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# An Investigation of Software Scaffolds Supporting Modeling Practices

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Abstract

Modeling of complex systems and phenomena is of value in science learning and is increasingly emphasised as an important component of science teaching and learning. Modeling engages learners in desired pedagogical activities. These activities include practices such as planning, building, testing, analysing, and critiquing. Designing realistic models is a difficult task. Computer environments allow the creation of dynamic and even more complex models. One way of bringing the design of models within reach is through the use of scaffolds. Scaffolds are intentional assistance provided to learners from a variety of sources, allowing them to complete tasks that would otherwise be out of reach. Currently, our understanding of how scaffolds in software tools assist learners is incomplete. In this paper the scaffolds designed into a dynamic modeling software tool called Model-It are assessed in terms of their ability to support learners' use of modeling practices. Four pairs of middle school students were video-taped as they used the modeling software for three hours, spread over a two week time frame. Detailed analysis of coded videotape transcripts provided evidence of the importance of scaffolds in supporting the use of modeling practices. Learners used a variety of modeling practices, the majority of which occurred in conjunction with scaffolds. The use of three tool scaffolds was assessed as directly as possible, and these scaffolds were seen to support a variety of modeling practices. An argument is made for the continued empirical validation of types and instances of tool scaffolds, and further investigation of the important role of teacher and peer scaffolding in the use of scaffolded tools.

Key Words: scaffolding, scaffolds, modeling practices, modeling software

## Introduction

The use and creation of models is gaining popularity as an effort of science education reform (Clement, 2000; Gilbert, Boulter, & Rutherford, 1998; Gobert & Buckley, 2000; Harrison & Treagust; 1996; National Research Council (NRC), 1996). Modeling is a specific benchmark for scientific literacy (American Association for the Advancement of Science (AAAS), 1993). Models are frequently used as an instructional tool in science education to highlight important information, such as concepts and structures of a system (Gobert & Discenna, 1997). Models play a vital role in the construction of scientific knowledge (Magnani, Nersessian, & Thagard, 1999). With the increasing use of computers in science and science-education, computer based modeling has become a powerful way to facilitate students'[1] modeling activities (Penner, 2001; Stratford, 1997; Windschitl, 2000).

Middle school students face a number of difficulties with models for science learning including limited experience in creating and using models and a lack of advanced mathematical skills. Over the past decade, numerous researchers have constructed increasingly sophisticated educational software tools to explicitly address the issue of how to support learners as they engage in challenging scientific tasks (Jackson, 1999; Linn, 1998; Quintana, 2001; NRC, 1996; White & Frederiksen, 1998).

Research on these various software tools suggests that scaffolded tools, which support learners as they accomplish tasks they are ready to attempt but cannot yet do alone, enable learners to better perform complex, authentic, and pedagogically relevant activities. Even quite young learners can engage in scientific inquiry when properly supported, contrary to common developmental assumptions (Metz, 1995). Much of the existing research on scaffolds assesses a group of scaffolds collectively, and often relies on indirect evidence of success, such as artifacts or test scores, though some recent work (Davis & Bell, 2001) has examined specific scaffolds directly. What is needed is to begin building a picture of how specific scaffolds or types of scaffolds help students. Drawing on the studies of modeling and of scaffolds in learning tools (Jackson, 1999; Linn, 1998; Quintana, 2001; White & Frederiksen, 1998), this study investigates how the scaffolds designed into a dynamic modeling software program support the use of modeling practices by science students. Specifically we ask:

a) How often do modeling practices occur in conjunction with the use of scaffolds built into the tool?
b) Which modeling practices are most effectively supported by certain specific scaffolds?
c) What does student use of scaffolding look like as they engage in modeling practices?

### *Models and Modeling Practices*

A model is a simplified representation of a system or phenomenon that focuses attention on specific aspects or components of a system, such as ideas, objects, events or processes (Gilbert, Boulter, & Rutherford, 1998; Ingham & Gilbert, 1991). These specific aspects can be either complex or on a different scale to that which is normally perceived (Gilbert, 1991). Models, therefore, can reveal the hidden structures or processes that are fundamental to an understanding of a system or a phenomenon (Glynn, Britton, Semrud-Clikeman, & Muth, 1989). Creating a model involves various activities, such as identifying variables, making connections among variables, and verifying the accuracy of the model (Buckley, 2000; Harrison & Treagust, 2000). We define this model creation process as *modeling*.

Modeling in turn consists of a set of modeling practices. Earlier research done by Stratford and colleagues (Stratford, Krajcik, & Soloway, 1998) characterised high school students' modeling process with the use of Model-It. Model-It is a software tool that uses multiple scaffolds in a graphical interface to assist learners in creating dynamic models of complex systems, which they do by specifying objects and variables, linking them with relationships, and engaging in cycles of testing and revision. The aforementioned research found that students engaged in four types of activities during modeling: (1) *analysing* (decomposing a system under study into parts); (2) *relational reasoning* (exploring how parts of a system are causally related); (3) *synthesising* (ensuring that the model represents the complete phenomenon); and (4) *testing and debugging* (testing the model, trying different possibilities, and identifying problems with its behavior and looking for solutions). These activities indeed are similar to what scientists do in their daily scientific practices. Observations of phenomena motivate scientists to construct models representing objects and defining interactions and relationships between them (Hestenes, 1992). The follow-up testing and evaluation that is done drive further observations and revision of the original model. As science educators envision ideal science learning including engaging students in inquiry activities that approximate the real-world science, modeling can serve as an avenue for students to develop and apply a variety of scientific practices valued in science education, such as identifying questions, generating explanations, and using justifications (NRC, 1996; Penner, Lehrer, & Schauble, 1998; Stewart, Hafner, Johnson, & Finkel, 1992). In this study, these scientific practices related to the modeling process are regarded as *modeling practices*.

