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Object Orientation, Open Regional Science, and Cumulative Knowledge Building

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Abstract

Despite the growing need for an improved understanding of complex relationships among interacting systems, critical air, water, energy and socio-economic system research is carried out independently far too often. When it is comprehensively approached within integrated modeling environments, research teams often must recreate modeling foundations on which to base their own research, often because they are unable to access similar foundations already established by others. Moreover, there is an increasing awareness that energy, water, and environmental issues are best studied at the regional level, and many of the most relevant human-environmental interactions are tied to production and consumption technologies that themselves are tightly bound to regional economic systems that comprise national economies. We need to integrate and model these interacting systems comprehensively, and in an open access environment that promotes

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interaction among scholars, and database and model sharing to eliminate wasteful and redundant foundation infrastructure building. The pace of new knowledge development can be advanced radically by adopting a common and well-tested integrated systems modeling approach for widespread scientific use and development, supporting a research community that spans a wide range of problem domains.

The future of regional science research thus lies in the integrated and comprehensive modeling of interacting systems. This paper describes our vision of this open science future, which we believe will rest on an open source and object-oriented foundation. We describe OASIS, a specific exemplar project now underway designed to fill the current integrated systems science infrastructure void with a framework whose evolutionary character will ultimately reflect the conceptual strengths and contributions of a large community of scholars. The result will be distinguished not only by the collective wisdom of the modeling community, but also by careful attention to the mechanisms that support replication and reproducibility. With the advantage of 21st century technology, object oriented open source open science will deepen our understanding and radically accelerate the pace of knowledge building in coming decades. We see this as a fundamentally new knowledge building paradigm that will dominate future integrated systems research.

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1 The Future of Regional Science Modeling

Integrating human and physical systems is a daunting challenge that spans a great many problem domains, including social and economic production systems, residential behaviors, environmental exchange, and resource and land use. Because so much current research continues to be focused within rather than across these areas, our cumulative knowledge in many respects is little more than a simple summation of various disciplinary and sub-disciplinary learning curves, rather than a truly integrated, synergistic base of understanding. Indeed, a complete understanding of any subdomain may not even be possible in the absence of domain integraion. Even *within* some subdomains, there may be very few instances of truly cumulative science, where one scholar's work adopts another's directly as the foundation for a new and tightly integrated cumulative model. If it were possible to speed the diffusion of modeling innovations and research findings within and among subdomains, the cumulative frontiers of knowledge could be expected also to advance apace.

We believe that the future of research in regional science, and indeed in all social science modeling, will be based on a research infrastructure that leverages the power of networked individuals focusing their collective intellect on problem solving in a community effort as we move science from the domain of individual ivory towers and research silos to a fully integrated common workplace. The research environment we envision stands to *accelerate research integration and cumulative knowledge-building* within and across human and physical systems problem domains.

2 OS^2: Open Science and Open Source

Open science and open source are strongly related but not identical concepts. Open science refers to a scientific field that moves forward as a collective and is open to all participants. Open source refers to equal public access to and development of problem domain content, primarily the computer code that supports modeling and solution algorithms applied within a given problem domain. We refer to this powerful combination of open science and open source development as OS^2.

2.1 Open Science

The rise of the open science movement is a recent phenomenon, and as such, regional modeling has been slow to engage with this movement (Rey, 2014). A key tenet of open science is that for the traditional error-detection and self-correction mechanisms to be fully effective, all aspects of the scientific process need to be open. In theory, open access to the data, models, and work-flow that underly a scientific study should allow other researchers to reproduce the findings of that study. Lacking reproducibility, the contribution of an investigation to the body of knowledge is called into question.

Reproducibility is vital to the integrity of the scientific process and assumes a central position the open science movement. Yet open science is about much more than enhancing reproducibility. New forms of open collaboration as well as open publishing hold the potential to advance the pace of scientific discovery as well as the ensuring the provenance of scientific knowledge. While collaboration has always been central to scientific progress, the scale of collaboration afforded by new technologies is now on the brink of a radical transformation. Advances in high performance computing (HPC) in the form of distributed systems provides unprecedented opportunities for addressing scientific problems once viewed as beyond our reach. However, realization of this potential will require collaboration between domain scientists together with computer scientists with expertise in HPC. That collaboration, in turn, will require open computing frameworks with well developed application programming interfaces (API). Scaling our existing regional modeling software to take advantage of advances in modern HPC architectures is one area where this form of collaboration will have high payoff.

In many ways, the lineage of these "new" open science practices can be traced to the open source movement. Community innovation networks are already commonplace in open source software development, where legions of developers often contribute to evolutionary community resource infrastructures such as XWindows, the Linux operating system, and the Python language and its numerous graphical and numerical processing libraries. Indeed, the suggestion that this kind of approach should be adopted in social sciences dates back at least two decades to Jackson's "Object-Oriented Modeling in Regional Science: An Advocacy View" (1994), a call to action failed to gain momentum for two main reasons. First, object orientation, essential to the success of the proposed approach, was still in early stages of development, and was not stably supported in widely used and freely accessibly computer software. This has changed dramatically in recent years, especially notable with the popular and widely used open source Python programming language. Second, the notion of collaborative innovation networks (Gloor, 2002, 2006; Gloor et al., 2004) and associated support infrastructures had not yet been formally recognized or well established and supported.

Common workplaces such as GitHub.com, which provides controlled access, version control, and other mechanisms such as code repositories and community forums to rationalize the development process are now much more common, more effective, and well supported. The development and convergence of these tools, along with a winnowing of methods for modeling national and regional economic systems makes this perfect time to *move from silo-based research efforts to a mode of collective open science knowledge building.*

2.2 Open Source

The philosophy of open science that informs our project is also reflected in our choice of open source software and development practices in implementation of the modeling framework. Recent developments in the Python programming language make it an ideal solution for the development of the proposed model. Python is an object oriented scripting language that facilitates rapid prototyping of software. Because Python's numerical functions (in NumPy and SciPy) will be readily recognizable by those who program using traditional econometric modeling software (GAUSS and MatLab), leveraging legacy code written in those languages and porting to an object oriented design becomes feasible.

The Python scientific community has also been at the forefront of the recent drive for reproducible research. Tools such as the Jupyter Notebook (http://jupyter.org) allow modelers to combine live code together with narrative text, equations, visualizations and other media to encode a complete and reproducible record of computation. These notebooks can be made available to other researchers via GitHub repositories to facilitate open collaboration.

By relying on public GitHub repositories the nature of collaboration on regional modeling projects not only becomes more efficient, but also may obtain a scalability that is unparalled. Now, any interested regional modeler can "fork" the project to begin their exploration of the underlying code base.

