

Earth System Modeling Framework

ESMF User Guide

Version 3.0

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- The Inpack configuration attributes package from NASA Goddard, which was adapted for use in ESMF by members of NASA Global Modeling and Assimilation group
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- The Common Component Architecture (CCA) effort within the DoE, from which we drew many ideas about how to design components
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- The Portable, Extensible Toolkit for Scientific Computation (PETSc) package from Argonne National Laboratories, on which we based our initial makefile system

Contents

1	What is the Earth System Modeling Framework?	5
2	The ESMF User's Guide	5
3	How to Contact User Support and Find Additional Information	5
4	How to Submit New Requirements	6
5	Quick Start	7
5.1	Downloading ESMF	7
5.1.1	From the ESMF web site	7
5.1.2	From the SourceForge web site	7
5.2	Unpacking the download	7
5.3	Directory Structure	7
5.4	Building ESMF	8
5.4.1	Environment Variables	8
5.4.2	gmake info	9
5.4.3	GNU make	11
5.4.4	Build makefile Targets	12
5.4.5	Testing makefile Targets	12
6	Building and Installing the ESMF	13
6.1	ESMF Download Options	13
6.2	System Requirements	13
6.3	ESMF Environment Variables	13
6.4	Supported Platforms	18
6.5	Building the ESMF Library	19
6.6	Building the ESMF Documentation	20
6.7	Installing the ESMF	20
7	Porting the ESMF	20
7.1	The ESMF Build System	21
7.1.1	General Structure	21
7.1.2	Build Configuration	22
7.1.3	Source Code Configuration	22
7.2	Porting the ESMF to New Platforms	22
7.2.1	Customizing the <code>build_rules.mk</code> fragment	23
7.2.2	Customizing <code>ESMC_Conf.h</code> and <code>ESMF_Conf.inc</code>	27
8	Validating and Running with ESMF	27
8.1	Running ESMF Self-Tests	27
8.1.1	Running ESMF Unit Tests	28
8.1.2	Running ESMF System Tests	30
8.2	Running ESMF Examples	32
8.2.1	Example Source Code	32
8.2.2	Building and Running Examples	32
8.3	Using the ESMF	34
8.3.1	Shared Object Libraries	34
8.3.2	Customized SITE Files	34
8.4	Demonstration Application	35

8.4.1	Running the Demonstration	35
9	Architectural Overview	36
9.1	Key Concepts	36
9.1.1	Modularity	36
9.1.2	Flexibility	36
9.1.3	Hierarchical Organization	37
9.1.4	Communication Within Components	37
9.1.5	Uniform Communication API	37
9.2	Superstructure	37
9.2.1	Import and Export State Classes	37
9.2.2	Interface Standards	39
9.2.3	Gridded Component Class	39
9.2.4	Coupler Component Class	39
9.2.5	Flexible Data and Control Flow	39
9.3	Infrastructure	41
9.3.1	Bundle, Field and Array Classes	41
9.3.2	Grid Class	42
9.3.3	Time and Calendar Management Class	42
9.3.4	Config Resource File Manager	42
9.3.5	DELayout and Virtual Machine	42
9.3.6	Logging and Error Handling	42
9.3.7	I/O Classes	42
10	ESMF_COUPLED_FLOW Demonstration Program	43
10.1	Introduction	43
10.2	ESMF_COUPLED_FLOW Description	43
11	Program Organization	43
12	Framework Usage Details	43
12.1	Fortran: Module Interface CoupledFlowApp.F90 - Main program source file for demo (Source File: CoupledFlowApp.F90) 4	
12.1.1	Namelist Input Parameters for CoupledFlowApp:	43
12.1.2	Example of Initializing the Framework:	44
12.1.3	Example of Calendar and Clock Creation and Usage:	45
12.1.4	Example of Grid Creation:	45
12.2	Fortran: Module Interface CoupledFlowDemo.F90 - Top level Gridded Component source (Source File: CoupledFlowDemo.F90) 4	
12.2.1	Example of Set Services Usage:	46
12.2.2	Example of Component Creation:	46
12.2.3	Example of State Creation:	47
12.3	Fortran: Module Interface FlowSolverMod.F90 - Source file for Flow Solver Component (Source File: FlowSolverMod.F90) 4	
12.3.1	Namelist Input Parameters for Flowsolver:	47
12.3.2	Example of FieldHalo Usage:	48
12.4	Fortran: Module Interface FlowArraysMod.F90 - Source file for Data for Flow Solver (Source File: FlowArraysMod.F90) 48	
12.4.1	Example of Field Creation and Array Usage:	49
12.5	Fortran: Module Interface CouplerMod.F90 - Source for 2-way Coupler Component (Source File: CouplerMod.F90) 49	
12.5.1	Example of Redist Usage:	49
12.6	Fortran: Module Interface InjectorMod - Fluid Injection Component (Source File: InjectorMod.F90) .	49
12.7	Namelist Input Parameters for Injector:	50

13 How to Adapt Applications for ESMF	50
13.1 Individual Components	50
13.2 Full Application	51
14 Glossary	53
References	58

1 What is the Earth System Modeling Framework?

The Earth System Modeling Framework (ESMF) is a structured collection of software building blocks that can be used or customized to develop Earth system model components, and assemble them into applications. The simplest view of the ESMF is that it consists of an *infrastructure* of utilities and data structures for creating model components, and a *superstructure* for coupling them. User code sits between these two layers, making calls to the infrastructure libraries beneath it and being scheduled and synchronized by the superstructure above it. The configuration resembles a sandwich, as shown in Figure 1.

The ESMF architecture is scalable, flexible paradigm for building highly complex climate, weather, and related applications from components such as atmospheric models, land models, and data assimilation systems. The ESMF is not a single master application into which all components must fit; rather it is a way of developing components so that they can be used in many different user-written applications. Model components that adopt ESMF are usable in different contexts without code modification, and may be incorporated into other ESMF-based modeling systems within the Earth science community. In addition to high-level organization, ESMF provides a set of robust, portable, performance optimized libraries for regridding, data transfers, I/O, time management, and other common modeling functions. ESMF users may choose to extensively rewrite their codes to take advantage of the ESMF infrastructure, or they may decide to simply wrap user-written components in ESMF interfaces in order to adopt the ESMF architecture and utilize framework coupling services.

2 The ESMF User's Guide

This *ESMF User's Guide* will eventually serve as an installation and build guide for the new ESMF user and as a reference for the experienced user. This edition of the *User's Guide* is designed to guide you through the introduction process to the software. We strongly encourage you to download the ESMF software and try running a demonstration program, `ESMF_COUPLED_FLOW`, that illustrates both ESMF utilities and coupling services.

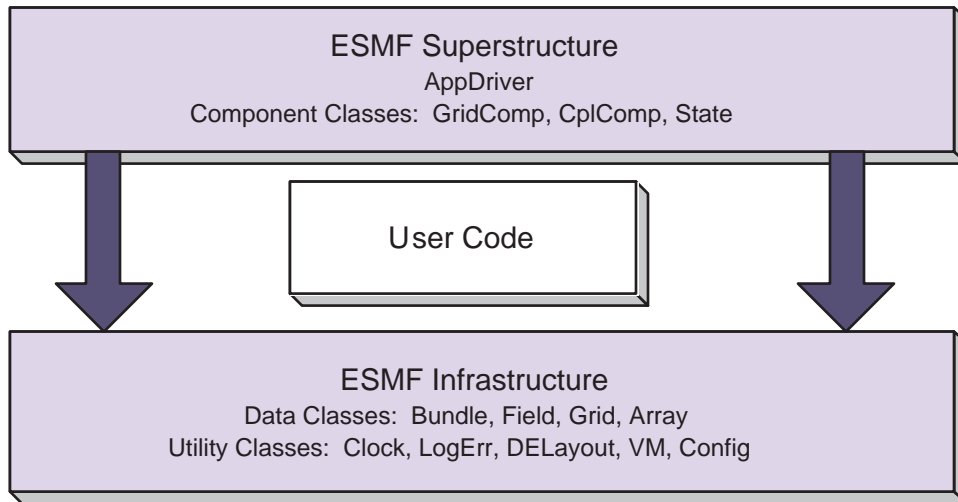
The next two sections, 3 and 4, concern user support and how to submit comments on the ESMF system to our development team. Sections 5 through 8 contain a *Quick Start* guide that explains how to install the ESMF software and run the self-tests, followed by more detail on ESMF structure and operation, such as a description of the directory structure and how to build and run the ESMF examples and demonstration programs. Section 9 is an architectural overview that describes the framework's basic goals and features. The next few Sections, beginning with 10, describe in detail the `ESMF_COUPLED_FLOW` demo application. Section 13 details the steps required to adapt a component for use with ESMF. Finally, to help you become familiar with ESMF terminology, the last section in the *User's Guide* is a glossary.

3 How to Contact User Support and Find Additional Information

The ESMF team can provide assistance in using the framework in your applications. For user support, please contact `esmf_support@ucar.edu`.

More information on the ESMF project as a whole is available on the ESMF website, <http://www.esmf.ucar.edu>. The website includes a description of ESMF testbed applications, related projects, the ESMF management structure, and much more. Those curious about specific interfaces should refer to the *ESMF Reference Manual for Fortran*, which contains a detailed listing and description of the ESMF API. Other documents available on the ESMF site include an exhaustive *ESMF Requirements Document* and an *ESMF Developer's Guide* that details our project procedures and conventions.

Figure 1: Schematic of the ESMF “sandwich” architecture. In this design the framework consists of two parts, an upper level **superstructure** layer and a lower-level **infrastructure** layer. User code is sandwiched between these two layers.



4 How to Submit New Requirements

The **Development** link on the ESMF website includes on-line forms for the submission of new requirements, if it seems that the current API does not satisfy the needs of your application. We welcome input on any aspect of the ESMF project; general questions and comments should be sent to esmf@ucar.edu.

5 Quick Start

This section gives a brief description of how to get the ESMF software, build it, and run the self-tests to verify the installation was successful. More detailed information on each of these steps, as well as information on running a demonstration application and linking the ESMF with your own code is found in Sections 6 and 8.

5.1 Downloading ESMF

5.1.1 From the ESMF web site

ESMF is distributed as a source code tar file. The tar file for the latest public release, release notes, known bugs, supported platforms, documentation, and other related information can be found on the ESMF Web site, under the “Download” Tab:

```
http://www.esmf.ucar.edu -> Download
```

The source code for all other releases including the HEAD of the CVS trunk and the last stable version can be found by following the “View All Releases” link on the left hand navigation bar under “Download”:

```
http://www.esmf.ucar.edu -> Download -> View All Releases
```

5.1.2 From the SourceForge web site

ESMF can also be downloaded from the SourceForge web site from the "Files" link:

```
http://sourceforge.net/projects/esmf -> Files
```

Follow the directions on that web page to download a tar file.

5.2 Unpacking the download

The source code comes as a zipped tar file. First unzip the file:

```
gunzip esmf*.tar.gz
```

Then untar the file:

```
tar -xf esmf*.tar
```

This will create a directory called esmf.

5.3 Directory Structure

The current list of directories is:

- README
- application
- build
- build_config
- makefile
- scripts
- src

The build_config directory contains subdirectories for different operating system, compiler combinations. This is a useful area to examine if porting ESMF to a new platform.

5.4 Building ESMF

After downloading and unpacking the ESMF tar file, the build procedure is:

1. Set the required environment variables.
2. Type `gmake info` to view and verify your settings
3. Type `gmake` to build the library.
4. Type `gmake check` to run self-tests to verify the build was successful.

See the following sections for more information on each of these steps.

5.4.1 Environment Variables

The syntax for setting environment variables depends on which shell you are running. Examples of the two most common ways to set an environment variable are:

```
ksh export ESMF_DIR=/home/joeuser/esmf
```

```
csh setenv ESMF_DIR /home/joeuser/esmf
```

The shell environment variables listed below are the ones most frequently used. There are others which address needs on specific platforms or are needed under more unusual circumstances; see Section 6 for the full list.

ESMF_DIR The environment variable `ESMF_DIR` must be set to the full pathname of the top level ESMF directory before building the framework. This is the only environment variable which is required to be set on all platforms under all conditions.

ESMF_BOPT This environment variable controls the build option. To make a debuggable version of the library set `ESMF_BOPT` to `g` before building. The default is `O` (capital oh) which builds an optimized version of the library. If `ESMF_BOPT` is `O`, `ESMF_OPTLEVEL` can also be set to a numeric value between 0 and 4 to select a specific optimization level.

ESMF_COMM On systems with a vendor-supplied MPI communications library the vendor library is chosen by default for communications and `ESMF_COMM` need not be set. For other systems (e.g. Linux or Darwin) a multitude of MPI implementations is available and `ESMF_COMM` must be set to indicate which implementation is used to build the ESMF library. Set `ESMF_COMM` according to your situation to: `mpich`, `mpich2`, `lam`, `openmpi` or `intelmpi`. `ESMF_COMM` may also be set to `user` indicating that the user will set all the required flags using advanced ESMF environment variables.

Alternatively, ESMF comes with a single-processor MPI-bypass library which is the default for Linux and Darwin systems. To force the use of this bypass library set `ESMF_COMM` equal to "mpiuni".

ESMF_COMPILER The ESMF library build requires a working Fortran90 and C++ compiler. On platforms that don't come with a single vendor supplied compiler suite (e.g. Linux or Darwin) `ESMF_COMPILER` must be set to select which Fortran and C++ compilers are being used to build the ESMF library. Notice that setting the `ESMF_COMPILER` variable does *not* affect how the compiler executables are located on the system. `ESMF_COMPILER` (together with `ESMF_COMM`) affect the name that is expected for the compiler executables. Furthermore, the `ESMF_COMPILER` setting is used to select compiler and linker flags consistent with the compilers indicated.

By default Fortran and C++ compiler executables are expected to be located in a location contained in the user's `PATH` environment variable. This means that if you cannot locate the correct compiler executable via the `which` command on the shell prompt the ESMF build system won't find it either!

There are advanced ESMF environment variables that can be used to select specific compiler executables by specifying the full path. This can be used to pick specific compiler executables without having to modify the PATH environment variable.

Use 'gmake info' to see which compiler executables the ESMF build system will be using according to your environment variable settings.

To see possible values for ESMF_COMPILER, cd to \$ESMF_DIR/build_config and list the directories there. The first part of each directory name corresponds to the output of 'uname -s' for this platform. The second part contains possible values for ESMF_COMPILER. In some cases multiple combinations of Fortran and C++ compilers are possible, e.g. there is intel and intelgcc available for Linux. Setting ESMF_COMPILER to intel indicates that both Intel Fortran and C++ compilers are used, whereas intelgcc indicates that the Intel Fortran compiler is used in combination with GCC's C++ compiler.

If you do not find a configuration that matches your situation you will need to port ESMF.

ESMF_ABI If a system supports 32-bit and 64-bit (pointer wordsize) application binary interfaces (ABIs), this variable can be set to select which ABI to use. Valid values are 32 or 64. By default the most common ABI is chosen.

ESMF_SITE The SourceForge esmfcontrib repository contains makefiles which have already been customized for certain machines. If one exists for your site and you wish to use it, download the corresponding files into the build_contrib directory and set ESMF_SITE to your location (which corresponds to the last part of the directory name). See the SourceForge site <http://sourceforge.net/projects/esmfcontrib> for more information.

ESMF_INSTALL_PREFIX This variable specifies the prefix of the installation path used during the installation process accessible through the install target. Libraries, F90 module files, header files and documentation all are installed relative to ESMF_INSTALL_PREFIX by default. The ESMF_INSTALL_PREFIX may be provided as absolute path or relative to ESMF_DIR.

5.4.2 gmake info

gmake info is a command that assists the user in verifying that the ESMF variables have been set appropriately. It also tells the user the paths to various libraries e.g. MPI that are set on the system. The user reviews this information to verify their settings. In the case of a build failure, this information is invaluable and will be the first thing asked for by the ESMF support team. Below is an example output from /t gmake info:

```
-----  
Make version:  
GNU Make version 3.79, by Richard Stallman and Roland McGrath.  
Built for powerpc-apple-darwin7.0  
Copyright (C) 1988, 89, 90, 91, 92, 93, 94, 95, 96, 97, 98, 99  
    Free Software Foundation, Inc.  
This is free software; see the source for copying conditions.  
There is NO warranty; not even for MERCHANTABILITY or FITNESS FOR A  
PARTICULAR PURPOSE.
```

Report bugs to <bug-make@gnu.org>.

```
-----  
Fortran Compiler version:  
Pro Fortran 9.0  
ERROR: No input files.
```

C++ Compiler version:
g++ (GCC) 3.3 20030304 (Apple Computer, Inc. build 1666)
Copyright (C) 2002 Free Software Foundation, Inc.
This is free software; see the source for copying conditions. There is NO
warranty; not even for MERCHANTABILITY or FITNESS FOR A PARTICULAR PURPOSE.