Practice has been described as doing within a social and historical context (Wenger, 1998). Practices in classrooms involve interactions among learners and their environment. Three aspects of practices – conceptual, social, and material – have been discussed by a number of researchers (e.g., Roth, 1996; Wenger, 1998). The conceptual aspect involves students' development of conceptual understandings. The social aspect refers to social and discursive interactions among class members (including teachers and students). The material aspect focuses on how material resources, such as a technological tool, provided in the context enable students to demonstrate certain practices. We recognise that the three aspects are intertwined when students enact scientific practices within a learning context (Barab, Hay, Barnett, & Squire, 2001; Roth, 1996). Given the relatively little research about how specific scaffolds embedded in a computer-based tool support students' enactment of modeling practices, this study aims to explore specifically the material aspect involved in students' modeling practices by viewing Model-It as a set of resources and scaffolds within a learning environment.

### *Scaffolding*

A scaffold, or scaffolding, is defined, for the purposes of this study, as intentional assistance provided to a learner from a more knowledgeable "other," for pedagogical ends, that either fades (or can fade) after some period of time. Scaffolding is sometimes referred to as support provided within a learner's zone of proximal development (Hogan & Pressley, 1997). The term zone of proximal development (ZPD) was coined by Vygotsky (1978) to describe the vital developmental area between what a learner could do alone, and what s/he could do with the assistance of a more capable other. A parent might initially use a number line to graphically illustrate addition and subtraction, and then fade the use of that scaffold as the child gains the ability to work basic sums mentally. While scaffolding can be provided by a variety of sources, this study will focus on the scaffolds provided in the Model-It software.

It is important to distinguish between supports and scaffolds. Scaffolds are provided intentionally, in some sort of instructional context, to meet the needs of a learner. Supports are tools or features that allow a task to be accomplished, but that remain in place over time for all users. Software tools can have supports or functions, like a spreadsheet's automatic recalculation function, that simply make the process easier for everyone to accomplish. These are not scaffolds, since even the most advanced user has need of them. Furthermore, a computer and software package cannot (yet) be aware of a learner's past history, unique needs, and goals as a teacher can be. When considering tool scaffolds, one makes the assumption that the tool designer plays the role of the teacher, and the learner is really the larger group for which the tool is intended. The software contains the "voice of the programmer" (Griffin, Belyaheva, Soldatova, & VHC, 1993). The tool provides scaffolds for the needs of a hypothetical learner or group of learners. Another issue for scaffolds is "fading" (Jackson, Krajcik, & Soloway, 1999), the ability of the scaffolding to change (or be changed) in response to learner development; this is considered a requirement to differentiate between a scaffold and more permanent tool interface elements. Recognising the present limits of software programming, we require only that the scaffold could fade, not that it actually fades in the current iteration of the program.

Since the earliest research on computer software that assists learning, researchers have been concerned with the issue of design and supporting learners through design. The work of Wood, Bruner, and Ross (1976) and their list of tutoring scaffolds (e.g., constraining the task, making the implicit explicit) clearly informs the work of present day researchers. Bell and Davis (2000) found that cognitive scaffolding such as prompts and decomposing the task can assist important science learning practices. Quintana (2001) sought to assess the ability of learners to use a suite of scaffolded tools for science inquiry, and provided scaffolds for decomposing the task, managing artifacts, and hiding complexity. He observed that they could conduct a sustained investigation with this assistance. Guzdial (Guzdial, Konneman, Walton, Hohmann, & Soloway, 1998) sought to assist students in the learning and doing of computer programming, and his analysis of student actions while creating programs (as well as evaluation of the programs themselves) showed that learners using a scaffolded tool produced better programs with less effort. Early research on a dynamic modeling tool, Model-It, showed that when a variety of scaffolds were provided in a software tool, even very young learners could master the use of the software (Jackson, 1999), and the models they created were of substantial quality (Stratford, 1996).

*Scaffolds in Model-It*

Model-It is a software tool for building dynamic models of scientific phenomena. Inspired by a Learner Centered Design (LCD) philosophy (Soloway, Guzdial, & Hay, 1994), Model-It seeks to address the unique needs of learners. By providing a set of scaffolds in the tool, Model-It makes the important task of modeling accessible to even young learners with only basic mathematical skills. In Model-It, learners create computer models that represent their understanding of a given system or phenomenon. For example, students building a model of water quality use three different modes (Plan, Build, Test) as they specify key components of a model: Objects (such as water or fish), Variables (such as temperature and number), and Relationships (such as between water temperature and number fish). Each component can be customised in various ways, and each component has an area where learners are to articulate their ideas. While the result of this work looks somewhat like a concept map, it is in fact a dynamic model with which the learners can interact. This dynamic component allows learners to run and observe the behavior of their models while they manipulate independent variables. This testing can make errors in design and reasoning apparent, and the learners can then de-bug their models as well as their understanding.

Model-It is typically used by science classes to create models that represent learner understanding of material being presented in the curriculum. Thus, in a multi-week unit on water quality, pairs of students might create initial models of what variables are related to water quality, and how they interact. Then later in the unit, students can revisit their models one or more times, refining them based on their growing body of knowledge and experience (e.g., from doing water quality testing, walking along a nearby stream, or doing additional research). In Model-It, learners have to articulate not only the various variables relating to water quality as one would with a concept map, but also have to specify how and why they interact. Whereas in a concept map, "temperature" and "dissolved oxygen" would be connected by an arrow, in Model-It the students must specify direction and degree of the relationship, and complete a sentence description/justification of the relationship. Students collaborate and build a shared artifact of their understanding, while thinking about complex phenomena and confronting misconceptions.

