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# MiniGhost: A Miniapp for Exploring Boundary Exchange Strategies Using Stencil Computations in Scientific Parallel Computing; Version 1.0

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# MiniGhost: A Miniapp for Exploring Boundary Exchange Strategies Using Stencil Computations in Scientific Parallel Computing; Version 1.0

A broad range of scientific computation involves the use of difference stencils. In a parallel computing environment, this computation is typically implemented by decomposing the spacial domain, inducing a “halo exchange” of process-owned boundary data. This approach adheres to the Bulk Synchronous Parallel (BSP) model. Because commonly available architectures provide strong inter-node bandwidth relative to latency costs, many codes “bulk up” these messages by aggregating data into a message as a means of reducing the number of messages. A renewed focus on non-traditional architectures and architecture features provides new opportunities for exploring alternatives to this programming approach.

In this report we describe miniGhost, a “miniapp” designed for exploration of the capabilities of current as well as emerging and future architectures within the context of these stencil-based applications. MiniGhost joins the suite of miniapps developed as part of the Mantevo project, http://mantevo.org.

# Acknowledgment

## Acknowledgment

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# Executive Summary

A broad range of scientific computation involves the use of difference stencils. In a parallel computing environment, this computation is typically implemented by decomposing the spacial domain, inducing a "halo exchange" of process-owned boundary data. This approach adheres to the Bulk Synchronous Parallel (BSP) model. Because commonly available architectures provide strong inter-node bandwidth relative to latency costs, many codes "bulk up" these messages by aggregating data into a message as a means of reducing the number of messages. A renewed focus on non-traditional architectures and architecture features provides new opportunities for exploring alternatives to this programming approach.

In this report we describe miniGhost, a "miniapp" designed for exploration of the capabilities of current as well as emerging and future architectures within the context of these stencil-based applications. MiniGhost joins the suite of miniapps developed as part of the Mantevo project, `http://mantevo.org`.

Our work is motivated by recent experiences with new node interconnect architectures, including that used by Cielo [11, 17, 20].

Various experiments involving miniGhost have already been completed, supporting the value of miniGhost as a proxy for represented applications. Additional experiments have been defined, with implementations underway. Future reports will describe the outcome of those experiments, and will also include the definition and use of a performance model incorporating many issues defined by the DOE exascale codesign efforts [3, 12, 18].

This document is released in support of the initial release of miniGhost. As miniapps are intended to be modified, additional supporting documentation is expected to be produced.

# Chapter 1

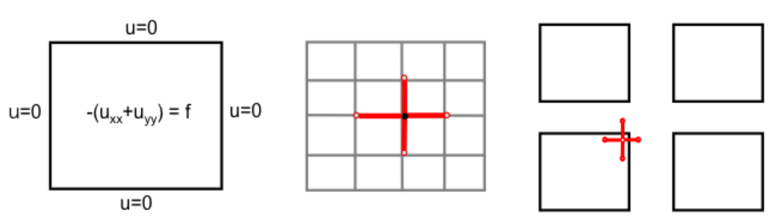
# Introduction

A broad range of physical phenomena in science and engineering can be described mathematically using partial differential equations. Determining the solution of these equations on computers is commonly accomplished by mapping the continuous equation to a discrete representation. One such solution technique is the finite differencing method, which lets us solve the equation using a difference stencil, updating the grid as a function of each point and its neighbors, presuming some discrete time step. The algorithmic structure of the finite difference method maps naturally to the parallel processing architecture and single-program multiple-data (SPMD) programming model. For example, on a regular, structured grid, $O(n^2)$ computation is performed, with nearest neighbor $O(n)$ inter-process communication requirements.

On parallel processing architectures, these stencil computations require data from neighboring processes. Inter-process communication is typically abstracted into some sort of functionality that may be loosely described as *boundary exchange* (likewise also called ghost-exchange or halo-exchange) This notion of mapping a continuous problem to discrete space and the inter-process communication requirement induced by spatially decomposing the grid across parallel processes is illustrated in Figure 1.1.

**Figure 1.1.** Stencil inter-process communication requirement

*The left figure shows a partial differential equation (the Poisson equation) described on a continuous domain, with homogeneous Dirichlet boundary conditions. The discretization of this problem is shown in the figure on the middle. The right figure illustrates the inter-process communication requirements when the discretized domain is decomposed across four parallel processes.*




This approach adheres to the bulk-synchronous parallel programming model (BSP [19]), arguably the dominant model for implementing high performance portable parallel processing scientific applications. As widely available parallel processing architectures focused node interconnect performance on bandwidth (relative to latency), code developers often aggregated data from various structures into single messages [4]. Although many such applications have continued to perform well even up to peta-scale [2, 7], the situation appears to be changing with the push to exascale [1, 18].

