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Pre-Service Secondary Science Teachers' Understanding and Use of Modeling

Bryan J. Meeker

Pre-Service Secondary Science Teachers' Understanding and Use of Modeling

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Bryan J. Meeker

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Abstract

The purpose of this study was to examine the understandings and uses of models and modeling by pre-service secondary science teachers. Models and modeling are described at length within the Next Generation Science Standards (NGSS) as being useful components of an effective science curriculum and have been analyzed in the literature. However, much of this research lacks real-world examples and usable techniques for instructors, creating misunderstandings about models and modeling. This work incorporates relevant literature as well as participant interviews in an effort to clarify these terms. Results of this study demonstrate a limited understanding of the use of models and modeling as shown by an overwhelming preference for only physical representations. It is clear that a gap has begun to form between the established standards and actual teacher practice.

Chapter I. Introduction

Educators are continually striving to find the most effective way to teach their students, often utilizing an amalgam of different teaching strategies. The Next Generation Science Standards (NGSS), implemented in 2013 and revised from the 1996 National Science Education Standards, mandate the material to be taught by science educators to create scientifically-literate students. While not offering specific teaching techniques, the NGSS does include performance tasks designed to demonstrate student proficiency, i.e. students should develop, revise, and/or use a model based on evidence to illustrate and/or create predictions about a given scenario (NGSS Lead States, Appendix F). The NGSS also functions as a consistent and uniform set of guidelines to assist educators in organizing and developing their own thorough and adaptive curricula. The question for teachers becomes how best to cover "the content standards for his or her subject in such a way that state assessments demonstrate that students are meeting or exceeding achievement goals based on those standards" (Bender, 2012, p. 159). While the standards are a representation of science content to be taught to create scientifically-literate students, they unfortunately remain open to interpretation.

The NGSS has modernized explanations along with increased compartmentalization including Scientific Practices (the major practices used by engineers and scientists to build systems), Crosscutting Concepts (concepts that have applications and importance across numerous domains of science), and Disciplinary Core Ideas (a concise set of ideas and practices to enable students to evaluate and create lasting scientific knowledge) (NGSS Lead States, Executive Summary). The NGSS places emphasis on inquiry, stating students cannot gain lasting comprehension of scientific ideas without engaging in it in the classroom (NGSS Lead States, Appendix F). Inquiry is delineated into 'scientific inquiry' (the creation of a question to be answered through investigation) and 'engineering inquiry' (the formation of a problem to be solved through design) (NGSS Lead States, Three Dimensions). These forms of inquiry and their respective skills "are acquired through questioning and becoming engaged in authentic investigation and problem solving," (Hamm & Adams, 2013, p. 43). These teaching techniques are then used by effective science educators in an effort to create scientifically-literate students.

Teaching through inquiry is not a new idea, alluded to as early as 1914 by authors emphasizing that "the best results are obtained by the students themselves making as many of the experiments as possible" (Stewart, 1914, p. 67). With a mystery at the forefront of the educational process, "students are naturally stimulated to ask questions and search for explanatory concepts" (O'Connell, 2008, p. 355), getting the opportunity to "experience the process of science in order to view science as a way of knowing, rather than a body of knowledge" (Udovic, Morris, Dickman, Postlethwait, and Wetherwax, 2002, p. 272).

Within inquiry are the concepts of models and modeling, the practical side of how best to have students 'do' science instead of memorizing it. The NGSS performance tasks that incorporate models and modeling are poorly defined, providing few exemplars, instead vaguely suggesting students be able to 'develop' or 'use' a model'. As a result, models and modeling are sometimes misinterpreted and misconstrued by both educators and students alike. In Schwarz' study, only 3 out of 24 pre-service instructors used models and modeling in a manner consistent with model-based learning (Schwarz & Gwekwerere, 2006, p. 170). It is clear that "science teachers today have often not been explicitly educated and trained in this theme [models and modeling]" (Gilbert, 2004, p. 126). This relates how the sheer volume of definitions and delineations serves to only frustrate teachers who engage their students in scientific inquiry and modeling (Schwarz, et al., 2006, p. 159). Ultimately, this overabundance of definitions negatively affects students, "seeming to have a less sophisticated understanding of models in the frame of biology than in physics or chemistry" (Krell, Reinisch, and Kruger, 2014).

Research Questions

In an effort to understand the gap between standards and practices, the purpose of this study was to examine pre-service secondary science teachers' understandings and use of models and modeling and compare these findings to descriptions of these topics in the NGSS.

The questions driving this research include:

1. How do participating pre-service high school science teachers understand and define models and modeling?
2. What are some examples of models and modeling that the participating pre-service high school science teachers are using (or plan to use) in their instructional plans?
3. What are the similarities and differences between models and modeling as defined by the NGSS versus its use and understanding by the participating pre-service secondary school science teachers?

Chapter II. Review of Existing Literature

Models and modeling have become topics of great discussion and debate within the literature, with many authors offering their own definitions and delineations in an effort to satisfy both their own curiosity along with their own research. This review, in an effort to clarify the use of models and modeling has been delineated into four main sections in addition to a section on the working definitions present within this work and their basis within the literature: Models and Modeling in the Literature, Models and Modeling in Science, Models and Modeling in Science Education, Models and Modeling in the Science Classroom, and Working Definitions of Models and Modeling.

Models and Modeling in the Literature

Ideas often require exemplars to facilitate comprehension, both in the scientific community and within science education. These exemplars have numerous nomenclatures, but many authors have coalesced on the term *model*. These models "influence and constrain the kinds of questions asked about the natural world and the types of evidence they seek in support of particular arguments" (Cartier, Stewart, and Zoellner, 2006, p.334). They can also function as a guide for students' perceptions of what is involved in natural processes (Passmore & Stewart, 2002).

While there are a multitude of definitions within the scientific literature, a brief summary demonstrating the variety of nomenclatures for models can be found below.

a) Mental models are psychological representations of real or imaginary situations (Ornek, 2008, p.35).
b) Conceptual models are external representations created by teachers or scientists that aid in the teaching of systems or concepts (Ornek, 2008, p. 37)

c) Mathematical models are descriptions or summarizations of important features of a real-world system or phenomenon in terms of symbols, equations, and numbers. (Ornek, 2008, p. 41).

d) Physical models are a construct of real situations and can be carried, touched, or held. (Ornek, 2008, p.41).

e) Computational models are simulations or programs designed to "be used in an instructional setting to provide an environment or an aspect of reality that would otherwise not be possible to explore within the confines of the classroom" (Kiboss, Ndirangu, and Wekesa, 2004, p. 208). This gives students a mechanism to interact with previously-unavailable concepts and "has the potential to profoundly change the nature of inquiry in science and science teaching" (Minogue, Jones, Broadwell, and Oppewal, 2006, p. 29).

Many authors within both the realms of science education and science itself have created their own unique descriptions and definitions of models and modeling, often to meet their own hypotheses, but most are similar to the aforementioned classifications. It is unfortunate this diversity of characterizations, with the intent to clarify, continues to do the opposite, causing difficulty in both the agreement and application of models and modeling.

Models and Modeling in Science

Within the scientific community, models are taken seriously and seen as central to doing science (Bailer-Jones, 2002). The NGSS (and many within the literature) strongly encourage instructors to align science curricula with the content and practices of science by engaging students in model-based learning and inquiry (Halloun, 2007, NGSS Lead States, Appendix F). Most scientists, in describing the relationship between models and their own practice, agree that a model “serves as a research tool that is used to obtain information about the target which itself cannot be easily observed or measured directly” and also potentially as “a representation of scientific knowledge about the target, to be used to facilitate making decisions about issues” (Van Der Valk, Van Driel, and De Vos, 2007, p. 481).

These varied definitions of models blossom from the idea that “scientific models are mental representations that, depending on the properties they abstract from and idealize, are possibly physically realizable but not necessarily so” (Ducheyne, 2008, p.122). Ducheyne helps to clarify potential models by stating that although they may begin as conceptual constructs, their implementation in the physical sense can allow for a deeper level of comprehension and less confusion on behalf of scientists, instructors, and students. Further, Ducheyne serves to describe models as occurring along a vast spectrum from simplistic physical models (e.g. two-dimensional maps) to complex conceptual models (i.e. brainstormed analogues of the physical world), meaning that students should be able to describe and delineate between the two (but need not worry about the numerous definitions put forth by other authors). Scientists using models only serve to reinforce the belief that models can be a vital part of any science curriculum.

Effective implementation of models and modeling within the classroom can serve to mimic the work of scientists and those within the scientific field. This allows students to experience how “scientific knowledge is tentative but robust, no single scientific method exists, creativity and imagination influence the development of scientific knowledge, there is a distinction between observations and inferences, there is a distinction between theory and law, and theory-ladenness (subjectivity) and sociocultural contexts affect scientific knowledge” (Akerson, Townsend, Donnelly, Hanson, Tira, and White,, 2009, p. 22). Science itself as a collaborative and reflective process is shown to be created, tested, and revised as exemplified by instructors successfully using models and explanatory modeling in their classrooms.

Models and Modeling in Science Education

In the science education literature, ‘models’ and ‘modeling’ have been used to describe a variety of varied teaching techniques, most of which stem from the use of models and modeling within science itself – “It is this broad goal of science – the construction of process models – that remains a primary learning outcome for us and provides the focus for our [educational research] work” (Passmore, et al., 2002, p.188).

Models offer students a mechanism to express their thoughts that might otherwise not be possible in that “having the model to manipulate and to provide a focus for…thinking allowed [the students] to represent her knowledge to an extent that is much greater than would have been the case had there been no model” (Seiler, Tobin, and Sokolic, 2001, p.760). To this end, students should “come to understand the nature and significance of the models that played key roles in the development of particular themes in the sciences. They should also develop the capacity to produce, test, and evaluate models of those phenomena that are of interest to science” (Gilbert, 2004, p.117). Through this process, students gain skills reminiscent of scientists and are not simply receivers of knowledge presented by the traditional and seemingly omnipresent passive instruction. This learning experience is primarily “about *inscription of traded knowledge* [italics original] in student minds, mostly in short-term memory, and seldom about formation of experiential knowledge” (Halloun, 2007, p. 678) – Students are expected to memorize instead of comprehend, repeat instead of explain.

Modeling, then, is the way in which effective instructors and students "learn to develop and justify scientific models as they do scientific inquiry" (Anderson & Farnsworth, 2000, p. 4), using their models to create deep and lasting comprehension unavailable in a passively-taught static classroom. The impetus remains on human interaction and ingenuity to make these models into valuable and robust exemplars of the concepts they represent.

How do we best utilize these models while attempting to eliminate confusion about their nomenclature? In the interest of clarity, I have analyzed a multitude of definitions and organized these varying descriptions into two categories for models (physical and conceptual) and three categories for modeling, (illustrative, expository, and explanatory). While some authors attempt to offer a definition or delineation for every possible model use, it is my belief that fewer categories will assist in comprehension. A comparison of models and modeling as defined in this work and others follows in **Table 1.**

Models and Modeling in the Science Classroom

Modeling is an active learning technique, meaning that students are encouraged to "take control of their own learning experiences" (Huffaker & Calvert, 2003, p. 326) and be "actively involved in one or the other form of learning and thus [get] a chance to develop the key aspects of the course" (Srinath, 2014, p. 21). This active environment often includes student problem solving, collaboration, and discussion, often with physical animations, simulations, and case studies (Gardner & Belland, 2012). Modeling, as an active learning technique, contrasts with passive teaching, correcting "many weaknesses of the traditional lecture-demonstration method, including the fragmentation of knowledge, student passivity, and the persistence of naïve beliefs about the physical world" (Jackson, Dukerich, and Hestenes, 2008, p.11). When students are actively involved in their education, they gain comprehension instead of a memorized amalgam of facts.

