Survey of Multiscale and Multiphysics Applications and Communities

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Multiscale and multiphysics applications are now commonplace, and many researchers focus on combining existing models to construct new multiscale models. This concise review of multiscale applications and their source communities in the EU and US outlines differences and commonalities among approaches and identifies areas in which collaboration between disciplines could be particularly beneficial.

Many physical problems we seek to understand are complex, consisting of separate physical processes that each contribute to the overall problem. These processes each take place on a specific space or time scale. In biology, for example, the interactions between molecules typically occur on a space scale of several nanometers and a time scale of several nanoseconds. However, the interactions on the cellular level require considerably larger space and time scales.

Historically, many problems have been investigated by modeling or simulating a physical process in isolation and, from the outcome of that exercise, determining its contribution to the overall (complex) physical problem. In the past two decades, however, a new approach has become widespread, in which researchers construct models and simulations that capture multiple physical processes in individual *submodels*. This approach is now known as *multiscale modeling* or *multiscale simulation*. (Here, we use the term *multiscale modeling* to refer to both the modeling and simulation of physical problems).

Multiphysics modeling or *multiphysics simulation* refers to a model that captures multiple physical processes that each capture a different type of physics. For example, a model of a star cluster that uses one submodel to resolve Newtonian gravitational interactions and another to resolve the aging of stars is considered to be a multiphysics model, even if these submodels were (hypothetically) to operate on the same space and time scale. However, a star cluster model that uses two different submodels for the Newtonian gravitational interaction of stars generally isn't considered to be multiphysics, even if the models are applied on a different space or time scale.

Multiscale and multiphysics modeling are therefore two different concepts, but they do have one prime commonality: they both consist of submodels that have been combined (or *coupled*). A major challenge in multiscale as well as multiphysics modeling lies in coupling these submodels such that the overall model is both accurate enough to be scientifically relevant and reproducible, and efficient enough to be executed conveniently by modern compute resources. Multiscale and multiphysics applications exist in a wide range of scientific and engineering communities. By its nature, multiscale modeling is highly interdisciplinary, with developments occurring independently across research domains.

Here, we review a range of multiscale applications and communities residing within different scientific domains. We describe several major projects for each domain and present the results of our investigation on the popularity of multiscale simulation and modeling. Through our work, we found that multiscale methods are adopted in hundreds of projects both in the EU and US, and that the

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popularity of multiscale simulation and modeling has increased considerably in recent years. Although our survey covers many major multiscale simulation and modeling activities, it's by no means exhaustive. For readability reasons, we provide only a limited number of references here. However, a full literature list is available as a Web-based supplement for those wishing to delve deeper into work performed by the various multiscale simulation and modeling communities (see the Web extra at doi:10.1109/MCSE.2013.47). Also, our "Related Work in Multiscale Simulations" sidebar offers additional information on related research efforts.

Overview of Multiscale Communities

Multiscale simulations are most frequently applied in six major domains: astrophysics, biology, energy, engineering, environmental science, and material science. Within these domains, a number of coherent multiscale communities and initiatives emerged and grew over the past decades. We also found a number of multiscale projects outside these domains, which were typically about theoretical mathematical modeling of multiscale problems and only indirectly related to the other scientific fields.

Astrophysics

The astrophysics community hosts many active multiscale projects, mainly due to the large scale and multiphysics nature of many astrophysical problems. Because of gravitation's intrinsic properties, phenomena on relatively small-length scales—for example, close encounters between massive stars or galaxies—can have a considerable effect on much larger systems. It's therefore essential in many cases to model these phenomena using a multiscale approach. Researchers have developed multiscale models in a range of astrophysical topics, including cosmology, star cluster dynamics, thermonuclear supernovae, and space weather systems. The Space Weather Modeling Framework (http://csem.engin.umich.edu/tools/swmf/index.php) is one of the domain-specific toolkits that emerged in this community.

Cactus (www.cactuscode.org) is a toolkit for coupling simulation codes that was originally used to model black holes, neutron stars, and boson stars. Cactus is now used by researchers in a variety of disciplines, some of which have adopted the tool to combine single-scale models and construct multiscale simulations. The Astrophysical Multipurpose Software Environment (Amuse, www.amusecode.org) is an extensive and highly versatile toolkit for constructing multiscale simulations using a wide range of astrophysical codes.