In the BSP/message aggregation (BSPMA) model, data from multiple (logical) memory locations are combined into a user-managed array with other data, then subsequently transmitted to the target process. This step incurs three additional costs, none of which directly advances the computation: memory utilization (the message buffers), on-node bandwidth (copies into the buffer), and synchronization (leading up to and including the data transfer). Further, this model interferes in some sense with the natural mapping of algorithms to programming languages in that the code developer must organize computation with the intent to aggregate and exchange data as a means of maximizing bandwidth and avoiding latency rather than organizing computation in a manner natural to the algorithm.

A renewed focus on non-traditional architectures and architecture features provides new opportunities for exploring alternatives to this programming approach. In previous work [17, 20] we saw that codes configured for the BSPMA model realized an evolutionary improvement in performance. However, codes that sent a large number of small messages realized a significant improvement in performance. This improvement is attributable to the significantly increased message injection rate of the node interconnect and supported by the node architecture, a trend we see continuing as nodes become more powerful and complex.

In order to study the performance characteristics of the BSPMA configuration within the context of computations widely used across a variety of scientific algorithms, we have developed a “miniapp”, called miniGhost. As a miniapplication [13], miniGhost is designed for modification and experimentation. It is an open source, self-contained, stand-alone code, with a simple build and execution system. It creates an application-specific context for experimentation, allowing investigation of different programming models and mechanisms, existing, emerging, and future architectures, and enabling investigation of entirely new algorithmic approaches for achieving effective use of the computing environment within the context of complex application requirements.

We begin with a discussion of difference stencils, followed by a description of the miniGhost miniapp, focusing on its computation and communication requirements. We include a discussion of the implementation, with a description of some MPI semantic options for implementing the boundary exchange. We then describe CTH, an application code for which miniGhost is intended to serve as a proxy, including a listing of the intentional differences between miniGhost and the implementation of CTH. Next we present some runtime results that serve to support the claim that intended connection. We conclude with a summary of this initial work and a discussion of future work.

# Chapter 2

# miniGhost

Stencil computations form the basis for finite difference, finite volume, and in fact many other algorithms. The basic idea is to update a value as an average of that value and some set of neighboring points. In the simplest case, heat diffusing across a homogeneous two dimensional domain is modeled as the non-weighted averages of the points surrounding the point to be updated. This can be described using a 5-point stencil defined as

$$u^{t+1}_{i,j,k} = \frac{u^t_{i,j-1,k} + u^t_{i-1,j,k} + u^t_{i,j,k} + u^t_{i+1,j,k} + u^t_{i,j+1,k}}{5}, \text{for} \;\; i,j,k = 1,\dots n, \;\; \text{for} \;\; \text{timestep} \;\; t.$$

A 9-point stencil would include the (up to four) points diagonally adjacent to

$$u^t_{i,j,k} : u^t_{i-1,j-1,k}, u^t_{i-1,j+1,k}, u^t_{i+1,j-1,k}, \;\; \text{and} \;\; u^t_{i+1,j+1,k}.$$

A three dimensional domain might need to include neighbors in adjacent two dimensional "slices", creating 7-point (analogous to 5-point) stencil or 27-point (analogous to a 9-point) stencil.

A Fortran implementation of the 5-point stencil shown in Figure 2.1 with the notion of decomposing across parallel processes illustrated above in Figure 1.1.

This problem definition presumes regular, equally spaced grid points across the global domain. This greatly simplifies the implementation of the algorithm, allowing us to focus in on the performance aspects of interest in our experiments.

## 2.1 Implementations

The basis of miniGhost is the BSPMA implementation described above. Since miniGhost was originally developed to explore alternative message passing implementations, we include a variant[1], which also uses MPI for parallelization. The three options are:

[1]Future plans include additional variants.

**Figure 2.1.** Five point stencil in Fortran

*This codesegment implements a five point differencing scheme on a three dimensional* ( `NX` × `NY` × `NZ` ) *grid. Note the extra (ghost) space allocated for the boundary condition.*

```
REAL, DIMENSION(0:NX+1,0:NY+1,0:NZ+1) ::  X, Y

DO K = 1,NZ
   DO J = 1,NY
      DO I = 1,NX
         X(I,J,K) =                                      &
                         ( Y(I-1,J,K)+                    &
            Y(I,J-1,K) + Y(I,J,K) + Y(I,J+1,K) +         &
                           Y(I+1,J,K) )                   &
                    / 5.0
      END DO
   END DO
END DO
```