In order to facilitate this level of comprehension, educators must "acknowledge that students arrive in their heterogeneous classroom with differing levels of development, interests, and exposure to a plethora of environments and experiences" (VanTassel-Baska & Stambaugh, 2005, p. 211). To effectively acknowledge varied levels of ability and prior knowledge, instructors must be willing to modify their instruction to meet the demands of students with varied abilities and learning styles (Carolan & Guinn, 2007). We as educators do not simply "adapt our instructional techniques to meet [student] needs; we prepare students for the variety of learning and life situations they will encounter" (Wormelli, 2007, p.9). Differentiation, then, is more than a buzzword. Teachers must assist "students in instruction through different approaches to learning, by appealing to a range of interests, and by using varied rates of instruction along with varied degrees of complexity and differing support systems" (Tomlinson, 2014, p. 2). This includes gifted students as well as those with disabilities whose IEP or 504 grants them accommodations to allow for an equal opportunity for learning (Conderman & Katsiyannis, 1995, IDEA, 2004). Of the strategies used by educators to facilitate differentiation, the most commonly-used strategies "rating between very effective and moderately effective were *modeling*, [emphasis added] adjusting questions, and lecture with question and answer" (Hootstein, 1998, p. 5). It is clear effective use of models and modeling instructors can enhance student comprehension.

Table 1. Comparison of Models and Modeling in Literature

	Cartier (2000)	Ornek (2008)	Meeker (2015)
Types of Models	"Scientific"	"Physical" "Computational"	"Physical"
		"Mental" "Conceptual" "Mathematical"	"Conceptual"
Types of Modeling	Explanatory	Mathematical Physics	Illustrative Expository Explanatory
Definition of Models	"A set of ides that describes a natural process" (Cartier, 2000, p.7)	"Mental models are psychological representations of real or imaginary situations" (Ornek, 2008, p. 35). "Conceptual models are simplified and idealized representations of real objects, phenomena, or situations" (Ornek, 2008, p. 37).	Models are physical or conceptual constructs with the intent to represent a system or components therein to aid in the development and refinement of ideas.
Definition of Modeling	"A scientific model so conceived can be mentally run, given certain constraints, to explain or predict natural phenomena" (Cartier, 2000, p.7)	"[Mathematical] modeling…shows the usage of the real-world problem…and translates it to a mathematical problem by formulation of a mathematical model" (Ornek, 2008, p. 38) "[Physics] modeling involves making a simplified, idealized physics model of a messy real-world situation by means of approximations" (Ornek, 2008, p.42).	Modeling is the process by which scientists, teachers, and students create, evaluate, and refine their own models of the world, represent a system or components therein, help the development of questions and explanations, generate data for making predictions, and communicate ideas.

Working Definitions of Models and Modeling

In an effort to simplify the numerous different descriptions of models and modeling while working to maintain their effectiveness in the classroom, the following delineations were made. Models were divided into physical and conceptual while modeling, not often discussed in great detail, was divided into illustrative, expository, and explanatory modeling, with explanatory functioning as the level of modeling requiring the greatest amount of critical thinking and comprehension about the content presented.

Physical Models.

A physical model refers to a physical construct of the given concept or content. Physical models include but are not limited to replicas, diagrams, drawings, figures, maps, organisms etc. and may be manipulated, touched, or held. A physical model can include *physical* experiments or scenarios designed specifically for testing and revision as in a laboratory setting. A physical model is often used in tandem with conceptual background and explanation given by the instructor. As an example, an instructor might use a printed diagram or map of a given area to show students the locations of various bodies of water and geological formations (NGSS Lead States, 2-ESS2-2.). Retrieving information from this physical model does not require or inspire a deep conceptual understanding. In order to make this model part of a robust model-based curriculum, the instructor must use modeling, perhaps facilitating a dialogue about the map in which students are asked to make predictions about how various geological formations or bodies of water came to be located in their present locations. In this way, an effective instructor, "by giving students a hands-on activity…can help them grasp invisible abstract concepts by making them tangible through representational means" (Patro, 1998, p. 86).

Conceptual Models.

A conceptual model refers to a conceptual construct of the given concept or content. Conceptual models include but are not limited to visualizations, ideas, and hypotheses of non-observable things, phenomena, or processes including mathematical expressions. Conceptual models can include *conceptual* experiments or scenarios designed for testing and revision as in a laboratory setting. “Mental models play a central and unifying role in representing objects, states of affairs, sequences of events, the way the world is, and the social and psychological actions of daily life” (Johnson-Laird, 1983, p. 397).

A conceptual model represents everything not possibly made tangible. A conceptual model often elicits and supports student brainstorming, imagining, and visualizing about topics. As an example, an instructor might describe how the total number of atoms does not change in a chemical reaction by having students utilize and study a chemical equation by examining a conceptual representation of the atoms present in the reaction (NGSS Lead States, MS-PS1-5.) This conceptual model allows students to work through the reaction without any sort of physical interaction with the atoms, keeping the reaction ‘in their head,’ as it were, allowing for permutations and testing. This work might prompt an effective instructor to use expository modeling, (perhaps asking students to hypothesize about what the significance of the conservation of matter might be or what the consequences might be if matter was not conserved, etc.) or even explanatory modeling, (perhaps asking students to create, test, and revise their own ideas about the reaction).

The working definitions for models and modeling in this study are as follows – Models are physical or conceptual constructs with the intent to represent a system or components therein to aid in the development and refinement of ideas, and modeling is the process by which scientists, instructors, and students create, evaluate, and refine their own models of the world, represent a system or components therein, help the development of questions and explanations, generate data for making predictions, and communicate ideas. While information can be obtained from these physical or conceptual models, it is modeling that turns these representations into powerful educational tools, as shown below.

Illustrative Modeling.

Illustrative modeling refers to modeling in which a scientist, instructor, or student is able to gain a simplistic study of a given concept, usually the composition and location of components. As an example, an instructor might, in describing the shape and characteristics of various land and bodies of water, utilize a map or diagram to assist students in their understanding (NGSS Lead States, 2-ESS2-2.). The intent of the instructor in this example is for students to simply illustrate the location and composition of the geography. Students can gain familiarity with the given content before ideally moving to higher levels of modeling to gain deeper levels of comprehension about the topics and concept presented, e.g. the instructor could ask students to hypothesize how these land formations and bodies of water formed or what effects mankind might have.

For example, one author explained how he had devised a project in which "students [make] a model cell, either plant or animal, from Styrofoam. Once the model was constructed, students labeled cell parts and organelles" (Cohen, 2014, p. 544). He added that "for the nucleus, symbols for nucleic acid molecules were correctly located; however, no further activity with the nucleus was planned for this version of the model" (Cohen, 2014, p. 547). In this way, physical models were used with illustrative modeling to give students a gloss of the material with the instructor assessing them only on their ability to label, locate, and denote various cellular components.

He later moved into expository modeling, asking students to "explain the making of a protein, beginning with the cell's DNA, until it is ready for transfer through the membrane" (Cohen, 2014, p. 549). Given student comprehension of the composition and location of items demonstrated by illustrative modeling, an instructor can feel comfortable to explore their understanding at a deeper level using expository modeling.

Expository Modeling.

Expository modeling refers to modeling in which a scientist, instructor, or student is able to create an exposition or interpretation about the components of the concept presented. This definition parallels suggestions in the literature that physical models "are expected to put a phenomenon in a larger theoretical context and provide insight more than accuracy" (Bailer-Jones, 2002, p. 298). Bailer-Jones, here talking about the best 'use' for physical models, is in effect talking about the modeling commonly done by instructors and students. Expository modeling, going beyond the modeling described by illustrative modeling, requires more from students, a deeper understanding and knowledge of the given content, ideally leading to explanatory modeling later in their coursework. As an example, an instructor might, in describing the solar system, utilize a physical model of a solar system to aid in the description of the interplay between the sun, planets, moons, and seasons (NGSS Lead States, MS-ESS1-1.). This physical model in a static passive environment may be insufficient to achieve a deep comprehension of the interplay between these spatial bodies and the seasons. An effective instructor could use expository modeling (perhaps a thorough background or scaffolding) to guide students to a depth of understanding beyond simple memorization and description of the aforementioned spatial bodies.

Explanatory Modeling.

Expository modeling refers to modeling in which a scientist, instructor, or student studies a model with the purpose of creation, testing, and revision. My definition of explanatory modeling parallels authors within the science education literature, writing that modeling is used to "discuss specific aspects of a model (models are based on empirical evidence, models are tentative because they may change in light of new evidence, modeling is a subjective process because of the learner's prior knowledge and experiences, etc.)" (Akerson, et al., 2008, p. 31) and "are constructed in the service of developing and testing ideas and explanations about phenomena" (Grosslight, 1991, p. 819) **–** It is this creation, testing, and revision of models that sets modeling apart.

These working definitions offer instructors a simplified path to determine and develop their own model usage as well as better defining the kind of modeling they are able to and plan to do within their classroom. Instead of stating broadly that models were used, an effective educator might state that a physical model of a skeleton was used along with illustrative before moving up to expository modeling and finally explanatory modeling with a subsequent laboratory exercise. With these working definitions in mind, we have an idea, with very little confusion, of the activities and assessments that occurred. It is for this reason, clarify of purpose, that these delineations of nomenclature were made.

An explanation of the different types of models and modeling as defined in this work is available in **Table 2** and **Table 3.**

Table 2. Types of Models and Modeling with Definitions and Examples

Type of Model	Description	Examples
Physical	A physical model refers to a **physical** construct of the given concept or content.	Replicas, diagrams, drawings, figures, maps, organisms, etc. Physical models and may be manipulated, touched, or held.
Conceptual	A conceptual model refers to a **conceptual** construct of the given concept or content.	Visualizations, ideas, and hypotheses of non-observable things, phenomena, or processes including mathematical expressions.
Type of Modeling	Description	Examples
Illustrative	This kind of modeling is simplistic and focuses on identification, location, and description of components within a system.	An instructor uses a physical model of an eyeball and has students take notes on the components they see and their relative location.
Expository	This kind of modeling is more demonstrative, focusing on deeper conceptual understandings of the physical concept represented.	An instructor uses a physical model of an eyeball and asks students deeper concept-based questions like, "How do you think images are focused? What would happen if the optic nerve was damaged? How do you think the shape affects the image?" These questions require the student to have a cursory knowledge of the eyeball and now begin to think critically.
Explanatory	This kind of modeling is the highest level, with students asked to predict, test, and revise based on evidence gathered from the model.	An instructor passes out physical models of eyeballs to groups of students and asks them to predict what would happen if the optic nerve was damaged, test their hypotheses, and revise their ideas. This is the highest level of modeling.

Table 3. NGSS Models & Modeling Usages

This table contains examples and descriptions of the 43 NGSS standards sorted into the Scientific Practice *Developing and Using Models.* They have organized into the model and modeling categories as defined within this work.

Type of Model	Number of Uses	NGSS Example / Explanation
Physical	27	**K-ESS3-1. Use a model to represent the relationship between the needs of different plants and animals (including humans) and the places they live.** This standard likely has instructors and students using physical models (e.g. a diagram, flowchart, concept map, etc.) in an effort to represent the relationship between organisms and their habitats.
Conceptual	10	**MS-LS1-7. Develop a model to describe how food is rearranged through chemical reactions forming new molecules that support growth and/or release energy as this matter moves through an organism.** This standard likely has instructors and students using conceptual models (e.g. brainstorming, imagining, visualizing, etc.) to represent the process of food being broken down via chemical reactions to release energy.
Physical and/or Conceptual	6	**MS-ETS1-4. Develop a model to generate data for iterative testing and modification of a proposed object, tool, or process such that an optimal design can be achieved.** This standard likely has instructors and students using both physical (drawings, diagrams, schematics, etc.) and conceptual (brainstorming, organizing, visualizing, etc.) models in an effort to test, modify, and improve a proposed idea.
Type of Modeling	Number of Uses	NGSS Example / Explanation
Illustrative	2	**2-ESS2-2. Develop a model to represent the shapes and kinds of land and bodies of water in an area.** This standard likely has instructors and students using illustrative modeling as the main focus is to locate and identify elements of a physical model and not to garner a deeper conceptual understanding of the elements or their interrelationship.
Expository	37	**MS-PS1-5. Develop and use a model to describe how the total number of atoms does not change in a chemical reaction and thus mass is conserved.** This standard likely has instructors and students using expository modeling as they use mathematics to gain a deeper conceptual understanding about chemical reactions.
Explanatory	4	**HS-ESS2-3. Develop a model based on evidence of Earth's interior to describe the cycling of matter by thermal convection.** This standard likely has instructors and students using explanatory modeling as they use evidence to demonstrate understanding, leading to the creation, testing, and revision of their own hypotheses about the cycling of matter by thermal convection in the Earth's interior.