Related Work in Multiscale Simulations

Aside from numerous publications, project websites, and domain-specific reviews, we've identified a few sources that provide information on multiscale simulations in various scientific domains. One such source of information is the *Journal of Multiscale Modeling and Simulation* (epubs.siam.org/mms), which defines itself as an interdisciplinary journal focusing on the fundamental modeling and computational principles underlying various multiscale methods. The *Journal of Multiscale Modeling* (www.worldscinet.com/jmm) is also targeted at multiscale modeling in general. Several books present multiscale research in a range of domains,[1,2] as do the many multiscale modeling workshops, including the Multiscale Materials Meeting (www.mrs.org.sg/mmm2012) and the Modelling and Computing Multiscale Systems Workshop (www.computationalscience.nl/MCMS2013).

Several articles focus on the theoretical aspects of multiscale modeling across domains. Aidong Yang and his colleagues present a thorough and systematic review of the computational and (especially) the conceptual toolkits for multiscale modeling.[3] In addition, Alfons G. Hoekstra and his colleagues investigate the modeling aspects of multiscale simulations, emphasizing simulations using Cellular Automata.[4]

References

1. J. Fish, *Multiscale Methods: Bridging the Scales in Science and Engineering*, Oxford Univ. Press, 2009.
2. S. Attinger and P. Koumoutsakos, *Multiscale Modeling and Simulation*, Springer-Verlag, 2004.
3. A. Yang, "On the Common Conceptual and Computational Frameworks for Multiscale Modeling," *Industrial & Eng. Chemistry Research*, vol. 52, no. 33, 2013, pp. 11451–11462.
4. A. Hoekstra et al., *Complex Automata: Multi-scale Modeling with Coupled Cellular Automata*, Springer-Verlag, 2010, pp. 29–57.

Amuse has been applied, for example, for coupling a gravitational *N*-body simulation with a stellar evolution code to model both the dynamical movements and aging of stars in a star cluster.[1] The Flash 4 code[2] combines hydrodynamic solvers with magnetic field models to simulate the surfaces of compact stars, such as white dwarves and neutrons. Both Amuse and Flash provide extra flexibility by allowing alternative implementations of their components to coexist and be interchanged with each other. They also provide simple and elegant mechanisms to customize code functionalities, without requiring modifications to each component's core implementation.

Biology

Biological systems also span many orders of magnitude through the length and time scales. Although it's uncommon for researchers to model systems much larger than the human body (epidemiology is a notable exception), the human body itself already spans many scales, ranging from the molecular scale up to whole-body processes. The sequence from the genome, proteome, metabolome, and physiome to health comprises multiscale systems biology of the most ambitious kind.

Multiscale modeling in biology has already been widely reviewed. For example, Santiago Schnell and colleagues[3] provide an excellent introduction to the field, while Joseph Dada and Pedro Mendes[4] provide an overview of multiscale modeling efforts in biology, and Peter Sloot and Alfons Hoekstra[5] present an overview of these efforts in computational biomedicine. Several coupling tools were originally developed to construct biomedical multiscale simulations, such as GridSpace (dice.cyfronet.pl/gridspace) and the Multiscale Coupling Library (Muscle 2; www.qoscosgrid.org/trac/muscle). In addition, a sizeable number of markup languages have emerged, such as CellML and Systems Biology Markup Language (SBML), that let users exchange single-scale model definitions and system information—an important aspect of constructing multiscale models.

The Virtual Physiological Human (VPH) Initiative is a large, active community within the biomedical computing domain. Multiscale simulations and models have a central role within the VPH, which supports multiscale modeling efforts in Europe (such as VPH-NoE; www.vph-noe.eu), the US (such as the Multiscale Modeling Consortium; www.imagwiki.nibib.nih.gov), and worldwide through the Physiome project (www.physiome.org). One recently published example involves the coupling of atomistic and continuum subcodes to model blood flow in the brain[6] (here and in the following, *subcode* refers to the implementation of a corresponding submodel).

Energy

Many problems within the energy domain can be resolved using single-scale models, but multiscale simulations are nonetheless considered fundamentally important,[7] especially for nuclear energy problems.

Modeling a complete nuclear reactor is a highly complicated multiscale problem. Here, testing both the efficiency and the durability of reactor parts includes a diverse range of physical processes that all must be resolved accurately in computational submodels. Indeed, a major flaw in one submodel could render the whole reactor ineffective. Several tools emerged that assist in coupling fusion applications, such as the Universal Access Layer (UAL; www.efda-itm.eu/ITM/html/isip_ual.html), the Framework Application for Core-Edge Transport Simulations (Facets; www.facetsproject.org), and the Integrated Plasma Simulator (IPS; cswim.org/ips). Additionally, developments in the GriPhyN high-energy physics computing project (www.griphyn.org) resulted in Swift, a generalized toolkit for workflow-style multiscale simulations.[8]

A specific example in this domain is the European Fusion Development Agreement (EFDA) Task Force on Integrated Tokamak Modeling (www.efda-itm.eu), a European initiative aimed at developing a generic yet comprehensive Tokamak simulator. This simulator can then be applied to investigate a range of existing and future fusion devices. The simulator's layout is modular and multiscale, including submodels that, for example, resolve equilibrium effects, magnetohydrodynamical stability, and heating with ab initio quantum models to be incorporated in the future.

