Object-Oriented Implementation of the NAS Parallel Benchmarks using Charm++*

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1 Introduction

This report describes experiences with implementing the NAS Computational Fluid Dynamics benchmarks using a parallel object-oriented language, Charm++. Our main objective in implementing the NAS CFD kernel benchmarks was to develop a code that could be used to easily experiment with different domain decomposition strategies and dynamic load balancing. We also wished to leverage the object-orientation provided by the Charm++ parallel object-oriented language [7, 8], to develop reusable abstractions that would simplify the process of developing parallel applications.

We first describe the Charm++ parallel programming model and the parallel object array abstraction, then go into detail about each of the Scalar Pentadiagonal (SP) and Lower/Upper Triangular (LU) benchmarks, along with performance results. Finally we conclude with an evaluation of the methodology used.

2 The Charm++ parallel object-oriented programming model

This work is based on the parallel object-oriented language Charm++[7, 8], an extension of C++. Charm++ is an explicitly parallel language, whose parallel constructs are modeled after the Charm parallel programming system [4]. Its innovative features include message driven execution for latency tolerance and modularity, dynamic creation and load balancing of concurrent objects, branched objects which have a representative on every processor, and multiple specific information sharing abstractions. This section describes the essential features, syntax, and implementation of Charm++.

Charm++ was designed to address the issues of portability, need to deal with communication latencies, support for irregular and dynamic computation structures, and reuse of parallel software modules.

2.1 Message Driven Execution

Charm++ uses message driven execution to overcome the problem of communication latency. In message driven execution, computation is initiated in response to the availability of a message. In Charm++, messages are directed to a method inside an object. Messages received from the network are kept in a queue, from which the system scheduler picks a message, and invokes the specified method within the object at which the incoming message is directed.

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Message-driven execution, combined with an asynchronous (non-blocking) model of communication, exhibits latency tolerance by overlapping computation and communication adaptively and automatically. Each processor typically has multiple objects waiting to be scheduled based on availability of messages directed at them. A remote operation (such as fetching remote data), is initiated by an object by sending a message asynchronously to an object on the remote processor and returning control to the runtime system. The runtime system schedules pending computations in any other objects on the processor. When the remote data finally arrives in the form of a message, the runtime system can schedule the requesting object again. Multiple remote operations could be initiated by a single object and could be processed in the order these operations finish. Thus message-driven execution has several advantages over the traditional “blocking-receive” based communication, offering better performance through adaptive scheduling of computations. Message-driven execution also helps to promote modularity and reuse in parallel programs without losing efficiency, by allowing the overlap of computations across modules.

2.2 Dynamic Object Creation: chares and messages

In order to support irregular computations in which the amount of work on a processor changes dynamically and unpredictably, Charm++ allows dynamic creation of parallel objects (chares), which can then be mapped to different processors to balance loads. A chare is identified by a handle, which is a global pointer.

Chares communicate using messages. Sending a message to an object corresponds to an asynchronous method invocation. Message definitions have the form:

```
message class MessageType {
    // List of data and function members as in C++
};
```

Chare definitions have the form:

```
chare class ChareType {
    // Data and member functions as in C++.
    // One or more entry functions of the form:
    entry:
        void FunctionName(MessageType *MsgPointer) {
            C++ code block
        }
};
```

The entry function definition specifies code that is executed atomically when a message is received and scheduled for processing. Only one message per chare is executed at a time. Thus a chare object defines a boundary between sequential and parallel execution: actions within a chare are sequential, while those across chares may happen in parallel. Entry functions are public object methods with message as a parameter and no return value. The handle of a chare is of type “ChareType handle”, and is unique across all processors. While multiple inheritance, dynamic binding, and overloading are supported for sequential objects by C++, Charm++ extends these concepts for chares (concurrent objects), thus permitting inheritance hierarchies of chare classes.

Every Charm++ program must have a chare type named main, which must have the function main. There can be only one instance of the main chare type, which usually executes on processor 0. Execution of a Charm++ program begins with the system creating an instance of the main chare and invoking its main function. Typically, this function is used by the programmer to create chares and branched chares and initialize shared objects.
Chares are created using the operator newchare, similar to the new in C++:
\[ \text{newchare ChareType(MsgPointer),} \]
where ChareType is the name of a chare class. This operator deposits the seed for a new chare in a pool of seeds and returns immediately. Later, the runtime system will actually create the chare on some processor, as determined by the dynamic load balancing strategy. When the chare is created, it is initialized by executing its constructor entry function with the message contained in MsgPointer as parameter. The user can also specify a processor number as an optional argument to create the chare on specific processor, thereby overriding the dynamic load balancing strategy. A chare can obtain its own handle once it has been created and pass it to other objects in messages.

Messages are allocated using the C++ new operator. Messages can be sent to chares using the notation\[ \text{ChareHandle}\Rightarrow\text{EF(MsgPointer)} \]
This sends the message pointed to by MsgPointer to the chare having handle ChareHandle at the entry function EF, which must be a valid entry function of that chare type.

2.3 Dynamic load balancing

Charm++ supports dynamic object creation with dynamic load balancing libraries which help to map newly created chares to processors so that the work is balanced. Since the patterns of object creation vary widely among applications, and the characteristics of the underlying parallel machine also vary, different dynamic load balancing strategies become suitable in different circumstances. Charm++ provides many generic libraries for dynamic load balancing, which can be selected by the user at link time, depending on the requirements of the application. These libraries are implemented as modules on top of the basic runtime system.

2.4 Branched chares

A branched chare is a group of chares with a single name. A branched chare has one representative (branch) chare on each processor, and has a single global handle. One can asynchronously invoke a method on (i.e. send a message to) a representative of a branched chare by specifying its handle as well as the processor. In addition, one can synchronously (i.e. just like a sequential function call) invoke a method within the local representative of a branched chare.

Branched chares can be used to implement distributed services such as distributed data structures, global operations and high level information sharing abstractions, thereby encapsulating concurrency. They can be used for static load-balancing in object-parallel computations (each representative performs the same computation on the data owned by it). They also provide a convenient mechanism for distributed data exchange between modules: the representatives of a branched chare in one module hand over the data to the representatives in the other module on their own processors, without the need for centralized transfer. Finally, branched chares can also be used to encapsulate processor-specific information. (Indeed branched chares are used to implement many dynamic load balancing strategies.)

It is important to underscore that branched chares are objects. In particular, there may be multiple instances of the same branched chare class. So, simple local function calls do not provide the same service as the invocation of a method in a local representative branch.

Branched chares are also created with the newchare operator: newchare ChareType(MsgPointer). This causes the runtime system to create a branch on every processor and initialize it by executing

\[ \text{(Note the syntactic difference between asynchronous message sending and sequential method invocation as in C++)} \]
its constructor entry function. Branched chares are usually created in the main function of the main chare, in which case this operator returns the handle of the newly created branched chare. 

ChareHandle[LOCAL]->DataMember and ChareHandle[LOCAL]->FunctionMember() are used to access public members of the local branch of a branched chare. 

ChareHandle[P]->EF(MsgPointer) sends a message to the function EF in the branch of a branched chare on the processor P. 

ChareHandle[ALL]->EF(MsgPointer) results in a message being broadcast to all branches of a branched chare (i.e. to all processors).

2.5 Specific information sharing abstractions

Charm++ provides specific abstract object types for sharing information. Each abstraction for information sharing may be thought of as a template of an abstract object, with methods whose code is to be provided by the user. These shared objects have a global handle (name), and can be accessed on all processors, but only through their specific methods. These abstractions may be implemented differently on different architectures by the Charm++ runtime system, for efficiency. Some of the abstractions provided by Charm++ are: read-only variables, distributed tables, accumulators, and monotonic variables. Additional abstractions may be added as libraries, as the need for them arises.

2.6 Other Charm++ features

Prioritized Execution: Charm++ provides many strategies that the user can select for managing queues of messages waiting to be processed. Some of them (FIFO, LIFO, etc) are based solely on the temporal order of arrival of messages. However, in many applications (such as algorithms with a critical path, search-based algorithms, and discrete event simulations), it is necessary to allow the application to influence the order of processing of messages by assigning message priorities. Charm++ supports integer priorities as well as bit-vector priorities (with lexicographical comparison of bit-vectors determining order of processing), which are especially useful for prioritizing combinatorial search algorithms.

Conditional Message Packing: Charm++ allows arbitrarily complex data structures in messages. On private memory systems, pointers are not valid across processors, hence it is necessary to copy (pack) the pointer-linked structure into a contiguous block of memory before sending the message. However, packing is wasteful if the message is sent to an object on the same processor, or on shared memory systems. To allow optimal performance in this context, for messages involving pointers, the user is required to specify the methods pack and unpack in the message class for packing and unpacking messages that are called by the system just before sending and after receiving a message, respectively. Thus only messages that are actually sent to other processors are packed.

Quiescence Detection: Since the Charm++ model provides independently executing parallel objects, there is no single global thread of control, hence detecting quiescence (termination) of a program is difficult. Charm++ provides a quiescence detection library for this purpose, which detects quiescence (when no object is executing any computation and all messages sent have been processed). The programmer may then choose to simply exit, or start the next phase of the parallel program.

2.7 Implementation

Charm++ has been implemented as a translator and a runtime system. The translator converts Charm++ constructs into C++ constructs and calls to the runtime system. The runtime system is
layered into a language independent portable layer *Converse*, on top of which is the *Chare Kernel* layer.

### 2.7.1 Converse: Portability and interoperability

The Converse layer provides a portable machine interface which supports the essential parallel operations on MIMD machines. These includes synchronous and asynchronous sends and receives, global operations such as broadcast, atomic terminal I/O, and other advanced features. Some important principles that guided the development of Converse include need-based cost (e.g., Charm++ should not need to pay the overhead of a tag-based receive mechanism provided by an underlying layer, since Charm++ uses message-driven execution; also, a system such as PVM should not have to pay the cost of prioritized scheduling that Charm++ needs), efficiency (the performance of programs developed on top of Converse should be comparable to native implementations) and component based design (the Converse layer is divided into components with well-defined interfaces and possibly multiple implementations which can be plugged in as required by higher layers).

Converse is designed to help modules from different parallel programming paradigms to interoperate in a single application. In addition to common components such as the portable machine interface, it provides paradigm-specific components such as message managers and thread objects, that can be customized and used to implement individual language runtime layers. Converse supports both SPMD style programs (which have no concurrency within a processor and explicit, static flow of control) as well as message-driven objects and threads (which have concurrency within a processor and implicit, adaptive scheduling).

The Converse machine interface has been ported to most parallel machines. Languages implemented on the Converse framework include Charm, Charm++, PVM (messaging), threaded PVM, SM (a simple messaging layer), and DP (a data parallel language).

### 2.7.2 Chare Kernel

The Chare Kernel layer was developed originally to support Charm, but was modified to support C++ interfaces required for Charm++ too. It implements various functions such as system initialization, chare creation, message processing (to identify the target object and deliver the message to it), performance measurements, quiescence detection, etc.

One important function of the Chare Kernel is to map parallel class and function names into consistent integer ids which can be passed to other processors. This is required because function and method pointers may not be identical across processors, especially in a heterogeneous execution environment. The Charm++ translator cannot assign unique ids to classes and methods at compile time, because Charm++ supports separate compilation, and the translator does not know about the existence of other modules. Also, while passing ids for methods across processors, this mapping must be implemented so as to support inheritance and dynamic binding: when a sender sends a message to a chare C at an entry function E defined in C’s base class, C must call its own definition of E if it has been redefined, otherwise it must call its base class’ definition of E.

To meet these requirements the Chare Kernel provides a function registration facility, which maintains the mapping from ids to pointers. The translator-generated code uses this registration facility during initialization at run-time to assign globally unique indices to chare and entry function names. This unique id can be passed in messages across modules. The translator also generates stub functions for every entry function in every chare class. When a message is received and scheduled for processing, the Chare Kernel uses this stub function to invoke the correct method in the correct chare object. For dynamic binding to work, the stub function invoked is the one corresponding
to the static type of the chare handle at the call site; the C++ virtual function mechanism then invokes the correct method depending on the actual type of the chare object.

The Chare Kernel uses a scheduler (defined as a component of Converse) which is essentially a "pick and process" loop. It picks up incoming messages from the Converse message buffer, enqueues them by priority according to a user-selected queueing strategy, and then picks the highest priority message from the queue for processing.

Finally, the Chare Kernel also manages chare handles (which are essentially global pointers), and does the mapping from local object pointers to chare handles and vice versa. Branched chare handles need to be managed slightly differently, since they have a single global handle for a group of chares: the Chare Kernel needs to ensure that a consistent handle is used on all processors.

3 Parallel Array Abstraction

Since the NAS parallel benchmarks involved computations on a three dimensional data space, the natural parallelization scheme was to divide these arrays in many smaller cubes and perform computations on these cubes in parallel while preserving data dependencies. In order to represent a multi-dimensional array in parallel, we developed a parallel object array abstraction for Charm++ [9]. This abstraction allows the programmer to create an array of parallel objects, map it to processors according to the parallel algorithm requirements, send messages to selected elements, perform global operations such as multicasts, and specify new mappings for dynamic decompositions.

A parallel array is a group of objects (the array elements) with a common global name (id), which are organized in a multidimensional, distributed array, with each array element identified by its coordinates. The mapping of array elements to processors is specified by a user-provided mapping function. A default mapping is also provided for cases when the mapping is not significant. The data space of the problem could be partitioned into contiguous blocks and could be assigned to parallel objects that are elements of the parallel array.

3.1 Parallel Array Definition

A parallel array is defined as a normal parallel object (chare) class in Charm++, except that it must inherit from the system-defined base class array. This base class provides the following data fields:

- thishandle: this gives the unique handle (global pointer) of the array element.
- thisgroup: this gives the global id by which the whole array is known.
- thisi, thisj, thisk: these give the coordinates of the array element2.

Messages that are sent between array elements must inherit from the system-defined message class arraymsg. The following code gives an example of an array definition.

```cpp
message class MessageType : public arraymsg {
    // list of data fields to be sent
};
```

2Currently, only 1, 2, or 3-dimensional arrays are supported, although this can be easily extended to higher dimensions. For brevity, all the examples in this section assume a 2-dimensional array.
```c++
chare class MyArray : public array {
    // list of private and public data and function members
    entry:
        // list of "entry functions" where messages are received
        MyArray(MessageType *m); // constructor
        void EntryFunction(MessageType *m);
};
```

### 3.2 Parallel Array Creation

A parallel array is created using the operator `newgroup`, which has the following syntax:

```c++
MapFunctionType mymapfn;
MessageType *msgptr;
MyArray group arrayidl = newgroup MyArray[XSize][Ysize](msgptr);
MyArray group arrayid2 = newgroup (mymapfn) MyArray[XSize][Ysize](msgptr);
```

The code above creates two-dimensional parallel arrays with sizes XSize and YSize in X and Y dimensions. The `newgroup` operator causes all the array element objects to be created (and their constructors invoked) on their respective processors. The parameter `msgptr` is sent to all processors as the parameter to the constructor for each array element. The first array above uses the default mapping function. The second array has a user-specified mapping function `mymapfn`, which takes the coordinates of an element as input and returns the processor where the element is located. `newgroup` is a non-blocking operator that immediately returns the id of the newly created array, which has the type `MyArray group`, and is analogous to a global pointer to an array. Because of its non-blocking nature, the elements of an array might not have been created when `newgroup` returns the array id. If necessary, the programmer may explicitly synchronize after initialization of all array elements on all processors by using a suitable reduction or synchronization operation. Currently, parallel arrays may be created only from processor 0.

### 3.3 Asynchronous messaging: remote method invocation

The parallel array library provides both point-to-point as well as multicast messaging. All messaging is asynchronous (no reply value is allowed), in keeping with the non-blocking communication paradigm of Charm++. If a reply is desired, the receiving object must send a reply message back to the sender object.

The syntax for point-to-point asynchronous messaging is:

```c++
arrayid[i][j] => EntryFunction(msgptr);
```

where `arrayid` is the "global pointer" to the parallel array, `i,j` are the coordinates of the recipient array element, `EntryFunction` is the function to be invoked in the receiving object, and `msgptr` is the message to be sent across, which is passed as the sole parameter to the function.

The syntax for multicast asynchronous messaging is:

```c++
arrayid[i1..i2][j1..j2] => EntryFunction(msgptr); // multicast to sub-array
arrayid[ALL][j] => EntryFunction(msgptr);       // multicast to column
arrayid[i][ALL] => EntryFunction(msgptr);       // multicast to row
arrayid[ALL][ALL] => EntryFunction(msgptr);     // multicast to whole array
```

If an array element is known to be on the local processor, its data and function members may be accessed as in sequential C++:

```c++
arrayid[i][j] -> datamember
arrayid[i][j] -> functionmember(...)
```
3.4 Remapping and migration

The parallel array library supports both synchronous remapping and asynchronous object migration. Synchronous remapping must be initiated from processor 0 as follows:

```c
arrayid->remap((MapFunctionType)newmapfn, return_chare.handle,
                &(ReturnChareType::ReturnFunction));
```

$newmapfn$ is the new mapping function. All array elements will be moved from their original locations to their new locations as specified by the new mapping function. After all elements have been installed on their new locations, a message is sent to the function $ReturnFunction$ in the $chare$ object specified by $return_chare.handle$. This provides a synchronization point after remapping. The user program must ensure that no messages are sent to any elements of the array being re-mapped.

Sometimes such synchronization is impossible or inefficient. Asynchronous remapping or “migration” is activated by each array element independently, by calling the function $migrate((MapFunctionType)newmapfn)$ on the array element to be moved. The $newmapfn$ parameter specifies the new mapping function, which tells the run-time library the destination processor for the array element. The call results in only the specified object being moved to its destination processor. The run-time library will correctly forward messages directed to the migrating array element to its new location.

The actual steps performed by the runtime system while migrating an object are:

1. Before migrating an object, the runtime library calls a user-provided $pack$ function on the object, which copies the object’s data area into a contiguous message buffer. The programmer must provide a pack function for every object type that needs migration. (In future, we plan to automatically generate such pack and unpack functions based on the interface specification for array elements.)

2. Send the message to the object’s destination processor.

3. Create the new object.

4. Initialize the object’s data area using the message buffer. This is done by another user-provided $unpack$ function. (Note: the pack and unpack functions are virtual functions defined in the base class $array$).

5. Forward messages directed to the object from the old processor to the new processor.

3.5 Implementation

The parallel array library is implemented on top of the Converse interoperable run-time framework [6]. The library can thus be used in conjunction with modules written in other programming systems such as PVM and MPI. Although the parallel array concepts we developed were implemented in the context of the Charm++ parallel object-oriented language, the essential features are language-independent. Currently we are in the process of modifying the Charm++ translator to translate the parallel array syntax into calls to C++ functions in the runtime library. The runtime library provides functions to create an array, send message to all elements of an array or to a subset of array, and various utility functions.
3.6 Typical Usage of Array Abstraction

In this section we describe how to use the Array abstraction in the current form (that is, without the translator modifications supporting the syntax described in earlier section.)

CreateArray function creates a parallel array of objects. The programmer needs to provide the CreateArray function with a mapping function. The mapping function takes group id and the coordinates as input parameters and returns a processor number on which the array element will be placed. An example of a simple mapping function is given below.

```c
int Grid3D(int gid, int x, int y, int z)
{
    return (x%NX + (y%NY)*NX + (z%NZ)*NX*NY);
}
```

Where total number of processors is \(NX \times NY \times NZ\).

An array is typically created in the main function of the main char. One needs to allocate a message and fill in the appropriate fields in the message that will be sent to each element of the array for initialization. An example of array creation is given below:

```c
msgptr = new CreateMessage;
msgptr->m = thishandle;
msgptr->dt = dt;
msgptr->omega = omega;
msgptr->itmax = itmax;

//cubearray = CreateArray(Chare(cube), EP(cube, cube), msgptr,
//        Grid3D, ncy, ncz);

cubearray = CreateArray(_CK_chare_cube, _CK_ep_cube_cube, msgptr,
        Grid3D, ncy, ncz);
```

Here, a message of type CreateMessage is being sent to the newly created array of cube chares at the constructor entry function of each char. The name mangling will be handled by the translator once it supports the array abstraction. However, currently the programmer needs to take care of it. (One can use macros Chare and EP to achieve this as shown in comments in the above example.) Chare names are translated to integers of the form _CK_chare_charename and the entry functions are translated as _CK_ep_charename_entryname. ncx, ncy, and ncz are the sizes of the array in X, Y and Z directions respectively.

The synchronization requirement after the creation of array demands that the newly created chares in the array perform a global reduction. This synchronization code needs to be provided by the programmer. Typically, this could be achieved by each char sending a message to the main char and awaiting a message from the main char to trigger computation. The main char keeps track of how many synchronization messages it receives and then sends a message to all the elements of the array to start computation. Messages could be sent to a particular element of an array using SendArray function or multicast to the entire array (or its subset) using SendArrayRange function.

4 The NAS Scalar Pentadiagonal (SP) benchmark

The NAS Scalar Pentadiagonal (SP) benchmark [1] is one of three simulated Computational Fluid Dynamics benchmarks in the NAS benchmark suite. It is intended to represent the principal computation and communication requirements of CFD applications in use today.

The SP benchmark involves the solution of multiple independent systems of scalar pentadiagonal equations which are not diagonally dominant. The computational space is a three-dimensional
structured mesh consisting of 64 x 64 x 64 grid points. The method used is an iterative Alternating Direction Implicit (ADI) method. In each iteration there are three "sweeps" successively along each of the three coordinate axes. Thus the method involves global spatial data dependences.

Our main objective in implementing the NAS SP benchmark was to develop a code that could be used to easily experiment with different domain decomposition strategies. We also wished to leverage the object-orientation provided by the Charm++ parallel object-oriented language [7, 8], to develop reusable abstractions that would simplify the process of developing parallel applications.

4.1 Parallelization schemes

The steps in the numerical algorithm [3] which are significant for parallelization are:

- Computation of the RIIS vector of the partial differential equation. Each grid point in the cubical mesh needs values of the $U$ matrix from two neighboring grid points on either side, in each of the three dimensions. This corresponds to six "parallel-shift" operations.

- Solution of a system of linear equations in the $x$-direction. Each grid point initially needs values from two succeeding grid points in the $x$-direction (corresponding to a shift operation in the negative-$x$ direction). Then there is a sweep along the positive-$x$ direction in which each grid point computes values that are needed by the next two points.

- Solution of a system of linear equations in the $y$-direction. This is similar to the previous step, except that communication is along the $y$-direction.

- Solution of a system of linear equations in the $z$-direction. This is similar to the previous step, except that communication is along the $z$-direction.

Parallelizing these steps requires decomposition of the three-dimensional computational array among processors. This decomposition must be done so as to balance computational load across processors as well as reduce inter-processor data communication.

Three of the most common methods used to parallelize ADI methods are [11]:

- Pipelined static block decomposition: each processor is statically allocated a contiguous three-dimensional block of grid points for the entire length of the computation. The block is made as close to cubical as possible to minimize the amount of communication (which is proportional to surface-area of the block). During the sweeps, each processor receives boundary data from the previous processor in the sweep direction, computes its data, and sends its boundary data on to the next processor. In order to reduce idle times while processors wait for data from previous processors, the computation is pipelined: each processor works on a slice of its grid points, sends the resulting boundary on to the next processor, and then goes on to the next slice. The disadvantage of this decomposition is that many processors idle at the beginning and end of the sweeps; moreover, there are many small messages sent between processors corresponding to the boundary data for each slice, which could cause significant overhead on machines with large message latencies.

- Transpose-based dynamic block decomposition: the three-dimensional mesh is divided into slabs oriented along the X direction first. After the X-direction sweep completes a transpose operation is done to orient the slabs along the Y-direction, in preparation for the Y-sweep. Finally, a third transpose operation is needed before the X-sweep of the next iteration. Thus there are a total of three transpose operations needed per iteration. The advantage of this
method is that computations within each sweep are completely local to a processor. However, the transpose operations between sweeps can result in significant overhead on bandwidth-limited machines.

