DRAWING MODELS: EXPLORING PATTERNS OF STUDENT MODEL CONSTRUCTION IN THE ELEMENTARY CLASSROOM

by

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(Under the Direction of Michael J. Hannafin)

ABSTRACT

Student-centered activity in education has the potential to promote constructivist learning. However, how students engage in the activities and respond to classroom cues can mediate the degree to which constructivist thinking and learning occur. Research on constructivist-oriented instruction and learning tends to focus on activity itself and student responses to the activity as a bound unit of analysis. While much has come out of this research, there still exists the need to understand how students engage in student-centered, constructivist activity in the classroom. The present study assessed the influence of key teaching-learning resources on student engagement during student-centered activity. Model-based instruction provides the framework for student-centered, constructivist activity in a sixth grade class at a public school. On four separate occasions students generated visual models as artifacts to demonstrate their understanding during a unit on microorganisms. The models were analyzed for common class-wide patterns as well as differences in specific student responses. Teacher behavior and prompts were compared with that analysis to interpret differences between enactments. Students did not fully demonstrate constructivist thinking as anticipated, but constructivist elements and other emergent behaviors were identified. Key areas that influenced modeling behavior included framing a problem, receiving feedback, and receiving scaffolded support. Students elaborated their models through scaffolded conversations with the teacher. Student-teacher interactions to elicit constructivist modeling indicated a cognitive apprenticeship for helping students reason via model construction. Findings suggest a need for research that examines how students grow in modeling skills and in reasoning skills during model construction.

INDEX WORDS: Student-centered, Learner-centered, Constructivism, Constructionism, Model-based learning, Model-based instruction, Science Education, Elementary Education

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DEDICATION

For my dear wife who has been a dedicated companion, editor, supporter and friend. And for each of my six children, some of whom learned the word dissertation among their first words. Their support and sacrifice have deeply touched me, but are not limited to this season; they have been characteristic of the way our family has lived together – for that I am forever thankful.

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CHAPTER 1

EXAMINING STUDENT-CENTERED MODELING IN CONTEXT

Efforts to support students as they engage in constructivist-inspired school-based learning have become especially prominent during the past 30 years as talk of paradigm shifts and the need for education reforms have increased (Driver, Asoko, Leach, Mortimer, & Scott, 1994; Glasersfeld, 1996; Papert & Harel, 1991). Educators and researchers have advanced ideas and methods for placing the student at the center of learning activity in such a way that constructivist learning is promoted (APA Workgroup of the Board of Educational Affairs, 1997; Hannafin, Hill, & Land, 1997; Lambert & McCombs, 1998; Land, Hannafin, & Oliver, 2012). There have been interesting and promising results from an array of strategies and methods (Driver et al., 1994; Jonassen, 2007; Savery & Duffy, 1996). There still remains the challenge of integrating such practices into the classroom. Attention must be paid to the role of teachers and students in making student-centered practice contribute to constructivist learning. In this research project I seek to clarify the kinds of interactions that can promote constructivist learning in the traditional classroom during one form of student-centered practice: model-based learning.

Student-Centered Learning

The primary goal of student-centered learning is to support effective learning by putting the learner at the center of learning activity. Traditional classroom approaches are sometimes called teacher-centered or curriculum-centered and can be characterized as acquiescence or compliance during lectures, readings and quizzes (McCaslin & Good, 2008). Advocates of student-centered practice assert that such instructional methods rely on passive activity that fails to promote critical thinking and active learning (Hannafin & Land, 1997) consistent with research on effective learning. In contrast, they claim that student-centered learning supports more effective learning experiences because it requires the student to engage in a range of activities to actively involve the student in making learning choices (Shapiro, 2008), generating solutions to real-world problems (Savery, 2006; Vanderbilt, 1992), and using learning content to engage in the practices of the professional community (Concannon & Brown, 2008). Student-centered learning advocates encourage active engagement which requires the higher-order thinking skills that students need in the information society (Hannafin & Land, 1997).

