The Design and Implementation of *hypre*, a Library of Parallel High Performance Preconditioners

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Summary. The *hypre* software library provides high performance preconditioners and solvers for the solution of large, sparse linear systems on massively parallel computers. One of its attractive features is the provision of *conceptual interfaces*. These interfaces give application users a more natural means for describing their linear systems, and provide access to methods such as geometric multigrid which require additional information beyond just the matrix. This chapter discusses the design of the conceptual interfaces in *hypre* and illustrates their use with various examples. We discuss the data structures and parallel implementation of these interfaces. A brief overview of the solvers and preconditioners available through the interfaces is also given.

1 Introduction

The increasing demands of computationally challenging applications and the advance of larger more powerful computers with more complicated architectures have necessitated the development of new solvers and preconditioners. Since the implementation of these methods is quite complex, the use of high performance libraries with the newest efficient solvers and preconditioners becomes more important for promulgating their use into applications with relative ease.

The *hypre* library [16, 21] has been designed with the primary goal of providing users with advanced scalable parallel preconditioners. Multigrid preconditioners are a major focus of the library. Issues of robustness, ease of use, flexibility and interoperability have also been important. It can be used both as a solver package and as a framework for algorithm development. Its object model is more general and flexible than most current generation solver libraries [10]. The *hypre* library also provides several of the most commonly used solvers, such as conjugate gradient for symmetric systems or GMRES

for nonsymmetric systems to be used in conjunction with the preconditioners. The code is open source and available for download from the web [21].

A unique and important design innovation in *hypre* is the notion of *conceptual (linear system) interfaces*. These interfaces make it possible to provide an array of powerful solvers that have largely not been available before in linear solver library form. By allowing users to access *hypre* in the way they naturally think about their problems, these interfaces ease the coding burden and provide extra application information required by certain solvers. For example, application developers that use structured grids typically think of their linear systems in terms of stencils and grids, so an interface that involves stencils and grids is more natural. Such an interface also makes it possible to supply solvers like geometric multigrid that take advantage of structure. In addition, the use of a particular conceptual interface does not preclude users from building more general sparse matrix structures (e.g., compressed sparse row) and using more traditional solvers (e.g., incomplete LU factorization) that do not use the additional application information. In fact, the construction of different underlying data structures is done internally by *hypre* and requires almost no changes to user code. The conceptual interfaces currently implemented include stencil-based structured and semi-structured interfaces, a finite-element based unstructured interface, and a traditional linear-algebra based interface.

The primary focus of this paper is on the design and implementation of the conceptual interfaces in *hypre*. The paper is organized as follows. The first two sections are of general interest. We begin in Section 2 with an introductory discussion of conceptual interfaces and point out the advantages of matching the linear solver interface with the natural concepts (grids, stencils, elements, etc.) used in the application code discretization. In Section 3, we discuss *hypre*'s object model, which is built largely around the notion of an operator. Sections 4 through 7 discuss specific conceptual interfaces available in *hypre* and include various examples illustrating their use. These sections are intended to give application programmers an overview of each specific conceptual interface. We then discuss some implementation issues in Section 8. This section may be of interest to application programmers, or more likely, others interested in linear solver code development on large scale parallel computers. The next two sections are aimed at application programmers potentially interested in using *hypre*. Section 9 gives a brief overview of the solvers and preconditioners currently available in *hypre*, and Section 10 contains additional information on how to obtain and build the library. The paper concludes with some comments on future plans to enhance the library.

2 Conceptual Interfaces

Each application to be implemented lends itself to natural ways of thinking of the problem. If the application uses structured grids, a natural way of formu-

lating it would be in terms of grids and stencils, whereas for an application that uses unstructured grids and finite elements it is more natural to access the preconditioners and solvers via elements and element stiffness matrices. Consequently, the provision of different conceptual views of the problem being solved (*hypre*'s so-called conceptual interfaces) facilitates the use of the library.

Conceptual interfaces also decrease the coding burden for users. The most common interface used in linear solver libraries today is a linear-algebraic one. This interface requires that the user compute the mapping of their discretization to row-column entries in a matrix. This code can be quite complex; for example, consider the problem of ordering the equations and unknowns on the composite grids used in structured AMR codes. The use of a conceptual interface merely requires the user to input the information that defines the problem to be solved, leaving the forming of the actual linear system as a library implementation detail hidden from the user.

Another reason for conceptual interfaces—maybe the most compelling one—is that they provide access to a large array of powerful scalable linear solvers that need the extra application information beyond just the matrix. For example, geometric multigrid (GMG) cannot be used through a linear-algebraic interface, since it is formulated in terms of grids. Similarly, in many cases, these interfaces allow the use of other data storage schemes with less memory overhead and provide for more efficient computational kernels.

Figure 1 illustrates the idea behind conceptual interfaces (note that the figure is not intended to represent the current state within *hypre*, although it is highly representative). The level of generality increases from left to right. On the left are specific interfaces with algorithms and data structures that take advantage of more specific information. On the right are more general interfaces, algorithms and data structures. Note that the more specific interfaces also give users access to general solvers like algebraic multigrid (AMG) or incomplete LU factorization (ILU). The top row shows various concepts: structured grids, composite grids, unstructured grids, or just matrices. In the second row, various solvers and preconditioners are listed. Each of these requires different information from the user, which is provided through the conceptual interfaces. For example, GMG needs a structured grid and can only be used with the leftmost interface. AMGe [5], an algebraic multigrid method, needs finite element information, whereas general solvers can be used with any interface.

The bottom row contains a list of data layouts or matrix-vector storage schemes that can be used for the implementation of the various algorithms. The relationship between linear solver and storage scheme is similar to that of interface and linear solver. One minor difference, however, is that solvers can appear more than once. Consider ILU, for example. It is easy to imagine implementing ILU in terms of a structured-grid data layout. In the figure, such a solver would appear in the leftmost box (with the GMG solver) since it requires information about the structure in the linear system.
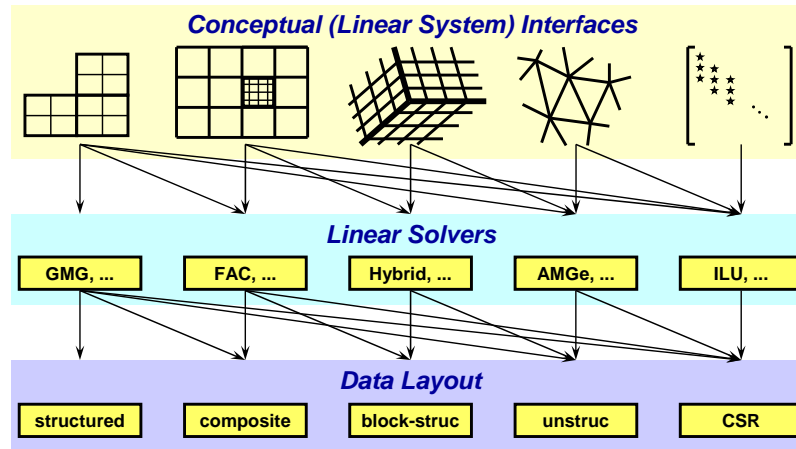
Fig. 1. Graphic illustrating the notion of conceptual interfaces.

In *hypre*, four conceptual interfaces are currently supported: a structured-grid interface, a semi-structured-grid interface, a finite-element interface, and a linear-algebraic interface. For the purposes of this paper, we will refer to these interfaces by the names `Struct`, `semiStruct`, `FEI`, and `IJ`, respectively; the actual names of the interfaces in *hypre* are slightly different. Similarly, when interface routines are discussed below, we will not strictly adhere to the prototypes in *hypre*, as these prototypes may change slightly in the future in response to user needs. Instead, we will focus on the basic design components and basic use of the interfaces, and refer the reader to the *hypre* documentation [21] for current details.