ESMF_VERSION_STRING ``3.0.1 beta snapshot``

* ESMF environment variables *
ESMF_DIR: /Users/murphys/esmf_head
ESMF_OS: Darwin
ESMF_MACHINE: default
ESMF_ABI: 32
ESMF_COMPILER: absoft
ESMF_BOPT: 0
ESMF_COMM: mpiuni
ESMF_SITE: default
ESMF_EXHAUSTIVE: OFF
ESMF_PTHREADS: ON
ESMF_TESTWITHTHREADS: OFF
ESMF_ARRAY_LITE: FALSE
ESMF_NO_INTEGER_1_BYTE: FALSE
ESMF_NO_INTEGER_2_BYTE: FALSE
ESMF_FORTRANSYMBOLS: default

* ESMF environment variables pointing to 3rd party software *

* ESMF environment variables for final installation *
ESMF_INSTALL_PREFIX: ./DEFAULTINSTALLDIR
ESMF_INSTALL_HEADERDIR: include
ESMF_INSTALL_MOODIR: mod/mod0/Darwin.absoft.32.mpiuni.default
ESMF_INSTALL_LIBDIR: lib/lib0/Darwin.absoft.32.mpiuni.default
ESMF_INSTALL_DOCDIR: doc

* Compilers, Linkers, Flags, and Libraries *
Location of the preprocessor: /usr/bin/gcc
Location of the Fortran compiler: /Applications/Absoft/bin/f90
Location of the Fortran linker: /Applications/Absoft/bin/f90
Location of the C++ compiler: /usr/bin/g++
Location of the C++ linker: /usr/bin/g++

* ESMF environment variables for final installation *

```
ESMF_INSTALL_PREFIX:      ./DEFAULTINSTALLDIR
ESMF_INSTALL_HEADERDIR:  include
ESMF_INSTALL_MODDIR:     mod/mod0/Darwin.absoft.32.mpiuni.default
ESMF_INSTALL_LIBDIR:     lib/lib0/Darwin.absoft.32.mpiuni.default
ESMF_INSTALL_DOCDIR:     doc
```

* Compilers, Linkers, Flags, and Libraries *

```
Location of the preprocessor:  /usr/bin/gcc
Location of the Fortran compiler: /Applications/Absoft/bin/f90
Location of the Fortran linker:  /Applications/Absoft/bin/f90
Location of the C++ compiler:   /usr/bin/g++
Location of the C++ linker:     /usr/bin/g++
```

Fortran compiler flags:

```
ESMF_F90COMPILEOPTS: -O -YEXT_NAMES=LCS -YEXT_SFX=_
ESMF_F90COMPILEPATHS: -p/Users/murphys/esmf_head/mod/mod0/Darwin.absoft.32.mpiuni.default
include
ESMF_F90COMPILECPPFLAGS: -DS32=1 -DESMF_MPIUNI
```

Fortran linker flags:

```
ESMF_F90LINKOPTS:
ESMF_F90LINKPATHS: -L/Users/murphys/esmf_head/lib/lib0/Darwin.absoft.32.mpiuni.default
ESMF_F90LINKRPATHS:
ESMF_F90LINKLIBS: -lstdc++
ESMF_F90ESMFLINKLIBS: -lesmf -lstdc++
```

C++ compiler flags:

```
ESMF_CXXCOMPILEOPTS: -O
ESMF_CXXCOMPILEPATHS: -I/Users/murphys/esmf_head/src/include -I/Users/murphys/esmf_head/src
ESMF_CXXCOMPILECPPFLAGS: -DS32=1 -D__SDIR__='src/doc' -DESMF_MPIUNI
```

C++ linker flags:

```
ESMF_CXXLINKOPTS:
ESMF_CXXLINKPATHS: -L/Users/murphys/esmf_head/lib/lib0/Darwin.absoft.32.mpiuni.default -L/
ESMF_CXXLINKRPATHS:
ESMF_CXXLINKLIBS: -lf90math -lfio -lac -lf77math -lm
ESMF_CXXESMFLINKLIBS: -lesmf -lf90math -lfio -lac -lf77math -lm
```

Compiling on Mon May 14 14:54:47 MDT 2007 on glass.scd.ucar.edu
Machine characteristics: Darwin glass.scd.ucar.edu 7.9.0 Darwin Kernel Version 7.9.0: Wed M
/xnu-517.12.7.obj~1/RELEASE_PPC Power Macintosh powerpc
=====

5.4.3 GNU make

The ESMF build system uses the GNU make program; it is normally named `gmake` but may also be simply `make` or `gnumake` on some platforms. ESMF does not use `configure` or `autoconf`; the selection of various options is done by setting environment variables before building the framework.

5.4.4 Build makefile Targets

The makefiles follow the GNU target standards where possible. The most frequently used targets for building are listed below:

lib build the ESMF libraries only (default)

all build the libraries, unit and system tests, examples, and demos

doc build the documentation (requires specific latex macros packages and additional utilities; see Section 6 for more details on the requirements). The ESMF web site contains pre-built pdf and html versions of all documentation under the "Downloads & Documentation" link.

info print out extensive system configuration information about what compilers, libraries, paths, flags, etc are being used

clean remove all files built for this platform/compiler/wordsize.

clobber remove all files built for all architectures

install install the ESMF library in a custom location

5.4.5 Testing makefile Targets

To build and run the unit and system tests in non-exhaustive mode, type:

```
gmake check
```

A summary report of success and failures will be printed out at the end.

Other test-related targets are:

all_tests build and run all available tests and demos

build_all_tests build tests only, do not execute

run_all_tests run tests without rebuilding and print a summary of the results

check_all_tests print out the results summary without re-executing the tests again

clean_all_tests remove all test and demo executables

For all the targets listed above, the string `all_tests` can be replaced with one of the strings listed below to select a specific type of test:

unit_tests unit tests exercise a single part of the system

system_tests system tests combine functions across the system

examples examples contain code illustrating a single type of function

demos demos are example applications showing the use of the system

For example, `gmake build_examples` recompiles the example programs but does not execute them. `gmake clean_system_tests` removes all executables and files associated with the system tests.

For the unit tests only, there is an additional environment variable which affects how the tests are built:

ESMF_EXHAUSTIVE If this variable is set to ON before compiling the unit tests, longer and more exhaustive unit tests will be run. Note that this is a compile-time and not run-time option.

6 Building and Installing the ESMF

This section goes into more detail about how to build and install the ESMF software.

6.1 ESMF Download Options

Major releases of the ESMF software can be downloaded by following the instructions on the the **Downloads & Documentation** link on the ESMF website, <http://www.esmf.ucar.edu>.

The ESMF is distributed as a full source code tree. You will need to compile the code into the `libesmf.a` library. On some platforms a shared library, `libesmf.so`, is also created. Follow the instructions in the following sections to build the library and link it with your application.

6.2 System Requirements

The following compilers and utilities are required for compiling, linking and testing the ESMF software:

- Fortran90 (or later) compiler;
- C++ compiler;
- MPI implementation compatible with the above compilers (but see below);
- GNU's gcc compiler - for a standard cpp preprocessor implementation;
- GNU make;
- Perl - for running test scripts.

Alternatively ESMF can be built using a single-processor MPI-bypass library that comes with ESMF. It allows ESMF applications to be linked and run in single-process mode.

In order to build html and pdf version of the ESMF documentation, \LaTeX , the latex2html conversion utility, and the Unix/Linux dvipdf utility must be installed.

6.3 ESMF Environment Variables

The following is a full alphabetical list of all environment variables which are used by the ESMF build system. In many cases only `ESMF_DIR` must be set. On Linux and Darwin systems `ESMF_COMPILER` and `ESMF_COMM` must also be set to select the appropriate Fortran and C++ compilers and MPI implementation. The other variables have default values which work for most systems.

ESMF_ABI Possible value: 32, 64

If a system supports 32-bit and 64-bit (pointer wordsize) application binary interfaces (ABIs), this variable can be set to select which ABI to use. Valid values are 32 or 64. By default the most common ABI is chosen.

ESMF_ARRAY_LITE Possible value: TRUE, FALSE (default)

Not normally set by user. ESMF auto-generates subroutine interfaces for a wide variety of data arrays of different ranks, shapes, and types. If no data of rank greater than 4D will be used, setting this variable to any value will prevent ESMF from generating interfaces for 5D to 7D arrays. This will shrink the amount of autogenerated code.

ESMF_BATCH Possible value: `lsf.ibmpjl`, `lsf.ibmpjl.batch`

On IBM systems using the LSF batch system `ESMF_BATCH` is used to select the correct method to launch parallel execution.

ESMF_BATCHOPTIONS Possible value: *system-dependent*

Variable used to pass system-specific queue options to the batch system. Typically the queue, project and limits are set using `ESMF_BATCHOPTIONS`.

ESMF_BOPT Possible value: `g`, `O` (default)

This environment variable controls the build option. To make a debuggable version of the library set `ESMF_BOPT` to `g` before building. The default is `O` (capital oh) which builds an optimized version of the library. If `ESMF_BOPT` is `O`, `ESMF_OPTLEVEL` can also be set to a numeric value between 0 and 4 to select a specific optimization level.

ESMF_COMM Possible value: *system-dependent*

On systems with a vendor-supplied MPI communications library the vendor library is chosen by default for communications and `ESMF_COMM` need not be set. For other systems (e.g. Linux or Darwin) a multitude of MPI implementations is available and `ESMF_COMM` must be set to indicate which implementation is used to build the ESMF library. Set `ESMF_COMM` according to your situation to: `mpich`, `mpich2`, `lam`, `openmpi` or `intelmpi`. `ESMF_COMM` may also be set to `user` indicating that the user will set all the required flags using advanced ESMF environment variables.

Alternatively, ESMF comes with a single-processor MPI-bypass library which is the default for Linux and Darwin systems. To force the use of this bypass library set `ESMF_COMM` equal to "mpiuni".

ESMF_COMPILER Possible value: *system-dependent*

The ESMF library build requires a working Fortran90 and C++ compiler. On platforms that don't come with a single vendor supplied compiler suite (e.g. Linux or Darwin) `ESMF_COMPILER` must be set to select which Fortran and C++ compilers are being used to build the ESMF library. Notice that setting the `ESMF_COMPILER` variable does *not* affect how the compiler executables are located on the system. `ESMF_COMPILER` (together with `ESMF_COMM`) affect the name that is expected for the compiler executables. Furthermore, the `ESMF_COMPILER` setting is used to select compiler and linker flags consistent with the compilers indicated.

By default Fortran and C++ compiler executables are expected to be located in a location contained in the user's `PATH` environment variable. This means that if you cannot locate the correct compiler executable via the `which` command on the shell prompt the ESMF build system won't find it either!

There are advanced ESMF environment variables that can be used to select specific compiler executables by specifying the full path. This can be used to pick specific compiler executables without having to modify the `PATH` environment variable.

Use `'gmake info'` to see which compiler executables the ESMF build system will be using according to your environment variable settings.

To see possible values for `ESMF_COMPILER`, cd to `$ESMF_DIR/build_config` and list the directories there. The first part of each directory name corresponds to the output of `'uname -s'` for this platform. The second part contains possible values for `ESMF_COMPILER`. In some cases multiple combinations of Fortran and C++ compilers are possible, e.g. there is `intel` and `intelgcc` available for Linux. Setting `ESMF_COMPILER` to `intel` indicates that both Intel Fortran and C++ compilers are used, whereas `intelgcc` indicates that the Intel Fortran compiler is used in combination with GCC's C++ compiler.

If you do not find a configuration that matches your situation you will need to port ESMF.

ESMF_CXX Possible value: *executable*

This variable can be used to override the default C++ compiler and linker front-end executables. The executable may be specified with absolute path overriding the location determined by default from the user's `PATH` variable.

ESMF_CXXCOMPILEOPTS Possible value: *flag*

This variable can be used to prepend flags to default compiler flags.

ESMF_CXXCOMPILER Possible value: *executable*

This variable can be used to override the default C++ compiler front-end executables. The executable may be specified with absolute path overriding the location determined by default from the user's PATH variable.

ESMF_CXXLINKDIRS Possible value: *flag*

This variable can be used to prepend directories to default linker directories.

ESMF_CXXLINKLIBS Possible value: *flag*

This variable can be used to prepend libraries to default linker libraries.

ESMF_CXXLINKOPTS Possible value: *flag*

This variable can be used to prepend flags to default linker flags.

ESMF_CXXLINKER Possible value: *executable*

This variable can be used to override the default C++ linker front-end executables. The executable may be specified with absolute path overriding the location determined by default from the user's PATH variable.

ESMF_CXXOPTFLAG Possible value: *flag*

This variable can be used to override the default C++ optimization flag.

ESMF_DIR Possible value: *absolute path*

The environment variable ESMF_DIR must be set to the full pathname of the top level ESMF directory before building the framework. This is the only environment variable which is required to be set on all platforms under all conditions.

ESMF_EXHAUSTIVE Possible value: ON, OFF (default)

Variable specifying how to compile the unit tests. If set to the value ON, then all unit tests will be compiled and will be executed when the test is run. If unset or set to any other value, only a subset of the unit tests will be included to verify basic functions. Note that this is a compile-time selection, not a run-time option.

ESMF_F90 Possible value: *executable*

This variable can be used to override the default Fortran90 compiler and linker front-end executables. The executable may be specified with absolute path overriding the location determined by default from the user's PATH variable.

ESMF_F90COMPILEOPTS Possible value: *flag*

This variable can be used to prepend flags to default compiler flags.

ESMF_F90COMPILER Possible value: *executable*

This variable can be used to override the default Fortran90 compiler front-end executables. The executable may be specified with absolute path overriding the location determined by default from the user's PATH variable.

ESMF_F90IMOD Possible value: *flag*

This variable can be used to override the default flag used to specify the F90 module directory.

ESMF_F90LINKDIRS Possible value: *flag*

This variable can be used to prepend directories to default linker directories.

ESMF_F90LINKLIBS Possible value: *flag*

This variable can be used to prepend libraries to default linker libraries.

ESMF_F90LINKOPTS Possible value: *flag*

This variable can be used to prepend flags to default linker flags.

ESMF_F90LINKER Possible value: *executable*

This variable can be used to override the default Fortran90 linker front-end executables. The executable may be specified with absolute path overriding the location determined by default from the user's PATH variable.

ESMF_F90OPTFLAG Possible value: *flag*

This variable can be used to override the default Fortran90 optimization flag.

ESMF_INSTALL_PREFIX Possible value: *relative or absolute path*

This variable specifies the prefix of the installation path used during the installation process accessible through the install target. Libraries, F90 module files, header files and documentation all are installed relative to ESMF_INSTALL_PREFIX by default. The ESMF_INSTALL_PREFIX may be provided as absolute path or relative to ESMF_DIR.

ESMF_INSTALL_DOCDIR Possible value: *relative or absolute path*

Location into which to install the documentation during installation. This location can be specified as absolute path or relative to ESMF_INSTALL_PREFIX.

ESMF_INSTALL_HEADERDIR Possible value: *relative or absolute path*

Location into which to install the header files during installation. This location can be specified as absolute path or relative to ESMF_INSTALL_PREFIX.

ESMF_INSTALL_LIBDIR Possible value: *relative or absolute path*

Location into which to install the library files during installation. This location can be specified as absolute path or relative to ESMF_INSTALL_PREFIX.

ESMF_INSTALL_MODDIR Possible value: *relative or absolute path*

Location into which to install the F90 module files during installation. This location can be specified as absolute path or relative to ESMF_INSTALL_PREFIX.

ESMF_MACHINE Possible value: output of `uname -m` where available.

Not normally set by user. This variable indicates architectural details about the machine on which the ESMF library is being built. The value of this variable will affect which ABI settings are available and what they mean. ESMF_MACHINE is set automatically.