In an effort to promote effective learning experiences, advocates of student-centered learning seek to connect instructional methods to constructivist views of how people learn. Piaget proposed that learning and development are the result of cognitive processes made possible by interactions with the surrounding world. As such, constructivism, at its elemental level, requires combining prior understanding with new knowledge, which is stimulated through such interactions. While there are many forms of constructivism, two threads – learning through interactions and combining new with previous knowledge – are at the heart of various constructivist theories (Atwater, 1996; Girvan & Savage, 2010).

Constructivism is an epistemological foundation for developing education practices that support that kind of learning. Student-centered learning, as advocated in recent decades, attempts to initiate learning environments that accommodate constructivist learning. While there is no formal set of practices or unifying theory for the design of student-centered learning environments, Land, Hannafin, and Oliver (2012) proposed a set of core values and assumptions: "(a) centrality of the learner in defining meaning; (b) scaffolded participation in authentic tasks and sociocultural practices; (c) importance of prior and everyday experiences in meaning construction; (d) and access to multiple perspectives, resources, and representations" (p. 8). A diverse set of constructivist-inspired practices promote individually unique learning, including problem-based learning (Savery & Duffy, 1996; Savery, 2006), anchored instruction (Vanderbilt, 1992), open learning environments (Hannafin, Land, & Oliver, 1999), and constructionism (Papert & Harel, 1991).

Critics argue that student-centered methods lack evidence of effectively promoting desired learning outcomes. They assert that so-called minimal guidance often associated with student-centered activity cannot be reconciled with current understanding of cognition, and thus stands in contrast with empirically validated methods (Kirschner, Sweller, & Clark, 2006; Mayer, 2004). In some cases, empirical research, for example, demonstrates that "non-student-centered instruction" (guidance via, for example, worked examples and direct instruction) contributes to better results in the form of quantifiable learning outcomes (Kirschner et al., 2006; Klahr & Nigam, 2004). At the same time, outcomes related to constructivist learning, such as personally meaningful understanding and ability to perform in real-world contexts are difficult to quantify and measure. Rather than view these two perspectives as dichotomously opposed, some researchers and educators recently supported constructivist learning via student-centered activities that are scaffolded through various forms of teacher-guided instruction (Alfieri, Brooks, Aldrich, & Tenenbaum, 2011; Land et al., 2012). Thus, the challenge is determining how much guidance and self-initiated activity is needed to promote effective and meaningful learning.

Student-centered learning in practice. While tools and environments afford opportunities for thinking and learning, students are inevitably the primary negotiators of how, when and how effective they become. Students must strategize and decide how to accomplish a task and how available resources and strategies will be employed. Thus, while the design of a tool is important, how it is used by the student is critical. In this sense, student-centered learning is a negotiated constructive process involving the learner and resources and instructors.

Implementation of student-centered classroom learning, therefore, presents challenges including conflicting mandates and standards (Aydeniz & Southerland, 2012; DeBoer, 2002), cultural barriers to change (Hannafin et al., 1997), the need for professional development to support change (Pedersen & Liu, 2003; Polly & Hannafin, 2011), as well as students' habits of mind (Felder & Brent, 1996). Often, traditional classroom approaches involve characteristics that may conflict with student-centered practices. Student-centered learning requires cognitive processes that promote deep understanding (Hannafin, Hannafin, & Gabbitas, 2009; Land, 2000) and rely on authentic practices that situate content (Hannafin & Land, 1997; Savery, 2006); standardized tests require isolated bits of knowledge often learned through discreet, rote practices and in isolation from authentic contexts (Hume & Coll, 2008; Wiggins, 1993). Student-centered learning activities often require time to arrive at content goals; classroom teachers are required to cover large amounts of disconnected content in limited periods of time (DeBoer, 2002; Southerland, Smith, Sowell, & Kittleson, 2007). These conflicts indicate that transforming classroom methods to support constructivist's epistemological assumptions may well involve steady, incremental change.

Researchers and designers must be sensitive to the importance of context in order to refine both research and design for the varied learning environments. Educators and learning environment designers need to create and evaluate tools and methods that are practical in today's classroom, while leveraging the promises and resources of constructivist theorists. Current research in model-based learning offers methods and perspectives to address some issues and challenges associated with student-centered, constructivist learning in the classroom.