Users of *hypre* only need to use one conceptual interface in their application code. The best choice of interface depends on the application, but it is usually better to use a more specific one that utilizes as much application information as possible (e.g., something further to the left in Figure 1). Access to more general solvers and data structures are still possible and require almost no changes to the user code. Note, finally, that *hypre* does not determine the parallel partitioning of the problem, but builds the internal parallel data structures (often quite complicated) according to the partitioning provided by the user.

3 Object Model

In this section, we discuss the basic object model for *hypre*, illustrated in Figure 2. This model has evolved since the version presented in [10], but the core design ideas have persisted. We will focus here on the primary components of the *hypre* model, but encourage the reader to see [10] for a discussion of other useful design ideas also utilized in the library.

Note that, although *hypre* uses object-oriented (OO) principles in its design, the library is actually written in C, which is not an object-oriented language (the PETSc library [3, 4, 25] employs a similar approach). The library also provides an interface for Fortran, still another non-OO language. In addition, the next generation of interfaces in *hypre* are being developed through a tool called Babel [2], which makes it possible to generate interfaces automatically for a wide variety of languages (e.g., C, C++, Fortran77, Fortran90, Python, and Java) and provides support for important OO concepts such as polymorphism. An object model such as the one in Figure 2 is critical to the use of such a tool.
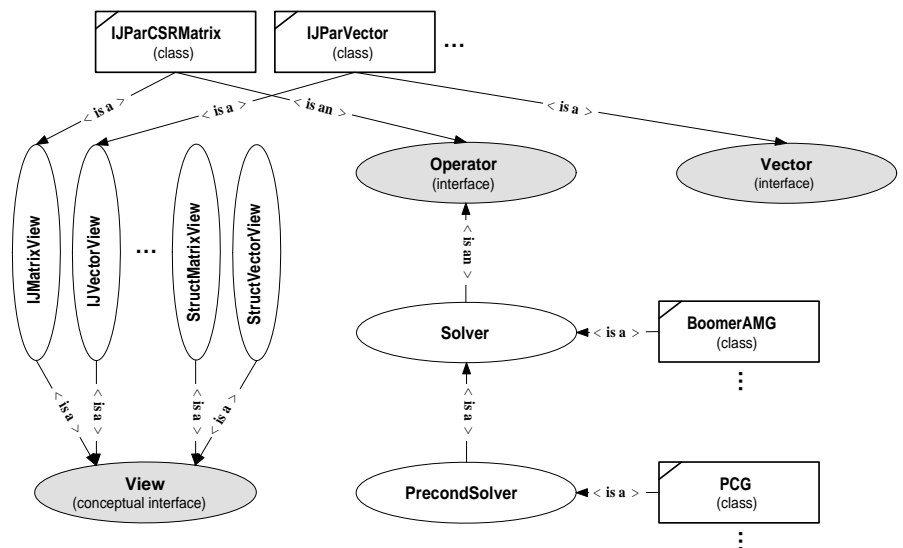

Fig. 2. Illustration of the *hypre* object model. Ovals represent abstract interfaces and rectangles are concrete classes. The `View` interface encapsulates the conceptual interface idea described in Section 2.

Central to the design of *hypre* is the use of multiple inheritance of interfaces. An *interface* is simply a collection of routines that can be invoked on an object, e.g., a matrix-vector multiply routine (for readers familiar with OO languages, the term interface is the same as in Java, and the same as an abstract base class in C++). The base interfaces in the *hypre* model are: `View`, `Operator`, and `Vector` (note that we use slightly different names here than those used in the *hypre* library). The `View` interface represents the notion of a conceptual interface as described in Section 2. This interface serves as our means of looking at (i.e., "viewing") the data in matrix and vector objects. Specific views such as `IJMatrixView` are inherited from, or *extend*, the base

interface. That is, `IJMatrixView` contains the routines in `View`, plus routines specific to its linear-algebraic way of looking at the data.

The `Vector` interface is fairly standard across most linear solver libraries. It consists of basic routines such as `Dot()` (vector inner product) and `Axpy()` (vector addition).

The `Operator` interface represents the general notion of operating on vectors to produce an output vector, and primarily consists of the routine `Apply()`. As such, it unifies many of the more common mathematical objects used in linear (and even nonlinear) solver libraries, such as matrices, preconditioners, iterative methods, and direct methods. The `Solver` and `PrecondSolver` interfaces are extensions of the `Operator` interface. Here, `Apply()` denotes the action of solving the linear system, i.e., the action of "applying" the solution operator to the right-hand-side vector. The two solver interfaces contain a number of additional routines that are common to iterative methods, such as `SetTolerance()` and `GetNumIterations()`. But, the main extension is the addition of the `SetOperator()` routine, which defines the operator in the linear system to be solved. The `PrecondSolver` extends the `Operator` interface further with the addition of the `SetPreconditioner()` routine.

One novel feature of the *hypre* object model is the extensive use of the `Operator` interface. In particular, note that both `Solver` and `PrecondSolver` are also `Operator` interfaces. Furthermore, the `SetOperator()` interface routine takes as input an object of type `Operator`, and the `SetPreconditioner()` routine takes as input an object of type `Solver` (an `Operator`). The latter fact is of interest. In *hypre*, there is currently no specific preconditioner type. Instead, preconditioning is considered to be a *role* played by solvers. The ability to use solvers for preconditioning is available in many other packages, but most employ additional design constructs to achieve this. For example, the linear algebra part of the Diffpack package [26, 27] utilizes a special class that bridges solvers and preconditioners.

Another fundamental design feature in the *hypre* library is the separation of the `View` and `Operator` interfaces in matrix classes such as `IJParCSRMatrix`. In this particular class, both interfaces are present, and the underlying data storage is a parallel compressed sparse row format. This format is required in solvers like BoomerAMG. However, the inherited `IJMatrixView` interface is generic, which allows users to write generic code for constructing matrices. As a result, the underlying storage format can be changed (giving access to potentially different solvers) by modifying only one or two lines of code.

The separation of the `View` and `Operator` interfaces also makes it possible for objects to support one functionality without supporting the other. The classic example is the so-called matrix-free linear operator (or matrix-free preconditioner), which is an object that performs matrix-vector multiplication, but does not offer access to the coefficients of the matrix. This has proven to be a useful technique in many practical situations.

For the OO-aware reader and users of *hypre*, we comment that Figure 2 is an accurate model for the current Babel interface in *hypre*, but it is not fully reflective of the native C interface. In particular, much of the polymorphism in the model is currently not implemented. Also, the native `View` interface follows the "Builder" design pattern discussed in [19] instead of the model in the figure, but the difference is trivial in practice. Finally, we remark that since *hypre* is moving toward using Babel for all of its interfaces in the future, the so-called native C interface mentioned here (and its shortcomings) will soon be moot.

4 The Structured-Grid Interface (`Struct`)

The `Struct` interface is appropriate for scalar applications on structured grids with a fixed stencil pattern of nonzeros at each grid point. It provides access to *hypre*'s most efficient scalable solvers for scalar structured-grid applications, the geometric multigrid methods SMG and PFMG. The user defines the *grid* and the *stencil*; the matrix and right-hand-side vector are then defined in terms of the grid and the stencil.

The `Struct` grid is described via a global d-dimensional *index space*, i.e. via integer singles in 1D, tuples in 2D, or triples in 3D (the integers may have any value, positive or negative). The global indices are used to discern how data is related spatially, and how it is distributed across the parallel machine. The basic component of the grid is a *box*: a collection of abstract cell-centered indices in index space, described by its "lower" and "upper" corner indices (see Figure 3). The scalar grid data is always associated with cell centers, unlike the more general `semiStruct` interface which allows data to be associated with box indices in several different ways. Each process describes the portion of the grid that it "owns", one box at a time. Note that it is assumed that the data has already been distributed, and that it is handed to the library in this distributed form.

