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MODELING AS THE PRACTICE OF REPRESENTATION

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ABSTRACT

One of the characteristics of being human is *to model*. In our history, we began with representations of animals made from natural materials, and painted on cave walls. We also made regular marks on animal bones. While the modern accounting of these products is art (animal representations) and mathematics (bone marks), a more comprehensive understanding points to modeling in both cases. We saw or imagined things, and then we made models of our experience. One could say to be human is to model. Since the inception of modeling, we created areas of knowledge and have divided things into many groups. These groups have sub-groups to where our knowledge resembles a large house with its artificial partitions. And yet, modeling is still pervasive although it differs slightly in form among these subdivisions that we now refer to as *disciplines*. Since modeling is ubiquitous, it serves as a basis to reframe our activities in the information age. We claim that models are natural transformers from human experience to *information*; to create information for object X, create a model of X. Even simplistic activities such as grabbing a drink from the refrigerator or taking a walk translate into information management and processing, made evident through modeling.

1 DEFINING "MODEL"

We defined modeling (Fishwick 1994, p.2) as "something that we use in lieu of the real thing in order to understand something of that thing," and then referred to Mach's quote about natural law: "The communication of scientific knowledge always involves description, that is, a mimetic reproduction of facts in thought, the object of which is to replace and save the trouble of new experience" (Mach 1894). Mach's indirect reference to modeling, which leads to theories and laws, captures the need to abstract or simplify reality. More recently, Maria (1997) asks "What is Modeling?" and then qualifies modeling as a "tradeoff between realism and simplicity." Sometimes, modeling is linked directly with "simulation" to form modeling and simulation (M&S). Ören (2006) creates a comprehensive account for M&S and its vocabularies. White and Ingalls (2016) define model as "an entity that is used to represent some other entity for some defined purpose." Modeling within the Digital Humanities broadens and deepens how modeling is defined and discussed (McCarty 2004, Ciula and Marras 2016) within science and engineering. This idea of *representation* is common in these definitions, and as we will suggest, lies at the heart of defining "model."

How broad do we make the study of modeling and its definition? We can tie modeling to a specific discipline (e.g., systems biology, manufacturing, health care, operations research, electronics) or we may link it directly with what is done with the model (e.g., analysis, simulation, communication). Similarly, we may restrict our view of modeling to the notations or languages used (e.g. mathematical, System Dynamics) in representation. We also observe that a model can be a *model-of* or a *model-for* with the latter connotation capturing model as prototype for something not yet created. "Model Of" is empirical and "Model For" is prototypical.

We have decided to take a hybrid cultural, historical, and multi-disciplinary approach. The task of modeling, to create models, is as old as our species. Only by adopting this broad brush can we hope to engage about modeling across disciplines from art and humanities to mathematics, science, and engineering. There are advantages behind this line of reasoning:

- We can talk of modeling with numerous colleagues since in most disciplines, modeling is already present as an activity despite differences in vocabulary
- We can interrelate model types to inform each other of developments in model-making
- We can enhance our pedagogy on modeling by choosing a student's diverse background, rather than trying to cram the idea of modeling down a specific delivery pipe

If modeling is a form of representation, and our goal is to cover model-making as a diverse activity spanning disciplines, we need to get a handle on *what modeling isn't*, or at least try to embed modeling within broader disciplines that span the academy. We need to begin with two old types of representing as valid models: writing and drawing. Natural language and pictures were early forms of modeling in our evolution. We should continue to think of these communicative media as models.

2 THE PRACTICE OF REPRESENTATION

Modeling began with regular marks on a medium. The Ishango bone (Pletser and Huylebrouck 1999) is a baboon fibula, and it contains several sets of regularly spaced scratches. Archeologists differ on how to interpret the bone's marks, and therefore it is unclear whether the bone represents a tally stick. The stick could be the earliest representation of number (Ifrah 2000). Numbers are classic, simple models since they abstract away all but the mathematical characteristics of a target. Historically, we regard numbers as preceding natural language at a time when areas like mathematics and language had no meaning.