That exploration can take place without the modeler having to first receive permission for copying the project. Thus the entry costs for engaging with the modeling project essentially fall towards zero.

Not only does OS^2 allow for an expansion of the modeling community, but it does so in a a highly efficent way. Individual efforts undertaken as part of the community, receive rapid feedback often virtually at the moment of the newly shared contribution. This can include the users' test, bug reports, new feature requests, etc. In this way, the research workflow can be transfigured into a nearly continuous iterative process among geographically distant collaborators.

As Wallach (2016) has argued, research at the frontier of the social sciences is no longer a choice between computer science *or* social science but must be a synergy of the two moving forward. We see OS^2 as an integrating framework that addresses this call by fusing the practice of regional modeling together with modern principles of computer science.

3 Object Orientation

Object orientation is an abstraction mechanism that is used to focus on the essential constructs within a problem domain, and to eliminate the complexities of non-essentials. Object oriented (OO) modeling is a conceptual approach that can be used to better understand a problem domain. It is analogous in this sense to general systems theory in its provision of a recipe to follow in defining and understanding a problem. Object oriented analysis focuses first on the identification and enumeration of the objects that comprise the system, rather than on system functionality. Object models describe as fully as possible the objects, their attributes and behaviors, and their relationships to and associations with other objects, and are most often the first to be constructed (Rumbaugh et al., 1991). A functional model complements the object model, defining object behavior and how objects and their data values can change. These changes are defined by transformation rules, functions, and mappings, and may conform to constraints and follow various patterns of dependency. A dynamic model is the final complement, defining the sequence control of the problem domain. The dynamic model identifies the data transformation triggers described by the functional model. Object oriented analysis involves the systematic construction of these three "orthogonal views" of a problem domain, as shown in Figure 1. An object oriented model includes an enumeration of the ways in which a system transforms its values, and an elaboration of the timing, sequencing and control of events.

There are many reasons to pursue the object oriented approach. First, if a model is to form the foundation of experimental research, that foundation should be as stable as possible. The objects of most problem domains are much more stable than is their functionality. Indeed, most research focuses precisely on the effects on a system's objects (and overall performance) of specified behavioral (functional) changes. object oriented modeling establishes a solid foundation that provides a stable reference for subsequent use, re-use, and extension. Second, the modeling sequence is both rearranged and structured more explicitly. Whereas most traditional modeling approaches focus first on functionality, Object oriented modeling focuses first on the objects of the model. The recipes we follow to build our understandings shape the processes and outcomes of inquiry. New recipes may well lead to new questions, new hypotheses, and ultimately a more comprehensive understanding of a problem domain.

A third reason for exploring object oriented modeling is the potential to benefit from increased interaction. Scientists each have particular areas of expertise and specialization. Adopting a common modeling approach and foundational reference model can enhance and facilitate communication of the essence of each application domain. Extensibility is a fourth and exceptionally strong reason for adopting object oriented model. Object classes can be extended easily and independently without the need to modify interactions among class objects, because of the encapsulated nature of class data and behavior. Similarly, small models (modules) can be extended, modified, and integrated by other researchers more easily than in a traditional modeling approach.

Importantly for the present context, models can be developed incrementally. All problem domain modules need not be fully specified to productively develop subdomain modules. Teams of researchers can begin to collaborate much more effectively. A model of a production system, for example, might use a naive representation of households until another individual, with expertise in household consumption or residential choice behavior, develops a more comprehensive and realistic household module.

Finally, alternative behavioral propositions can be represented in class specifications. Suppose, for example, that a researcher wanted to isolate the environmental impacts on a system of introducing two alternative power-generating technologies. She could then design one class representing each technology, run the model simulation once with the original technology class representation, and once with each of the alternative technologies and compare the outcomes. This simulation approach parallels the "plug and play" design characteristics of modern personal computers, where parts with slightly different functionality (e.g., different sound cards) can be interchanged freely. Because they have the same system interface features, the inner workings can differ in important ways yet still compatible with the overall system.

3.1 The Case for Objects

Model integration strategies have been less successful than it could have been, partly due to the failure of modelers to recognize the advantages of object-based modeling paradigms and more recently available supporting modeling platforms. These combined with technologies that support collaborative innovation networks and knowledge building enterprises now hold great promise for integrative, cumulative science.

Whereas most attempts at model integration link modules through aggregate and summary variables, module integration can be facilitated by *the explicit recognition of individual object integration* as a mechanism for linking modeling subdomains. As a simple example, consider that laborers who earn wages and salaries are the same individuals who shop, who commute, who migrate, who choose residences that consume electricity and water, who have children, etc. The cars they purchase are the ones they use in their journeys to work, and are the same ones that pollute the atmosphere. Laborers, therefore, constitute one logical class of objects in models of any of these activities. Thus, when modeling two of these problem subdomains together, maintaining the identity of individual laborers (among other objects) can provide the useful linkage mechanism for more effective integration – yet with the exception of the related class of agent-based models, which usually take on a very focused character, few models explicitly incorporating object identity have been developed.

A common modeling language can also promote cumulative and integrated model building. Mathematical formalization plays this role with some success, but mathematics is a low-level formalization, in the same sense that assembly language is a lower level programming language than FORTRAN or Matlab©. Commonalities among subdomains, as a consequence, are not always readily apparent from their formal mathematical representations. Quite often, even subtle differences in modeling notation can be a barrier to effective cross-domain fertilization and integration. In the absence of a common modeling language, specialists in one subdomain often find it difficult to grasp quickly the essentials of a model in another.

The most frequently used objects of mainstream economic models are deterministic and stochastic equations, endogenous and exogenous variables, recursive and simultaneous blocks of equation systems, etc. In stark contrast, the object oriented economic model is comprised of objects like households, firms, industries, markets, etc. which represent the entities of the economy more directly. The object oriented model can be designed not to approximate objects along a continuum fromagent based modeling (ABM) to aggregates. Financial sectors or industries, for example, could either be modeled as aggregates or as individual banks or establishments. This is not to diminish the importance of the ABM approach, but rather to emphasize the opportunities of the object oriented approach for both micro level and macro level modeling. In terms of object oriented programming, a class can represent anything from a typical agent to an entire system of regional interindustry linkages.

Fortunately, human and physical systems modelers can benefit from the experience of software engineers who have had to model increasingly complex computer-related systems that would quickly overwhelm any individual programmer. Computer and information sciences have made great strides in developing common workplaces and computer languages with effective diagrammatic toolkits that support a variety of conceptual representations, including those that are founded on object identity. Most graphical user interfaces, e.g., are built with windows, panels, dialog boxes, text fields, drop-down lists and the like, which are modeled as objects with specified attributes and event-driven behaviors, and that send and receive signals to and from other objects and algorithms. As a result of their efforts, computer modeling of complex systems via collaboration and teamwork is now commonplace.