Chapter III. Conceptual Framework and Methodology

In an effort to best obtain and analyze available participant data, this methodology section will be divided into two main parts, Research Design and Data Analysis. Within the Research Design portion, the use of a case study method is described along with the interview process and protocol. Within Data Analysis, the participant recruitment information is described along with a summary of the NGSS Models and Modeling Standards & Functionality Analysis (Appendix C) and the Models and Modeling Transcript Analyses (Appendix D-I).

Research Design

Case Study Method.

With approval from the DePaul Institutional Review Board (#BM030415EDU), the choice was made to use a case study as "this design is chosen precisely because researchers are interested in insight, discovery, and interpretation rather than hypothesis testing" (Merriam, 1998, p.28-29). When approaching the topic of models and modeling, the perspectives and ideas pre-service secondary science teachers might possess was unknown, allowing this process to proceed organically. Participant interview responses led to changes and improvements in the direction of this study, and these interviews specifically allowed for an honest and specific dialogue as "the main purpose of an interview is to obtain a special kind of information" (Merriam, 1998, p. 71) and was "necessary when we cannot observe behavior, feelings, or how people interpret the world around them" (Merriam, 1998, p. 72). Without direct classroom observations, these participant interviews, (in conjunction with their constructed concept maps and instructional artifacts), allowed us to triangulate our thoughts on the understandings and use of models and modeling by these pre-service secondary science teachers.

Interview Process & Protocol.

I met with participants at the Education Building at DePaul University's Lincoln Park campus. The Interview Protocol was developed with the intent that the "interview questions [should be] developed on the basis of the results of the study of the relevant literature…and models and modeling in science education" (Henze & Van Driel, 2011, p. 247).

The Interview Protocol, (Appendix A), includes a list of questions and gives the general focus of the interviews. The Pulse Smartpen system was used, allowing for the recording of both audio and visual data enabling the participants to augment their verbal descriptions with visual concept maps and notes. The first interview focused on pre-service secondary school teachers' understandings and uses of models and modeling while the second compared these understandings to the NGSS definition and explanation. At this second interview, participants were encouraged to bring relevant instructional materials (lesson plans, assessments, etc.) to better explain their planned use of models and modeling in the classroom. At the conclusion of the interviews, the data were analyzed "so as to find any relationships between the teachers' personal knowledge about educational activities on models and modeling" (Henze et al., 2011, p. 255).

Data Collection

Participant Recruitment.

In an effort to include the greatest number of pre-service secondary school participants, TCH 424 (an introductory teacher education course in the TEACH program), TCH 590, or T&L 590 (the latter two for students participating in student teaching) were considered appropriate applicant pools. The only other qualification was that participants needed to be English-speakers.

With the assistance of the Director of Field Experiences at DePaul University, participants were invited via an informational flyer (included in Appendix B). This flyer gave potential participants a brief outline of the purpose of the study as well as potential time commitments and benefits for participation.

Of the ~100 students contacted, five students showed interest in participating in the study. Unfortunately, due to personal conflicts, two students were forced to withdraw from the study. The remaining three students were given coded names known only to the principal investigator and co-principal investigator. Within the remainder of this paper, participant responses are denoted by these codes (1C, 2A, or 3B). When studying the transcript data, the code is augmented with either an I (for Initial Interview) or F (for Final Interview) along with the respective line number, i.e. (3BF, 12-24) would denote Participant 3B's Final Interview, Lines 12-24.

These participants had different academic standing, with two currently in undergraduate programs and one in a graduate program. This academic standing was also reflected in the amount of content hours accumulated by the participants, with the graduate student having accumulated the greatest number of hours. In terms of student teaching, one participant was currently teaching, another was set to begin in Fall 2015, and another was still a year away from starting.

Table 3. Participant Information

	Participant 1C	Participant 2A	Participant 3B
Content Area	Physics	Biology	Biology
Background in Science	Participant 1C took high school physics courses and is pursuing a Bachelor's of Science in Secondary Education Physics.	Participant 2A took numerous Biology courses before receiving a Bachelor's of Arts in both Sociology and Chemistry.	Participant 3B has completed more hours than required to receive a Bachelor's of Science in Secondary Education Biology.
Content Hours (Undergraduate or Graduate)	54	110	70
Academic Degree Currently Pursuing	Bachelor's Degree in Secondary Education Physics	Master's Degree in Education Biology Endorsement	Bachelor's Degree in Secondary Education Biology
Current Status toward Professional Educator's License (PEL)	Undergraduate Coursework with Student Teaching to occur in Fall 2015.	Student Teaching in Spring 2016	Student Teaching Spring 2015 (Currently)

NGSS Models and Modeling Standards & Functionality Analysis.

It was the intent of this study to develop a theory about the understandings and uses of models and modeling by pre-service secondary school teachers utilizing a systematic coding analysis. After a thorough examination of the relevant literature, categories were created with the intent of simplifying the various nomenclatures for models and modeling. Participant interview responses, informational materials, and imported concept maps allowed for refinement of these delineations. I did not approach this research with a pre-determined course of action in mind, but let the obtained information guide my theory development. The descriptions of models and modeling available both in the literature and from the participants offered both support and frustration in the creation of categories, but definite trends were noted.

With the categories created, I analyzed the 43 standards associated with the scientific practice of *Developing and Using Models* and sorted them into the categories I created. Most of these standards do not include suggestions or exemplars about the best kind of model to use, only providing the preamble 'develop a model…" followed by the required content or skill. While the NGSS have placed increased emphasis on models and modeling, this lack of clear, understandable, and usable examples is problematic and most likely part of the reason for the lack of understanding of these standards shown by this study's participants. While the sorting is certainly debatable, I made my decisions keeping in mind the most likely intent of the NGSS standard. The NGSS Models and Modeling Standards & Functionality Analysis is included in Appendix C.

Models and Modeling Transcript Analysis.

Using the SmartPen audio recordings of the participant interviews, I manually created written transcriptions, adding line numbers for future reference.

With the transcriptions complete, I worked through the transcripts and highlighted any phrases, sentences, lines, etc. applicable to models and modeling. Each of these highlighted portions was studied, leading to the creation and modification of my devised categories. With tentative categories taking shape as a result of my study of the relevant literature, it was these participant interviews and transcriptions that worked to solidify my delineation and creation of the two categories of model and three categories of modeling.

These highlighted portions were then sorted into their respective categories, a summary of which is available in Table 4; the transcript lines and placement are available in Appendices D-I.

Chapter IV. Analysis of the Information, Material Data

Information collected within this study included transcribed interview responses, instructional materials, and imported concept maps. To aid in comprehension, this chapter has been divided into three main sections, Types of Models and Modeling (to focus on the definitions and understandings shown by participants), Examples of Models and Modeling (to focus on the real techniques and products suggested or used by participants), and Similarities and Differences between NGSS and Participant Model and Modeling Usage (to focus on the differences between the given standards and teaching practice). In this way, the data have been delineated to reflect the research questions posed at the beginning of this study.

Types of Models and Modeling

In defining models, each participant offered different definitions. Participant 1C said models were “a document (Venn Diagram, flow chart, data sheet, etc.) or 3-D product that illustrates students’ understandings of a scientific concept” (1CF, 47-48), divided into two categories, “mathematical models or pictorial models” (1CI, 45) while Participant 2A stated “everything is a model” (2AI, 293), adding how they function as “a representation of a concept within life” (2AF, 72-73), similar to Participant 3B who stated “models are some sort of physical representation of a real-life concept within science” (3BF, 74-75).

With her delineations, Participant 1C effectively divided models in a manner similar to this study, with physical (pictorial) models and conceptual (mathematical) categories. These models, she emphasized, should gain complexity to engender deeper student comprehension (1CF, 63-64), and “allows us to analyze the situation we’re looking at” (1CF, 72-73), in this way paralleling the expository modeling, to be discussed shortly.

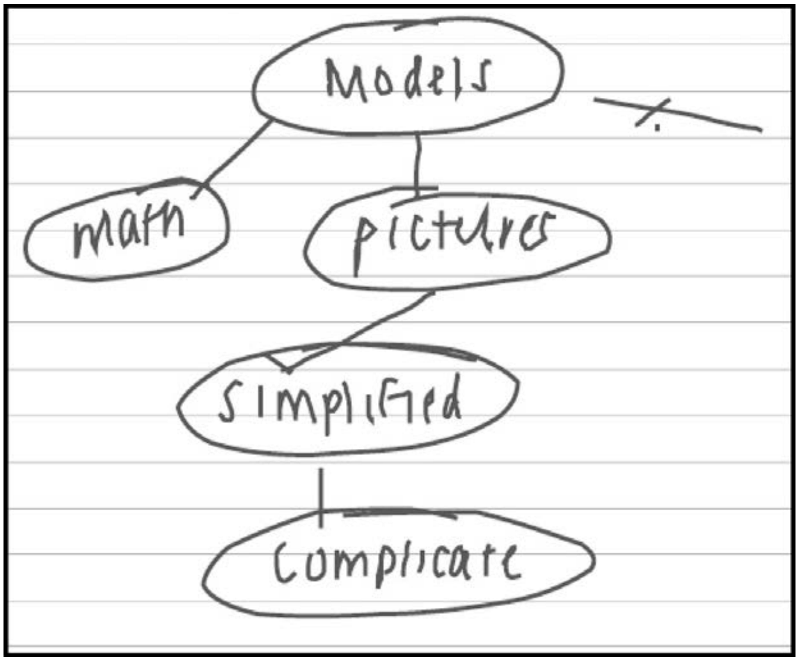

Figure 1. Participant 1C Models and Modeling Concept Map

As shown in the concept map, Participant 1C held a very simplistic understanding of models although similar to the description of models given in this work. Lacking was the inclusion of purely conceptual models as shown in the frequency of each kind of models used. With the fewest content hours of the three participants, it is possible that Participant 1C was describing models and modeling as it had been described to her. It is worth noting that while Figure 2 shows a high frequency of conceptual models, these mentions were primarily mathematical in nature and not conceptual in terms of brainstorming, imagining, and visualizing as it has been described here.