- The multi-partition or Bruno-Capello decomposition [10, 2]: this is a static decomposition where the computational mesh is divided into cubes, and each cube is assigned to a processor such that all processors are active at all stages in each of the three sweeps. In other words, each coordinate plane in the computational space contains cubes on all processors. Thus processor loads are balanced during all stages of all sweeps, and also no transpose operations are needed. The minimum number of cubes needed for this decomposition is \( P^{3/2} \) (where \( P \) is the number of processors), so that each processor has \( \sqrt{P} \) cubes. The cube with coordinate \((i, j, k)\) is allocated to processor \((i - k)\%s + s((j - k)\%s) + 1\), where \( s = \sqrt{P} \) and \( 1 \leq i, j, k \leq s \). The tradeoff in the multi-partition method is that computations within a sweep involve cross-processor messaging.

4.2 Implementing the SP benchmark using parallel arrays

We developed the following abstraction for the NAS SP benchmark code: The computational space is represented as a three-dimensional array of cubical sub-spaces. Each cube is represented by a parallel object in Charm++, which communicates with other cubes by sending and receiving messages. Thus the parallel program consists of a network of communicating objects.

The different decomposition/mapping strategies are expressed by simply specifying a different mapping function for the parallel array. E.g. the mapping function for the multipartition (Bruno-Capello) decomposition is:

```c
int MultiPartitionMapFn(int arrayid, int i, int j, int k) {
    // return processor number owning object (i,j,k)
    return (XArraySize*(i-k+XArraySize)%XArraySize) +
            (j-k+YArraySize)%YArraySize;
}
```

For the transpose method, all adjacent cubes along the direction of the sweep are mapped to the same processor. E.g. the mapping function for the sweep along the X-axis is:

```c
int XSweepMapFn(int arrayid, int i, int j, int k) {
    return (ZArraySize * j + k);
}
```

The transpose is effected by simply doing a remap operation on the parallel array between sweeps, with the mapping function corresponding to the orientation of the next sweep. Thus we have a very flexible, elegant code which allows us to concentrate on experiments with the application, instead of getting involved in the details of implementing the decomposition.

The asynchronous migration facility provided with parallel arrays allows us to further optimize the transpose method by overlapping communication and computation. Each cube object migrates itself as soon as it has completed its work along one sweep. Thus the communication overhead of transferring its data to another processor is overlapped with the computation performed by other cubes. This overlap gives significant performance advantages over the traditional loosely-synchronous (separate phases of computation and communication) implementations.
4.3 Performance results

Table 1 presents performance results for the different decompositions in the Charm++ implementation of the NAS SP benchmark. Sync-Transpose is the transpose-based dynamic block decomposition. Async-Transpose is the dynamic block decomposition with asynchronous migration of parallel objects for moving data between sweeps. Note that the only modification needed to change the decompositions for the different runs was to change the mapping function.

<table>
<thead>
<tr>
<th>Processors</th>
<th>4</th>
<th>16</th>
<th>64</th>
<th>256</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sync-Transpose</td>
<td>-</td>
<td>8.98</td>
<td>3.01</td>
<td>1.98</td>
</tr>
<tr>
<td>Async-Transpose</td>
<td>-</td>
<td>7.81</td>
<td>2.54</td>
<td>1.40</td>
</tr>
<tr>
<td>Multipartition</td>
<td>24.63</td>
<td>7.60</td>
<td>1.98</td>
<td>1.00</td>
</tr>
</tbody>
</table>

Table 1: Time (in milliseconds) for different decompositions for the NAS SP benchmark (size A) on the Intel Paragon.

The results show that the multipartition (Bruno-Capello) decomposition is the best overall, with the Async-Transpose and Sync-Transpose decompositions being successively worse. The absolute performance of our program does not compare well with performance numbers quoted by vendors for the NAS benchmarks. This is mainly because our focus was on flexible parallelization issues, and not on tuning the algorithm or code for sequential or absolute performance.

5 The NAS Lower/Upper Triangular (LU) benchmark

The LU benchmark is one of the three CFD kernels in NAS benchmarks. It solves a regular-sparse, block (5 X 5) lower and upper triangular system. This represents the computations associated with the implicit operator of a newer class of implicit CFD algorithms, and has a lower degree of parallelism compared with other benchmarks in this suite. All the data-dependencies in this benchmark are local (nearest neighbor.) The system of linear equations obtained by replacing the spatial derivatives by second-order accurate, central finite difference operators is solved using the symmetric successive over-relaxation scheme. Each iteration of this algorithm consists of

- Computing the Right Hand Side explicitly.
- Forming and solving the regular, sparse, block lower triangular system.
- Forming and solving the regular, sparse, block upper triangular system.
- Updating the solution.

We used a spatial domain decomposition strategy to split the computational domain into a number of cubes. Different communication patterns develop as a result of data dependences in the above steps in each iteration. Computing RHS explicitly in the first step requires domain boundaries to be communicated between neighboring cubes (in both positive and negative X, Y and Z directions.) In the second step, forming the lower triangular system is a completely local operation and does not need any data from neighbors. However, solving the system requires wave-like communication pattern in the direction of diagonal of the computation domain. This is a
result of data-dependence where an element \((i, j, k)\) needs elements \((i, j-1, k-1)\), \((i-1, j, k-1)\), and \((i-1, j-1, k)\). Computation in step 3 requires a wave-like communication similar to step 2 but in opposite direction. Thus, data-dependence mandates that there be three different communication patterns in each iteration. Also, the local data-dependence requires that these steps cannot be executed parallely within the same iteration. This reduces the degree of parallelism in this benchmark significantly. Figure 1 shows that the available degree of parallelism in our algorithm in initial stages of the wave is very small. In the middle stages, where the wave reaches the principal diagonal of the 3-D data space, the degree of parallelism is high and then it reduces again in the later stages of the wave.

![Figure 1: Degree of Parallelism in LU](image)

In algorithms such as these, the only sources of enhancing performance are proper scheduling of work and overlapping communication and computation. One of the advantages of programming this application in a message-driven language such as Charm++ is that, the programmer only has to code the data-dependencies and leave the scheduling and overlapping communication and computation to the run-time system.

The implementation of this benchmark using the parallel array abstraction in Charm++ for domain decomposition is similar to the implementation of SP benchmark described in earlier section. This substantiates one of our main claims in this work that, using parallel object-oriented languages such as Charm++, one could develop reusable abstractions which could be used in development of several applications. However, the approach taken to develop the parallel code for LU differs from that of SP. In developing LU benchmark, we first converted the implementation of sequential LU algorithm from FORTRAN to C++, forming private methods for individual cubes in the process. Using the array abstraction to parallelize the C++ code was a very trivial task then. One of the
The main advantage of this approach was that we were able to eliminate errors due to base-language variation early in the process using tools for sequential programs, which are more advanced than their counterparts in parallel programming.

We observed that the LU benchmark showed dependence to some extent on the actual placement of the cubes and the results of our experiments with different placement strategies reflect this observation. Our use of the parallel array abstraction in Charm++ allowed us to efficiently experiment with different placement strategies as well as different domain decomposition strategies.

One of the placement strategies we used is shown in figure 2. For simplicity, we have shown a wave-parallel placement pattern for a 2-dimensional $4 \times 4$ grid, placed using this strategy on 4 processors. The advantage of this placement strategy is that as the wave advances from one diagonal to the another, all the objects executing methods concurrently are placed on different processors. Therefore, we utilize all the processors optimally.

![Figure 2: Wave-Parallel Placement Strategy](image)

### 5.1 Performance Results

Our experiments were carried out on IBM-SP at Argonne National Laboratories. Charm++ is implemented on top of the native MPL communication library on IBM-SP systems. We conducted our experiments using 4 different decomposition strategies with 4, 8 and 16 processors and four different placement strategies (using different mapping functions during array creation.) The times are given for 25 iteration in seconds (The complete benchmark requires 250 iterations.) The different decompositions indicate the number of divisions of the computational domain in each direction. For example, a $8 \times 8 \times 1$ decomposition means the computational domain was split into 8 parts in
X and Y direction, but was left untouched in the Z direction, thus forming 64 cubes. Our results are comparable to numbers reported in [3] considering the experience of other users of IBM-SP at Argonne National Labs that it is slower than other installations of IBM-SP by almost factor of 2 for most programs. Also, we have not optimized the sequential part of computations that are coded in C++ rather than in FORTRAN which has a better set of optimization tools available for such scientific computations.

<table>
<thead>
<tr>
<th>Processors</th>
<th>4 x 4 x 1</th>
<th>4 x 4 x 4</th>
<th>8 x 8 x 1</th>
<th>8 x 8 x 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>370.580</td>
<td>308.072</td>
<td>322.450</td>
<td>-</td>
</tr>
<tr>
<td>8</td>
<td>231.840</td>
<td>151.379</td>
<td>179.884</td>
<td>413.638</td>
</tr>
<tr>
<td>16</td>
<td>210.931</td>
<td>96.273</td>
<td>119.704</td>
<td>81.930</td>
</tr>
</tbody>
</table>

Table 2: Time (in seconds) for different decompositions for the NAS LU benchmark (size A) on the IBM SP using Wave-Parallel Mapping function.

<table>
<thead>
<tr>
<th>Processors</th>
<th>4 x 4 x 1</th>
<th>4 x 4 x 4</th>
<th>8 x 8 x 1</th>
<th>8 x 8 x 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>453.809</td>
<td>298.159</td>
<td>300.545</td>
<td>-</td>
</tr>
<tr>
<td>8</td>
<td>430.003</td>
<td>289.487</td>
<td>220.567</td>
<td>343.630</td>
</tr>
<tr>
<td>16</td>
<td>423.968</td>
<td>289.297</td>
<td>219.503</td>
<td>320.542</td>
</tr>
</tbody>
</table>

Table 3: Time (in seconds) for different decompositions for the NAS LU benchmark (size A) on the IBM SP using 1D Grid Mapping function.

<table>
<thead>
<tr>
<th>Processors</th>
<th>4 x 4 x 1</th>
<th>4 x 4 x 4</th>
<th>8 x 8 x 1</th>
<th>8 x 8 x 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>389.677</td>
<td>267.771</td>
<td>296.191</td>
<td>-</td>
</tr>
<tr>
<td>8</td>
<td>237.368</td>
<td>171.202</td>
<td>182.077</td>
<td>335.665</td>
</tr>
<tr>
<td>16</td>
<td>208.387</td>
<td>131.432</td>
<td>137.044</td>
<td>66.602</td>
</tr>
</tbody>
</table>

Table 4: Time (in seconds) for different decompositions for the NAS LU benchmark (size A) on the IBM SP using 2D Grid Mapping function.

5.2 Performance Analysis of LU

This section presents our work on the performance analysis of the LU code performed using a performance analysis tool for Charm and Charm++ programs, called Projections. Projections is available as a trace generation facility for Chare kernel, the run-time system of Charm and Charm++ languages; and as a performance visualization and analysis tool. It includes an expert system that works with the trace data generated by the program and analyzes for critical paths, phases and degree of parallelism within the code. For enabling projections trace generations, a


<table>
<thead>
<tr>
<th>Processors</th>
<th>$4 \times 4 \times 1$</th>
<th>$4 \times 4 \times 4$</th>
<th>$8 \times 8 \times 1$</th>
<th>$8 \times 8 \times 8$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>384.666</td>
<td>287.692</td>
<td>297.734</td>
<td>-</td>
</tr>
<tr>
<td>8</td>
<td>358.427</td>
<td>163.656</td>
<td>294.130</td>
<td>255.330</td>
</tr>
<tr>
<td>16</td>
<td>233.877</td>
<td>108.904</td>
<td>185.241</td>
<td>65.016</td>
</tr>
</tbody>
</table>

Table 5: Time (in seconds) for different decompositions for the NAS LU benchmark (size A) on the IBM SP using 3D-Grid Mapping function.

Charm++ program should be linked by specifying `-execmode projections` on the Charm linker command line. When this program is run, it produces trace files, one per processor. These files are then used as input for the X-windows based Projections visualizations tool. This section presents some of the analysis we did using Projections on the LU code.

One of the main reasons for performance degradation of parallel programs is the improper load-balancing. Proper load-balancing is characterized by equal amount of computation on all nodes. We checked the performance of LU for the amount of processing on each node. The processing time on each processor is shown in figure 3. It is in the range of 48 to 56 percent of the total time on each processor. This busy time is calculated based on the entire run of the program that includes the Charm initialization time during which most processors are idle. However, during the SSOR iterations, the busy time was 70 to 85 percent. Therefore, we concluded that LU is properly load balanced.

Though the total load across all nodes was determined to be similar, the regular structure of our application demanded that each type of computations should be distributed in equal amounts on all nodes for proper load balance. The main types of computations in LU are building the matrices (setiv), solving the lower and upper triangular systems (blts and buts respectively), and computing the RHS (rhs). We have made each of these computations into entry methods of the chare cube, therefore, determining the amount of each of these computations across all processors amounts to finding out how many times each of these entry methods were invoked on each chare. Figure 4 shows this in a graphical format. We can conclude from figure 4 that the individual computations were load balanced as well.

Another reason for the performance degradation especially in the light of our finding of low busy time per processor is the overhead imposed by the run-time system in the form of message sending, message processing and internal copying etc. However, the log files generated by Projections indicated that a total of 4424 messages were processed for each iteration of LU by each processor. From table 2, each iteration of LU takes 3.24 seconds. Thus the average grainsize of computation during the iteration is 732.368 $\mu$seconds. Another experiment was run on SP2, which calculated the overhead per message creation and processing. This involved running a simple pingpong program written in Charm++ that transferred messages back and forth between two processors. This experiment indicated that the average overhead per message processing was 126 $\mu$seconds. This amounts to 17 % overhead per message.

Next we viewed the aggregate work on all processors as a function of time. And noticed the distinct peaks for each of the iterations of LU. An iteration is characterized by forming RHS, solving the lower triangular system and solving the upper triangular system. We noticed that the amount of work done is at its peak in the middle of an iteration. This was expected since the degree of parallelism is at its highest in a wave-parallel distribution when the wave reaches the diagonal of the cube. Thus we figured out that this dependence is the main cause of low performance. We analyzed
Figure 3: Busy Time Per Processor
Figure 4: Individual Computations Per Processor
the trace data using the expert analysis tool of projections. Projections performed a critical path analysis and showed that almost all the computations for each cube are on critical path and that the average degree of parallelism is low. This degree of parallelism can be usually increased, as suggested by the expert system, by breaking the entry points into multiple entry points which could be executed in any order. However, this did not seem to be possible because of the dependences present in the problem. We have already split the dependences within each direction into different entry methods. However, the computations could be performed upon the arrival of these messages from all direction. Therefore, all of those entry methods will have to be on the critical path. Thus we concluded that the available degree of parallelism within the problem was very low and further optimizations were infeasible.

6 Conclusions

We have implemented the CFD kernels in the NAS Parallel Benchmarks using Charm++, a parallel object-oriented language. In order to simplify expression of multi-dimensional parallel arrays in Charm++, we implemented a parallel array abstractions using facilities provided by Charm++ and its runtime system, Converse. We have shown that the abstractions developed using Charm++ are indeed reusable by implementing both the Scalar Pentadiagonal (SP) and Lower-Upper Triangulation (LU) benchmarks without any modifications to the abstractions. The higher level array abstraction allowed us to experiment with many placement strategies and load-balancing without any significant programming overhead. Also, the benchmark code was developed such that the communication harness could be reused efficiently by plugging in different code for local computations. We have presented the performance results for both the codes using different placement and decomposition strategies. However, the main objective of this project was not to demonstrate the performance of the code but to demonstrate the ease of programming and experimentation using abstractions in parallel object-oriented languages such as Charm++. The later was demonstrated by the parallel array abstraction that made it possible to switch between different placement and domain decomposition strategies by merely providing a different mapping function at array creation time.

A Pseudo-Code for LU Benchmark

Figure 5 shows pseudo-code for the cube chare in the LU benchmark. This pseudo-code is written using a notation called Structured Dagger [5], which is a coordination language built on top on Charm++.

References


char cube
{
    // char-local variables declarations

    struct entry iterations: (InitMessage *message)
    {
        atomic {
            Initialization();
            // Send Startup Messages Containing Boundary Elements
            // To Neighbors' rhs_entry points
        }
        while (iter < maxiter) {
            atomic { rhs_init(); }
            overlap {
                when rhs_entry_xm1(Bdry *xm1), rhs.entry.xp1(Bdry *xp1) {
                    rhs.x(xm1, xp1);
                }
                when rhs_entry_ym1(Bdry *ym1), rhs.entry.yp1(Bdry *yp1) {
                    rhs.y(ym1, yp1);
                }
                when rhs_entry_zm1(Bdry *zm1), rhs.entry.zp1(Bdry *zp1) {
                    rhs.z(zm1, zp1);
                }
                if (x == 0 && y == 0 && z == 0) {
                    // Start the first sweep by sending messages to +1 neighbors
                }
                when XmBdry(Bdry *xmmsg), YmBdry(Bdry *ymmsg), ZmBdry(Bdry *zmmsg) {
                    atomic {
                        bits(); Jacld();
                        // Continue the sweep by sending messages to +1 neighbors'
                        // XmBdry, YmBdry, ZmBdry entry-points
                    }
                }
                if (x == maxx && y == maxy && z == maxz) {
                    // Start the reverse sweep by sending messages to -1 neighbors
                }
                when XpBdry(Bdry *xmsg), YpBdry(Bdry *ymsg), ZpBdry(Bdry *zmsg) {
                    atomic {
                        buts(); Jacu();
                        // Continue reverse sweep by sending messages to -1 neighbors'
                        // XpBdry, YpBdry, ZpBdry entry-points
                        updateu();
                        // Send updated boundaries to neighbors' rhs_entry points
                        iter++;
                    }
                }
            }
        }
    }
}

Figure 5: LU Benchmark Program


NAS SP Benchmark Source Code

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Dept of Computer Science, University of Illinois, Urbana, IL 61801
E-mail: {sanjeev,milind,kale}@cs.uiuc.edu
#include <stdio.h>
#include <string.h>

#include "array.h"
#include "cube.h"
#include "controlboc.h"
#include "min.h"

extern readonly Cube group cubearray;
extern readonly int NumCubes;

char str[1024];

extern readonly ControlBoc group controlboc;

extern "C" double sqrt(double);

extern "C" void getsn(int i, int j, int k);
extern "C" void initp(int i);
extern "C" void cyplz(int double *, double *, int, int);
extern "C" void cyyplz(int double *, double *, int, int);
extern "C" void cnnplz(int double *, double *, int, int);
extern "C" void cnmllz(int double *, double *, int, int);
extern "C" void gnhllz(int double *, double *, int, int);
extern "C" void gnh2llx(int double *, int, int);
extern "C" void gnhllz(int double *, int, int);
extern "C" void gnhl2z(int double *, int, int);
extern "C" void gnhl2z(int double *, int, int);
extern "C" void gnhllz(int double *, int, int);
extern "C" void gintr(int);
extern "C" void calv(double *, double *, double *);

ControlBoc:ControlBoc(SomeMsg *m)
{
  cubearray = 0;    /* this is because cubearray is created AFTER
                    nummsg to avoid initialization problems */

  myhandle = thisgroup;

  MYPE = CMyPeNum();
  NCMPROC = CMaxPeNum();
  isetp = 1;

  initp(&MYPE);
  getsn(&nxa, &nya, &nxm, &krimax);
}

NumRSDNorms = 0;
for (int i = 0; i < 3; i++)
  TotRSDNorm[i] = 0;

NumCubesDone = 0;
NumProcDone = 0;

NumPhi1x = 0; NumPhi1y = 0; NumPhi1z = 0;
NumPhi2x = 0; NumPhi2y = 0; NumPhi2z = 0;
NumPhi3 = 0;

phi1x = new double [nx+1];
phi1y = new double [ny+1];
phi1z = new double [nx+ny+1];
phi2x = new double [ny+1];
phi2y = new double [nx+ny+1];
phi2z = new double [nx+ny+1];
lasttime = 0;

mainhandle->InitialSync(m);
}

void
ControlBoc:InitialSync(SomeMsg *m)
{
  NumCubesDone++;

  if (NumCubesDone < NumCubes/CNumPe())
    delete m;
  return;
  NumCubesDone = 0;

  myhandle[0] = InitialSync0(m);
}

void
ControlBoc:InitialSync0(SomeMsg *m)
{
  NumProcDone++;

  if (NumProcDone < CNumPe())
    delete m;
  return;
  NumProcDone = 0;

  /* Start Timer */
  begintime = CTimer();
}
controlboc.P  

// Start first iteration */
SendArrayRange(cubearray, CK.ep.Cube, StartRHS,I, m, -1,-1,-1,-1,-1,-1);
}

///// CODE FOR RHS /////

void
ControlBoc::EndRHSISync(SomeMsg *m)
{    
  NumCubesDone++;
  if ( NumCubesDone < NumCubes ){
    delete m;
    return;
  }
  NumCubesDone = 0;

  SendArrayRange(cubearray, CK.ep.Cube, StartRHS,J, m, -1,-1,-1,-1,-1,-1);
}

void
ControlBoc::EndRHSISync(SomeMsg *m)
{    
  NumCubesDone++;
  if ( NumCubesDone < NumCubes ){
    delete m;
    return;
  }
  NumCubesDone = 0;

  SendArrayRange(cubearray, CK.ep.Cube, StartRHS,K, m, -1,-1,-1,-1,-1,-1);
}

///// CODE FOR LENorm /////

void
ControlBoc::GlobalRSDNorms(NormsMsg *m)
{    
  /* compute global sum and actual norm and print it */
  for ( int i=0; i<5; i++ )
    TotRSDNorm[i] += m->num[i];
  delete m;
  NumRSDNorms++;
  if ( NumRSDNorms < NumCubes ){
    return;
  }
}

controlboc.P

for ( i=0; i<5; i++ )
  TotRSDNorm[i] = sqrt( TotRSDNorm[i] /
                      ( (nx-2) * (ny-2) * (nz-2) ) );

memcpy(LatestRSDNorm, TotRSDNorm, sizeof(double)*5);
NumRSDNorms = 0;
for ( i=0; i<5; i++ )
  TotRSDNorm[i] = 0.0;

SomeMsg *m2 = new SomeMsg;
SendArrayRange(cubearray, CK.ep.Cube, StartADI,Isweep, m2, -1,-1,-1,-1,-1,-1);
}

///// CODE FOR ADI LOOP /////

void
ControlBoc::EndADILISync(SomeMsg *m)
{    
  NumCubesDone++;
  if ( NumCubesDone < YArraySize*ZArraySize ){
    // Only cubes for which m->msg==0 send a sync msg here
    delete m;
    return;
  }
  NumCubesDone = 0;

  #ifdef TRANSPOSE
  ArrayRemap(cubearray, Jsweep, Maps, &ControlBoc::FinishedJsweepRemap);
  #endif