ESMF_MPIRUN Possible value: *executable*

This variable can be used to override the default utility used to launch parallel execution of ESMF test applications. The executable in ESMF_MPIRUN may be specified with path.

ESMF_MPIRUNOPTIONS Possible value: *flags*

This variable can be used to provide additional options to ESMF_MPIRUN.

ESMF_NETCDF_INCLUDE Possible value: *absolute path*

This variable can be used to point to the desired NETCDF header files.

ESMF_NETCDF_LIBPATH Possible value: *absolute path*

This variable can be used to point to the desired NETCDF library files.

ESMF_NO_INTEGER_1_BYTE Possible value: TRUE, FALSE (default)

Not normally set by user. Setting this variable to ON will prevent ESMF from generating data array interfaces for data types of 1-byte integers.

ESMF_NO_INTEGER_2_BYTE Possible value: TRUE, FALSE (default)

Same as ESMF_NO_INTEGER_1_BYTE but for 2-byte integers.

ESMF_OPTLEVEL Possible value: *numerical value*

See ESMF_BOPT for details.

ESMF_OS Possible value: output of `uname -s` except when cross-compiling or for UNICOS/mp where ESMF_OS is `Unicos`.

Not normally set by user unless cross-compiling. This variable indicates the target system for which the ESMF library is being built. Under normal circumstances, i.e. ESMF is being build on the target system, ESMF_OS is set automatically. However, when cross-compiling for a different target system ESMF_OS must be set to the respective target OS. For example, when compiling for the Cray X1 on an interactive X1 node ESMF_OS will be set automatically. However, when ESMF is being cross-compiled for the X1 on a Linux host the user must set ESMF_OS to `Unicos` manually in order to indicate the intended target platform.

ESMF_PTHREADS Possible value: ON (default on most platforms), OFF

This compile-time option controls ESMF's dependency on a functioning Pthreads library. The default option is set to ON with the exception of IRIX64 and platforms that don't provide Pthreads. On IRIX64 the use of Pthreads in ESMF is disabled by default because the Pthreads library conflicts with the use of OpenMP on this platform.

The user can override the default setting of ESMF_PTHREADS on all platforms that provide Pthread support. Setting the ESMF_PTHREADS environment variable to OFF will disable ESMF's Pthreads feature set. On platforms that don't support Pthreads, e.g. IBM BlueGene/L or Cray XT3, the default OFF setting cannot be overridden!

ESMF_SITE Possible value: *site string*, default

Build configure file site name or the value default. If not set, then the value of default is assumed. When including platform-specific files, this value is used as the third part of the directory name (parts 1 and 2 are the ESMF_OS value and ESMF_COMPILER value, respectively.)

The Sourceforge `esmfc contrib` repository contains makefiles which have already been customized for certain machines. If one exists for your site and you wish to use it, download the corresponding files into the `build_contrib` directory and set ESMF_SITE to your location (which corresponds to the last part of the directory name). See the Sourceforge site <http://sourceforge.net/projects/esmfc contrib> for more information.

ESMF_STDCXX_LIBRARY Possible value: `gcc`

When ESMF_COMPILER is set to `intel` this variable can be used to indicate the use of GCC's standard C++ library instead of Intel's.

ESMF_TESTWITHTHREADS Possible value: ON, OFF (default)

If this environment variable is set to ON *before* the ESMF system tests are build they will activate ESMF threading in their code. Specifically each component will be executed using ESMF single threading instead of the default non-threaded mode. The difference between non-threaded and ESMF single threaded execution should be completely transparent. Notice that the setting of ESMF_TESTWITHTHREADS does *not* alter ESMF's dependency on Pthreads but tests ESMF threading features during the system tests. An ESMF library that was compiled with disabled Pthread features (via the ESMF_PTHREADS variable) will produce ESMF error messages during system test execution if the system tests were compiled with ESMF_TESTWITHTHREADS set to ON.

Environment variables must be set in the user's shell or when calling gmake. It is *not* necessary to edit ESMF makefiles or other build system files to set these variables. Here is an example of setting an environment variable in the csh/tcsh shell:

```
setenv ESMF_ABI 32
```

In bash/ksh shell environment variables are set this way:

```
export ESMF_ABI=32
```

Environment variables can also be set from the gmake command line:

```
gmake ESMF_ABI=32
```

6.4 Supported Platforms

The following two tables list various combinations of environment variable settings used by the ESMF build system. A `default` value in the compiler column indicates the vendor compiler. A `mpi` value in the comm column indicates the vendor MPI implementation.

The first table lists the exact combinations which are tested regularly and are fully supported. The second table lists all possible combinations which are included in the build system.

Fully tested combinations:

	ESMF_OS	ESMF_COMPILER	ESMF_COMM	ESMF_ABI
IBM SP	AIX	default	mpi	32,64
Mac	Darwin	absoft	lam,mpiuni	32
Mac	Darwin	nag	lam,mpiuni	32
Mac	Darwin	xl	lam,mpiuni	32
Mac	Darwin	xlfgcc	lam,mpiuni	32
SGI Mips	IRIX64	default	mpi	32,64
PC	Linux	absoftintel	mpich	32
PC	Linux	g95	mpich	32
HP IA64	Linux	intel	lam	64
SGI Altix	Linux	intel	mpi	64
PC	Linux	intel	mpich	32
PC	Linux	lahey	mpiuni	32
PC	Linux	nagintel	mpich	32
IBM Opteron	Linux	pathscale	mpich	64
IBM Opteron	Linux	pgi	mpich	64
PC	Linux	pgi	mpich,mpiuni	32
HP/Compaq	OSF1	default	mpi	64
Cray X1	Unicos	default	mpi	64

All possible options. Where multiple options exist and the default is independent of `ESMF_MACHINE` the default value is in bold:

ESMF_OS	ESMF_COMPILER	ESMF_COMM	ESMF_ABI
AIX	default	mpi,mpiuni,user	32,64
Darwin	absoft	mpiuni,mpich,mpich2,lam,openmpi,user	32
Darwin	g95	mpiuni,mpich,mpich2,lam,openmpi,user	32
Darwin	gfortran	mpiuni,mpich,mpich2,lam,openmpi,user	32
Darwin	nag	mpiuni,mpich,mpich2,lam,openmpi,user	32
Darwin	xlfort	mpiuni,mpich,mpich2,lam,openmpi,user	32
Darwin	xlfgcc	mpiuni,mpich,mpich2,lam,openmpi,user	32
IRIX64	default	mpi,mpiuni,user	32,64
Linux	absoft	mpiuni,mpich,mpich2,lam,openmpi,user	32, 64
Linux	absoftintel	mpiuni,mpich,mpich2,lam,openmpi,user	32, 64
Linux	intel	mpiuni,mpi,mpich,mpich2,intelmpi,lam,openmpi,user	32, 64
Linux	intelgcc	mpiuni,mpi,mpich,mpich2,lam,openmpi,user	32, 64
Linux	lahey	mpiuni,mpich,mpich2,lam,openmpi,user	32
Linux	nag	mpiuni,mpich,mpich2,lam,openmpi,user	32
Linux	nagintel	mpiuni,mpich,mpich2,lam,openmpi,user	32
Linux	pathscale	mpiuni,mpich,mpich2,lam,openmpi,user	64
Linux	pgi	mpiuni,mpich,mpich2,lam,openmpi,user	32, 64
Linux	pgigcc	mpiuni,mpich,mpich2,lam,openmpi,user	32, 64
Linux	xlfort	mpiuni,mpich,mpich2,lam,openmpi,user	32
OSF1	default	mpi,mpiuni,user	64
Unicos	default	mpi,mpiuni,user	64
Unicos	pgi	mpi,mpiuni,user	64

Building the library for multiple architectures or options at the same time is supported; building or running the tests or examples is restricted to one platform/architecture at a time. The output from the test cases will be stored in a separate directories so the results will be kept separate for different architectures or options.

6.5 Building the ESMF Library

GNU make is required to build the library. On some systems this will be just the command make. On others it might be installed as gmake or even gnumake. In any event, use the `-version` option with the make command to determine if it is GNU make.

Build the library with the command:

```
gmake
```

Makefiles throughout the framework are configured to allow users to compile files only in the directory where gmake is entered. Shared libraries are rebuilt only if necessary. In addition the entire ESMF framework may be built from any directory by entering `gmake all`, assuming that all the environmental variables are set correctly as described in Section 6.3.

Users may also run examples or execute unit tests of specific classes by changing directories to the desired class examples or tests directories and entering `gmake run_examples` or `gmake run_unit_tests`, respectively. For non-multiprocessor machines, uni-processor targets are available as `gmake run_examples_uni` or `gmake run_unit_tests_uni`.

6.6 Building the ESMF Documentation

The ESMF source documentation consists of an *ESMF User's Guide* and an *ESMF Reference Manual for Fortran*.

The tarballs on the ESMF website for ESMF versions 3.0.1 and later do not contain the ESMF documentation files. The documentation is available on the ESMF website in html or pdf form and most users should not need to build it from the source.

If a user does want to build the documentation, they will need to download the `esmfc` module from the ESMF SourceForge repository (see section 5.1.1. `Latex` and `latex2html` must be installed.

To build documentation:

```
gmake doc                ! Builds the manuals, including pdf and html.
```

The resulting documentation files will be located in the top level directory `$ESMF_DIR/doc`

6.7 Installing the ESMF

The ESMF build system offers the standard `install` target to install all necessary files created during the build process into user specified locations. The installation procedure will also install the ESMF documentation if it has been built successfully following the procedure outlined above.

The installation location can be customized using five `ESMF_` environment variables:

- `ESMF_INSTALL_PREFIX`
- `ESMF_INSTALL_HEADERDIR`
- `ESMF_INSTALL_LIBDIR`
- `ESMF_INSTALL_MOODIR`
- `ESMF_INSTALL_DOCDIR`

Install ESMF with the command:

```
gmake install
```

Check the ESMF installation with the command:

```
gmake installcheck
```

7 Porting the ESMF

This section goes into more detail about the ESMF build system and how to port the ESMF software to new platforms.

7.1 The ESMF Build System

For most users the description of the build system in previous sections should be sufficient. Some users, however, may wish to have a more detailed knowledge of the make system either for configuring different build options or for porting to unsupported platforms.

7.1.1 General Structure

The main components of the build system are:

- **Build directories with makefile fragments**

There are two directories containing makefile fragment files used by the ESMF build system.

The `build` directory contains the generic makefile fragment file `common.mk` that is included by the top level `makefile` in the source tree. The `common.mk` contains generic build system settings and build rules used across all platforms. A user should have no reason to edit `common.mk`.

The `build_config` directory contains subdirectories with makefile fragments (`build_rules.mk`) for each supported platform defining compilers, compiler flags and the various other definitions that are necessary to build on each platform. One of the `build_rules.mk` files will be included by the `build/common.mk` file depending on the values of the environment variables `ESMF_OS`, `ESMF_COMPILER` and `ESMF_SITE`. See below for more details on environment variables.

- **Environment variables**

Environment variables with the prefix `ESMF_` are used to pass user specified information to the ESMF build system. A full list of `ESMF_` environment variables is provided in section 6.3 of this document.

Most environment variables are optional and the ESMF build system will use default settings if it finds these variable unset. One piece of information that must always be provided by setting the respective environment variable is the root of the ESMF directory. There are three sets of source codes the build system supports. All need environment variables set to point to their top level source code directories.

ESMF Library

To build the ESMF library, `ESMF_DIR` needs to be set to the top level ESMF library source code directory.

Implementation Report

The build system needs `ESMF_IMPL_DIR` set to the top level source code directory of the Implementation Report source tree to build the report and to build and run the examples.

EVA Applications

An EVA source code tree does not contain a copy of the ESMF build system. Instead it uses a copy found in an ESMF library source code tree. Building the EVA applications requires that `ESMF_EVA_DIR` and `ESMF_DIR` be set. `ESMF_EVA_DIR` has to be set to the top directory of the EVA source code. `ESMF_DIR` has to be set to the top directory of an ESMF source code tree.

- **Makefiles**

Every source tree contains a `makefile` in its top level directory. This `makefile` includes the `common.mk` file from the `build` directory which in turn includes the platform specific `build_rules.mk` file from one of the `build_config` subdirectories. The top level `makefile` contains makefile settings specific for the source code that it is found in.

Each directory in the source tree contains a `makefile` which includes the top level `makefile`. These local `makefiles` include definitions that allow the local files and documents to be built.

7.1.2 Build Configuration

A single makefile or makefile fragment from the build system never constitutes a complete set of build rules and settings. Starting from the local makefile, successive include commands are used to string together makefiles and makefile fragments to create a complete system of build rules and settings. Configuration of the build system is done by including a configuration makefile fragment. A configuration for a specific machine or compiler is referred to as a site configuration.

The string of files included is fairly short. Makefiles below the top level makefile include the top level makefile. The top level makefile includes `build/common.mk` and then `build/common.mk` includes a configuration file from the `build_config` directory. The configuration files in the `build_config` directory contain the platform and site specific build settings. The os, compiler and site that a file configures is determined by its name. The configuration makefile fragments follow the naming convention

```
build_config/ESMF_OS.ESMF_COMPILER.ESMF_SITE/build_rules.mk
```

where `ESMF_OS`, `ESMF_COMPILER` and `ESMF_SITE` are environment variables either set by the user or given default values by the build system. `ESMF_OS` is the target operating system. If the build is performed *on* the target system `ESMF_OS` will typically have the value returned by the command `uname -s`. `ESMF_COMPILER` is the compiler name. `ESMF_SITE`, if set, is generally the current machine name, the location, or the organization (e.g. mit, cola). If there are no site specific files for a particular platform, then `ESMF_COMPILER` and `ESMF_SITE` will be set to default. Examples:

```
! Default configuration for IBM AIX systems
build_config/AIX.default.default/build_rules.mk

! Linux configuration using lahey compilers.
build_config/Linux.lahey.default/build_rules.mk
```

7.1.3 Source Code Configuration

Some of the ESMF C++ and Fortran source files contain preprocessor directives to configure the source code for specific platforms. The directives are included in the source code and are pre-processed before the source code is compiled. The directives are used to determine among other things, the size of variable types.

The ESMF build system provides preprocessor directives in `ESMC_Conf.h` and `ESMF_Conf.inc` files that are included in the source code. These files are located in

```
build_config/ESMF_OS.ESMF_COMPILER.ESMF_SITE/ESMC_Conf.h
build_config/ESMF_OS.ESMF_COMPILER.ESMF_SITE/ESMF_Conf.inc
```

where `ESMF_OS`, `ESMF_COMPILER` and `ESMF_SITE` are environment variables set by the user or given default values by the build system. Based on the settings of these environment variables the build system provides a path to the correct files during source code compilation.

7.2 Porting the ESMF to New Platforms

The ESMF build system can be ported to other Unix platforms by adding a new platform specific makefile fragment and two associated configuration files. These files (`build_rules.mk`, `ESMC_Conf.h`, `ESMF_Conf.inc`) must be

placed into a new subdirectory of the `build_config` directory, following the `ESMF_OS . ESMF_COMPILER . ESMF_SITE` naming convention.

When porting to a new platform it is often helpful to start with a copy of the configuration of an existing ESMF port. You may, for example, want to start with a copy of the `build_config/Linux.g95.default` directory when working on a new Linux configuration.

7.2.1 Customizing the `build_rules.mk` fragment

The purpose of the `build_rules.mk` makefile fragment is to customize the build procedure for a specific platform. The customization is done via makefile variables. The main makefile at the top level of the ESMF directory structure first includes the `common.mk` makefile fragment. This common makefile fragment defines a large number of variables, setting them either to generally valid default values or to specific values the user has set in their environment using `ESMF_` style environment variables.

The platform specific `build_rules.mk` makefile fragment is included by `common.mk` *after* the variables have been initialized, but *before* any rules are defined in `common.mk` using these variables. This gives `build_rules.mk` a chance to modify these variables as it may be necessary to accommodate platform specific properties.

Fortunately only a very small subset of variables pre-defined in `common.mk` typically need to be modified or overridden in `build_rules.mk` with platform specific settings. However, there are some variables that *must* be set in every `build_rules.mk` file. These are variables that are not pre-set in `common.mk`.

ESMF_CXXDEFAULT Default C++ compiler to be used on this platform. This variable will be used by `common.mk` to set the associated `ESMF_CXX` variables.