The stencil is described by an array of integer indices, each representing a relative offset (in index space) from some gridpoint on the grid. For example, the geometry of the standard 5-pt stencil can be represented in the following way:

$$\begin{bmatrix} & (0,1) & \\ (-1,0) & (0,0) & (1,0) \\ & (0,-1) & \end{bmatrix}. \tag{1}$$

After the grid and stencil are defined, the matrix coefficients are set using the `MatrixSetBoxValues()` routine with the following arguments: a box specifying where on the grid the stencil coefficients are to be set; a list of stencil entries indicating which coefficients are to be set (e.g., the "center", "south", and "north" entries of the 5-point stencil above); and the actual coefficient values.
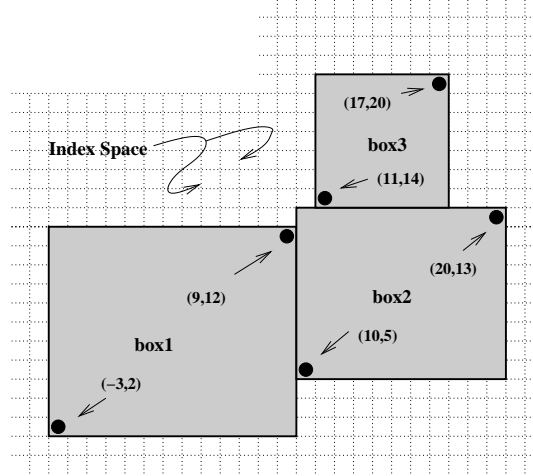
Fig. 3. A box is a collection of abstract cell-centered indices, described by its minimum and maximum indices. Here, three boxes are illustrated.

5 The Semi-Structured-Grid Interface (`semiStruct`)

The `semiStruct` interface is appropriate for applications with grids that are mostly—but not entirely—structured, e.g. block-structured grids, composite grids in structured AMR applications, and overset grids. In addition, it supports more general PDEs than the `Struct` interface by allowing multiple variables (system PDEs) and multiple variable types (e.g. cell-centered, face-centered, etc.). The interface provides access to data structures and linear solvers in *hypre* that are designed for semi-structured grid problems, but also to the most general data structures and solvers.

The `semiStruct` grid is composed out of a number of structured grid *parts*, where the physical inter-relationship between the parts is arbitrary. Each part is constructed out of two basic components: boxes (see Section 4) and *variables*. Variables represent the actual unknown quantities in the grid, and are associated with the box indices in a variety of ways, depending on their types. In *hypre*, variables may be cell-centered, node-centered, face-centered, or edge-centered. Face-centered variables are split into x-face, y-face, and z-face, and edge-centered variables are split into x-edge, y-edge, and z-edge. See Figure 4 for an illustration in 2D.

The `semiStruct` interface uses a *graph* to allow nearly arbitrary relationships between part data. The graph is constructed from stencils plus some additional data-coupling information set by the `GraphAddEntries()` routine. Another method for relating part data is the `GridSetNeighborbox()` routine, which is particularly suited for block-structured grid problems. Several examples are given in the following sections to illustrate these concepts.
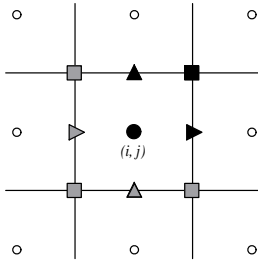
Fig. 4. Grid variables in *hypre* are referenced by the abstract cell-centered index to the left and down in 2D (and analogously in 3D). So, in the figure, index (i, j) is used to reference the variables in black. The variables in grey, although contained in the pictured cell, are not referenced by the (i, j) index.

5.1 Block-Structured Grids

In this section, we describe how to use the `semiStruct` interface to define block-structured grid problems. We will do this primarily by example, paying particular attention to the construction of stencils and the use of the `GridSetNeighborbox()` interface routine.

Consider the solution of the diffusion equation

$$-\nabla \cdot (D\nabla u) + \sigma u = f \tag{2}$$

on the block-structured grid in Figure 5, where D is a scalar diffusion coefficient, and $\sigma \geq 0$. The discretization [29] introduces three different types of variables: cell-centered, x-face, and y-face. The three discretization stencils that couple these variables are given in Figure 6. The information in these two figures is essentially all that is needed to describe the nonzero structure of the linear system we wish to solve. Traditional linear solver interfaces require that this information first be translated to row-column entries of a matrix by defining a global ordering of the unknowns. This translation process can be quite complicated, especially in parallel. For example, face-centered variables on block boundaries are often replicated on two different processes, but they should only be counted once in the global ordering. In contrast, the `semiStruct` interface enables the description of block-structured grid problems in a way that is much more natural.

Two primary steps are involved for describing the above problem: defining the grid (and its associated variables) in Figure 5, and defining the stencils in Figure 6. The grid is defined in terms of five separate logically-rectangular parts as shown in Figure 7, and each part is given a unique label between 0 and 4. Each part consists of a single box with lower index $(1, 1)$ and upper index $(4, 4)$ (see Section 4), and the grid data is distributed on five processes such that data associated with part p lives on process p. Note that in general, parts may be composed out of arbitrary unions of boxes, and indices may consist of
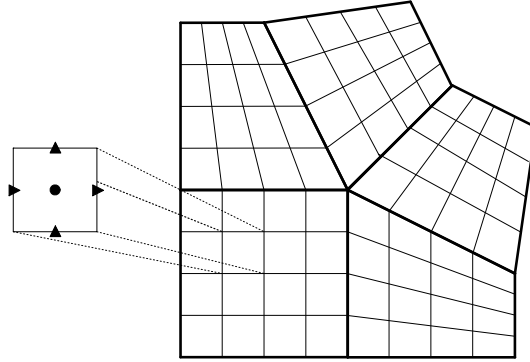
Fig. 5. Block-structured grid example with five logically-rectangular blocks and three variables types: cell-centered, x-face, and y-face.
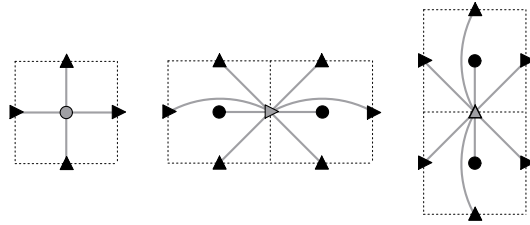

Fig. 6. Discretization stencils for the cell-centered (left), x-face (middle), and y-face (right) variables for the block-structured grid example in Figure 5.

non-positive integers (see Figure 3). Also note that the `semiStruct` interface expects a domain-based data distribution by boxes, but the actual distribution is determined by the user and simply described (in parallel) through the interface.

For simplicity, we restrict our attention to the interface calls made by process 3. Each process describes through the interface only the grid data that it owns, so process 3 needs to describe the data pictured in Figure 8. That is, it describes part 3 plus some additional neighbor information that ties part 3 together with the rest of the grid. To do this, the `GridSetExtents()` routine is first called, passing it the lower and upper indices on part 3, $(1,1)$ and $(4,4)$. Next, the `GridSetVariables()` routine is called, passing it the three variable types on part 3: cell-centered, x-face, and y-face.