Three of Model-It's scaffolds are examined in detail in this paper. The scaffolds examined were the *process map* scaffold, which decomposes the entire modeling task for students, the *articulation text box* scaffold which prompts learners to articulate explanations and descriptions (of objects, variables, and relationships), and the *dynamic testing* scaffold which provides learners with multiple representations that can be manipulated. We focused on these particular scaffolds because they were the more obvious and assessable of the various scaffolds in Model-It, and for their particular salience for modeling practices in which we were interested. Each of these scaffolds will be discussed in more detail below.

The process map (Figure 1) breaks the modeling process into three modes, to allow the learners to master the modeling process in steps and to reduce the complexity of

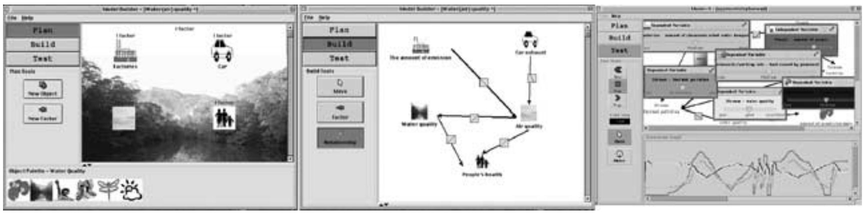


*Figure 1:* The Process Map (Plan/Build/Test modes, buttons in upper left).

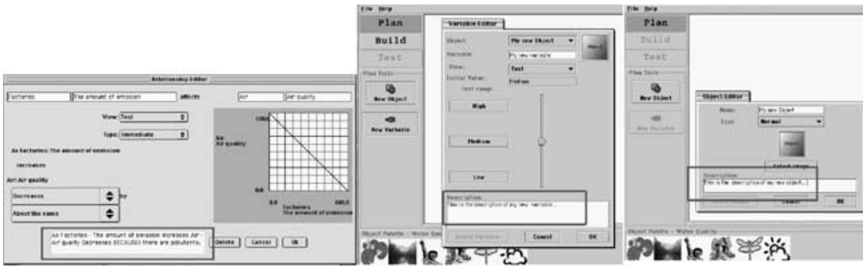


*Figure 2:* Articulation text boxes in relationship/variable/object windows.

the modeling task. By decomposing the task into three modes that follow scientific practice – plan, build, and test – the learner is presented with a constrained set of choices. In each mode, different features are presented, as appropriate. For example, as the learner is starting the model, in plan mode, they have tools to create objects and variables, but not for creating relationships or testing. This ensures that the modeling task does not initially overwhelm the learners, and is intended to make it possible for the learners to shift between modes easily as their experience and skill increase. Quintana's (2001) research with a scaffolded suite of tools to support science inquiry showed that process maps provide important support to students engaged in a complex science inquiry task (i.e., a cycle of collecting environmental data from a database, displaying and graphing it, and forming and testing hypotheses until a conclusion was reached). In Model-It, this scaffold is intended to indirectly assist learners with modeling practices like planning and analysing by giving a structure to the initial modeling process, and later encouraging learners to be non-linear and opportunistic in their work pattern. This scaffold is at a different grain size than most of the others, in that it provides assistance throughout all aspects of the modeling process. Were this scaffold to be fully faded, the student would be presented with all tools and functions on a single screen.

The articulation text boxes are designed to encourage learners to articulate their reasoning when creating objects, variables, and relationships (Figure 2). Each window for creating these items has a text box for entering this information. The relationship editor also has a partly filled out sentence in the box, in the form of "as X increases Y increases/descreases, because..." Research has indicated that although learners do not create self-explanations easily or consistently, eliciting self-explanations from learners can help them develop better understanding (Chi, 2000).

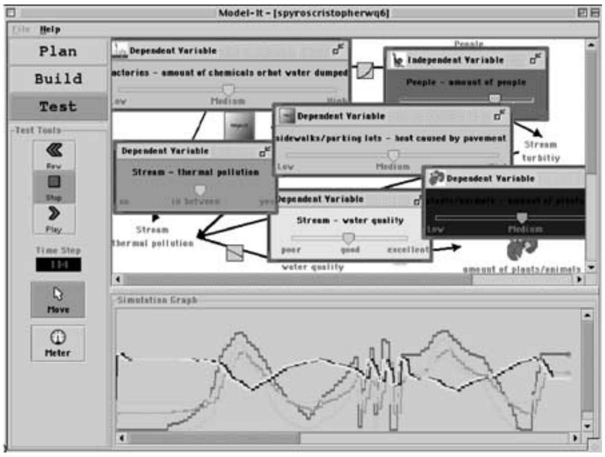


*Figure 3:* Meters and graph in dynamic test mode. Colors on meters correspond to colors on graph.

Research on similar "activity prompts" (Davis & Linn, 2000; Linn & Songer, 1991) showed that they assisted students in completing a task like articulating their reasoning behind a scientific design. Model-It's articulation text boxes are intended to assist with a number of modeling practices, particularly analysing, synthesising, and explaining. Having to make their thinking visible and explicitly describe their model's components, as well as how and why they interact, should provide many opportunities for learners to employ modeling practices. If this scaffold were to be fully faded it would be absent, as in, for example, commercial 3D modeling software, where the assumption is that the user or expert does not need or want to be pressed to justify their actions as they create their model.