How fundamental is the task of modeling? In the M&S community, we have our own type of models that we find useful to the task at hand—everything from agent-based models and mathematical models to hybrid models. Models come in all shapes and sizes. We posit that modeling is a critical component of human cognition. Modeling is pre-linguistic, and can be linked to sign formation and semiotics (Fishwick 2007). Queuing networks and Petri nets (Fishwick 1994) are artificial languages since no human culture converses or writes with these structures. Languages like Chinese or English are natural languages, and so we have a division between natural vs. artificial that seems to suggest that most model structures in M&S fall into the category of artificial.

And yet, representing a target process or object in natural language is logical. The most accessible first attempt at representing a line of people waiting in line would be something like "The people waiting in the grocery store line queued up with most of the people facing forward toward the cashier. As the person being served by the cashier exited the front of the line, the next in line stepped forward. The remainder of the line moved forward in a chain reaction beginning with the person just behind the person exiting." To a seasoned modeler, this seems like a lot to put down as a model. But to represent our experience in natural language is fundamental because we are all familiar with this language—assuming we are both literate and fluent.

In the area of dynamic, system modeling, there are at least three points of reference for the idea that we begin with natural language in both characterizing and modeling systems. Since its inception in the 1960s, Forrester developed the methodology of *System Dynamics* (Roberts 1982, Meadows 2008) as an incrementally staged approach to modeling. The beginning of a system description is composed of individual concepts in natural language. Balci et al. (1995) create a similar approach, but by focusing on pictures. A gradual engineering shift is then made from natural language in the earliest phase to ordinary differential equations, the final phase. Checkland and Scholes (1990) promote "rich pictures" and other diagrammatic constructs which encourage drawing and relations in natural language. Robinson et al. (2010) have covered research in conceptual modeling for discrete-event type systems, reflecting the phase of modeling where there are not enough detailed specifications or data. The soft systems model and conceptual model occur after a natural language formulation. We conclude that models often begin with drawing and writing before we transition to more detailed formalisms.

If early formulations of models begin with drawing and writing, which can be considered representational, then where does this situate modeling? Models in other areas involve physical contrivances sometimes referred to as scale models (within science and engineering), or maquettes (within the arts). Hopwood and Chadarevian (2004) emphasize a history with physical models, especially prior to the invention of computers. To the extent that all models, whether drawn, written, or made from plaster are forms of communication, we can draw a parallel of modeling with topics such as semiotics, language, and linguistics.

3 TOWARD A BROAD MODELING WORLDVIEW

We can discuss the philosophy of modeling, and its history, but it remains vital to see where this point of view takes us from a practical perspective. If several notches on a bone represent numbers, which in turn are models of phenomena (e.g., lunar cycle), then how does this change what we do with, or how we teach, modeling. We claim:

1. *Modeling is a cultural phenomenon*. The ways in which we model reflect modes of representation that are intimately associated with social groups, norms, and practices. There is no preferred modeling type except that which satisfies a social group's desire for efficient communication for a particular purpose.
2. *Disciplines reflect different types of modeling*. Natural language artifacts are models, numbers and all mathematical notations are models. The idea of a model captures a long sequence of historical events around the notion that one object can represent phenomena. Therefore, modeling is what happens *when we do this representation*—the practice. Modeling is a pre-disciplinary mode of thinking and representation.
3. *Mathematics is a mental framework for abstraction*. Mathematics can sometimes be conflated with the written or printed notation. However, as Devlin (2000) points out, the notation is not mathematics. If the notation is not the mathematics, where, and what, is it? Mathematical concepts provide a layer of reasoning connecting human experience to formal concepts. For example, the number we represent verbally or in writing as "one" or "1" is actually a mental concept that links numerous examples of one with one or more representations of one. The mathematics is in the mental realization that all of the empirical instances of one are similar in a very specific abstract sense. This similarity is reified in notation.
4. *Computer programs are models of intelligence*. Programming represents modeling of intelligent decision making and processing. To this extent, the majority of computer programs are *models of thought*. Programming is a type of modeling of decision making. For modeling decision-making, we often use control flow. Data flow, conversely, is for modeling dynamic systems of real-world events where we are not modeling decisions and thought, but instead, modeling brain-independent object behaviors and their encompassing systems.
5. *Modeling transforms reality into information*. A convenient aspect of modeling, at the core of representation, is that by creating a model, we turn that which we study (or prototype) into information (Shannon and Weaver 1971). For example, if we admire an oak tree we can effectively digitize the tree through measurement and knowledge-acquisition where the tree is partially replaced by its digital representation (e.g., a semantic network, a graph for capturing connectivity of branches). A convenient example of this transformation is the digital camera. A camera is a device that turns an image to an array of numbers. The *array* is a model of the scene.
6. *The virtual and the physical are converging*: if we create a model, which is a representation, it can be physical or virtual (e.g., using computer graphics, virtual or augmented reality) to the

extent that in virtual spaces, we use the same senses, and sense of presence. Therefore, a model of a 3D geometrical surface may be constructed from plaster or within a virtual world. We sense both in similar ways, and as technology improves, presumably this convergence will increase.

Modeling is therefore fundamental and foundational to human cognition. It captures what we do when *we represent* (via practical results) the world. While this may not be too controversial in appearance, this idea creates a cornucopia of ideas on how to teach modeling in the large whether in non-formal or information settings (e.g., libraries, museums) or in formal settings (K-12 and higher learning at colleges and universities).

This worldview with claims opens the possibilities of increasing the scope and power of modeling, not only for the purpose of simulation, but also for teaching modeling. Some ramifications of the claims are:

- CLAIM 1: There are conferences and journals devoted to models of one specific type of language. In some cases two social groups may use the same underlying formalism, and yet represent that formalism differently (e.g., state machines). For example, in keyframe animation, the underlying formalism is a sequential linear graph, and yet the culture of animation embraces an often unique vocabulary involving "keys." The word "culture" is employed in a way similar to "community of practice." One way of quantifying this cultural diversity is through content analysis (Mustafee et al. 2015, Mustafee and Fishwick 2017, Diallo et al. 2015).
- CLAIM 2: If modeling is at the core of representation, then language should play a greater role in thinking about modeling and creating phases for its use. We earlier noted that Forrester's System Dynamics promotes early use of natural language for elucidating concepts. Concept maps (Novak 1984) and concept graphs (Sowa 1984) also achieve this although they are an end in themselves rather than serving as a stepping stone to more detailed modeling. The standard notational languages of mathematics are already well situated within M&S literature so no need to argue for their inclusion.
- CLAIM 3: It is all too easy to think of mathematical notation as being equivalent to mathematics, but this is inaccurate for at least two reasons: (1) notation creates one of several ways to represent mathematics, and (2) strict adherence to this equivalence demotes other diagrammatic or performative measures we use as representations of mathematical concepts. Consider the long evolution of notation (Cajori 1929). In our expressions and activity in mathematics, we would be hard-placed to use anything but the standard notations. However, seeing mathematics as a mental product encourages exploration of multiple representations (Ainsworth et al. 1997). This multiplicity serves to create concrete analogs to the abstract concepts.
- CLAIM 4: Computer programming is infrequently thought of as a type of modeling, and yet for imperative programs, the control-based structure of programs is modeling something—the human brain and its decision-making. Programming is thus, both a means to speed computation as well as a mode of interpretation of the world. Programming (or "coding" in modern parlance) is *modeling the world with text*. When we discuss programs, we can do so as models of intelligent decision making within brains. This approach to modeling is termed "control flow" and is characterized by a model of a brain, as opposed to "data flow" where the model is of a non-brain system.
- CLAIM 5: The role of information has taken over, not just the usual fields of computer science, library science, and information technology, but also biology (e.g., genomics). Everything is interpreted as a collection of information with models being made to