3.2 Object-Oriented Modeling Fundamentals[1]

Object orientation is a systematic approach to modeling that can improve our conceptual understanding of social science problem domains. The modeling constructs that comprise object oriented modeling coupled with an intuitive graphical notation provide an expressive set of conceptual descriptors that can be used to enhance the clarity of our models. Object oriented modeling shares much in common with a number of other approaches, such as Entity-Relationship (ER) modeling, agent-based modeling and simulation, and micro-simulation generally. In our view, the advantages of object oriented modeling, *per se*, include its precise and easily understood terminology, its orthogonal object, functional, and dynamic conceptual frames, graphical tools for depicting objects and associations, and its parallels with programming language terminology and functionalities. Below, we review the fundamentals of object oriented modeling, beginning with a more formal definition of objects.

Objects are the fundamental entities of the object oriented model. They are abstractions of the essential aspects of a problem domain, and are easily distinguished from one another in form and in function. Objects are of various types, or classes, and are individual instances of the classes to which they belong. They are described by their properties, which consist of attributes and behaviors. An object's attributes are its quantifiable characteristics that can take on data values. Its behaviors capture its functionality, and include the operations it can perform and the services it can provide, including self-contained operations and signals it can send and receive. Conducting a residential search, e.g., is a part of a household's functionality and is therefore one of several of household object behaviors. Other behaviors can be much simpler, such as setting or reporting the value of an attribute to another object in response to an event. Figure 2 illustrates an object diagram for a simplified integrated model.

Identity, classification, inheritance, aggregation, polymorphism, and encapsulation define the essence of an object oriented model. Identity is established when an object is created (instantiated). Without identity, objects,

[1]Parts of section draw heavily on Jackson (1994) and Jackson (1995). Seminal contributions and more complete descriptions can be found, inter alia, in Booch (1994), Rumbaugh et al. (1991), Coad and Yourdon (1991b), Coad and Yourdon (1991a), and Jackson (1995)

classification, and encapsulation lack meaning. With identity, they can come into or go out of existence. Business establishments start up and shut down, can adopt and adapt managerial schemes, and can adopt new and abandon old technologies; individuals are born and die, and can change residences; and government policies can be implemented, modified, and retracted, all while maintaining their respective identities throughout their lifetimes. Because of object identity, all objects, as members, or instances of classes, are distinct even if all of their attribute values and behaviors are identical. An object can change its attribute values, but still be identified as the same object.

Classification is an abstraction mechanism fundamental to human understanding. In object oriented modeling, objects with identical properties belong to classes. A class is an invariant description of object structure. All establishment objects, for example, have "number of employees" as an attribute. The value of this attribute will differ from object instance to object instance, but all establishment objects will have this and other attributes in common. The classification exercise promotes a focus on the essential, inherent aspects of the problem domain and its elements, and provides a structured context within which the modeling abstractions can be placed and ordered.

Inheritance refers to the class – subclass relationship. A sub class inherits the properties of, and is distinguished from its super-class by new and distinctive properties. The inheritance mechanism is used to implement the is a (or is a kind of) relationship, and serves to reduce repetition and complexity in model-building. Subclasses at a lower level in a class hierarchy are derived from their antecedents, or superclasses. Inheritance allows different classes to share fundamental structure, which enhances the conceptual clarity of a model by reducing the number of distinct cases to be understood and analyzed. Inheritance also promotes model *extensibility*. Given a particular class hierarchy, extending it to model similar objects that have additional essential attributes or behaviors – such as additional exchanges with the environment as new knowledge becomes available – is straightforward.

An easy to understand example of inheritance can be found in Járosi and Jackson's (2015) proof of concept technical document. They defined a household superclass (parent object) to have a the Cobb-Douglas utility function, and the Stone-Geary type household was derived from it as a subclass (child object). The child/parent analogy is apt, as children and subclasses inherit the attributes and behaviors of their parents and superclasses, respectively. But like children, subclass properties may be redefined and overwritten, and other properties (attributes and behaviors) can be added.

Objects are related through a variety of associations. Aggregation is a special type of association for which objects of a given class are all part of a composite object. Actions taken on the composite can be automatically taken on the component parts. As an example, where no information is available, an industry might be modeled as an aggregate, but where data are available and intra-industry variation is important, individual establishment objects might comprise an industry aggregate. When the industry receives a signal to satisfy accumulated demand, its establishments receive the signal to provide their contributions to the industry response. Whereas generalization and inheritance describe the relationships among an object's associated classes and super-classes, aggregation relates objects of two distinct classes, one of which is a part of the other.

With polymorphism a) an operation of the same name can behave differently on objects of different classes, and b) an identically named attribute of two classes may be represented by different data structures. Operations of different classes can share the same semantics, but be implemented in a fashion appropriate to each. *Multiplication*, for example, is an operation whose semantic meaning is clear, but whose *implementation* differs with the nature of the operands. We can apply polymorphism to such concepts as industrial plant vs. human aging, service vs. manufacturing *production*, and wetland vs. cropland conversion. As a more concrete example, in the traditional equation system-based CGE models, it tends to be difficult to replace a constant returns to scale Cobb-Douglas production function by an increasing returns to scale production function, or even a CES type production function. A small change, even in a single equation, can cause many unexpected and unintended consequences for the whole equation system. This happens because traditional modeling effectively forces researchers to "think in equations" rather than in terms of objects and behaviors. The one-two punch of encapsulation and polymorphism combines to underscore the advantages of the object-oriented approach.

Encapsulation refers to the process of hiding the internal details of object properties and behavioral implementations from view, and binding (or coupling) attributes and behaviors more tightly. Encapsulation reduces unnecessary interdependencies among objects in a problem domain, and localizes any changes to the system. Through encapsulation, objects become virtually self-contained entities. They can be used confidently in one or many modules (and ultimately, models) in which they play an essential role. As long as the interface for an object is not diminished, it can be used, re-used, modified and extended (by, e.g., adding additional object behaviors), without fear of altering either the data values of other objects or the ability of other objects to access object data or trigger object behavior. Should a household object from a production model be integrated with a housing stock model, for example, it would be appropriate to add to it attributes such as square footage, but without altering other roles played by the household object in integrated problem domains. Likewise, should an industry switch technologies, only properties within that object need be altered.

Class and inheritance relationships are consistent with the way in which humans organize information to understand better the world around them. Object identity provides a mechanism for linking different subdomains to capture interdependencies that surpass our ability to express analytically. Encapsulation ensures the integrity of data and behavior of objects, modules, and models, and protects against unintended consequences that are more likely to occur in classical structural programming approaches. Object models and associated class hierarchies are extensible. Encapsulation and extensibility should facilitate the cumulative science enterprise.