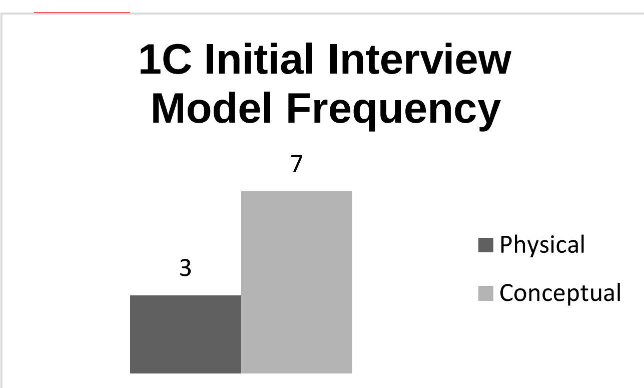

Figure 2. Participant 1C Initial Model Frequency

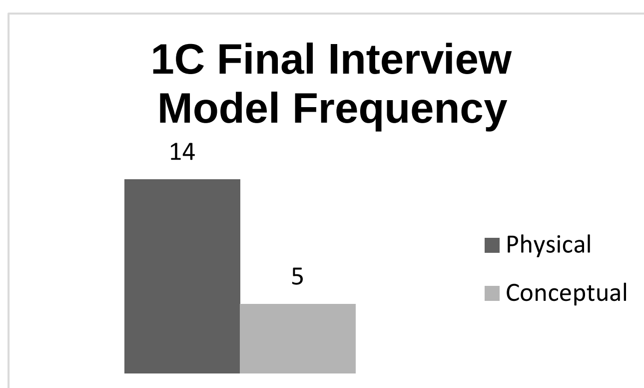

Figure 3. Participant 1C Final Model Frequency

With her delineations, Participant 2A created vast categories for models, essentially stating with the right background information and preamble, anything can function as a model. While expansive in the same vein as the NGSS definition of models, noting physical models like dissections, skeletons, and other ‘tangible’ representations, she later showed confusion, stating an instructor could function as a model in that “how a teacher reacts to being in the classroom and interacts with her students and their personality and how they come off with their students is a huge model that students pick up on without realizing it” (2AF, 36-38). In this way, she asserts an instructor can be a “covert” model, that is, a model being used without student knowledge, but this usage of ‘model’ is incorrect. While the teacher instructor could function as a model for a human being, educator, etc., the teacher functioning as a representation of best practices is inconsistent.

Participant 2A, having had the greatest amount of content hours and being a graduate student, may have ‘over-applied’ her understanding of models and modeling. Her statements in regards to anything being a model is essentially correct, but her definition and explanation of these ‘covert models’ is unclear and muddled. With this in mind, Participant 2A’s explanation of ‘overt models’ is very similar to the definition of ‘physical models’ as set forth in this work. As Participant 2A does not student teach until Spring 2016, it is probable that additional educational courses (and practical experience with models and modeling) will assist her in clarifying her understanding and use of models and modeling.

Her concept map is shown on the following page.

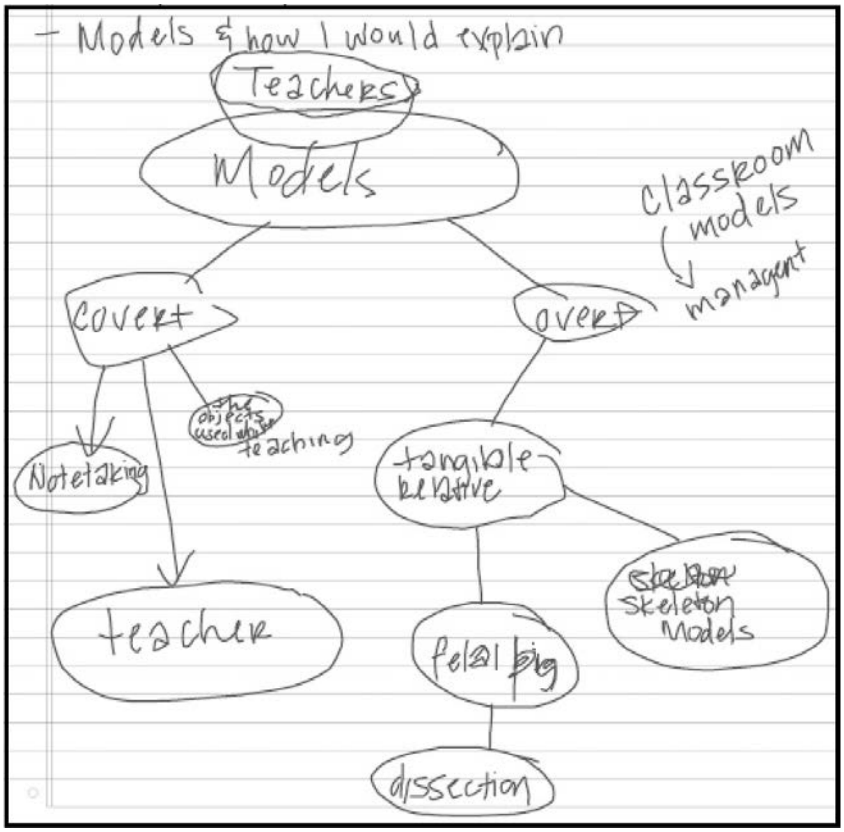

Figure 4. Participant 2A Models and Modeling Concept Map

In a similar vein to Participant 1C, Participant 2A also showed a preference for physical representations. It should be noted again that the conceptual models noted in Figure 6 were mathematical in nature, still lacking a purely conceptual understanding of models.

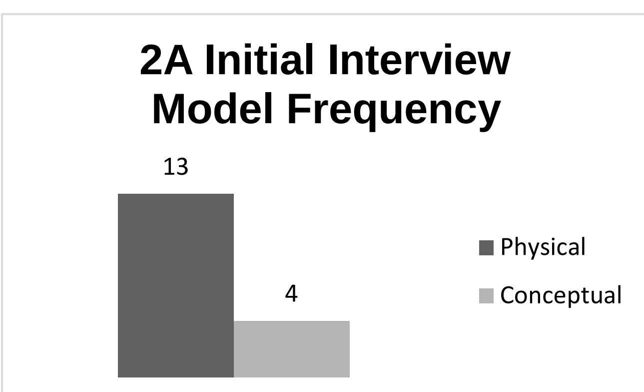

Figure 5. Participant 2A Initial Model Frequency

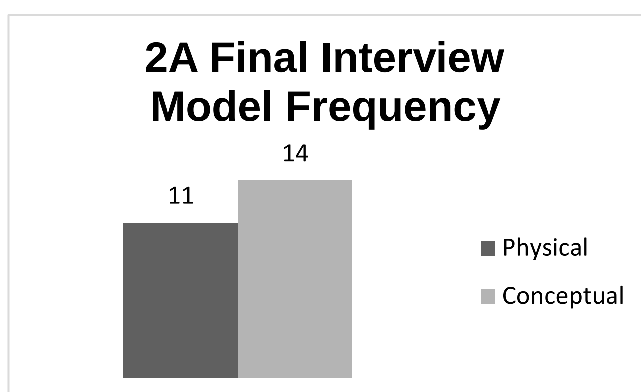

Figure 6. Participant 2A Final Model Frequency

Participant 3B, when asked to portray models and modeling, came up with the example of a Punnett Square, a physical model, to show the mechanism of genetics. When asked to clarify her definition of potential models, she quoted from the NGSS statement on models, noting they can include "diagrams, physical replicas, mathematical representations, analogies, and computer simulations, and it's all based off of evidence" (3BF, 91-92). With a good amount of content hours behind her, Participant 3B was able to offer practical examples but was lacking in an understanding of the purely conceptual side of models. Currently student teaching, it is perhaps her classroom experience that led her to mention these practical examples – Her example is shown below.

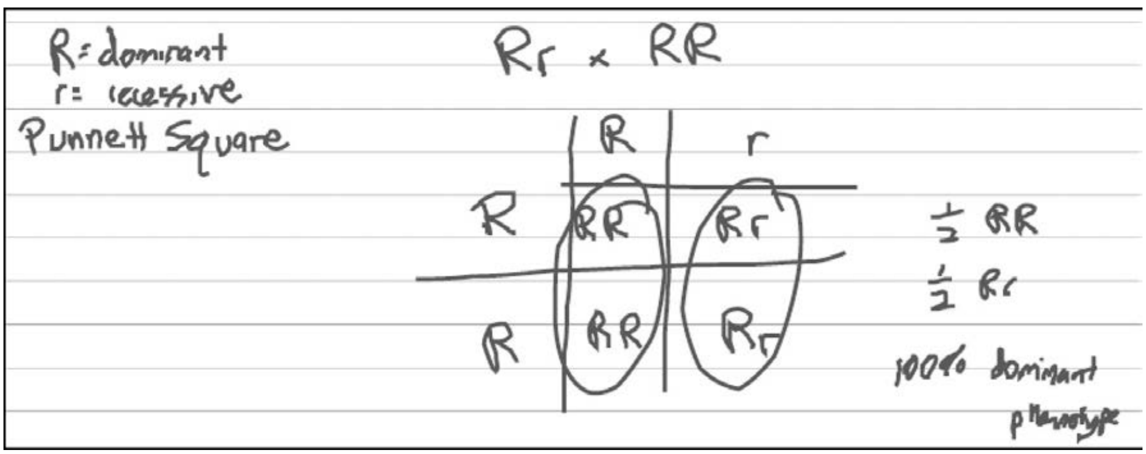

Figure 7. Participant 3B Models and Modeling Example

As with the other participants, Participant 3B showed a preference for physical models, shown below in the frequency of model usage in her interviews.

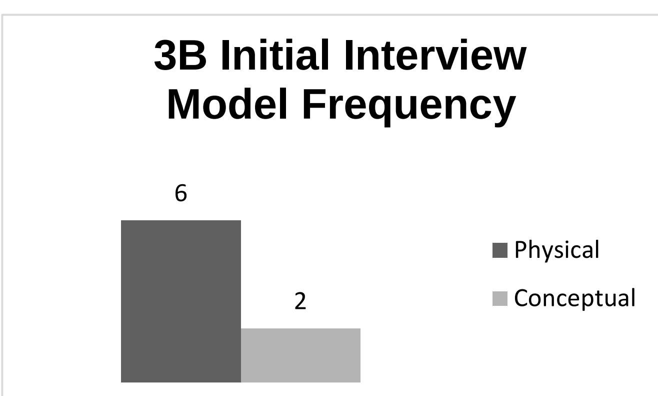

Figure 8. Participant 3B Initial Model Frequency

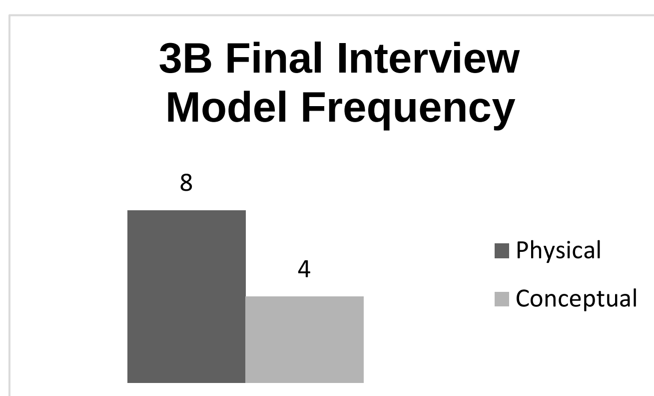

Figure 9. Participant 3B Final Model Frequency

In terms of modeling, each participant gave differing definitions, altogether vague and lacking in an abundance of examples of how modeling could be used and what sort of models might be used to facilitate it. Participant 1C described modeling as “the process students go through to organize content or ideas that leads to the creation of a model” (1CF, 50-51), “directly [helping] them understand concepts (1CF, 158), while Participant 2A said modeling was “using a representation to assist in the understanding of concepts within life (2AF, 81) and Participant 3B felt modeling was “using models of certain systems and processes to convey ideas to students” (3BF, 15-16). These definitions and the subsequent dialogue lacked an abundance of examples of how an instructor might use modeling in the classroom, but they did give a hint as to how these participants might use modeling.

Their definitions were overwhelmingly reminiscent of the definition of expository modeling put forth in this work, implying a goal of deeper understanding beyond simply the illustration and naming of components yet not including the creation, testing, and revising of ideas as to be qualified as explanatory modeling, perhaps an area of improvement for these participants in the future. As the category of explanatory modeling is regarded as the highest level of modeling, it is our hope that additional educational courses and practical experience will aid the participants to expand their understanding of both the conceptual side of models and the skills necessary to use explanatory modeling within their classrooms.

As aforementioned and shown in frequency of use from the transcribed interviews (Figures 10-15), the overwhelming abundance of modeling was expository in nature.