Engineering

Multiscale simulations have been applied to a wide range of engineering problems, as microscopic properties can be of crucial importance for the quality of the overall design. In this work, engineering is presented disjoint from materials science: the former focuses on simulating certain structures, devices, or chemical processes, whereas the latter focuses more on the properties of individual materials.

Jacob Fish edited a comprehensive review of the field's most commonly used multiscale techniques.[9] Additionally, the *International Journal of Multiscale Computational Engineering* emphasizes multiscale simulation in engineering. Multiscale engineering projects are common within the domain of chemical engineering,[10] but also include efforts in aerospace engineering (such as Desider and Flomania), nonequilibrium physics, chemical engineering, stochastic simulations of kinetic theory models, and hydrology's coupling of atomistic and continuum methods.

One of the tools that emerged from the engineering domain is the Multiphysics Object-Oriented Simulation Environment (Moose) toolkit (www.inl.gov/research/moose). Moose is a graphical environment that was originally used for reactor engineering simulations, but now has been reused for a range of scientific purposes. A second multiscale coupling environment that recently emerged from this domain is the Coupled Physics Environment (CouPE; sites.google.com/site/coupempf).

CouPE allows users to couple different submodels that rely on mesh-based solvers.

Environmental Science

Environmental science covers topics such as ecology studies, climate modeling, geosciences, and hydrology, all of which benefit strongly from multiscale simulation approaches. The diverse collection of initiatives in these areas include hydrology simulations, weather forecasting, climate modeling, and disaster predictions. Rupert Klein and his colleagues provide a broad review of multiscale (fluid dynamics) methods in meteorology.[11] Researchers in this domain have also developed several general-purpose toolkits, such as the Model Coupling Toolkit (MCT; www.mcs.anl.gov/mct), the Pyre framework (www.cacr.caltech.edu/projects/pyre), OpenPalm (www.cerfacs.fr/globc/PALM_WEB), Oasis (verc.enes.org/oasis), OpenMI,[12] and the Bespoke Framework Generator (BFG; http://cnc.cs.man.ac.uk/projects/bfg.php). The Distributed Research Infrastructure for Hydrometeorology project (DRIHM; www.drihm.eu) aims to develop a distributed research infrastructure, rather than a single toolkit, to facilitate multiscale hydrometeorological simulations.

The European Network for Earth System Modeling (www.enes.org) is a large consortium developing a European network for the multiscale modeling of earth systems. In this consortium, the Ensembles project (ensembles-eu.metoffice.com) uses multiscale ensemble simulations to simulate the Earth system for climate predictions, which include physical, chemical, biological, and human-related feedback processes.

Materials Science

Materials science applications are inherently multiscale, as the macroscopic properties of many materials are largely characterized through interactions occurring on the microscopic level. Linking our understanding of the physical world at very small scales with the observable behaviour at the macroscale is a major focus within this area of science, and the applications are extremely varied. A popular technique in this field is coarse-graining, in which multiple atoms are resolved as a single coarse-grained particle with a pre-imposed potential.[13] Several tools have emerged that facilitate coarse-graining, including Votca (www.votca.org) and MagiC (code.google.com/p/magic). The topics covered in these projects range from multiscale modeling of radiation damage (such as RadInterfaces) to the modeling of multilayered surface systems (such as M3-2S) and multiscale heterogeneous modeling of solids.[14]

Multiscale Modeling and Simulation comprehensively presents numerous projects within the materials sciences.[15] Additionally, the MMM@HPC project (www.hpc.cineca.it/projects/mmmhpc) develops a unified infrastructure for multiscale materials modeling that covers applications from first principle quantum mechanics to continuum simulations to model properties beyond the atomistic scale. An example of distributed multiscale materials modeling is the clay-polymer nanocomposites application.[16] Coupling toolkits are relatively uncommon within this domain, although the FEniCS (www.fenicsproject.org) is a tool that enables multiscale finite-element simulations.

