup>:

**NONE** No preconditioning, i.e. the preconditioner is just a copy operator.

- **DIAG** Diagonal scaling; each entry of the input vector is multiplied by the reciprocal of the sum of the absolute values of the coefficients in the corresponding row of matrix A;
- **BJAC** Precondition by a factorization of the block-diagonal of matrix A, where block boundaries are determined by the data allocation boundaries for each process; requires no communication. Only the incomplete factorization ILU(0) is currently implemented.

<sup>&</sup>lt;sup>3</sup>The string is case-insensitive

# psb\_precbld — Builds a preconditioner

```
call psb_precbld(a, desc_a, prec, info)
```

Type: Synchronous.

#### On Entry

a the system sparse matrix. Scope: local

Type: **required**Intent: **in**, target.

Specified as: a sparse matrix data structure psb\_spmat\_type.

**prec** the preconditioner.

Scope: **local**Type: **required**Intent: **inout**.

Specified as: an already initialized precondtioner data structure psb\_prec\_type

desc\_a the problem communication descriptor. Scope: local

Type: **required**Intent: **in**, target.

Specified as: a communication descriptor data structure psb\_desc\_type.

# On Return

 ${\bf prec}\;$  the preconditioner.

Scope: local Type: required Intent: inout.

Specified as: a precondtioner data structure psb\_prec\_type

info Error code.

Scope: local Type: required Intent: out.

### psb\_precaply — Preconditioner application routine

call psb\_precaply(prec,x,y,desc\_a,info,trans,work)
call psb\_precaply(prec,x,desc\_a,info,trans)

Type: Synchronous.

#### On Entry

prec the preconditioner. Scope: local

Type: **required** Intent: **in**.

Specified as: a preconditioner data structure psb\_prec\_type.

 $\mathbf{x}$  the source vector. Scope: local

Type: **required** Intent: **inout**.

Specified as: a double precision array.

 $\mathbf{desc\_a}$  the problem communication descriptor. Scope:  $\mathbf{local}$ 

Type: required Intent: in.

Specified as: a communication data structure psb\_desc\_type.

# trans Scope:

Type: **optional** Intent: **in**.

Specified as: a character.

work an optional work space Scope: local

Type: **optional** Intent: **inout**.

Specified as: a double precision array.

### On Return

y the destination vector. Scope: local

Type: **required** Intent: **inout**.

Specified as: a double precision array.

info Error code.

Scope: local Type: required Intent: out.

# $psb\_precdescr$ — Prints a description of current preconditioner

```
call psb_precdescr(prec)
call psb_precdescr(prec, iout)
```

Type: Asynchronous.

### On Entry

 $\mathbf{prec}\,$  the preconditioner. Scope:  $\mathbf{local}\,$ 

Type: **required** Intent: **in**.

Specified as: a preconditioner data structure psb\_prec\_type.

iout output unit. Scope: local

Type: **optiona** Intent: **in**.

Specified as: an integer number.

# 11 Iterative Methods

In this chapter we provide routines for preconditioners and iterative methods. The interfaces for Krylov subspace methods are available in the module psb\_krylov\_mod.

### psb\_krylov — Krylov Methods Driver Routine

This subroutine is a driver that provides a general interface for all the Krylov-Subspace family methods implemented in PSBLAS version 2.

The stopping criterion is the normwise backward error, in the infinity norm, i.e. the iteration is stopped when

$$err = \frac{||r_i||}{(||A|| ||x_i|| + ||b||)} < eps$$

or the 2-norm residual reduction

$$err = \frac{\|r_i\|}{\|b\|_2} < eps$$

according to the value passed through the istop argument (see later). In the above formulae,  $x_i$  is the tentative solution and  $r_i = b - Ax_i$  the corresponding residual at the *i*-th iteration.

Type: Synchronous.

On Entry

**method** a string that defines the iterative method to be used. Supported values are:

**CG:** the Conjugate Gradient method;

**CGS:** the Conjugate Gradient Stabilized method;

**BICG:** the Bi-Conjugate Gradient method;

BICGSTAB: the Bi-Conjugate Gradient Stabilized method;

**BICGSTABL:** the Bi-Conjugate Gradient Stabilized method with restarting;

**RGMRES:** the Generalized Minimal Residual method with restarting.

**a** the local portion of global sparse matrix A.

Scope: local
Type: required
Intent: in.

Specified as: a structured data of type psb\_spmat\_type.

**prec** The data structure containing the preconditioner.

Scope: **local**Type: **required**Intent: **in**.

Specified as: a structured data of type  ${\tt psb\_prec\_type}.$ 

**b** The RHS vector.

Scope: local
Type: required
Intent: in.

Specified as: a rank one array.

 $\mathbf{x}$  The initial guess.

Scope: local
Type: required
Intent: inout.

Specified as: a rank one array.

**eps** The stopping tolerance.

Scope: **global**Type: **required**Intent: **in**.

Specified as: a real number.

desc\_a contains data structures for communications.

Scope: local
Type: required
Intent: in.