Model-Based Learning

In science education, some educators and researchers are using student-centered modeling to support inquiry and constructivist learning. Modeling is a useful practice in real-world science inquiry with ever-expanding capabilities due to advances in technology. Often, discoveries in science are advanced through modeling (see for example, Frigg & Hartmann, 2012; Otto-Bliesner et al., 2014; Schlessinger et al., 2011). Consequently scientific modeling is considered a desirable target skill in science education (Baek, Schwarz, Chen, Hokayem, & Zhan, 2011; Gobert et al., 2011). A model is an externalized representation that students construct, manipulate or interpret (Clement & Rea-Ramirez, 2008). Students can use modeling as inquiry practice to study and learn science. And models provide hands-on, learner-centered opportunities for students. For example, in modeling projects students created mini-ecosystems with living organisms (Lehrer, Schauble, & Lucas, 2008), used computers to simulate and observe accelerated processes (Wilensky & Reisman, 2006), and created artifacts to communicate their understanding (H. Lee, Linn, Varma, & Liu, 2010).

Evidence suggests that how and how long models are used can support conceptual change and concept growth across a variety of implementations. Students can use a microcosm of a complex system to make their own observations of that system (Stratford, Krajcik, & Soloway, 1998). Students can make successive changes to a model to observe outcomes and test hypotheses (Jackson, Krajcik, Soloway, & Jacobson, 2000). A student can work with others in the class to co-create a model, using the model as a means of detecting and resolving discrepancies in understanding (Nuñez-Oviedo & Clement, 2008). As the implementations of models vary so do the time scales involved. Researchers have looked at significant events during model-based learning that occur in a few moments during conversations, in the course of several days while building models or over a year in which modeling is integrated into the curriculum (Clement, 2008a). Such variety in implementations provides numerous options for educators to consider when working with models.

Increased understanding of student reasoning during model-based learning offers insights into the role that models play during learning. Researchers report that students using models engage in analogic reasoning and that young children grow in complex reasoning (Goswami, 2001). Furthermore, the nature of the model can influence the kind of reasoning students engage in during modeling (Löhner, Van Joolingen, Savelsbergh, & Van Hout-Wolters, 2005) and the kind of learning students achieve (Gobert & Clement, 1999). Cognitive activities important to conceptual growth and change happen when use of the models includes events that induce critical analysis and discomfiture such as questioning (Clement, 2008b), testing the model (Jackson et al., 2000), and transforming knowledge across multiple models (Shen & Confrey, 2007, 2010).

Constructivist modeling. Creating models can require constructivist processes of integrating ideas and experiences to construct meaning and knowledge. In constructivist modeling the process is more important than the final product, though product is an important artifact of that process. In model-based learning, students are often asked to generate models as part of the larger instructional frame. For example, some modules in WISE (“WISE: Web-based Inquiry Science Environment,” 2012) ask students to draw their own representations of a phenomenon and then use the online program to share and revise in collaboration with others in the class. In the program Model-It™ (“Model-It,” 2012) students are guided though the process of modeling a complex system that they are learning about as they build objects and object relationships and then test the model. The task of generating original models leverages constructionist ideas that students are able to better construct understanding when constructing public entities (Papert & Harel, 1991). Building constructivist models requires students to engage in cognitive processes and inquiry practices that deepen understanding of a science topic and can lead to conceptual change (Clement, 2008c; Jonassen, Strobel, & Gottdenker, 2005; C. B. Lee, Jonassen, & Teo, 2011). During model construction, students must sort out relevant ideas, build explanations, define problems, seek information and test and revise theories (Spitulnik, Krajcik, & Soloway, 1999).

To understand model-based learning based solely on the features and attributes of the model would be a model-centric view which leaves out critical aspects of the student in the learning environment. Lehrer and Schauble (2006) point out that the meaning of the model is "determined by the intentions and purposes of modelers." They go on to say that, despite the features of models, "their status as models relies on interpretation" (p. 373). Open, student-centered modeling activity is a negotiation of various aspects of the environment. The student appropriates prior knowledge and classroom resources and responds according to personal goals and perceived expectations.