Other Communities

One community of considerable size is the fluid dynamics community, comprising numerous active areas of research on multiscale simulation. These research topics include multiscale methods to model multiphase fluids, fluids with particles, biofluids, and magnetorheological fluids. The Mapper project (www.mapper-project.eu) features several multiscale fluid dynamics applications—for example, an application to model blood flow and sediment formation in rivers. The *International Journal of Multiscale Computational Engineering* and the *Journal of Multiscale Modelling* contain numerous articles on multiscale fluid dynamics as well.

The multiscale modeling and simulation efforts within fluid dynamics frequently occur in the context of other scientific domains, such as biology (in the case of blood flow simulations) and environmental science (in the case of river or oceanic simulations). To accommodate this, we haven't sought to treat fluid dynamics as a separate domain, but instead categorized the projects in accordance with their application domain.

Review of Multiscale Communities

In characterizing the following scientific communities, we focus on the prevalence and nature of the multiscale research they perform. We also review many commonly used multiscale coupling tools and reflect on the approaches used in different domains for coupling single-scale submodels.

We distinguish here between two multiscale simulation methods:

- *Acyclically coupled* simulations are applications in which subcodes are run, producing results that in turn are used as input for the execution

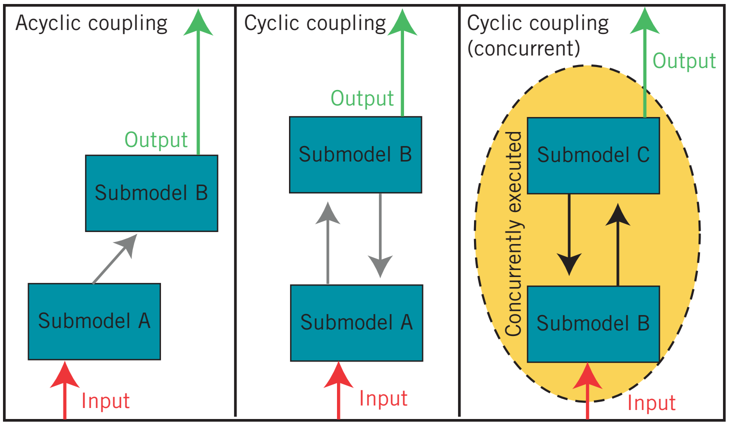

Figure 1. Multiscale simulation methods. (a) An acyclically coupled model. (b) Cyclically coupled model. (c) A cyclically coupled in which the submodels (blue boxes) are executed concurrently. The concurrent execution is frequently managed by a software tool (yellow ellipse) that supports cyclic coupling. The arrows indicate data transfers.

of a subsequent subcode. The most characteristic aspect of acyclically coupled simulations is that there are no cases in which two or more subcodes are mutually dependent during execution.

- *Cyclically coupled* simulations have this mutual dependency, and require at least two of the subcodes to be either run concurrently or in alternating fashion.

Figure 1 shows several schematic examples of multiscale models that use acyclic coupling and cyclic coupling. Although these examples feature two submodels, it's not uncommon for multiscale models to consist of three or more different submodels.

Classification of Multiscale Communities

Table 1 shows a brief characterization of multiscale computing in the six scientific domains. Concurrent cyclic coupling is especially common in astrophysics, and the tight integration of codes required to make concurrent cyclic coupling possible might be why researchers in that domain tend to favor custom-tailored domain-specific coupling solutions. Acyclic coupling is commonly found in the engineering and materials domains, where statistical averages of smaller-scale simulations are frequently applied to inform larger-scale models.

Geographically distributed multiscale simulations are less common, although we did find at least one example for five of the six domains, and several of them in biology. Multiscale efforts in biology, energy, and environmental sciences have resulted in many general-purpose coupling tools. We're unsure why this is the case, but these three domains all have large, internationally coordinated initiatives such as the VPH, ITER (originally an acronym for International Thermonuclear Experimental Reactor), and the European Network for Earth System Modeling (ENES). Such initiatives might have encouraged researchers to adopt generalized approaches.

Figure 2 shows a schematic view of the space and time scales commonly chosen in different research disciplines. Each discipline has a unique scale range given by a parallelogram. For example, the left-bottom corner of the parallelogram for materials sciences is indicative of roughly the time steps used in quantum-mechanical studies, while the top-right corner is indicative of the duration of mesoscale materials simulations (such as those using finite-element methods). Likewise, cosmological dark matter simulations typically adopt scales that reside at the top end of the astrophysics parallelogram.