  #else
  SendArrayRange(cubearray, CK.ep.Cube, StartADI, Jsweep, m, -1,-1,-1,-1,-1,-1);
  #endif

void
ControlBoc::FinishedJsweepRemap(SomeMsg *m)
{    
  SendArrayRange(cubearray, CK.ep.Cube, StartADI, Jsweep, m, -1,-1,-1,-1,-1,-1);
}

void
ControlBoc::EndADILISync(SomeMsg *m)
{    
  NumCubesDone++;
  if ( NumCubesDone < YArraySize*ZArraySize ){
    // Only cubes for which m->msg==0 send a sync msg here
    delete m;
    return;
  }
}
```c

NumCubesDone = 0;

if (!TRANSPOSE
    ArrayRemap(cubarray, KsweepMapfn, &((ControlBoc::FinishedKsweepRemap),
    thinhandle));
#else
    SendArrayRange(cubarray, CK.ep.Cube.StartADI.Ksweep, m, -1, -1, -1, -1, -1, -1);
#endif

void
ControlBoc::FinishedKsweepRemap(SomeMsg *m)
{
    SendArrayRange(cubarray, CK.ep.Cube.StartADI.Ksweep, m, -1, -1, -1, -1, -1, -1);
}

void
ControlBoc::EndADIFileSync(SomeMsg *m)
{
    NumCubesDone++;
    if (NumCubesDone < XArraySize*YArraySize) {
        // Only cubes for which msg==0 send a sync msg here
        delete m;
        return;
    }
    NumCubesDone = 0;

    if (!TRANSPOSE
        ArrayRemap(cubarray, IrkweepMapfn, &((ControlBoc::FinishedIrkweepRemap),
        thinhandle);
    #else
        SendArrayRange(cubarray, CK.ep.Cube.StartRHS.I, m, -1, -1, -1, -1, -1, -1, -1);
    #endif
}

void
ControlBoc::FinishedIrkweepRemap(SomeMsg *m)
{
    SendArrayRange(cubarray, CK.ep.Cube.StartRHS.I, m, -1, -1, -1, -1, -1, -1, -1);
}

/**** CODE FOR computing the norms of pseudo-time iteration corrections ****/

void
ControlBoc::GlobalCNorms(NormsMsg *m)
{
    /* compute global sum and actual norm and print it */
    for (int i=0; i < C; i++)
    ToRSDNorm[i] += m->sum[i];
    NumRSDNorms++;
    delete m;
    if (NumRSDNorms < NumCubes)
        return;
    for (int i=0; i < C; i++)
        ToRSDNorm[i] = sqrt(ToRSDNorm[i] /
            (nx-2) * (ny-2) * (nz-2));
    NumRSDNorms = 0;
    for (int i=0; i < C; i++)
        ToRSDNorm[i] = 0.0;
    SomeMsg *m2 = new SomeMsg;
    SendArrayRange(cubarray, CK.ep.Cube.StartRHS.I, m2, -1, -1, -1, -1, -1, -1, -1);
}

/***** CODE FOR STUFF AFTER FINISHING ADI LOOP *****/

void
ControlBoc::FinalSync(SomeMsg *m)
{
    delete m;
    NumCubesDone++;
    if (NumCubesDone < NumCubes)
        return;

    /* End Timer */
    int endtime = CTimer();
    CPrintln("FinalTime for %d iterations: %d milliseconds, begin %d end %d\n", n, endtime - begin, begin, endtime);
    NumCubesDone = 0;
    SomeMsg *m2 = new SomeMsg;
    SendArrayRange(cubarray, CK.ep.Cube.FinishedADILoop, m2, -1, -1, -1, -1, -1, -1, -1);
}

void
ControlBoc::GlobalError(NormsMsg *m)
{
    /* compute global sum and error norm and print it */
    for (int i=0; i < C; i++)
        ToRSDNorm[i] += m->sum[i];
    delete m;
    NumRSDNorms++;
```
```c
if ( NumRSDNorms < NumCubes )
    return ;

for ( i=0; i<5; i++ )
    TotRSDNorm[i] = sqrt( TotRSDNorm[i] /
        ( (nx-2) * (ny-2) * (nz-2) ) );

CPrint("Norm of error in soln. to \( \lambda^c \) ;
sprintf(str,"First pde = 1.5e\( \sigma \),TotRSDNorm[0] ;
CPrint(("Ta",str)) ;
sprintf(str,"Second pde = 1.5e\( \sigma \),TotRSDNorm[1] ;
CPrint(("Ta",str)) ;
sprintf(str,"Third pde = 1.5e\( \sigma \),TotRSDNorm[2] ;
CPrint(("Ta",str)) ;
sprintf(str,"Fourth pde = 1.5e\( \sigma \),TotRSDNorm[3] ;
CPrint(("Ta",str)) ;
sprintf(str,"Fifth pde = 1.5e\( \sigma \),TotRSDNorm[4] ;
CPrint(("Ta",str)) ;

NumRSDNorms = 0 ;

CharmExit() ;
}
}

void
ControlBoc::ReceivePhi1x(PhiMag *m)
{
/* Store the phi + */
    int begin1 = m->myx * (nx/XArraySize) ;
    int begin2 = m->myx * (nx/XArraySize) ;
cphi1x.(phi1x.m->phi1x.begin1,&begin2) ;

    delete m ;
    NumPhi1x++ ;

    if ( NumPhi1x < XArraySize*ZArraySize )
        return ;

gphi1x.(phi1x);
    GlobalPIntg();
}

void
ControlBoc::ReceivePhi2x(PhiMag *m)
{
/* Store the phi + */
    int begin1 = m->myx * (nx/XArraySize) ;
    int begin2 = m->myx * (nx/XArraySize) ;
cphi2x.(phi2x.m->phi2x.begin1,&begin2) ;

    delete m ;
    NumPhi2x++ ;

    if ( NumPhi2x < XArraySize*ZArraySize )
        return ;

gphi2x.(phi2x);
    GlobalPIntg();
}

void
ControlBoc::ReceivePhi1y(PhiMag *m)
{
/* Store the plus */
    int begin1 = m->myy * (ny/YArraySize) ;
    int begin2 = m->myy * (ny/YArraySize) ;
cphy1y.(phy1y.m->phy1y.begin1,&begin2) ;

    delete m ;
    NumPhi1y++ ;

    if ( NumPhi1y < XArraySize*ZArraySize )
        return ;

gphi1y.(phi1y);
    GlobalPIntg();
}

void
ControlBoc::ReceivePhi2y(PhiMag *m)
{
/* Store the plus */
    int begin1 = m->myy * (ny/YArraySize) ;
    int begin2 = m->myy * (ny/YArraySize) ;
cphy2y.(phy2y.m->phy2y.begin1,&begin2) ;

    delete m ;
    NumPhi2y++ ;

    if ( NumPhi2y < XArraySize*ZArraySize )
        return ;

gphi2y.(phi2y);
    GlobalPIntg();
}

void
ControlBoc::ReceivePhi1z(PhiMag *m)
{
/* Store the plus */
    int begin1 = m->myz * (nz/ZArraySize) ;
    int begin2 = m->myz * (nz/ZArraySize) ;
cphi1z.(phi1z.m->phi1z.begin1,&begin2) ;
```
```c
delete m;
NumPhi1s++;
if ( NumPhi1s < XArraySize*YArraySize )
    return;

gphi1z.(phi1z);
GlobalPintgr();
}

void 
ControlBloc::ReceivePhi2z(PhiMsg *m)
{
  // Store the phi z /
  int begin1 = m->myx * (mx/XArraySize);
  int begin2 = m->myy * (my/YArraySize);
cppphi2z.(phi2z,m-phi1,&begin1,&begin2);

delete m;
NumPhi2z++;
if ( NumPhi2z < XArraySize*YArraySize )
    return;

gphi2z.(phi2z);
GlobalPintgr();
}

void 
ControlBloc::GlobalPintgr()
{
NumPsi++;
if ( NumPsi == 6 )
{
  CPintgr(*td1 In GlobalPintgr(x*,MYPE);
gaintl.);
calli.(LatestRSDNorm,TotRSDNorm);

  CharmExit();
}
```
```c
message class NormsMsg {
  public: double num[9],
};

class ControlBoc : public groupmember {

  ControlBoc group myhandle;

  int istep;
  int itmax; // number of ADI iterations
  int MYPE;
  int NUMROCS;
  int nx, ny, nz;
  int NumRSDNoms;
  double TotRSDNorm[9];
  double LastRSDNorm[9];

double *phi1x, *phi2x, *phi1y, *phi2y, *phi1z, *phi2z;
  int NumPhi1x, NumPhi2x, NumPhi1y, NumPhi2y, NumPhi1z, NumPhi2z;
  int NumPhi;

  int NumCubesDone;
  int NumProcDone;

  int lasttime;
  int begintime;

  entry:
    ControlBoc(SomeMsg *m);

    void InitialSync(SomeMsg *m);
    void InitialSyncX(SomeMsg *m);

    void EndRHSFileSync(SomeMsg *m);
    void EndRHSFileSync(SomeMsg *m);
    void GlobalRSDNormS(NormsMsg *m);

    void EndADLFileSync(SomeMsg *m);
    void EndADLFileSync(SomeMsg *m);

  /**** CODE FOR computing the norms of pseudo-time iteration corrections ****/
  entry:
    void GlobalCNormS(NormsMsg *m);

  /***** CODE FOR STUFF AFTER FINISHING ADI LOOP *****/
  entry:
    void FinalSync(SomeMsg *m);
    void GlobalError(NormsMsg *m);

    void ReceivePhiIx(PhiMsg *m);
    void ReceivePhiIy(PhiMsg *m);
    void ReceivePhiIz(PhiMsg *m);
    void ReceivePhi2x(PhiMsg *m);
    void ReceivePhi2y(PhiMsg *m);
    void ReceivePhi2z(PhiMsg *m);

  public:
    void GlobalPrintG();
};
```
extern int JswepMapfn(int gid, int i, int j, int k);
extern int JswepMapfl(int gid, int i, int j, int k);
extern int JswepMapfr(int gid, int i, int j, int k);

void 
pval.(double *val)
{
  if (CMypel() == 10)
    CPrinf("[Ed] Val is %.12e\n", CMypel(), *val);
}

void 
pval.(int *i, double *val)
{
  if (CMypel() == 10)
    CPrinf("[Ed] %d %.12e\n", CMypel(), *i, *val);
}

Cube::Cube(SomeMsg *msg)
{
  intep = 0;
  getNn(nz, nz, nz, nz, kitmax);
  // Set all my local variables */
  mnx = thix;
  myy = thix;
  myz = thix;
  eachx = nx/XArraySize;
  eachy = ny/YArraySize;
  eachz = nz/ZArraySize;
  int alloc = eachx + 4;  // two boundary rows on either side
  int alloc = eachy + 4;
  int alloc = eachz + 4;

  // Allocate n_rad, n_tr in message to prevent copying while migrating */
  int cubecize = (sizetof(Cube)/8 + 1) * 8;  // make double word boundary
  int sizeof = cubecize;
  int alloc = alloc * alloc 
  alloc = sizeof(double);
  int alloc += 3*alloc;
  dataarea = new (sizeof) PackMsg;
  char pptr = dataarea->data + cubecize;
  u = (double *ptr);
  ptr += alloc;
  pptr = (double *)&ptr;
  pptr = (double *)&ptr;
cube.P

/* Allocate space for all local arrays */
a = new double[allocx*sizeof(double)];
b = new double[allocy*sizeof(double)];
c = new double[allocz*sizeof(double)];
d = new double[allocx*sizeof(double)];
e = new double[allocy*sizeof(double)];
memset(a, 0, sizeof(double));
memset(b, 0, sizeof(double));
memset(c, 0, sizeof(double));
memset(d, 0, sizeof(double));
memset(e, 0, sizeof(double));

/* set global indices of my array section */
gtx = eachx + myx + 1;
gty = eachy + myy + 1;
gtz = eachz + myz + 1;
igtx = &gtx;
igty = &gty;
igtz = &gtz;
igtx = &gtz;
igty = &gty;
igtz = &gtx;

setglobals(&eachx, &eachy, &eachz, &igtx, &igty, &igtz, &igtx, &igty, &igtz);

NumBoundaries = 0;
BfleErth();

// NEW
controlboc[LOCAL] = InitialSync(m);

DoneRHSJ = DoneRHSJ = DoneADJ = DoneADJ = 0;
InitializedKx = InitializedKx = 0;

void PrintArray(char *, double *, int);

void Cube::SetBoundary(BoundaryMag *m1)
{
  if (m1 == NULL)
BoundaryMsg *m1;
setglobals(&icons, &iinds, igs0x, igdx, igty, igmdy, igdz, igmdz);

switch( whicharrays )
{
    case U.ONLY:
        UBoundaryMsg *m = new ( &size ) UBoundaryMsg;
        int count = 1;
        getb(u, m->u, &type, &count);
        m1 = m;
        break;
    case RSD.ONLY:
        RSBoundaryMsg *m = new ( &size ) RSBoundaryMsg;
        int count = 1;
        getb(rad, m->rad, &type, &count);
        m1 = m;
        break;
    case ALL.ARRAYS:
        int sizes[4];
        sizes[0] = sizes[1] = size;
        sizes[2] = sizes[3] = size/sqrt(3);
        // c. d have only 3 subarrays
        AllBoundaryMsg *m = new ( sizes ) AllBoundaryMsg;
        int count = 1;
        getb(a, m->u, &type, &count);
        count = 1;
        getb(rad, m->rad, &type, &count);
        count = 1;
        getfl(c, m->c, &type, &count);
        getfl(d, m->d, &type, &count);
        m1 = m;
        break;
}

m1->type = type;
m1->whicharrays = whicharrays;
return m1;

void Cube::BvVErhs()
{
    setglobals(&icons, &iinds, igs0x, igdx, igty, igmdy, igdz, igmdz);
    setv(rad, igdx, igty, igmdy, igdz);
    setv(a, igdx, igty, igdz);
    erhs(frc, igdx, igty, igmdy, igdz);
}

/***************************** THESE ROUTINES ARE FOR SENDING BOUNDARIES *****************/

void Cube::SendPrev(int type)
{
    if ( myy == 0 )
        NumBoundaries++;
    return;
}

BoundaryMsg *m = GetBoundary(JPREV.U.ONLY);

if ( type == ADI )
    SendArray(cubarray, .C.K.sp.Cube.DoADILsweep, m, myx-1, myy, myz);
else
    SendArray(cubarray, .C.K.sp.Cube.DoRHS.I, m, myx-1, myy, myz);
}

void Cube::SendNext()
{
    if ( myy == XArraySize-1 )
        NumBoundaries++;
    return;
}

BoundaryMsg *m = GetBoundary(INEXT.U.ONLY);
SendArray(cubarray, .C.K.sp.Cube.DoRHS.I, m, myx+1, myy, myz);
}

void Cube::SendPrev(int type)
{
    if ( myy == 0 )
        NumBoundaries++;
    return;
}

BoundaryMsg *m = GetBoundary(JPREV.U.ONLY);
if ( type == ADI )
    SendArray(cubearray, .CK.ep.Cube_DoADILsweep, m, myx, myy-1, myy);
else
    SendArray(cubearray, .CK.ep.Cube_DoRHS,J, m, myx, myy-1, myy);
}

void Cube::SendNextJ()
{
    if ( myz == YArraySize-1 ) {
        NumBoundaries++;
        return;
    }

    BoundaryMsg *m = GetBoundary(JNEXT,U,ONLY);
    SendArray(cubearray, .CK.ep.Cube_DoRHS,J, m, myx, myy+1, myy);
}

void Cube::SendPrevK(int type)
{
    if ( myz == 0 ) {
        NumBoundaries++;
        return;
    }

    BoundaryMsg *m = GetBoundary(KPREV,U,ONLY);
    if ( type == ADI )
        SendArray(cubearray, .CK.ep.Cube_DoADILsweep, m, myx, myy, myz-1);
    else
        SendArray(cubearray, .CK.ep.Cube_DoRHS,K, m, myx, myy, myz-1);
}

void Cube::SendNextK()
{
    if ( myz == ZArraySize-1 ) {
        NumBoundaries++;
        return;
    }

    BoundaryMsg *m = GetBoundary(KNEXT,U,ONLY);
    SendArray(cubearray, .CK.ep.Cube_DoRHS,K, m, myx, myy, myz+1);
}

/******* THESE ROUTINES ARE FOR THE RHS SWEEPS *******/

void Cube::StartRHSJ(SomeMsg *m)
{
    istep++;
    if ( istep > itmax ) {
        SomeMsg *m2 = new SomeMsg;
        controlBox[m2] = FinalSync(m2);
        return;
    }

    SendPrev(RHS);
    SendNext();
    InitializedRHS,J = 1;
    if ( XArraySize == 1 )
        DoRHS,J(NULL);
}

void Cube::DoRHS,J(BoundaryMsg *m)
{
    if ( InitializedRHS,J == 0 ) {
        SendArray(thisgroup, .CK.ep.Cube_DoRHS,J, m, myx, myy, myz);
        return;
    }

    if ( NumBoundaries < 2 ) {
        SetBoundary(m);
        NumBoundaries++;
        if ( NumBoundaries < 2 )
            return;
    }

    setglobals(&eachx, &eachy, &eachz, igtx, igtnx, igty, igtdy, igtz, igtdz);
    rhx(u,us,frt,igtx, igtnx, igty, igtdy, igtz, igtdz);
    DoneRHS,J = 1;
    NumBoundaries = 0;
    InitializedRHS,J = 0;
    StartRHS,J(NULL);
}

void Cube::StartRHS,J(SomeMsg *m)
{
    SendPrevJ(RHS);
    SendNextJ();
    InitializedRHS,J = 1;
    if ( YArraySize == 1 )
```c
void Cube::DoRHSJ(NULL) {
}

void Cube::DoRHSJ(BoundaryMag *m) {
  if (DoneRHSJ == 0 || InitializedRHSJ == 0) {
    SendArray(thisgroup, CK Ja .Cube .DoRHSJ m, myx, myy, myz); return ;
  }
  if (NumBoundaries < 2) {
    SetBoundary(m);
    NumBoundaries++;
    if (NumBoundaries < 2) return ;
  }
  setglobals (k, b, k, k, c, c, d, s, g, g, g, g, g, g, g);
  rhy (a, nd, frc, gtxt, igemx, igemx, igemx, igemx, igemx, igemx, igemx);
 _DONE = 1;
  DoneRHSJ = 0;
  NumBoundaries = 0;
  InitializedRHSJ = 0;
  StartRHSJ (NULL);
}

void Cube::StartRHSJ(NumMag *m) {
  SendPrevK (RHS);
  SendNextK() ;
  InitializedRHSJ = 1;
  if (ZArraySize == 1) DoRHSJ(NULL);
}

void Cube::DoRHSJ(BoundaryMag *m) {
  if (DoneRHSJ == 0 || InitializedRHSJ == 0) {
    SendArray(thisgroup, CK Ja .Cube .DoRHSJ m, myx, myy, myz);
    return ;
  }
  if (NumBoundaries < 2) {
    SetBoundary(m);
    NumBoundaries++;
    if (NumBoundaries < 2) return ;
  }
  setglobals (k, b, k, k, c, c, d, s, g, g, g, g, g, g, g);
  rhy (a, nd, frc, gtxt, igemx, igemx, igemx, igemx, igemx, igemx, igemx, igemx);
  DONE = 1;
  DoneRHSJ = 0;
  NumBoundaries = 0;
 InitializedRHSJ = 0;
  StartRHSJ (NULL);
}

.semantic
This routine is for local RS D norms */
void Cube::LocalRSDNorms() {
  NormMag *m = new NormMag ;
  for (int i = 0; i < 1; i++)
    m = new[m] = 0.0;
  setglobals (k, b, k, k, c, c, d, s, g, g, g, g, g, g, g);
  controlOcc[0] = GlobalRSDNorm (m);
}

These 3 routines are for the ADI sweeps */
void Cube::StartADI_Sweep(NumMag *m) {
  SendPrevI (ADI);
  if (myz == XArraySize - 1)
    NumBoundaries++;
  InitializedSweep = 1;
  if (XArraySize == 1)
    DoADI_Sweep (NULL);
}

void
```
Cube::DoADLsweep(BoundaryMsg *m)
{
  if (Initializedsweep == 0)
    SendArray(thigroup, CK::Cube::DoADLsweep, m, myx, myy, myz);
  return;
}

if (NumBoundaries < 2 || m != NULL)
  NumBoundaries++;

if (NumBoundaries < 2)
return;

NumBoundaries = 0;
Initializedsweep = 0;  // reset for next run

setglobals(koachx, koachy, koachz, igtxt, igtdx, igtdy, igtdz, igtdn);
adxz(a, red, frct, a, b, c, e, igdx, igdxe, igdys, igdzn);

if (myx != XArraySize-1)
  BoundaryMsg = GetBoundary(INEXT, ALL, ARRAYS);
  SendArray(cubearray, CK::Cube::DoADLsweep, m2, myx+1, myy, myz);
else
  ADLback sweep(NULL);

void
Cube::ADLback sweep(BoundaryMsg *m)
{
  if (myy != YArraySize-1)
    SetBoundary(m);

  setglobals(koachx, koachy, koachz, igtxt, igtdx, igtdy, igtdz, igtdn);
  adxz(a, red, frct, a, b, c, e, igdx, igdxe, igdys, igdzn);

  if (myx != 0)
    BoundaryMsg = GetBoundary(IPREV, BSD, ONLY);
    SendArray(cubearray, CK::Cube::ADLback sweep, m2, myx-1, myy, myz);

  #ifdef NOSYNCS
else
  SomeMsg = new SomeMsg;
  control[0]=EndADLSync(m2);
  #endif
  DoneADII = 1;

  void
Cube::StartADLsweep(SomeMsg *msg)
{
  SendPrev(ADI);

  if (myy == 0)
    NumBoundaries++;

  Initializedsweep = 1;

  if (YArraySize == 1)
    DoADLsweep(NULL);

  void
Cube::DoADLsweep(BoundaryMsg *m)
{
  if (DoneADII == 0 || Initializedsweep == 0)
    SendArray(thigroup, CK::Cube::DoADLsweep, m, myx, myy, myz);
  return;

  if (NumBoundaries < 2 || m != NULL)
    SetBoundary(m);

  NumBoundaries++;

  if (NumBoundaries < 2)
    return;

  NumBoundaries = 0;
  Initializedsweep = 0;  // reset for next run

  setglobals(koachx, koachy, koachz, igtxt, igtdx, igtdy, igtdz, igtdn);
  adxz(a, red, frct, a, b, c, e, igdx, igdxe, igdys, igdzn);

  if (myy != YArraySize-1)
    BoundaryMsg = GetBoundary(INEXT, ALL, ARRAYS);
void Cube::ADBackJswep(BoundaryMsg *m)
{
    if (mry != ZArraySize - 1) {
        SetBoundary(m);
    }
    setglobals(lenachx, lenachy, lenachz, igpx, igpy, igpz, igpxy, igpxz, igpyz, igpzd);
    badiz(xrd, frcx, a, b, c, d, e, igpx, igpy, igpz, igpxy, igpxz, igpyz, igpzd);
    if (mry != 0) {
        BoundaryMsg *m2 = GetBoundary(KPRES.BRD.ONLY);
        SendArray(cubearray, CK.sp.Cube, ADBackJswep, m2, mry, mry - 1, mry);
    }
    #ifdef NOSYNCS
    SomeMsg *m2 = new SomeMsg;
    controlbuf[l] = EndADLJSync(m2);
    #endif
    DoneADIY = 1;
    #ifdef NOSYNCS
    SomeMsg *m = new SomeMsg;
    SendArray(cubearray, CK.sp.Cube, StartADI.Kswep, m, mry, mry, mry);
    #ifdef TRANPOSE
    migrate(KswepMapfn);
    #endif
    #endif
}

void Cube::StartADI.Kswep(SomeMsg *msg)
{
    SendPrevK(ADI);
    if (mzy == ZArraySize - 1)
        NumBoundaries++;
    InitializedKswep = 1;
    if (ZArraySize == 1)
        return;
}

void Cube::DoADI.Kswep(Null)
{
}

void Cube::DoADI.Kswep(BoundaryMsg *m)
{
    if (DoneADIY == 0 || InitializedKswep == 0)
    {
        SendArray(cubearray, CK.sp.Cube, ADKswep, m, mry, mry, mry);
        return;
    }
    if (DoneADIY == 0 && mry != NULL)
    {
        SetBoundary(m);
        NumBoundaries++;
        if (NumBoundaries < 2)
            return;// reset
    }
    NumBoundaries = 0;
    DoneADIY = 0;
    InitializedKswep = 0;
    // reset for next run
    setglobals(lenachx, lenachy, lenachz, igpx, igpy, igpz, igpxy, igpxz, igpyz, igpzd);
    badiz(xrd, frcx, a, b, c, d, e, igpx, igpy, igpz, igpxy, igpxz, igpyz, igpzd);
    if (mzy != ZArraySize - 1)
    {
        BoundaryMsg *m2 = GetBoundary(KPRES.ACCESS.ARRAYS);
        SendArray(cubearray, CK.sp.Cube, ADKswep, m2, mzy, mzy, mzy + 1);
    }
    else
        ADBackJswep(NULL);
}

void Cube::ADBackKswep(BoundaryMsg *m)
{
    if (mzy == ZArraySize - 1)
    {
        SetBoundary(m);
    }
    setglobals(lenachx, lenachy, lenachz, igpx, igpy, igpz, igpxy, igpxz, igpyz, igpzd);
    badiz(xrd, frcx, a, b, c, d, e, igpx, igpy, igpz, igpxy, igpxz, igpyz, igpzd);
    if (mzy != 0)
    {
        BoundaryMsg *m2 = GetBoundary(KPRES.BRD.ONLY);
        SendArray(cubearray, CK.sp.Cube, ADBackKswep, m2, mzy, mzy - 1);
    }
    #ifdef NOSYNCS
    else
    #endif
}
SomeMsg *m2 = new SomeMsg;
    controlbock[0] = EndADILKSync(m2);
}
#endif

mymsgid(u,ro,l,igtxt, igendx, igxty, igendy, igtxt, igendz);

#define NOSYNCS
    SomeMsg *num = new SomeMsg;
    SendArray(thegroup, CKsp,Cube,StartRHS1, mm, myx, myy, mzz);
#define TRANSPOSE
    migrate[sweepMapfn];
#endif
#endif