Understanding How Children Model in the Classroom

Research is emerging that offers insights into both the kinds of models that can be employed as well as how students reason with models. Research has supported the potential of models for promoting various forms of reasoning in science learning (Buckley et al., 2004; Clement & Steinberg, 2008; Lehrer & Schauble, 2006), especially when students are engaged in constructing models (Shen & Confrey, 2007; Spitulnik et al., 1999). However, much of the research has focused on contexts where the models are highly technical either in details of the planned implementation or in the tools offered for model construction. Research in such environments provides evidence of reasoning and learning in specific contexts. However, it can be useful to understand students' model-based reasoning as a natural process of thinking. For instance, a student may use a software tool to build a model, but the availability of a defined set of tools in the software will influence the student's perceptions of what is expected and what can be done. The student learns a contextualized language – the software's resources – in order to create a model that meets the demands of the situation. However, in a more open, student-centered learning environment, what resources do students appropriate while externalizing models when there are fewer pre-defined resources? This aspect of modeling can be thought of as the difference between germane modeling activities (those that are natural for students to engage) and induced modeling activities (those that are achieved through guidance and instruction).

The potential of student modeling as both an inquiry skill and as an instructional practice to promote effective learning in the classroom is compelling. Some efforts in model-based learning have focused on elementary grade students. Lehrer and Schauble (2006) have undertaken work with teachers to create classroom environments that help children develop model-based reasoning skills across grades of school. Elementary level children have demonstrated foundational reasoning skills with models. Children can infer ideas and knowledge from models and use that knowledge to think about the referent in nature (Lehrer et al., 2008). This form of analogical reasoning with models varies and depends, in part, on how much the models resemble the referent (Lehrer & Schauble, 2006). Furthermore, when students create models of a natural phenomenon, they are more likely to represent the resultant state rather than the process, but can learn to add features to represent intangible or unseen attributes in order to make the model more explanatory (Schwarz et al., 2009). The abilities to map analogical representations and to model unseen natural phenomena are critical skills for children to be able to participate in scientific modeling and to construct models. Less is known about what processes children engage to construct models. In a student-centered context where students are encouraged to create their own models without detailed instruction in how to complete the task, what resources do they use? To what extent do students use previous knowledge, integrated with newly learned content to construct? Do they transform information across multiple models or from personal experience? What intentions guide their reasoning when they transform and make connections? What aspects of the learning environment promote and inhibit constructivist learning during model construction? Research in this area can help build a framework for understanding children's natural reasoning during scientific modeling. Furthermore, research is needed that considers students in a student-centered environment in order to better understand how student-centered environments can support scientific modeling. The value of such research is not necessarily in examining learning environments where modeling practices are regularly taught and supported, but rather examining students' natural responses and inclinations to learning through modeling in the traditional classroom. Such a research focus can help support transitions toward student-centered practice and model-based instruction.

Statement of the Problem

While many efforts exist to promote constructivist thinking in elementary school-age students, less is understood about the classroom factors that may influence *how* students engage in such activities. Research suggests that constructing models has the potential of helping young students construct understanding of phenomena, but such reported activities reveal little about the environment in which those activities are enacted. To better understand how importing student-centered modeling activities in the classroom can promote constructivist learning, there is a need for understanding the environment and the teacher actions that promote or hinder constructivist modeling during student-centered activity.

Key Definitions

I define how I use some key terms in this study:

Constructivism. There are many theoretical and philosophical views of constructivism. For this study constructivism refers to the idea that people construct knowledge and understanding through interactions with the world. Furthermore the process involves combining one's current knowledge and experiences with new experiences.

Modeling. Modeling refers to constructing and working with representations. This includes many ways of interacting with models and many kinds of representation.

Constructivist modeling. This term describes the use of models to promote constructivist learning. Learners interact and reason with a model in such a way that he or she constructs new ideas, personal theories, or explanations.