At this stage, the description of the data on part 3 is complete. However, the spatial relationship between this data and the data on neighboring parts is not yet defined. To do this, we need to relate the index space for part 3 with the index spaces of parts 2 and 4. More specifically, we need to tell the interface that the two grey boxes neighboring part 3 in Figure 8 also correspond to boxes on parts 2 and 4. To do this, two calls are made to the `GridSetNeighborbox()` routine. With this additional neighbor informa-
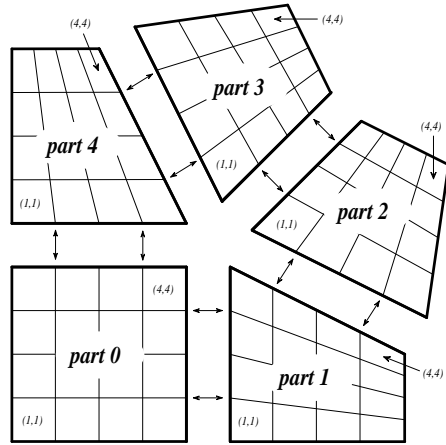
Fig. 7. Assignment of parts and indices to the block-structured grid example in Figure 5. In this example, the data for part p lives on process p.
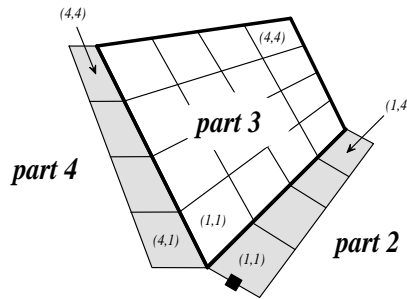

Fig. 8. Grid information given to the `semiStruct` interface by process 3 for the example in Figure 5. The shaded boxes are used to relate part 3 to parts 2 and 4.

tion, it is possible to determine where off-part stencil entries couple. Take, for example, any shared part boundary such as the boundary between parts 2 and 3. Along these boundaries, some stencil entries reach outside of the part. If no neighbor information is given, these entries are effectively zeroed out, i.e., they don't participate in the discretization. However, with the additional neighbor information, when a stencil entry reaches into a neighbor box it is then coupled to the part described by that neighbor box information.

An important consequence of the use of the `GridSetNeighborbox()` routine is that it can declare variables on different parts as being the same. For example, consider the highlighted face variable at the bottom of Figure 8. This is a single variable that lives on both part 2 and part 1. Note that process 3 cannot make this determination based solely on the information in the figure; it must use additional information on other processes. Also note that a variable may be of different types on different parts. Take for example the

face variables on the boundary of parts 2 and 3. On part 2 they are x-face variables, but on part 3 they are y-face variables.

The grid is now complete and all that remains to be done is to describe the stencils in Figure 6. For brevity, we consider only the description of the y-face stencil, i.e. the third stencil in the figure. To do this, the stencil entries are assigned unique labels between 0 and 8 and their "geometries" are described relative to the "center" of the stencil. This process is illustrated in Figure 9. Nine calls are made to the routine `StencilSetEntry()`. As an example, the call that describes stencil entry 5 in the figure is given the entry number 5, the offset $(-1, 0)$, and the identifier for the x-face variable (the variable to which this entry couples). Recall from Figure 4 the convention used for referencing variables of different types. The geometry description uses the same convention, but with indices numbered relative to the referencing index $(0, 0)$ for the stencil's center.
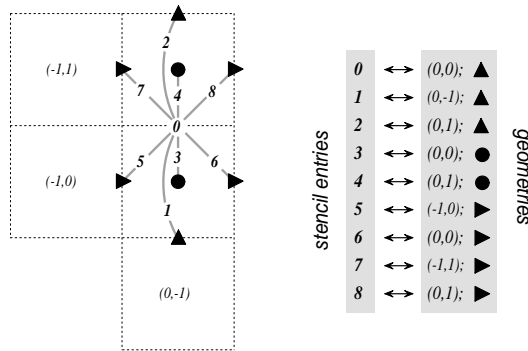

Fig. 9. Assignment of labels and geometries to the y-face stencil in Figure 6. Stencil geometries are described relative to the $(0, 0)$ index for the "center" of the stencil. The $(0, 0)$ index is located at the center of the cell just above the cell marked $(0, -1)$.

With the above, we now have a complete description of the nonzero structure for the matrix. The matrix coefficients are then easily set using the `MatrixSetValues()` routine in a manner similar to what is described in Sections 4 and 5.2. See the *hypre* documentation [21] for details.

An alternative approach for describing the above problem through the interface is to use the `GraphAddEntries()` routine. In this approach, the five parts are explicitly "sewn" together by adding non-stencil couplings to the matrix graph (see Section 5.2 for more information on the use of this routine). The main downside to this approach for block-structured grid problems is that variables along block boundaries are no longer considered to be the same variables on the corresponding parts that share these boundaries. For example, the face variable at the bottom of Figure 8 would now represent two different variables that live on different parts. To "sew" the parts together cor-

rectly, we need to explicitly select one of these variables as the representative that participates in the discretization, and make the other variable a dummy variable that is decoupled from the discretization by zeroing out appropriate entries in the matrix.

5.2 Structured Adaptive Mesh Refinement

We now briefly discuss how to use the `semiStruct` interface in a structured AMR application. Consider Poisson's equation on the simple cell-centered example grid illustrated in Figure 10. For structured AMR applications, each refinement level should be defined as a unique part. There are two parts in this example: part 0 is the global coarse grid and part 1 is the single refinement patch. Note that the coarse unknowns underneath the refinement patch (gray dots in Figure 10) are not real physical unknowns; the solution in this region is given by the values on the refinement patch. In setting up the composite grid matrix [28] for *hypre* the equations for these "dummy" unknowns should be uncoupled from the other unknowns (this can easily be done by setting all off-diagonal couplings to zero in this region).
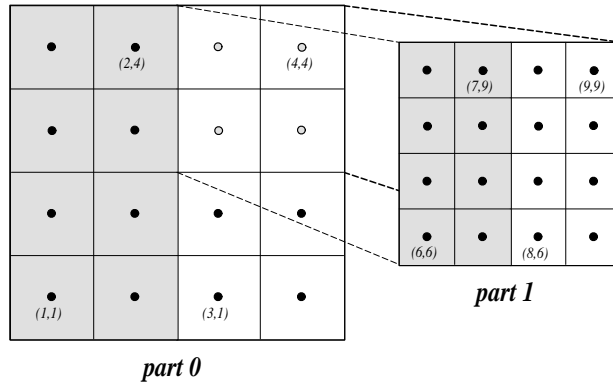

Fig. 10. Structured AMR grid example with one refinement patch (part 1) in the upper-right quadrant of the coarse grid (part 0). Shaded regions correspond to process 0, unshaded to process 1. The grey dots are dummy variables.

In the example, parts are distributed across the same two processes with process 0 having the "left" half of both parts. For simplicity, we discuss the calls made by process 0 to set up the composite grid matrix. First to set up the *grid*, process 0 will make `GridSetVariables()` calls to set the one variable type, cell-centered, and will make `GridSetExtents()` calls to identify the portion of the grid it owns for each part: *part 0*, $(1,1) \times (2,4)$; *part 1*, $(6,6) \times (7,9)$. Recall that there is no rule relating the indexing of different parts. Also note that there is no way to define hierarchies in the interface. In

hypre, this additional information is passed directly into the solvers that need it, e.g., in the Fast Adaptive Composite Grid method (FAC).

Next, the *stencil* is set up. In this example we are using a finite volume approach resulting in the standard 5-point stencil (1) in both parts.

The grid and stencil are used to define all intra-part coupling in the graph, the non-zero pattern of the composite grid matrix. The inter-part coupling at the coarse-fine interface is described by `GraphAddEntries()` calls. This coupling in the composite grid matrix is typically the composition of an interpolation rule and a discretization formula. In this example, we use a simple piecewise constant interpolation, i.e. the solution value at any point in a coarse cell is equal to the solution value at the cell center. Then the flux across a portion of the coarse-fine interface is approximated by a difference of the solution values on each side. As an example, consider the illustration in Figure 11. Following the discretization procedure above results in an equation for the variable at cell $(6,6)$ involving not only the stencil couplings to $(6,7)$ and $(7,6)$ on part 1 but also non-stencil couplings to $(2,3)$ and $(3,2)$ on part 0. These non-stencil couplings are described by `GraphAddEntries()` calls. The syntax for this call is simply the part and index for both the variable whose equation is being defined and the variable to which it couples. After these calls, the non-zero pattern of the matrix (and the graph) is complete. Note that the "west" and "south" stencil couplings simply "drop off" the part, and are effectively zeroed out.
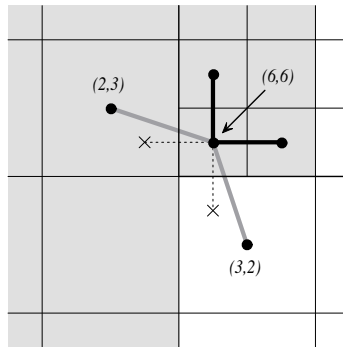
Fig. 11. Coupling for equation at corner of refinement patch. Black lines (solid and broken) are stencil couplings. Gray line are non-stencil couplings.