/** THIS ROUTINE IS FOR LOCAL NORMS of pseudo-time iteration correction*****/
void Cube::LocalCNorms(SomeMsg *m2)
{
    NormsMsg *m = new NormsMsg
    for (int i=0, i<5, i++)
        m->sum[i] = 0.0;
    setglobal((koachx, kouchy, kouchz, igtxt, igendx, igxty, igendy, igtxt, igendz);
    cnorms[0].m->sum);
    controlbock[0] = GlobalCNorms(m);
}

******/ CODE FOR STUFF AFTER FINISHING ADI LOOP ******/
void Cube::FinishADI(SomeMsg *m2)
{
    /* This is for the local error */
    NormsMsg *m = new NormsMsg
    for (int i=0, i<5, i++)
        m->sum[i] = 0.0;
    setglobal((koachx, kouchy, kouchz, igtxt, igendx, igxty, igendy, igtxt, igendz);
    error[0].m->sum, igtxt, igendx, igxty, igendy, igtxt, igendz);
    controlbock[0] = GlobalError(m);
}

/** THIS ROUTINE IS for local pegdy() ******/
void Cube::LocalPegdy(SomeMsg *m2)
{
    /* If on a boundary, send phi's to proc 0 */
    setglobal((koachx, kouchy, kouchz, igtxt, igendx, igxty, igendy, igtxt, igendz);
    if (myx == 0) {
        int size = (eachx+4) * (eachx+4);
        PhiMsg *m = new (size) PhiMsg;
        m->myy = myy; m->myz = myz; m->mxz = myz;
        memset(m->mphi,0,sizeof(double)/size);
        getix(u, m->mphi);
        controlbock[0] = ReceivePhi2x(m);
    }
    if (myy == XArraySize-1) {
        int size = (eachy+4) * (eachy+4);
        PhiMsg *m = new (size) PhiMsg;
        m->myx = myx; m->myz = myz; m->myz = myz;
        memset(m->mphi,0,sizeof(double)/size);
        getix(u, m->mphi);
        controlbock[0] = ReceivePhi2y(m);
    }
    if (myz == YArraySize-1) {
        int size = (eachz+4) * (eachz+4);
        PhiMsg *m = new (size) PhiMsg;
        m->myx = myx; m->myy = myy; m->myz = myz;
        memset(m->mphi,0,sizeof(double)/size);
        getiz(u, m->mphi);
        controlbock[0] = ReceivePhi2z(m);
    }
    if (myz == ZArraySize-1) {
        int size = (eachz+4) * (eachz+4);
        PhiMsg *m = new (size) PhiMsg;
        m->myx = myx; m->myy = myy; m->myz = myz;
        memset(m->mphi,0,sizeof(double)/size);
        getiz(u, m->mphi);
        controlbock[0] = ReceivePhi2z(m);
    }
}
cube.P

PhMsg *m = new (knew) PhMsg;
mx = myx = mry = myy = mxz = myz;
memset(m+->phi, 0, sizeof(double)*size);
gtx = (m +-> phi);
controlc[0] = ReceivePhi2(m);
}

/* These are the pack and unpack functions for the cube char */

ArrayMsg *
Cube::pack(EntryPointType *unpackep)
{
  *unpackep = L(Cube::Unpack);
  memcpy(dataarea + data, this, sizeof(Cube));
  delete a;
  delete b;
  delete c;
  delete d;
  delete e;

  return dataarea;
}

void Cube::Unpack(PackMsg ep)
{
  char *ptr = p->data;
  memcpy(this, ptr, sizeof(Cube));

  int allocx = mx/XArraySize + 4;  // two boundary rows on either side
  int allocy = my/YArraySize + 4;
  int allocz = nz/ZArraySize + 4;

  /* Allocate space for local arrays */
  a = new double[3 * allocx * allocy * allocz];
  b = new double[3 * allocx * allocy * allocz];
  c = new double[3 * allocx * allocy * allocz];
  d = new double[3 * allocx * allocy * allocz];
  e = new double[3 * allocx * allocy * allocz];

  igtx = &gtx;
  igx = &igtx;
  igtx = &igx;
  igy = &igy;
  igy = &igy;
  igz = &igz;

  int cubenew = (sizeof(Cube) / 8 + 1) * 8;
  int eacharray = 5 * allocx * allocy * allocz * sizeof(double);
  ptr += cubenew;
  u = (double *)ptr;
  ptr += eacharray;
  rd = (double *)ptr;
  ptr += eacharray;
  frc = (double *)ptr;

  dataarea = p;
}

void PrintArray(char *file, double *a, int size)
{
  FILE *fp = fopen(file, "w");
  for (int i = 0; i < size; i++)
    fprintf(fp, "%f\t", a[i]);
  fprintf(fp, "\n");
  fclose(fp);
}
#define XARRAYSIZE 1
#define YARRAYSIZE 1
#define ZARRAYSIZE 1
#define IPREV 1
#define INEXT 2
#define JPREV 3
#define JNEXT 4
#define KPREV 5
#define KNEXT 6
#define UONLY 1
#define RSDONLY 2
#define ALLARRAYS 3
#define ADI 123
#define RHS 456

message class SourceMsg : public ArrayMsg { public: int x; };
message class BoundaryMsg : public ArrayMsg { public: int type; int whicharrays; };
message class UBoundaryMsg : public BoundaryMsg { public: double u[VARSIZE]; // MUST be aligned at 8 byte boundary! };
message class RSDBoundaryMsg : public BoundaryMsg { public: double rds[VARSIZE]; };
message class AllBoundaryMsg : public BoundaryMsg { public: double u[VARSIZE];
  double rds[VARSIZE];
  double c[VARSIZE];
  double d[VARSIZE]; };
message class PhiMsg { public: int myx, myy, myz;
  int type;
  double phi[VARSIZE]; };
message class PackMsg : public ArrayMsg { public: char data[VARSIZE]; };

char class Cube : public array { public:
  int istep, itmax;
  int myx, myy, myz;
  int gx, gy, gz;
  int gndx, gndy, gndz;
  int sigdx, sigdy, sigdz, sigsdx, sigsdy, sigsdz;
  int eacx, eacy, eacz;
  int NumBoundaries;
  PackMsg *dataarea;
  double *u, *rds, *sfrt;
  double *a, *b, *c, *d, *e;
  int DoneHSI, DoneHSJ, DoneADI, DoneADJ;
  int InitializedSweep, InitializedJsweep, InitializedKsweep;
  int InitializedHSI, InitializedHSJ, InitializedHJS;
  entry:
    Cube(SomeMsg *m) ;

  public:
    void SetBoundary(BoundaryMsg *m1) ;
    BoundaryMsg * GetBoundary(int type, int whicharrays) ;
    void BrvExh() ;
    void SendPreV(int) ;
    void SendNextV() ;
    void SendPreVJ(int) ;
    void SendNextVJ() ;
    void SendPreVK(int) ;
    void SendNextVK() ;
    void LocalRSDNorm() ;

  /*************** THESE 3 EPS ARE FOR THE RHS SWEEPS *************/
  entry:
    void StartHSJ(SomeMsg *m) ;
void DoRHS.J(BoundaryMsg *m) ;

void StartRHS.J(SomeMsg *m) ;

void DoRHS.J(BoundaryMsg *m) ;

void StartRHS.K(SomeMsg *m) ;

void DoRHS.K(BoundaryMsg *m) ;

/*************** THESE 3 Eqs ARE FOR THE ADI SWEEPS ************/
entry:
  void StartADLsweep(SomeMsg *msg) ;
  void DoADLsweep(BoundaryMsg *m) ;
  void ADBack.sweep(BoundaryMsg *m) ;
  void StartADLsweep(SomeMsg *msg) ;
  void DoADLsweep(BoundaryMsg *m) ;
  void ADBack.sweep(BoundaryMsg *m) ;
  void StartADI.Ksweep(SomeMsg *msg) ;
  void DoADI.Ksweep(BoundaryMsg *m) ;
  void ADBack.Ksweep(BoundaryMsg *m) ;

/******** THIS ROUTINE IS FOR LOCAL NORMS of pseudo-time iteration corrections**********/
  void LocalCNorms(SomeMsg *m) ;
  void FinishedADI.sweep(SomeMsg *) ;

/******** THIS ROUTINE IS FOR local printr() ******/
entry:
  void LocalPrintr(SomeMsg *m) ;

/******** These are the pack and unpack functions for the cube char ******/
public:
  ArrayMsg *pack(EntryPointType *unpackptr) ;

entry:
  void Unpack(PackMsg *p) ;
} ;
```c
#include "stdio.h"
#include "array.h"
#include "cube.h"
#include "controlboc.h"
#include "main.h"

extern "C" MAIN(int); 

MAIN(int)
{}

extern "C" double sqrt(double);

readonly ControlBoc group controlboc;
readonly Cube group cubearray;
readonly int NumCubes;

int BrunoCapelloMapFn(int gid, int i, int j, int k)
{
  if ( XArraySize != YArraySize && YArraySize != ZArraySize )
    CPrintf("ERROR: ArraySize is not same in all dim(n)!");

  /* General expression for 3-D Bruno-Capello is :  
     Map(i,j,k) = i((k-week)/k) + (j-week)/k 
   where s is the side of the cube  
   This is ONLY for the case where ArraySize is sqrt(NumProcs).  
   E.g. 64 cubes on 16 procs or 8 cubes on 4 procs */
  return ( XArraySize*(i+k*XArraySize)%XArraySize ) + 
          (j+k*XArraySize)%XArraySize ;
}

int NaiveMapFn(int gid, int i, int j, int k)
{  
  if ( XArraySize != YArraySize && YArraySize != ZArraySize )
    CPrintf("ERROR: ArraySize is not same in all dim(n)!");

  return ( 2*(i%2) + j%2 );
}

int IwsepMapFn(int gid, int i, int j, int k)
{
  return ( ZArraySize * i + k ) ;
}

int IwsepMapFn(int gid, int i, int j, int k)
{ /* Long blocks given to one proc */
  return (XArraySize * k + i) ;
}

int IwsepMapFn(int gid, int i, int j, int k)
{ /* Long blocks given to one proc */
  return (YArraySize * i + j) ;
}

/** MAIN CHARE **/

main::main()
{
  CPrintf("Started Charm++ pgm. creating ControlBoc(n)!");
  NumCubes = XArraySize * YArraySize * ZArraySize ;
  SomeMsg *m = new SomeMsg ;
  controlboc = newgroup ControlBoc(m) ;
  NumCubesDone = 0 ;
}

void main::InitialSync(SomeMsg *m)
{
  NumCubesDone++ ;
  if ( NumCubesDone < CNumProcs() )
  
    delete m ;
    return ;

  NumCubesDone = 0 ;
  cubearray = CreateArray(&Cube, &Cube, &Cube, &Cube, &Cube, 
                         &BrunoCapelloMapFn, 
                         XArraySize, YArraySize, ZArraySize);
}
```
class main
{
    int NumCubesDone;

public:
    main();

entry:
    void InitialSync(SomeMsg *m);
};
implicit real*8 (a-h,o-z)

parameter ( isiz1 = 64, isiz2 = 64, isiz3 = 64 )
parameter ( xsize = 36, ysize = 36, zsize = 36 )
parameter ( eachx = 32, eachy = 32, eachz = 32 )
parameter ( c1 = 1.40d+00, c2 = 0.40d+00,
$ c3 = 1.00d-01, c4 = 1.00d+00,
$ c5 = 1.40d+00 )

real timer, tstart, tend

integer ex, ey, ez, ex1, ey1, ez1, ex2, ey2, ez2,
$ sx, sy, sz,
$ sx1, syl, sz1, sx2, sy2, sz2,
$ sx3, ex1, sy3, ey1, sz3, ez3,
$ gstx, gendx, gsty, gendy, gstdz, gendz,
$ sxm2, sym2, szm2, sxm2, sym2, szm2,
$ sxm1, sym1, szm1, sxm1, sym1, szm1

common parallel/ ex, ey, ez, ex1, ey1, ez1, ex2, ey2, ez2,
$ sx, sy, sz,
$ sx1, syl, sz1, sx2, sy2, sz2,
$ sx3, ex1, sy3, ey1, sz3, ez3,
$ gstx, gendx, gsty, gendy, gstdz, gendz,
$ sxm2, sym2, szm2, sxm2, sym2, szm2,
$ sxm1, sym1, szm1, sxm1, sym1, szm1

common boundaries/ bx1(5,isiz2,isiz3), bxnx(5,isiz2,isiz3),
$ by1(5,isiz1,isiz3), byny(5,isiz1,isiz3),
$ bz1(5,isiz1,isiz2), bznz(5,isiz1,isiz2)

common/cgrid/ nx, ny, nz,
$ iil, ii2, ji1, ji2, ki1, ki2, idum1,
$ dx1, deta, dzeta,
$ tx1, tx2, tx3,
$ ty1, ty2, ty3,
$ tz1, tz2, tz3

common/disp/ dx1,dx2,dx3,dx4,dx5,
$ dy1,dy2,dy3,dy4,dy5,
$ dz1,dz2,dz3,dz4,dz5,
$ dssp

common/cvvar/ u(5,isiz1,isiz2,isiz3),
$ rsd(5,isiz1,isiz2,isiz3),
$ frct(5,isiz1,isiz2,isiz3)
subroutine initsp(ipe)

***driver for the performance evaluation of the solver for
five coupled, nonlinear partial differential equations.

Author: Sisira Weeratunga
NASA Ames Research Center
(10/25/90)

include 'appsp.incl'

***open file for input data
open (unit=5, file='appsp.input', status='old',
  access='sequential', form='formatted')
rewind 5

***read the unit number for output data
read (5,*)
read (5,*) iout

***flag that controls printing of the progress of iterations
read (5,*)
read (5,*) ipr, inorm

***set the maximum number of pseudo-time steps to be taken
read (5,*)
read (5,*) itmax

***set the magnitude of the time step
read (5,*)
dt

***set the value of over-relaxation factor for SSOR iterations
read (5,*)
read (5,*) omega

***set the steady-state residual tolerance levels
read (5,*)
read (5,*) tolrsd(1), tolrsd(2),
  tolrsd(3), tolrsd(4), tolrsd(5)

***read problem specification parameters

***specify the number of grid points in xi, eta and zeta directions
read (5,*)
read (5,*) nx, ny, nz

***open the file for output data
if (iout.eq.7) then
  open (unit=7, file='output.data', status='unknown',
    access='sequential', form='formatted')
  rewind 7
end if

if (nx .lt. 5) .or.
  write (*,2001)
  2001
  format (5x,'PROBLEM SIZE IS TOO SMALL - ',
    /5x,'SET EACH OF NX, NY AND NZ AT LEAST EQUAL TO 5')
  stop

end if

if (ny .lt. 5) .or.
  write (*,2002)
  2002
  format (5x,'PROBLEM SIZE IS TOO LARGE - ',
    /5x,'NX, NY AND NZ SHOULD BE LESS THAN OR EQUAL TO ',
    /5x,'ISIZ1, ISIZ2 AND ISIZ3 RESPECTIVELY')
end if

dx1 = 1.0d+00 / (nx - 1)
deta = 1.0d+00 / (ny - 1)
dzeta = 1.0d+00 / (nz - 1)
tx1 = 1.0d+00 / (dx1 * dx1)
tx2 = 1.0d+00 / (2.0d+00 * dx1)
tx3 = 1.0d+00 / dx1
ty1 = 1.0d+00 / (deta * deta)
ty2 = 1.0d+00 / (2.0d+00 * deta)
ty3 = 1.0d+00 / deta
tz1 = 1.0d+00 / (dzeta * dzeta)
tz2 = 1.0d+00 / (2.0d+00 * dzeta)
tz3 = 1.0d+00 / dzeta

ii1 = 2
ii2 = nx - 1
jl1 = 2
jl2 = ny - 2
kl1 = 3
kl2 = nz - 1

frc1 = 0.0d+00
frc2 = 0.0d+00
frc3 = 0.0d+00

dx1 = 0.75d+00
dx2 = dx1
dx3 = dx1
dx4 = dx1
dx5 = dx1
dy1 = 0.75d+00
dy2 = dy1
dy3 = dy1
dy4 = dy1
dy5 = dy1
dz1 = 1.00d+00
dz2 = dz1
dz3 = dz1
dz4 = dz1
dz5 = dz1

dssp = ( max ( dx1, dy1, dz1 ) ) / 4.0d+00

cce(1,1) = 2.0d+00
cce(1,2) = 0.0d+00
cce(1,3) = 0.0d+00
cce(1,4) = 4.0d+00
cce(1,5) = 5.0d+00
cce(1,6) = 3.0d+00
cce(1,7) = 5.0d-01
cce(1,8) = 2.0d-02
cce(1,9) = 1.0d-02
cce(1,10) = 3.0d-02
cce(1,11) = 5.0d-01
cce(1,12) = 4.0d-01

cce(1,13) = 3.0d-01

cce(2,1) = 1.0d+00
cce(2,2) = 0.0d+00
cce(2,3) = 0.0d+00

cce(2,4) = 0.0d+00
cce(2,5) = 1.0d+00
cce(2,6) = 2.0d+00
cce(2,7) = 3.0d+00
cce(2,8) = 1.0d-02
cce(2,9) = 3.0d-02
cce(2,10) = 2.0d-02
cce(2,11) = 4.0d-01
cce(2,12) = 3.0d-01

cce(2,13) = 5.0d-01

cce(3,1) = 2.0d+00
cce(3,2) = 2.0d+00
cce(3,3) = 0.0d+00
cce(3,4) = 0.0d+00
cce(3,5) = 0.0d+00
cce(3,6) = 2.0d+00
cce(3,7) = 3.0d+00
cce(3,8) = 4.0d-02
cce(3,9) = 3.0d-02
cce(3,10) = 5.0d-02
cce(3,11) = 3.0d-01
cce(3,12) = 5.0d-01

cce(3,13) = 4.0d-01

cce(4,1) = 2.0d+00
cce(4,2) = 2.0d+00
cce(4,3) = 0.0d+00
cce(4,4) = 0.0d+00
cce(4,5) = 0.0d+00
cce(4,6) = 2.0d-01
cce(4,7) = 3.0d-01

cce(4,8) = 3.0d-02
cce(4,9) = 5.0d-02
cce(4,10) = 4.0d-02
cce(4,11) = 2.0d-01
cce(4,12) = 1.0d-01

cce(4,13) = 3.0d-01

cce(5,1) = 5.0d+00
cce(5,2) = 4.0d+00
cce(5,3) = 3.0d+00
cce(5,4) = 2.0d+00
cce(5,5) = 1.0d-01

cce(5,6) = 4.0d-01

cce(5,7) = 3.0d-01

cce(5,8) = 5.0d-02

cce(5,9) = 4.0d-02

cce(5,10) = 3.0d-02

cce(5,11) = 1.0d-01
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ce(5,12) = 3.0d-01
ce(5,13) = 2.0d-01

return
end

*************** this control code is now in C++ ***************

***set the boundary values for dependent variables
  call setbv

***set the initial values for dependent variables
  call setiv

***compute the forcing term based on prescribed exact solution
  call erhs

***perform scalar approximate factorization iterations
  call adi

***compute the solution error
  call error

***compute the surface integral
  call pintgr

***verification test
  call verify ( rsdum, errum, frc )

***print the CPU time
  write (iout,1001) ttotal
c1001 format (/5x,'Total CPU time = ',1pe12.4,' sec.' )

return
end

*****************************************************************

*****************************************************************

subroutine getns ( inx, iny, inz, iitmax )

***return isiz parameters

Author: Sanjeev Krishnan

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include 'appsp.incl'

integer inx, iny, inz

inx = nx
iny = ny
inz = nz

iitmax = iitmax

return
end

subroutine setglobals ( iex, iey, iez, igstx, igendx, igstyz, igendy, igstz, igendz)

$  

***set global variables for parallelization

Author: Sanjeev Krishnan

include 'appsp.incl'

integer iex, iey, iez, igstx, igendx, igstyz, igendy, igstz, igendz

NOTE : sx1, ex, sx2, ex2 etc
change from cube to cube. So they have to be passed as parameters
or set in setglobals.

ex = iex + 2
ey = iey + 2
ez = iez + 2
sx = 3
sy = 3
sz = 3

xsize = iex + 4
ysize = iey + 4
zsize = iez + 4

gstx = igstx
gstyx = igstyx
gstz = igstz
gendx = igendx
gendy = igendy
gendz = igendz

sx1 = sx
syl = sy
szl = sz
if ( gstx .eq. 1 ) sx1 = sx + 1
if ( gstyx .eq. 1 ) syl = sy + 1
if ( gstdz .eq. 1 ) szl = sz + 1

c
exl = ex
eyl = ey
ezl = ez
if ( gsendx .eq. nx ) exl = ex - 1
if ( gsendy .eq. ny ) eyl = ey - 1
if ( gsendz .eq. nz ) ezl = ez - 1

c
sx2 = sx
sy2 = sy
sz2 = sz
if ( gastx .eq. 1 ) sx2 = sx + 2
if ( gaty .eq. 1 ) sy2 = sy + 2
if ( gatz .eq. 1 ) sz2 = sz + 2

c
ex2 = ex
ey2 = ey
ez2 = ez
if ( gsendx .eq. nx ) ex2 = ex - 2
if ( gsendy .eq. ny ) ey2 = ey - 2
if ( gsendz .eq. nz ) ez2 = ez - 2

c
sx3 = sx
sy3 = sy
sz3 = sz
if ( gastx .eq. 1 ) sx3 = sx + 3
if ( gaty .eq. 1 ) sy3 = sy + 3
if ( gatz .eq. 1 ) sz3 = sz + 3

c
ex3 = ex
ey3 = ey
ez3 = ez
if ( gsendx .eq. nx ) ex3 = ex - 3
if ( gsendy .eq. ny ) ey3 = ey - 3
if ( gsendz .eq. nz ) ez3 = ez - 3

/* some more bounds: Sanjeev */

sx1 = sx - 1
sy1 = sy - 1
sz1 = sz - 1
if ( gastx .eq. 1 ) sx1 = sx
if ( gaty .eq. 1 ) sy1 = sy
if ( gatz .eq. 1 ) sz1 = sz
ex1 = ex + 1
ey1 = ey + 1
ez1 = ez + 1
if ( gsendx .eq. nx ) ex1 = ex
if ( gsendy .eq. ny ) ey1 = ey
if ( gsendz .eq. nz ) ez1 = ez

c
sx2 = sx - 2
sy2 = sy - 2
sz2 = sz - 2
if ( gstdx .eq. 1 ) sx2 = sx
if ( gaty .eq. 1 ) sy2 = sy