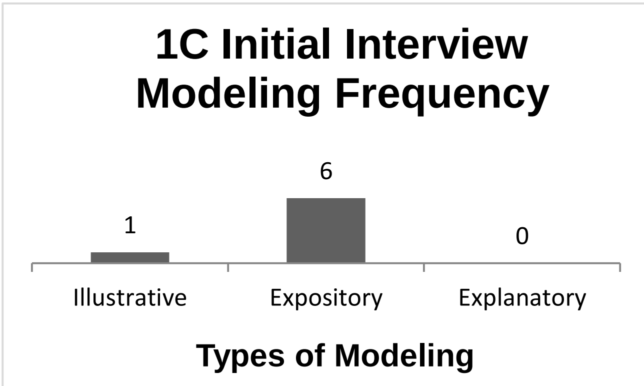

Figure 10. Participant 1C Initial Modeling Frequency

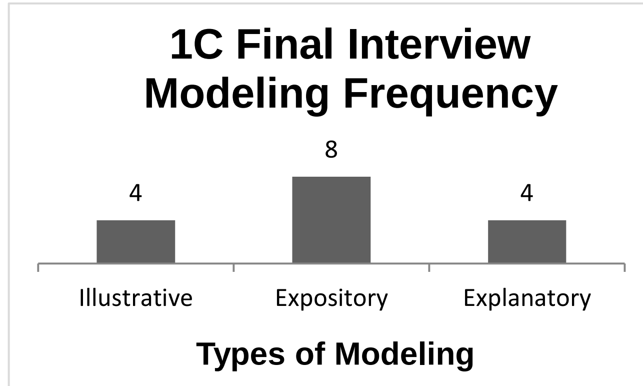

Figure 11. Participant 1C Final Modeling Frequency

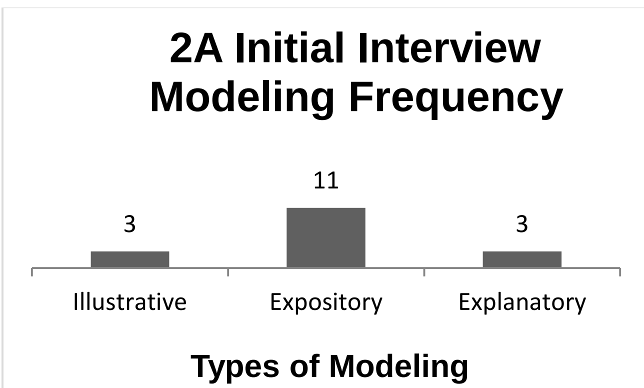

Figure 12. Participant 1C Initial Modeling Frequency

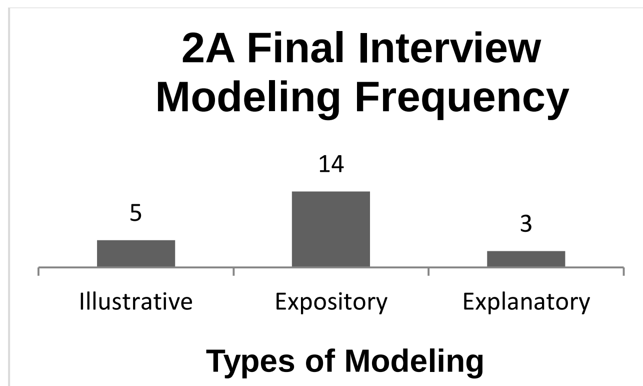

Figure 13. Participant 1C Final Modeling Frequency

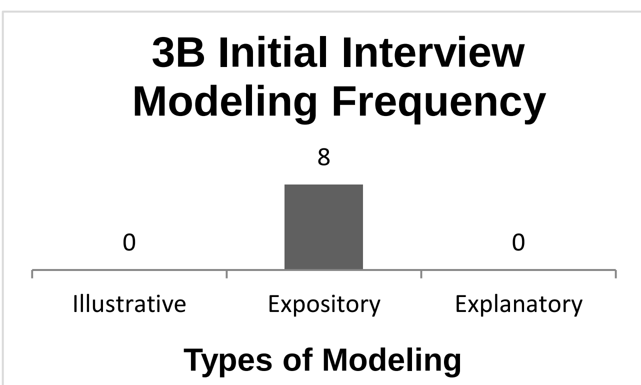

Figure 14. Participant 1C Initial Modeling Frequency

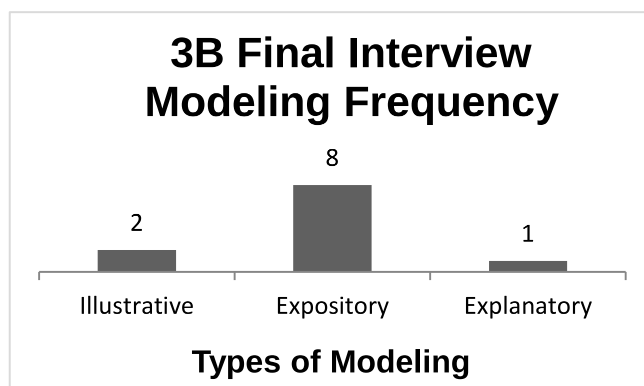

Figure 15. Participant 1C Final Modeling Frequency

Table 4. Total Participant Usage of Models and Modeling

This table serves as an analysis of the total usages of models and modeling as shown by the participants during their interviews as delineated into the two categories of model and three categories of modeling defined within this work. In some instances, as noted in Appendices D-I, a type of model or modeling was unclear and was omitted or multiple forms of model or modeling were used and were counted twice.

Participant	Frequency Of Model Use	Frequency of Modeling Use
1C	*Physical* (17)	*Illustrative* (4)
		Expository (10)
		Explanatory (3)
	Conceptual (12)	*Illustrative* (1)
		Expository (9)
		Explanatory (1)
2A	*Physical* (24)	*Illustrative* (8)
		Expository (17)
		Explanatory (4)
	Conceptual (18)	*Illustrative* (5)
		Expository (15)
		Explanatory (3)
3B	*Physical* (14)	*Illustrative* (2)
		Expository (14)
		Explanatory (1)
	Conceptual (6)	*Illustrative* (1)
		Expository (7)
		Explanatory (1)

Examples of Models and Modeling

In terms of practical examples, the participants were able to divulge some instances of models and modeling they had used or planned to use in their future classrooms.

Participant 1C mentioned having her students "draw a model of [an] alternative energy source so that their peers could see what it looked like. They [The students] had to reference it and explain how it worked, what natural resource it used to generate energy, and then the benefits and downsides of it" (1CF, 28-30). She added that her students could "use large white boards so that everyone could see it" (1CF, 36) and that the point of the exercise was "more like recalling and pointing out parts" (1CF, 37-38). The modeling described with this activity has both illustrative components (point out components, recall, physical description, etc.) but also had expository components, with discussion about benefits and detriments and explanation about how the alternative energy source worked. This participant included a copy of the assessment rubric she used, with increasing point values available if students demonstrate 'understanding of how alternative energy sources works by making use of models when explaining how alternative energy sources works.'

Here, in her own words, Participant 1C has placed emphasis on students going beyond the labeling and identification of components to an expository understanding, allowing for them to teach their classmates and thereby demonstrate a deeper level of comprehension.

Participant 2A, when discussing practical examples of models and modeling, noted the importance of anatomy, speaking about the use of "sheep brains and cow spinal cords" (2AI, 232) and how this work focused on "figuring out which part was the medulla, the pons, and that's basically memorization and not application" (2AI, 234-235).

She emphasized the importance of application, stating that her professor, when assessing students, used “questions that you had to go back to a whole bunch of models you had learned to answer one question” (2AI, 236-237). In this way, it was not simple notation of location and composition of the dissected objects, but deeper conceptual understandings that had been developed by working with multiple models. In this way, similar to Participant 1C, she gave examples of both illustrative and expository modeling, first illustrative (to identify the components) and later expository (to explain and draw trends). Lacking again was an emphasis on explanatory modeling, the creation, testing, and revision of ideas, or an acknowledgement that the understanding needed to complete the assessments itself required a working conceptual model of the specimens studied. These exercises seemed to be ‘cookbook exercises’ which did not allow for students to work with their own ideas, engendering in students a desire to ‘finish the recipe’ as it were instead of gaining real comprehension.

Participant 3B, like her colleagues, gave examples of mostly physical models paired with illustrative and expository modeling. When describing a photosynthesis activity, she described how “students would actually hold parts of the photosynthesis process and move physically using Nerf balls. They could use Nerf balls as molecules and in that way create an interactive way to demonstrate the process to the class” (3BI, 62-64). The Nerf balls and students, creating a physical model of photosynthesis, allow for both illustrative and expository modeling. Students work to identify the components and their location within the process, (illustrative modeling), while also watching and studying the photosynthetic process take place, (expository modeling).

She also suggested “using paper plates and pipe cleaners to represent chromosomes and demonstrate meiosis. By the use of modeling, they were able to physically demonstrate their understanding of meiosis” (3BI, 65-67). She provided a copy of the worksheet she used for this, entitled ‘Meiosis Comprehension Project.’ This document, with a primary focus on identification of components, also contains a number of questions that require students to gain a deeper conceptual understanding of the process beyond simple identification. Sample questions include, ‘How does meiosis lead to increased genetic variation?’ and ‘How would the gametes be affected if a pair of chromatids failed to separate in the second meiotic division?’ These questions demand more from students than to count chromosomes or locate genetic material – They should be able to synthesize their own understanding of the process they had simulated.

Similarities and Differences between NGSS and Participant Model and Modeling Usage

Participant 1C, when asked about models and modeling as portrayed in the NGSS, stated that “I interpret that [models and modeling] from NGSS is students physically making something; I think they also included it as students analyzing their data and communicating that verbally or through written work” (1CF, 9-11). After studying the Models & Modeling information in Appendix F, Participant 1C clarified, stating that she hadn’t been “thinking about including the scientific processes” (1CF, 74) and felt that the NGSS, while doing a good job explaining modeling, left “room for multiple interpretations” (1CF, 95).

For Participant 2A, her definition of modeling as “using a representation to assist in the understanding of concepts within life” (2AF, 81) went unchanged after studying the NGSS document, noting that the use of “diagrams, physical replicas, mathematical representations, analogies, and computer simulations…are stereotypical” (2AF,125-126). This participant felt confident in her analysis of models and modeling, going on to say that “models are often used to explain certain things, for students to see how certain mechanisms actually work, making theories seem a little more tangible through models even though it may not be exact, and giving students a visual cue to learn what it is that is being taught” (2AF, 18-21). This participant, however, ultimately felt that the NGSS definitions of models made her feel “more constrained in what it is that I can write down as what sort of modeling I used or what it is that I can write in a lesson plan including models” (2AF, 150-151).

Participant 3B initially stated models are a “physical representation of a real-life concept within science” (3BF, 74) and modeling simply “using these models or items in order to represent a certain scientific idea” (3BF, 78-79). After reviewing the NGSS statement on models and modeling, she improved her definition, clarifying that “models aren’t just limited to physical representations or diagrams but they’re pretty much anything. Modeling is a bit broader than I initially assumed” (3BF, 93-94). However, her new understanding of modeling caused anxiety; she noted a desire to see “what more examples of modeling would be because I’m still not very clear – They give broad examples but not specific examples, so I’d be interested in seeing what a model is, maybe some specific examples” (3BF, 97-99). Participant responses support the hypothesis that the exact definitions of models and modeling are unclear and in need of practical exemplars.

All three participants showed varying levels of competency in their understandings and uses of models and modeling in comparison to the NGSS standards. No participant incorporated all the qualities of models and modeling as is presented in the standards, but each participant offered their own interpretation of models and modeling and seemed to gain clarity and confirmation after reviewing the NGSS document.