The dynamic testing scaffold (Figure 3) allows learners to interact with the model in real time, manipulating meters and observing changes on graph representations of meter values. This scaffold removes the burden of repeatedly entering discrete values in equations, and instead this visual and dynamic scaffold allows the simultaneous observation of multiple values as elements of the model interact. As research on multimedia and the interpretation of graphs has shown, presenting the learner with multiple representations enhances the learning of information (Mayer, 2001) and the development of understanding about relationships (Leinhardt, Zsalavsky, & Stein, 1990). When learners have access to multiple/different representations of data, they find different aspects accessible to varying degrees, thus offering multiple representations is important (Shah, 2002). This scaffold can help the learner detect errors in the model's function, encouraging a cycle of debugging and improvement. By providing a meter to control input, and providing multiple representations of values (meter and graph), this scaffold makes a variety of modeling practices possible in the area of analysing, explaining, and evaluating, such as critiquing function, identifying anomalies, and identifying solutions. Were this scaffold to be fully faded, either the meters or graph area could be removed.

Table 1
*Scaffolds and Their Purpose and Intended Modeling Practices.*

| Scaffold | Purpose | Modeling practice(s) |
|---|---|---|
| Process map | Decompose modeling task into modes, provide initial linear progression through task, constrain complexity by making only relevant tools and options available in each mode | Modeling task in general<br>Planning (e.g., deciding on focus of model, content and structure) |
| Articulation text boxes | Encourage specific writing and discussion of the properties of objects, variables, and relationships | Planning<br>Searching (e.g., refer to text or notes)<br>Synthesising (e.g., combining information from 2 different class activities)<br>Explaining (e.g., how and why "x" affects "y" in the model) |
| Dynamic testing | Allow direct input and manipulation of values when running the model, present multiple representations of variable values (meter and graph) | Analysing (e.g., assessing model function)<br>Evaluating (e.g., comparing behavior of model to real life)<br>Explaining |

Table 1 summarises the purposes and the modeling practices each of these three scaffolds are intended to support.

## Research Context and Methods

### *Participants, Curriculum, and Technology*

The participants of this study ($N = 31$) were 7th grade science learners in an independent grade 6–12 school in a mid-sized midwestern university city. The software was integrated into a project-based curriculum that was in use for several years (Novak & Gleason, 2001). Model-It was used several times during the school year, and this study examines the first use.

The seventh grade learners were mostly white and upper middle class, and nearly all had access to a computer at home. The learners were paired for the duration of the modeling activity with one other student, with whom they collaborated in and out of school, and with whom they completed their model and any other projects for that unit. Class size in each of the two classes studied was approximately 15. In each class, teachers selected two pairs of target students to be video-taped, with the criteria of having learners who were neither particularly high nor low performers, and who would be likely to verbalise their thinking while working on the computer. Learners used Model-It for three days to make models of some aspect of water quality. Learners had been exposed to related content for two weeks prior to software use, including trips to examine local streams and conducting water quality tests.

Teaching these classes were regular science teachers with 11 and 27 years experience respectively. The curriculum features long term projects approximately a semester in length, and students make a model in the early part of the unit as a formative assessment. Prior to their first use, the teacher introduced students to Model-It through a half-hour demonstration. The teacher reviewed the modes and functions of Model-It while demonstrating how to create a basic model. The Model-It tool was a new addition to the classroom, but the teachers were both experienced technology users.

The classrooms each had eight networked iMac computers, linked to a teacher station that functioned as a server. Students used the computers for a variety of other classroom tasks in addition to Model-It (such as report generation and web research). Students used the computers in pairs, and very occasionally in groups of three. The version of Model-It tended to be reliable, with only occasional bugs being seen. Model-It was one of many technology tools used in these classrooms during the year-long use of project-based science curricula.

### *Analytic Methods*

This study used a combination of established and emerging techniques to make a detailed examination of how scaffolding is used in classroom contexts. In order to capture both how the learners were using the tool and what they were saying, process video stations (Krajcik, Simmons, & Lunetta, 1988) converted and recorded the computer screen video and microphones captured the discussion of two target pairs. The process video tapes were transcribed to create detailed descriptions, coded, and then analysed using NUD*IST (N4) software to gather evidence to address the research questions. Coding and analysis of the data were an iterative process.

Each tape was transcribed according to agreed upon conventions, full verbatim transcripts were not generated. In general each half hour of tape yielded three to five pages of text. The conventions included: demographics such as date/time/class period, what type of conversations were to be captured verbatim, how to denote speakers, when to break up paragraphs and episodes, and so on. Transcripts captured: (1) students' use of the tool (e.g., creating a variable or a relationship, testing their model, or shifting to another mode); (2) students' activities when using the tool (e.g., making explanations, generating ideas, or seeking information); (3) thoughtful