ESMF_CXXCOMPILER_VERSION Command that when executed will provide information about the version of the C++ compiler to stdout.

ESMF_F90DEFAULT Default Fortran compiler to be used on this platform. This variable will be used by `common.mk` to set the associated `ESMF_F90` variables.

ESMF_F90COMPILER_VERSION Command that when executed will provide information about the version of the F90 compiler to stdout.

ESMF_MPIRUNDEFAULT Default MPI job launch facility to be used on this platform. This variable will be used by `common.mk` to set the associated `ESMF_MPIRUN` variables.

The following is a complete alphabetical list of variables that are pre-set in `common.mk` before `build_rules.mk` is included. Some of these variables correspond to `ESMF_` environment variables while others have a more complicated dependency on the environment variables set by the user.

ESMF_ABI

ESMF_AR

ESMF_ARCREATEFLAGS

ESMF_ARCREATEFLAGSDEFAULT

ESMF_ARDEFAULT

ESMF_AREXTRACTFLAGS

ESMF_AREXTRACTFLAGSDEFAULT
ESMF_ARRAY_LITE
ESMF_BOPT
ESMF_BUILD
ESMF_BUILD_DOCDIR
ESMF_COMM
ESMF_COMPILER
ESMF_CONFDIR
ESMF_CPP
ESMF_CPPDEFAULT
ESMF_CXXCOMPILECPPFLAGS
ESMF_CXXCOMPILEOPTS
ESMF_CXXCOMPILEPATHS
ESMF_CXXCOMPILEPATHSLOCAL
ESMF_CXXCOMPILER
ESMF_CXXCOMPILERDEFAULT
ESMF_CXXESMFLINKLIBS
ESMF_CXXLINKER
ESMF_CXXLINKERDEFAULT
ESMF_CXXLINKLIBS
ESMF_CXXLINKOPTS
ESMF_CXXLINKPATHS
ESMF_CXXLINKRPATHS
ESMF_CXXOPTFLAG
ESMF_CXXOPTFLAG_G
ESMF_CXXOPTFLAG_O
ESMF_CXXOPTFLAG_X
ESMF_DIR
ESMF_DOCDIR
ESMF_EXDIR
ESMF_EXHAUSTIVE

ESMF_F90COMPILECPPFLAGS
ESMF_F90COMPILEFIXCPP
ESMF_F90COMPILEFIXNOCPP
ESMF_F90COMPILEFREECPP
ESMF_F90COMPILEFREENOCPP
ESMF_F90COMPILEOPTS
ESMF_F90COMPILEPATHS
ESMF_F90COMPILEPATHSLOCAL
ESMF_F90COMPILER
ESMF_F90COMPILERDEFAULT
ESMF_F90ESMFLINKLIBS
ESMF_F90IMOD
ESMF_F90LINKER
ESMF_F90LINKERDEFAULT
ESMF_F90LINKLIBS
ESMF_F90LINKOPTS
ESMF_F90LINKPATHS
ESMF_F90LINKRPATHS
ESMF_F90MODDIR
ESMF_F90OPTFLAG
ESMF_F90OPTFLAG_G
ESMF_F90OPTFLAG_O
ESMF_F90OPTFLAG_X
ESMF_GREPV
ESMF_INCDIR
ESMF_INSTALL_DOCDIR
ESMF_INSTALL_DOCDIR_ABSPATH
ESMF_INSTALL_HEADERDIR
ESMF_INSTALL_HEADERDIR_ABSPATH
ESMF_INSTALL_LIBDIR
ESMF_INSTALL_LIBDIR_ABSPATH

ESMF_INSTALL_MODDIR
ESMF_INSTALL_MODDIR_ABSPATH
ESMF_INSTALL_PREFIX
ESMF_INSTALL_PREFIX_ABSPATH
ESMF_LDIR
ESMF_LIBDIR
ESMF_MACHINE
ESMF_MODDIR
ESMF_MPIRUN
ESMF_MV
ESMF_NO_INTEGER_1_BYTE
ESMF_NO_INTEGER_2_BYTE
ESMF_OS
ESMF_OPTLEVEL
ESMF_PTHREADS
ESMF_PTHREADSDEFAULT
ESMF_RANLIB
ESMF_RANLIBDEFAULT
ESMF_RM
ESMF_RPATHPREFIX
ESMF_SED
ESMF_SEDDEFAULT
ESMF_SITE
ESMF_SITEDIR
ESMF_SL_LIBLIBS
ESMF_SL_LIBLINKER
ESMF_SL_LIBOPTS
ESMF_SL_LIBS_TO_MAKE
ESMF_SL_SUFFIX
ESMF_STDIR
ESMF_TEMPLATES

ESMF_TESTDIR

ESMF_TESTWITHTHREADS

ESMF_UTCDIR

ESMF_UTCSCRIPTS

ESMF_WC

7.2.2 Customizing `ESMC_Conf.h` and `ESMF_Conf.inc`

The `ESMC_Conf.h` file is used to define several important macros used during compilation of ESMF library code written in C++.

FTN(func) Macro that will correctly expand "func" to match the Fortran symbol convention.

ESMF_PRESENT(arg) Macro for a boolean expression that returns TRUE if "arg" is a "present" argument passed from Fortran into C++.

ESMF_IS_32BIT_MACHINE This macro will be defined on a 32-bit architecture.

ESMF_IS_64BIT_MACHINE This macro will be defined on a 64-bit architecture.

ESMF_F90_PTR_BASE_SIZE Value in bytes used to calculate the size of the Fortran dope vector.

ESMF_F90_PTR_PLUS_RANK Value in bytes used to calculate the size of the Fortran dope vector.

ESMC_POINTER_SIZE Size of C pointer in bytes.

The `ESMF_Conf.inc` file is used to *optionally* define two important macros:

ESMF_NO_INITIALIZERS If this macro is defined ESMF will assume that initializers inside Fortran derived type definitions are not supported.

ESMF_SEQUENCE_BUG If this macro is defined ESMF will not use the `SEQUENCE` specifier inside Fortran derived types under certain circumstances.

8 Validating and Running with ESMF

This section goes into more detail about how to run the tests which are included with the ESMF software, how to run the examples, demos, and `quick_start` software, and how to link your own applications with ESMF.

8.1 Running ESMF Self-Tests

Robustness and portability are primary goals of the ESMF development effort. To ensure that these goals are met, the ESMF includes a comprehensive suite of tests. They allow testing and validation of everything from individual functions to complete system tests. These test suites are used by the ESMF development team as part of their regular development process. ESMF users can run the testing suites to verify that the framework software was built and installed properly, and is running correctly on a particular platform.

Test targets will compile the ESMF library if it has not already been built.

8.1.1 Running ESMF Unit Tests

The unit tests provided with the ESMF library evaluate the following:

- correctness of individual functions
- behavior of individual modules or classes
- appropriate error handling

Unit tests can be run in either an exhaustive or a non-exhaustive (sanity check) mode. The exhaustive mode includes the sanity check tests. Typically, sanity checks for each ESMF capability include creating and destroying an object and testing its basic function using a valid argument set. In the exhaustive mode, a wide range of valid and non-valid arguments are evaluated for correct behavior.

The following commands are used to build and run the unit tests provided with the ESMF:

```
gmake [ ESMF_EXHAUSTIVE=<ON,OFF> ] tests
gmake [ ESMF_EXHAUSTIVE=<ON,OFF> ] tests_uni
```

The `tests_uni` target runs the tests on a single processor. The `tests` target runs the test on multiple processors.

The non-exhaustive set of unit tests should all pass. At this point in development, the exhaustive tests do not all pass. Current problems with unit tests are being tracked and corrected by the ESMF development team.

The results of running the unit tests can be found in the following location:

```
${ESMF_DIR}/test/test${ESMF_BOPT}/${ESMF_OS}.${ESMF_COMPILER}.${ESMF_ABI}.${ESMF_SITE}
```

For example, if your esmf source files have been placed in:

```
/usr/local/esmf
```

If your platform is a Linux uni-processor that has an installed Lahey Fortran compiler and `ESMF_COMPILER` has been set to `lahey`, then the build system configuration file will be:

```
build_config/Linux.lahey.default/build_rules.mk
```

If you want to run a debug version of non-exhaustive unit tests, then you use these commands from `/usr/local/esmf`:

```
setenv ESMF_DIR /usr/local/esmf
gmake ESMF_BOPT=g ESMF_SITE=lahey ESMF_EXHAUSTIVE=OFF tests_uni
```

If you are using `ksh`, then replace the `setenv` command with:

```
export ESMF_DIR=/usr/local/esmf
```

The results of the unit tests will be in:

```
/usr/local/esmf/test/testg/Linux.lahey.32.default/
```

At the end of unit test execution a script runs to analyze the results.

The script output indicates whether there are any unit test failures. The following is a sample from the script output:

There are a total of 1224 exhaustive multi processor unit tests, 1220 pass and 4 fail.

The unit tests in the following files all pass:

```
src/Infrastructure/Array/tests/ESMF_ArrayUTest.F90
src/Infrastructure/ArrayDataMap/tests/ESMF_ArrayDataMapUTest.F90
src/Infrastructure/Base/tests/ESMF_BaseUTest.F90
src/Infrastructure/Bundle/tests/ESMF_BundleUTest.F90
src/Infrastructure/BundleDataMap/tests/ESMF_BundleDataMapUTest.F90
src/Infrastructure/Config/tests/ESMF_ConfigUTest.F90
src/Infrastructure/DELayout/tests/ESMF_DELayoutUTest.F90
src/Infrastructure/Field/tests/ESMF_FRoute4UTest.F90
src/Infrastructure/Field/tests/ESMF_FieldUTest.F90
src/Infrastructure/FieldComm/tests/ESMF_FieldGatherUTest.F90
src/Infrastructure/FieldDataMap/tests/ESMF_FieldDataMapUTest.F90
src/Infrastructure/Grid/tests/ESMF_GridUTest.F90
src/Infrastructure/IOSpec/tests/ESMF_IOSpecUTest.F90
src/Infrastructure/LocalArray/tests/ESMF_ArrayDataUTest.F90
src/Infrastructure/LocalArray/tests/ESMF_ArrayF90PtrUTest.F90
src/Infrastructure/LocalArray/tests/ESMF_LocalArrayUTest.F90
src/Infrastructure/LogErr/tests/ESMF_LogErrUTest.F90
src/Infrastructure/Regrid/tests/ESMF_Regrid1UTest.F90
src/Infrastructure/Regrid/tests/ESMF_RegridUTest.F90
src/Infrastructure/TimeMgr/tests/ESMF_AlarmUTest.F90
src/Infrastructure/TimeMgr/tests/ESMF_CalRangeUTest.F90
src/Infrastructure/TimeMgr/tests/ESMF_ClockUTest.F90
src/Infrastructure/TimeMgr/tests/ESMF_TimeIntervalUTest.F90
src/Infrastructure/TimeMgr/tests/ESMF_TimeUTest.F90
src/Infrastructure/VM/tests/ESMF_VMBarrierUTest.F90
src/Infrastructure/VM/tests/ESMF_VMBroadcastUTest.F90
src/Infrastructure/VM/tests/ESMF_VMGatherUTest.F90
src/Infrastructure/VM/tests/ESMF_VMScatterUTest.F90
src/Infrastructure/VM/tests/ESMF_VMSendVMRecvUTest.F90
src/Infrastructure/VM/tests/ESMF_VMUTest.F90
src/Superstructure/Component/tests/ESMF_CplCompCreateUTest.F90
src/Superstructure/Component/tests/ESMF_GridCompCreateUTest.F90
src/Superstructure/State/tests/ESMF_StateUTest.F90
```

The following unit test files failed to build, failed to execute or crashed during execution:

```
src/Infrastructure/TimeMgr/tests/ESMF_CalendarUTest.F90
src/Infrastructure/VM/tests/ESMF_VMSendRecvUTest.F90
```

The following unit test files had failed unit tests:

```
src/Infrastructure/Field/tests/ESMF_FRoute8UTest.F90
src/Infrastructure/Grid/tests/ESMF_GridCreateUTest.F90
```

The following individual unit tests fail:

```
FAIL DELayout Get Test, ESMF_FRoute8UTest.F90, line 139
FAIL Grid Distribute Test, ESMF_GridCreateUTest.F90, line 198
```

The stdout files for the unit tests can be found at:
/home/bluedawn/svasquez/script_dirs/daily_builds/esmf/test/testO/AIX.default.64.default

The following is an example of the output generated when a unit test fails:

```
ESMF_FieldUTest.stdout: FAIL Unique default Field names Test, FLD1.5.1 & 1.7.1,
                        ESMF_FieldUTest.F90, line 204 Field names not unique
```

8.1.2 Running ESMF System Tests

The system tests provided with the ESMF library evaluate:

- interface agreement between parts of the system
- behavior of the system as a whole

The current system test suite includes tests that perform layout reduction operations, redistribution-transpose, halo operations, component creation and intra-grid communication. Some of the system tests are no longer compatible with the current API, but are included in the release for completeness. A complete description of each available system test and its current compatibility status can be found at the ESMF website, <http://www.esmf.ucar.edu>. The testing and validation page is accessible from the **Development** link on the navigation bar.

The following commands are used to build and run the system tests:

```
gmake [SYSTEM_TEST=xxx] system_tests
gmake [SYSTEM_TEST=xxx] system_tests_uni
```

The `system_tests_uni` target runs the tests on a single processor. The `system_tests` target runs the test on multiple processors.

If a particular `SYSTEM_TEST` is not specified, then all available system tests are built and run.

The results of the test can be found in the following location:

```
${ESMF_DIR}/test/test${ESMF_BOPT}/${ESMF_OS}.${ESMF_COMPILER}.${ESMF_ABI}.${ESMF_SITE}
```

For example, if your ESMF source files have been placed in your home directory:

~/esmf

and your platform and compiler configuration is:

Alpha multi-processor using the native compiler

and you want to run an optimized version of system test SimpleCoupling, then you use these commands from the directory ~/esmf.

```
setenv ESMF_PROJECT <project_name>
gmake ESMF_DIR='pwd' SYSTEM_TEST=ESMF_SimpleCoupling system_tests
```

If you are using ksh then replace the setenv command with this:

```
export ESMF_PROJECT=<project_name>
```

The results will be in:

~/esmf/test/test0/OSF1.default.64.default/ESMF_SimpleCouplingSTest.stdout

At the end of system test execution a script runs to analyze the results.

The script output indicates whether there are any system test failures. The following is a sample from the script output:

There are 14 system tests, 12 passed and 2 failed.

The following system tests passed:

```
src/system_tests/ESMF_CompCreate/ESMF_CompCreateSTest.F90
src/system_tests/ESMF_FieldExcl/ESMF_FieldExclSTest.F90
src/system_tests/ESMF_FieldHalo/ESMF_FieldHaloSTest.F90
src/system_tests/ESMF_FieldHaloPer/ESMF_FieldHaloPerSTest.F90
src/system_tests/ESMF_FieldRedist/ESMF_FieldRedistSTest.F90
src/system_tests/ESMF_FieldRegrid/ESMF_FieldRegridSTest.F90
src/system_tests/ESMF_FieldRegridMulti/ESMF_FieldRegridMultiSTest.F90
src/system_tests/ESMF_FieldRegridOrder/ESMF_FieldRegridOrderSTest.F90
src/system_tests/ESMF_FlowComp/ESMF_FlowCompSTest.F90
src/system_tests/ESMF_FlowWithCoupling/ESMF_FlowWithCouplingSTest.F90
src/system_tests/ESMF_SimpleCoupling/ESMF_SimpleCouplingSTest.F90
src/system_tests/ESMF_VectorStorage/ESMF_VectorStorageSTest.F90
```

The following system tests failed, did not build, or did not execute:

```
src/system_tests/ESMF_FieldRegridConserv/ESMF_FieldRegridConsrvtSTest.F90
src/system_tests/ESMF_RowReduce/ESMF_RowReduceSTest.F90
```

The stdout files for the system_tests can be found at:
/home/bluedawn/svasquez/script_dirs/daily_builds/esmf/test/test0/AIX.default.64.default

8.2 Running ESMF Examples

8.2.1 Example Source Code

Example source code for each class is found in the class's example directory. For example, source code for the Time Manager class examples are found in this directory:

```
ESMF_DIR/src/Infrastructure/TimeMgr/examples/
```

While the example code is formatted to be included in the documentation, it also runs and compiles to ensure accuracy. Examples generally contain simple usage of the basic methods for the class.