Research Questions

In order to pursue this line of inquiry, I conducted a research study focused on how elementary children construct models of content they are learning in the classroom. I used the following questions to guide the study:

1. *What characteristics of student-generated models reflect (or do not reflect) constructivist processes?* Students incorporate various features from home and objects from classroom demonstrations used to represent abstract phenomena in their drawings. This question guided analysis of how students incorporated constructivist

elements into models. The purpose was to develop indicators and resources for using constructivist models.

2. *How do students reason as they construct personal models?* When students generate models, they decide what to create and they appropriate resources to represent their understanding. Do they simply reproduce teacher/curricular models or is there evidence of unique accommodation with the student's background? The purpose was to identify common activities and exceptional activities that describe reasoning during modeling.
3. *How do the teacher's instructions during model generation and subsequent interactions affect the students' construction of models?* The teacher's implementation of modeling may be a key influence in promoting constructivist modeling. I analyzed the teacher's implementation and compared that with students' modeling to examine the teacher's impact on modeling.

CHAPTER 2

FRAMEWORK

In this chapter I explain how model-based learning can provide constructivist, student-centered learning in the curriculum. I then present a framework for studying constructivist modeling in the elementary classroom. I conclude with recommendations for research in this area.

Constructivism and Student-Centered Learning

While educators pursue the common goal to promote effective learning, differences exist in approaches evident during practice. For example, schools and standardized tests often assess factual recall to measure student learning. This approach is criticized by some who say factual recall only measures surface understanding (Shepard, 2000). These critics say that effective learning includes abilities and habits of mind that aren't easily assessed in multiple choice assessments, but are instead found in the application of knowledge to authentic problems and contexts (Hannafin & Land, 1997). Interpretation of effective learning is, implicitly or explicitly, connected to epistemological views for both students (Watters & Watters, 2007) and teachers (Chan, 2011).

Student-centered learning has its roots in constructivist views of learning. Piaget is often credited as a founder of constructivism because of his ideas about human learning and development (though some also trace its philosophical roots to much earlier [Glasersfeld, 1989]). Piaget's work influenced psychology and education with the idea that people construct knowledge and understanding through interactions with their world (Glasersfeld, 1996; Watts &

Pope, 1989). This view stands in contrast to a view of learning as the transmission of knowledge from teacher to student. With this shift, educators and researchers have sought ways to support students to actively construct knowledge rather than passively receive information. Student-centered learning, then, places the student at the center of the learning activity, providing experiences whereby the learner may interact with authentic settings and construct understanding (Hannafin et al., 1997).

The term *student-centered learning* is used broadly and often without definition, suggesting it has a shared or understood meaning (Paris & Combs, 2006). It is sometimes described as being the opposite of a teacher-centered classroom in which the teacher is the major focus of activity (Blair, 2009; Kember, 1997). This shift in focus requires the student to be involved in, if not completely responsible for, making decisions and navigating learning resources to arrive at some goal, thereby becoming more actively engaged in the learning processes of constructing meaning and developing conceptual understanding (Hannafin et al., 1997).

Student-centered learning is better understood as a description of *how* the learner works. A variety of practices have been developed that are aligned with the goals of constructivist, student-centered learning, including problem-based learning (Savery & Duffy, 1996; Savery, 2006), anchored instruction (Vanderbilt, 1992), open learning environments (Hannafin et al., 1999), and constructionism (Papert & Harel, 1991). Each of these has distinct characteristics as a designed learning environment, yet they all provide similar opportunities for constructing knowledge through active engagement.

Instead of a single theory or method to embody student-centered learning, Land, Hannafin, and Oliver (2012) propose a set of core values and assumptions: “(a) centrality of the learner in defining meaning; (b) scaffolded participation in authentic tasks and sociocultural practices; (c) importance of prior and everyday experiences in meaning construction; (d) and access to multiple perspectives, resources, and representations" (p. 8). . The values and assumptions may be acceptable without objection by most educators. The key contribution is how these assumptions are put into practice. Past studies have shown that beliefs may not align with practices (Fang, 1996). In one study researchers found teachers who were supported in adapting learner-centered pedagogies espoused practices but did not enact those practices (Polly & Hannafin, 2011). Each of the proposed values and assumptions of student-centered learning contributes to an experience in which the learner is the primary actor in constructing meaning from experiences. And while these values and assumptions are sufficiently broad to allow for diverse enactments, the authors demonstrate how each offers guidance for the design of learning environments. Table 1 shows design guidelines they propose based on these assumptions.