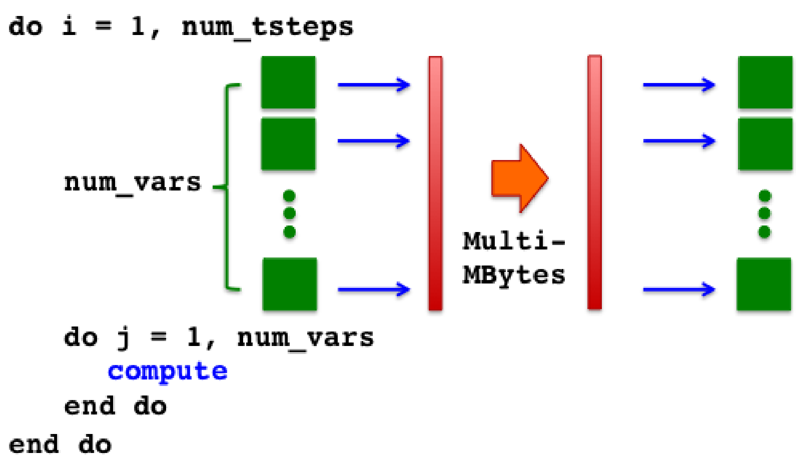
**Bulk synchronous parallel with message aggregation** (BSPMA) Face data is accumulated from each variable into user managed buffers. The buffers are then transmitted to (up to) six neighbor processes, and computation of the selected stencil is applied to each variable. (This implementation is illustrated in Figure 2.3(a).)

**Single variable, aggregated face data** (SVAF) This version transmits data as soon as computation on a variable is completed, face data aggregated. Thus six messages are transmitted for each variable (up to 40), one to each neighbor, each time step. (Illustrated in Figure 2.3(b), this eliminates the inner `END DO` and `DO I = 1, NUM_VARS` from the BSPMA implementation.)

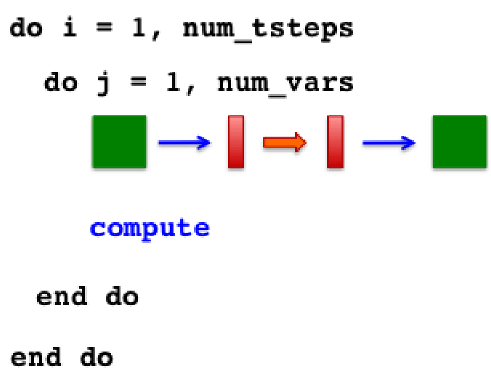
**Skeleton app** Although not an "official" implementation, by selecting the "no stencil" option (see Table 2.1), miniGhost runs in pure communication mode, based on the above configurations. This could serve as an interconnect stress test.

Optionally, summation of the (grid) elements for each variable may be computed, injecting collective communication into the execution. The MPI collective `MPI_ALLREDUCE` forms the global value, adding a runtime stress point typically seen in codes of this sort.

**Figure 2.2.** MiniGhost boundary exchange and computation




(a) BSPMA




(b) SVAF

## 2.2 Execution and Verifying Correctness

MiniGhost is not configured to solve any particular problem, allowing the user to control running time, by setting the number of time steps executed. The `GRID` arrays are loaded with random values (using the Fortran subroutine `RANDOM_NUMBER`). Because homogeneous Dirichlet boundary conditions are used, the grid values will eventually become zeros, so randomly generated source terms (called *spikes*) can be applied in order to maintain non-zero computation. Each spike will induce the requested number of time steps to be performed. That is, if 10 spikes and 50 times steps are requested, each spike will be inserted every 50 time steps, resulting in $50 \times 10 = 500$ total time steps.

The reference version of a Mantevo miniapp may execute serially, or with parallel processes using MPI, optionally including OpenMP threads. In serial mode using the default settings, miniGhost is run as

```
% ./miniGhost.x
```

In MPI mode using the default settings, miniGhost is run as

```
% mpirun -np 1024 ./miniGhost.x
```

When using OpenMP with MPI, the number of threads per MPI rank is set using environment variable `OMP_NUM_THREADS`.

Runtime input parameters are listed in Table 2.1, and may also be listed using runtime input `--help`, i.e.

```
% ./miniGhost.x --help
```

or

```
% mpirun -np 1024 ./miniGhost.x --help
```

Correctness is ensured by comparing the current state (the sum of the global domain values), added to sum of the flux out of the domain, with the initial values. That is, the sum of each `GRID` array should be equal to the inserted source term (within some specified tolerance). The current implementation uses a scaled error check:

$$\frac{\texttt{SOURCE\_TOTAL(IVAR)} - \texttt{GRIDSUM}_{\texttt{IVAR}}}{\texttt{SOURCE\_TOTAL(IVAR)}} < \texttt{TOL}, \text{for } \texttt{IVAR} = 1, \ldots, \texttt{NUM\_VARS}.$$