8.2.2 Building and Running Examples

The GNU makefile targets `examples` and `examples_uni` build and run programs found in a class's examples directory. After the examples are built, the `examples` target runs the examples using multiple processors, while `examples_uni` runs the examples on a single processor.

These targets first build the ESMF library.

Run from `ESMF_DIR`, this command will build and run all examples on multiple processors:

```
gmake examples
```

If the command is run in an example source code directory, then only the example from that directory will be built and run. The examples and output files are created in this directory:

```
ESMF_DIR/examples/examples$ESMF_BOPT/$ESMF_OS.$ESMF_COMPILER.$ESMF_ABI.$ESMF_SITE/
```

The name of an output file will begin with the name of the example that created it followed by `.stdout`.

At the end of examples execution a script runs to analyze the results.

The script output indicates whether there are any examples failures. The following is a sample from the script output:

```
There are 34 examples, 32 passed and 2 failed.
```

The following examples passed:

```
src/Infrastructure/Array/examples/ESMF_ArrayCreateEx.F90
src/Infrastructure/Array/examples/ESMF_ArrayGetEx.F90
src/Infrastructure/ArrayComm/examples/ESMF_ArrayCommEx.F90
src/Infrastructure/ArrayDataMap/examples/ESMF_ArrayDataMapEx.F90
src/Infrastructure/ArraySpec/examples/ESMF_ArraySpecEx.F90
src/Infrastructure/Bundle/examples/ESMF_BundleCreateEx.F90
src/Infrastructure/BundleDataMap/examples/ESMF_BundleDataMapEx.F90
src/Infrastructure/DELayout/examples/ESMF_DELayoutEx.F90
src/Infrastructure/Field/examples/ESMF_FieldCreateEx.F90
src/Infrastructure/Field/examples/ESMF_FieldFromUserEx.F90
src/Infrastructure/Field/examples/ESMF_FieldGlobalEx.F90
src/Infrastructure/Field/examples/ESMF_FieldWriteEx.F90
src/Infrastructure/FieldComm/examples/ESMF_FieldCommEx.F90
src/Infrastructure/FieldDataMap/examples/ESMF_FieldDataMapEx.F90
src/Infrastructure/LogErr/examples/ESMF_LogErrEx.F90
src/Infrastructure/Regrid/examples/ESMF_RegridEx.F90
src/Infrastructure/Route/examples/ESMF_RouteEx.F90
src/Infrastructure/TimeMgr/examples/ESMF_AlarmEx.F90
src/Infrastructure/TimeMgr/examples/ESMF_CalendarEx.F90
src/Infrastructure/TimeMgr/examples/ESMF_ClockEx.F90
src/Infrastructure/TimeMgr/examples/ESMF_TimeEx.F90
src/Infrastructure/VM/examples/ESMF_VMAllFullReduceEx.F90
src/Infrastructure/VM/examples/ESMF_VMComponentEx.F90
src/Infrastructure/VM/examples/ESMF_VMDefaultBasicsEx.F90
src/Infrastructure/VM/examples/ESMF_VMGetMPICommunicatorEx.F90
src/Infrastructure/VM/examples/ESMF_VMScatterVMGatherEx.F90
src/Infrastructure/VM/examples/ESMF_VMSendVMRecvEx.F90
src/Superstructure/Component/examples/ESMF_AppMainEx.F90
src/Superstructure/Component/examples/ESMF_CplEx.F90
src/Superstructure/Component/examples/ESMF_GCompEx.F90
src/Superstructure/State/examples/ESMF_StateEx.F90
src/Superstructure/State/examples/ESMF_StateReconcileEx.F90
```

The following examples failed, did not build, or did not execute:

```
src/Infrastructure/Grid/examples/ESMF_GridCreateEx.F90
src/Infrastructure/TimeMgr/examples/ESMF_TimeIntervalEx.F90
```

The stdout files for the examples can be found at:

/home/bluedawn/svasquez/script_dirs/daily_builds/esmf/examples/examplesO/AIX.default.64.de

8.3 Using the ESMF

To use an ESMF library to compile and link your application against you will need to tell the compiler where the ESMF module and ESMF library files are located. If this has already been documented by the installer of the ESMF library, follow the directions given. However, if not, then you must add the correct compiler and linker flags yourself.

In order to compile a Fortran application against ESMF add the directory that contains the ESMF *.mod file(s):

```
$ESMF_DIR/mod/mod$ESMF_BOPT/$ESMF_OS.$ESMF_COMPILER.$ESMF_ABI.$ESMF_SITE
```

For most Fortran compilers this path is identified either with a `-I` or a `-M`. Linking against the ESMF library is a bit more complex because of ESMF's dependency on the Fortran90 *and* C++ runtime libraries. Generally it is not enough to specify the location of the ESMF library:

```
$ESMF_DIR/lib/lib$ESMF_BOPT/$ESMF_OS.$ESMF_COMPILER.$ESMF_ABI.$ESMF_SITE
```

via the `-L` flag followed by `-lesmf!` However, ESMF provides a file called `esmf.mk` that is generated during the library build and stored in the same location as the ESMF library (see path just above). This makefile fragment defines several variables indicating compiler options, include paths, library paths and libraries necessary to compile and link against ESMF with Fortran or C++ compilers. Look at "esmf.mk" to pull out the necessary flags to compile and link your own code against the installed ESMF library.

Alternatively, you may want to include "esmf.mk" from within your own build system. All of the variables defined in "esmf.mk" have prefix "ESMF_" as to prevent name space conflicts with users' makefiles. Notice that "esmf.mk" is a self-contained file and is not affected by environment variables. It is not necessary to set any ESMF_ environment variables to use an ESMF library that has been installed on your system!

When building the ESMF libraries on platforms that support both 32 and 64 bit application binary interfaces, verify that the ESMF_ABI environment variable is set to match the compile option that was specified to build your application.

8.3.1 Shared Object Libraries

On some platforms, a shared object library is created in addition to the standard .a archive library. Shared object libraries are libraries that are loaded by the first program that uses them. All programs that start afterwards automatically use the existing shared library. The library is kept in memory as long as any active program is still using it.

Shared object libraries can be pre-linked to system libraries and using them can simplify dealing with ESMF's dependency on Fortran90 and C++ runtime libraries.

8.3.2 Customized SITE Files

In an effort to provide platform specific information for building ESMF and linking the libraries with your application, a SourceForge site, `esmfcontrib`, has been created. To locate the platform makefiles for a specific institution, check out the `build_config_files` using the appropriate CVSROOT. The URL for the `esmfcontrib` SourceForge site is:

```
http://sourceforge.net/projects/esmfcontrib/
```

Additionally, you may check out all the platform makefile fragments for a particular institution from the `esmfcontrib` site. For example, to check out the available makefile fragments for platforms at the National Center for Atmospheric Research, `ncar`, change directories to

```
$ESMF_DIR/build_config
```

and use the following CVS command:

```
cvs -z3 -d:ext:$username@cvs.sourceforge.net:/cvsroot/esmfcontrib checkout ncar
```

The following directories will be checked out:

```
AIX.default.bluesky  
Linux.lahey.longs
```

To build using these makefiles you must set the environment variable `ESMF_SITE` to `bluesky`, or `longs`.

At the present time, we have files for the following institutions:

```
anl - Argonne National Laboratory  
cola - Center for Ocean-Land-Atmosphere Studies  
gsfc - Goddard Space Flight Center  
mit - Massachusetts Institute of Technology  
ncar - National Center for Atmospheric Research
```

Users are encouraged to contribute pertinent information to the `esmfcontrib` repository.

8.4 Demonstration Application

The `ESMF_COUPLED_FLOW` demonstration illustrates use of both the ESMF infrastructure and superstructure. It is described in detail in Section 10.

8.4.1 Running the Demonstration

To run the `ESMF_COUPLED_FLOW` demo starting from ESMF source code, type

```
gmake ESMF_COUPLED_FLOW
```

or

```
gmake ESMF_COUPLED_FLOW_uni
```

from the `$ESMF_DIR` directory. This will compile both the ESMF library and the demo and then run the demo.

To simply run the demo, type:

```
gmake run_demos
```

or

```
gmake run_demos_uni
```

9 Architectural Overview

The ESMF architecture is characterized by the layering strategy shown in Figure 1. User code components that implement the *science* portions of an application, for example a sea ice or land model, are sandwiched between two layers. The upper layer is denoted the **superstructure** layer and the lower layer the **infrastructure** layer. The role of the superstructure layer is to provide a shell which encompasses user code and provides a context for interconnecting input and output data streams between components. The key elements of the superstructure are described in Section 9.2. These elements include classes that wrap user code, ensuring that all components present consistent interfaces. The infrastructure layer provides a foundation that developers of science components can use to speed construction and to ensure consistent, guaranteed behavior. The elements of the infrastructure include constructs to support parallel processing with data types tailored to Earth science applications, specialized libraries to support consistent time and calendar management and performance, error handling and scalable I/O tools. The infrastructure layer is described in Section 9.3. A hierarchical combination of superstructure, user code components, and infrastructure are joined together to form an ESMF application.

9.1 Key Concepts

The ESMF architecture and programming paradigm are based upon five key concepts: modularity, flexibility, hierarchical organization, communication within components, and a uniform communication API.

9.1.1 Modularity

The ESMF design is based upon modular components. There are two types of components, one of which represents models (Gridded Components) and one which represents couplers (Coupler Components). Data are always passed between components using a data structure called a State, which can store Fields, Bundles of Fields, Arrays, and other States. A Gridded Component stores no information about the internals of the Gridded Components that it interacts with; this information is passed in through the argument lists of its initialize, run, and finalize methods. The information that is passed in through the argument list can be a State from another Gridded Component, or it can be a function pointer that performs a computation or communication on a State. These function pointers (not yet implemented) are called Transforms, and they are created by Coupler Components. They are called inside the Gridded Component they are passed into. Although Transforms add some complexity to the framework (and their use is not required), they are what will enable ESMF to accommodate virtually any model of communication between components.

Modularity means that an ESMF component stores nothing about the internals of other components. This allows components to be used more easily in multiple contexts.

9.1.2 Flexibility

The ESMF does not dictate how models should be coupled; it simply provides tools for creating couplers. For example, both a hub-and-spokes type coupling strategy and pairwise strategies are supported. The ESMF also allows model communications to occur mid-timestep, if desired. Sequential, concurrent, and mixed modes of execution are supported.

The ESMF does not impose restrictions on how data flows through an application. This accommodates scientific innovation - if you want your atmospheric model to communicate with your sea ice model mid-timestep, ESMF will not stop you.

9.1.3 Hierarchical Organization

The ESMF allows applications to be composed hierarchically. For example, physics and dynamics modules can be defined as separate Gridded Components, coupled together with a Coupler Component, and all of these nested within a single atmospheric Gridded Component. The atmospheric Gridded Component can be run standalone, or can be included in a larger climate or data assimilation application. See Figure 2 for an illustrative example.

The data structure that enables scalability in ESMF is the derived type Gridded Component. Fortran alone doesn't allow you to create generic components - you'd have to create derived types for PhysComp, and DynComp, and PhysDynCouplerComp, and AtmComp. In ESMF, these are always of type GridComp or CplComp, so they can be called by the same drivers (whether that driver is a standard ESMF driver or another model), and use the same methods without having to overload them with many specific derived types. It's the same idea when you want to support different implementations of the same component, like multiple dynamics.

The ESMF defines a hierarchical, scalable architecture that is natural for organizing very complex applications, and for allowing exchangeable components.

9.1.4 Communication Within Components

Communication in ESMF always occurs within a component. It can occur internal to a Gridded Component, and have nothing to do with interactions with other components (setting aside synchronization issues), or it can occur within a Coupler Component or a Transform generated by a Coupler Component. A result of the rule that all communication happens within a component is that Coupler Components must always be defined on the union of all the components that they couple together. Models can choose to use whatever mechanism they want for intra-model communications.

The point is that although the ESMF defines some simple rules for communication, the communication mechanism that the framework uses is not hardwired into its architecture - the sends and receives or puts and gets are enclosed within Gridded Components, Coupler Components and Transforms. The intent is to accommodate multiple models of communication and technical innovations.

9.1.5 Uniform Communication API

ESMF is developing a single API for shared and distributed memory that, unlike MPI, accounts for NUMA architectures and does not treat all processes as being identical. It's possible for users to set ESMF communications to a strictly message passing mode and put in their own OpenMP commands.

The goal is to create a programming paradigm that is performance sensitive to the architecture beneath it without being discouragingly complicated.

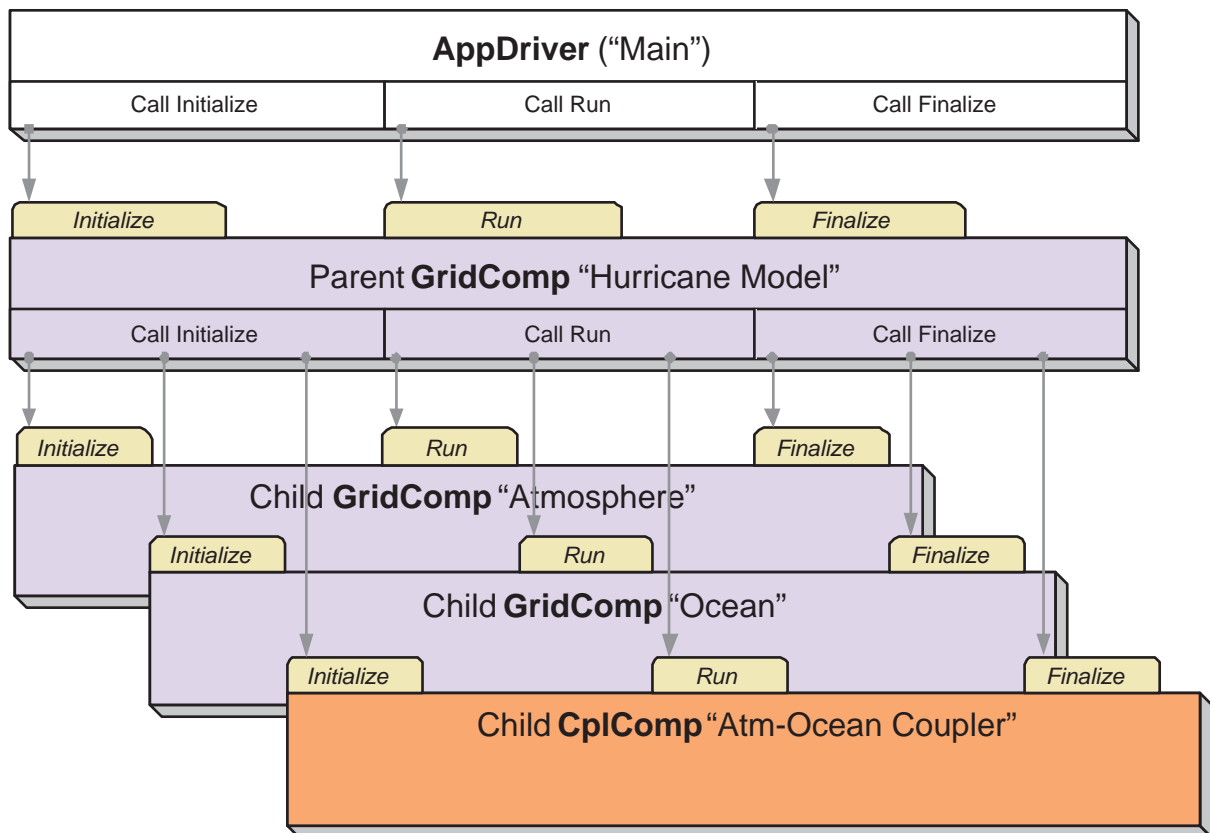
9.2 Superstructure

The ESMF superstructure layers in an application furnish a unifying context within which user components are interconnected. Classes called **Gridded Components**, **Coupler Components**, and **States** are used within the superstructure to achieve this flexibility. We describe these classes below:

9.2.1 Import and Export State Classes

User code components under ESMF use special interface objects for component to component data exchanges. These objects are of type import State and export State. These special types support a variety of methods that allow user

Figure 2: A typical building block for an ESMF application consists of a parent Gridded Component, two or more child Gridded Components, and a Coupler Component. The parent Gridded Component is called by an Application Driver. All ESMF components have initialize, run, and finalize methods. The diagram shows that when the Application Driver calls initialize on a parent Gridded Component, the call cascades down to all of its children, so that the result is that the entire “tree” of components is initialized. The run and finalize methods work the same way. In this example a hurricane simulation is built from ocean and atmosphere Gridded Components. The data exchange between the ocean and atmosphere is handled by an ocean-atmosphere Coupler Component. Since the whole hurricane simulation is a Gridded Component, it could be easily be treated as a child and coupled to another Gridded Component, rather than being driven directly by the Application Driver. A similar diagram could be drawn for an atmospheric model containing physics and dynamics components, as described in Section 9.1.3.



code components to, for example, fill an export State object with data to be shared with other components or query an import State object to determine its contents. In keeping with the overall requirements for high-performance it is permitted for import State and export State contents to use references or pointers to component data, so that costly data copies of potentially very large data structures can be avoided where possible. The content of an import State and an export State can be made self-describing.