Table 1. Core values and assumptions of student-centered learning.

Values and Assumptions	Design Implications	Learner Activity
Centrality of the learner in defining meaning	Includes increasingly complex problems built around main concept.	Learner articulates ideas, gathers information, creates artifacts.
Scaffolded participation in authentic tasks and sociocultural practices	Learning, ideas, and activities are situated in authentic contexts.	Learner encounters new content and applies new skills and content in real-world or simulated contexts.
Importance of prior and everyday experiences in meaning construction	Opportunities provided for students to externalize personal beliefs and ideas. Familiar/local problems can illicit personal ideas.	Learner generates ideas and artifacts that can be communicated, tested and revised.
Access to multiple perspectives, resources, and representations	Learning environment incorporates multiple views, interactions with teacher and students, and various representations.	Learner shares emerging ideas; structures and applies new ideas gained through interactions.

Adapted from Land, Hannafin, and Oliver, 2012.

There have been mixed reports of student-centered learning's impact on desirable outcomes. Some studies have found that with more learner-centered practices in the classroom come better performance on outcomes such as grades and standardized tests (Weinberger & McCombs, 2001) as well as student attitudes and motivation (Daniels & Perry, 2003; McCombs, Daniels, & Perry, 2008; Weinberger & McCombs, 2001). Some researchers assert that student-centered practices are not always ideal. For instance, Kirschner, Sweller, and Clark (2006) famously made the case that minimal guidance is both less effective and less efficient than guided instruction in many learning contexts. While student-centered practices appear to provide mixed results in certain outcomes, student-centered learning practices may promote other behaviors that are harder to measure but still highly valued. For instance, students working in student-centered learning environments have been observed to engage in higher-order thinking and engagement with their work (Cornelius-White, 2007). Learner-centered environments have been found to have high correlation with critical and creative thinking (Cornelius-White, 2007). Student-centered activities have been shown to promote analytic reasoning (Cox, 1999).

Thus, student-centered learning is viewed by some as a desirable practice for promoting ways of thinking and learning. However, given the mixed results found in research studies (Hmelo-Silver, Duncan, & Chinn, 2007; Kirschner et al., 2006; Mayer, 2004), it is reasonable to conclude that student-centered learning is not a one-size fits all approach. Instead, attention needs to be paid to characteristics of the context in which instructional interventions will be deployed; student-centered practices must be adapted to fit the particular needs of a given classroom context (Perkins, 1999). For example, given that novice learners do not perform certain tasks well with minimal guidance (Kirschner et al., 2006), adjustments can be made in terms of the amount of scaffolding to create a well-balanced environment (Alfieri et al., 2011; Peters, 2010) that achieves some of the benefits of student-centered learning.

Challenges in the classroom. Bringing student-centered learning into the classroom presents practical challenges at multiple levels, including policy, teacher practice and student engagement. At the policy level, teachers are required to meet various mandates and standards which seem to conflict with many student-centered practices. The accountability movement with accompanying standardized tests has led to highly detailed standards that focus on content and leave little room for student-centered learning (DeBoer, 2002). Furthermore, the content focus of standards tends to specify a broad range of knowledge, leading to the “mile-wide, inch-deep” problem, which further shifts teachers’ focus to covering material and transmitting knowledge, rather than leading students through constructivist learning experiences (Hume & Coll, 2008). Despite attempts to call attention to the need for learning processes and inquiry (see, for example, Board on Science Education, 2012), the focus on content that is caused by testing and standardization (Southerland et al., 2007) is not likely to go away soon given policy that requires careful standardized testing to qualify for federal education funds and meet adequate yearly progress.

The change process required of the teacher is another source of difficulty in implementing student-centered practice in the classroom. Teachers can find it difficult to change from familiar practices and routines to new practices. Transitions to implementing student-centered practice require teacher professional development (Polly & Hannafin, 2011). And regardless of stated goals by teachers, teachers’ beliefs about student learning and effective class management must be aligned with target practices (Mansour, 2009; Ogan-Bekiroglu & Akkoc, 2009).