**Table 2.1.** Input parameters

**default setting; See* `MG_OPTIONS.F` *for list of all parameterized options.*

| *Parameter* | *Description* | *Options* |
|---|---|---|
| `--scaling` | Parallel scaling configuration | `SCALING_STRONG`<br>`SCALING_WEAK`* |
| `--comm_method` | Boundary exchange implementation. | `COMM_METHOD_BSPMA`*<br>`COMM_METHOD_SVAF` |
| `--stencil` | Stencil to be applied. | `STENCIL_NONE`<br>`STENCIL_2D5PT`<br>`STENCIL_2D9PT`<br>`STENCIL_3D7PT`<br>`STENCIL_3D27PT`* |
| `--nx --ny --nz`<br>*or*<br>`--ndim` for `nx = ny = nz` | Grid dimension in $(x, y, z)$ directions.<br>Global values if strong scaling,<br>local values if weak scaling. | $> 0$; $10^*$ |
| `--num_vars` | Number of `GRID` arrays operated on. | $1 - 40^*$ |
| `--percent_sum` | (Approximate) percentage of variables<br>summation reduced | 0-100; $0^*$ |
| `--num_tsteps` | Number of time steps iterated. | $> 0$; $10^*$ |
| `--num_spikes` | Number of source spikes inserted. | $> 0$; $1^*$ |
| `--npx --npy --npz`<br>*or*<br>`--npdim` for `npx = npy = npz` | Logical processor grid in $(x, y, z)$. | $> 0$; `(numpes,1,1)`* |
| `--error_tol` | Error tolerance. | $10^{-error\_tol}$ |
| `--report_diffusion` | Write error to `stdout`<br>every $n$ time steps. | $n \geq 0^*$ |
| `--debug_grid` | Initialize grids to 0,<br>insert heat source in center. | 0 or $1^*$ |
| `--report_perf` | Reporting options | $0^*$, 1, 2 |
| `--help` | Lists input parameters, and aborts. | |

The default error tolerance is $10^{-8}$ for REAL8 and $10^{-4}$ for REAL4. Note that all variables are checked, each requiring a global summation, which can significantly impact execution time.

A special problem is configured to enable easier tracking of the diffusion of values across the domain. Setting the runtime parameter grid_debug to 1 initializes the GRID arrays to 0, inserts a source term in the middle of the global domains, and then tracks the sources as they propagates throughout the arrays.

## 2.3 Output

Output is controlled by the command line option report_perf. By default it is set to 0, resulting in the problem configuration and performance results written to a file named result.yaml, formatted using YAML[2]. By setting this option to 1, this information is also written to a text file named result.txt. Setting it to 2 adds per processor communication times to the result.txt file.

## 2.4 Code description

MiniGhost is constructed using a modular design, illustrated in Figure 2.3. In particular, the separation of the stencil computation and boundary exchange communication enables experimentation in a variety of ways. For example, new stencils, adding weights to the stencils, or alternative MPI functionality could be configured. Significantly different implementations of the required functionality can also be configured, with some examples described in this report's summary, Chapter 3.

MiniGhost is (mostly) implemented using the Fortran programming language[3], requiring at least a Fortran 90 compliant compiler. Parallelism, described in Section 2.5, is enabled using functionality defined by the MPI specification [15]. Each variable (representing for example a material state) is stored in a distinct three dimensional Fortran array (named GRIDx, for $\mathtt{x} = 1, \ldots, 40$), across which the stencil is computed using a triply nested DO loop. Type precision is configurable as either single (four bytes) or double (eight bytes, the default), managed in module MG_CONSTANTS. Pre-processor compiler directives manage the interface with MPI functionality. That is, MG_MPI_REAL is set to MPI_REAL4 or MPI_REAL8, depending on the precision requested. Most other variables are declared using the default INTEGER or REAL, unless otherwise required or recommended. For example, timings are determined at double precision, using MPI_Wtime under MPI and the Fortran function SYSTEM_CLOCK for serial execution. Accumulation of profiling data could require increased precision, so eight

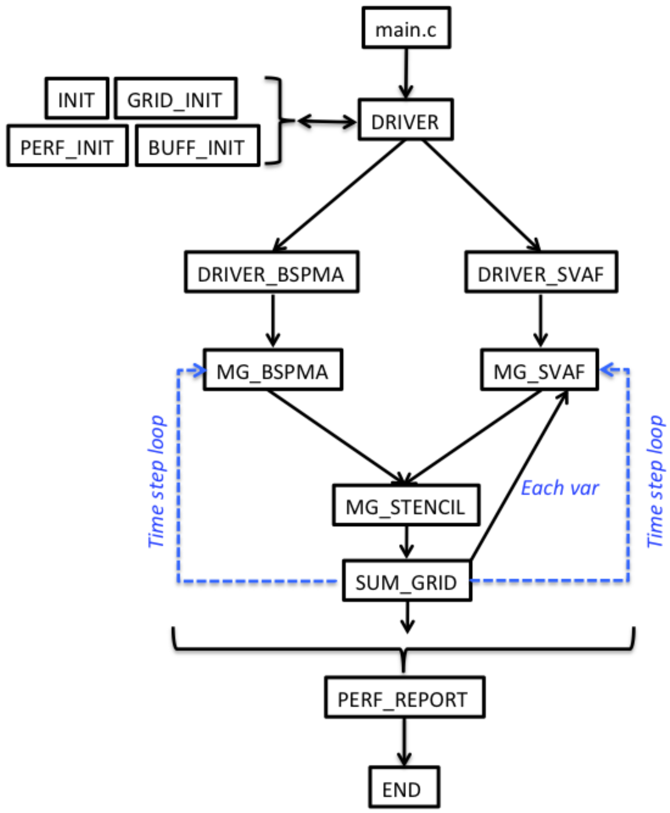
[2] http://yaml.org

[3] The main program is configured using the C programming language, which enables more flexible parsing of command line input.

byte integers are employed.