Chapter V. General Conclusions

As a result of the data analysis, there were several main points in regards to the unique understandings and use of models and modeling by the participating pre-service secondary science teachers. An analysis of the relevant literature, participants' interview responses, instructional materials, and concept maps aided in the creation of the model and modeling categories. Models were often described in the physical sense, with participants often unable to clearly explain modeling itself although their definitions and descriptions most closely aligned with expository modeling. In addition, participants lacked a deeper understanding of the conceptual side of models and failed to adequately describe or demonstrate the use of explanatory modeling.

Each of the three participants gave a multitude of descriptions, affirming "there is considerable diversity among definitions and descriptions of scientific models" (Bailer-Jones, 2002, p. 291) although each seemed to favor models in the physical sense but lacked the conceptual side of models as described and examined in the literature, that "models can be highly abstract and are certainly no longer seen as merely heuristic devices or visual aids" (Bailer-Jones, 2002, p. 298). When discussing the use of models, participants named objects and items to aid teaching, but none described models as a set of ideas or the brainstormed idea students must have before attempting to truly understand a given concept. While in line with Van Der Valk in that "a model is always a representation of the target, but the way in which the target is represented in the model (e.g. three dimensional model, mathematical equation) may be quite different, mostly depending on the purpose of the model" (2007, p. 471), an acknowledgement and understanding of the purely conceptual side of models is an area of improvement for these participants.

The participant's definitions were mostly akin to the definition of *physical model* given in this study in that they 'represent' something within the content but lacked emphasis on the conceptual side of models or specifics about how these physical models could be used to gain conceptual understanding. It is likely given further instruction, participants might be “able to select, develop and/or change, existing curricular models related to the topics to be taught” (Gilbert, 2004, p. 127) but it would benefit all involved if the science education community would consolidate their numerous definitions to eliminate confusion caused by unfamiliar nomenclature.

Each participant demonstrated a lack of understanding about modeling as well. Within the literature, modeling is shown to be the process individuals go through to gain understanding of given material, able to “influence and constrain the kinds of questions scientists ask about the natural world and the types of evidence they seek in support of particular arguments” (Passmore, et al., 2002, p. 189), essentially guiding the process of inquiry and discovery, “introducing students to important explanatory models in scientific disciplines and providing opportunities for them to use, revise, and assess those models in realistic ways” (Passmore, et al., 2002, p. 187). Modeling can be summarized as a “higher-order process skill” (Akerson, et al., 2009, p. 22) incorporating numerous skills and activities to be completed by scientists, instructors, and students alike including “observing, questioning, hypothesizing, predicting, collecting, analyzing data, and formulating conclusions” (Akerson, et al., 2009, p. 22).

It was evident participants with more experience and content hours with models and modeling were better able to define them. Like teaching through inquiry, models and modeling are ideas that require specific explanation and are not something taught by proxy. One purpose of this work was to attempt to clarify modeling itself by delineating it into three forms, ideally used by an effective educator in tandem with a physical or conceptual model to move students beyond a cursory understanding (available with illustrative modeling) to a point of real comprehension (available with expository and explanatory modeling).

In this way, the three categories of modeling serve to parallel Bloom's Taxonomy and its "increasing complexity and a cumulative hierarchical structure" (Anderson, 1999, p.8). Just as instructors use the two forms of model and three increasing levels of modeling to facilitate student progress from cursory understandings to deep comprehension, they are suggested to work through the skills described in Bloom's Taxonomy including "the six major cognitive objects (recall, comprehension, application, analysis, synthesis, and evaluation)" (Kegan, 1977, p. 67).

With illustrative modeling, the simplest form of modeling, we as educators expect our students to be able to label, identify, and locate various systems or components within a system. This is most similar to recall and comprehension as discussed by Bloom. With expository modeling, as we begin to probe our students' understanding beyond simple notation and identification, we parallel Bloom's application and analysis. We expect our students to be able to point out systems or components of systems already – Now, we begin to ask our students to think critically about them. Finally, with explanatory modeling, the highest level of modeling as described within this work, we as educators expect our students to be readily able to synthesize and evaluate new ideas about the given material. Beyond simple identification and more complex than the interplay between different elements, we now drive our students to create, test, and revise their own ideas about the topics presented, ideally beginning to form their own questions and respective solutions.

As educators, if we are able to guide our students through these three forms of modeling (with either a physical or conceptual model), we will have not only worked through the vague NGSS standards but engendered in our students a deep (and working) understanding of the scientific practices our curriculums should mimic.

The NGSS, for all their eloquence, leave too much room for interpretation, shown clearly when each participant looked through the NGSS Models & Modeling document and interpreted given phrases and terms in different ways. While some teachers may feel uncomfortable with the NGSS offering suggestions for instruction, the language in these standards should be clarified and elaborated in such a way any teacher can effectively pick a useful model and design a lesson so as to work through these forms of modeling.

As prospective educators prepare for their teaching careers, it is imperative that preparatory courses contain dedicated work on models and modeling – "Through the use of models and simulated practice, teachers can discover how the [modeling] methods are implemented in actual practice" (Boiarsky, 1985, p. 28). In addition, future educators must be provided "theoretical aspects followed by actual implementation of methods" allowing trainers to "demonstrate the relationships between theory and practice" (Boiarsky, 1985, p.28). For students, it is imperative that "modeling activities are diversified so as to help individual students develop a balanced diversity of skills pertaining to both exploratory inquiry and inventive research" (Halloun, 2007, p. 675) – Scientists, instructors, and students must work to incorporate models and modeling into their teaching practice to create an inclusionary, differentiated, and robust environment for students.

The findings of this study will benefit those in the science education community, (notably instructors of pre-service teachers), professional development programs, and in-service teachers who may gain clarification about models and modeling. It is our hope that programs instructing future teachers will give model and modeling renewed focus and providing practical examples coupled with clear unambiguous terminology. Professional development programs, usually working with in-service teachers, can help educators to also gain clarification and gain confidence in describing and using these terms in their teaching practice, lesson plans, and curriculum.

Limitations of the Study

Limitations in this study included a small sample size along with only a few forms of evidence available for analyzing. It would have been ideal to include more participants to get a wider range of responses and instructional artifacts. The evidence collected, transcribed interview responses, instructional materials, and imported concept maps, offered a glimpse of teacher practices and understanding, but the lack of classroom observations removed the ability to observe these practices and materials put to practical use. It may have also been beneficial to conduct the study over a longer period of time with additional interviews to determine if participant conceptions changed over time.

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Appendix

Appendix A. Interview Protocol

Introduction

Thank you for your agreement to participate in this study.

Before we begin, do you have any questions or concerns about the Informational Flyer or the study itself? *Await response.*

This interview is being recorded for research purposes. Please let me know if you do not agree to being recorded. You may request that the recording stop at any time.

Do you agree to being recorded? *Await response.*

The recording will now begin. *Begin recording.*

Initial Interview (30-45 minutes)

1. Tell me about the science subject(s) you plan to teach?
2. What are some of the core ideas in your subject area?
3. What are the instructional strategies you will use to teach your subject?
4. Tell me about the scientific practices listed in the NGSS? *Show list of Practices.*
5. Can you indicate the practices that you are familiar with? We will be focusing on models and modeling in this study.
6. Tell me about 'models and modeling.' Take a few minutes and draw a diagram.
7. Tell me about your diagram.
8. Tell me about your experience with models and modeling in the collegiate science courses you have taken.
9. Tell me about some topics that you might use models and modeling to teach?
10. What do you think is the purpose of using models and modeling in instruction?
11. What challenges do you foresee in using models and modeling in your instruction?
12. How do models and modeling help students understand scientific concepts?

Final Interview (30-45 minutes)

1. Tell me what you know about scientific practices in NGSS.
2. Tell me what you know about models and modeling in NGSS.
3. What do you think are the reasons for the emphasis on modeling in NGSS?
4. Tell me about the instructional materials you brought.
5. How did you use models and modeling in relation to these instructional materials?
6. How would you define models and modeling in the context of science education?

   [NGSS Models & Modeling Related Standard Statements will be provided.]
7. Please read the provided NGSS statement. What do you think about models and modeling as it is described in each statement?
8. What are the similarities and differences between your definition of modeling and the definition laid out in the standards?
9. What are some questions you might have if you were asked to design your science instruction in alignment with this statement?
10. How does the NGSS (or NSES) influence your understanding and use of modeling?

Appendix B. Informational Flyer

Project Title: Pre-Service Secondary Science Teachers' Understanding and Use of Modeling
Principal Investigator: Bryan J. Meeker **Faculty Sponsor:** Dr. Eunmi Lee
Institution: DePaul University – Chicago, IL

The purpose of this study is to explore pre-service secondary science teachers' understanding and use of modeling in their instruction as described by NGSS (Next Generation Science Standards) and National Science Education Standards (NSES).

If you agree to be in this study, you will be asked to participate in two interviews at the College of Education, (30-45 minutes), held two weeks apart to explore pre-service secondary science teachers' understanding and use of modeling; both undergraduate and graduate students are eligible for participation. The two interviews are intended to help us better understand pre-service teachers' perceptions about models and modeling.

The first interview will include:

a) **Q&A session about Modeling** (audio-recorded using the Pulse Smartpen system) – If there are questions you do not wish to answer, you may skip them. The interview will be recorded for research purposes. Please let us know if at any time during the interview you wish me to stop recording.

The second interview will include:

a) **Q&A session about Modeling** (audio-recorded using the Pulse Smartpen system) – These questions will be about models and modeling related to the standards.
b) **Instructional Materials** – We will request that you bring hard-copy or electronic versions of any science instructional materials that you generated from any coursework (including but not limited to lesson plans, assessments, learning aids, worksheets, etc.) Hard-copy materials will be returned and electronic versions will be discarded at the conclusion of the study.

Your information will be confidential – Pseudonyms will be used, and audio recordings of the interviews will be used to create a transcript and destroyed at the completion of the study.

Your participation is strictly voluntary. Participants can withdraw at any time without penalty during the study. Collected data from these participants will be destroyed. Please inform Mr. Meeker or Dr. Lee and we will respect your wishes. There will be no negative consequences if you decide not to participate or change your mind later after you begin the study. There is no remuneration for participation, and the total participation time for this study should be between 90-120 minutes.

Contact information- If you would like to participate in this study or have questions or concerns, please contact Mr. Meeker (bryanjmeeker@gmail.com or 217-898-9982) or Dr. Eunmi Lee (elee38@depaul.edu or 773-325-4745).

If you have questions about your rights as a research subject you can contact Susan Loess-Perez, DePaul University's Director of Research Compliance, Office of Research Services at sloesspe@depaul.edu or 312-362-7593.

You can also contact DePaul's Office of Research Services if:

- Your questions, concerns, or complaints are not being answered by the research team.
- You wish to talk to someone besides the research team or cannot reach the research team.

Thank you again for your consideration; you may keep (or print) this information for your records.

Appendix C. NGSS Models & Modeling Standards & Functionality Analysis

This analysis of the NGSS is a sorting of the standards based upon my literature review, my own practical teaching experiences, and the constructed categories aforementioned within this work. The first bullet point denotes whether the standard likely uses a physical or conceptual model. The second bullet point denotes which type of modeling would most likely be used by an instructor to effectively use the model. It should be noted that an effective instructor should use multiple types of modeling in an effort to create an active differentiated learning environment for our increasingly diverse body of students. It is my hope that the inclusion of practical examples and suggestions for instruction will assist educators to plan an effective robust curriculum.

K-ESS3-1.
Use a model to represent the relationship between the needs of different plants and animals (including humans) and the places they live.

- This standard likely uses a **physical** model, e.g. a *map, diagram, or demonstration*
- This standard likely uses **expository** modeling as it expresses a relationship between components and not simply the location and naming of components within nor does it lend itself easily to creation, testing, or revision of ideas.

2-LS2-2.
Develop a simple model that mimics the function of an animal in dispersing seeds or pollinating plants.