Table 2
*Sample of Coding Scheme.*

| Activities | Scaffolds | Modeling practices |
|---|---|---|
| Plan | Tool Scaffolds | Planning |
| (e.g., Create Object, | Process Map | (e.g., Generating ideas, Stating |
| Modify Object, Delete | Articulation Text Boxes | goals, Specifying relationships, |
| Object, Create Variable) | Dynamic Testing | Discussing variables/objects) |
| Build | Others (e.g., Making context | Searching |
| (e.g., Create Relationship, | personally relevant: personalize, | (e.g., Seeking information, |
| Modify Relationship, | Hiding Complexity) | Gathering resources) |
| Delete Relationship) | Teacher Scaffolds | Synthesising |
| Test | Conceptual (e.g., critiquing | (e.g., Discussing relationships, |
| (e.g., Open meter, | structure of model) | Making connections) |
| Assign variables to graph, | Utility (e.g., how to use | Analysing |
| Change meter value) | certain software function) | (e.g., Deciding about course |
| Other | Task (e.g., refer students | of action, Recognising |
| (e.g., Shifting, Off task) | to textbook, notebooks) | the need for testing) |
| | Content (e.g., explain pH | Explaining |
| | range/scale) | (e.g., Explaining why/how, |
| | Strategy (e.g., suggest need | Justifying arguments, |
| | for more planning) | Elaborating ideas) |
| | Peer Scaffolds | Evaluating |
| | (see Teacher, above) | (e.g., Predicting what |
| | | should happen, Identifying |
| | | anomalies, Critiquing/interpreting |
| | | the results, Identifying |
| | | /proposing solutions) |

conversations between students; and (4) scaffolds provided by the tool, teachers, and peers. The transcripts were imported into an N4 database and coded line by line, in accordance with the coding scheme, and reviewed by a different researcher as a final consistency and error check.

The coding scheme (Table 2) was developed iteratively, and focuses on activities (i.e., students' use of the tool in each mode), scaffolds (provided by tool, teachers, or peers), and modeling practices. This process of refining codes iteratively is a well established method (Chi, 1997; Miles & Huberman, 1994), and ensures that the data are fully explored. To create codes for activities, we identified the main actions students could take in each mode. For example, in the plan mode, students could use the tool to create, modify, and delete objects. To create codes for scaffolding, we identified types of scaffolds that could be provided by the tool, teachers, and peers during the modeling process. Data on teachers and peers was gathered primarily in support of other research questions not addressed in this paper, but where it informs our discussion, it will be referred to in this paper. Though Table 2 presents codes for all three sources of scaffolds, in this paper we focus most of our attention on tool scaffolds, and in particular on the three scaffolds described above. Finally, building on Stratford and colleagues' (Stratford, Krajcik, & Soloway, 1998) work we identified modeling practices such as planning, analysing, and synthesising, as well as sub-types of these six modeling practices. Similar to the conventions used for transcription, a list of what counts as evidence for each code was agreed upon by all coders. For modeling practices, and the articulation scaffolds, this evidence was generally verbal or written. For other scaffolds, the process video of the computer screen provided evidence of how the software was used.

The database was used to generate reports that would provide evidence to help answer the research questions. For example, reports that cross-indexed a given scaffold with all modeling practices could identify every line of all transcripts where these codes co-occurred. An additional report of all practice codes would provide a large text document of every time any pair had been coded as using a modeling practice. These text reports were then reviewed line by line to verify each instance of the code. These summary counts are what appear in the tables to follow. In addition, this review provided a collection of examples of how these tool scaffolds were or were not working to support modeling practices. This allowed a detailed review of how several specific tool scaffolds occurred in conjunction with various modeling practices, and what discussions or activities went on during these times. To illustrate how each scaffold supported the use of modeling practices, frequency counts were combined with examples from transcripts in the results that follow.

## Results

We sought to assess how well the scaffolds designed into Model-It assisted the use of modeling practices by learners, both in an overall sense and by examining three scaffolds in detail. Recall that our research question was: What scaffolds designed into a dynamic modeling program support modeling practices? Specifically we ask: How often do modeling practices occur in conjunction with the use of scaffolds built into the tool? Which modeling practices are most effectively supported by certain specific scaffolds? What does student use of scaffolding look like as they engage in modeling practices?

*Summary of Modeling Practices with and without Scaffolds*

Across all student pairs, a total of 366 uses of modeling practices were identified. Tool scaffolds were in use during about one quarter of these scaffolded modeling practices. Table 3 shows occurrences of modeling practices overall, and with tool scaffolds specifically subdivided into the three modes (plan, build, test) to provide more detail. Looking across modes is important since not all scaffolds examined occur in each mode. For example, the plan and build mode contain the articulation text box scaffolds, while test mode contains the dynamic testing scaffold. Teachers and peers also provided scaffolds in support of modeling practices, but because of our overall interest in technology mediated scaffolds, we focus here on the tool. The lowest number of tool-scaffolded modeling practices was seen in the build mode, where articulation text boxes provided support for modeling practices but a large number of modeling practices occurred with support from teachers and peers.

Among 101 instances of using modeling practices in plan mode across the three sessions, tool scaffolds accounted for 26 (or 26%) of these practices, with teacher and peer scaffolds accounting for the rest. Among 131 instances of using modeling practices in the build mode, tool scaffolds supported 24 (or 18%) of those practices. In test mode, there were 134 instances of modeling practices, and tool scaffolds supported 48 (or 36%) of those instances. We next asked which modeling practices were supported by the specific scaffolds, both in terms of which specific practices the scaffolds supported and examples of what that support looked like.