The remaining step is to define the actual numerical values for the composite grid matrix. This can be done by either `MatrixSetValues()` calls to set entries in a single equation, or by `MatrixSetBoxValues()` calls to set entries for a box of equations in a single call. The syntax for the `MatrixSetValues()` call is a part and index for the variable whose equation is being set and an ar-

ray of entry numbers identifying which entries in that equation are being set. The entry numbers may correspond to stencil entries or non-stencil entries.

6 The Finite Element Interface (FEI)

The finite element interface is appropriate for users who form their systems from a finite element discretization. The interface mirrors typical finite element data structures. Though this interface is provided in *hypre*, its definition was determined elsewhere [11]. A brief summary of the actions required by the user is given below.

The use of this interface to build the underlying linear system requires two phases: initialization and loading. During the initialization phase, the structure of the finite-element data is defined. This requires the passing of control data that defines the underlying element types and solution fields; data indicating how many aggregate finite-element types will be utilized; element data, including element connectivity information to translate finite-element nodal equations to systems of sparse algebraic equations; control data for nodes that need special handling, such as nodes shared among processes; and data to aid in the definition of any constraint relations local to a given process. These definitions are needed to determine the underlying matrix structure and allocate memory for the load step.

During the loading phase, the structure is populated with finite-element data according to standard finite-element assembly procedures. Data passed during this step includes: boundary conditions (essential, natural, and mixed boundary conditions); element stiffness matrices and load vectors, passed as aggregate element set abstractions; and constraint relations, defined in terms of nodal algebraic weights and tables of associated nodes.

For a more detailed description with specific function call definitions, the user is referred to [11], the web site [17] which contains information on newer versions of the FEI, as well as the *hypre* user manual. The current FEI version used in *hypre* is version 2.x, and comprises additional features not defined in [11].

7 The Linear-Algebraic Interface (IJ)

The IJ interface is the traditional linear-algebraic interface. Here, the user defines the right hand side and the matrix in the general linear-algebraic sense, i.e. in terms of row and column indices. This interface provides access only to the most general data structures and solvers and as such should only be used when none of the grid-based interfaces is applicable.

As with the other interfaces in *hypre*, the IJ interface expects to get the data in distributed form. Matrices are assumed to be distributed across p

processes by contiguous blocks of rows. That is, the matrix must be blocked as follows:

$$\begin{pmatrix} A_0 \\ A_1 \\ \vdots \\ A_{p-1} \end{pmatrix}, \tag{3}$$

where each submatrix A_k is "owned" by a single process k. A_k contains the rows $n_k, n_k + 1, ..., n_{k+1} - 1$, where n_0 is arbitrary (n_0 is typically set to either 0 or 1).

First, the user creates an empty IJ matrix object on each process by specifying the row extents, n_k and $n_{k+1} - 1$. Next, the object type needs to be set. The object type determines the underlying data structure. Currently only one data structure, the ParCSR matrix data structure, is available. However, work is underway to add other data structures. Additional data structures are desirable for various reasons, e.g. to be able to link to other packages, such as PETSc [3, 4, 25]. Also, if additional matrix information is known, more efficient data structures are possible. For example, if the matrix is symmetric, it would be advantageous to design a data structure that takes advantage of symmetry. Such an approach could lead to a significant decrease in memory usage. Another data structure could be based on blocks and thus make better use of the cache. Small blocks could naturally occur in matrices derived from systems of PDEs, and be processed more efficiently in an implementation of the nodal approach for systems AMG.

After setting the object type, the user can give estimates of the expected row sizes to increase efficiency. Providing additional detail on the nonzero structure and distribution of the matrix can lead to even more efficiency, with significant savings in time and memory usage. In particular, if information is given about how many column indices are "local" (i.e., between n_k and $n_{k+1} - 1$), and how many are not, both the ParCSR and PETSc matrix data structures can take advantage of this information during construction.

The matrix coefficients are set via the MatrixSetValues() routine, which allows a great deal of flexibility (more than its typical counterpart routines in other linear solver libraries). For example, one call to this routine can set a single coefficient, a row of coefficients, submatrices, or even arbitrary collections of coefficients. This is accomplished with the following parameters, describing which matrix coefficients are being set:

- nrows (scalar integer): the number of rows,
- ncols (array of integers): the number of coefficients in each row,
- rows (array of integers): the global indices of the rows,
- cols (array of integers): the column indices of each coefficient,
- values (array of doubles): the actual values of the coefficients.

It is also possible to add values to the coefficients with the MatrixAddValues() call.

Figure 12 illustrates this for the example of an 11×11-matrix, distributed across 3 processes. Here, rows 1–4 reside on process 0, rows 5–8 on process 1 and rows 9–11 on process 2. We now describe how to define the above parameters to set the coefficients in the boxes in Figure 12.
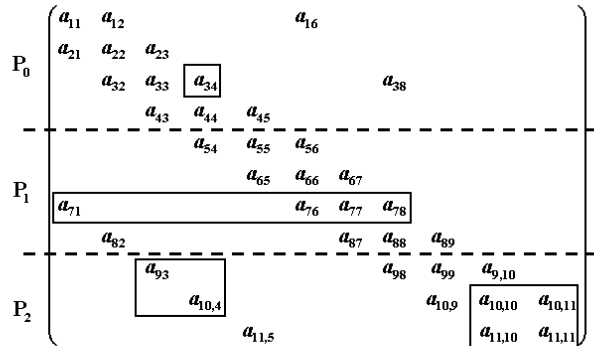
$$
\begin{array}{l}
\mathrm{P_0} \\[3.2em]
\mathrm{P_1} \\[2.6em]
\mathrm{P_2}
\end{array}
\left(
\begin{array}{ccccccccccc}
a_{11} & a_{12} & & & & a_{16} & & & & & \\
a_{21} & a_{22} & a_{23} & & & & & & & & \\
& a_{32} & a_{33} & \boxed{a_{34}} & & & & a_{38} & & & \\
& & a_{43} & a_{44} & a_{45} & & & & & & \\
& & & a_{54} & a_{55} & a_{56} & & & & & \\
& & & & a_{65} & a_{66} & a_{67} & & & & \\
a_{71} & & & & & a_{76} & a_{77} & a_{78} & & & \\
& a_{82} & & & & & a_{87} & a_{88} & a_{89} & & \\
& & a_{93} & & & & & a_{98} & a_{99} & a_{9,10} & \\
& & & a_{10,4} & & & & & a_{10,9} & a_{10,10} & a_{10,11} \\
& & & & a_{11,5} & & & & & a_{11,10} & a_{11,11}
\end{array}
\right)
$$

Fig. 12. An example of a ParCSR matrix, distributed across 3 processes.

On process 0, only one element a_{34} is to be set, which requires the following parameters: `nrows` = 1, `ncols` = [1], `rows` = [3], `cols` = [4], `values` = $[a_{34}]$. On process 1, the third (local) row is defined with the parameters: `nrows` = 1, `ncols` = [4], `rows` = [7], `cols` = [1,6,7,8], `values` = $[a_{71}, a_{76}, a_{77}, a_{78}]$. On process 2, the values contained in two submatrices are to be set. This can be done by two subsequent calls setting one submatrix at a time, or more generally, all of the values can be set in one call with the parameters: `nrows` = 3, `ncols` = [1, 3, 2], `rows` = [9, 10, 11], `cols` = [3, 4, 10, 11, 10, 11], `values` = $[a_{93}, a_{10,4}, a_{10,10}, a_{10,11}, a_{11,10}, a_{11,11}]$.