process information. This trend strengthens the role of model as link between the experienced world and information. To turn a thing into information, model it.
- CLAIM 6: Since we have entered an era where the virtual extends the physical, we need to consider both the physical and virtual as converging with respect to the possibilities for representation. This convergence is enhanced through technology, and is a large subset of the prior claim: to convert reality into information is to map the physical to the virtual. The virtual becomes a workable model of the real evolving to the point where the two may eventually become indistinguishable at the most detailed level of representation.

Figure 1 positions modeling as prior to areas where differing representations abound. *Linguistics* is used as a placeholder for the related areas of semiotics, language, and communication. Through experiencing the world, we model, which in turn creates artifacts that are now associated with different disciplines. For much of our history, there were no differentiations among areas such as language, arts, and mathematics. Figure 1 is necessarily incomplete so enough disciplines are shown to illustrate modeling's core role in representation.

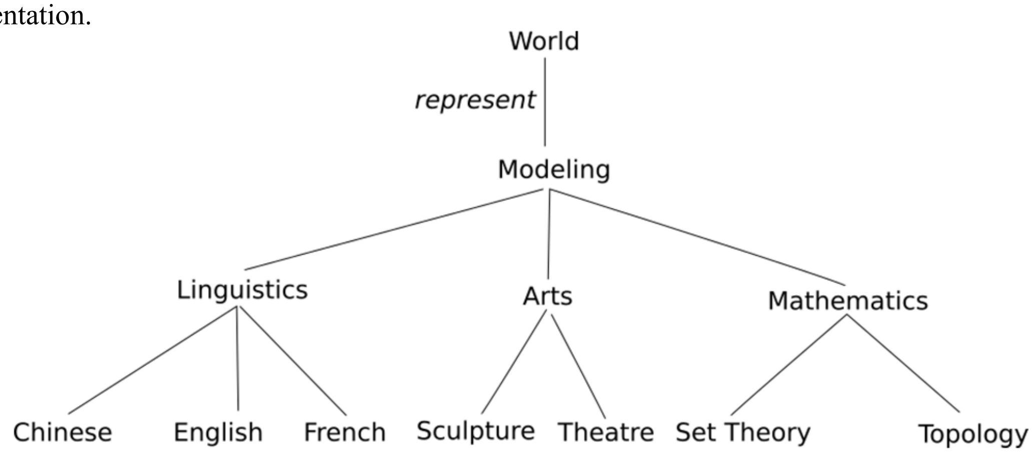

Figure 1: Modeling as the act of representing (partial hierarchy).

4 A HIGH-LEVEL TYPOLOGY FOR MODELING

The following three classes of model have been found useful in bridging model types used by different groups of people. These classes are not distinct since several types of models may combine two or three of the types. The model classes will be discussed from a pedagogical view, but all models are seen as information-generators.

- *Knowledge*: models of information where that information is encoded as basic structure, frequently static. Examples: predicate logic, semantic networks, concept maps, data structures.
- *Space*: models of information about shape and geometry. For example, a shape that is encoded as a list of polygonal vertices, edges, and faces is a spatial model of a physical or virtual object.
- *Time*: models of information which capture temporal aspects of a system. This is the type of model most often associated with publications within conferences involving simulation.

Some prefer the concept of *mental model* (Gentner and Stevens 1983, Johnson-Laird 2010) to precede other forms of physically instantiated modeling. A mental model is a purely cognitive construct. The issue with conferring the label of "model" onto cognition and brain activity is that until the mental model is externalized, it cannot be used in the processes of discourse, communication, and direct reflection. To be a model, we claim that there must be a representation external to body and mind. Even in the case of the auditory channel (e.g., music, verbal language), there is an externalized entity however ephemeral.