Figure 2.3 shows the runtime flow. For the most part, the names refer to the subrou-

**Figure 2.3.** miniGhost code flow diagram




tine as well as the file name. Where convenient, names are parameterized. For example, `MG_STENCIL_xDyPT` refers to a $y$-point stencil in $x$ dimensions. Currently this set includes 5- and 9-point stencils in two dimensions and 7- and 27-point stencils in three dimensions.

A listing of the source code files that compose miniGhost is shown in Table 2.2. Table 2.3 lists the MPI functionality employed by miniGhost. Appendix A provides a breakdown of the source code. The number of lines of code is magnified by the redundancy employed by the implementation as a means of clarity as well as the inclusion of several options to the basic BSP message aggregation model. The basics are captured in the boundary exchange and stencil computation procedures. (Note that for the asynchronous versions, these two functional requirements are combined into a single procedure.)

**Table 2.2.** MiniGhost functionality

| *Functionality* | *Function* | *Alternatives* |
|---|---|---|
| | MINI_GHOST<br>MG_BUFINIT<br>MG_CONSTANTS<br>MG_OPTIONS<br>MG_PROFILING<br>MG_UTILS | |
| Boundary exchange driver | DRIVER_BSPMA | DRIVER_SVAF |
| Boundary exchange | MG_BSPMA<br>MG_BSPMA_DIAGS | MG_SVAF<br>MG_SVAF_DIAGS |
| Driver for stencil option<br>y-point stencil computation in x dimensions | MG_STENCIL<br>MG_STENCIL_xDyPT | |
| Manages the reduction (sum) across a grid<br>Performs the reduction (sum) across a grid | MG_SUM_GRID<br>MG_ALLREDUCE | |
| Post non-blocking receives | MG_IRECV | |
| Pack face into message buffer | MG_PACK | |
| Send boundaries | MG_SEND_BSPMA<br>MG_SEND_SVAF | |
| Message completion | MG_UNPACK_BSPMA | MG_UNPACK_SVAF |
| Unpack message buffer into GRIDs ghost space | MG_GET_FACE | |
| Captures heat lost to flux.<br>Correctness check functionality. | MG_FLUX_ACCUMULATE | |
| Driver | main.c | |

**Table 2.3.** MPI functionality employed

| *Subroutine* | *Use* |
|---|---|
| MPI_IRECV<br>MPI_SEND<br>MPI_WAITANY | Core functionality |
| MPI_ALLREDUCE<br>MPI_ISEND<br>MPI_RECV | Optional Core functionality |
| MPI_ABORT<br>MPI_BCAST<br>MPI_COMM_DUP<br>MPI_COMM_RANK<br>MPI_COMM_SIZE<br>MPI_ERRHANDLER_SET<br>MPI_INIT<br>MPI_GATHER<br>MPI_FINALIZE<br>MPI_REDUCE | Support functionality |

## 2.5 Parallel Programming Model

MiniGhost is configured using the Single Program Multiple Data (SPMD) parallel programming model, with parallelism enabled using functionality defined in the MPI specification [15]. MPI provides a wealth of mechanisms and configurations for point-to-point interprocess communication. Our choice is motivated by that employed by the widest number of applications in our experience, reinforced by discussions with many MPI implementers. Here, non-blocking receives for all communication partners are posted, followed by all non-blocking sends, followed by completion of these procedures as a whole. Sends are preceded by data copies into message buffers where needed; upon completion, receives are followed by unpacking of data into appropriate data structures where needed. Figure 2.4 illustrates the idea with a code fragment. We anticipate that different configurations might result in meaningfully different (and perhaps better) performance on different platforms with different MPI implementations, an issue we intend to explore as a general study using this and other miniapps.

The OpenMP implementation explicitly enables processor and memory affinity using an explicit first touch algorithm when initializing the `GRIDx` arrays. Parallel loops are enabled in the stencil computations, summation across the `GRIDx` arrays, and the packing and unpacking of the halos.

**Figure 2.4.** Sketch of miniGhost boundary exchange

```
DO I = 1, NUM_RECVS
   CALL MPI_IRECV ( ..., MSG_REQ(I), ... )
END DO

!  Perhaps some buffer packing

DO I = 1, NUM_SENDS
   CALL MPI_ISEND ( ..., MSG_REQ(I+NUM_RECVS), ... )
END DO

DO I = 1, NUM_RECVS + NUM_SENDS

   CALL MPI_WAITANY ( NUM_RECVS + NUM_SENDS, MSG_REQ, IWHICH, ISTAT, IERR )

   IF ( IWHICH <= NUM_RECVS ) THEN
   !  Perhaps some unbuffer packing
   !  else completed send, no action required.
   END IF

END DO
```

## 2.6 Peer implementations

Mantevo miniapps are designed to serve as a tractable means of describing key performance issues within the context of large scale scientific and engineering application codes. As such, they are purposely written using the most ubiquitous languages (C, C++, Fortran) and parallel programming mechanism (MPI) with an option to use OpenMP [10] within a node, providing what we refer to as the *reference implementation*. This provides a means for exploring alternative, emerging and future architectures. The current distribution includes support for the OpenACC version 1.0 specification[4]. We anticipate implementations based on Fortran co-arrays, as well as alternative and developing programming models and languages, such as Chapel [8] and X10 [9], and perhaps some functional languages. We also anticipate developing an implementation based on the C programming language.