8 Implementation

This section discusses implementation issues of the various interfaces. It describes the data structures and discusses how to obtain neighborhood information. The focus is on those issues which impact performance on a large scale parallel computer. A more detailed analysis can be found in [14].

8.1 `IJ` Data Structure and Communication Package

Currently only one data structure, the ParCSR matrix data structure, is available. It is similar to the parallel AIJ matrix format in PETSc [3, 4, 25], but is not the same. It is based on the sequential compressed sparse row (CSR) data structure.

A *ParCSR matrix* consists of p parts A_k, $k = 1, \ldots, p$ (see (3)), where A_k is stored locally on processor k. Each A_k is split into two matrices D_k and O_k. D_k is a square matrix of order $n_k \times n_k$, where $n_k = r_{k+1} - r_k$ is the number of rows residing on processor k. D_k contains all coefficients a_{ij}^k, with $r_k \leq i, j \leq r_{k+1} - 1$, i.e. column indices pointing to rows stored locally. The second matrix O_k contains those coefficients of A_k, whose column indices j point to rows that are stored on other processors with $j < r_k$ or $j \geq r_{k+1}$. Both matrices are stored in CSR format. Whereas D_k is a CSR matrix in the usual sense, in O_k, which in general is extremely sparse with many zero columns and rows, all non-zero columns are renumbered for greater efficiency. Thus, one needs to generate an array of length n_{O_k} that defines the mapping of local to global column indices, where n_{O_k} is the number of non-zero columns of O_k. We denote this array as COL_MAP_O_k.

An example of an 11×11 matrix that illustrates this data structure is given in Figure 13. The matrix is distributed across 3 processors, with 4 rows on processor 1 and processor 2, and 3 rows on processor 3. The 4×4 matrices D_1 and D_2 and the 3×3 matrix D_3 are illustrated as boxes. The remaining coefficients are compressed into the 4×3 matrix O_1 (with COL_MAP_O_1 = (5,6,8)), the 4×4 matrix O_2 (with COL_MAP_O_2 = (1,2,4,9)) and the 3×4 matrix O_3 (with COL_MAP_O_3 = (3,4,5,8)). Since often O_p is extremely sparse, efficiency can be further increased by introducing a row mapping that compresses zero rows by renumbering the non-zero rows.

For parallel computations it is necessary to generate the neighborhood information, which is assembled in a communication package. The communication package is based on the concept of what is needed for a matrix-vector multiplication. Let us consider the parallel multiplication of a matrix A with a vector $\mathbf{x}$. Processor k owns rows r_k through $r_{k+1} - 1$ as well as the corresponding chunk of $\mathbf{x}$, $\mathbf{x}_k = (x_{r_k}, \ldots, x_{r_{k+1}-1})^T$. In order to multiply A with $\mathbf{x}$, processor k needs to perform the operation $A_k \mathbf{x} = D_k \mathbf{x}_k + O_k \tilde{\mathbf{x}}_k$, where $\tilde{\mathbf{x}}_k = (x_{col\_map\_O_k(1)}, \ldots, x_{col\_map\_O_k(n_{O_k})})^T$. While the multiplication of D_k and $\mathbf{x}_k$ can be performed without any communication, the elements of $\tilde{\mathbf{x}}_k$ are owned by the *receive processors* of k. Another necessary piece of information is the amount of data to be received by each processor. In general processor k owns elements of $\mathbf{x}$ that are needed by other processors. Consequently processor k needs to know the indices of the elements that need to be sent to each of its *send processors*.

In summary, the communication package on processor k consists of the following information:
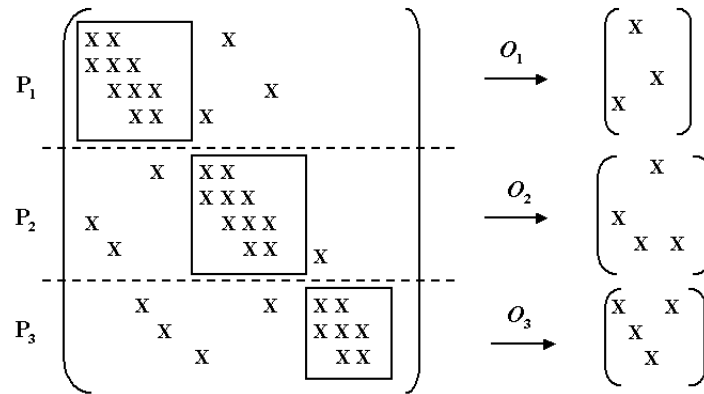
- the IDs of the receive processors

Fig. 13. An example of a ParCSR matrix, distributed across 3 processors. Matrices with local coefficients, D_1, D_2 and D_3, are shown as boxes within each processor. The remaining coefficients are compressed into the matrices O_1, O_2 and O_3.

- the size of data to be received by each processor
- the IDs of the send processors
- the indices of the elements that need to be sent to each send processor

Recall that each processor by design has initially only local information available, i.e. its own range and the rows of the matrix that it owns. In order to determine the communication package, it needs to get more information from other processors. There are various ways of dealing with this situation. We will overview two approaches here (for a more detailed analysis, see [14]).

The simpler approach is to allow each processor to own the complete partitioning information, which is easily communicated via MPI_ALLGATHER. From this it can determine its receive processors. This is a reasonable approach when dealing with computers with a few thousand processors. However, when using a supercomputer with 100,000 or more processors, this approach is expensive, requiring $O(p)$ computations and memory usage.

A better approach for this case would be to use a so-called distributed directory algorithm [30], which is a rendezvous algorithm that utilizes a concept we refer to as an assumed partitioning [14]. The idea is to assume a partitioning that is known by all processors, requires only $O(1)$ storage, and can be queried by an $O(1)$ function. In general, this function does not describe the actual partitioning, but should not be too far from it. This approach consists of two main steps. In the first step, the so-called distributed directory

is set up. Here, each processor sends information about the data it owns in the actual partitioning to the processors responsible for that data in the assumed partitioning. Once this is done, each processor knows how the data in its piece of the assumed partitioning is distributed in the actual partitioning. Hence, it is now possible to answer queries through the distributed directory (in $O(\log p)$ time) about where data lives in the actual partitioning. Step two involves just such a set of queries. That is, each processor determines where its needed receive data lives in the assumed partitioning, then contacts the responsible processors for the needed receive processor information. In this step, it is necessary to use a distributed termination detection (DTD) algorithm to figure out when to stop servicing queries. This latter fact is the sole reason for the $O(\log p)$ cost (instead of $O(1)$) [14].

If matrix A has a symmetric structure, the receive processors are also send processors, and no further communication is necessary. However, this is different in the non-symmetric case. In the current implementation, the IDs of the receive processors and the amount of data to be obtained from each receive processor are communicated to all processors via a MPI_ALLGATHERV. For a moderate number of processors, even up to 1000, this is a reasonable approach, however it can become a potentially high cost if we consider 100,000 processors. This can be avoided by a using a DTD algorithm in a similar manner to step two above.

When each processor knows its receive and send processors, the remaining necessary information can be exchanged directly. For most PDE-based linear systems and data partitionings, the number of neighbors and the amount of data is independent of p. Hence, the computational complexity and the storage requirement is $O(1)$.

8.2 `Struct` Data Structure and Neighborhood Information

The underlying matrix data structure, *Struct matrix*, contains the following.