4 Object Oriented OS^2 in Action

OS^2 Among others, systems models are ideal candidates for the object oriented open source development mode. Typical systems models are comprised of multiple subsystems, and the subsystems themselves may in turn be comprised of additional subsystems. The subsystems comprising the next level system may be additive collections or may themselves be interacting. Figure 3 conveys this idea graphically, where the larger system represented by the gray circle is comprised of three relatively independent subsystems, and three heavily interacting subsystems. Three of these first level subsystems are further comprised of second level subsystems, and three of these have fourth level subsystems. Each of these systems might correspond to identifiable problem domains, and the larger system might span multiple disciplines.

As we progress further in the knowledge building enterprise, each of these subsystems might well represent a problem domain that would encompass the entire knowledge base of a domain specialist. Likewise, a specialist in a system at any of these levels might well be required to make substantive improvements to a model of that system. The value of subsystem changes and their impact on the model of the whole system, however, can sometimes only be fully known in the context of the larger and more comprehensive system model. Historically, modelers who wished to work on subsystems of larger comprehensive systems would be faced with a choice. The first option would be to become familiar enough with the encompassing system to develop a model that could be used as a kind of "backbone" that would provide at least a skeletal representation of the salient behavior of the system. They would then demonstrate the model behavior with and without their system modifications to gain an understanding of the partial effect of introducing their subsystem behavioral changes. The second option is to identify a backbone model that is already in use and attempt to first gain access to it from the model's owners, and if they are able to access such a model, attempt to integrate their subsystem with its behavioral modeling improvements into the borrowed modeling framework.

The first option has the disadvantage of requiring individual subsystem experts to devote their time, energy, and intellectual capital to activities that lie outside of their primary fields of expertise. If there are multiple scientists working to enhance understand of the same problem domain, this mode of operation clearly results in duplication of effort, since each of them is working outside their areas of expertise on developing a backbone, when if there were one available for common use, none of them would need to redirect their efforts, and the time saved could instead be focused on researchers' own focus areas. Perhaps less obvious is that if multiple experts develop subsystem modeling alternatives *along with* their own backbone models, then the difference in overall system behaviors will be a function not only of differences in subsystems, but also of the system backbones they have developed. This renders comparisons among subsystem models difficult if not impossible, and further, it makes it unlikely or impossible for other modelers to replicate.

The second option has particular disadvantages first in contexts where it is difficult to gain access to backbone models to use in their experiments, either because such models have been developed only in proprietary environments (either commercial or public laboratories where intellectual property is closely guarded), or because such models are so involved that thousands of lines of code support the system models and transferring the models is difficult due to place or modeler dependency. The second option's second largest disadvantage becomes apparent when the subsystem domain specialist is faced with the often-daunting task of identifying mechanisms for integrating the new subsystem behavior within the larger modeling framework, and doing so without unintended consequences that often result when models are not developed with the kinds of modularity that supports modeling extensions and enhancements. Replicability in this operational mode is also difficult if not impossible.

Operating in object oriented OS^2 mode addresses all of these traditional research mode disadvantages. Scientists who are expert in the higher levels of the system model can focus on developing the backbone. The wisdom of the crowd ensures that the salient features of the backbone are present and that new approaches to enhancing the backbone are those that have endured and survived the scrutiny of numerous others with similar expertise. The backbone itself can accommodate competing perceptions of appropriate means of representing systems, using an interface that can provide users with a menu of customizable features (e.g., endogenous vs. exogenous government sectors, various model closure assumptions, etc.). The customization of such options can be documented in a metadata configuration file, which enables replicability and simplifies comparison of outcomes from competing models, or models with differing subsystem modules. Because of the encapsulation and modularity of object orientation, modules with differing behavior can be substituted easily for one another, which facilitates model comparisons.

In the remainder of this section, we lay out our vision of a regional science model that could serve as an exemplar for the object oriented OS^2. We begin with our problem-specific motivation, a description of the general class of models to which the exemplar belongs, a description of our approach to model development and implementation, and comparisons to other modeling approaches.

4.1 Technology, Economy, and Environment: The Motivation

Environmental and socioeconomic consequences of technology and technological transitions are becoming the dominant discussion in scientific and policy arenas. Deepening our understanding of human and physical systems and the complexities of their interactions has been a goal at the federal level since the formation of the Committee on Human Dimensions of Global Change in 1989 by the National Research Council and other supporting agencies, and a great many related federal agency programs and initiatives have emerged in the subsequent decades. Examples include the U.S. Department of Agriculture National Institute of Food and Agriculture program that targets improved economic, environmental, and social conditions, and NSF programs such as the Science, Engineering, and Education for Sustainability (NSF-SEES) aimed at informing "the societal actions needed for environmental and economic sustainability and human well-being", and the Environment, Society, and the Economy initiative (NSF-ESE) to "encourage productive interdisciplinary collaborations between the geosciences and the social, behavioral, and economic sciences." Likewise, the recent Congressional Research Service report (Carter, 2013) on the Water-Energy Nexus highlights the interdependencies among energy and water systems that calls for a more integrated approach to addressing the challenges of confronting related issues that impact human welfare so forcefully.

Instead of comprehensive systems integration research, however, all too often the best we see are models that achieve some level of integration but that are developed and used only for specific problems and problem domains without the benefits of reuse and extension that would lead to *cumulative science and effective knowledge building.* Far too many scientific explorations begin with modelers reestablishing their own variations of modeling foundations that others already have formulated, on which their own conceptual and theoretical extensions and advances will be built. The result is a scientific milieu in which the commonalities among models that result from individual research efforts are low, and model comparability and interoperability become excruciatingly difficult or simply impossible. What should be a steady march in a community-wide *cumulative knowledge building enterprise* instead becomes an atomistic process where countless hours and substantial resources are wasted in foundation-building activities that duplicate the efforts of others. As a consequence, advances in knowledge accumulate much more slowly than they otherwise could and should.