The visually observed height and width of the corresponding parallelograms show each discipline's space and time scale range. Here, relatively small parallelograms (as in mechanical engineering and environmental science) point to a higher probability of overlapping space and/or time scales between subcodes in those disciplines. When scales between subcodes overlap, cyclic interactions between submodels are essential to obtaining an accurate result, and it becomes difficult to accurately model the system using acyclic coupling alone. Hoekstra and colleagues provide more details on the challenges that arise when scales overlap.[17] On the other hand, large parallelograms point to a larger range of submodels, and an increased likelihood that three or more submodels are required to solve complex problems within these disciplines.

In general, we observe a roughly linear trend between the time scale and the space scale of simulations across disciplines. This correlation is expected, as shorter-range interactions tend to operate on shorter time scales as well. Additionally, phenomena within a space range between 10^{-4} m and 10^4 m and a time range between 10^0s and 10^4s are commonly addressed in many scientific disciplines. This region of overlap might be particularly interesting when opting for interdisciplinary approaches or reusable multiscale simulation tools. Additionally, when high accuracy is required in a simulation operating on these overlapping scales, it might become increasingly relevant to incorporate phenomena from other overlapping scientific disciplines, given that these phenomena are sufficiently proximate.

Table 1. Assessed characteristics of six multiscale simulation domains.						
Scientific Domain	**Astrophysics**	**Biology**	**Energy**	**Engineering**	**Environmental**	**Materials**
Acyclic coupling?	Some	Some	Some	Most	Many	Most
Cyclic coupling?	Most	Most	Most	Some	Many	Some
Concurrent cyclic coupling?	Most	Many	Many	Few	Many	Few
Distributed multiscale?	Few	Some	Few	Unknown*	Few	Few
Dominant style of coupling	D	G	D&G	D	G	S&D

*Due to the commercial nature of many of its multiscale projects, we're unsure about the presence of distributed multiscale simulations in the engineering domain. Also, we've listed the dominant style of coupling as "D" (domain-specific solutions), "G" (general-purpose/domain-independent), and/or "S" (collections of handwritten scripts).

Prevalence of Multiscale Research

To gain some understanding of the size of existing multiscale research communities, we explored several project databases from large funding agencies. These included the European Community Research and Development Information Service (Cordis), as well as the project databases of the US National Institute for Health (NIH), the US Department of Energy (DOE), and the US National Science Foundation (NSF). We found the projects by first searching the project databases for the words "multiscale" and "multi-scale." For DOE and NIH, we selected only those projects that had either term directly in the title; in Cordis and NSF, we also searched for the terms in the abstracts.

Once we selected the projects, we removed any projects with identical titles, as these are often continuations of the same project from the previous year. Also, we eliminated any project that didn't describe explicit multiscale modeling or simulation in its abstract. We found more than a thousand multiscale simulation and modeling grants, which ranged from multimillion euro international projects to awards for individual postdoctoral researchers.

We provide an overview of these projects by scientific domain (Figure 3) and starting year (Figure 4). Our statistics here are by no means exhaustive, as we searched only for explicit mentions of multiscale and didn't investigate nationally funded projects in the EU, US-based projects funded by other organizations, or projects outside the EU and US. Our results should therefore be interpreted only as a rough indication of the multiscale community as a whole and as a lower bound on its size.

As Figure 3 shows, most multiscale projects reside within the domain of biology and materials,

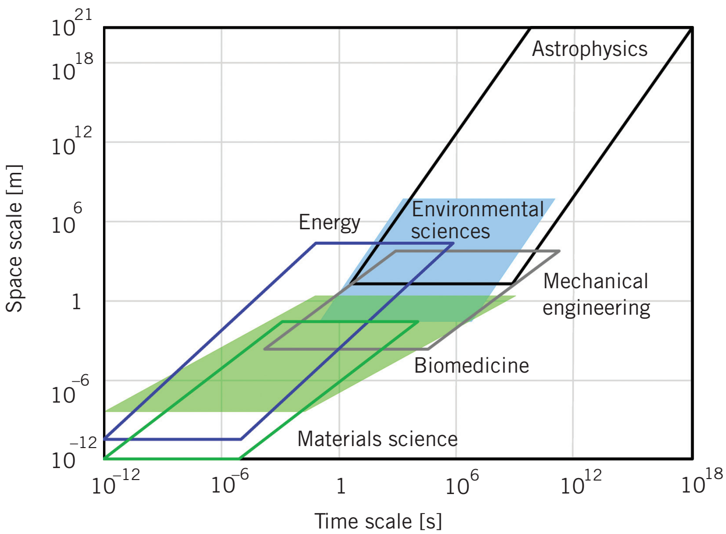

Figure 2. Schematic view of space and time scales for multiscale simulations in the studied scientific domains. Each domain is represented as a colored parallelogram.

although there are also many engineering projects funded in the US. The number of EU projects in the astrophysics domain is quite low, most likely because international collaboration within theoretical astrophysics tends to focus on more informal international collaborations and national sources of funding.