- *Struct grid*: describes the boxes owned by the processor (local boxes) as well as information about other nearby boxes (the actual data associated with these nearby boxes lives on other processors). Note that a box is stored by its "lower" and "upper" indices, called the box's *extents*.
- *Struct stencil*: an array of indices defining the coupling pattern in the matrix.
- *data*: an array of doubles defining the coupling coefficients in the matrix.

The corresponding vector data structure is similar except is has no stencil and the data array defines the vector values. In both the vector and matrix the data array is stored so that all values associated with a given box are stored contiguously. To facilitate parallel implementation of a matrix-vector product, the vector data array includes space for values associated with a box somewhat larger than the actual box; typically including one boundary layer of cells or ghost cells (see Figure 14). Assuming that the boxes are large, the

additional storage of these ghost cells is fairly small as the boundary points also take only a small percentage of the total number of points. Some of these ghost cells may be part of other boxes, owned by either the same or a different processor. Determining communication patterns for updating ghost cells is the major task in implementing the `Struct` interface in a scalable manner.
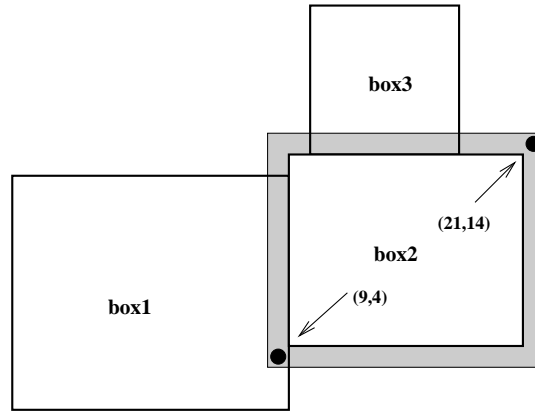

Fig. 14. For parallel computing, additional storage is allocated for cells nearby a box (ghost cells). Here, the ghost cells for BOX2 are illustrated.

Recall that in the interface, a given processor k is passed only information about the grid boxes that it owns. Determining how to update ghost cell values requires information about nearby boxes on other processors. This information is generated and stored when the Struct grid is assembled. Determining which processors own ghost cells is similar to the problem in the `IJ` interface of determining the receive processors. In the `IJ` case, this requires information about the global partitioning. In the `Struct` case, it requires information about the global grid.

The algorithm proceeds as follows. Here we let p denote the number of processors and b denote the total number of boxes in the grid (note $b \geq p$). First we accumulate information about the global grid by each processor sending the extents of its boxes to all other processors. As in the `IJ` case, this can be done using MPI_ALLGATHER with $O(\log p)$ operations. Memory usage is of order $O(b)$, since the global grid contains b boxes.

Once the global grid is known, each local box on processor k is compared to every box in the global grid. In this box-by-box comparison a *distance index* is computed which describes the spatial relationship in the index space of one box to another. This comparison of each local box to every global box involves $O(b)$ computations. Once the comparison is done, all global boxes within a specified distance (typically 2) from a local box are stored as part of a *neighborhood* data structure on processor k. Boxes not in this neighborhood

can be deleted from processor k's description of the global grid. The storage requirement for the neighborhood is independent of p.

To perform the matrix-vector product, processor k must have up-to-date values in all ghost cells that will be "touched" when applying the matrix stencil at the cells owned by processor k. Determining these needed ghost cells is done by taking each box owned by the processor, shifting it by each stencil entry and finding the intersection of the shifted box with boxes in the neighborhood data structure. As an example, consider the same layout of boxes as before with each box on a different processor (see Figure 15). If the matrix has the 5-pt stencil (1), then shifting BOX2 by the "north" stencil entry and intersecting this with BOX3 produces one of the dark shaded regions labeled as a receive box. Using this procedure, a list of receive boxes and corresponding owner processors is generated. The procedure for determining
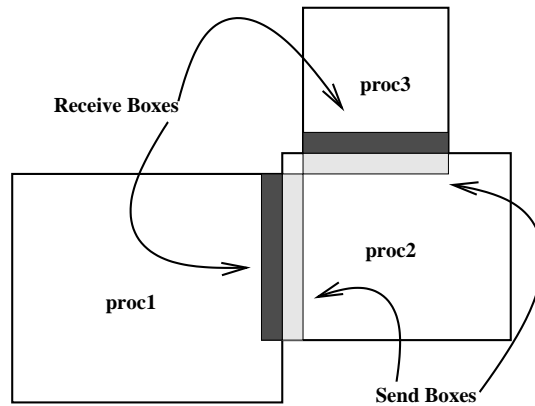

Fig. 15. The communication package for processor 2 contains send boxes (values owned by processor 2 needed by other processors) and receive boxes (values owned by other processors need by processor 2.)

the cells owned by processor k that are needed to update ghost cells on other processors is similar.

The current `Struct` interface implementation shares some of the same drawbacks as the current `IJ` interface implementation. The storage requirement in generating the neighborhood structure is $O(b)$ as the global grid is initially gathered to all processors and the box-by-box comparison to determine neighbors involves $O(b)$ operations, again note $b \geq p$. One possible approach to eliminate these drawbacks would be similar to the assumed partitioning approach described in Section 8.1. The idea is to have a function describing an assumed partitioning of the index space to processors and have this function available to all processors. Unlike the one-dimensional `IJ` partitioning, this partition would be d-dimensional. A processor would be able to determine its neighbors in the assumed partition in $O(1)$ computations

and storage. A multi-phase communication procedure like that previously described for the `IJ` case could be used to determine the actual neighbors with $O(\log p)$ complexity.

8.3 `semiStruct` Data Structure

The `semiStruct` interface allows the user to choose from two underlying data structures for the matrix. One option is to use the ParCSR matrix data type discussed in Section 8.1. The second option is the *semiStruct matrix* data type which is based on a splitting of matrix non-zeros into structured and unstructured couplings $A = S + U$. The S matrix is stored as a collection of Struct matrices and the U matrix is stored as a ParCSR matrix. In our current implementation, the stencil couplings within variables of the same type are stored in S, all other couplings are stored in U. If the user selects the ParCSR data type, then all couplings are stored in U (i.e. $S = 0$.)

Since the `semiStruct` interface can use both Struct and ParCSR matrices, the issues discussed in the previous two sections impact its scalability as well. The major new issue impacting scalability is the need to relate the semi-structured description of unknowns and the global ordering of unknowns in the ParCSR matrix, i.e. the mapping $M(\text{PART},\text{VAR},\text{INDEX}) = \text{GLOBAL\_RANK}$. The implementation needs this mapping to set matrix entries in U. The global ordering of unknowns is an issue internal to the `semiStruct` implementation; the user is not aware of this ordering, and does not need to be.

In our implementation of the semi-structured grid we include the concept of BoxMap to implement this mapping. There is a BoxMap for each variable on each part; the purpose is to quickly compute the global rank corresponding to a particular index. To describe the BoxMap structure we refer to Figure 16. By cutting the index space in each direction by lines coinciding with boxes in the grid, the index space is divided into regions where each region is a either empty (not part of the grid) or is a subset of a box defining the grid. The data structure for the BoxMap corresponds to a d-dimensional table of BoxMapEntries. In three dimensions, BoxMapEntry$[i][j][k]$ contains information about the region bounded by cuts i and $i+1$ in the first coordinate direction, cuts j and $j + 1$ in the second coordinate direction, cuts k and $k + 1$ in the third coordinate direction. Among the information contained in BoxMapEntry is the first global rank (called *offset*) and the extents for the grid box which this region is a subset of. The global rank of any index in this region can be easily computed from this information.