9.2.2 Interface Standards

The import State and export State abstractions are designed to be flexible enough so that ESMF does not need to mandate a single format for fields. For example, ESMF does not prescribe the units of quantities exported or imported; instead it provides mechanisms to describe units, memory layout, and grid coordinates. This allows the ESMF software to support a range of different policies for physical fields. The interoperability experiments that we are using to demonstrate ESMF make use of the emerging CF conventions [1] for describing physical fields. This is a policy choice for that set of experiments. The ESMF software itself can support arbitrary conventions for labeling and characterizing the contents of States.

9.2.3 Gridded Component Class

The Gridded Component class describes a user component that takes in one import State and produces one export State. Examples of Gridded Components are major Earth system model components such as land surface models, ocean models, atmospheric models and sea ice models. Components used for linear algebra manipulations in a state estimation or data assimilation optimization procedure are also created as Gridded Components. In general the fields within an import State and export State of a Gridded Component will use the same discrete grid.

9.2.4 Coupler Component Class

The other top-level component class supported in the ESMF architecture is a Coupler Component. This class is used for components that take one or more import States as input and map them through spatial and temporal interpolation or extrapolation onto one or more output export States. In a Coupler Component it is often the case that the export State(s) is on a different discrete grid to that of the import State(s). For example, in a coupled ocean-atmosphere simulation a Coupler Component might be used to map a set of sea-surface fields in an ocean model to appropriate planetary boundary layer fields in an atmospheric model.

9.2.5 Flexible Data and Control Flow

Import States, export States, Gridded Components and Coupler Components can be arrayed flexibly within a superstructure layer. Using these constructs it is possible to configure a set of components with multiple pairwise Coupler Components, Figure 4. It is also possible to configure a set of concurrently executing Gridded Components joined through a single Coupler Component of the style shown in Figure 3.

The set of superstructure abstractions allows flexible data flow and control between components. However, components will often use different discrete grids, and time-stepping components may march forward with different time intervals. In a parallel compute environment different components may be distributed in a different manner on the underlying compute resources. The ESMF infrastructure layer provides elements to manage this complexity.

Figure 3: ESMF supports configurations with a single central Coupler Component. In this case inputs from all Gridded Components are transferred and regridded through the central coupler.

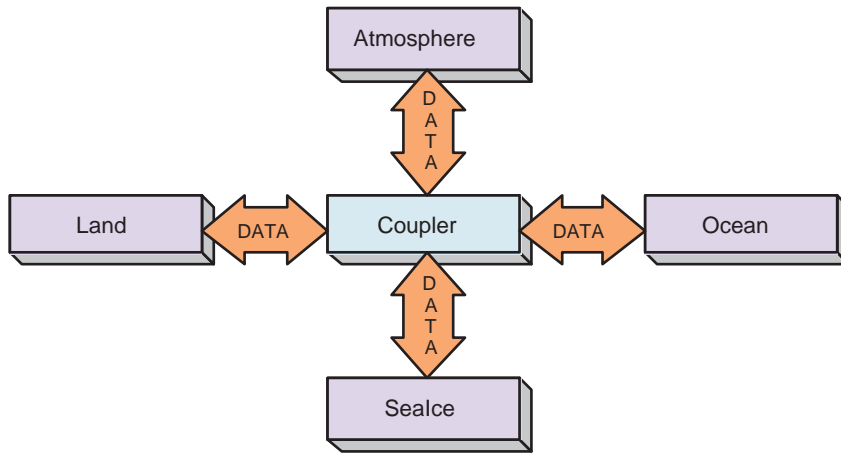


Figure 4: ESMF also supports configurations with multiple point to point Coupler Components. These take inputs from one Gridded Component and transfer and regrid the data before passing it to another Gridded Component. This schematic shows a flow of data between two Coupler Components that connect three Gridded Components: an atmosphere model with a land model, and the same atmosphere model with a data assimilation system.

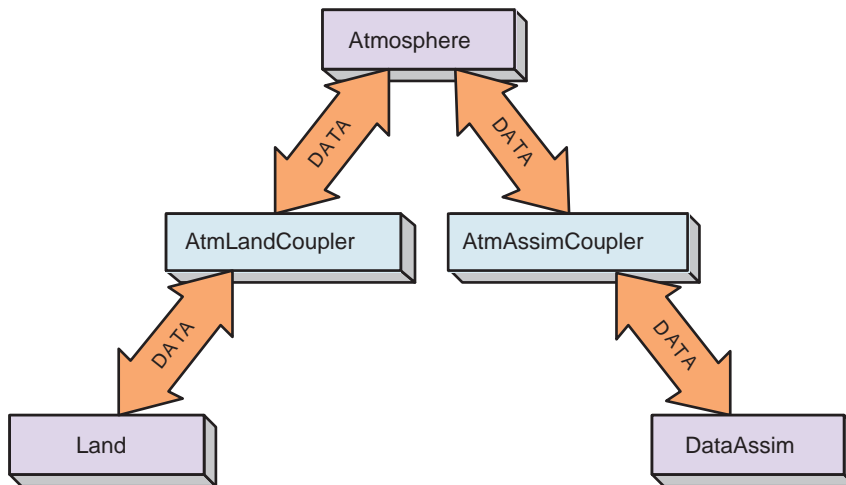
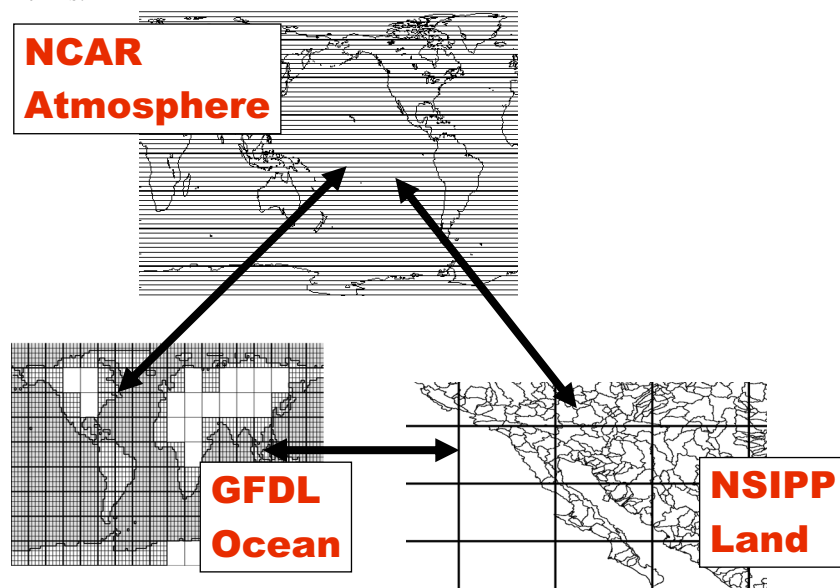


Figure 5: Schematic showing the coupling of components that use different discrete grids and different time-stepping. In this example, component *NCAR Atmosphere* might use a spectral grid based on spherical harmonics, component *GFDL Ocean* might use a latitude-longitude grid but with a patched decomposition that does not include land masses and component *NSIPP Land* might use a mosaic-based grid for representing vegetation patchiness and a catchment area based grid for river routings. The ESMF infrastructure layer contains tools to help develop software for coupling between components on different grids, mapping between components with different distributions in a multi-processor compute environment and synchronizing events between components with different time-stepping intervals and algorithms.



9.3 Infrastructure

Figure 5 illustrates three Gridded Components, each with a different grids, being coupled together. In order to achieve this coupling several steps beyond defining import State and export State objects to act as data conduits are required. Coupler Components are needed that can interpolate between the different grids. The necessary transformations may also involve mapping between different units and/or memory layout conventions for the fields that pass between components. In a parallel compute environment the Coupler Components may also be required to map between different domain decompositions. In order to advance in time correctly the separate Gridded Components must have compatible notions of time. Approaches to parallelism within the Gridded Components must also be compatible. The **Infrastructure** layer contains a set of classes that address these issues and assist in managing overall system complexity. We describe these classes below:

9.3.1 Bundle, Field and Array Classes

Bundle, Field and Array classes contain data together with descriptive physical and computational attribute information. The physical attributes include information that describes the units of the data. The computational attributes include information on the layout in memory of the field data. The Field class is primarily geared toward structured data. A comparable class called Location Stream, not yet implemented, will provide a self-describing container for unstructured observational data streams.

9.3.2 Grid Class

The *Grid* class is an extensible class that holds discrete grid information. It has subtypes that allow it to serve as a container for the full range of different physical grids that might arise in a coupled system. In the example in figure 5 objects of type *Grid* would hold grid information for each of the spectral grid, the latitude-longitude grid, the mosaic grid and the catchment grid.

The *Grid* class is also used to represent the decomposition of a data structure into subdomains, typically for parallel processing purposes. The class is designed to support a generalized “ghosting” for tiled decompositions of finite difference, finite volume and finite element codes.

9.3.3 Time and Calendar Management Class

To support synchronization between components *Time*, *Time Interval*, *Calendar*, *Clock*, and *Alarm* classes are provided. These classes allow *Gridded* and *Coupler Component* processing to be latched to a common controlling clock, and to schedule notification of regular events (such as a coupling intervals) and unique events.

9.3.4 Config Resource File Manager

The *Config* class is a utility for accessing configuration files that are in ASCII format. This utility enables configuration files to be prepared using more flexible formatting than Fortran namelists - for example, it permits the input of tables of data.

9.3.5 DELayout and Virtual Machine

To provide a mechanism for ensuring performance portability ESMF defines *DELAYOUT* and *Virtual Machine* classes. These classes provide a set of high-level platform independent interfaces to performance critical parallel processing communication routines. These routines can be tuned to specific platforms to ensure optimal parallel performance on many platforms.

9.3.6 Logging and Error Handling

The *LogErr* class is designed to aid in managing the complexity of multi-component applications. It provides ESMF with a unified mechanism for managing logs and error reporting.

9.3.7 I/O Classes

The infrastructure layer will define a set of *I/O* classes for storing and retrieving *Field* and *Grid* information to and from persistent storage. *I/O* classes are not yet implemented.

10 ESMF_COUPLED_FLOW Demonstration Program

10.1 Introduction

This section describes the organization of a demonstration program which uses the ESMF Framework, including use of both the Superstructure and Infrastructure.

10.2 ESMF_COUPLED_FLOW Description

The ESMF_COUPLED_FLOW application is comprised of two ESMF Gridded Components and a Coupler Component. The first Gridded Component, FlowSolver, solves the compressible time-dependent fluid flow equations. The algorithm applies an explicit solution technique to a staggered, Arakawa C grid that is cartesian and uniform. State variables, including density, pressure, viscosity and temperature, are located at cell-centers, while velocities are located at cell faces. This component is initialized with a steady-state, one-dimensional flow. The second Gridded Component, Injector, injects fluid into the first normal to the flow along one of the boundaries. The injected fluid can have arbitrary velocity, temperature, density and duration, effectively setting some of the boundary conditions for the first component. The FlowSolver and Injector Components sit on different cartesian grids. The Coupler Component redistributes boundary condition data from the Injector to the FlowSolver.

11 Program Organization

The demonstration program consists of a top level Application Driver, a top level Gridded Component, and nested within this Gridded Component are 3 subcomponents: a Coupler Component and 2 Gridded Components.

The following diagram shows this organization. Note that there is no direct communication between the subcomponents; all interactions are mediated by the top level Gridded Component.

Each component communicates via Initialize, run, and finalize subroutine calls. These go through the ESMF where they are checked for validity, default values are supplied, and only those components involved in the computation are invoked.

12 Framework Usage Details

12.1 Fortran: Module Interface CoupledFlowApp.F90 - Main program source file for demo (Source File: CoupledFlowApp.F90)

ESMF Application Wrapper for Coupled Flow Demo. This file contains the main program, and creates a top level ESMF Gridded Component to contain all other Components.

12.1.1 Namelist Input Parameters for CoupledFlowApp:

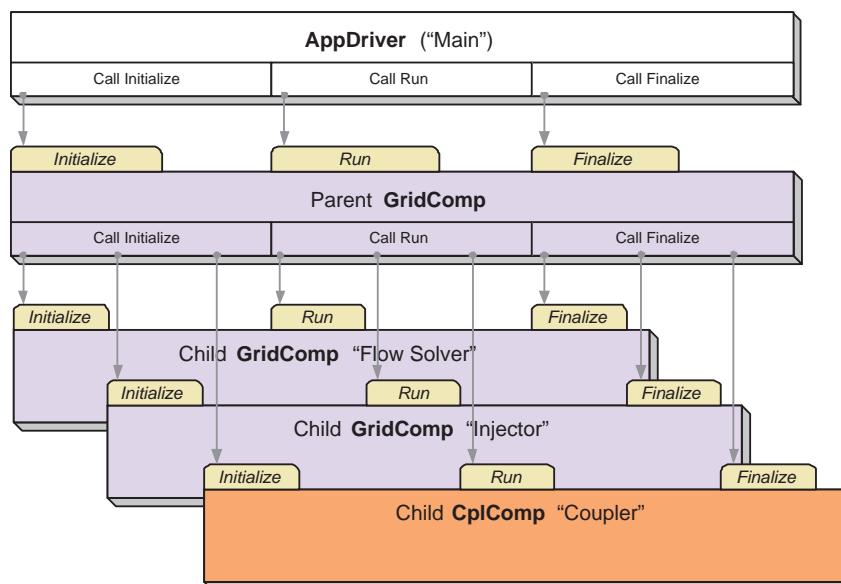
The following variables must be input to the CoupledFlow Application to run. They are located in a file called "coupled_app_input."

The variables are:

i_max Global number of cells in the first grid direction.

j_max Global number of cells in the second grid direction.

Figure 6: Structure of the demonstration program.



x_min Minimum grid coordinate in the first direction.

x_max Maximum grid coordinate in the first direction.

y_min Minimum grid coordinate in the second direction.

y_max Maximum grid coordinate in the second direction.

s_month Simulation start time month (integer).

s_day Simulation start time day (integer).

s_hour Simulation start time hour (integer).

s_min Simulation start time minute (integer).

e_month Simulation end time month (integer).

e_day Simulation end time day (integer).

e_hour Simulation end time hour (integer).

e_min Simulation end time minute (integer).

12.1.2 Example of Initializing the Framework:

The first call to ESMF must be the initialize method. As part of initialization the default Calendar can be specified, some options for logging can be set, and the default global VM can be returned. Here we are setting the default Calendar to be Gregorian, and getting back the global VM:

```
! Initialize ESMF, get the default Global VM, and set
! the default calendar to be Gregorian.
call ESMF_Initialize(vm=vm, defaultCalendar=ESMF_CAL_GREGORIAN, rc=rc)
```

```
! Create the top level Gridded Component.
compGridded = ESMF_GridCompCreate(name="Coupled Flow Demo", rc=rc)
```

12.1.3 Example of Calendar and Clock Creation and Usage:

The following piece of code provides an example of Clock creation used in the Demo. Note that the Gregorian calendar was set as the default in the ESMF_Initialize() call above. As shown in this example, we first initialize a time interval (timestep) to 2 seconds:

```
call ESMF_TimeIntervalSet(timeStep, s=2, rc=rc)
```

And then we set the start time and stop time to input values for the month, day, and hour (assuming the year to be 2003):

```
call ESMF_TimeSet(startTime, yy=2003, mm=s_month, dd=s_day, &
                  h=s_hour, m=s_min, s=0, rc=rc)

call ESMF_TimeSet(stopTime, yy=2003, mm=e_month, dd=e_day, &
                  h=e_hour, m=e_min, s=0, rc=rc)
```

With the time interval, start time, and stop time set above, the Clock can now be created:

```
clock = ESMF_ClockCreate(timeStep=timeStep, startTime=startTime, &
                         stopTime=stopTime, rc=rc)
```

Subsequent calls to ESMF_ClockAdvance with this clock will increment the current time from the start time by the timestep.