As Figure 4 shows, multiscale projects emerged in the late 1990s, and the number of those projects in the EU has gradually increased in recent years. The number of multiscale US-based projects peaked in 2009 and has gradually diminished in the past few years. This is in part because the DOE database contains no projects starting after 2009 (multiscale or otherwise) and in part because the

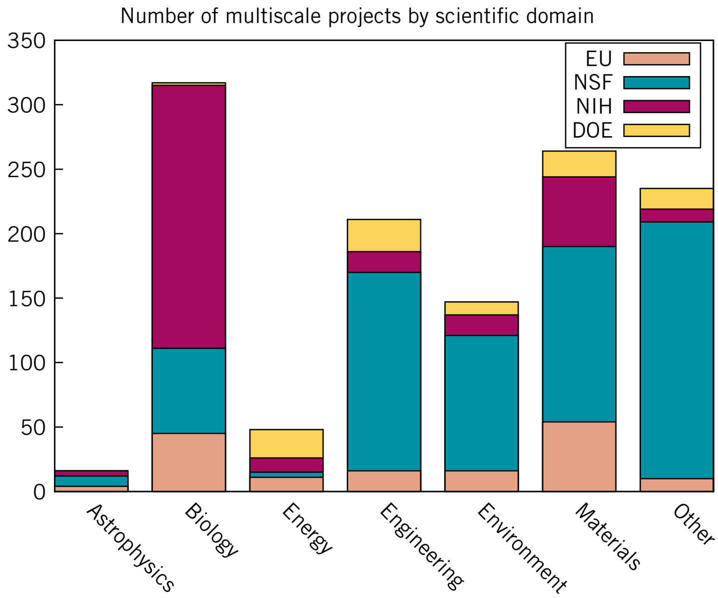

Figure 3. Overview of multiscale projects by scientific domain. We obtained the data from the EU Cordis database (cordis.europa.eu), the National Institute of Health (projectreporter.nih.gov), the OSTI database of the US Department of Energy (www.osti.gov), and the US National Science Foundation (www.nsf.gov).

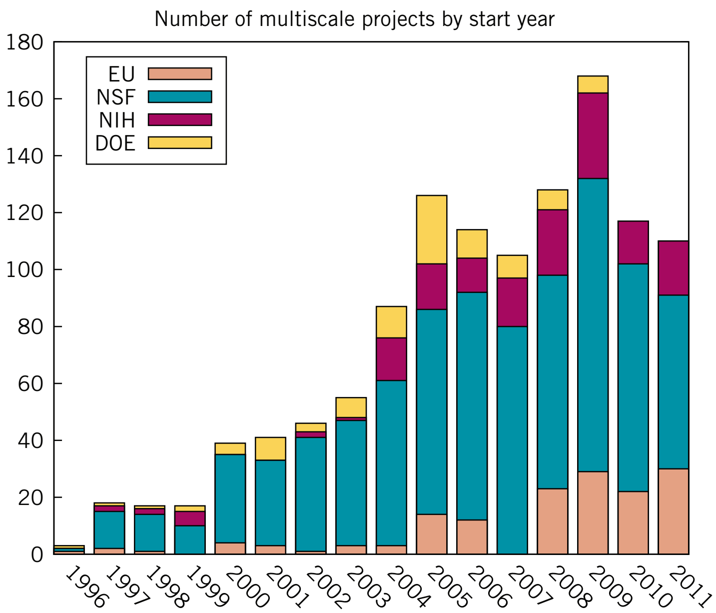

Figure 4. Overview of multiscale projects by starting year. We didn't find any EU Framework projects (multiscale or otherwise) that started in 1999 or 2007. Additionally, we found no projects in the US Department of Energy database that started in 2010 or 2011.

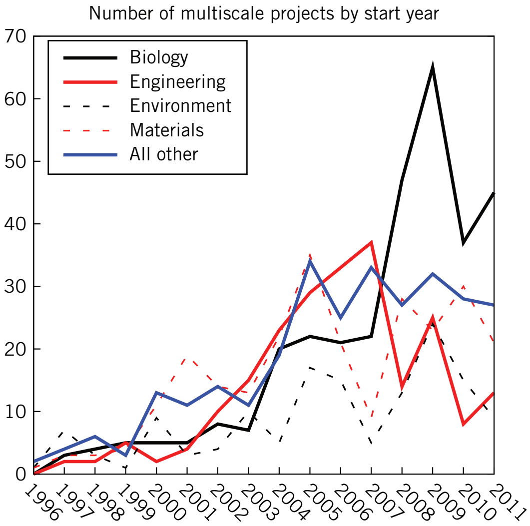

Figure 5. Overview of multiscale projects by starting year and domain. Due to the limited number of projects in energy and astrophysics, we merged these domains into the "Other" category.