The mapping $M(\text{PART},\text{VAR},\text{INDEX}) = \text{GLOBAL\_RANK}$ is computed by accessing the BoxMap corresponding to PART and VAR, searching in each coordinate direction to determine which cuts INDEX falls between, retrieving the offset and box extents from the appropriate BoxMapEntry, and computing GLOBAL_RANK from this retrieved information. This computation has $O(1)$ (independent of number of boxes and processors) complexity except for the searching step. The searching is done by a simple linear search so worst case
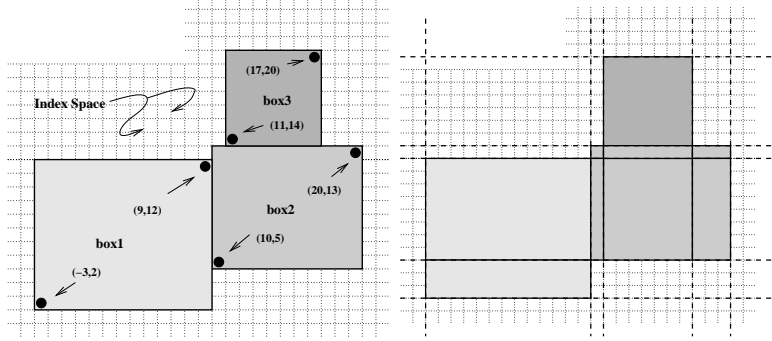
Fig. 16. The BoxMap structure divides the index space into regions defined by cuts in each coordinate direction.

complexity is $O(b)$ since the number of cuts is proportional to the number of boxes. However, we retain the current position in the BoxMap table, and in subsequent calls to the mapping function, we begin searching from this position. In most applications, subsequent calls will have map indices nearby the previous index and the search has $O(1)$ complexity. Further optimization is accomplished by retrieving BoxMapEntries not for a single index but for an entire box of indices in the index space.

The BoxMap structure does allow quick mapping from the semi-structured description to the global ordering of the ParCSR matrix, but it does have drawbacks: storage and computational complexity of initial construction. Since we store the structure on all processors, the storage costs are $O(b)$ where b is the global number of boxes (again b is at least as large as p, the number of processors). Constructing the structure requires knowledge of all boxes (accomplished by the MPI_Allgather with $O(\log p)$ operations and $O(b)$ storage as in the Struct case), and then scanning the boxes to define the cuts in index space (requiring $O(b)$ operations and storage.) As in the IJ and Struct cases, it may be possible to use the notion of an assumed partitioning of the index space to remove these potential scalability issues.

9 Preconditioners and Solvers

The conceptual interfaces provide access to several preconditioners and solvers in *hypre* (we will refer to them both as solvers in the sequel, except when noted). Table 1 lists the current solver availability. We expect to update this table continually in the future with the addition of new solvers in *hypre*, and potentially with the addition of solvers in other linear solver packages (e.g., PETSc). We also expect to update the Struct interface column, which should be completely filled in.

	Conceptual Interfaces			
Solvers	`Struct`	`semiStruct`	`FEI`	`IJ`
Jacobi	x			
SMG	x			
PFMG	x			
Split		x		
MLI		x	x	x
BoomerAMG		x	x	x
ParaSails		x	x	x
PILUT		x	x	x
Euclid		x	x	x
PCG	x	x	x	x
GMRES	x	x	x	x
BiCGSTAB	x	x	x	x
Hybrid	x	x	x	x

Table 1. Current solver availability via *hypre* conceptual interfaces.

Great efforts have been made to generate highly efficient codes. Of particular concern has been the scalability of the solvers. Roughly speaking, a method is *scalable* if the time required to produce the solution remains essentially constant as both the problem size and the computing resources increase. All methods implemented here are generally scalable per iteration step, the multigrid methods are also scalable with regard to iteration count.

The solvers use MPI for parallel processing. Most of them have also been threaded using OpenMP, making it possible to run *hypre* in a mixed message-passing / threaded mode, of potential benefit on clusters of SMPs.

All of the solvers can be used as stand-alone solvers, except for ParaSails, Euclid, PILUT and MLI which can only be used as preconditioners. For most problems, it is recommended that one of the Krylov methods be used in conjunction with a preconditioner. The Hybrid solver can be a good option for time-dependent problems, where a new matrix is generated at each time step, and where the matrix properties change over time (say, from being highly diagonally dominant to being weakly diagonally dominant). This solver starts with diagonal-scaled conjugate gradient (DSCG) and automatically switches to multigrid-preconditioned conjugate gradient (where the multigrid preconditioner is set by the user) if DSCG is converging too slowly. SMG [32, 7] and PFMG [1, 15] are parallel semicoarsening methods, with the more robust SMG using plane smoothing and the more efficient PFMG using pointwise smoothing. The Split solver is a simple iterative method based on a regular splitting of the matrix into its "structured" and "unstructured" components, where the structured component is inverted using either SMG or PFMG. This is currently the only solver that takes advantage of the structure information passed in through the `semiStruct` interface, but solvers such as the Fast Adaptive Composite-Grid method (FAC) [28] will also be made available in

the future. MLI [6] is a parallel implementation of smoothed aggregation [33]. BoomerAMG [20] is a parallel implementation of algebraic multigrid with various coarsening strategies [31, 12, 18, 13] and smoothers (including the conventional pointwise smoothers such as Jacobi, as well as more complex smoothers such as ILU, sparse approximate inverse and Schwarz). ParaSails [8, 9] is a sparse approximate inverse preconditioner. PILUT [24] and Euclid [22, 23] are ILU algorithms, where PILUT is based on Saad's dual-threshold ILU algorithm, and Euclid supports variants of ILU(k) as well as ILUT preconditioning.

After the matrix and right hand side are set up as described in the previous sections, the preconditioner (if desired) and the solver are set up, and the linear system can finally be solved. For many of the preconditioners and solvers, it might be desirable to choose parameters other than the default parameters, e.g. the strength threshold or smoother for BoomerAMG, a drop tolerance for PILUT, the dimension of the Krylov space for GMRES, or convergence criteria, etc. These parameters are defined using `Set()` routines. Once these parameters have been set to the satisfaction of the user, the preconditioner is passed to the solver with a `SetPreconditioner()` call. After this has been accomplished, the problem is solved by calling first the `Setup()` routine (this call may become optional in the future) and then the `Solve()` routine. When this has finished, the basic solution information can be extracted using a variety of `Get()` calls.

10 Additional Information

The *hypre* library can be downloaded by visiting the *hypre* home page [21]. It can be built by typing `configure` followed by `make`. There are several options that can be used with configure. For information on how to use those, one needs to type `configure --help`. Although *hypre* is written in C, it can also be called from Fortran. More specific information on *hypre* and how to use it can be found in the users manual and the reference manual, which are also available at the same URL.

11 Conclusions and Future Work

The introduction of conceptual interfaces in *hypre* gives application users a more natural means for describing their linear systems, and provides access to an array of powerful linear solvers that require additional information beyond just the matrix. Work continues on the library on many fronts. We highlight two areas: providing better interfaces and solvers for structured AMR applications and scaling up to 100,000's of processors.

As in the example in Section 5.2, the current `semiStruct` interface can be used in structured AMR applications. However, the user must explicitly

calculate the coarse-fine coupling coefficients which are typically defined by the composition of two equations: a structured grid stencil coupling and an interpolation formula. A planned extension to the `semiStruct` interface would allow the user to provide these two equations separately, and the composition would be done inside the *hypre* library code. This extension would make the `semiStruct` interface more closely match the concepts used in AMR application codes and would further ease the coding burden for potential users. We are also finishing the implementation of a new FAC [28] solver in *hypre*. This is an efficient multigrid solver specifically tailored to structured AMR applications.

Another area of work is ensuring good performance on very large numbers of processors. As mentioned previously, the current implementations in *hypre* are appropriate for thousands of processors but do have places where, say, the storage needed is $O(p)$. These potential bottlenecks may be of real importance on machines with 100,000 processors. The crux of the problem is that the interfaces only provide local information and determining neighboring processors requires global information. We have mentioned the assumed partitioning approach as one way we are trying to overcome this hurdle.

Acknowledgments

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