Finally students may be presented with opportunities to engage in constructivist learning, but that does not guarantee that they will engage. Motivation can influence whether a student acts with intention to just meet requirements or to engage learning deeply (Nieswandt & Shanahan, 2008). In the classroom, students often act strategically, finding shortcuts and using resources that may not involve constructivist learning to complete a task. Furthermore, in traditional classrooms students have been accustomed to seeking to meet the teacher's expectations (McCaslin & Good, 1992) and may interact with external motivations thus minimizing constructivist learning processes.

The challenges of providing student-centered learning in the present classroom context signify a need for strategies that can be integrated into existing practices. Practical student-centered methods would not require the teacher to radically alter the existing curriculum, but would instead support, to some extent, the demands and practices the teacher employs routinely. The primary goals of such methods would be to support constructivist learning by helping students integrate existing knowledge as they construct new understanding, all within a workable framework for practicing teachers. Characteristics of student-centered activities that support such learning include authentic practice, requirements to build or construct a relevant entity, and a degree of open-endedness. One potential area for addressing these needs is modeling in science education. Model-based learning provides resources for integrating extant curricular practices as models and prompting students to construct models.

Model-Based Learning

In the field of science education, the central ideas of constructivism have influenced a shift in how science is taught. Based on the premise that science knowledge is constructed through multiple processes, educators and researchers placed greater emphasis on science inquiry

(Driver et al., 1994). Terms like “think like a scientist” (Williams, Papierno, Makel, & Ceci, 2004) and “habits of mind” (Georgia Department of Eduation, 2004) are used in textbooks and state standards thereby shifting the focus from teaching content knowledge to engaging students in the “processes of science” with science content (National Research Council, 1996).

Inquiry-based science learning has distinguished between learning science content and learning science inquiry. For many, the goal in the classroom is to teach science content through inquiry methods, thus inducting students into the practices of the scientific community (Driver et al., 1994; National Research Council, 1996). Model-based learning is an emerging science education focus that involves science inquiry practice while simultaneously engaging students in constructing understanding of science content.

Modeling in science. The use of models is common and fundamental to scientific research. A model is a simplification of a real-world phenomenon. A model can come in any form including a drawing, a 3-D scaled model, a graph chart, an analogy, or a computer-based animation. A model may be a static representation or a dynamic model (Rea-Ramirez, M. A., & Nunez-Oviedo, 2008; Schwarz et al., 2009). Models are useful because they simplify complexity while focusing on essential aspects. Indeed, modeling is a fundamental aspect of human endeavor to understand the world. Feurzeig and Roberts (1999) described the fundamentality of models:

> …in simplifying the complexities of the real world, they enable us to concentrate our attention on those aspects of it that are of greatest interest or significance. It has been suggested that our ability to create, examine, and refine such models is crucial to our understanding of the world and that without this ability, we would literally be unable to “think” as humans (p. xv).

Science models play a significant role in advancing scientific research (Magnani, Nersessian, & Thagard, 1999). Scientists create models in order to test a theory that would otherwise be untestable, such as changes in species distribution over hundreds of years of climate change (Pearson & Dawson, 2003). Scientists also use models to communicate their ideas with others; scientists sometimes create formal or informal models as a means of thinking through a problem (N. J. Nersessian, 1995).

The significance of modeling as inquiry recently spawned interest in making modeling a part of the science curriculum and standards (Georgia Department of Eduation, 2004; National Research Council, 2012). Researchers have increased interest in various aspects of models in science education including the ability of students to think with models (Lehrer & Schauble, 2005), the effects of different kinds of models (Löhner et al., 2005), how teachers use models (Kenyon, Davis, & Hug, 2011), and how technology enhances opportunities for modeling (Blikstein & Wilensky, 2009).