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if ( gstdz .eq. 1 ) szm2 = sz
exm2 = ex + 2
eym2 = ey + 2
ezm2 = ez + 2
if ( gsendx .eq. nx ) exm2 = ex
if ( gsendy .eq. ny ) eym2 = ey
if ( gsendz .eq. nz ) ezm2 = ez

c
return
end

/* function iglob (i) */

c
include 'appsp.incl'
integer i,iglob

c
itemp = gastx + i - 3
iglob = itemp

c
return
end

/* function jglob (j) */

c
include 'appsp.incl'
integer j,jglob


c
jtemp = gaty + j - 3
jglob = jtemp

c
return
end

/* function kglob (k) */

c
include 'appsp.incl'
integer k,kglob


c
ktemp = gatz + k - 3
kglob = ktemp

c
return
end

/* subroutine setb(b, data, type) */

c
include 'appsp.incl'
real *8 b(5, xsize, ysize, zsize)
real *8 data(*)
integer type
integer count

count = 1

if ( type .eq. 2 ) then
  do i = sx-2, sx-1
    do j = sy, ey
      do k = sz, ez
        do m = 1, 5
          b(m, i, j, k) = data(count)
          count = count + 1
        end do
      end do
    end do
  end do
else if ( type .eq. 1 ) then
  do i = ex+1, ex+2
    do j = sy, ey
      do k = sz, ez
        do m = 1, 5
          b(m, i, j, k) = data(count)
          count = count + 1
        end do
      end do
    end do
else if ( type .eq. 4 ) then
  do i = sx, ex
    do j = ey-2, ey-1
      do k = sz, ez
        do m = 1, 5
          b(m, i, j, k) = data(count)
          count = count + 1
        end do
      end do
    end do
else if ( type .eq. 3 ) then
  do i = sx, ex
    do j = ey+1, ey+2
      do k = sz, ez
        do m = 1, 5
          b(m, i, j, k) = data(count)
          count = count + 1
        end do
      end do
    end do
else if ( type .eq. 6 ) then
  do i = ex, ex
    do j = sy, ey
      do k = sz-2, sz-1
        do m = 1, 5
          b(m, i, j, k) = data(count)
          count = count + 1
        end do
      end do
    end do
else if ( type .eq. 5 ) then
  do i = sx, ex
    do j = ey, ey
      do k = ez+1, ez+2
        do m = 1, 5
          b(m, i, j, k) = data(count)
          count = count + 1
        end do
      end do
    end do
end do
else if ( type .eq. 1 ) then
  do i = ex+1, ex+2
    do j = sy, ey
      do k = sz, ez
        do m = 1, 3
          cd(i, j, k, m) = data(count)
          count = count + 1
        end do
      end do
    end do
else if ( type .eq. 1 ) then
  do i = ex+1, ex+2
    do j = sy, ey
      do k = sz, ez
        do m = 1, 3
          cd(i, j, k, m) = data(count)
          count = count + 1
        end do
      end do
    end do
end do

end do

end do

end do

end if

c
return
end

c

c

subroutine setcd(cd, data, type)
c
include 'appsp.incl'
c
real *8 cd(xsize, ysize, zsize, 3)
c
real *8 data(*)
c
integer type
integer count
c
count = 1

c
if ( type .eq. 2 ) then
  do i = sx-2, sx-1
    do j = sy, ey
      do k = sz, ez
        do m = 1, 5
          cd(i, j, k, m) = data(count)
          count = count + 1
        end do
      end do
    end do
  end do
else if ( type .eq. 1 ) then
  do i = ex+1, ex+2
    do j = sy, ey
      do k = sz, ez
        do m = 1, 3
          cd(i, j, k, m) = data(count)
          count = count + 1
        end do
      end do
    end do
  end do
else if ( type .eq. 4 ) then
  do i = sx, ex
    do j = ey-2, ey-1
      do k = sz, ez
        do m = 1, 5
          cd(i, j, k, m) = data(count)
          count = count + 1
        end do
      end do
    end do
else if ( type .eq. 3 ) then
  do i = sx, ex
    do j = ey+1, ey+2
      do k = sz, ez
        do m = 1, 5
          cd(i, j, k, m) = data(count)
          count = count + 1
        end do
      end do
    end do
else if ( type .eq. 6 ) then
  do i = ex, ex
    do j = sy, ey
      do k = sz-2, sz-1
        do m = 1, 5
          cd(i, j, k, m) = data(count)
          count = count + 1
        end do
      end do
    end do
end do
end do
end do
end do
end do
else if ( type .eq. 4 ) then
do i = sx, ex
  do j = sy-2, sy-1
    do k = sz, ez
      do m = 1, 3
        cd(i,j,k,m) = data(count)
        count = count + 1
      end do
    end do
  end do
end do
else if ( type .eq. 3 ) then
do i = sx, ex
  do j = ey+1, ey+2
    do k = sz, ez
      do m = 1, 3
        cd(i,j,k,m) = data(count)
        count = count + 1
      end do
    end do
  end do
end do
else if ( type .eq. 6 ) then
do i = sx, ex
  do j = sy, ey
    do k = sz-2, sz-1
      do m = 1, 3
        cd(i,j,k,m) = data(count)
        count = count + 1
      end do
    end do
  end do
end do
else if ( type .eq. 5 ) then
do i = sx, ex
  do j = sy, ey
    do k = ez+1, ez+2
      do m = 1, 3
        cd(i,j,k,m) = data(count)
        count = count + 1
      end do
    end do
  end do
end do
else if ( type .eq. 4 ) then
do i = sx, ex
  do j = ey-1, ey
    do k = sz, ez
      do m = 1, 5
        data(count) = b(m,i,j,k)
        count = count + 1
      end do
    end do
  end do
end do
else if ( type .eq. 5 ) then
do i = sx, ex
  do j = sy, ey
    do k = sz, sz+1
      do m = 1, 5
        data(count) = b(m,i,j,k)
        count = count + 1
      end do
    end do
end do
c
return
c
c subroutine getb(b, data, type, count)
data(count) = b(m,i,j,k)
count = count + 1
end do
end do
end do
else if ( type .eq. 6 ) then
do i = sx, ex
do j = sy, ey
do k = ez-1, ez
do m = 1,3
data(count) = b(m,i,j,k)
count = count + 1
end do
end do
endif

return
end
c

c subroutine gcd(c, data, type, count)
c
include 'appsp.incl'
c
real *8 cd(xsize,ysize,zsize,3)
real *8 data(*)
integer type
integer count

if ( type .eq. 1 ) then
do i = sx, sx+1
do j = sy, ey
do k = sz, ez
do m = 1,3
data(count) = cd(i,j,k,m)
count = count + 1
end do
end do
else if ( type .eq. 2 ) then
do i = ex-1, ex
do j = sy, ey
do k = sz, ez
do m = 1,3
data(count) = cd(i,j,k,m)
count = count + 1
end do
end do
else if ( type .eq. 3 ) then
do i = sx, ex
do j = sy, sy+1
do k = sz, ez
do m = 1,3
data(count) = cd(i,j,k,m)
count = count + 1
end do
end do
else if ( type .eq. 4 ) then
do i = sx, ex
do j = ey-1, ey
do k = sz, ez
do m = 1,3
data(count) = cd(i,j,k,m)
count = count + 1
end do
end do
else if ( type .eq. 5 ) then
do i = sx, ex
do j = sy, ey
do k = sz, sz+1
do m = 1,3
data(count) = cd(i,j,k,m)
count = count + 1
end do
end do
else if ( type .eq. 6 ) then
do i = ex-1, ex
do j = sy, ey
do k = ez-1, ez
do m = 1,3
data(count) = cd(i,j,k,m)
count = count + 1
end do
end do
endif
c
return
end
c subroutine setbv(u, igstx, igendx, igsty, igendy, igstz, igendz)
c
***set the boundary values of dependent variables
c
C Author: Sisira Weeratunga
C NASA Ames Research Center
C (10/25/90)
c
c include 'appsp.incl'
c
real *8 u(5,xsize,ysize,zsize)
integer igstx, igendx, igsty, igendy, igstz, igendz

c
gstx = igstx
gendx = igendx
gsty = igsty
gendy = igendy
gstz = igstz
gendz = igendz

c
***set the dependent variable values along the top and bottom faces
c
do j = sy, ey
do i = sx, ex
c
call exact ( iglob(i), jglob(j), l, bzl( 1, i, j ) )
call exact ( iglob(i), jglob(j), nz, bznz( 1, i, j ) )
c
c end do
c
if ( gstz .eq. 1 ) then
  do j = sy, ey
  do i = sx, ex
call exact ( iglob(i), jglob(j), l, u( 1, i, j, sz ) )
c end do
cendif

if ( gendz .eq. nz ) then
  do j = sy, ey
  do i = sx, ex
call exact ( iglob(i), jglob(j), nz, u( 1, i, j, ez ) )
c end do
cendif
c
***set the dependent variable values along east and west faces
c
do k = sz, ez
do j = sy, ey
do i = sx, ex
c
end if
c
if ( gendx .eq. nx ) then
  do k = sz, ez
  do j = sy, ey
call exact ( 1, jglob(j), kglob(k), wnx( 1, j, k ) )
c end do
cendif

if ( gstx .eq. 1 ) then
  do k = sz, ez
  do j = sy, ey
call exact ( 1, jglob(j), kglob(k), bx1( 1, i, j, k ) )
c end do
cendif

if ( gendx .eq. nx ) then
  do k = sz, ez
  do j = sy, ey
call exact ( nx, jglob(j), kglob(k), u( 1, ex, j, k ) )
c end do
cendif

***set the dependent variable values along north and south faces
c
do k = sz, ez
do i = sx, ex
c
end do
c
return
end

subroutine setiv(u,igstx,igsty,igstz)

***set the initial values of independent variables based on tri-linear interpolation of boundary values in the computational space.

include 'appsp.incl'

real *8 u(5,xsize,ysize,zsize)
integer igstx, igsty, igstz

gstx = igstx
gsty = igsty
gstz = igstz

Author: Sisira Weeratunga
NASA Ames Research Center
(10/25/90)

do k = szl, ezl

kg = kglob(k)

zeta = ( dfloat(kg-1) ) / ( nz - 1 )

do j = syl, eyl

jg = jglob(j)

eta = ( dfloat(jg-1) ) / ( ny - 1 )

do i = sxl, exl

ig = iglob(i)

xi = ( dfloat(ig-1) ) / ( nx - 1 )

do m = 1, 5

$ pxi = ( 1.0d+00 - xi ) * bx1(m,j,k)
 $ + xi * bxnx(m,j,k)

$ peta = ( 1.0d+00 - eta ) * by1(m,i,k)
 $ + eta * byny(m,i,k)

$ pzeta = ( 1.0d+00 - zeta ) * bz1(m,i,j)
 $ + zeta * bznz(m,i,j)

$ u(m, i, j, k) = pxi + peta + pzeta

$ - pxi * peta - peta * pzeta - pzeta * pxi

$ + pxi * peta * pzeta

end do

end do

end do

end

end do

return
end

end

*************** THIS IS OLD CODE FOR BEGINNING OF ADI ************

subroutine adi

***to perform pseudo-time stepping iterations

for five coupled, nonlinear pde's.

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(10/25/90)

include 'appsp.incl'

dimension idmax(5), jmax(5), kmax(5),
$ imax(5), jmax(5), kmax(5),
$ delnum(5)

parameter ( one = 1.0d+00 )

lnorm = 2

***compute the steady-state residuals

call rhs

***compute the norms of the residuals

if ( lnorm .eq. 1 ) then

 call maxnorm ( isiz1, isiz2, isiz3,
 $ nx, ny, nz,
 $ imax, jmax, kmax,
 $ rsd, rsdnn )

if ( ipr .eq. 1 ) then

 write (iout,* ) ' Initial Residual norms'

 write (iout,1003) ( rsdnn(m),
 $ imax(m), jmax(m), kmax(m), m = 1, 5 )

 end if

else if ( lnorm .eq. 2 ) then

call l2norm ( rsd, rsdnn )
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if ( ipr.eq.1 ) then
  write (iout,*) ' Initial Residual norms'
  write (iout,*)
  write (iout,1007) ( rsd(m), m = 1, 5 )
end if
end if

begin pseudo-time stepping iterations

tstart = timer( )
do istep = 1, itmax

*************** END OF OLD CODE AT BEGINNING OF ADI ********

subroutine adix(u,r,sd,frct,a,b,c,d,igstx, igendx, igsty, igendz)
$ include 'appsp.incl'

real *8 u(5,xsize,ysize,zsize), rd(5,xsize,ysize,zsize),
  frct(5,xsize,ysize,zsize), a(xsize,ysize,zsize,3),
  b(xsize,ysize,zsize,3), c(xsize,ysize,zsize,3),
  d(xsize,ysize,zsize,3), e(xsize,ysize,zsize,3)

dimension jmax(5), kmax(5),
$ delnum(5)

integer igstx, igendx, igsty, igendy, igstz, igendz

igstx = igstx
igendx = igendx
igsty = igsty
igendy = igendy
igstz = igstz
igendz = igendz

**** This code was formerly at the beginning of the ADI loop ********

if ( ( mod ( istep, inorm ) .eq. 0 ) .and.
( ipr .eq. 1 ) ) then
  write (iout, 1001) istep
end if

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do k = sz, ez
  do j = sy, ey
    do i = sx, ex
      do m = 1, 5
        rsd(m,i,j,k) = dt * rsd(m,i,j,k)
      end do
    end do
  end do
end do

perform 3-factor, scalar ADI iterations

perform the block diagonal inversion

call txinvr(u,rsd)

c**perform the xsi-direction sweep

call jacx ( 3, u, a(1,1,1,1), c(1,1,1,1),
  d(1,1,1,1), e(1,1,1,1) )
c
  call spentax3 ( a(1,1,1,1), b(1,1,1,1), c(1,1,1,1),
  d(1,1,1,1), e(1,1,1,1),
  rsd )
c
  call jacx ( 4, u, a(1,1,1,2), c(1,1,1,2),
  d(1,1,1,2), e(1,1,1,2) )
c
call spentax ( 4, a(1,1,1,2), b(1,1,1,2), c(1,1,1,2),
  d(1,1,1,2), e(1,1,1,2),
  rad )
c
  call jacx ( 5, u, a(1,1,1,3), c(1,1,1,3),
  d(1,1,1,3), e(1,1,1,3) )
c
call spentax ( 5, a(1,1,1,3), b(1,1,1,3), c(1,1,1,3),
  d(1,1,1,3), e(1,1,1,3),
  rad )
c
return

1001 format (1x/5x,'pseudo-time Scalar ADI iteration no.=',i4/)

end

subroutine badix(u,r,frct,a,b,c,d,e,igstx, igendx, igsty, igendy, igstz, igendz)
$ include 'appsp.incl'
```c
real *8 u(5,xsize,ysize,zsize), rsd(5,xsize,ysize,zsize),
$ frc(5,xsize,ysize,zsize), a(xsize,ysize,zsize,3),
$ b(xsize,ysize,zsize,3), c(xsize,ysize,zsize,3),
$ d(xsize,ysize,zsize,3), e(xsize,ysize,zsize,3)
$ 
dimension idmax(5), jmax(5), kmax(5),
$ $ delumn(5)
$ parameter ( one = 1.0d+00 )
$c integer igstx, igendx, igsty, igendy, igstz, igendz
$c gstx = igstx
gendx = igendx
gsty = igsty
gendy = igendy
gstz = igstz
gendz = igendz
$c Backward substitution
$c call bspentax3 ( a(1,1,1), b(1,1,1), c(1,1,1),
$ d(1,1,1), e(1,1,1),
$ rsd )
$c call bspentax ( 4, a(1,1,2), b(1,1,2), c(1,1,2),
$ d(1,1,2), e(1,1,2),
$ rsd )
$c call bspentax ( 5, a(1,1,3), b(1,1,3), c(1,1,3),
$ d(1,1,3), e(1,1,3),
$ rsd )
$c return
$c
$c subroutine adiy(u,rsd,frct,a,b,c,d,e,igstx, igendx, igstz, igendz
$ $ include 'appsp.incl'
$c real *8 u(5,xsize,ysize,zsize), rsd(5,xsize,ysize,zsize),
$ frc(5,xsize,ysize,zsize), a(xsize,ysize,zsize,3),
$ b(xsize,ysize,zsize,3), c(xsize,ysize,zsize,3),
$ d(xsize,ysize,zsize,3), e(xsize,ysize,zsize,3)
$ dimension idmax(5), jmax(5), kmax(5),
$ $ delumn(5)
$ parameter ( one = 1.0d+00 )
$c integer igstx, igendx, igsty, igendy, igstz, igendz
$c gstx = igstx
gendx = igendx
gsty = igsty
gendy = igendy
gstz = igstz
gendz = igendz
$c
```
c $ delunm(5)  
  parameter ( one = 1.0d+00 )  
  integer igstx, igendx, igsty, igendy, igstz, igendz  
  gstx = igstx  
  gendx = igendx  
  gsty = igsty  
  gendy = igendy  
  gstz = igstz  
  gendz = igendz

***backward sweep

  call bsptonay ( a(1,1,1), b(1,1,1), c(1,1,1),  
    d(1,1,1), e(1,1,1),  
    rsd )

  call bsptonay ( 4, a(1,1,2), b(1,1,2), c(1,1,2),  
    d(1,1,2), e(1,1,2),  
    rsd )

  call bsptonay ( 5, a(1,1,3), b(1,1,3), c(1,1,3),  
    d(1,1,3), e(1,1,3),  
    rsd )

return

end

subroutine adiz(u,rsd,frct,a,b,c,d,e,igstx,igendx,igsty,igendy,igstz,igendz)
  include ‘appsp.incl’

real *8 u(5,xsize,ysize,zsize), rsd(5,xsize,ysize,zsize),  
  frct(5,xsize,ysize,zsize), a(xsize,ysize,zsize,3),  
  b(xsize,ysize,zsize,3), c(xsize,ysize,zsize,3),  
  d(xsize,ysize,zsize,3), e(xsize,ysize,zsize,3)

dimension idmax(5), jdxmax(5), kdxmax(5),  
  imax(5), jmax(5), kmax(5),  
  delunm(5)  
  parameter ( one = 1.0d+00 )

integer igstx, igendx, igsty, igendy, igstz, igendz  
  gstx = igstx  
  gendx = igendx  
  gsty = igsty  

subroutine badiz(u,rsd,frct,a,b,c,d,e,igstx,igendx,igsty,igendy,igstz,igendz)
  include ‘appsp.incl’

real *8 u(5,xsize,ysize,zsize), rsd(5,xsize,ysize,zsize),  
  frct(5,xsize,ysize,zsize), a(xsize,ysize,zsize,3),  
  b(xsize,ysize,zsize,3), c(xsize,ysize,zsize,3),  
  d(xsize,ysize,zsize,3), e(xsize,ysize,zsize,3)

dimension idmax(5), jdxmax(5), kdxmax(5),  
  imax(5), jmax(5), kmax(5),  
  delunm(5)  
  parameter ( one = 1.0d+00 )
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```fortran
integer igstx, igendx, igsty, igendy, igstz, igendz

gstx = igstx
gendx = igendx
gsty = igsty
gendy = igendy
gstz = igstz
gendz = igendz

!!! This code was formerly near the end of the ADI loop !!!!!!!!

call prsd(rsd)
call bspentax ( a(1,1,1,1), b(1,1,1,1), c(1,1,1,1),
  $      d(1,1,1,1), e(1,1,1,1),
  $      rsd )
call bspentax ( 4, a(1,1,1,2), b(1,1,1,2), c(1,1,1,2),
  $      d(1,1,1,2), e(1,1,1,2),
  $      rsd )
call bspentax ( 5, a(1,1,1,3), b(1,1,1,3), c(1,1,1,3),
  $      d(1,1,1,3), e(1,1,1,3),
  $      rsd )

return
end

subroutine mvmul(u,rsd,igstx, igendx, igsty, igendy, igstz, igendz)

  include 'appsp.incl'

  real *8 u(5,xsize,ysize,zsize), rsd(5,xsize,ysize,zsize)
  parameter ( one = 1.0d+0 )

  integer igstx, igendx, igsty, igendy, igstz, igendz

gstx = igstx
gendx = igendx
gsty = igsty
gendy = igendy
gstz = igstz
gendz = igendz

!***perform the block diagonal matrix-vector multiplication

call tzetax(u,rsd)

!***update the variables
```

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```fortran
do k = sz1, ez1
do j = sy1, ey1
do i = sx1, ex1
   do m = 1, 5
      $ u( m, i, j, k ) = u( m, i, j, k )
      + rsd( m, i, j, k )
   end do
   end do
   end do
   end do

return
end

subroutine cnorms(rsd,delnum)

  include 'appsp.incl'

  implicit real *8 ( a-h,o-z)

  real *8 rsd(5,xsize,ysize,zsize)

  dimension idmax(5), jmax(5), kmax(5),
  $    imax(5), jmax(5), kmax(5),
  $    delnum(5)
  parameter ( one = 1.0d+0 )
  real *8 tmp(5)

!***compute the norms of pseudo-time iteration corrections

  lnorm = 2

  if ( mod ( istep, lnorm ) .eq. 0 ) then
     if ( lnorm .eq. 1 ) then
        call maxnorm ( isiz1, isiz2, isiz3,
        $      nx, ny, nz,
        $      idmax, jmax, kmax,
        $      rsd, delnum )
     if ( ipr .eq. 1 ) then
        write ( iout,1002 ) ( delnum(m),
        $      idmax(m), jmax(m), kmax(m), m = 1, 5 )

```
end if
else if ( lnorm .eq. 2 ) then
  call l2norm ( rsd, tmp )
  if ( impr .eq. 1 ) then
    write (iout,1006) ( tmp(m), m = 1, 5 )
  end if
end if

end do

***compute the steady-state residuals
This is called from the C++ code

return

1002 format ( 1x/1x,'max-norm of Scalar ADI-iteration correction ',$ 9x,' for first pde = ',1pe12.5,/
  9x,' max-norm of Scalar ADI-iteration correction ',$ 9x,' for second pde = ',1pe12.5,/
  9x,' max-norm of Scalar ADI-iteration correction ',$ 9x,' for third pde = ',1pe12.5,/
  9x,' max-norm of Scalar ADI-iteration correction ',$ 9x,' for fourth pde = ',1pe12.5,/
  9x,' max-norm of Scalar ADI-iteration correction ',$ 9x,' for fifth pde = ',1pe12.5,/
  9x,' max-norm of Scalar ADI-iteration correction ',$

1006 format ( 1x/1x,'RMS-norm of scalar adi-iteration correction ',$ 9x,' for first pde = ',1pe12.5,/
  9x,' RMS-norm of scalar adi-iteration correction ',$ 9x,' for second pde = ',1pe12.5,/
  9x,' RMS-norm of scalar adi-iteration correction ',$ 9x,' for third pde = ',1pe12.5,/
  9x,' RMS-norm of scalar adi-iteration correction ',$ 9x,' for fourth pde = ',1pe12.5,/
  9x,' RMS-norm of scalar adi-iteration correction ',$ 9x,' for fifth pde = ',1pe12.5)

***compute the norms of the residuals

lnorm = 2

if ( ( mod ( istep, lnorm ) .eq. 0 ) .or.
  ( istep .eq. itmax ) ) then
  if ( lnorm .eq. 1 ) then
    call maxnorm ( isiz1, isiz2, isiz3,
      nx, ny, nz,
      imax, jmax, kmax,
      rsd, radmn )
  if ( impr .eq. 1 ) then
    write (iout,1003) ( radmn(m), m = 1, 5 )
  end if
else if ( lnorm .eq. 2 ) then
  call l2norm ( rsd, radmn )
  if ( impr .eq. 1 ) then
    write (iout,1007) ( radmn(m), m = 1, 5 )
  end if
end if
end if

do m = 1, 5
   rnorm(m) = rnorm(m) + rsdnm(m)
end do

*** check the pseudo-time iteration residuals against the tolerance levels

if ( (rsdnm(1) .lt. tolrds(1)) .and.
     (rsdnm(2) .lt. tolrds(2)) .and.
     (rsdnm(3) .lt. tolrds(3)) .and.
     (rsdnm(4) .lt. tolrds(4)) .and.
     (rsdnm(5) .lt. tolrds(5))) then
   write (iout,1004) istep
canjev return
end if

return

1003 format (1x/1x,'max-norm of steady-state residual for ',
   $ 'first pde = ',lpe1.2.5/,
     $ 49x,('14',',14',',14',',14',')/,'.
   $ 'second pde = ',lpe1.2.5/,
     $ 49x,('14',',14',',14',',14',')/,'.
   $ 'third pde = ',lpe1.2.5/,
     $ 49x,('14',',14',',14',',14',')/,'.
   $ 'fourth pde = ',lpe1.2.5/,
     $ 49x,('14',',14',',14',',14',')/,'.
   $ 'fifth pde = ',lpe1.2.5/,
     $ 49x,('14',',14',',14',',14','),

1004 format (1x/1x,'convergence was achieved after ',i4,
   $ 'pseudo-time steps')

1007 format (1x/1x,'RMS-norm of steady-state residual for ',
   $ 'first pde = ',lpe1.2.5/,
   $ 'second pde = ',lpe1.2.5/,
   $ 'third pde = ',lpe1.2.5/,
   $ 'fourth pde = ',lpe1.2.5/,
   $ 'fifth pde = ',lpe1.2.5)

end
**end if**

**end do**

**end do**

**end do**

return

**end**

**subroutine l2norm ( v, sum )**

***compute the 12-norm of vector v.***

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(10/25/90)

**include 'appsp.incl'**

**implicit real *8 (a-h.o-z)**

**dimension v(5,ldx,ldy,*),**

**real *8 v(5,xsize,ysize,zsize), sum(5)**

**do m = 1, 5**

**sum(m) = 0.0d+00**

**end do**

**do k = sz1, ez1**

**do j = syl1, ey1**

**do i = sx1, ex1**

**do m = 1, 5**

**sum(m) = sum(m) + v(m,i,j,k) * v(m,i,j,k)**

**end do**

**end do**

**end do**

**do m = 1, 5**

**sum(m) = sqrt( sum(m) / (nx-2) * (ny-2) * (nz-2) )**

**end do**

**return**

**end**

**subroutine erhs(frct,igstx, igendx, igsty, igendy, igstz, igendz)**

***compute the right hand side based on exact solution***

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(10/25/90)