Specified as: a structured data of type psb\_desc\_type.

itmax The maximum number of iterations to perform.

Scope: **global**Type: **optional**Intent: **in**.

Default: itmax = 1000.

Specified as: an integer variable  $itmax \ge 1$ .

itrace If > 0 print out an informational message about convergence every itrace

iterations.
Scope: global
Type: optional
Intent: in.

irst An integer specifying the restart parameter.

Scope: **global**Type: **optional**.
Intent: **in**.

Values: irst > 0. This is employed for the BiCGSTABL or RGMRES

methods, otherwise it is ignored.

**istop** An integer specifying the stopping criterion.

Scope: **global**Type: **optional**.
Intent: **in**.

Values: 1: use the normwise backward error, 2: use the scaled 2-norm of

the residual. Default: 2.

#### On Return

 $\mathbf{x}$  The computed solution.

Scope: local
Type: required
Intent: inout.

Specified as: a rank one array.

iter The number of iterations performed.

Scope: **global**Type: **optional**Intent: **out**.

Returned as: an integer variable.

**err** The convergence estimate on exit.

Scope: **global**Type: **optional**Intent: **out**.

Returned as: a real number.

**cond** An estimate of the condition number of matrix A; only available with the

CG method. Scope: global Type: optional Intent: out.

Returned as: a real number.

info Error code.

Scope: local
Type: required
Intent: out.

# References

- [1] G. Bella, S. Filippone, A. De Maio and M. Testa, A Simulation Model for Forest Fires, in J. Dongarra, K. Madsen, J. Wasniewski, editors, Proceedings of PARA 04 Workshop on State of the Art in Scientific Computing, pp. 546–553, Lecture Notes in Computer Science, Springer, 2005.
- [2] A. Buttari, D. di Serafino, P. D'Ambra, S. Filippone, 2LEV-D2P4: a package of high-performance preconditioners, Applicable Algebra in Engineering, Communications and Computing, Volume 18, Number 3, May, 2007, pp. 223-239
- [3] P. D'Ambra, S. Filippone, D. Di Serafino On the Development of PSBLAS-based Parallel Two-level Schwarz Preconditioners Applied Numerical Mathematics, Elsevier Science, Volume 57, Issues 11-12, November-December 2007, Pages 1181-1196.
- [4] Dongarra, J. J., DuCroz, J., Hammarling, S. and Hanson, R., An Extended Set of Fortran Basic Linear Algebra Subprograms, ACM Trans. Math. Softw. vol. 14, 1–17, 1988.
- [5] Dongarra, J., DuCroz, J., Hammarling, S. and Duff, I., A Set of level 3 Basic Linear Algebra Subprograms, ACM Trans. Math. Softw. vol. 16, 1– 17, 1990.
- [6] J. J. Dongarra and R. C. Whaley, A User's Guide to the BLACS v. 1.1, Lapack Working Note 94, Tech. Rep. UT-CS-95-281, University of Tennessee, March 1995 (updated May 1997).
- [7] I. Duff, M. Marrone, G. Radicati and C. Vittoli, Level 3 Basic Linear Algebra Subprograms for Sparse Matrices: a User Level Interface, ACM Transactions on Mathematical Software, 23(3), pp. 379-401, 1997.
- [8] I. Duff, M. Heroux and R. Pozo, An Overview of the Sparse Basic Linear Algebra Subprograms: the New Standard from the BLAS Technical Forum, ACM Transactions on Mathematical Software, 28(2), pp. 239–267, 2002.
- [9] S. Filippone and M. Colajanni, *PSBLAS: A Library for Parallel Linear Algebra Computation on Sparse Matrices*, ACM Transactions on Mathematical Software, 26(4), pp. 527–550, 2000.
- [10] S. Filippone, P. D'Ambra, M. Colajanni, Using a Parallel Library of Sparse Linear Algebra in a Fluid Dynamics Applications Code on Linux Clusters, in G. Joubert, A. Murli, F. Peters, M. Vanneschi, editors, Parallel Computing - Advances & Current Issues, pp. 441–448, Imperial College Press, 2002.
- [11] Karypis, G. and Kumar, V., METIS: Unstructured Graph Partitioning and Sparse Matrix Ordering System. Minneapolis, MN 55455: University of Minnesota, Department of Computer Science, 1995. Internet Address: http://www.cs.umn.edu/~karypis.
- [12] Lawson, C., Hanson, R., Kincaid, D. and Krogh, F., Basic Linear Algebra Subprograms for Fortran usage, ACM Trans. Math. Softw. vol. 5, 38–329, 1979.

- [13] Machiels, L. and Deville, M. Fortran 90: An entry to object-oriented programming for the solution of partial differential equations. ACM Trans. Math. Softw. vol. 23, 32–49.
- [14] Metcalf, M., Reid, J. and Cohen, M. Fortran 95/2003 explained. Oxford University Press, 2004.
- [15] M. Snir, S. Otto, S. Huss-Lederman, D. Walker and J. Dongarra, *MPI: The Complete Reference. Volume 1 The MPI Core*, second edition, MIT Press, 1998.