12.1.4 Example of Grid Creation:

The following piece of code provides an example of Grid creation used in the Demo. The extents of the Grid were previously read in from an input file, but the rest of the Grid parameters are set here by default. The Grid spans the Application's PET list, while the type of the Grid is assumed to be horizontal and cartesian x-y with an Arakawa C staggering. The Grid name is set to "source grid":

```
counts(1) = i_max
counts(2) = j_max
g_min(1) = x_min
g_min(2) = y_min
g_max(1) = x_max
g_max(2) = y_max
grid = ESMF_GridCreateHorzXYUni(counts=counts, &
                                minGlobalCoordPerDim=g_min, &
                                maxGlobalCoordPerDim=g_max, &
```

```

        horzStagger=ESMF_GRID_HORZ_STAGGER_C_NE, &
        name="source grid", rc=rc)
    call ESMF_GridDistribute(grid, delayout=DELayoutTop, rc=rc)

```

The Grid can then be attached to the Gridded Component with a set call:

```

    call ESMF_GridCompSet(compGridded, grid=grid, rc=rc)

```

12.2 Fortran: Module Interface CoupledFlowDemo.F90 - Top level Gridded Component source (Source File: CoupledFlowDemo.F90)

ESMF Coupled Flow Demo - A Gridded Component which can be called either directly from an Application Driver or nested in a larger application. It contains 2 nested subcomponents and 1 Coupler Component which does two-way coupling between the subcomponents.

12.2.1 Example of Set Services Usage:

The following code registers with ESMF the subroutines to be called to Init, Run, and Finalize this component.

```

    ! Register the callback routines.

    call ESMF_GridCompSetEntryPoint(comp, ESMF_SETINIT, &
                                   coupledflow_init, ESMF_SINGLEPHASE, rc)
    call ESMF_GridCompSetEntryPoint(comp, ESMF_SETRUN, &
                                   coupledflow_run, ESMF_SINGLEPHASE, rc)
    call ESMF_GridCompSetEntryPoint(comp, ESMF_SETFINAL, &
                                   coupledflow_final, ESMF_SINGLEPHASE, rc)

```

12.2.2 Example of Component Creation:

The following code creates 2 Gridded Components on the same set of PETs (persistent execution threads) as the top level Component, but each of the Grids used by these Components will have a different connectivity. It also creates a Coupler Component on the same PET set.

```

    cnameIN = "Injector model"
    INcomp = ESMF_GridCompCreate(name=cnameIN, rc=rc)

    cnameFS = "Flow Solver model"
    FScomp = ESMF_GridCompCreate(name=cnameFS, rc=rc)

    cplname = "Two-way coupler"
    cpl = ESMF_CplCompCreate(name=cplname, rc=rc)

```

12.2.3 Example of State Creation:

The following code creates Import and Export States for the Injection subcomponent. All information being passed between subcomponents will be described by these States.

```
INimp = ESMF_StateCreate("Injection Input", ESMF_STATE_IMPORT, rc=rc)
INexp = ESMF_StateCreate("Injection Feedback", ESMF_STATE_EXPORT, rc=rc)
```

12.3 Fortran: Module Interface FlowSolverMod.F90 - Source file for Flow Solver Component (Source File: FlowSolverMod.F90)

This component does a finite difference solution of the PDE's for semi-compressible fluid flow. It uses an explicit solution method on a staggered mesh with velocities and momentum located at cell faces and other physical quantities at cell centers. The component assumes a logically rectangular two-dimensional cartesian mesh with constant cell spacing. It also employs a donor-cell advection scheme. Although the algorithm is general, the boundary conditions are coded to assume constant inflow on the left, outflow on the right, and free-slip insulated boundaries on the top and bottom. This component will allow the user to construct flow obstacles with different energies, and it accepts a second inflow from the bottom boundary that can be controlled by a second component. For material properties, this component uses an ideal gas equation of state, and assumes constant ratio of specific heats, thermal conductivity, and specific heat capacity. There is no system of units assumed by the component – it is up to the user to ensure dimensional consistency.

The following are the semi-compressible flow equations used in this component.

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u}{\partial x} + \frac{\partial \rho v}{\partial y} = 0$$

$$\frac{\partial \rho u}{\partial t} + \frac{\partial \rho u^2}{\partial x} + \frac{\partial \rho uv}{\partial y} = -\frac{\partial(p+q)}{\partial x}$$

$$\frac{\partial \rho v}{\partial t} + \frac{\partial \rho uv}{\partial x} + \frac{\partial \rho v^2}{\partial y} = -\frac{\partial(p+q)}{\partial y}$$

$$\frac{\partial pI}{\partial t} + \frac{\partial \rho u I}{\partial x} + \frac{\partial \rho v I}{\partial y} = -(p+q) \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right) + \frac{k}{b} \left(\frac{\partial^2 I}{\partial x^2} + \frac{\partial^2 I}{\partial y^2} \right)$$

$$p = (\gamma - 1)\rho I$$

$$q = -q_o \rho u_{in} (dx^2 + dy^2)^{1/2} \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right)$$

$$if q < 0 set q = 0$$

ρ density
 t time
 u x-component of velocity
 v y-component of velocity
 p pressure

Where q artificial velocity
 I standard internal energy
 γ ratio of specific heats
 k thermal conductivity
 b specific heat capacity
 q_o artificial viscosity coefficient, dimensionless
 u_{in} inflow velocity (representative velocity)

12.3.1 Namelist Input Parameters for Flowsolver:

The following variables must be input to the FlowSolver Component to run. They are located in a file called "coupled_flow_input."

The variables are:

uin Inflow velocity at left boundary.

rhoin Inflow density at left boundary.

siein Inflow specific internal energy at left boundary.

gamma Ratio of specific heats for the fluid (assumed constant).

akb Thermal conductivity over specific heat capacity (assumed constant).

q0 Dimensionless linear artificial viscosity coefficient (should be between 0.1 and 0.2).

u0 Initial velocity in the first grid direction.

v0 Initial velocity in the second grid direction.

sie0 Initial specific internal energy.

rho0 Initial density.

printout Number of cycles between graphical output files.

sieobs Specific internal energy of the obstacles.

nobsdesc Number of obstacle descriptors. Each descriptor defines a block of cells that will serve as an obstacle and not allow fluid flow.

iobs_min Minimum global cell number in the first grid direction defining a block of cells to be an obstacle. Must be [nobsdesc] number of these.

iobs_max Maximum global cell number in the first grid direction defining a block of cells to be an obstacle. Must be [nobsdesc] number of these.

jobs_min Minimum global cell number in the second grid direction defining a block of cells to be an obstacle. Must be [nobsdesc] number of these.

jobs_max Maximum global cell number in the second grid direction defining a block of cells to be an obstacle. Must be [nobsdesc] number of these.

iflo_min Minimum global grid cell number for the second inflow along the bottom boundary.

iflo_max Maximum global grid cell number for the second inflow along the bottom boundary.

12.3.2 Example of FieldHalo Usage:

The following piece of code provides an example of haloing the data in a Field. Currently the Field halo routine assumes the entire halo is updated completely; i.e. the user cannot specify halo width or side separately. Field halo uses a Route object to transfer data from the exclusive computational domain of one DE to the halo region of another.

```

call ESMF_FieldHalo(field_rhou, halohandle, rc=status)
if(status .NE. ESMF_SUCCESS) then
  print *, "ERROR in FlowRhoVel: rhou halo"
  return
endif

```

12.4 Fortran: Module Interface FlowArraysMod.F90 - Source file for Data for Flow Solver (Source File: FlowArraysMod.F90)

Allocate and deallocate ESMF objects which handle data arrays including ESMF_Fields, ESMF_Grids, and ESMF_Arrays.

12.4.1 Example of Field Creation and Array Usage:

The following piece of code provides an example of Field creation used in the demo. In this example we create a Field from an ArraySpec, which designates the rank, type, and kind of the data. First initialize the ArraySpec with rank 2 for a two-dimensional array and kind ESMF_KIND_R4:

```
call ESMF_ArraySpecSet(arrayspec, rank=2, typekind=ESMF_TYPEKIND_R4)
```

Next, create a Field named "SIE" using the ArraySpec with a relative location (relloc) at the cell centers:

```
field_sie = ESMF_FieldCreate(grid, arrayspec, horzRelloc=ESMF_CELL_CENTER, &  
    haloWidth=haloWidth, name="SIE", rc=status)
```

Once the Field has been created, we get a pointer to the Array data (the Fortran 90 array), and call it "sie". Inside the Component "sie" can be used like an array made by an F90 allocation but will reference the data inside "field_sie."

```
call ESMF_FieldGetDataPointer(field_sie, sie, ESMF_DATA_REF, rc=status)
```

12.5 Fortran: Module Interface CouplerMod.F90 - Source for 2-way Coupler Component (Source File: CouplerMod.F90)

The Coupler Component provides two-way coupling between the Injector and FlowSolver Models. During initialization this Component is responsible for setting that data "is needed" from the export state of each model. In its run routine it calls route to transfer the needed data directly from one Component's export state to the other Component's import state.

12.5.1 Example of Redist Usage:

The following piece of code provides an example of calling the data redistribution routine between two Fields in the Coupler Component. Unlike regrid, which translates between different Grids, redistrib translates between different DELayouts on the same Grid. The first two lines get the Fields from the States, each corresponding to a different subcomponent. One is an Export State and the other is an Import State.

```
call ESMF_StateGetField(importState, datanames(i), srcfield, rc=rc)  
call ESMF_StateGetField(exportState, datanames(i), dstfield, rc=rc)
```

The redistrib routine uses information contained in the Fields and the Coupler VM object to call the communication routines to move the data. Because many Fields may share the same Grid association, the same routing information may be needed repeatedly. Route information is saved so the precomputed information can be retained. The following is an example of a Field redistrib call:

```
call ESMF_FieldRedist(srcfield, dstfield, routehandle, rc=rc)
```

12.6 Fortran: Module Interface InjectorMod - Fluid Injection Component (Source File: InjectorMod.F90)

This is a user-supplied fluid injection component which interacts with a separate fluid flow model component by altering the inflow boundary conditions during a user-specified time interval. The energy, velocity, and density of the inflow fluid during the injection time interval are user-specified. The location of the inflow is determined by the fluid flow model component through a set of boundary condition flags which are supplied to this component in the import state. The energy, velocity, and density fields of the calculation are updated by this component and returned to the fluid flow solver for the next computational time step in the export state.

12.7 Namelist Input Parameters for Injector:

The following variables must be input to the Injector Component to run. They are located in a file called "coupled_inject_input."

The variables are:

on_month Injector start time month (integer).

on_day Injector start time day (integer).

on_hour Injector start time hour (integer).

on_min Injector start time minute (integer).

off_month Injector stop time month (integer).

off_day Injector stop time day (integer).

off_hour Injector stop time hour (integer).

off_min Injector stop time minute (integer).

in_energy Standard internal energy of the injector flow.

in_velocity Vertical velocity of the injector flow.

in_rho Density of the injector flow.

13 How to Adapt Applications for ESMF

In this section we describe how to bring existing applications into the framework.

13.1 Individual Components

- Decide what parts will become Gridded Components

A Gridded Component is a self-contained piece of code which will be initialized, will be called once or many times to run, and then will be finalized. It will be expected to either take in data from other components/models, produce data, or both.

Generally a computational model like an ocean or atmosphere model will map either to a single component or to a set of multiple nested components.

- Decide what data is produced

A component provides data to other components using an ESMF State object. A component should fill the State object with a description of all possible values that it can export. Generally, a piece of code external to the component (the AppDriver, or a parent component) will be responsible for marking which of these items are actually going to be needed. Then the component can choose to either produce all possible data items (simpler but less efficient) or only produce the data items marked as being needed. The component should consult the CF data naming conventions when it is listing what data it can produce.

- Decide what data is needed

A component gets data from other components using an ESMF State object. The application developer must figure out how to get any required fields from other components in the application.

- Make the data blocks private

A component should communicate to other components only through the framework. All global data items should be private to Fortran modules, and ideally would be isolated to a single derived type which is allocated at run time.

- Divide the code up into start/middle/end phases

A component needs to provide 3 routines which handle initialization, running, and finalization. (For codes which have multiple phases of initialize, run, and finalize it is possible to have multiple initialize, run, and finalize routines.)

The initialize routine needs to allocate space, initialize data items, boundary conditions, and do whatever else is necessary in order to prepare the component to run.

For a sequential application in which all components are on the same set of processors, the run phase will be called multiple times. Each time the model is expected to take in any new data from other models, do its computation, and produce data needed by other components. A concurrent model, in which different components are run on different processors, may execute the same way. Alternatively, it may have its run routine called only once and may use different parts of the framework to arrange data exchange with other models. This feature is not yet implemented in ESMF.

The finalize routine needs to release space, write out results, close open files, and generally close down the computation gracefully.

- Make a "Set Services" subroutine

Components need to provide only a single externally visible entry point. It will be called at start time, and its job is to register with the framework which routines satisfy the initialize, run, and finalize requirements. It can also register the address of its private data block.

- Create ESMF Fields and Bundles for holding data

An ESMF State object is fundamentally an annotated list of other ESMF items, most often expected to be ESMF Bundles (groups of Fields on the same grid). Other things which can be placed in a State object are Fields, Arrays (raw data with no gridding/coordinate information) and other States (generally used by coupling code). Any data which is going to be received from other components or sent to other components needs to be represented as an ESMF object.

To create an ESMF Field the code must create an ESMF Array object to contain the data values, and usually an ESMF Grid object to describe the computational grid where the values are located. If this is an observational data stream the locations of the data values will be held in an ESMF Location Stream object instead of a Grid. (Location Streams are not yet fully implemented.)

- Be able to read an ESMF clock

During the execution of the run routine, information about time is transferred between components through ESMF Clocks. The component needs to be able to at least query a Clock for the current time using framework methods.

- Decide how much of the lower level infrastructure to use

The ESMF framework provides a rich set of time management functions, data management and query functions, IO functions, and other utility routines which help to insulate the user's code from the vast differences in hardware architectures, system software, and runtime environments. It is up to the user to select which parts of these functions they choose to use.

13.2 Full Application

- Decide on which components to use

Select from the set of ESMF components available.

- Understand the data flow in order to customize a Coupler Component

Examine what data is produced by each component and what data is needed by each component. The role of Coupler Components in the ESMF is to set up any necessary regridding and data conversions to match output data from one component to input data in another.

- Write or adapt a Coupler Component

Decide on a strategy for how to do the coupling. There can be a single coupler for the application or multiple couplers. Single couplers follow a "hub and spoke" model. Multiple couplers can couple between subsets of the components, and can be written to couple either only one-way (e.g. output of component A into input of component B), or two-way (both A to B and B to A).

The coupler must understand States, Fields, Bundles, Grids, and Arrays and ESMF execution/environment objects such as DELayouts.

- Use or adapt a main program

The main program can be an unchanged copy of the file found in the `AppDriver` directory. The only customization needed is to set the name of the top level Gridded Component, and to set the name of the `SetServices` routine. The template file includes a call to `ESMF_Initialize()` which ensures the framework initialization code is run, and will provide the environment for components to be created and run.

Although ESMF provides source code for the main program, it is **not** considered part of the framework and can be changed by the user as needed.

The final thing the main program must do is call `ESMF_Finalize()`. This will close down the framework and release any associated resources.

The main program is responsible for creating a top-level Gridded Component, which in turn creates other Gridded and Coupler Components. We encourage this hierarchical design because it aids in extensibility. The top-level component contains the main time loop and is responsible for calling the `SetServices` entry point for each child component it creates.

14 Glossary

This glossary defines terms used in Earth system modeling to describe parallel computer architectures, grids and grid decompositions, and numerical and computational methods.