For the Winter Simulation Conference (Goldsman et al. 2010), most models in the 70s and 80s were focused on time, but not so much on using graphics since the state of computer graphics was nascent. More recently, most commercial simulation packages use as many geometric models as models of time-changing state and event. In simulation, while time is at the core of our area, knowledge plays an increasing role with the interest in concepts and the conceptual. Likewise, space plays a role in agent-based simulation and in any simulation where shapes are integral (e.g., use of computer graphics).

5 MODELING FOR THE MASSES

The modeling claims in Section 3 create new pedagogical opportunities for modeling. We can teach about modeling within a specific discipline or we can talk of modeling the way we do of mathematics: abstract and conceptual. These claims extend and build upon a prior WSC conference panel (Fishwick et al. 2014). We choose the latter view, but emphasize that to understand the ways of modeling, we need to teach abstract concepts by way of example and analogy. Such treatment has the potential to widen audiences from K-20 education and academic disciplines to pre-professional and professional audiences seeking to broaden their training.

The simulation community has long been interested in making modeling more accessible to larger audiences. This interest manifests itself through research papers related to communication, learning, and education. Padilla et al. (2015, 2016) emphasize learning science, technology, engineering, and mathematics (STEM) content through simulation building and game development and play.

Figure 2 shows the entry into the Boston Museum of Science exhibit entitled "Making Models" (BOS 2017). It is one of the most comprehensive museum exhibits that is dedicated to modeling. The exhibit contains many scale, or physical, models, virtual models, and diagrammatic representations of real-world objects and their behaviors.

Figure 2: Making Models exhibit at the Boston Museum of Science.

Our goal is to convey modeling to a wide array of people who lay outside of the usual disciplines of computer science, physical science, industrial and management engineering, and operations research. These people are unlikely to have a detailed technical or mathematical background, and like visitors to Boston Museum of Science, the people come from a wide demographic. Fortunately, the claims about modeling in Section 3 suggest ways to achieve this goal.

A lot depends on the personal interests of the learner. Consider learners who actively fabricate from materials, or from 3D printing. If the goal is to teach this learner about the concept of queuing, the person can be shown the usual queues of people and automobiles, but also they can make physical queues out of plastic parts.

6 INFORMATION AND MODELING CULTURE

Thinking about information has accelerated since the 20th century and is largely catalyzed by the use of digital computers. The emergence of internet of things, where everything has a digital equivalent, is one of the driving forces behind the notion that information is not simply a byproduct of technology but instead is an integral aspect of our communities of practice. These communities represent a type of culture. We have modeled since we invented language but now we can assert that modeling is cultural, and therefore, information is also as cultural as how we speak and write (Johnson 1997, Gleick 2012).

If information is cultural, then we need to explore the ways in which we operate within an information-based set of interactions. At the University of Texas at Dallas, we have taught a course entitled *Creative Automata*. In that course, the purpose has been to convey key aspects of information through cultural contextualization. Examples of this purpose include: (1) Taking a data type or structure and creatively representing the structure using physical or virtual materials; (2) Representing the knowledge of a cultural scene using concept or mind maps; and (3) Representing the flow of control and of data related to historical and cultural approaches to cooking.

Before transitioning to examples from the class, we feel the need to emphasize the importance of talking about modeling as an abstraction that is not discipline-specific. A discipline can serve to create examples of the abstractions. But, like mathematics, modeling creates a set of information-based abstractions and types of flow and interconnections. It is these abstractions which hold the keys to modeling. The connection to mathematics is important: model constructs and behaviors are like mathematical objects and representations—they go beyond specific cases. Let us treat modeling like mathematics—a collection of concepts whose meaning is enhanced with multiple representations.