*Scaffold One – Process Maps*

We sought to understand how the process map scaffold might support the use of modeling practices. Recall that the process map scaffold breaks the modeling task into a sequence of plan, build, and test. Since this scaffold is rarely if ever explicitly discussed by learners, the evidence of its use would have to come from how the tool is used, and so the process video for the six target pairs is used. To gather evidence

Table 3
*Scaffold Use Across Three Modes, Overall and in Conjunction with Modeling Practices.*

| | Plan mode | Build mode | Test mode | Overall |
|---|---|---|---|---|
| Instances of modeling practices | 101 | 131 | 134 | 366 |
| # of modeling practices that occurred with tool scaffolds | 26 (26%) | 24 (18%) | 48 (36%) | 98 (27%) |

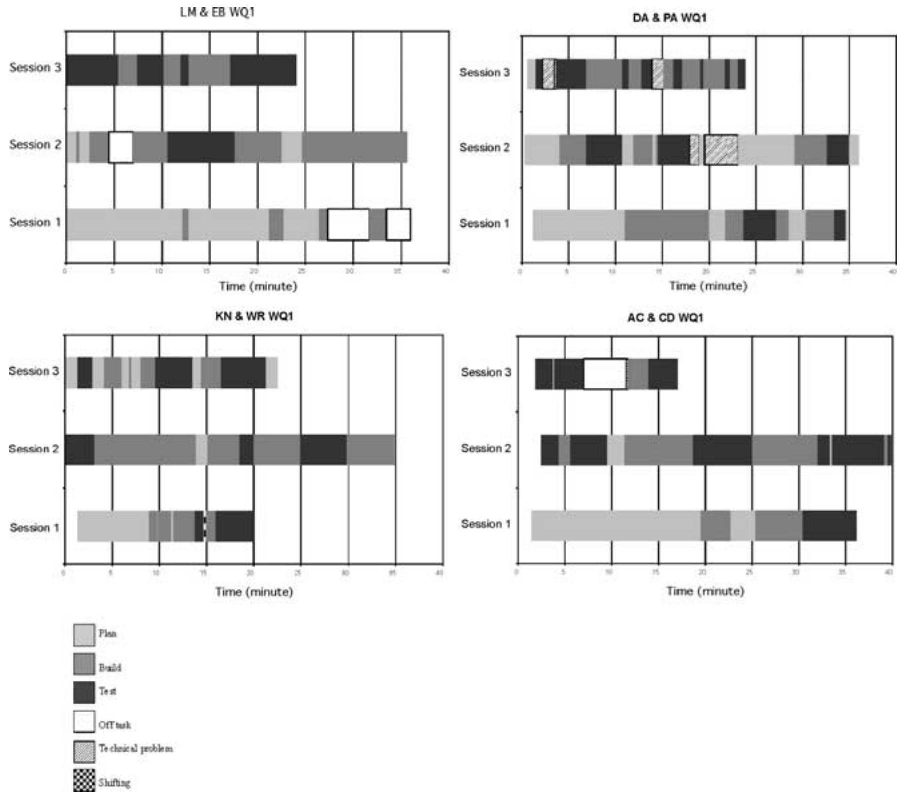


*Figure 4:* Charts showing four learner pairs' use of the Plan/Build/Test modes in Model-It.

about this scaffold, the time marks on the transcripts for each shift in tool mode (the three modes provided on the process map), were plotted for each pair of students, per minute, across each session of use. Charts summarising these shifts can be seen in Figure 4.

The charts show that during the first session in the water quality unit, students spent most of their time on planning, but all pairs did get to the build mode and make at least one relationship, and four pairs did enter test mode at least once. During the first session, three out of four pairs worked through all three modes and started testing. In the second session, the pairs spent most of their time in build and test modes. Students sometimes went back to the plan mode to create or modify objects and variables, but usually did not stay longer than three minutes. In the third session, the emphasis was on testing and revision, and four of the pairs did not go back to the plan mode at all. The switches among the three modes indicate these seventh grade students were able to use the intentionally designed process map to follow the initial sequence of modeling modes and use the modes opportunistically thereafter.

*Scaffold Two – Articulation Text Boxes*

The articulation scaffold in Model-It occurs in the text boxes for description (in the case of objects and variables) and "because statements" (for relationships, where the learners decribe why one variable affects another). They serve to prompt and facilitate the explicit articulation of students' thinking. These scaffolds are found in the plan and build modes of Model-It. In response to these scaffolds, students have to articulate what they are trying to accomplish and explain what they are doing. In looking across the plan and build modes this scaffold accounts for 41 of the 50 instances of the modeling practices supported by scaffolds, about 80%. This scaffold was most frequently seen in conjunction with the practices planning and synthesising. The transcripts provide evidence of how students' discussions are precipitated by these scaffolds in Model-It. In the examples provided below, student speakers are abbreviated with their initials.

In Example 1, students are reviewing relationships and their "because statements." Students have the text box on the screen as part of the relevant relationship that they are creating or checking. The example highlights conversation where modeling practices, such as synthesising (discussing relationships), are in use. Specifically, they read text from the articulation boxes three separate times, and subsequently propose revisions to their model. The students are led to make connections between variables, and review the appropriateness of their relationships. Students may choose to remove a relationship that is technically correct, perhaps due to it not fitting in to the overal purpose of the model.

Walt reads the text "As outhouses increases, stream conductivity [increases because] . . . " "We do not need conductivity, should we?"
Kristin: "Yeah."
Walt: "As the amount of waste increases . . . "
Kristin: "Oh, wait, cancel, we should not have this." [points to a stream variable] "We should connect from this to this."
Walt agrees. He cancels and clicks from variable Stream to variable Outhouse.
Walt reads the text again, "as stream conductivity increases outhouse the amount of waste . . . woo! Get rid of that conductivity . . . "
Kristin: "Do we want to get rid of this one?"

In Example 2 following, students are first reviewing their existing relationships and show a tendency to articulate their reasoning even when reviewing their model. They discuss relationships and also justify their argument. Their later discussion shows how having to justify their relationship plays a central role in their discovery of a problem in their model structure. While the accuracy of model content is always a concern (for researchers as well as teachers), the focus here is on the process of students working through the science.