## 2.7 Checkpointing

Checkpointing is a common resilience technique used to recover from program or system failures. A checkpoint contains enough program state to restart execution from the current time step as opposed to starting the run from time step zero. Depending on the checkpoint

[4] http://www.openacc-standard.org/

| *Subroutine* | *Use* |
|---|---|
| MPI_FILE_OPEN<br>MPI_FILE_CLOSE | File management |
| MPI_TYPE_EXTENT<br>MPI_TYPE_GET_EXTENT<br>MPI_TYPE_CONTIGUOUS<br>MPI_TYPE_CREATE_STRUCT<br>MPI_TYPE_CREATE_SUBARRAY<br>MPI_TYPE_COMMIT<br>MPI_TYPE_FREE | Derived type construction |
| MPI_FILE_SET_VIEW<br>MPI_FILE_WRITE<br>MPI_FILE_WRITE_ALL<br>MPI_FILE_READ<br>MPI_FILE_READ_ALL | Data movement |

**Table 2.4.** MPI-IO functionality employed for checkpointing

size and host system performance, checkpointing can be an expensive operation.

MiniGhost includes an MPI-IO based checkpoint module that lets users study checkpoint performance on targeted platforms. (A list of MPI-IO functionality employed is shown in Table 2.4.) At the end of every time step, there is an opportunity to checkpoint the current state of miniGhost. If the checkpoint interval is greater than zero and the current time step matches the interval, a checkpoint is performed. Each checkpoint appends a small header plus the problem variables (`GRIDx`) to the checkpoint file. The first checkpoint has some additional overhead including file creation and the writing of a global header. At the end of each checkpoint, a checkpoint counter in the global header is incremented and the file is closed to ensure a consistent file state.

Checkpoint file I/O is implemented using the parallel I/O API from the MPI 2.2 specification [14]. The miniGhost checkpoint module uses MPI derived datatypes to the describe the relationship between the in-memory data representation and the file representation. The simplest datatypes are arrays of integers constructed with `MPI_TYPE_CONTIGUOUS`. These datatypes are used to write the list of problem variables active in this run (`GRIDS_TO_SUM`). The active problem variable list is fixed after startup and common to all the PEs, so the root PE writes the array with `MPI_FILE_WRITE` as part of the global header, while the other PEs are idle. More complicated datatypes for writing the problem variables (`GRIDx`) are constructed using `MPI_TYPE_CREATE_SUBARRAY`. Writing the problem variables requires two derived datatypes. The first datatype (`CP_NOGHOST_TYPE` describes the local in-memory grid without the ghost cells. Because the ghost cells are copied from other PEs, there is no reason to save the ghost cells. The second datatype (CP_TSGRID_TYPE is a compound type composed of CP_NOGHOST_TYPE elements that describes the distribution of each problem variable across the PEs. Every PE calls MPI_FILE_WRITE_ALL to write the entire grid to disk. The combination of these datatypes results in a complete contiguous grid in the checkpoint file without ghost cells.

# Chapter 3

# Summary

MiniGhost is a miniapp developed within the scope of the Mantevo project. It is designed to provide a means to explore the Bulk Synchronous Parallel programming model, supplemented with message aggregation, in the context of exchanging inter-process boundary data typically seen in finite difference and finite volume computations. This programming model is employed across a breadth of science domains, typically for solving partial differential equations. MiniGhost was inspired by the multi-decades experiences by the authors with these sorts of parallel programs, and the desire to explore alternative configurations on current, emerging, and future computing environments. It also provides a means for exploring alternative programming languages as well as alternative semantics of MPI.

An alternative boundary communication strategies are included for the boundary exchange, designed to explore the capabilities of computer node inter-connects. Additionally, collective communication may be inserted throughout the time steps, adding an additional level of realism for many application programs. Further, computation may be “turned off”, providing a skeleton app capability whereby inter-process communication requirements may used as a “stress test” to explore inter-connect capabilities external of computation.

A methodology for determining how a miniapp is predictive of a full application is presented in [5]. Some results from the use of miniGhost within the context of a full application has been presented in [6].