**include 'appsp.incl'**

**real *8 frct(5,xsize,ysize,zsize)**

**dimension flux(5,zsize), ue(5,zsize)**

**integer igstx, igsty, igstz**

**gtx = igstx**

**gendx = igendx**

**gsty = igsty**

**gendy = igendy**

**gstz = igstz**

**gendz = igendz**

**dsspm = dssp**

**do k = sz, ez**

**do j = sy, ey**

**do i = sx, ex**

**do m = 1, 5**

**frct(m, i, j, k) = 0.0d+00**

**end do**

**end do**

**end do**

**end do**

**end do**

**end do**

**do k = szl, ez1**

**do j = syl, ey1**

**do i = sx1, ex1**

**kg = kglob(k)**

**zeta = ( dfloat(kg-1) ) / ( nz - 1 )**

**do j = syl, ey1**

**jg = jglob(j)**

**eta = ( dfloat(jg-1) ) / ( ny - 1 )**

**do i = sxm2, exm2**
c
\[ \text{i} = \text{ilog(}i\text{)} \]
\[ x_i = \frac{\text{dfloat}(\text{i} - 1)}{\text{nx} - 1} \]
c
\[ \text{do } m = 1, 5 \]
\[ \text{ue}(m, i) = \text{ce}(m, 1) \]
\[ + \text{ce}(m, 2) * \text{x}_i \]
\[ + \text{ce}(m, 3) * \text{eta} \]
\[ + \text{ce}(m, 4) * \text{eta} * \text{x}_i \]
\[ + \text{ce}(m, 5) * \text{zeta} \]
\[ + \text{ce}(m, 6) * \text{zeta} * \text{eta} \]
\[ + \text{ce}(m, 7) * \text{zeta} * \text{zeta} \]
\[ + \text{ce}(m, 8) * \text{x}_i * \text{x}_i \]
\[ + \text{ce}(m, 9) * \text{eta} * \text{x}_i \]
\[ + \text{ce}(m, 10) * \text{zeta} * \text{zeta} * \text{zeta} \]
\[ + \text{ce}(m, 11) * \text{x}_i * \text{x}_i * \text{eta} \]
\[ + \text{ce}(m, 12) * \text{eta} * \text{eta} * \text{x}_i \]
\[ + \text{ce}(m, 13) * \text{zeta} * \text{zeta} * \text{zeta} \]
\[ \text{end do} \]
c
\[ \text{flux}(\text{l}, i) = \text{ue}(\text{l}, i) \]
\[ \text{u}_{21} = \text{ue}(\text{2}, i) / \text{ue}(\text{l}, i) \]
\[ q = 0.50d+00 * ( \text{ue}(\text{2}, i) * \text{ue}(\text{2}, i) \]
\[ + \text{ue}(\text{3}, i) * \text{ue}(\text{3}, i) \]
\[ + \text{ue}(\text{4}, i) * \text{ue}(\text{4}, i) \]
\[ ) / \text{ue}(\text{l}, i) \]
\[ \text{flux}(\text{2}, i) = \text{ue}(\text{2}, i) * \text{u}_{21} + c_2 * ( \text{ue}(\text{5}, i) - q ) \]
\[ \text{flux}(\text{3}, i) = \text{ue}(\text{3}, i) * \text{u}_{21} \]
\[ \text{flux}(\text{4}, i) = \text{ue}(\text{4}, i) * \text{u}_{21} \]
\[ \text{flux}(\text{5}, i) = ( c_1 * \text{ue}(\text{5}, i) - c_2 * q ) * \text{u}_{21} \]
\[ \text{end do} \]
\[ \text{do } i = \text{sxl}, \text{exl} \]
\[ \text{do } m = 1, 5 \]
\[ \text{frct}(\text{m}, i, \text{k}) = \text{frct}(\text{m}, i, \text{k}) \]
\[ - \text{tx}_i * ( \text{flux}(\text{m}, i+1) - \text{flux}(\text{m}, i-1) ) \]
\[ \text{end do} \]
\[ \text{end do} \]
\[ \text{do } i = \text{sxl}, \text{exml} \]
\[ \text{tmp} = 1.0d+00 / \text{ue}(\text{l}, i) \]
\[ \text{frct}(\text{4}, i, \text{k}) = \text{frct}(\text{4}, i, \text{k}) \]
\[ + \text{tx}_i * \text{c}_3 * \text{c}_4 * ( \text{flux}(\text{4}, i+1) - \text{flux}(\text{4}, i) \]
\[ + \text{tx}_i * \text{tx}_i * ( \text{ue}(\text{4}, i-1) \]
\[ - 2.0d+00 * \text{ue}(\text{4}, i) \]
\[ \text{end do} \]
\[ \text{frct}(\text{5}, i, \text{k}) = \text{frct}(\text{5}, i, \text{k}) \]
\[ + \text{tx}_i * \text{c}_3 * \text{c}_4 * ( \text{flux}(\text{5}, i+1) - \text{flux}(\text{5}, i) \]
\[ + \text{tx}_i * \text{tx}_i * ( \text{ue}(\text{5}, i-1) \]
\[ - 2.0d+00 * \text{ue}(\text{5}, i) \]
\[ \text{end do} \]
Fourth-order dissipation

if ( gstx .eq. 1 ) then
  do m = 1, 5
    frc(m,sx1,j,k) = frc(m,sx1,j,k)
    - dsspm * ( + 5.0d+00 * u(m,sx1) )
    - 4.0d+00 * u(m,sx2)
    + u(m,sx3) )
  end do
endif

do i = sx1, ex3
  do m = 1, 5
    frc(m,i,j,k) = frc(m,i,j,k)
    - dsspm * ( - 4.0d+00 * u(m,sx1) )
    + 6.0d+00 * u(m,sx2) + 4.0d+00 * u(m,sx3) + u(m,sx+4) )
  end do
end do

if ( gendx .eq. nx ) then
  do m = 1, 5
    frc(m,ex2,j,k) = frc(m,ex2,j,k)
    - dsspm * ( - 4.0d+00 * u(m,ex-4) )
    + 6.0d+00 * u(m,ex2) + 4.0d+00 * u(m,ex1) )
  end do
endif
end do

eta-direction flux differences

do k = szl, ez1
  kg = kglob(k)
  zeta = ( dfloat(kg-1) / ( nz - 1 )
  do i = sx1, ex1
    ig = iglob(i)
    xi = ( dfloat(ig-1) / ( nx - 1 )
    do j = sym2, eym2
      jg = iglob(j)
      eta = ( dfloat(jg-1) / ( ny - 1 )
      do m = 1, 5
        u(m,j) = ce(m,1)
        + ce(m,2) * xi
        + ce(m,3) * eta
        + ce(m,4) * zeta
        + ce(m,5) * xi * xi
        + ce(m,6) * eta * eta
        + ce(m,7) * zeta * zeta
        + ce(m,8) * xi * xi * xi
        + ce(m,9) * eta * eta * eta
        + ce(m,10) * zeta * zeta * zeta
        + ce(m,11) * xi * xi * xi
        + ce(m,12) * eta * eta * eta
        + ce(m,13) * zeta * zeta * zeta
      end do
    end do
  end do
end do

flux(1,j) = u(3,j)

u31 = u(3,j) / u(1,j)

q = 0.50d+00 * ( u(2,j) * u(2,j)
  + u(3,j) * u(3,j)
  + u(4,j) * u(4,j) )
  / u(1,j)

flux(2,j) = u(2,j) * u31

flux(3,j) = u(3,j) * u31 + c2 * ( u(5,j) - q )

flux(4,j) = u(4,j) * u31

flux(5,j) = ( c1 * u(5,j) - c2 * q ) * u31
end do

do j = syl, ey1
do m = 1, 5
    frct(m,i,j,k) = frct(m,i,j,k)
    - ty2 * (flux(m,j+1) - flux(m,j-1))
end do
end do

do j = syl, eym1
    tmp = 1.0d+00 / ue(1,j)
    u21j = tmp * ue(2,j)
    u31j = tmp * ue(3,j)
    u41j = tmp * ue(4,j)
    u51j = tmp * ue(5,j)

    tmp = 1.0d+00 / ue(1,j-1)
    u21jml = tmp * ue(2,j-1)
    u31jml = tmp * ue(3,j-1)
    u41jml = tmp * ue(4,j-1)
    u51jml = tmp * ue(5,j-1)

    flux(2,j) = ty3 * (u21j - u21jml)
    flux(3,j) = (4.0d+00/3.0d+00) * ty3 * (u31j - u31jml)
    flux(4,j) = ty3 * (u41j - u41jml)
    flux(5,j) = 0.50d+00 * (1.0d+00 - c1*c5) * ty3 * ((u21j)**2 + u1jml**2 - u1jml**2)
         + (1.0d+00/6.0d+00)
         * ty3 * (u1jml**2 - u1jml**2)
         + c1 * c5 * ty3 * (u51j - u51jml)
end do

do j = syl, eyl
    frct(1,i,j,k) = frct(1,i,j,k)
        + dy1 * tyl1 * (ue(j,j-1)
                    - 2.0d+00 * ue(1,j))
end do

frct(2,i,j,k) = frct(2,i,j,k)
    + dy2 * tyl1 * (ue(2,j-1)
                    - 2.0d+00 * ue(2,j))
end do

frct(3,i,j,k) = frct(3,i,j,k)
    + dy3 * tyl1 * (ue(3,j-1)
                    - 2.0d+00 * ue(3,j))
end do

frct(4,i,j,k) = frct(4,i,j,k)
    + dy4 * tyl1 * (ue(4,j-1)
                    - 2.0d+00 * ue(4,j))
end do

frct(5,i,j,k) = frct(5,i,j,k)
    + dy5 * tyl1 * (ue(5,j-1)
                    - 2.0d+00 * ue(5,j))
end do

if (gdsty .eq. 1) then
    do m = 1, 5
        frct(m,i,syl,k) = frct(m,i,syl,k)
            - dsspm * (+ 5.0d+00 * ue(m,syl)
                        - 4.0d+00 * ue(m,syl))
        end do
end if

do j = syl3, ey3
    frct(1,i,j,k) = frct(1,i,j,k)
        - dsspm * (+ 1.0d+00 * uem(j-1)
                    - 6.0d+00 * uem(j))
end do

if (gendy .eq. ny) then
    do m = 1, 5
        frct(m,i,ey2,k) = frct(m,i,ey2,k)
            - dsspm * (+ 4.0d+00 * uem(ey-4)
                        + 6.0d+00 * uem(ey3))
        end do
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frct(2,i,j,k) = frct(2,i,j,k)
- 2.0d+00 * u(1,k)
  +  u(1,k-1)
frct(3,i,j,k) = frct(3,i,j,k)
+ tz3 * t31 * ( flux(2,k+1) - flux(2,k) )
+ dz2 * t31 * ( u(2,k) )
- 2.0d+00 * u(2,k)
+  u(2,k-1)
frct(4,i,j,k) = frct(4,i,j,k)
+ tz4 * t41 * ( flux(4,k+1) - flux(4,k) )
+  u(4,k-1)
frct(5,i,j,k) = frct(5,i,j,k)
+ tz5 * t51 * ( flux(5,k+1) - flux(5,k) )
+  u(5,k-1)
endif
enddo

if ( gdstz .eq. 1 ) then
      do m = 1, 5
        frct(m,i,j,szl) = frct(m,i,j,szl)
        - dsrpm * ( + 5.0d+00 * u(m,szl)
                      - 4.0d+00 * u(m,sz3) )
        frct(m,i,j,sz2) = frct(m,i,j,sz2)
        - dsrpm * ( - 4.0d+00 * u(m,szl)
                      + 6.0d+00 * u(m,sz2)
                      - 4.0d+00 * u(m,sz3)
                      +  u(m,sz4) )
      enddo
enddo

write(iout,*) igstx, igsty, igstz, 'frct3', frct(2,4,4,8)
return
end

subroutine exact ( i, j, k, u000ijk )
c***compute the exact solution at (i,j,k)
cAuthor: Sisira Weeratunga
NASA Ames Research Center
(10/25/90)
cinclude 'appsp.incl'
cdimension u000ijk(*)
cSanjeev: DON'T change these i,j,k to global values! the caller does it
xi = ( dfloat ( i - 1 ) ) / ( nx - 1 )
eta = ( dfloat ( j - 1 ) ) / ( ny - 1 )
zeta = ( dfloat ( k - 1 ) ) / ( nz - 1 )

do m = 1, 5
c
u000ijk(m) = ce(m,1)
$ + ce(m,2) * xi
$ + ce(m,3) * eta
$ + ce(m,4) * zeta
$ + ce(m,5) * xi * xi
$ + ce(m,6) * eta * eta
$ + ce(m,7) * zeta * zeta
$ + ce(m,8) * xi * xi * xi
$ + ce(m,9) * eta * eta * eta
$ + ce(m,10) * zeta * zeta * zeta
$ + ce(m,11) * xi * xi * xi * xi
$ + ce(m,12) * eta * eta * eta * eta
$ + ce(m,13) * zeta * zeta * zeta * zeta

c end do
return
end

c subroutine error(u, enorme, igstx, igndx, igsty, igndy, igstz, $ igendz)
c c***compute the solution error
c c Author: Sisira Weeratunga
NASA Ames Research Center
(10/25/90)
c include 'appsp.incl'
real *8 u(5, xsize, ysize, zsize)
real *8 enorms(5)
c dimension imax(5), jmax(5), kmax(5), $ u000ijk(5), ermax(5)
c integer igstx, igndx, igsty, igndy, igstz, igendz
c
gstx = igstx
gendx = igndx
gsty = igsty
gndy = igndy
gstz = igstz
gendlz = igendz
c
lnorm = 2
if ( lnorm .eq. 1 ) then
do m = 1, 5
   ermax(m) = 1.0d+20
end do
else if ( lnorm .eq. 2 ) then
do m = 1, 5
   errm(m) = 0.0d+00
end do
c
do k = szl, ezl
do j = syl, eyl
do i = sxl, exl
c call exact ( iglob(i), jglob(j), kglob(k), u000ijk )
do m = 1, 5
tmp = abs ( u000ijk(m) - u(m,i,j,k) )
if ( tmp .gt. ermax(m) ) then
ermax(m) = tmp
imax(m) = iglob(i)
jmax(m) = jglob(j)
kmax(m) = kglob(k)
end if
c end do
end do
c
c write (iout,1001) ( errmax(m), $ imax(m), jmax(m), kmax(m), m = 1, 5 )
c else if ( lnorm .eq. 2 ) then
do m = 1, 5
   errm(m) = 0.0d+00
end do
c
do k = szl, ezl
do j = syl, eyl
do i = sxl, exl
c call exact ( iglob(i), jglob(j), kglob(k), u000ijk )
do m = 1, 5
tmp = ( u000ijk(m) - u(m,i,j,k) )
errm(m) = errm(m) + tmp ** 2
end do
end do
end do
c do m = 1, 5
erm(m) = sqrt ( errm(m) / ( nx-2)*(ny-2)*(nz-2) ) 
end do
c  end do

c  write (iout,1002) ( errnm(m), m = 1, 5 )

do m = 1, 5
  enorms(m) = enorms(m) + errnm(m)
end do

c  end if

c 1001 format (/5x,'max. error in soln. to first pde = ',1pe12.4/,
  $5x,'and its location = (',i4,'','i4','','i4','')/',
  $5x,'max. error in soln. to second pde = ',1pe12.4/,
  $5x,'and its location = (',i4,'','i4','','i4','')/',
  $5x,'max. error in soln. to third pde = ',1pe12.4/,
  $5x,'and its location = (',i4,'','i4','','i4','')/',
  $5x,'max. error in soln. to fifth pde = ',1pe12.4/,
  $5x,'and its location = (',i4,'','i4','','i4','')' )

c 1002 format (1lx/1x, 'RMS-norm of error in soln. to ',
  $ 'first pde = ',1pe12.5/,
  $ 'second pde = ',1pe12.5/,
  $ 'third pde = ',1pe12.5/,
  $ 'fourth pde = ',1pe12.5/,
  $ 'fifth pde = ',1pe12.5)'

c  return

c  end

c

c subroutine jact ( m, u,a,b,c,d,e )

 c***form the xi-direction pentadiagonal system

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 c (10/25/90)

 c include `appsp.incl'

 c real *8 u(5,usize,ysize,zsize), a(usize,ysize,zsize),
 c b(usize,ysize,zsize), c(usize,ysize,zsize),
 c dxsize(ysize,zsize), exsize(ysize,zsize)

 c dimension cv(xsize), aa(xsize), rhon(xsize)

 c r43 = 4.0d+00 / 3.0d+00

 c34 = c3 * c4
 c1345 = c1 * c3 * c4 * c5

 c if ( m.eq. 3 ) then
 c sn = 0.0d+00
 c else if ( m.eq. 4 ) then
 c sn = 1.0d+00
 c else if ( m.eq. 5 ) then
 c sn = -1.0d+00
 c end if

c do k = szl, ezl
 c do j = syl, eyl

 c do i = sxm, exm

 c rul = 1.0d+00 / u(1,i,j,k)
 c uu = rul * u(2,i,j,k)
 c vv = rul * u(3,i,j,k)
 c ww = rul * u(4,i,j,k)

 c q = 0.50d+00 * ( uu ** 2 + vv ** 2 + ww ** 2 )

c cv(i) = uu
 c aa(i) = sqrt ( c1 * c2 * ( rul * u(5,i,j,k) - q ) )

 c rhon(i) = max ( dxl,  
 c $ dx2 + r43 * c34 * rul,  
 c $ dx3 + c34 * rul,  
 c $ dx4 + c34 * rul,  
 c $ dx5 + c1345 * rul )

 c end do

c if ( gstmt .eq. 1 ) then
 c a(sx,j,k) = 0.0d+00
 c b(sx,j,k) = 0.0d+00
 c c(sx,j,k) = 1.0d+00
 c d(sx,j,k) = 0.0d+00
 c e(sx,j,k) = 0.0d+00
 c else
 c e(sx-1,j,k) = 0.0d+00
 c e(sx-2,j,k) = 0.0d+00
 c endif

 c do i = sx1, ex1
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\begin{verbatim}

a(i,j,k) = 0.0d+00
b(i,j,k) = - dt * tx2 * ( cv(i-1) + sn * aa(i-1) )
\$ - dt * rhot(i-1) * tx1
$c(i,j,k) = 1.0d+00$
\$ + dt * rhot(i) * tx1 * 2.0d+00
$d(i,j,k) = dt * tx2 * ( cv(i+1) + sn * aa(i+1) )$
\$ - dt * rhot(i+1) * tx1
$e(i,j,k) = 0.0d+00$
end do

if ( gendx .eq. nx ) then
a(ex1,j,k) = 0.0d+00
b(ex1,j,k) = 0.0d+00
c(ex1,j,k) = 1.0d+00
d(ex1,j,k) = 0.0d+00
e(ex1,j,k) = 0.0d+00
endif

***fourth order dissipation

if ( gdstx .eq. 1 ) then
$c(sx1,j,k) = c(sx1,j,k) + dt * dssp * ( + 5.0d+00 )$
$d(sx1,j,k) = d(sx1,j,k) + dt * dssp * ( - 4.0d+00 )$
\$ e(sx1,j,k) = e(sx1,j,k) + dt * dssp * ( + 1.0d+00 )$
\$ b(sx2,j,k) = b(sx2,j,k) + dt * dssp * ( - 4.0d+00 )$
$c(sx2,j,k) = c(sx2,j,k) + dt * dssp * ( + 6.0d+00 )$
$d(sx2,j,k) = d(sx2,j,k) + dt * dssp * ( - 4.0d+00 )$
\$ e(sx2,j,k) = e(sx2,j,k) + dt * dssp * ( + 1.0d+00 )$
else
$e(sx-1,j,k) = e(sx-1,j,k) + dt * dssp * ( + 1.0d+00 )$
\$ e(sx-2,j,k) = e(sx-2,j,k) + dt * dssp * ( + 1.0d+00 )$
endif

begin = sxm2
if ( gdstx .eq. 1 ) begin = sx + 3
end = exm2
if ( gendx .eq. nx ) end = ex - 3

do i = sx3, ex3
     a(i,j,k) = a(i,j,k) + dt * dssp * ( + 1.0d+00 )
     b(i,j,k) = b(i,j,k) + dt * dssp * ( - 4.0d+00 )
     c(i,j,k) = c(i,j,k) + dt * dssp * ( + 6.0d+00 )
     d(i,j,k) = d(i,j,k) + dt * dssp * ( - 4.0d+00 )
     e(i,j,k) = e(i,j,k) + dt * dssp * ( + 1.0d+00 )
end do

if ( gendx .eq. nx ) then
     a(ex2,j,k) = a(ex2,j,k) + dt * dssp * ( - 1.0d+00 )
     b(ex2,j,k) = b(ex2,j,k) + dt * dssp * ( - 4.0d+00 )
     c(ex2,j,k) = c(ex2,j,k) + dt * dssp * ( + 6.0d+00 )
     d(ex2,j,k) = d(ex2,j,k) + dt * dssp * ( - 4.0d+00 )
end if
\end{verbatim}

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\begin{verbatim}
a(exl,j,k) = a(exl,j,k) + dt * dssp * ( + 1.0d+00 )
b(exl,j,k) = b(exl,j,k) + dt * dssp * ( - 4.0d+00 )
c(exl,j,k) = c(exl,j,k) + dt * dssp * ( + 5.0d+00 )
end do
c
end do
c
return
end