Walt reads the text on the relationship editor: "as plant – the amount of leaves increases stream-conductivity increases 'more and more,' that's right."
Kristin: "That's not quite 'more and more'."

Walt: "Yeah, as the leaves keep falling in the stream, they will be decomposed and dissolved."
Kristin: "That makes sense. The amount of leaves affect dissolved oxygen, too."
Walt: "Right; as plant – the amount of leaves increases dissolved oxygen decreases by ... "
(Later)
Students then read and type in the description window: "We are assuming that high conductivity would affect or indicate poor water quality because ... "
Walt: "But it still does not explain how conductivity affects water quality ... "
Kristin: "It affects people's health."
Walt: "How?"
Researcher: "If the relationship is that important, then it might be good to have conductivity affects water quality and water quality affects people's health."
Students dismiss the relationship editor and check what they have in the model. Then they reopen the relationship editor again to check the relationship and read: "We are assuming high conductivity would indicates poor human health because high conductivity indicates poor water quality."
Kristin: "OK, poor conductivity would affect water quality ... we do not - have water quality!"

They are making connections and elaborating on their ideas. The scaffold makes their thinking visible to each other, as well as the researcher, and fosters the use of modeling practices and more specifically, leads them to improve their model.

These two examples show students using modeling practices like synthesising and explaining, by making connections and justifying arguments. By sharing these explanations, and coming to a common understanding, students discover errors in their understanding and/or their models.

*Scaffold Three – Dynamic Testing*

The dynamic testing scaffold occurs only in test mode. Here, students can interact with their model and compare multiple representations of model function. In test mode, tool scaffolds are used in conjunction with over a third of modeling practices. This is more than the 26 or 18% seen in other modes, most likely due to the number and depth of discussions caused by the dynamic testing scaffold. The dynamic testing scaffold accounts for 37 of 48 instances of modeling practices supported by tool scaffolds in the test mode, about 75%.

In Example 3 below, students are manipulating the meters using various strategies, and watching the graphs. They use modeling practices to find anomalies, analyse, and propose solutions to errors in their model output. While their conversation is a bit telegraphic, they are essentially observing the overall model output as it runs, while examining variables sequentially to see if each variable is having the intended effect on the major dependent variable (water quality in this case). They also refer here to a previous session where they identified and fixed a problem where changes in water temperature were not linked to water quality.

Charles: "Let's start with pH. No, we can't move that."
Charles then adjusts the meter of runoff.
Amber: "The conductivity is finally raising up."
Charles: "How will it affect... oh, runoff, yeah."
Students observe the graph a while.
Amber: "A lot of stuff is running up the quality."
Charles: "It's really really going high."
Amber: "The turbidity really raises the highest."
Charles: "That's interesting. It's like in between." [the cursor points to the dumping chemicals]
Charles: "Animals are not affecting anything."
Amber: "The amount of them."
Amber: "Maybe the stream quality."
Charles: "If you have too many, it probably affects [the stream quality]."
Amber: "Finally the temp difference is rising, because we fixed that problem."
Charles: "This one only affects a little. Why don't we put everything on high?"
Amber: "We forgot the... dissolved oxygen."

In Example 4 below, students have noticed anomalies during testing and are proposing or have executed solutions. In Example 4, students are dealing with the unique nature of pH as a variable, which really requires a bell curve relationship. Since they have selected a linear positive relationship, they have an anomalous result where very high pH does not have a negative effect. They identify an anomaly (they have used a single variable for pH, but have selected a linear relationship versus a bell curve) and propose a solution (ideally, they could change to a bell curve relationship, but breaking the variable into two, as they propose, would also solve the problem).

Students start testing and notice some anomalies.
Students adjust all meters to high.
Charles: "You can put it medium though."
Charles: "pH one is weird."
Charles: "Maybe we need one variable for basic and one for acidity."

In Example 5 below, students are critiquing their model and interpreting the results with the assistance of the teacher, and they use the graphs as well as the ability to stop the simulation and review the scrolling graph, to identify the anomaly and propose a correction. This example shows the students struggling to integrate their knowledge into the model. One student feels another, moderating, variable should be added, while the other student thinks linking existing variables is sufficient.

Students bring up five variable meters and run the model.
Kristin: "Why is it always "dissolved oxygen" changing?"
Walt: "Stream conductivity really goes up (He refers to the peak on the graphic simulation window), wait . . . "
Teacher asks them to stop "now talk to each other, is this is really working?"
Walt scrolls and finds the peak of conductivity on the graphic simulation window.
Walt: "This is where you put the dissolved oxygen up."
Kristin: "OK, so dissolved oxygen goes up conductivity goes . . . "
Walt: "Goes up."
Walt: "We need a variable to put them in between them."
Kristin: "We need to link them."

These examples show the sort of rich discussions that students have about model content and structure when they manipulate the model in test mode. We see the dynamic test mode scaffold encourages the use of evaluating practices like interpreting results, identifying anomalies, and proposing solutions.

## Discussion

Scaffolds in general play an important role in students' use of Model-It, as the majority of modeling practices occur with them. The use of these modeling practices, and the creation of complex and dynamic models, is both challenging (in that it is often assumed to be beyond younger learners) (Metz, 1995) and valuable (in that developing these abilities is assumed to be of importance for science learning) (AAAS, 2000). Theories of scaffolding assert that providing assistance to learners assists development by allowing completion of tasks normally out of reach (Vygotsky & Cole, 1978; Wood, Bruner, & Ross, 1976). Fully three-quarters of the modeling practices observed occurred with some type of concomitant scaffolds (tool, teacher, or peer), and only one quarter of the practices occurred without any scaffolds. So, although it is only one of several important sources of assistance, tool scaffolding clearly plays a role in learners' use of modeling practices. This is in keeping with the idea that practices have a material aspect where tools and context allow the learner to demonstrate certain practices. A more detailed examination of three specific scaffolds provides a picture of how these scaffolds support learners as they create models.