7 CREATIVE AUTOMATA: A CASE STUDY

The most recent Creative Automata class was held in Spring 2017. The class was composed of computer scientists, artists, and designers. The software used was Cycling74 product called Max/Msp (MAX 2017). Max/Msp (referred to as “Max”) is a visual language capable of coding both data and control flows. Max is ideal for teaching modeling and simulation since (1) Max has an explicit concept of time, (2) Max can be used to model continuous and discrete event phenomena, and (3) Max operates naturally on digital media (e.g., images, video, sound, animation), which are discipline-neutral objects.

We began the semester with students being asked to represent text-based programming (e.g. Java, Python, C++) within Max. The following example indicates playing the “magic 8 ball” game originally coded in Python. This creation, in Figure 3, demonstrates the visual nature of the language. The user clicks the button object (at top) which then creates a random number, adjusted to be at least one by the [+] object. The button object is a classic Max example of being used for either input or output (ref. see the 3 output buttons toward the bottom of the patch).

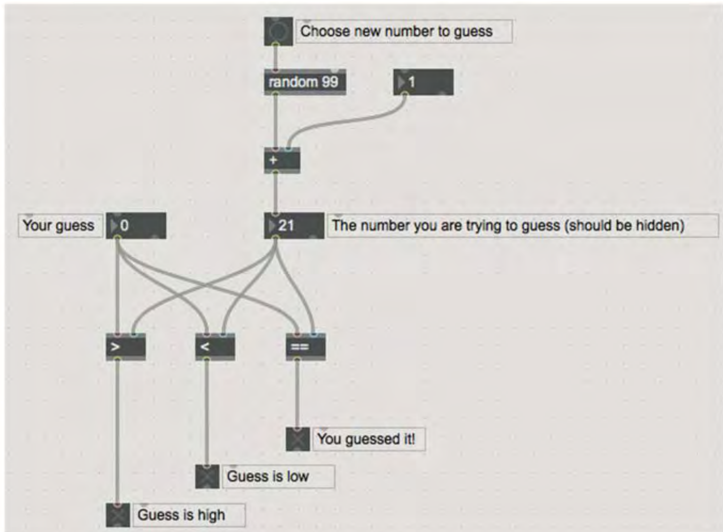

Figure 3: Max patch of Eight-Ball originally coded in Python (credit: Andrew Matocha).

For the four remaining projects, students were taught how to create subpatches, abstractions, and bpatching. Subpatches are patches within a patch, and so are similar to subroutines, procedures, and methods in conventional programming. Abstractions are convenient ways in which to identify subpatches and enable reuse. Bpatching is a way to take an object (represented above as dark grey rectangular boxes) and represent the object through interactive graphical media elements such as dials, display boxes, drawings, photos, images, videos, and signals. Students were asked to use Bpatches so that each major component in their static graph or flow graph was represented by something visual (e.g., an image or video loop) and a text caption.

Figure 4 captures a concept map for the 18th century making of chocolate ice cream, including the necessary kitchen instruments and authentic ingredients.