****form the eta-direction pentadiagonal system.

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include 'appsp.inc'

real *8 u(5,xsize,ysize,ysize), a(xsize,ysize,ysize),
$ b(xsize,ysize,ysize), c(xsize,ysize,ysize),$
$ d(xsize,ysize,ysize), e(xsize,ysize,ysize)$

dimension cv(ysize), aa(ysize), rhoq(ysize)
r34 = 4.0d+00 / 3.0d+00
c34 = c3 * c4
c1345 = c1 * c3 * c4 * c5
if ( m .eq. 3 ) then
sn = 0.0d+00
celse if ( m .eq. 4 ) then
sn = 1.0d+00
celse if ( m .eq. 5 ) then
sn = - 1.0d+00
cend if
c
do k = szl, ezl
do i = sxl, exl
do j = syml, eyml
\end{verbatim}
c
**fourth order dissipation**

```c
if ( gstry .eq. 1 ) then
c(i,i+1) = c(i,i+1) + dt * dssp * ( + 5.0d00 )
d(i,i+1) = d(i,i+1) + dt * dssp * ( - 4.0d00 )
e(i,i+1) = e(i,i+1) + dt * dssp * ( + 1.0d00 )
else
b(i,i+1) = b(i,i+1) + dt * dssp * ( - 4.0d00 )
c(i,i+1) = c(i,i+1) + dt * dssp * ( + 6.0d00 )
d(i,i+1) = d(i,i+1) + dt * dssp * ( - 4.0d00 )
e(i,i+1) = e(i,i+1) + dt * dssp * ( + 1.0d00 )
endif

begin = sym2
if ( gstry .eq. 1 ) begin = sy + 3
c
endif

if ( gendy .eq. ny ) end = ey - 3
if ( gendy .eq. ny )
do j = sy1, ey1
```

```c
a(i,j,k) = 0.0d00
b(i,j,k) = - dt * thy2 * ( cv(j-1) + sn * aa(j-1) )
c(i,j,k) = 1.0d00
d(i,j,k) = dt * thy2 * ( cv(j+1) + sn * aa(j+1) )
e(i,j,k) = 0.0d00
endif
```

```c
if ( gendy .eq. ny ) then
a(i,ey,k) = 0.0d00
b(i,ey,k) = 0.0d00
c(i,ey,k) = 1.0d00
d(i,ey,k) = 0.0d00
e(i,ey,k) = 0.0d00
endif
```
c***form the zeta-direction pentadiagonal system.
c
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c
c include '.appspot.incl'
c
c! real *8 u(5,xsize,ysize,zsize), a(xsize,ysize,zsize), $ b(xsize,ysize,zsize), c(xsize,ysize,zsize), $ d(xsize,ysize,zsize), e(xsize,ysize,zsize)

c dimension cv(zsize), aa(zsize), rhos(zsize)
c
r43 = 4.0d+00 / 3.0d+00
c34 = c3 * c4
c1345 = c1 * c3 * c4 * c5
c
if ( m .eq. 3 ) then
  sn = 0.0d+00
else if ( m .eq. 4 ) then
  sn = 1.0d+00
else if ( m .eq. 5 ) then
  sn = -1.0d+00
end if

do j = yjl, ey1
  do i = xsl, ex1
    do k = sz1, ez1
      rul = 1.0d+00 / u(1,i,j,k)
      uu = rul * u(2,i,j,k)
      vv = rul * u(3,i,j,k)
      ww = rul * u(4,i,j,k)

      q = 0.50d+00 * ( uu ** 2
                        + vv ** 2
                        + ww ** 2 )

      cv(k) = ww
      aa(k) = sqrt ( c1 * c2 * ( rul * u(5,i,j,k) - q ) )

      rhos(k) = max ( dz1,
                       dz2 + c34 * rul,
                       dz3 + c34 * rul,
                       dz4 + r43 * c34 * rul,
                       dz5 + c1345 * rul )

      a(i,j,k) = 0.0d+00
      b(i,j,k) = -dt * tz2 * ( cv(k-1) + sn * aa(k-1) )
      c(i,j,k) = 1.0d+00
      d(i,j,k) = dt * tz1 * 2.0d+00
      e(i,j,k) = 0.0d+00
    end do
  end do
end do

if ( getz .eq. 1 ) then
  a(i,j,sz) = 0.0d+00
  b(i,j,sz) = 0.0d+00
  c(i,j,sz) = 1.0d+00
  d(i,j,sz) = 0.0d+00
  e(i,j,sz) = 0.0d+00
else
  e(i,j,sz-1) = 0.0d+00
  e(i,j,sz-2) = 0.0d+00
endif

begin = szm2
if ( getz .eq. 1 ) begin = sz + 1
begin = exm2
if ( gendz .eq. nz ) end = ez - 1

begin = szm2

end do

if ( gendz .eq. nz ) then
  a(i,j,ez) = 0.0d+00
  b(i,j,ez) = 0.0d+00
  c(i,j,ez) = 1.0d+00
  d(i,j,ez) = 0.0d+00
  e(i,j,ez) = 0.0d+00
endif

c***fourth order dissipation

if ( getz .eq. 1 ) then
  c(i,j,sz1) = c(i,j,sz1) + dt * dssp * ( + 5.0d+00 )
  d(i,j,sz1) = d(i,j,sz1) + dt * dssp * ( - 4.0d+00 )
  e(i,j,sz1) = e(i,j,sz1) + dt * dssp * ( + 1.0d+00 )
  b(i,j,sz2) = b(i,j,sz2) + dt * dssp * ( - 4.0d+00 )
  c(i,j,sz2) = c(i,j,sz2) + dt * dssp * ( + 6.0d+00 )
  d(i,j,sz2) = d(i,j,sz2) + dt * dssp * ( - 4.0d+00 )
  e(i,j,sz2) = e(i,j,sz2) + dt * dssp * ( + 1.0d+00 )
else
  e(i,j,sz-1) = e(i,j,sz-1) + dt * dssp * ( - 1.0d+00 )
  e(i,j,sz-2) = e(i,j,sz-2) + dt * dssp * ( + 1.0d+00 )
endif

begin = szm2
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```fortran
if ( gsz .eq. 1 ) begin = sz + 3
end = ezm2
if ( gendz .eq. nz ) end = ez - 3

do k = sz3, ez3
  a(i,j,k) = a(i,j,k) + dt * dssp * ( + 1.0d+00 )
  b(i,j,k) = b(i,j,k) + dt * dssp * ( - 4.0d+00 )
  c(i,j,k) = c(i,j,k) + dt * dssp * ( + 6.0d+00 )
  d(i,j,k) = d(i,j,k) + dt * dssp * ( - 4.0d+00 )
  e(i,j,k) = e(i,j,k) + dt * dssp * ( + 1.0d+00 )
end do

if ( gendz .eq. nz ) then
  a(i,j,ez2) = a(i,j,ez2) + dt * dssp * ( + 1.0d+00 )
  b(i,j,ez2) = b(i,j,ez2) + dt * dssp * ( - 4.0d+00 )
  c(i,j,ez2) = c(i,j,ez2) + dt * dssp * ( + 6.0d+00 )
  d(i,j,ez2) = d(i,j,ez2) + dt * dssp * ( - 4.0d+00 )
  e(i,j,ez1) = e(i,j,ez1) + dt * dssp * ( + 1.0d+00 )
  b(i,j,ez1) = b(i,j,ez1) + dt * dssp * ( - 4.0d+00 )
  c(i,j,ez1) = c(i,j,ez1) + dt * dssp * ( + 5.0d+00 )
end if
end do
end do
return

subroutine ninvr(rsd)
***block-diagonal matrix-vector multiply

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include 'appsp.incl'
real *8 rsd(5,xsize,ysize,zsize)
bz = sqrt ( 0.50d+00 )
do k = szl, ezl
do j = syl, ey2
do i = sxl, exl

rsd(1,1,1,1,1) = - r2
rsd(2,1,1,1,1) = r1
rsd(3,1,1,1,1) = bt * ( r4 - r5 )
t1 = bt * r3
t2 = 0.50d+00 * ( r4 + r5 )
rhd(4,1,1,1,1) = - t1 * t2
rhd(5,1,1,1,1) = t1 * t2

end subroutine getl2(u, philz)
***compute the surface integral

close 'appsp.incl'
real *8 u(5,xsize,ysize,zsize)
dimension philz(xsize,ysize)
do j = syl, ey2
do i = sxl, exl

philz(i,j) = c2*( u(5,i,j,sz2) - 0.50d+00 * ( u(2,i,j,sz2) ** 2 + u(3,i,j,sz2) ** 2 + u(4,i,j,sz2) ** 2 ) / u(1,i,j,sz2) )
end do
end do
```

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subroutine get2z(u, phi2z)

***compute the surface integral

include 'appsp.incl'

real *8 u(5, xsize, ysize, zsize)

dimension phi2z(xsize, ysize)

do j = sy1, ey2

do i = sx1, ex1

phi2z(i, j) = c2*( u(5, i, j, ezl) ** 2
$ - 0.50d+00 * ( u(2, i, j, ezl) ** 2
$ + u(3, i, j, ezl) ** 2
$ + u(4, i, j, ezl) ** 2 )
$ / u(1, i, j, ezl) )

end do

end do

return
end

subroutine get2y(u, phi2y)

***compute the surface integral

include 'appsp.incl'

real *8 u(5, xsize, ysize, zsize)

dimension phi2y(xsize, ysize)

do k = sz2, ez1

do i = sx1, ex1

phi2y(i, k) = c2*( u(5, i, ey2, k) ** 2
$ - 0.50d+00 * ( u(2, i, ey2, k) ** 2
$ + u(3, i, ey2, k) ** 2
$ + u(4, i, ey2, k) ** 2 )
$ / u(1, i, ey2, k) )

end do

end do

return
end

subroutine get1x(u, philx)

***compute the surface integral

include 'appsp.incl'

real *8 u(5, xsize, ysize, zsize)

dimension philx(ysize, zsize)

do k = sz2, ez1

do j = sy1, ey2

philx(j, k) = c2*( u(5, sx1, j, k) ** 2
$ - 0.50d+00 * ( u(2, sx1, j, k) ** 2
$ + u(3, sx1, j, k) ** 2
$ + u(4, sx1, j, k) ** 2 )
$ / u(1, sx1, j, k) )

end do

end do

return
end
return
end

subroutine get2x(u, phi2x)
***compute the surface integral
include 'appsp.incl'
real *8 u(5,xsize,ysize,zsize)
dimension phi2x(ysize,zsize)
do k = szz2, ez1
  do j = sy1, ey2
    phi2x(j,k) = c2*( u(5,ex1,j,k) \\
    - 0.50d+00 * ( u(2,ex1,j,k) ** 2 \\
    * + u(3,ex1,j,k) ** 2 \\
    * + u(4,ex1,j,k) ** 2 ) \\
    / u(1,ex1,j,k) )
  end do
end do
return
end

subroutine cpphiy(phi, data, iii, kkk)
***compute the surface integral
include 'appsp.incl'
real *8 phi(isizl,isiz3), data(xsize,zsize)
do k = 1, zsize-4
  do i = 1, xsize-4
    phi(i+iii,k+kkk) = data(i+2,k+2)
  end do
end do
return
end

subroutine cpphiy(phi, data, iii, jjj)
***compute the surface integral
include 'appsp.incl'
real *8 phi(isizl,isiz2), data(xsize,ysize)
do j = 1, ysize-4
  do i = 1, xsize-4
    phi(i+iii,j+jjj) = data(i+2,j+2)
  end do
end do
return
end

subroutine cpphiy(phi, data, jjj, kkk)
***compute the surface integral
include 'appsp.incl'
real *8 phi(isiz2,isiz3), data(ysize,zsize)
do k = 1, zsize-4
  do j = 1, ysize-4
    phi(j+jjj,k+kkk) = data(j+2,k+2)
  end do
end do
return
end

subroutine gphilz(phi)
***compute the global surface integral
include 'appsp.incl'
real *8 philz(isizl, isiz2)
do j = jil, ji2-1
do i = iil, ii2-1
frcl = frcl + ( philz(i, j)
$ + philz(i-1, j)
$ + philz(i, j+1)
$ + philz(i+1, j+1) )
end do
doit do return end

subroutine gphi2z(phi2z)
***compute the global surface integral
include 'appsp.incl'
real *8 phi2z(isizl, isiz2)
do j = jil, ji2-1
do i = iil, ii2-1
frcl = frcl + ( phi2z(i, j)
$ + phi2z(i+1, j)
$ + phi2z(i, j+1)
$ + phi2z(i+1, j+1) )
end do
doit do return end

subroutine gphiwy(phiwy)
***compute the global surface integral
include 'appsp.incl'
real *8 phiwy(isizl, isiz3)
do k = kil, ki2-1
do i = iil, ii2-1
frc2 = frc2 + ( phiwy(i, k)
$ + phiwy(i+1, k)
$ + phiwy(i, k+1)
$ + phiwy(i+1, k+1) )
end do
doit do return end

subroutine gphiw(phiw)
***compute the global surface integral
include 'appsp.incl'
real *8 phiw(isiz2, isiz3)
do j = jil, ji2-1
frc3 = frc3 + ( phi1x(j,k) + phi1x(j+1,k) + phi1x(j,k+1) + phi1x(j+1,k+1) )
end do
end do
return
end

subroutine gphi2x(phi2x)
***compute the global surface integral
include 'appsp.incl'
real *8 phi2x(isiz2,isz3)
do k = k1, k2-1
do j = j1, j2-1
frc3 = frc3 + ( phi2x(j,k) + phi2x(j+1,k) + phi2x(j,k+1) + phi2x(j+1,k+1) )
end do
end do
return
end

subroutine gintgr()
***compute the global surface integral
include 'appsp.incl'
frc1 = dx1 * deta * frc1
frc2 = dx1 * dzeta * frc2
frc3 = deta * dzeta * frc3
frc = 0.25d+00 * ( frc1 + frc2 + frc3 )
write (iout,1001) frc
c
return
end

subroutine pfct(frct)
include 'appsp.incl'
real *8 frct(5,xsize,ysize,zsize)
write(iout,'*') 'FRCT', frct(2,4,4,8)
return
end

subroutine prsd(rsd)
include 'appsp.incl'
real *8 rsd(5,xsize,ysize,zsize)
do i = sx, ex
  do j = sy, ey
    do k = sz, ez
      do m = 1, 5
        b = rsd(m,i,j,k)
        write(iout,'*') i,j,k,b
      end do
    end do
  end do
end do
write(iout,'*') 'Done writing rsd'
return
end

subroutine rhsx(u,rsd,frct,igstx,igendx,igsty,igendy,igstz,igendz)

***compute the right hand sides

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include 'appsp.incl'

real *8 u(5,xsize,ysize,zsize), rsd(5,xsize,ysize,zsize),
frct(5,xsize,ysize,zsize)
dimension flux(5,xsize)
integer igstx, igendx, igsty, igendy, igstz, igendz
gstx = igstx
gendx = igendx
gstty = igsty
gendy = igendy
gstz = igstz
gendz = igendz
do k = sz, ez
  do j = sy, ey
    do i = sx, ex
      do m = 1, 5
        rsd(m,i,j,k) = - frct(m,i,j,k)
      end do
    end do
  end do
call prsd(rsd)
c
***xi-direction flux differences
do k = szl, ezl
  do j = syl, eyl
    do i = sx1, ex1
      flux(1,i) = u(2,i,j,k)
      u21 = u(2,i,j,k) / u(1,i,j,k)
      q = 0.50d+00 * ( u(2,i,j,k) * u(1,i,j,k) + u(3,i,j,k) * u(3,i,j,k) + u(4,i,j,k) * u(4,i,j,k) ) / u(1,i,j,k)
      flux(2,i) = u(2,i,j,k) * u21 + c2 * ( u(5,i,j,k) - q )
      flux(3,i) = u(3,i,j,k) * u21
      flux(4,i) = u(4,i,j,k) * u21
      flux(5,i) = ( c1 * u(5,i,j,k) - c2 * q ) * u21
    end do
  end do

do i = sx1, ex1
do m = 1, 5
  rsd(m,i,j,k) = rsd(m,i,j,k)
  - tx2 * ( flux(m,i+1) - flux(m,i-1) )
end do
do i = sx1, ex1
  tmp = 1.0d+00 / u(1,i,j,k)
  u21i = tmp * u(2,i,j,k)
  u31i = tmp * u(3,i,j,k)
  u41i = tmp * u(4,i,j,k)
  u51i = tmp * u(5,i,j,k)
tmp = 1.0d+00 / u(1,i-1,j,k)
  u21lim = tmp * u(2,i-1,j,k)
  u31lim = tmp * u(3,i-1,j,k)
  u41lim = tmp * u(4,i-1,j,k)
  u51lim = tmp * u(5,i-1,j,k)
flx(2,i) = (4.0d+00/3.0d+00) * tx3 * ( u21i - u21lim )
flx(3,i) = tx3 * ( u31i - u31lim )
flx(4,i) = tx3 * ( u41i - u41lim )
flx(5,i) = 0.50d+00 * ( 1.0d+00 - c1*c5 )
  * tx3 * ( u21i**2 + u31i**2 + u41i**2 )
  + ( u21lim**2 + u31lim**2 + u41lim**2 )
  + tx3 * ( u21i**2 - u21lim**2 )
  + c1 * c5 * tx3 * ( u51i - u51lim )
end do
do i = sx1, ex1
  rsd(1,i,j,k) = rsd(1,i,j,k)
  + dx1' * tx1' * ( u(1,i,j,k) - 2.0d+00 * u(1,i,j,k) )
end do
doi = 1, 5
  rsd(2,i,j,k) = rsd(2,i,j,k)
  + tx3 * c3 * c4 * ( flx(2,i+1) - flx(2,i) )
  + dx2 * tx1' * ( u(2,i,j,k) - 2.0d+00 * u(2,i,j,k) )
end do
doi = 1, 5
  rsd(3,i,j,k) = rsd(3,i,j,k)
  + tx3 * c3 * c4 * ( flx(3,i+1) - flx(3,i) )
  + dx3 * tx1' * ( u(3,i,j,k) - 2.0d+00 * u(3,i,j,k) )
end do
if ( gdx .eq. nx ) then
doi = 1, 5
  rsd(4,i,j,k) = rsd(4,i,j,k)
  + tx4 * tx1' * ( u(4,i,j,k) - 2.0d+00 * u(4,i,j,k) )
end do
if ( gdx .eq. nx ) then
doi = 1, 5
  rsd(5,i,j,k) = rsd(5,i,j,k)
  + tx5 * tx1' * ( u(5,i,j,k) - 2.0d+00 * u(5,i,j,k) )
end do
write(iout,* 'RSD', rsd(2,4,4,8)

***Fourth-order dissipation
if ( gdst .eq. 1 ) then
doi = 1, 5
  rsd(m,sx1,j,k) = rsd(m,sx1,j,k)
  - dssp * ( + 5.0d+00 * u(m,sx1,j,k) - 4.0d+00 * u(m,sx2,j,k) + u(m,sx3,j,k) )
end do
endif
do i = sx3, ex3
  do m = 1, 5
    rsd(m,i,j,k) = rsd(m,i,j,k)
    - dssp * ( u(m,i-2,j,k) - 4.0d+00 * u(m,i-1,j,k) + 6.0d+00 * u(m,i+1,j,k) - u(m,i+2,j,k) )
  end do
if ( gendx .eq. nx ) then
do m = 1, 5
  rsd(m,ex2,j,k) = rsd(m,ex2,j,k)
  - dssp * ( u(m,ex-4,j,k) - 4.0d+00 * u(m,ex-1,j,k) + 6.0d+00 * u(m,ex+1,j,k) - u(m,ex+4,j,k) )
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do j = syl, eyl

rsd(1,i,j,k) = rsd(1,i,j,k)
  + dy1 * tyl * ( u1,i,j-1,k)  
  - 2.0d00 * ( u1,i,j,k) 
end do

rsd(2,i,j,k) = rsd(2,i,j,k)
  + tyl * c3 * c4 * ( flux2(j+1) - flux2(j) ) 
  - 2.0d00 * u2,i,j,k ) 
end do

rsd(3,i,j,k) = rsd(3,i,j,k)
  + tyl * flux3(j+1) - flux3(j) 
  - 2.0d00 * u3,i,j,k ) 
end do

rsd(4,i,j,k) = rsd(4,i,j,k)
  + tyl * flux4(j+1) - flux4(j) 
  - 2.0d00 * u4,i,j,k ) 
end do

rsd(5,i,j,k) = rsd(5,i,j,k)
  + tyl * flux5(j+1) - flux5(j) 
  - 2.0d00 * u5,i,j,k ) 
end do

end do

****fourth-order dissipation

if ( gsty .eq. 1 ) then
  do m = 1, 5
    rsd(m,i,syl,k) = rsd(m,i,syl,k)
    - dspp * ( + 5.0d00 * u(m,i,syl,k) 
      - 4.0d00 * u(m,i,sy2,k) 
      + u(m,i,sy3,k) ) 
  end do

  rsd(m,i,sy2,k) = rsd(m,i,sy2,k)
  - dspp * ( - 4.0d00 * u(m,i,sy2,k) 
    + 6.0d00 * u(m,i,sy3,k) 
    - 4.0d00 * u(m,i,sy4,k) )
end do

end if

do j = syl3, ey3
  do m = 1, 5

rsd(m,i,j,k) = rsd(m,i,j,k)
  - dspp * ( + 4.0d00 * u(m,i,j-1,k) 
    + 6.0d00 * u(m,i,j,k) 
    - 4.0d00 * u(m,i,j+1,k) 
    + u(m,i,j+2,k) )
end do

end do

end do

****compute the right hand sides

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(10/25/90)

include 'appsp.incl'
real * 8 u(5,xsize,ysize,ysize), rsd(5,xsize,ysize,ysize),
  frcx(5,xsize,ysize,ysize)

dimension flux(5,zsize)
integer igstx, igendx, igsty, igendy, igstz, igendz
**zeta-direction flux differences**

do j = syl, eyl

do i = sxl, exl

do k = szml, ezml

```
flux(1,k) = u(4,i,j,k) 
us1 = u(4,i,j,k) / u(1,i,j,k) 
qu = 0.50d+00 * ( u(2,i,j,k) * u(2,i,j,k) 
+ u(3,i,j,k) * u(3,i,j,k) 
+ u(4,i,j,k) * u(4,i,j,k) ) 
/ u(1,i,j,k) 
flux(2,k) = u(2,i,j,k) * us1 
flux(3,k) = u(3,i,j,k) * us1 
flux(4,k) = u(4,i,j,k) * us1 * c2 * ( u(5,i,j,k) - q ) 
flux(5,k) = ( c1 * u(5,i,j,k) - c2 * q ) * us1 
end do 
do k = szl, ezl 
do m = 1, 5 
rsd(m,i,j,k) = rsd(m,i,j,k) 
- tz2 * ( flux(m,k+1) - flux(m,k-1) ) 
end do 
```

do k = szl, ezml

tmp = 1.0d+00 / u(1,i,j,k)

```
u21k = tmp * u(2,i,j,k) 
u31k = tmp * u(3,i,j,k) 
u41k = tmp * u(4,i,j,k) 
u51k = tmp * u(5,i,j,k) 
tmp = 1.0d+00 / u(1,i,j,k-1) 
```

**fourth-order dissipation**

if ( gatz .eq. 1 ) then 
do m = 1, 5 
```
subroutine spentax (m, a, b, c, d, e, f)

**solution of multiple, independent systems of penta-diagonal systems**

using Gaussian elimination (without pivoting) algorithm

Author: Sisira Weeratunga

NASA Ames Research Center

(10/25/90)

include 'appsp.incl'

real *8 f(5, xsize, ysize, zsize), a(xsize, ysize, zsize),
  b(xsize, ysize, zsize), c(xsize, ysize, zsize),
  d(xsize, ysize, zsize), e(xsize, ysize, zsize)

**forward elimination**

do k = sz1, sz3
  do j = syl, ey1
    if ( gstat .eq. 1 ) then
      tmp1 = b(sxl, j, k) / c(sx, j, k)
      c(sx(j, k)) = c(sxl, j, k) - tmp1 * d(sx, j, k)
      d(sx(j, k)) = d(sx(j, k)) - tmp1 * e(sx, j, k)
      f(m, sx(j, k)) = f(m, sx(j, k)) - tmp1 * f(m, sx, j, k)
    endif
    do i = sx2, ex
      tmp2 = a(i, j, k) / c(i-2, j, k)
      b(i, j, k) = b(i, j, k) - tmp2 * d(i-2, j, k)
      c(i, j, k) = c(i, j, k) - tmp2 * e(i-2, j, k)
      f(m, i, j, k) = f(m, i, j, k) - tmp2 * f(m, i-2, j, k)
      tmpl = b(i, j, k) / c(i-1, j, k)
      c(i, j, k) = c(i, j, k) - tmp1 * d(i-1, j, k)
      d(i, j, k) = d(i, j, k) - tmp1 * e(i-1, j, k)
      f(m, i, j, k) = f(m, i, j, k) - tmp1 * f(m, i-1, j, k)
    enddo
  enddo
enddo

return
end
subroutine bspenta3 (a, b, c, d, e, f)

***solution of multiple, independent systems of penta-diagonal systems

using Gaussian elimination algorithm

Author: Sisira Weeratunga

NASA Ames Research Center

(10/25/90)

include 'appsp.incl'

real *$ f(xsize,ysize,zsize), a(xsize,ysize,zsize),
$ b(xsize,ysize,zsize), c(xsize,ysize,zsize),
$ d(xsize,ysize,zsize), e(xsize,ysize,zsize)

***forward elimination

do k = szl, ezl

do j = syl, eyl

if (gendx.eq.1) then
  tmp1 = b(sxl,j,k) / c(sxl,j,k)
  c(sxl,j,k) = c(sxl,j,k) - tmp1 * d(sxl,j,k)
  b(sxl,j,k) = b(sxl,j,k) - tmp1 * e(sxl,j,k)
  f(sxl,j,k) = f(sxl,j,k) - tmp1 * f(sxl,j,k)
endif

do i = sx2, sx1 - 1

  f(m.i,j,k) = (f(m.i,j,k) - d(i,j,k)*f(m.i+1,j,k)) / c(i,j,k)

end do

return

end

subroutine bspenta4 (a, b, c, d, e, f)