- This standard likely uses a **physical** model, e.g. a *map, diagram, or demonstration.*
- This standard likely uses **expository** modeling as it expresses the function of a component within a system and not simply the location and naming of components within nor does it lend itself easily to creation, testing, or revision of ideas.

2-ESS2-2.
Develop a model to represent the shapes and kinds of land and bodies of water in an area.

- This standard likely uses a **physical** model, e.g. a *map, diagram, or demonstration.*
- This standard likely uses **illustrative** modeling as the main focus of the standard appears to be the ability to denote and delineate between different features and not a deeper conceptual understanding of the geography itself. It also does not lend itself easily to creation, testing, or revision of ideas.

K-2-ETS1-2.
Develop a simple sketch, drawing, or physical model to illustrate how the shape of an object helps it function as needed to solve a greater problem.

- This standard likely uses a **physical** model, e.g. a *drawing, diagram, or demonstration.*
- This standard likely uses **expository** modeling as the main focus of this standard is to have students think about the ways the shape might affect function and not simply the location and naming of components. It does not lend itself to creation, testing, or revision of ideas.

3-LS1-1.
Develop models to describe that organisms have unique and diverse life cycles but all have in common birth, growth, reproduction, and death.

- This standard likely uses a **conceptual** model, e.g. *brainstorming, imagining, or visualizing.*
- This standard likely uses **expository** modeling as it involves broad stages of life and a deeper understanding needed to compare organisms. It involves more than the location and naming of components. It does not lend itself to creation, testing, or revision of ideas.

4-PS4-1.
Develop a model of waves to describe patterns in terms of amplitude and wavelength and that waves can cause objects to move.

- This standard likely uses a **physical** model, e.g. a *drawing, simulation, or demonstration*
- The standard likely uses **explanatory** modeling as it involves students creating, testing, and revising their understandings of the patterns mentioned. It is more detailed than simply naming or locating components and also seems to imply experimentation.

4-PS4-2.
Develop a model to describe that light reflecting from objects and entering the eye allows objects to be seen.

- This standard likely uses a **physical** model, e.g. a *drawing, diagram, or demonstration*.
- The standard likely uses **expository** modeling as it involves students doing more than naming or locating components but rather attempting to understand the concepts at a deeper level. This standard does not seem to lend itself to creation, testing, or revision of ideas.

4-LS1-2.
Use a model to describe that animals receive different types of information through their senses, process the information in their brain, and respond to information in different ways.

- This standard likely uses a **conceptual** model, e.g. *brainstorming, imagining, or visualizing.*
- The standard likely uses **expository** modeling as it involves students doing more than naming or locating components but rather attempting to understand the concepts at a deeper level. This standard does not seem to lend itself to creation, testing, or revision of ideas.

5-PS1-1.
Develop a model to describe that matter is made of particles too small to be seen.

- This standard likely uses a **physical** model, e.g. a *drawing, diagram, or demonstration.*
- The standard likely uses **expository** modeling as it states students should do more than name and locate the aforementioned particles but garner a deeper understanding of their properties and interactions. It does not lend itself easily to the creation, testing, or revision of ideas.

5-PS3-1.
Use models to describe that energy in animals' food (used for body repair, growth, motion, and to maintain body warmth) was once energy from the sun.

- This standard likely uses a **physical** model, e.g. a *drawing, diagram, or demonstration.*
- The standard likely uses **expository** modeling as students are expected to have a deeper conceptual understanding of this complex topic than simply being able to identify components. It does not lend itself easily to creation, testing, or revision of ideas.

5-LS2-1.
Develop a model to describe the movement of matter among plants, animals, decomposers, and the environment.

- This standard likely uses a **physical** model, e.g. a *drawing, simulation, or demonstration.*
- This standard likely uses **expository** modeling as students are expected to have a deeper conceptual understanding of the matter cycle than only being able to identify various components or systems. It does not lend itself easily to creation, testing, or revision of ideas.

5-ESS2-1.

Develop a model using an example to describe ways the geosphere, biosphere, hydrosphere, and/or atmosphere interact.

- This standard likely uses a **conceptual** model, e.g. *brainstorming, imagining, or visualizing.*
- This standard likely uses **expository** modeling as students should be able to do more than identify the layers, gaining a deeper conceptual understanding of how they interact. It does not, however, lend itself easily to creation, testing, or revising of ideas.

MS-PS1-1.

Develop models to describe the atomic composition of simple molecules and extended structures.

- This standard likely uses a **physical** model, e.g. a *drawing, 3-D structures, or simulations.*
- This standard likely uses **illustrative** modeling as the focus of student efforts seems to be simply the ability to describe the composition of simple molecules and structures. It does not lend itself easily to creation, testing, or revising of ideas.

MS-PS1-4.

Develop a model that predicts and describes changes in particle motion, temperature, and state of a pure substance when thermal energy is added or removed.

- This standard likely uses a **physical** model, e.g. a *drawing, diagram, or simulations.*
- This standard likely uses **expository** modeling as the standard states that students should be able to make predictions and descriptions (demonstrating a deeper knowledge than simply identifying the components of the given system.

MS-PS1-5.

Develop and use a model to describe how the total number of atoms does not change in a chemical reaction and thus mass is conserved.

- This standard likely uses a **conceptual** model, e.g. *mathematics, imagining, or visualizing.*
- This standard likely uses **expository** modeling as the standard states students should be able to describe how the total number of atoms does not change, requiring a deeper conceptual understanding than simply identifying the reactants or products.

MS-PS3-2.
Develop a model to describe that when the arrangement of objects interacting at a distance changes, different amounts of potential energy are stored in the system.

- This standard likely uses a **physical** model, e.g. a *drawing, diagram, or demonstration.*
- This standard likely uses **expository** modeling as the standard states that students should be able to describe how the arrangement might affect potential energy, requiring a deeper conceptual understanding than simply being able to identify the components in the system. An effective instructor might be able to use explanatory modeling in a laboratory setting.

MS-PS4-2.
Develop and use a model to describe that waves are reflected, absorbed, or transmitted through various materials.

- This standard likely use a **physical** model, e.g. a *drawing, diagram, or demonstration.*
- This standard likely uses **expository** modeling as the standard states students should be able to describe how waves are reflected, absorbed, and transmitted, requiring a deeper conceptual understanding than only identifying the components of the system. An effective instructor could use explanatory modeling here in a laboratory setting.

MS-LS1-2.
Develop and use a model to describe the function of a cell as a whole and ways parts of cells contribute to the function.

- This standard likely uses a **conceptual** model, e.g. *brainstorming, imagining, or visualizing.*
- This standard likely uses **expository** modeling as the standard states students should garner a conceptual understanding of the relationship between components of the cellular system. It does not lend itself easily to the creation, revision, or testing of ideas.

MS-LS1-7.
Develop a model to describe how food is rearranged through chemical reactions forming new molecules that support growth and/or release energy as this matter moves through an organism.

- This standard likely uses a **conceptual** model, e.g. *brainstorming, imagining, or visualizing.*
- This standard likely uses **expository** modeling as the standard states that students should be able to work through this complex process on a level higher than simple identification but not on a level of creation, testing, and revision of ideas as in an experiment.

MS-LS2-3.
Develop a model to describe the cycling of matter and flow of energy among living and nonliving parts of an ecosystem.

- This standard likely uses a **physical** model, e.g. a *drawing, diagram, or demonstration.*
- This standard likely uses **expository** modeling as the standard states that students should be able to do more than simply identify components (here perhaps within a food web or flowchart) but not at a level of creation, testing, and revision of these ideas.

MS-LS3-1.
Develop and use a model to describe why structural changes to genes (mutations) located on chromosomes may affect proteins and may result in harmful, beneficial, or neutral effects to the structure and function of the organism.

- This standard likely uses a **physical** model, e.g. a *drawing, simulation, or demonstration.*
- This standard likely uses **expository** modeling as the standard states students should make a connection between mutations and their effects but 'does not include specific changes at the molecular level, mechanisms for protein synthesis, or specific types of mutations.'

MS-LS3-2.
Develop and use a model to describe why asexual reproduction results in offspring with identical genetic information and sexual reproduction results in offspring with genetic variation.

- This standard likely use a **physical** model, e.g. a *drawing, simulation, or demonstration*
- This standard likely uses **expository** modeling as students should work through tasks (perhaps here using a Punnett Square) to gain an understanding of the effects of reproduction beyond only identifying the potential genotypes and phenotypes of offspring. An effective instructor might use explanatory modeling here in a laboratory setting.

MS-ESS1-1.
Develop and use a model of the Earth-sun-moon system to describe the cyclic patterns of lunar phases, eclipses of the sun and moon, and seasons.

- This standard likely use a **physical** model, e.g. a *drawing, 3-D structure, or simulation.*
- This standard likely uses **expository** modeling as the standard implies that students should get a deeper understanding of the processes involved more than just simple identification. It does not lend itself easily to creation, testing, or revision.

MS-ESS1-2.
Develop and use a model to describe the role of gravity in the motions within galaxies and the solar system.

- This standard could use a **physical** or **conceptual** model, e.g. a *diagram or simulation* (physical) or a *focus on the mathematical equations and proportions* (conceptual).
- The standard likely uses **expository** modeling with either type of model as the standard implies students should gain a deeper understanding of gravity in the cosmos. The vast implications of this standard do not lend themselves easily to creation, testing, or revision.

MS-ESS2-1.
Develop a model to describe the cycling of Earth's materials and the flow of energy that drives this process.

- This standard likely uses a **physical** model, e.g. a *drawing, simulation, or demonstration.*
- This standard likely uses **expository** modeling as the standard states that a deeper understanding is needed than identification or naming but does not lend itself easily to the creation, testing, or revision of ideas.

MS-ESS2-4.
Develop a model to describe the cycling of water through Earth's systems driven by energy from the sun and the force of gravity.

- This standard likely uses a **physical** model, e.g. a *drawing, simulation, or demonstration.*
- This standard likely uses **expository** modeling as the standard states that a deeper understanding is expected beyond only identification or naming. However, it does not lend itself easily to the creation, testing, or revision of ideas.

MS-ES22-6.
Develop and use a model to describe how unequal heating and rotation of the Earth cause patterns of atmospheric and oceanic circulation that determine regional climates.

- This standard likely uses a **physical** model, e.g. a *drawing, simulation, or demonstration.*
- This standard likely uses **expository** modeling as the standard itself is complex and would require a great deal of elaboration and clarification by the instructor. This vast topic does not lend itself easily to creation, testing, or revision of ideas.

MS-ETS1-4.
Develop a model to generate data for iterative testing and modification of a proposed object, tool, or process such that an optimal design can be achieved.

- This standard likely uses **physical** and **conceptual** models, e.g. *drawings, diagrams, or schematics* (physical) along with *brainstorming, imagining, or visualizing* (conceptual).
- This standard likely uses **explanatory** modeling as the standard states it is the process of creation, testing, and revising that is the primary focus of this standard.

HS-PS1-1.
Use the periodic table as a model to predict the relative properties of elements based on the patterns of electrons in the outermost energy level of atoms.

- This standard likely uses a **physical** model, e.g. a *table, diagram, or demonstration.*
- This standard likely uses **expository** modeling as the standard gives emphasis to students being able to do more than identify components but gather and achieve a deeper understanding about trends, similarities, and differences.

HS-PS1-4.
Develop a model to illustrate that the release or absorption of energy from a chemical reaction system depends upon the changes in total bond energy.

- This standard likely uses a **conceptual** model, e.g. *calculating, imagining, or visualizing.*
- This standard likely uses **expository** modeling as the standard emphasizes students being able to work through the mathematics (calculating the amount of energy released or absorbed based on the bonds being broken). With the utilization of a chart of bond energies, students should be able to become proficient with these calculations. It does not, however, lend itself easily to creation, testing, and revision of ideas.

HS-PS1-8.
Develop models to illustrate the changes in the composition of the nucleus of the atom and the energy released during the processes of fission, fusion, and radioactive decay.