Because increasing specialization is now more common than expanding breadth of knowledge across domains, it is unlikely that individual researchers will be able to achieve these science integration goals on their own, so changing the current *modus operandi* is likely only by shifting to a more cooperative and collaborative knowledge-building environment that forms a scientific milieu in which researchers build on, incorporate, and benefit mutually from others' expertise through participation in a collaborative innovation network. Our vision of the future centers around OS^2 knowledge-building enterprises, with object oriented as the foundation for organizing and managing the development of modeling applications in a range of problem domains. In this section, we describe the OASIS model (Object-oriented Analysis and Simulation of Industrial Systems), which will be the first foray into this kind of development in the economic and environmental systems modeling context. We envision a team of researchers working toward a *community-wide knowledge building enterprise by developing the underlying OS^2 modeling framework that will provide a common modeling foundation for future integrated systems research.*

There is an increasing recognition that for research in most problem domains, subnational regions are the appropriate geographical units of analysis. This is true for economic systems as reflected by the regionally focused programs of the U.S. Economic Development Administration (`http://eda.gov/oie/ris/`), and clearly also true for environmental, resource, and water issues, as reflected in the CRS report on the energy-water nexus referenced above. Of course, processes at the regional level often feed back and comprise their national counterparts, just as regional economies comprise their aggregate national counterparts, as in Figure 4 Environmental systems and processes may operate locally, but not in isolation from the global. Energy, environment, and even health policy models are often developed without the benefits of integration with easily accessible and reproducible economic models, while those who do recognize the need to link other systems to regional and national economy very often resort to prebuilt, proprietary and commercial sources. For these reasons, regions will play a prominent role in OASIS.

OASIS will model the U.S. and its regions, providing current and forecast input in the form of macroeconomic, household, and industry-level trends and constraints that establish the context for national economic systems models, nationally driven regional models, and integrating mechanisms for interregional and regional-to-national integration and feedbacks. The modeling platform will be open source and evolutionary, systematically embedding behaviors and characteristics of the foundational system model that are deemed by the broader research community to be essential and stable, and weeding out those behaviors and characteristics that can be replaced by more effective and realistic representations. Its implementation will enable individual researchers to select from among system features that have yet to earn consensus approval. This modeling paradigm will also allow for the selection from competing (alternative) behavioral modules — those that represent alternative characterizations of system behaviors. Indeed, an eventual suite of alternative modeling variations that have explicitly identifiable commonalities and differences will promote direct comparisons and contrasts of competing representations of reality.

A class of models described as space-time economics models will be the foundation for the OASIS model. STE models can be calibrated and parameterized to represent the existing structure of an economy, and to forecast, incorporate, and respond to changes in that structure. In the process, temporal changes in prices, interest rates, wage rates, output, employment, income and the like are determined, carrying clear implications for socioeconomic impacts across different groups in the economy. Terry Barker, who helped found Cambridge Econometrics – a group that has used STE's in wide ranging policy analysis contexts, provides an excellent discussion paper accentuating the strengths of the STE framework in the context of modeling the transition to sustainability (Barker, 2004). Unlike the existing models that have been developed in conventional fashion and programmed using the structural modeling paradigm, OASIS will be redesigned and re-engineered from scratch as an object oriented model. Its initial character will be influenced by existing models, but its implementation and eventual form will reflect not only the adaptability and flexibility of object orientation, but also the benefit of conceptual refinements of the project team and ultimately the broader research community.

Essential elements of the early OASIS model will be similar to many of the most common dynamic hybrid macroeconomic inter-industry models that have been developed and reported in the literature.[2] While STE model implementations differ, a general fundamental structure of these models is shown in Figure 5. These models most commonly include econometrically specified forecasts of key economy-wide variables such as interest rates, unemployment rates, final demand activities, and population. Some regional models rely on exogenous national forecasts, while others generate national forecasts endogenously. Coupled, linked, or fully integrated with these economic drivers are relationships within and among the industrial system, which ties the economy-wide forecasts to industrial activity, and to households and household consumption activities through payments to labor. Payments to governments by industry and returns to capital are also tracked by industry, and labor and non-labor income can feed back to savings, investment, and additional consumption behavior. Models developed for different purposes have focused on one or another specific aspect of system behavior, so while there is much in common across these models, there also are substantial differences. This allows for results that shed light differentially into different system behaviors, but it also results in great difficulty in comparing the outcomes of models with different fundamental structures. The OASIS backbone we envision will facilitate the isolation of impacts of specific model behaviors by providing a common foundation on which each of these behavioral extensions will be built.

Because of their position at the nexus of economy and environment, technologies will be represented explicitly as a primary class, providing a mechanism for linking economy to both economic and environmental systems. Technology plays a critical and potentially unifying role in virtually all of the most critical issues that give rise to the need for integrated systems

[2]Others who have developed and used STE type models include Dick Conway, who has used these models productively for decades in Washington State, Hawaii, and elsewhere; Geoffrey Hewings with models of Chicago, St. Louis, and the U.S. Midwest states region; Randall Jackson with models of Ohio and the US, José Manuel Rueda-Cantuche and Kurt Kratena for the EU-27, Sergio Rey for various California regions, Clopper Almon, Douglas Meade and others at the University of Maryland with the INFORUM model of the U.S. and many other countries, and Guy West, who has applied inter-industry econometric models to policy issues in Australia and its regions (for a small selection of related literature, see Conway, 1990; Donaghy et al., 2007; Kim et al., 2015; Israilevich et al., 1996, 1997; Kratena et al., 2013; Rey, 1997, 1998, 2000; Rey and Jackson, 1999; West, 1991; West and Jackson, 1998, 2014).

modeling. Human-environmental exchange takes place primarily through the operation of various technologies, be they transportation, agriculture, manufacturing, consumption, or power generation, and many of the most important such exchanges reside in the technologies used by industries in economic systems. Industrial processes use inputs from one another and from the environment, and their production activities alter air, water, and land characteristics. Hence, models that promise to integrate human and physical systems virtually all rely on mechanisms that provide meaningful representations of the economy, industry, technology, and environmental relationships. Technology is central, as it links directly to both economic and environmental systems.

Early OASIS subsystem enhancements will focus on industry and household objects. Industries are key to the modeling system because they dominate uses of the technologies that can be tied to both social and physical systems. Households are also key to system integration because of their critical role in driving economic activity via expressed demands, because they are the central providers of labor and are explicitly linked to industrial activity, and because differential demographic characteristics of households are dynamic and have been shown to have highly significant impact on consumption, housing, health, and environment (see e.g., Kim et al., 2015). Developing alternative classes of households and industries will enable early demonstrations of the object oriented modeling approach, and ways in which it speeds the knowledge building process.