***solution of multiple, independent systems of penta-diagonal systems

using Gaussian elimination algorithm

Author: Sisira Weeratunga

NASA Ames Research Center

(10/25/90)

include 'appsp.incl'

real *$ f(xsize,ysize,zsize), a(xsize,ysize,zsize),
$ b(xsize,ysize,zsize), c(xsize,ysize,zsize),
$ d(xsize,ysize,zsize), e(xsize,ysize,zsize)
**Back-substitution phase**

do k = sz1, ex1

do j = sy1, ey1

if ( gendx .eq. nx ) then
  f(1, ex1, j) = f(1, ex1, j) / c(ex1, j)
  f(1, ex1, j) = ( f(1, ex1, j) - d(ex1, j) * f(1, ex1, j) ) / c(ex1, j)
end if

f(2, ex1, j) = f(2, ex1, j) / c(ex1, j)

f(2, ex1, j) = ( f(2, ex1, j) - d(ex1, j) * f(2, ex1, j) ) / c(ex1, j)

f(3, ex1, j) = f(3, ex1, j) / c(ex1, j)

f(3, ex1, j) = ( f(3, ex1, j) - d(ex1, j) * f(3, ex1, j) ) / c(ex1, j)

end do

end do

return

**Forward elimination**

do k = sz1, ex1

do i = sx1, ex1

if ( gysty .eq. 1 ) then
  tmp1 = b(i, sy1, k) / c(i, sy1, k)
  c(i, sy1, k) = c(i, sy1, k) - tmp1 * d(i, sy1, k)
  d(i, sy1, k) = d(i, sy1, k) - tmp1 * e(i, sy1, k)
  f(m, i, sy1, k) = f(m, i, sy1, k) - tmp1 * f(m, i, sy1, k)
end if

end do

do j = sy2, ey1

tmp2 = a(j, k) / c(i, j-2, k)

b(i, j, k) = b(i, j, k) - tmp2 * d(i, j-2, k)

f(m, i, j, k) = f(m, i, j, k) - tmp2 * f(m, i, j-2, k)

tmpl = b(i, j, k) / c(i, j-1, k)

c(i, j, k) = c(i, j, k) - tmpl * d(i, j-1, k)

d(i, j, k) = d(i, j, k) - tmpl * e(i, j-1, k)

f(m, i, j, k) = f(m, i, j, k) - tmpl * f(m, i, j-1, k)

end do

end do

return

**Subroutine bspentay ( m, a, b, c, d, e, f )**

**Solution of multiple, independent systems of penta-diagonal systems using Gaussian elimination algorithm**
**forward elimination**

```c
if ( gsty .eq. 1 ) then
    tmp1 = b(i,syl,k) / c(i,sy,k)
    c(i,syl,k) = c(i,sy,k) - tmp1 * d(i,sy,k)
    d(i,syl,k) = d(i,sy,k) - tmp1 * e(i,sy,k)
    f(1,i,syl,k) = f(1,i,sy,k) - tmp1 * f(1,i,sy,k)
    f(2,i,syl,k) = f(2,i,sy,k) - tmp1 * f(2,i,sy,k)
    f(3,i,syl,k) = f(3,i,sy,k) - tmp1 * f(3,i,sy,k)
endif

do j = sy2, ey
    tmp2 = a(i,j,k) / c(i,j-2,k)
    b(i,j,k) = b(i,j,k) - tmp2 * d(i,j-2,k)
    c(i,j,k) = c(i,j,k) - tmp2 * e(i,j-2,k)
    f(1,i,j,k) = f(1,i,j,k) - tmp2 * f(1,i,j-2,k)
    f(2,i,j,k) = f(2,i,j,k) - tmp2 * f(2,i,j-2,k)
    f(3,i,j,k) = f(3,i,j,k) - tmp2 * f(3,i,j-2,k)
    tmpl = b(i,j,k) / c(i,j-1,k)
    c(i,j,k) = c(i,j,k) - tmpl * d(i,j-1,k)
    d(i,j,k) = d(i,j,k) - tmpl * e(i,j-1,k)
    f(1,i,j,k) = f(1,i,j,k) - tmpl * f(1,i,j-1,k)
    f(2,i,j,k) = f(2,i,j,k) - tmpl * f(2,i,j-1,k)
    f(3,i,j,k) = f(3,i,j,k) - tmpl * f(3,i,j-1,k)
end do
return
```

**back-substitution phase**

```c
do k = szl, ezl
    do i = sxl, exl
        if ( gendy .eq. ny ) then
            f(m,i,ey,k) = f(m,i,ey,k) / c(i,ey,k)
            f(m,i,ey-1,k) = ( f(m,i,ey-1,k) - d(i,ey-1,k)*f(m,i,ey,k) ) / c(i,ey-1,k)
        endif
        do j = ey2, sy, -1
            f(m,i,j,k) = ( f(m,i,j,k) - d(i,j,k)*f(m,i,j+1,k) - e(i,j,k)*f(m,i,j+2,k) ) / c(i,j,k)
        end do
    end do
    c(i,syl,k) = c(i,syl,k) - tmp1 * d(i,sy,k)
    d(i,syl,k) = d(i,syl,k) - tmp1 * e(i,sy,k)
    f(1,i,syl,k) = f(1,i,sy,k) - tmp1 * f(1,i,sy,k)
    f(2,i,syl,k) = f(2,i,sy,k) - tmp1 * f(2,i,sy,k)
    f(3,i,syl,k) = f(3,i,sy,k) - tmp1 * f(3,i,sy,k)
end do
```

**solution of multiple, independent systems of penta-diagonal systems using Gaussian elimination algorithm**

```c
subroutine spentay3 ( a, b, c, d, e, f )
c***solution of multiple, independent systems of penta-diagonal systems using Gaussian elimination algorithm

c Author: Sisira Weeratunga
NASA Ames Research Center
(10/25/90)
c include 'appsp.incl'
c real *8 f(5,xsize,y纵深,ysize,zsize), a(xsize,y纵深,ysize,zsize),
  $ b(xsize,y纵深,ysize,zsize), c(xsize,y纵深,ysize,zsize),
  $ d(xsize,y纵深,ysize,zsize), e(xsize,y纵深,ysize,zsize)
c
```
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c real *8 f(5, xsize, ysize, zsize), a(xsize, ysize, zsize),
$ b(xsize, ysize, zsize), c(xsize, ysize, zsize),
$ d(xsize, ysize, zsize), e(xsize, ysize, zsize)

c c** back-substitution phase
c do k = szl, exl
c do i = sx1, exl
c 
  if ( gendy .eq. ny ) then
    f(1, i, ey, k) = f(1, iy, ey, k) / c(i, ey, k)
    f(1, ie-1, k) = ( f(1, ie, ey, k) - d(i, ey-1, k)*f(1, i, ey, k) ) / c(i, ey-1, k)
  endif

do j = ey2, sy, -1
  f(1, i, j, k) = ( f(1, i, j, k) - d(i, j, k)*f(1, i, j+1, k)
    - e(i, j, k)*f(1, i, j+2, k) ) / c(i, j, k)
  f(2, i, j, k) = ( f(2, i, j, k) - d(i, j, k)*f(2, i, j+1, k)
    - e(i, j, k)*f(2, i, j+2, k) ) / c(i, j, k)
  f(3, i, j, k) = ( f(3, i, j, k) - d(i, j, k)*f(3, i, j+1, k)
    - e(i, j, k)*f(3, i, j+2, k) ) / c(i, j, k)
end do
end do
return

end

c subroutine bspentaz ( m, a, b, c, d, e, f )
c c** solution of multiple, independent systems of penta-diagonal systems
  using Gaussian elimination algorithm
  Author: Sisira Weeratunga
  NASA Ames Research Center

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c (10/25/90)
c include 'appsp.incl'
c
real *8 f(5, xsize, ysize, zsize), a(xsize, ysize, zsize),
$ b(xsize, ysize, zsize), c(xsize, ysize, zsize),
$ d(xsize, ysize, zsize), e(xsize, ysize, zsize)

c c** forward elimination
c do j = sy1, ey1
c do i = sx1, ex1
c 
  if ( gsetz .eq. 1 ) then
    tmp1 = b(i, j, szl) / c(i, j, sz)
    c(i, j, szl) = c(i, j, szl) - tmp1 * d(i, j, sz)
    d(i, j, szl) = d(i, j, szl) - tmp1 * e(i, j, sz)
    f(m, i, j, szl) = f(m, i, j, szl) - tmp1 * f(m, i, j, sz)
  endif

do k = sz2, ez
  tmp2 = a(i, j, k) / c(i, j, k-2)
  b(i, j, k) = b(i, j, k) - tmp2 * d(i, j, k-2)
  c(i, j, k) = c(i, j, k) - tmp2 * e(i, j, k-2)
  f(m, i, j, k) = f(m, i, j, k) - tmp2 * f(m, i, j, k-2)
  tmpl = b(i, j, k) / c(i, j, k-1)
  c(i, j, k) = c(i, j, k) - tmpl * d(i, j, k-1)
  d(i, j, k) = d(i, j, k) - tmpl * e(i, j, k-1)
  f(m, i, j, k) = f(m, i, j, k) - tmpl * f(m, i, j, k-1)
end do
end do
return
end

c subroutine bspentaz ( m, a, b, c, d, e, f )
c c** solution of multiple, independent systems of penta-diagonal systems
  using Gaussian elimination algorithm
  Author: Sisira Weeratunga
  NASA Ames Research Center
  (10/25/90)
include 'appsp.incl'

real *8 f(xsize,ysize,zsize), a(xsize,ysize,zsize),
$ b(xsize,ysize,zsize), c(xsize,ysize,zsize),$
$ d(xsize,ysize,zsize), e(xsize,ysize,zsize)

***back-substitution phase

do j = y1, y1

do i = x1, x1

if ( gendz ,eq. nz ) then

f(m,i,j,ez) = f(m,i,j,ez) / c(i,j,ez)

f(m,i,j,ez-1) = ( f(m,i,j,ez-1) - d(i,j,ez-1) * f(m,i,j,ez) ) / c(i,j,ez-1)

endif

k = ez2, sz, -1

f(m,i,j,k) = ( f(m,i,j,k) - d(i,j,k) * f(m,i,j,k+1)
$ - e(i,j,k) * f(m,i,j,k+2) ) / c(i,j,k)

end do

end do

return

end

subroutine spenta3 ( a, b, c, d, e, f )

***solution of multiple, independent systems of penta-diagonal systems
using Gaussian elimination algorithm

Author: Sisira Weeratunga
NASA Ames Research Center
(10/25/90)

include 'appsp.incl'

real *8 f(xsize,ysize,zsize), a(xsize,ysize,zsize),
$ b(xsize,ysize,zsize), c(xsize,ysize,zsize),$
$ d(xsize,ysize,zsize), e(xsize,ysize,zsize)

***forward elimination

do j = y1, y1

subroutine bspent3 ( a, b, c, d, e, f )

***solution of multiple, independent systems of penta-diagonal systems
using Gaussian elimination algorithm

Author: Sisira Weeratunga
NASA Ames Research Center
(10/25/90)

include 'appsp.incl'

real *8 f(xsize,ysize,zsize), a(xsize,ysize,zsize),
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```fortran
$ b(xsize,ysize,zsize), c(xsize,ysize,zsize),
 $ dixsize,ysize,zsize), e(xsize,ysize,zsize)

c***back-substitution phase
c do j = syl, eyl
c   do i = sx1, exl
   
   if ( gendz .eq. nz ) then
     f(1,i,j,ez) = f(1,i,j,ez) / c(i,j,ez)
     f(i,i,j,ez-1) = ( f(i,i,j,ez-1) - d(i,j,ez-1)*f(1,i,j,ez) ) / c(i,j,ez-1)
$  
f(2,i,j,ez) = f(2,i,j,ez) / c(i,j,ez)
   f(2,i,j,ez-1) = ( f(2,i,j,ez-1) - d(i,j,ez-1)*f(2,i,j,ez) ) / c(i,j,ez-1)
$f  
f(3,i,j,ez) = f(3,i,j,ez) / c(i,j,ez)
   f(3,i,j,ez-1) = ( f(3,i,j,ez-1) - d(i,j,ez-1)*f(3,i,j,ez) ) / c(i,j,ez-1)
$  
   do k = ez2, sz, -1
     f(1,i,j,k) = ( f(1,i,j,k) - d(i,j,k)*f(1,i,j,k+1) $  - e(i,j,k)*f(1,i,j,k+2) ) / c(i,j,k)
$  
f(2,i,j,k) = ( f(2,i,j,k) - d(i,j,k)*f(2,i,j,k+1) $  - e(i,j,k)*f(2,i,j,k+2) ) / c(i,j,k)
$  
f(3,i,j,k) = ( f(3,i,j,k) - d(i,j,k)*f(3,i,j,k+1) $  - e(i,j,k)*f(3,i,j,k+2) ) / c(i,j,k)

   end do
   end do
   end do
   
c call psval(4, f(1,4,4,4))

return
end

subroutine txinvr(u,rsd)

$c***block-diagonal matrix-vector multiplication
c
$Author: Sisira Weeratunga
 $NASA Ames Research Center
$c
(10/25/90)
```

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```fortran
c include 'appsp.incl'
c
real *8 u(xsize,ysize,zsize), rsd(5,xsize,ysize,zsize)
c
bt = sqrt ( 0.50d+00 )

do k = sz1, ezl
   do j = syl, eyl
      do i = sx1, exl
         
         rul = 1.0d+00 / u(1,i,j,k)
         uu = rul * u(2,i,j,k)
         vv = rul * u(3,i,j,k)
         ww = rul * u(4,i,j,k)
         
         q = 0.50d+00 * ( uu ** 2 $  + vv ** 2 $  + ww ** 2 )
         
         ac2 = c1 * c2 * ( rul * u(5,i,j,k) - q )
         
         if ( ac2 .le. 0.0d+00 ) then
            write (*,*) 'Speed of sound is zero' $  stop
         end if
         
         ac = sqrt ( ac2 )
         r1 = rsd(1,i,j,k)
         r2 = rsd(2,i,j,k)
         r3 = rsd(3,i,j,k)
         r4 = rsd(4,i,j,k)
         r5 = rsd(5,i,j,k)
         
         t1 = ( c2 / ac2 ) * ( q * r1 - uu * r2 $  - vv * r3 $  - ww * r4 $  + r5 )
         
         rsd(1,i,j,k) = r1 - t1
         rsd(2,i,j,k) = - rul * ( ww * r1 - r4 )
         rsd(3,i,j,k) = rul * ( vv * r1 - r3 )
         
         t2 = bt * rul * ( uu * r1 - r2 )
         t3 = ( bt * rul * ac ) * t1
         
         rsd(4,i,j,k) = - t2 + t3
         rsd(5,i,j,k) = t2 + t3
```
end do

c end do

c return

c end

subroutine tzetar(u, rsd)

***block-diagonal matrix-vector multiplication

Author: Sisira Weeratunga
NASA Ames Research Center
(10/25/90)

include 'appsp.incl'

real *8 u(5,xsize,ysize,zsize), rsd(5,xsize,ysize,zsize)

bt = sqrt ( 0.50d+00 )

do k = szl, ezl

do j = syl, eyl

do i = sxl, exl

ru1 = 1.0d+00 / u(1,i,j,k)

uu = ru1 * u(2,i,j,k)

vv = ru1 * u(3,i,j,k)

ww = ru1 * u(4,i,j,k)

q = 0.50d+00 * ( uu ** 2

   + vv ** 2

   + ww ** 2 )

ac2 = cl1 * c2 * ( ru1 * u(5,i,j,k) - q )

ac = sqrt ( ac2 )

alph = ( bt * u(1,i,j,k) ) / ac

r1 = rsd(1,i,j,k)

r2 = rsd(2,i,j,k)

r3 = rsd(3,i,j,k)

r4 = rsd(4,i,j,k)

r5 = rsd(5,i,j,k)

t1 = alph * ( r4 + r5 )

t2 = r3 + t1

t3 = bt * u(1,i,j,k) * ( r4 - r5 )

rsd(1,i,j,k) = t2

rsd(2,i,j,k) = - u(1,i,j,k) * r2 + uu * t2

rsd(3,i,j,k) = u(1,i,j,k) * r1 + vv * t2

rsd(4,i,j,k) = ww * t2 + t3

rsd(5,i,j,k) = u(1,i,j,k) * ( - uu * r2 + vv * r1 )

end do

c end do

c return

c end

subroutine callv ( finalrsdmm, finalerror )

include 'appsp.incl'

***verification test

real *8 finalrsdmm(*), finalerror(*)

call verify ( finalrsdmm, finalerror, frc )

***print the CPU time

write (fout,1001) ttotal

1001 format ('/5x,'Total CPU time = ',lpe12.4,' Sec. ')

return

c end

c end

subroutine verify ( xcr, xce, xci )
c***verification routine

c
Author: Sisira Weeratunga
NASA Ames Research Center
(10/25/90)

include 'appsp.incl'

dimension xcr(5), xce(5),
xrr(5), xre(5)

c***tolerance level

epsilon = 1.0e-08

if ( ( nx .eq. 12 ) .and. 
( ny .eq. 12 ) .and. 
( nz .eq. 12 ) ) then

**Reference values of RMS-norms of residual, for the (12X12X12) grid,
after 100 time steps, with DT = 1.50e-02

xrr(1) = 2.7470315451339479d-02
xrr(2) = 1.03607467055285417d-02
xrr(3) = 1.52357450500955532d-02
xrr(4) = 1.58405572244555615d-02
xrr(5) = 3.4849040609362460d-02

**Reference values of RMS-norms of solution error, for the (12X12X12) grid,
after 100 time steps, with DT = 1.50e-02

xre(1) = 2.7289258557377227d-05
xre(2) = 1.036446640837285d-05
xre(3) = 1.6154798287166471d-05
xre(4) = 1.575070499480102d-05
xre(5) = 3.4177666183390531d-05

**Reference value of surface integral, for the (12X12X12) grid,
after 100 time steps, with DT = 1.50e-02

xri = 7.8406293309126962e+00

**verification test for residuals

do m = 1, 5

tmp = abs ( ( xcr(m) - xrr(m) ) / xrr(m) )

if ( tmp .gt. epsilon ) then

write (iout,1001)

format('/5x,'VERIFICATION TEST FOR RESIDUALS FAILED')

go to 100

end if

c
end do

c
write (iout,1002)

1002 format('/5x,'VERIFICATION TEST FOR RESIDUALS',
$ 'IS SUCCESSFUL')

c
**verification test for solution error

100 continue

do m = 1, 5

tmp = abs ( ( xre(m) - xrr(m) ) / xre(m) )

if ( tmp .gt. epsilon ) then

write (iout,1003)

1003 format('/5x,'VERIFICATION TEST FOR SOLUTION ',
$ 'ERRORS FAILED')

go to 200

c
end if

c
end do

c
write (iout,1004)

1004 format('/5x,'VERIFICATION TEST FOR SOLUTION ERRORS',
$ 'IS SUCCESSFUL')

c
**verification test for surface integral

continue

tmp = abs ( ( xci - xri ) / xri )

if ( tmp .gt. epsilon ) then

write (iout,1005)

1005 format('/5x,'VERIFICATION TEST FOR SURFACE INTEGRAL FAILED')

c
else

write (iout,1006)

1006 format('/5x,'VERIFICATION TEST FOR SURFACE INTEGRAL',
$ 'IS SUCCESSFUL')

c
end if

c
write (iout,1007)

1007 format('/10x,'CAUTION',
$ '/5x,'REFERENCE VALUES CURRENTLY IN THIS VERIFICATION',
$ 'ROUTINE',
$ '/5x,'ARE VALID ONLY FOR RUNS WITH THE FOLLOWING PARAMETER ',
do m = 1, 5

tmp = abs ( ( xcr(m) - xrr(m) ) / xrr(m) )

if ( tmp .gt. epsilon ) then
    write (iout,1001)
    go to 400
endif
enddo

write (iout,1009)

format ('(1x,'"FOR THE PROBLEM PARAMETERS IN USE ",
"NO REFERENCE VALUES ARE PROVIDED"
)

1009 format ($(1x,'"IN THE CURRENT VERIFICATION ROUTINE - ",
"NO VERIFICATION TEST WAS PERFORMED")

cend if

creturn

cend
function timer(x)
  real x, timer
  real secs, tarray(2)

  sun version of timing routine

  secs = etime(tarray)
  timer = secs

  cray version of timing routine

  timer = second ()

  sgi version of timing routine

  secs = secnds(0.0)
  timer = secs

  return

  end
implicit real*8 (a-h,o-z)

parameter ( isiz1 = 64, isiz2 = 64, isiz3 = 64 )
parameter ( xsize = 68, ysize = 68, zsize = 68 )
parameter ( eachx = 64, eachy = 64, eachz = 64 )
parameter ( c1 = 1.40d+00, c2 = 0.40d+00, 
  c3 = 1.00d-01, c4 = 1.00d+00, 
  c5 = 1.40d+00 )

c real timer, tstart, tend
integer ex, ey, ez, ex1, ey1, ez1, ex2, ey2, ez2,
  sx, sy, sz,
  sx1, myl, sz1, sx2, sy2, sz2,
  sx3, ex3, my3, ey3, sz3, ez3,
  gtx, gtxy, gty, gtxz, gtyz, gtxyz,
  sxm1, sym2, szm2, exm1, eym2, ezm2,
  sxm1, sym1, szm1, exm1, eym1, em1

c
***for parallelization

common/parallel/ ex, ey, ez, ex1, ey1, ez1, ex2, ey2, ez2,
  sx, sy, sz,
  sx1, myl, sz1, sx2, sy2, sz2,
  sx3, ex3, my3, ey3, sz3, ez3,
  gtx, gtxy, gty, gtxz, gtyz, gtxyz,
  sxm1, sym2, szm2, exm1, eym2, ezm2,
  sxm1, sym1, szm1, exm1, eym1, em1

c
***boundaries for use in setiv - setbv

common/boundaries/ bkl(5,xsize,zsize), bkn(5,xsize,zsize),
  byl(5,xsize,zsize), byn(5,xsize,zsize),
  bzl(5,xsize,ysize), bzn(5,xsize,ysize)

c
***grid

common/cgcon/ nx, ny, nz,
  iii, iil, jj1, jj2, ki1, ki2, idum1,
  dx1, delta, dzeta,
  tx1, tx2, tx3,
  ty1, ty2, ty3,
  tz1, tz2, tz3

c
***dissipation

common/dis/ dx1, dx2, dx3, dx4, dx5,
  dy1, dy2, dy3, dy4, dy5,
  dz1, dz2, dz3, dz4, dz5,
  dss

c
***field variables and residuals

common/cvar/ u(5,isiz1,isiz2,isiz3),
  r5(5,isiz1,isiz2,isiz3),
  frct(5,isiz1,isiz2,isiz3)

c
***output control parameters
implicit real*8 (a-h,o-z)
parameter ( isiz1 = 12, isiz2 = 12, isiz3 = 12 )
parameter ( xsize = 10, ysize = 10, zsize = 10 )
parameter ( eachx = 6, eachy = 6, eachz = 6 )
parameter ( c1 = 1.40d+00, c2 = 0.40d+00,
c3 = 1.00d-01, c4 = 1.00d+00,
c5 = 1.40d+00 )

real timer, tstart, tend
t
integer ex, ey, ez, ex1, ey1, ez1, ex2, ey2, ez2,
$ sx, sy, sz,
$ sx1, sx2, sx3, sy1, sy2, sy3, sz1, sz2, sz3,
$ sx3, ex3, sy3, ey3, ez3,
$ gtx, gdx, gty, gdx, gtx, gty, gdx, gtx,
$ sxm2, szm2, exm2, eym2, ezm2,
$ sxm1, szm1, exm1, eym1, ezm1

c***for parallelization

common/parallel/ ex, ey, ez, ex1, ey1, ez1, ex2, ey2, ez2,
$ sx, sy, sz,
$ sx1, sx2, sx3, sy1, sy2, sy3, sz1, sz2, sz3,
$ sx3, ex3, sy3, ey3, ez3,
$ gtx, gdx, gty, gdx, gtx, gty, gdx, gtx,
$ sxm2, szm2, exm2, eym2, ezm2,
$ sxm1, szm1, exm1, eym1, ezm1

c***boundaries for use in setiv - setbv

common/boundaries/ bx1(5,isiz2,isiz3), bxm(5,isiz2,isiz3),
$ by1(5,isiz1,isiz3), bym(5,isiz1,isiz3),
$ bz1(5,isiz1,isiz2), bzm(5,isiz1,isiz2)

c***grid

common/cgcon/ nx, ny, nz,
$ i11, i12, j11, j12, k11, k12, idum1,
$ dx1, delta, dzeta,
$ tx1, tx2, tx3,
$ ty1, ty2, ty3,
$ tz1, tz2, tz3

c***dissipation

common/disp/ dx1,dx2,dx3,dx4,dx5,
$ dy1,dy2,dy3,dy4,dy5,
$ dz1,dz2,dz3,dz4,dz5,
$ dssp

c***field variables and residuals

common/cvar/ u(5,isiz1,isiz2,isiz3),
$ rsd(5,isiz1,isiz2,isiz3),
$ frct(5,isiz1,isiz2,isiz3)

c***output control parameters