The purpose of the process map scaffold is to decompose the task in a way that makes scientific norms visible, make only appropriate tools available depending on mode, and provide an initial linear path through the modes. Learners did succeed in creating models, and the process map was used successfully, even on day one, learners used all the modes and shifted easily between them. The general progression from planning to testing over three days also shows that this scaffold succeeded in helping learners master the task of creating a model. Scaffolds like the linear process map should provide valuable assistance to learners, by doing things like sequencing the task. As seen in principles of curriculum design, the sequence provided to learners makes visible the actual practice we want them to learn. Numerous software tools provide similar scaffolds based on the intuition that it would be helpful (e.g., the Inquiry Cycle, White & Frederiksen, 1998). While Quintana (2001) showed how linear process maps could be used to assist students using a suite of tools in a long term investigation, this study showed that linear process maps also assist learners in using a specific tool to accomplish a more focused task (i.e., model creation). This scaffold not only encourages an initial linear progression but also facilitates later movement between modes, in a manner Quintana (2001) referred to as "opportunistic." In this respect we contribute to a science of design, where scaffolds can be selected based on empirical success.

The articulation text box scaffold facilitated a great deal of discussion among pairs. The intent of this scaffold is to encourage students to be explicit in their descriptions of model components and the nature of the links between them, essentially making learner thinking visible. The creation of self-explanations and the cognitive conflict that often arose in learner pairs are both important in developing an understanding of the content of the model and the modeling task. By making thinking visible, this scaffold served as an instigator of many valuable learner discussions, where they applied modeling practices in planning and synthesising. This scaffold accounted for the majority of tool-supported scaffolds in plan and build modes, although tool scaffolds played a lesser role in build mode than other modes. This is most likely due to the amount of discussion teacher and peers provided when discussing and critiquing the developing model. This paper contributes further evidence that tool scaffolds can assist learners in accomplishing practices like planning and making explanations, which are important in scientific reasoning. In keeping with prior research on how students use similar articulation scaffolds (Davis & Linn, 2000) and the value of students' self-explanations in improving understanding (Chi, 2000), this paper showed how a tool scaffold can support the use of modeling practices, even by seventh grade learners.

The dynamic testing scaffold was very successful in supporting modeling practices in the areas of evaluating and analysing. The intent of this scaffold was to make the function of the model visible using multiple representations and let learners manipulate it directly, so they could examine their model's function in detail. While expert scientists or modelers might be expected to easily create and modify complex mathematical equations, and test one or several equations using discrete values, this task is clearly challenging for younger learners, who lack both familiarity with the modeling process and advanced mathematical skills. Also, multiple representations should assist learners in understanding the information being presented (Mayer, 2001; Shah, 2002). By making the simultaneous testing of multiple variables easier, and the task of model evaluation more explicit, this scaffold helps learners improve their models and master related modeling practices (e.g., analysing). This scaffold also served as an instigator of learner discussions, when they had to confront discrepancies between their model behavior and desired behavior. Within these discussions were the richest examples of modeling practices, as learners struggled with the function of their models in relation to their growing content knowledge. This is an excellent example of how tool scaffolds interact with other scaffolds in context to create important opportunities for learners to improve their understanding.

This study does not claim that a specific tool scaffold, or even tool scaffolds in general, are uniquely successful in helping learners. Assessing tool scaffolds addresses the material aspect of modeling practices. The tool scaffolds assessed were embedded in a complex classroom context with other sources of scaffolding, and accounting for the roles of other sources of scaffolding (including the social aspect as well as activity structures more generally) is an important next step.

## Implications and Future Directions

This study found, in keeping with prior research, that scaffolding can provide valuable assistance to learners, and help them accomplish tasks that might otherwise be out of reach. Using scaffolded tools, even young learners can begin to use modeling practices in their science learning efforts. In assessing several scaffolds directly this study contributes to the incomplete task of empirically validating scaffolds and types of scaffolds, towards the end of developing a taxonomy of scaffolds that might inform educators and software designers.

The three tool scaffolds, collectively, were found to support a large number and variety of modeling practices. Individually, they did enable the types of modeling practices they were intended to assist. Collectively, tool scaffolds work with scaffolds from teachers and peers to provide important assistance to learners in learning and engaging in modeling practices. The role of teachers and peers in association with tool scaffolds is a vitally important topic for future study, and studies that examine all three concomitantly are rare.

Future research might investigate the remaining scaffolds in Model-It, or other tools. The role of teacher and peer scaffolding could be addressed in more detail: What sort of assistance is best provided by the tool versus the teacher? The assessment of scaffolds and strategies used by pairs of students in relation to the quality of their final model artifacts could provide further evidence for the value of these scaffolds: Do pairs who consistently make adequate or examplary self-explanations create models of higher quality? Is the converse true? Experimental designs might compare versions of a tool that had different scaffolds, and look for differences in the use of modeling practices and in artifact quality. The goal of future research on scaffolds should be to make further contributions the idea of a design science, where tools are designed with context in mind and with scaffolds employed based on empirically validated guidelines rather than intuition. As knowledge of how to design and employ scaffolds improves, software tools can play an ever more effective role in supporting science education.

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## Notes

1. Throughout this paper, the terms learner and student are used essentially interchangeably, with student used to refer to specific subjects in actual classroom settings.


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