The advantages of the object oriented framework will become clear immediately. The OASIS model (Object-oriented Analysis and Simulation of Industrial Systems) will have commodity supply- and demand-pool market objects that act as clearinghouses for commodities produced and demanded by industry and other economic entities. Indicative of the increased adaptability and extensibility of the object oriented approach, consider the necessary actions to be taken when, as a simple example, a new industry is established in a region a region. In structurally programmed ECIO models, each industry's intermediate demand equation includes a term for demand from each and every other industry. Hence, if a traditional economic model has an industrial classification scheme with 200 industries, adding one new industry necessitates determining and making corresponding changes to the existing 200 equations and adding the 201st equation — just for the output module. Employment, income, and potentially other equations would have to be adjusted similarly. In the OASIS model, adding an industry will simply require defining it as a class or subclass if its behaviors are different from existing industry classes, creating an instance of the new industry, specifying its commodity and factor requirements and its output structure, then including it in the aggregation of industries that comprise the market, which receives signals from the econometric demand equations to meet demand requirements. Note also that the initial linear production functions derived from standard input-output accounts can be replaced straightforwardly by more sophisticated production functions, e.g., allowing for economies of scale, input and factor substitution, and each industry can have its own unique production functional form if and as desired.[3]

A second example advantage derives from flexibility in terms introducing exchanges among industries and the environment. Water, resources, and emissions accounting can be added to or modified within the system on an industry by industry basis as new and improved become available. As in other systems modeling frameworks (commonly commercially based), environmental stores for accounting can be added simply to the OASIS model, simply by creating those objects and modifying globally the respective industry class properties and object attributes. Additional system participants, such as environmental remediation processes, can be introduced as new classes and objects, with interfaces to environmental stores (as one approach). These simple examples demonstrate in rather dramatic fashion the advantages of encapsulation in object oriented modeling frameworks.

4.2 STE Feasibility and Data Requirements

As a proof of concept exercise, we recently designed and implemented a Computable General Equilibrium (CGE) model of a small (3-sector) economy based on a hypothetical social accounting matrix (SAM). The model we developed recasts the conceptual basis of the SAM to model industries and households as objects, and the industrial system as an aggregation of industries. See Járosi and Jackson (2015) for the example solution and accompanying computer code.

[3] A step further would allow for an industry to be comprised of collections of establishment level agents with more or less autonomous behaviors.

STE models are calibrated using a fairly extensive and wide-range base of supporting data. All of the data required for early versions of the OASIS model, however, are publicly available. Nearly all of the data are secondary data published by U.S. government agencies, and there is a variety of sources that make these data series available electronically. In addition to government agency websites, other groups compile and provide access to these data. Much of the data for an existing WVU hybrid econometric interindustry model, for example, are compiled and made available as a resource accompanying the freely and publicly available Fair econometric model. Likewise, the Inforum group at the University of Maryland, among others, provides metadata pointing to data of various kinds on their website.

4.3 Object Orientation *vs.* Other Modeling Approaches

Adopting the object oriented approach in no way supplants established theory. On the contrary, object oriented modeling provides a consistent framework within which established theory can be placed. Even in cases where no simulation model might ever be implemented, the conceptual process of placing existing models within a single integrated framework 1) forces the exploration of relationships among problem domains that currently are unspecified, 2) potentially identifies inconsistencies among models, and 3) identifies directions for profitably extending existing model specifications.

4.3.1 Early Systems Microsimulation Modeling

Although there is a natural similarity between the Object oriented approach outlined and the microsimulation approaches of the early and mid-1960's, Object oriented modeling has much greater potential for success, and for many reasons. First, neither the hardware capacity or the software tools were available then to model social science simulation aggressively. Today, there are graphical tools for designing software that not only assist us at the stage of conceptual design, but some can even automatically generate skeletal code in selected computer programming languages. Object oriented programming languages now allow the simple expression of constructs that once required intensive and meticulous project oversight and programming efforts. An

Object oriented conceptual model is a very short step from programming language code.

4.3.2 Modern MicroSimulation

There also is a separate body of literature founded on microsimulation simulation methods. Caldwell (1983), Clarke and Wilson (1986), Clarke and Holm (1987), and Amrhein and MacKinnon (1988), for example, have used microsimulation approaches in urban and regional labor market and planning models, while Birkin and Clarke (2011) provide an overview and prospective of spatial microsimulation methods and applications. While the experiences and results of microsimulation efforts can help to identify critical model formulation and evaluation issues, the microsimulation and object-orientation are fundamentally different conceptually and operationally.

4.3.3 Agent-based Modeling (ABM)

Agents in ABM share a conceptual heritage with objects in object oriented models. Although there are some strong commonalities, agents are generally autonomous entities that often require no external control mechanisms to initiate or govern their behaviors. Odell (2002, p 42) explains that among their fundamental distinguishing attributes, agents are capable of watching "out for their own set of internal responsibilities," and "when and how an agent acts is determined by the agent." In contrast, he continues, "objects are considered passive because their methods are invoked only when some external entity sends them a message." Control in an object oriented model is thus more centralized, which makes representation of a system of interrelated systems a much more tractable problem. Ultimately, of course, agents can comprise and or contain objects, and certain object behaviors might eventually take on characteristics of agents in ABM. There are other differences in terms of scope and computational requirements that lead us to object orientation as the preferred higher-level organizing structure for OASIS.

4.3.4 Computable general equilibrium (CGE) Modeling

CGE modeling is a well-established framework for impacts assessment research. It is founded squarely on neoclassical economics and produces outcomes from economic and policy shocks that correspond to values from restored equilibria in product, factor, and capital markets, optimizing with respect to firm and household behaviors. What distinguishes object oriented models from CGE models is the focus on individual objects rather than aggregates. Object oriented modeling allows us to specify as many different classes of elements in multiple systems as deemed appropriate, and to track the behavior and status of individual elements within these classes – including, e.g., how household structures change and how the size-composition of industries evolves. Although Barker (2004) and Scrieciu (2007) have cautioned against the use of CGE as a single integrated framework for sustainability impact assessment, behaviors similar to classical CGE models including household utility maximization and firm profit maximization or minimization could be incorporated in future versions of OASIS by modifying class behaviors. However, mechanisms available for linking a CGE model to transportation networks, land uses, and physical systems are much more limited, constrained, and opaque than they will be in the OASIS model. The focus on object identity provides options for specific mechanisms for subsystem model linkage and extensions. CGE modeling requires a relatively high level of economics training and computer programming skills to be used effectively, which could in turn limit the size of the innovation network were CGE models to form the basis of an OASIS-like effort. Nevertheless, parallel object oriented OS^2 CGE modeling could be pursued by researchers so inclined.

4.3.5 Inforum InterDyme

Of all of the STE models we have identified, the Inforum InterDyme system may be conceptually the closest to the modeling strategy proposed here. The INFORUM group has been among the most continually active and innovative in the U.S. Its InterDyme software is a package of programs for building interindustry dynamic macroeconomic models, developed by INFORUM and written in C++. Online documentation (`http://www.inforum.umd.edu/papers/inforum/software/dyme.pdf`) and personal correspondence with Inforum personnel suggest that the object-based character of the model is primarily applied to algorithmic aspects like matrix, vector, equation, and time series objects, so the object oriented conceptualizations in Inforum are fundamentally different from those of the proposed OASIS model. The Inforum models are viable econometric interindustry modeling options for certain analysts with strong and diverse programming and modeling skills, but our vision for OASIS is that it will be a platform that is much more accessible to and user-friendly for analysts with a wide range backgrounds and competencies.