- This standard likely uses a **conceptual** model, e.g. *calculating, imagining, or visualizing.*
- This standard likely uses **expository** modeling as the standard emphasizes students being able to work through the mathematics (calculating the amounts of fission, fusion, decay, etc.) and make relevant assumptions and predictions. It does not, however, lend itself easily to creation, testing, and revision of ideas.

HS-PS3-2.

Develop and use models to illustrate that energy at the macroscopic scale can be accounted for as a combination of energy associated with the motions of particles (objects) and energy associated with the relative position of particles (objects).

- This standard likely uses a **physical** model, e.g. a *drawing, diagram, or simulations.*
- This standard likely uses **expository** modeling as the standard emphasizes an understanding of the interaction between components rather than simple identification or naming. With a topic as complex as this, it is likely instructors would want to give students something tangible to work with otherwise not possible in the classroom.

HS-PS3-5.

Develop and use a model of two objects interacting through electric or magnetic fields to illustrate the forces between objects and the changes in energy of the objects due to the interaction.

- This standard likely uses a **physical** model, e.g. a *drawing, diagram, or simulation.*
- This standard likely uses **expository** modeling to emphasize interactions between components rather than identification. With a topic this complex, instructors would likely give students something tangible to work with otherwise not be possible in the classroom.

HS-LS1-2.

Develop and use a model to illustrate the hierarchical organization of interacting systems that provide specific functions within multicellular organisms.

- This standard likely uses a **physical** model, e.g. a *drawing, simulation, or demonstration.*
- This standard likely uses **expository** modeling as the complexity of the material might necessitate instructors giving students something tangible to both narrow their focus and provide tangible manipulatives to assist in their comprehension.

HS-LS1-4.

Use a model to illustrate the role of cellular division (mitosis) and differentiation in producing and maintaining complex organisms.

- This standard likely uses a **physical** model, e.g. a *drawing, simulation, or demonstration.*
- This standard likely uses **expository** modeling to emphasize an understanding of the role and relationship between different components instead of only identification. An effective instructor might be able to use explanatory modeling to test student comprehension.

HS-LS1-5.
Use a model to illustrate how photosynthesis transforms light energy into stored chemical energy.

- This standard likely uses both **physical** and **conceptual** models, e.g. *drawings or diagrams* (physical) as well as *mathematical equations* (conceptual).
- This standard likely uses **expository** modeling to assist students in gaining a deeper understanding than being able to name the components within. This standard could use explanatory modeling if an instructor were to devise a laboratory experiment to allow students to create, revise, and test their hypotheses about photosynthesis.

HS-LS1-7.
Use a model to illustrate that cellular respiration is a chemical process whereby the bonds of food molecules and oxygen molecules are broken and the bonds in new compounds are formed resulting in a net transfer of energy.

- This standard likely uses a **conceptual** model, e.g. *mathematics, imagining, and visualizing.*
- This standard likely uses **expository** modeling as students should not only be able to work through the mathematics to confirm a net transfer of energy but also understand the nature and importance of both the inputs and outputs in the respiration equation.

HS-LS2-5.
Develop a model to illustrate the role of photosynthesis and cellular respiration in the cycling of carbon among the biosphere, atmosphere, hydrosphere, and geosphere.

- This standard likely uses both **physical** and **conceptual** models, e.g. *drawings or diagrams to assist in organization* (physical) along with *mathematics and brainstorming* (conceptual).
- This standard likely uses **expository** modeling as students should be able to do more than work through the mathematics or identify components in these processes. Given the vast nature of this standard, it does not lend itself to the creation, testing, or revising of ideas.

HS-ESS1-1.
Develop a model based on evidence to illustrate the life span of the sun and the role of nuclear fusion in the sun's core to release energy in the form of radiation.

- This standard likely uses both **physical** and **conceptual** models, e.g. *drawings or diagrams to aid in elucidation about nuclear fusion* (physical) along with *mathematics and brainstorming to aid in determining the aforementioned numerical values* (conceptual).
- This standard likely uses **explanatory** modeling as students should do more than identify components or solve mathematical problems. Given the vast nature of this standard, it does not lend itself easily to the creation, testing, or revising of ideas, but the standard's emphasis on 'evidence' implies students should work with their ideas about the lifespan of the sun.

HS-ESS2-1.
Develop a model to illustrate how Earth's internal and surface processes operate at different spatial and temporal scales to form continental and ocean-floor features.

- This standard likely uses a **physical** model, e.g. a *drawing, diagram, or simulation.*
- This standard likely uses **expository** modeling as students should be able to do more than identify components of the Earth's structure but given the vast nature of this standard, the creation, revision, and testing of ideas is unlikely.

HS-ESS2-3.
Develop a model based on evidence of Earth's interior to describe the cycling of matter by thermal convection.

- This standard likely uses a **physical** model, e.g. a *map, seismic diagrams, or drawings.*
- This standard likely uses **explanatory** modeling as the standard places emphasis on the use of 'evidence' in demonstrating understanding. Students should be able to do more than identify and elaborate on components of convection, but be able to create, revise, and test their ideas about convection itself based on the available evidence.

HS-ESS2-4.
Use a model to describe how variations in the flow of energy into and out of Earth's systems result in changes in climate.

- This standard likely uses a **conceptual** model, e.g. *brainstorming, imagining, or visualizing*
- This standard likely uses **expository** modeling as students should be able to gain a deeper understanding than to only identify components in climate change but the vast nature of this standard likely precludes students from creating, revising, or testing their ideas.

HS-ESS2-6.
Develop a quantitative model to describe the cycling of carbon among the hydrosphere, atmosphere, geosphere, and biosphere.

- This standard likely uses both **physical** and **conceptual** models, e.g. *drawings or diagrams to assist in organization* (physical) along with *mathematics and brainstorming* (conceptual).
- This standard likely uses **expository** modeling as students should be able to do more than work through the mathematics or identify components in these processes. Given the vast nature of this standard, it does not lend itself to the creation, testing, or revising of ideas.

Appendix D. Models and Modeling Transcript Analysis (Candidate 1C Initial Interview)

Data (Line of Transcript)	Type of Model	Type of Modeling	Notes
45	Conceptual	Illustrative	
61	Conceptual		The participant only mentions a physical model but does not state anything about how it can be used.
64	Conceptual	Expository	
69-72	Physical or Conceptual	Expository	It is unclear if the participant is referring to a physical (diagram) or conceptual model (having students brainstorm). It is likely physical as dimensions are listed.
122	Conceptual	Expository	
123	Physical	Expository	
133-136	Physical or Conceptual	Expository	It is unclear if the participant is referring to a physical or conceptual model here.
158-159	Conceptual	Expository	

Appendix E. Models and Modeling Transcript Analysis (Candidate 1C Final Interview)

Data (Line of Transcript)	Type of Model	Type of Modeling	Notes
9	Physical		It is unclear from the participant what is being done with the physical model that has been created.
10	Conceptual	Expository	
28	Physical	Illustrative	
29	Physical	Expository	
36	Physical	Illustrative	
38	Physical	Illustrative	
47	Physical	Expository	
51	Physical	Explanatory	Participant talks about modeling as a process leading to the creation of a physical model.
58	Physical or Conceptual	Explanatory	It is unclear from the participant what kind of model is being discussed, but it is stated that students should be evaluating and refining them.
65	Physical	Illustrative and Expository	
66	Conceptual	Expository	
68	Physical	Expository	
74-78	Physical or Conceptual	Explanatory	It is unclear from the participant what kind of model is being discussed, but she states that they should revise them based on accumulated evidence.
111	Physical and Conceptual	Expository	The participant names both physical (diagrams, replicas) and conceptual (mathematical representations) here.
112-113	Physical	Expository	
119-121	Physical	Explanatory	

Appendix F. Models and Modeling Transcript Analysis (Candidate 2A Initial Interview)

Data (Line of Transcript)	Type of Model	Type of Modeling	Notes
88	Physical	Expository	
89	Physical	Illustrative	
91-94	Physical	Explanatory	
171	Conceptual	Expository	It is unclear what the participant means by 'validating' although a pen making an interview validated is not the same usage of models as was discussed earlier; it is far more abstract.
173	Physical	Expository	
174	Physical	Expository	
182	Physical	Expository	It is unclear what the participant meant by the paper being a model for the interview process; this is a far more abstract sense of representation and modeling than was discussed earlier.
188	Conceptual	Expository	Using the teacher as a model for teaching is not the same usage of models as was discussed earlier; it is far more abstract.
191	Physical	Expository	
193	Physical	Illustrative	
207	Physical	Illustrative	
220	Physical	Explanatory	
232	Physical	Expository	
275	Physical	Expository	
292-293	Physical	Expository	The participant does not clarify what kinds of models 'everything' can be.
310	Conceptual	Expository	Using the teacher as a model for teaching is not the same usage of models as was discussed earlier; it is far more abstract.
332-335	Conceptual	Explanatory	

Appendix G. Models and Modeling Transcript Analysis (Participant 2A Final Interview)

Data (Line of Transcript)	Type of Model	Type of Modeling	Notes
18-21	Physical and Conceptual	Illustrative / Expository	Participant mentions that models are used 'to explain certain things,' but discusses both conceptual and physical examples.
26	Physical	Expository	
28	Conceptual	Expository	
31	Physical	Expository	
35	Conceptual	Expository	
62	Conceptual	Expository	
64	Conceptual	Expository	
72-73	Physical or Conceptual	Illustrative / Expository	Participant says 'a representation of a concept within life' but it is not clear if it is a conceptual or physical representation.
78	Physical or Conceptual	Illustrative / Expository	Participant says 'anything that can be used to take the place of an idea or concept in life' but it is not clear if it is a physical or conceptual representation.
81	Physical or Conceptual	Illustrative / Expository	Participant says 'using a representation to assist in the understanding of concepts within life' but it is unclear if it is a physical or conceptual representation.
97	Physical or Conceptual	Explanatory	
101-103	Physical and Conceptual	Expository	
112	Conceptual	Expository	
112	Conceptual	Explanatory	
117-118	Physical or Conceptual	Illustrative / Expository	Participant says models are used 'to generate data that can be used to communicate' but it is unsure if it is a physical or conceptual representation.
125-126	Physical and Conceptual	Expository	
141	Physical	Explanatory	

Appendix H. Models and Modeling Transcript Analysis (Candidate 3B Initial Interview)

Data (Line of Transcript)	Type of Model	Type of Modeling	Notes
48	Physical	Expository	
54	Conceptual	Expository	
59	Physical	Expository	
63	Physical	Expository	
65	Physical	Expository	
71-72	Physical	Expository	
84	Physical or Conceptual	Expository	Unclear what kind of model participant is referring to; ‘demonstrating concepts rather than just talking about them.’

Appendix I. Models and Modeling Transcript Analysis (Candidate 3B Final Interview)

Data (Line of Transcript)	Type of Model	Type of Modeling	Notes
15	Physical or Conceptual	Expository	Unclear of what kind of model participant is referring to, but ‘conveying ideas to students’ implies expository modeling.
21	Physical or Conceptual	Expository	Unclear of what kind of model participant is referring to, but ‘encourages a more interactive perspective’ implies expository modeling.
26-29	Physical or Conceptual	Expository	Unclear of what kind of model participant is referring to, but ‘think critically,’ and ‘engage students’ implies expository modeling.
33-35	Physical	Expository	
38	Physical	Illustrative	
43	Physical	Expository	
74	Physical	Expository	
79		Illustrative or Expository	Unclear what kind of model is being used, but the definition presented of modeling is ‘to represent a certain scientific idea’ which implies either illustrative or expository as ‘creation, testing, or revision’ is not stated.
90-95	Physical and Conceptual	Expository Explanatory	Participant states that initial conceptions of only physical models was narrow and should include broader conceptual ideas to represent different ideas, based on evidence.