360-day calendar A calendar in which every one of twelve months has thirty days. See also Calendar, no-leap calendar.

Accumulator A facility for collecting and averaging data values. Generally accumulators are associated with temporal averaging, although they might be associated with other weighted averaging operations. ESMF does not yet have accumulators.

Address space (ASP) A term that refers to the memory that a computer program can write to directly using simple language primitives.

Application Programming Interface (API) API refers to the set of routines and types in a software package that are available to its users. It doesn't include private or internal routines or types.

Alarm Like a real alarm clock, the ESMF Alarm class notifies the user of an event that occurs at a particular time (or set of times). In order to determine whether it is "ringing", an ESMF Alarm is "read" by an explicit application action. An Alarm is associated with a particular Clock.

Application A coherent computational entity run as a single executable or set of communicating executables. It typically consists of a set of interacting components. See also component.

Array An ESMF class that represents a multi-dimensional data array. Unlike a native Fortran or C++ array, an ESMF Array can store information about halo points. See also halo.

Background grid A background grid associates each point in an observational data stream (Location Stream) with a location on a grid. A single grid cell may contain zero or more Location Stream points. See also Location Stream, cell.

BUFR Binary Universal Form of Representation. This is a World Meteorological Organization data format. See BUFR links.

Bundle The ESMF Bundle class represents a set of fields that are associated with the same physical grid and are distributed in the same fashion across the same physical axes. Fields within a Bundle may be staggered differently and may have different (non-distributed) dimensions. See also Field, Packed Bundle, Loose Bundle.

Calendar The Calendar is an ESMF class that stores a representation of a particular calendar type, such as Gregorian. See also specific calendar types such as 360-day and no-leap.

Cell A physical location that is specified by both its extent (vertices) and nominal central location, and is associated with a single integer index value or a set of integer index values (e.g. (i) for 1-d, (i,j) for 2-d, (i,j,k) for 3d). See also index.

CF Conventions Climate and Forecast Conventions. These are emerging conventions for expressing Earth science metadata. See the CF home page.

Change Review Board (CRB) The Change Review Board is the ESMF management body that sets project schedules and priorities. Its Terms of Reference are in the ESMF Project Plan.

Clock Clock is an ESMF class that tracks the passage of time and reports the current time instant. An ESMF Clock is stepped forward in increments of a time step, and can be associated with one or more Alarms. See also Time, Time Interval, Alarm.

Component The ESMF Component class represents large-scale computational entities associated with a particular physical process or computational function, such as a land model. Currently ESMF supports Gridded Component and Coupler Component classes. Components may be generic or user-supplied.

Computational domain For a given DE, the data points that have unique global indices and are updated by the DE. See also exclusive domain, total domain, halo.

Computational resource Something that appears as a physical or virtual computer resource. Example of computational resources are a CPU, a network connection, a communication API, a protocol, a particular network fabric or a piece of computer memory.

Concurrent execution Concurrent execution of model components occurs when two or more components, whether in the same or different executables, run simultaneously. See also sequential execution.

Congruent If all Fields in a Bundle contain the same data type, rank, shape, and relative locations, the Bundle is said to be congruent.

Coupler Component An ESMF Component that includes all data and actions needed to enable communication between two or more Gridded Components. See also component, Gridded Component.

Curvilinear grid A curvilinear grid is a logically rectangular grid in which coordinates in physical space must be specified by giving the explicit coordinates for each point. Curvilinear grids are often uniform or rectilinear grids that have been warped, for example in order to place a pole over land points so it does not affect the computations performed on an ocean model grid. See also logically rectangular grid, Uniform grid, Rectilinear grid.

Data dependency The property of a computational operator that defines the data indices required to perform the computation at a point.

Data parallel The quality of an application that allows roughly the same calculation to be performed by all processors at the same time on the same data set, which is partitioned among multiple memory locations. Single components that do not contain nested components are often data parallel. See also task parallel, SPMD, MPMD.

Data transpose Rearrangement of data arrays that share the same global domain.

Day of year The day number in the calendar year. January 1 is day 1 of the year. Day of year expressed in a floating point format is used to express the day number plus the time of day. For example, assuming a Gregorian calendar:

<u>date</u>	<u>day of year</u>
10 January 2000, 6Z	10.25
31 December 2000, 18Z	366.75

DE Short for Decomposition Element.

DELayout DELayout is the ESMF class that defines the topology of a set of DEs and specifies how the DEs are assigned to PETs in an ESMF Virtual Machine.

Decomposition Element (DE) A DE is the smallest unit of decomposition of a computational task. DEs are virtual units, not necessarily having a 1-to-1 correspondence to the Persistent Execution Threads (PETs) of a VM or the physical Processing Elements (PEs) in the underlying physical machine. Consequently there are no restrictions on the number of DEs that can be created. The application writer may chose the number of DEs to best match the computational problem and the employed algorithm. A DELayout assigns a topology to Decomposition Elements. See also DELayout.

Deep object In an environment in which the calling and implementation language of a library are different, deep objects are defined as those whose memory is allocated by the implementation language. See also shallow object.

Distributed Grid DistGrid is the ESMF class that defines the decomposition of a Grid's global index space across a DELayout. DistGrid objects are contained in an ESMF Grid. See also Grid, DELayout.

Distribution The function that expresses the relationship between the indices in a Distributed Grid and the elements in a DELayout. See also Distributed Grid, DELayout.

Domain decomposition The act of grid distribution: creating a DistGrid, and associating grid points with the DistGrid. The dimensionality of the domain decomposition is the same as the dimensionality of the associated DistGrid.

Exact The word exact is used to denote entities, such as time instants and time intervals, for which truncation-free arithmetic is required.

Exchange grid A grid whose vertices are formed by the intersection of the vertices of two overlying grids. Each cell in the exchange grid overlies exactly one cell in each grid of the exchange. See also grid, cell.

Exchange Packets Exchange Packets are a private ESMF class that contains data in an optimal form for data transfers.

Exclusive domain For a given DE, the set of data points that are not replicated on any other DE. See also total domain, computational domain, halo.

Executable A program that is under independent control by the operating system.

Export State The data and metadata that a component can make available for exchange with other components. This may be data at a physical boundary (e.g land-atmosphere interface) or in other cases, it might be the entire model state. See also State, import State.

Field The ESMF Field class represents a tangible or derived quantity defined within a continuous region of space. The Field class includes the physical grid associated with the quantity and a decomposition that specifies how data associated with points in the physical grid are distributed in computer memory and/or how computational work is divided among threads. A Field also includes a specification of gridpoint staggering and any metadata necessary for a full description of its data. See also Grid.

Framework We use the term framework to refer to a structured collection of software building blocks that can be used and customized to develop components, assemble them into an application, and run the application.

Generic component A generic component is one supplied by the framework. The user is not expected to customize or otherwise modify it. ESMF does not currently contain any generic components. See also user component, component.

Generic transform A generic transform is an operation supplied by the framework, for example, a method that converts gridded data from one supported grid and/or decomposition to another using a specified technique. See also user transform.

Global domain A global domain refers to the full extent of a DELayout or Grid.

Global reduction Reduction operations (sum, max, min, etc.) that condense data distributed over a global domain. See also global broadcast.

Global broadcast Scatter operations on data distributed over a global domain. See also global reduction.

Gregorian The Gregorian calendar is the most widely used calendar in the world. The calendar's zeroth year is at the birth of Jesus Christ. Years after the origin (anno Domini, or AD) are positive, and before (Before Christ, or BC) are negative. Several corrections (leap year, 100 year, 400 year) are necessary to keep the calendar aligned with solar cycles. See also Calendar.

GRIB The GRid in Binary Data format from the World Meteorological Organization. This format is frequently used by operational weather centers. See the GRIB and GRIB2 home pages.

Grid The discrete division of space associated with a particular coordinate system. The ESMF Grid class contains coordinate, domain decomposition, and memory organization information required to manipulate Fields, as well as to create and execute Grid transforms. See also Physical Grid, Distributed Grid, DELayout.

Grid staggering A descriptor of relative locations of scalar and vector data on a structured grid. On different staggered grids, vector data may lie at cell faces or vertices, while scalar data may lie in the interior.

Grid topology Description of data connectivities for a grid.

Grid union The formation of a new grid by taking the union of the vertices of two input grids. See also Grid.

Gridded Component An ESMF class that represents a component that is associated with one or more grids. No requirements may be placed on the physical content of a Gridded Component's data or on the nature of its computations. See also component, Coupler Component.

Halo For a given DE, a halo is a set of data points from the computational domains of neighboring DEs that are replicated locally for computational convenience. A halo can be defined as all the data points in a DE's total domain excluding those in its computational domain. See also computational domain, total domain, exclusive domain.

Halo update A halo update operation involves synchronization of the values of some or all halo points with the current values of those points on other DEs. See also halo.

Import State The data and metadata that a component requires from other components in order to run. See also State, export State.

Index An integer value associated with a set of coordinates.

Index space The space implied by a set of indices. An index space has a defined dimensionality and connectivity.

Index space location A location within an index space. An index space location may be fractional. See also physical location.

Instantiate To create an actual instance of a software class. For example, each variable of derived type Field in an ESMF Fortran application is an instance of the Field class.

Interface Used generally to refer to a set of operations that characterize the behavior of a class or a component. Also used to refer to the name and argument list of a particular method.

Joint Milestone Codeset(JMC) Joint Milestone Codeset. This is the set of climate, weather and data assimilation applications used as ESMF testbeds during the initial NASA-funded phase of ESMF development.

Joint Specification Team(JST) The JST is the body of developers and users who collaborate to create the ESMF software. The main form of communication for the JST is the weekly telecon. Terms of Reference are in the ESMF Project Plan.

LocalArray A LocalArray is the portion of an ESMF Array that resides on a particular DE. See also Array.

LocalTile A LocalTile is the portion of a grid Tile that resides on a particular DE. See also Tile.

Location Stream An ESMF class that represents a list of locations with no assumed relationship between these locations. The elements of a Location Stream are not assumed to share the same metadata. Location Streams are not yet implemented. See also background grid.

Logically rectangular grid A grid in which a set of coordinates (x,y,z, ...) in physical space can be mapped one-to-one to a set of regularly spaced points (i,j,k, ...) in a rectangular logical space, preserving proximate relationships. See also Grid.

Loose Bundle A loose Bundle is an ESMF Bundle object that contains fields whose data is not contiguous in memory. See also Bundle, packed Bundle.

Machine model A generic representation of the computing platform architecture.

Mask A data field marking a span within a larger data field.

Memory domain The portion of memory associated with the data on a given DE. The memory domain is always at least as large as the total domain. See also total domain.

Mosaic grid A mosaic grid is composed of multiple logically rectangular grid tiles that are connected at their edges, for example, a cubed sphere grid. See also grid tile.

MPMD Multiple Program Multiple Datastream. Multiple executables, any of which could itself be an SPMD executable, executing independently within an application. See also SPMD.

Namelist An I/O feature supported by Fortran that defines a structured syntax for creating text files of initial variable settings and defines language features for compactly reading the files. The syntax for Namelist files can be found in most Fortran manuals and tutorial texts.

NetCDF Network Common Data Form. This is a popular I/O library and data format in the Earth sciences. See NetCDF home page.

Node A node is a set of computational resources that is typically located in close proximity on a computing platform and that is associated with a single shared memory buffer.

No-leap calendar In this calendar every year uses the same months and days per month as in a non-leap year of a Gregorian calendar. See also Calendar, 360-day calendar.

Packed Bundle A packed Bundle is an ESMF Bundle object that contains a data buffer with field data arranged contiguously in memory. See also Bundle, loose Bundle.

Parallel execution The term parallel execution refers to the execution of a software application on more than one PE. See also serial.

PE Short for Processing Element.

PET Short for Persistent Execution Thread.

Persistent Execution Thread (PET) Provides a path for executing an instruction sequence. A PET has a lifetime at least as long as the associated data objects. The PET is a key abstraction used in the ESMF Virtual Machine.

Physical location A point in physical space to which a data point pertains. See also index space location.

Platform The processor hardware, operating system, compiler and parallel library that together form a unique compilation target.

Processing Element (PE) A Processing Element (PE) is the smallest physical processing unit available on a particular hardware platform.

Rectilinear grid A rectilinear grid is a logically rectangular grid in which the coordinates in physical space can be fully specified by the spacing of grid points along each grid axis. The gridpoints are located where the coordinate values intersect. The spacing along each axis may vary. See also logically rectangular grid, Uniform grid, Curvilinear grid.

Scheduler An operating system component that assigns system resources (processors, memory, CPU time, I/O channels, etc.) to executables.

Search Search refers to the process of determining which processors must exchange data (and how much) when regridding between decomposed grids. See also sweep.

Sequential execution Sequential execution of model components describes the case in which one component waits for another to finish before it begins to run. Components executing sequentially may be in the same or different executables and may have coincident or non-overlapping memory distributions. See concurrent execution glos:ConcurrentExecution.

Serial Execution The term serial execution refers to the execution of a software application on only one PET. See also parallel execution.

Shallow object In an environment in which the calling and implementation language of a library are different, shallow objects are defined as those whose memory is allocated by the calling language. See also deep object.

Span The physical extent associated with a grid.

SPMD Single Program Multiple Datastream. A single executable, possibly with many components (representing for example the atmosphere, the ocean, land surface) executing serially or concurrently. See also MPMD.

State The ESMF State class may contain Arrays, Bundles, Fields, or other States. It is used to transfer data between components. See also import State, export State.

Sweep Sweep refers to the regridding process of looping through lists of cells from one grid, hunting for interactions with a specified point or subsegment from the other grid. The type of interaction depends on the regrid method and is either an intersection with an identified subsegment or containment of an identified point. The limitation of the range of cells that must be examined is also considered part of the sweep algorithm. See also search.

System time Time spent doing system tasks such as I/O or in system calls. May also include time spent running other processes on a multiprocessor system. See also user time, wall clock time.

Task parallel The quality of an application that allows different calculations to be performed by different processors at the same time on what are usually different data sets. Large-scale task parallelism is often associated with multi-component applications in which each component represents a separate domain or function. Task parallel applications may be run with components executing either sequentially or concurrently, and either in a SPMD or MPMD mode. See also data parallel, SPMD, MPMD, sequential execution, concurrent execution.

Some grids used in Earth system modeling, such as cubed sphere grids, are most naturally represented as a set of logically rectangular grids that are connected at their edges. Following V. Balaji [2006] we refer to each of the logically rectangular grids in a composite grid, or mosaic grid, as a Tile. See also mosaic grid, LocalTile.

Time Time is an ESMF class that is made up of a time and date and an associated calendar. It may include a time zone. *Jan 3rd 1999, 03:30:24.56s, UTC* is one example of a Time. See also Calendar.

Time Interval Time Interval is an ESMF class that represents the period between any two time instants, measured in units, such as days, seconds, and fractions of a second. The periods *2 days and 10 seconds, 86400 and 1/3 seconds* and *31104000.75 seconds* are all possible values for Time Intervals. Mathematical operations such as addition, multiplication, and subdivision can be applied to Time Intervals, and they can have negative values. See also Time

Total domain For a given DE, the entirety of the data points allocated, included replicated points from neighboring DEs. See also computational domain, exclusive domain, halo

A logically rectangular grid in which the coordinates in physical space can be completely specified by the two sets of coordinates that define the opposing corner points of the physical span. The coordinates of each point in physical space can be obtained by interpolating from the corner points, using the evenly spaced logical grid to specify evenly spaced grid point locations. See also logically rectangular grid, Rectilinear grid, Curvilinear grid.

User component A component that is customized or written by the user. All ESMF components are currently user components. See also generic component.

User time Processor time actually spent executing a PET's code. See also system time, wall clock time.

User transform A user-supplied method that is used to extend framework capabilities beyond generic transforms. See also generic transform.

VM Short for Virtual Machine.

Virtual Machine (VM) An ESMF class that abstracts hardware and operating system details. The VM's responsibilities are resource management and topological description of the underlying compute resources in terms of PETs. In addition the VM provides a transparent, low level communication API.

Wall clock time Elapsed real-world time (i.e. difference between start time minus stop time). See also system time, user time.

References

- [1] Eaton, B., J. Gregory, B. Drach, K. Taylor, and S. Hankin. NetCDF Climate and Forecast (CF) Metadata Convention. <http://www.cgd.ucar.edu/cms/eaton/cf-metadata/index.html>.