US Federal Government made a one-time major investment in scientific research in 2009. As most projects often last three years or more, we estimate that there are more than 300 multiscale projects currently active.

Figure 5 shows the number of new projects per year by domain. Here, the number of new multiscale projects in biology is particularly high in 2008 and 2009, due largely to a growth in funded projects by the EU in 2008 (and due in part to approved projects within the VPH initiative) and a peak in new multiscale biology projects funded by the NSF and NIH in 2009. The number of multiscale projects in most other areas stabilized after 2005, although there are signs of a decreasing trend in the number of multiscale engineering projects after 2007. However, because ongoing projects might last as long as five years, we don't know whether the decrease we observe is indeed part of a longer-term trend.

Coupling Toolkits for Multiscale Simulation

Table 2 classifies coupling toolkits for multiscale simulation; all the toolkits featured here support modular switching and dynamic use of multiple submodels, and execute parallel multiscale simulations within a single compute resource. The table indicates various features, such as whether the tools feature a generic implementation, are intended to be reused in other domains, support specific types of coupling, and allow for multiscale simulations to be run distributed across multiple

Table 2. Assessed characteristics of the coupling toolkits.

Name	Domain of origin	Generic implementation?	Distributed across sites?	Acyclic coupling?	Cyclic coupling?	Interface presented to users	Year of last public release
Amuse	Astrophysics	No	Yes	Yes	Yes	Python	2013
BFG	Environment	Yes	No	Yes	Yes	Fortran	2012
Cactus	Astrophysics	Yes	Yes	Yes	Yes	Custom	2012
CouPE	Engineering	No	No	No	Yes	C++	2013
Facets	Energy	No	N/A*	N/A	Yes	C++	2013
Flash	Astrophysics	N/A	N/A	Yes	Yes	Fortran	2013
GridSpace	Biology	Yes	Yes	Yes	N/A	GUI	2013
IPS	Energy	No	No	Yes	Yes	Python	Not Public
MCT	Environment	Yes	Yes	Yes	Yes	Fortran	2012
Moose framework	Engineering	Yes	No	Yes	Yes	GUI	Not Public
Muscle	Biology	Yes	Yes	N/A	Yes	Java	2013
Oasis	Environment	No	No	N/A	Yes	Fortran/C	2012
OpenMI	Environment	No	Yes	Yes	Yes	Java/C#	2011
OpenPALM	Environment	Yes	No	N/A	Yes	GUI	2012
Pyre	Environment	Yes	No	Yes	Yes	Python	2005
Swift	Energy	Yes	Yes	Yes	No	C-like	2012
SWMF	Astrophysics	N/A	No	Yes	Yes	Fortran	Not Public
UAL	Energy	Yes	Yes	Yes	Yes	C/Fortran/JAVA	Not Public

* N/A indicates that the functionality appears to be outside of the toolkit's scope altogether.

computational sites. Allowing the distributed execution of multiscale simulations is beneficial, and sometimes essential, because the subcodes within each simulation tend to have heterogeneous resource requirements. For example, some subcodes might need larger compute resources than others or require nodes equipped with specialized hardware. Figure 6 offers a graphical overview of the toolkits, the originating domain, the type of interface used, and the level of generality.

Through our work, we discerned several distinct coupling strategies. Perhaps the most traditional multiscale coupling strategy is to develop hybrid codes that cover a set of scales within a single simulation code. These *monolithic* codes are often tailored for specific problems and can efficiently incorporate concurrent cyclic coupling

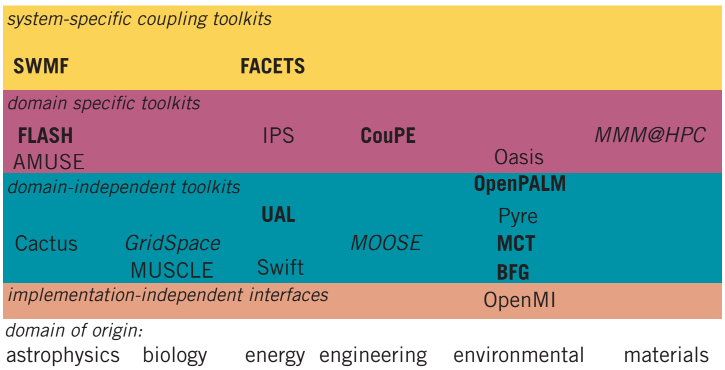

Figure 6. Graphical overview of the coupling toolkits. The names of the toolkits are horizontally positioned by their originating domain, and vertically positioned by their level of generality. Frameworks given in bold feature a user interface based on a compiled language, those in regular font on a scripted language, and those in cursive font on a GUI.