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# Appendix A

# Code categorization

This section provides a breakdown of the source code, as reported by CodeCount [16]. Cross referencing to Figure 2.3 should provide a general understanding of the source code for miniGhost. The distinction between a physical and logical line of code is discussed in the READ file (`USC_Read_Me-TXT.txt`) distributed with the CodeCount package:

```
   PHYSICAL SLOC : The number of physical SLOCs within a source file is defined
to be the sum of the number of physical SLOCs (terminated by a carriage return
or EOLN character) which contain program instructions created by project personnel
and processed into machine code by some combination of preprocessors, compilers,
interpreters, and/of assemblers.  It excludes comment cards and unmodified utility
software.  It includes job control language (compiler directive), format statements,
and data declarations (data lines).  Instructions are defined as lines of code
or card images.  Thus, a line containing two or more source statements count as
one physical SLOC; a five line data declaration counts as five physical SLOCs.
The physical SLOC definition was selected due to (1) compatibility with parametric
software cost modeling tools, (2) ability to support software metrics collection,
and (3) programming language syntax independence.

   LOGICAL SLOC : The number of logical SLOC within a source file is defined to
be the sum of the number of logical SLOCs classified as compiler directives, data
lines, or executable lines.  It excludes comments (whole or embedded) and blank
lines.  Thus, a line containing two or more source statements count as multiple
logical SLOCs; a single logical statement that extends over five physical lines
count as one logical SLOC. Specifically, the logical SLOC found within a file
containing software written in the PL/I programming language may be computed by
summing together the count of (1) the number of terminal semicolons, (2) the number
of terminal commas contained within a DECLARE (DCL) statement, and (3) the number
of logical compiler directives that do not terminate with a terminal semicolon,
i.e., JCL directives.  The logical SLOC definition was selected due to (1) compatibility
with parametric software cost modeling tools, and (2) ability to support software
metrics collection.  The logical SLOC count is susceptible to erroneous output
when the analyzed source code file contains software that uses overloading or
replacement characters for a few key symbols, e.g., ';' .
```

– End quoted text.

Table 2.3 above listed the MPI functionality employed by miniGhost. Figure A.1 lists the Fortran SLOC. Figure A.2 lists the Fortran SLOC required for the BSPMA implementation. The latter is shown with two caveats. First, a significant amount code is shared with the SVAF implementation, and second, this includes code needed only by the SVAF implementation.

File `main.c` adds 388 physical lines and 264 logical lines.

**Figure A.1.** miniGhost SLOC summary by file

| Total Lines | Blank Lines | Comments Whole | Comments Embedded | Compiler Direct. | Data Decl. | Exec. Instr. | Physical SLOC | File Type | Module Name |
|---|---|---|---|---|---|---|---|---|---|
| 209 | 36 | 43 | 4 | 0 | 4 | 126 | 130 | F77 | DRIVER.F |
| 141 | 28 | 41 | 7 | 0 | 4 | 68 | 72 | F77 | DRIVER_BSPMA.F |
| 140 | 26 | 41 | 8 | 0 | 4 | 69 | 73 | F77 | DRIVER_SVAF.F |
| 113 | 26 | 41 | 5 | 0 | 8 | 38 | 46 | F77 | MG_ALLREDUCE.F |
| 166 | 22 | 41 | 1 | 0 | 1 | 102 | 103 | F77 | MG_BSPMA.F |
| 196 | 27 | 40 | 4 | 0 | 2 | 127 | 129 | F77 | MG_BSPMA_DIAGS.F |
| 382 | 120 | 79 | 9 | 0 | 6 | 177 | 183 | F77 | MG_BUFINIT.F |
| 934 | 209 | 127 | 14 | 0 | 87 | 511 | 598 | F77 | MG_CHECKPOINT.F |
| 237 | 52 | 38 | 37 | 0 | 0 | 147 | 147 | F77 | MG_CONSTANTS.F |
| 130 | 24 | 37 | 2 | 0 | 5 | 64 | 69 | F77 | MG_FLUX_ACCUMULATE.F |
| 341 | 124 | 60 | 5 | 0 | 9 | 148 | 157 | F77 | MG_GET_FACE.F |
| 227 | 54 | 48 | 1 | 0 | 2 | 123 | 125 | F77 | MG_IRECV.F |
| 82 | 21 | 32 | 12 | 0 | 0 | 29 | 29 | F77 | MG_OPTIONS.F |
| 180 | 31 | 61 | 2 | 0 | 4 | 84 | 88 | F77 | MG_PACK.F |
| 1915 | 313 | 80 | 17 | 0 | 0 | 1522 | 1522 | F77 | MG_PROFILING.F |
| 237 | 50 | 52 | 2 | 0 | 3 | 132 | 135 | F77 | MG_SEND_BSPMA.F |
| 240 | 51 | 52 | 2 | 0 | 4 | 133 | 137 | F77 | MG_SEND_SVAF.F |
| 424 | 32 | 43 | 2 | 0 | 2 | 347 | 349 | F77 | MG_STENCIL.F |
| 335 | 90 | 91 | 12 | 0 | 18 | 136 | 154 | F77 | MG_STENCIL_COMPS.F |
| 154 | 18 | 39 | 2 | 0 | 3 | 94 | 97 | F77 | MG_SUM_GRID.F |
| 308 | 25 | 44 | 6 | 0 | 3 | 236 | 239 | F77 | MG_SVAF.F |
| 253 | 40 | 57 | 10 | 0 | 6 | 150 | 156 | F77 | MG_SVAF_DIAGS.F |
| 169 | 34 | 42 | 4 | 0 | 4 | 89 | 93 | F77 | MG_UNPACK_BSPMA.F |
| 177 | 38 | 46 | 4 | 0 | 5 | 88 | 93 | F77 | MG_UNPACK_SVAF.F |
| 1112 | 284 | 97 | 23 | 1 | 36 | 694 | 731 | F77 | MG_UTILS.F |