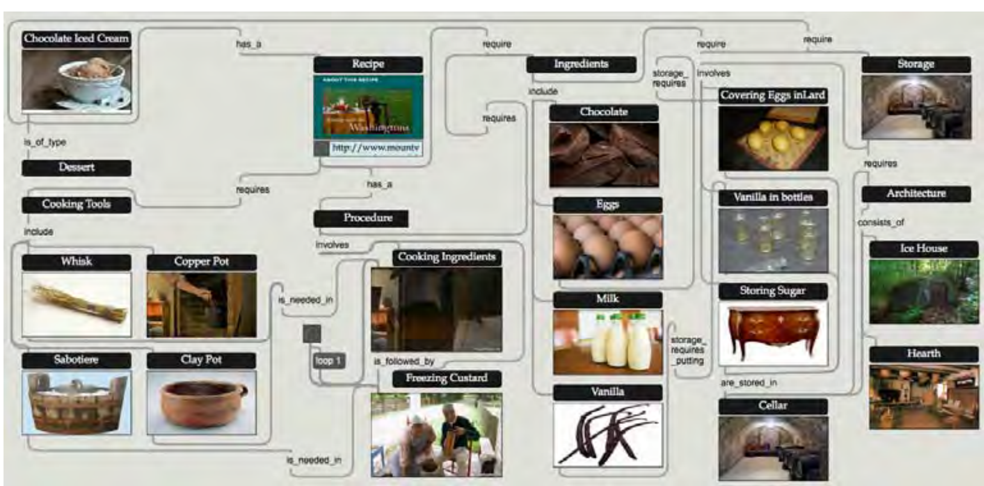

Figure 4: Concept map of chocolate ice cream (credit: Lakshmi Sharma).

Figure 4 is unusual for a concept map because of the layout and interaction. The layout has a picture for each instrument or ingredient as well as a text caption. Some concepts can be hyperlinked to web pages and other media. Figure 5 represents the final project for students where they were told to employ Bpatching for Petri net simulation. A partial Petri net simulation model is shown in Figure 5.

Figure 5: Partial Petri net representation for creating onion soup (credit: Daren Cheng).

8 TOWARD AN ENGINEERING PROCESS FOR MODELING

We have learned that for the non-technical audience, it is worthwhile beginning with pictures, storyboards, and natural language rather than immediately diving into a more symbolically represented, and often complex, model. We need to take a cue from System Dynamics and begin to treat modeling as a set of incremental phases. This is done in software engineering, but more can be done in model engineering. We also should consider carefully the type of representation employed. For example, the Petri net syntax in Fig. 5 caters to visual communication. Contrast this approach with a mathematical structure or even a diagram with common notation using circles and lines. The concept map representation in Fig. 4 departs from the pure text/arrow representation, which is more commonly found in the literature. Moving toward an engineering process means both (1) investigating natural representations of models in text and images, and (2) creating stepping-stones from the most basic of model representations to increasingly abstract representations. These two engineering approaches can be informally defined as "*start with what people already know (pictures, narratives) and create multiple pathways and links to increasingly formal, and abstract, model realizations*."

9 SUMMARY

We began our discussion with the goal of viewing modeling as a universal, broad activity spanning many disciplines that one would find at a college or university. Modeling is performed in every school and department, although being cultural, modeling may use different vocabularies and involve different social circles. Our plan has been to discuss core aspects of modeling using the following strategies: (1) teach modeling in a non-disciplinary manner by tying the sort of model to the student's interests and background, (2) provide an modeling and simulation environment that is visual, and therefore accessible to an array of student backgrounds, and (3) focus on modeling as an iterative process which starts with familiar stages such as drawing, taking pictures, and writing. It is still too early to declare success, failure, or something in between since no formal evaluation has been performed. It is assumed that by covering something of interest to the student, that effective learning will be facilitated.

Due to the author's joint appointment spanning engineering and the arts, the opportunity for customizing the learning of models such as state machines and data structures has been easier than if the goal of the class had to be tailored specifically to a field such as statistics, electrical engineering, or operations research. Perhaps, the proposed pedagogical methods in the paper point to the need to treat modeling as a liberal art rather than a vocationally-tuned set of methods and practices.

Since we are promoting starting to build models with raw materials which have always been at our disposal (writing, drawing), this leads to questions of whether we can form new relationships with those outside of science and engineering—in the arts and humanities, particularly. One thought that arose from the Spring 2017 course was whether modeling could be added to curricula on fine arts and liberal arts topics of composition, writing, and media. Two situations arose in the course to suggest this thought: (1) we were analyzing food recipes and interrelating model components and structure with English parts of speech: can this be a new model-enriched way of teaching English (or any natural language)?, and (2) a student was going through a Petri net that represented a process: could this be a new way to tell stories by using media-rich models?

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