4.4 Synergies and Flexibility

The long-run vision for OASIS is that of a flexible modeling foundation that will present analysts with a range of modeling options. We envision a graphical user interface for stable model versions that will present modeling default and alternative options to users in menu-like fashion. Industrial production function alternatives, household behavior options, model closure rules, and other modeling choices consistent with researchers' individual conceptual frameworks will be selectable, and model metadata describing in detail the model characteristics and assumptions will be generated with each model simulation run. Depending on the user selections, the model implemented might be closely aligned with CGE-type optimization models and features, or one with more linear input-output like behaviors, or a hybrid model wherein better known object behaviors are modeled with more sophistication and less well-understood objects' behaviors are modeled more simply. Irrespective of model configuration, simulation and impacts forecasting research will be replicable, and will form the basis for direct comparison of alternative futures with differences directly attributable to explicitly identifiable model differences.

5 Challenges and Opportunities

Shifting from a traditional to a new knowledge building paradigm will not be without its challenges. The first challenge will be the effective communication of the benefits to science of the new paradigm. It will be necessary to develop a critical mass of researchers who are willing to invest their time and effort into building the initial modeling infrastructures — the system backbones — for various problem domains. The transition will begin with the development of backbones for easily identifiable suitable systems of systems like the OASIS model. Models like these will be vitally important as platforms for demonstrating the advantages of working in the new way, which will include ease of model extension and use and speed of scientific advancement.

A second challenge will be overcoming the barriers erected by those feel that they have a vested interest in the older individualistic and proprietary paradigm. Those with commercialized models may at first feel threatened by encroachment of "free" alternatives. Paradoxically, however, we have already been witness to a large set of example developments, mostly related to software applications, where the open source community has developed applications under licenses that enable the unrestricted use, extension, and distribution of the open source code library. Many companies provide licensed and supported versions of software that originally developed — and in many cases continues to develop — in open source communities. As just one example, RedHat® is a highly successful commercial distributor of the Linux operating system, which continues to be developed and available as a free and open source operating system.

A third challenge will be arguments that stem from what we refer to as modeling religions. Within regional science and economic impacts modeling domain, for example, there are those who belong to the CGE church, those that belong to the STE church, those that belong to the church of input-output and social accounting, the church of cost-benefit analysis, and so on. There will be cases where some of these might co-exist as alternative options within the same system of systems modeling project, but there will also be as much room as individuals choose to make and use for developing multiple projects. Ideally, there also will be subsystems that can be integrated with more than one project. With the adoption of a consistent object oriented approach designed with the appropriate level of encapsulation and consistently defined object interfaces, domain experts can develop subsystems as modules for adoption and use in any cognate project. Class libraries grouped by problem domain will develop to support any modeler's or group's application development goals.

The last challenge we address here reflects implications for the publications process, which is a foundation for merit determinations in several environments, and certainly for promotion and tenure decisions in academia. Here it will be possible to associate the progenitor of new object oriented classes to be identified as such in the metadata that accompanies object oriented libraries. Domain experts also will be able to publish analytical results that compare outcomes of baseline simulations to those that incorporate their new model behaviors. Further, they will be able to devote much more time to the areas of their expertise because they will be freed from having to develop their own super-system backbones to focus more directly on their own problem domains. The results they publish will be replicable and immediately open to evaluation — and hence, validation — by the larger user community. And once open to the user community, they will also be immediately available as the basis for further development, refinement, and enhancement.

6 Summary

The future of regional science research, and indeed the majority of integrated human and physical research will be one of networked individuals contributing to problem domains in which they share common interests, and advancing more specific knowledge in which their particular expertise lies. We believe that this future will take the form of an object oriented OS^2 modeling paradigm that will accelerate the knowledge-building enterprise and deepen our understanding of the complex interactions among human and physical systems. It will begin in regional science with the development of OASIS, an Object-oriented Analysis and Simulation of Industrial Systems model, that will form a common foundation for experimentation and extensions that will form sequentially more comprehensive and reproducible models of integrated systems. OASIS will be the first fully object oriented open science simulation model of a complex, national and regional economic system. It will provide a common workplace for an open science enterprise dedicated to accelerating our understanding of the complexities of integrated systems across spatial scales and physical and human processes, and it will launch integrated systems science into the future by demonstrating the multifarious advantages that object oriented OS^2 has to offer.

While the structure and operation of the OASIS model will be shaped most directly by the initial OASIS development team, it will over time more strongly embody the best of the conceptual developments of the participating open source, innovation network community. Oasis will eliminate the need for researchers to duplicate efforts required to set up bases for integrated systems simulations, allowing scarce research resources to be directed instead to advances in knowledge and understanding. It will facilitate replication and comparative analysis, and will clarify and make explanations for alternative futures from different simulations more transparent.

OASIS will be an inclusive environment, open to participation by users and developers from all groups without reference to age, creed, or color, and will therefore include and serve underrepresented populations. It has the potential to contribute to deeper understanding and to inform policy across a wide array of problem human and physical problem domains, and because these domains can be integrated, it may potentially to do so in ways that identify unanticipated ecological impacts of changes in one system on others previously assumed to be largely independent.

OASIS will provide a common foundation for extensions to research across numerous problem domains and will allow valuable resources otherwise devoted to recreating and reinventing such foundations to be used much more effectively. It will significantly enhance the ability of regional modelers to generate reproducible research. It will enhance infrastructure for research and education, and it will accelerate knowledge creation, in turn increasing economic competitiveness. It will support policy analysis by providing comprehensive integrated models that are fully open and well documented, and that reflect the state of the science.

OASIS will establish a modeling support infrastructure to accelerate scientific advancement in integrative systems modeling research, enhancing the productivity of individual researchers and building a cumulative body of knowledge more rapidly than is possible under more fragmented approaches in use today. It will lay a comprehensive foundation for a more rapid knowledge development milieu, and it will demonstrate object oriented OS^2 use and value using a regional economic model of selected technology transition as an example.

OASIS will advance scientific knowledge in several ways. It will be the first integrated systems model of its kind in its foundational object-orientation, its extensibility to other problem domains, its replicability and reproducibility through version control and model provenance development, and as a transparent and well documented public resource. As a project, it will combine advances in computer-based conceptual modeling with state-of-the-art modeling in socio-economic sciences. In this and its open-science approach, the Oasis project and the paradigm it represents will radically transform the way regional modeling and integrative science are conducted, enhancing the pace of new knowledge and application in many areas of social, behavioral, and even physical sciences.