for a limited number of built-in submodels. However, monolithic codes are generally restricted in their modularity and extensibility. These limitations, combined with the ongoing increase in available compute capacity, have led to the emergence of more modular and flexible coupling approaches, which are easier to extend and refactor but might have performance limitations when data-intensive concurrent cyclic coupling is required.

Interestingly, the way different communities have adopted these new coupling approaches isn't at all uniform. For example, researchers in astrophysics and energy domains tend to focus on reusable domain-specific coupling solutions (such as Amuse and IPS), while researchers in biology and environmental science focus on general-purpose solutions (such as Muscle and OpenPalm). Making a tool general-purpose makes it directly usable for researchers in other fields, but it can also limit the tool's functionalities (for example, it might lack unit-conversion capability) or introduce additional complexity in its architecture to retain flexibility. We also provide a brief description of the tool's interface, which often provides a useful hint of its intended audience. Tools geared towards performance tend to rely often on Fortran and C/C++, tools geared towards flexibility on Python or Java, and tools geared towards ease-of-use on GUIs. Researchers in the materials sciences rarely adopt coupling toolkits, and tend to either employ inherent multiscale capabilities within molecular dynamics codes (for example, by using a "replica exchange" method to model a range of temperatures) or connect simulations using (often handwritten) pre- and post-processing scripts. In a few instances, however, they do rely on data conversion libraries such as Votca.

Using a single heavyweight, domain-specific toolkit for multiscale simulations is often convenient for the user in the short term, but it comes with several longer-term drawbacks. First, although it's often straightforward to switch between different solvers within these all-in-one coupling toolkits (sometimes it's as easy as replacing a single line of code), it's often much more difficult to switch from one coupling toolkit to another. This might be necessary if an existing toolkit becomes outdated, for example, or if the toolkit's subcodes need to be reused outside of the source domain. By constructing and adopting formalizations for defining multiscale coupling patterns (such as the Multiscale Modelling Language, MML)[18] we can diminish this drawback and improve the portability of multiscale simulations and, for example, allow them to be more easily moved to a different toolkit if the existing one becomes obsolete.

Another drawback of using traditional all-in-one approaches is that any new computational improvements in multiscale coupling (such as more powerful data abstractions or improvements in the data exchange performance between subcodes) might have to be applied separately to each toolkit to be used to full effect, resulting in duplicated integration, or even implementation, efforts. This is a major concern in any large software project; it can be mitigated in several ways, such as by strictly enforcing modularity in the toolkit design (assuming that the underlying components' developers use standardized APIs that remain consistent over time).

Our analysis of scales simulated by different multiscale computing communities shows a distinct overlap in the scales, upon which the simulations in these domains operate. In particular, many research domains feature simulations on a length scale of about a meter and a time scale of a few hours. As a result, general-purpose multiscale methods geared toward this scale might be particularly suitable for reuse by a range of scientific disciplines, and phenomena operating on these scales in one domain might be relevant to others.

A uniform strategy for multiscale simulations has yet to emerge, as different domains have adopted relatively disjoint approaches so far. Nevertheless, multiscale simulations have become widespread to the point where there are at least a few hundred active projects in the EU and the US alone. It's beyond the scope of this review to fully pronounce on the benefits of pursuing domain-specific versus general-purpose approaches for accelerating the progress of multiscale communities. However, based on our findings, we can clearly conclude that it's high time to open this interdisciplinary debate.

Acknowledgments

We thank our colleagues in the Mapper consortium, in particular Krzysztof Kurowski, Ilya Saverchenko, Kasia Rycerz, Alfons Hoekstra, Marian Bubak, Werner Dubitzky, Bastien Chopard, David Coster, James Suter, and Rupert Nash for their contributions. We also thank Daniel S. Katz, Oliver Henrich, and the participants of both the Distributed Multiscale Computing Workshop 2011 at IEEE e-Science and the Lorenz Center Workshop on Multiscale Modelling and

Computing 2013 for their valuable input. This work received funding from the Mapper European Commission *Seventh Framework Programme (*EC-FP7) project (grant RI-261507).

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