FORTRAN SOURCE LINES OF CODE COUNTING PROGRAM



(a) File listings

| Total Lines | Blank Lines | Comments Whole | Comments Embedded | Compiler Direct. | Data Decl. | Exec. Instr. | Number of Files | SLOC | File Type | SLOC Definition |
|---|---|---|---|---|---|---|---|---|---|---|
| 8802 | 1775 | 1372 | 195 | 1 | 220 | 5434 | 25 | 5655 | F77 | Physical |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | F90 | Physical |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | HPF | Physical |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | DATA | Physical |
| | | | | | | | | 5655 | <---Total Physical SLOCs | |
| 8802 | 1775 | 1372 | 195 | 1 | 196 | 3750 | 25 | 3947 | F77 | Logical |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | F90 | Logical |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | HPF | Logical |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | DATA | Logical |
| | | | | | | | | 3947 | <---Total Logical SLOCs | |

Ratio of Physical to Logical SLOC (FORTRAN-77)............... 1.43

(b) Summary

**Figure A.2.** miniGhost BSPMA SLOC summary by file

| Total | Blank | Comments | | Compiler | Data | Exec. | Physical | File | Module |
|---|---|---|---|---|---|---|---|---|---|
| Lines | Lines | Whole | Embedded | Direct. | Decl. | Instr. | SLOC | Type | Name |
| 209 | 36 | 43 | 4 | 0 | 4 | 126 | 130 | F77 | DRIVER.F |
| 141 | 28 | 41 | 7 | 0 | 4 | 68 | 72 | F77 | DRIVER_BSPMA.F |
| 113 | 26 | 41 | 5 | 0 | 8 | 38 | 46 | F77 | MG_ALLREDUCE.F |
| 166 | 22 | 41 | 1 | 0 | 1 | 102 | 103 | F77 | MG_BSPMA.F |
| 196 | 27 | 40 | 4 | 0 | 2 | 127 | 129 | F77 | MG_BSPMA_DIAGS.F |
| 382 | 120 | 79 | 9 | 0 | 6 | 177 | 183 | F77 | MG_BUFINIT.F |
| 237 | 52 | 38 | 37 | 0 | 0 | 147 | 147 | F77 | MG_CONSTANTS.F |
| 130 | 24 | 37 | 2 | 0 | 5 | 64 | 69 | F77 | MG_FLUX_ACCUMULATE.F |
| 341 | 124 | 60 | 5 | 0 | 9 | 148 | 157 | F77 | MG_GET_FACE.F |
| 227 | 54 | 48 | 1 | 0 | 2 | 123 | 125 | F77 | MG_IRECV.F |
| 180 | 31 | 61 | 2 | 0 | 4 | 84 | 88 | F77 | MG_PACK.F |
| 237 | 50 | 52 | 2 | 0 | 3 | 132 | 135 | F77 | MG_SEND_BSPMA.F |
| 424 | 32 | 43 | 2 | 0 | 2 | 347 | 349 | F77 | MG_STENCIL.F |
| 335 | 90 | 91 | 12 | 0 | 18 | 136 | 154 | F77 | MG_STENCIL_COMPS.F |
| 154 | 18 | 39 | 2 | 0 | 3 | 94 | 97 | F77 | MG_SUM_GRID.F |
| 169 | 34 | 42 | 4 | 0 | 4 | 89 | 93 | F77 | MG_UNPACK_BSPMA.F |
| 1112 | 284 | 97 | 23 | 1 | 36 | 694 | 731 | F77 | MG_UTILS.F |

(a) File listings

| Total | Blank | Comments | | Compiler | Data | Exec. | Number | | File | SLOC |
|---|---|---|---|---|---|---|---|---|---|---|
| Lines | Lines | Whole | Embedded | Direct. | Decl. | Instr. | of Files | SLOC | Type | Definition |
| 4753 | 1052 | 893 | 122 | 1 | 111 | 2696 | 17 | 2808 | F77 | Physical |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | F90 | Physical |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | HPF | Physical |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | DATA | Physical |
| | | | | | | | | 2808 | <---Total Physical SLOCs | |
| 4753 | 1052 | 893 | 122 | 1 | 111 | 2455 | 17 | 2567 | F77 | Logical |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | F90 | Logical |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | HPF | Logical |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | DATA | Logical |
| | | | | | | | | 2567 | <---Total Logical SLOCs | |

(b) Summary

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