

# The Earth System Modeling Framework: A High-Performance Software Architecture and Infrastructure for Climate and Weather Applications

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## 1 Introduction

The Earth System Modeling Framework (ESMF) collaboration, which consists of Earth scientists and computational experts from major U.S. modeling centers, is developing a robust, flexible set of software tools to enhance ease of use, performance portability, interoperability and reuse in climate, numerical weather prediction, and data assimilation applications. The ESMF allows diverse scientific groups to leverage common software to solve routine computational problems such as efficient data communication, component coupling and sequencing, time management, and parameter specification. In an open dialogue with the broader community, the ESMF effort is creating a standard application programming interface backed by a reference implementation so that groups at different institutions and in different disciplines can generate interoperable software components and easily assemble new modeling applications.

The ESMF is a three-year project funded by the NASA Earth Science Technology Office. Collaborators include the NSF/National Center for Atmospheric Research, NASA/Goddard Space Flight Center, the Massachusetts Institute of Technology, the University of Michigan, DOE/Argonne National Laboratory, DOE/Los Alamos National Laboratory, the NOAA/Geophysical Fluid Dynamics Laboratory, and the NOAA/National Centers for Environmental Prediction.

## 2 Motivation

The scientific challenge of developing advanced Earth system applications is a daunting task. Independently developed components may have incompatible interfaces and may be written in different computer languages. Performance is often a direct bound on scientific productivity, and high performance typically requires a combination of data and task parallelism. Communication patterns may be regular or irregular, global or nearest-neighbor. The high performance computing (HPC) platforms required by numerically intensive Earth System applications are complex, varied, rapidly evolving and multi-part systems themselves. Since the market for high-end systems is relatively small, there is little robust middleware to buffer the modeler from the difficulties of HPC programming. To complicate matters further, the collaborations required to develop large Earth system applications often span initiatives, institutions, and agencies, involve geoscience, software engineering, and computer science communities, and cross national borders.

The ESMF is a concerted response to these challenges. Led by leaders in the modeling community, the ESMF addresses the technical - and to some extent the cultural - aspects of Earth system modeling. It lays the groundwork for addressing the more difficult scientific aspects of multi-component modeling, such as the physical compatibility of components, in the future.

## 3 ESMF Applications

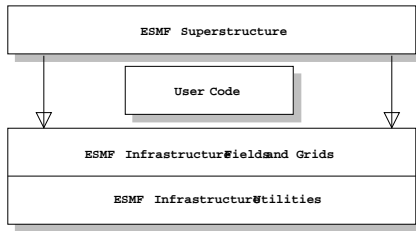
An ESMF application may include ocean, atmosphere, land, sea ice, or other geophysical components. It is also commonplace within the Earth science domain to break down a large component, such as an atmospheric model, into physics and dynamics subcomponents, or diagnostic model and data assimilation subcomponents, so that, for example, a different dynamics package may be swapped in.

There are 15 initial testbeds for ESMF, including both research and operational codes. These represent major national modeling and data assimilation efforts such as the Weather Research and Forecast (WRF) Model [2] and the Community Climate System Model (CCSM) [1]. In addition to the adoption of the ESMF in these 15 testbed codes, the ESMF project will complete 8 interoperability demonstrations that showcase new coupled configurations, including state-of-the-art models that have never been coupled before.

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



## 4 Technical Overview

The ESMF architecture is characterized by the layering strategy shown in Figure 1. User code components that implement the elements of an algorithm are sandwiched between two layers. The upper layer is denoted the *superstructure* and the lower layer the *infrastructure*. The superstructure wraps user code and provides a context and standardized data structures for interconnecting input and output data streams between components. Key classes in the superstructure include a `Component` base class and derived classes (such as a `CouplerComponent` for connecting other types of components). Another important superstructure class is `State`. `Import States` and `Export States` contain, respectively, the data that a `Component` requires to run and the data it can make available.

The infrastructure layer provides a foundation that developers of user components can use to speed construction and to ensure consistent, guaranteed behavior. The elements of the infrastructure layer 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 ESMF communication libraries offer a uniform interface to shared and distributed memory. Infrastructure classes include but are not limited to `Fields`, `Grids`, and `Arrays`. A hierarchical combination of superstructure, user code components and infrastructure are joined together to form an application in the ESMF programming paradigm.

The framework is implemented in a mixture of C++ and Fortran90, and offers bindings for both languages. Migration of C++ object-oriented capabilities across the language interface was essential for creating a system in which Fortran components could be treated in a generic fashion.

## 5 Status and Summary

The ESMF collaboration is building high-performance, flexible software infrastructure to increase ease of use, performance portability, interoperability, and ease of use in climate, weather prediction, data assimilation and other Earth science applications.

The ESMF is currently about half way through its three year funding cycle. A first ESMF Community Meeting was held in May, 2002 in Washington, D.C., to gather input on requirements. A second ESMF Community Meeting was held during May, 2003 at the Geophysical Fluid Dynamics Laboratory in Princeton, NJ. During this meeting, the ESMF team presented an initial application programming interface and prototype code, with a request for community input. A production version of the framework and the third Community Meeting is anticipated in May, 2004.

For additional information on the ESMF project, as well as extensive documentation and source code, please see the project website, <http://www.esmf.ucar.edu>.

## References

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