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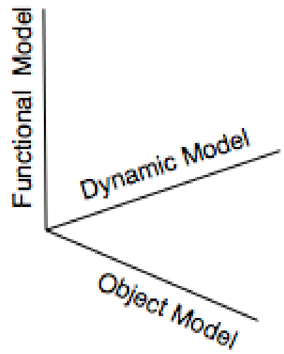

Figure 1: An Object Oriented Model's Orthogonal Views

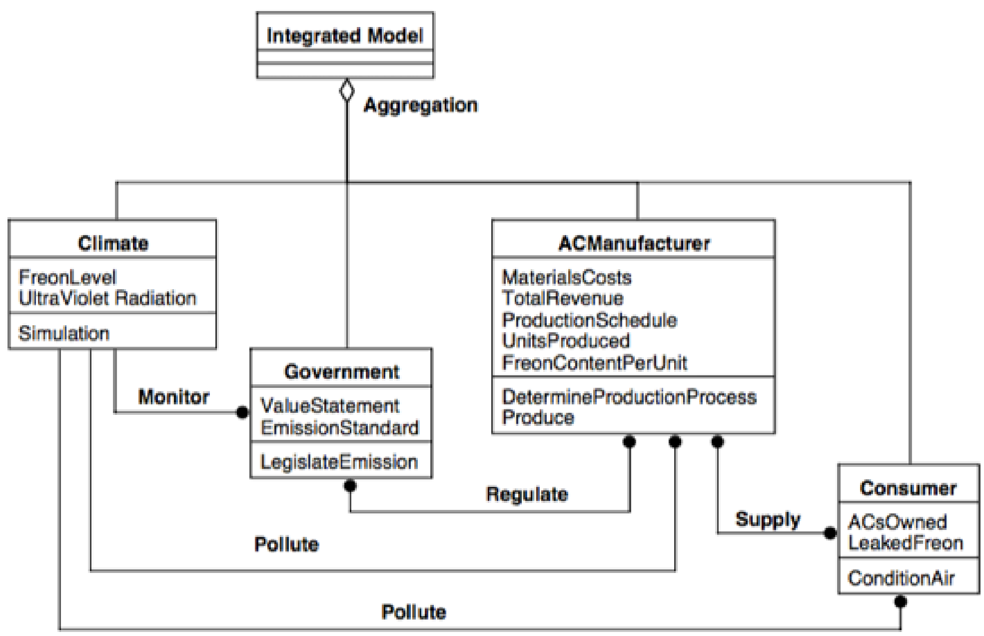

Figure 2: Integrated Model Object Diagram. Source: Jackson (1994)

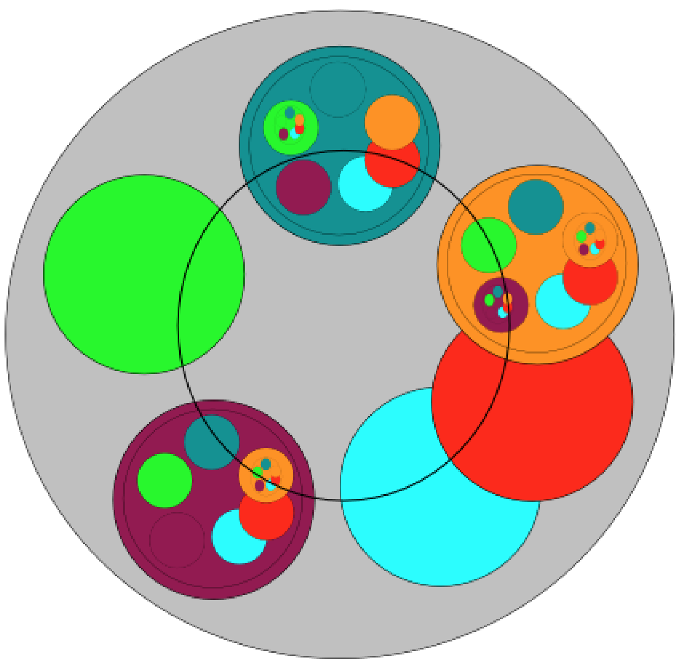

Figure 3: Models as Systems of Systems.

Figure 4: Interlocking Hierarchical Systems.

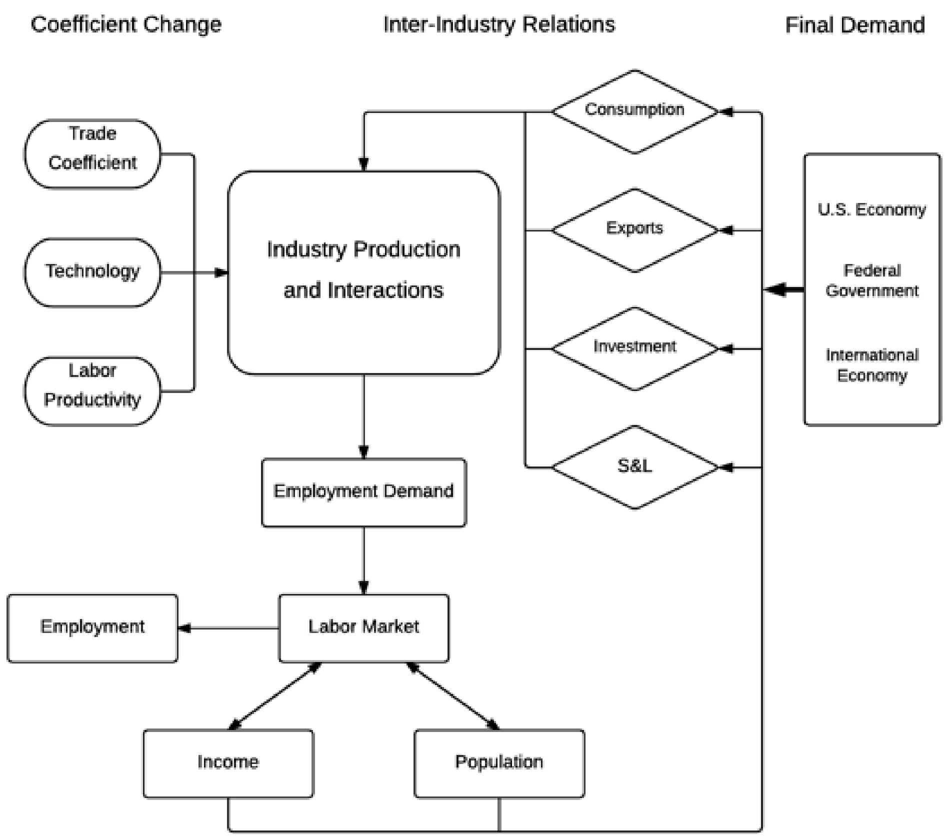

Figure 5: Fundamental Structure of STE Models. Source: Jackson (1994)