Modeling in science education. Modeling has become an increasingly common form of inquiry and practice in the sciences, described as the "form of inquiry most characteristic of the sciences" (Lehrer, Schauble, & Lucas, 2008, p. 514). Modeling has proven to be an especially useful alternative to the traditional scientific method taught for decades. Furthermore, modeling addresses a key science education issue of combining content with process; students learn neither "domain empty strategies" nor "inert facts" considered irrelevant to inquiry work (Lehrer et al., 2008). Because of these qualities, modeling is a core practice emphasized in the Next Generation Standards (NGSS, 2013).

In science education, researchers rely on a number of options to characterize a model. *Expert consensus models* represent the shared understanding of a phenomenon held by experts in the field (Clement, 2008b). A personal model or mental model, in contrast, can refer to one's current understanding of a concept or representation of the surrounding world (Ifenthaler & Seel, 2012; N. M. Seel, 2001). The goals of science education form the *target model* (also called *curriculum models* [Buckley, Boulter, & Gilbert, 1997]). According to Clement (2008), a target model refers to "the desired knowledge state that one wishes students to possess after instruction" (p. 12). *Curricular models* or *instructional models* are models used to teach a given concept. Various curriculum models may be used during instruction. Learning may be characterized as the process of changing or altering one's mental model. In fact, if humans reason with mental models as Johnson-Laird (Johnson-Laird, 1983)proposes, the interaction with external models will most likely influence or change related mental models. Education, in this sense, involves efforts to help the learner refine their mental model to more closely resemble the target model. Table 2 summarizes various models that are a part of science learning.

Table 2. Models in a typical learning environment.

Model	Form	Examples
Expert Consensus Model	Distributed, shared understanding	The body of scientific knowledge of the digestive system and all related processes
Target Model	Teacher goals, Standards	Understand and explain the function of the major organs in the digestive system
Instructional/curricular model	Externalized representations such as diagrams, animations, analogies, and physical models	Drawings in a text of the path food takes during digestion, a cartoon showing characters flying inside the body, and plastic reproductions of the stomach and intestines
Mental model	Assumptions, theories, and beliefs based on experiences	A young learner's understanding of a "food pipe" connected to a stomach followed by intestines

Model-Based Learning and Instruction

Model-based learning and instruction refers to learning contexts that employ an external model or a modeling process as a central figure in the learning environment. The exact nature of a model-based learning environment varies according to the kinds of models employed and how they are implemented. For example, a teacher may use a mini ecosystem in the form of pond life in a jar for students to observe for an extended time (Lehrer, Kim, & Schauble, 2007). Students may verbalize models with the teacher during class discussions to promote a shared model construction (Clement, 2008b) or use a computer to generate rules for a system and observe the consequences (Wilensky & Reisman, 2006). Thus, in contemporary practice and research of model-based learning, the model does not serve as a specific representation to transmit knowledge, but rather as a fulcrum for interactions through which students build understanding.

There is considerable diversity in how models are deployed and used in formal learning contexts. However, commonalities characterize a general understanding for how students learn with models. The learner constructs models, evaluates models and refines models, and forms or refines existing theories and ideas. Clement (2008a) refers to the process of evolving one's mental model as GEM: Generate, Evaluate, and Modify. Although the precise wording varies, multiple scholars employ similar activities to describe model-based learning (Buckley et al., 2004; Gobert, 2000).

Constructing models. Educators and researchers have implemented model construction to support model-based learning; model construction affords learners opportunities to think and analyze. Furthermore, model construction provides opportunities to engage in essentials of constructive learning, building knowledge and understanding through interaction with authentic contexts. Constructing a model represents a specific application of constructivism, where learners construct an external artifact (Papert & Harel, 1991). Constructionism has students assume the role of builders, constructing models, simulations, and static representations. Papert clarifies constructionism stating that constructivism “happens especially felicitously in a context where the learner is consciously engaged in constructing a public entity…” (Papert & Harel, 1991, p. 1).

Constructivist modeling is evident when the process of constructing supports constructivist learning. The process becomes more important than the product, as the product is merely a fulcrum around which important thinking and learning take place. The constructivist postulate that people create internal representations, or mental models, as they interact with the world (Johnson-Laird, 1983) makes working with models especially useful in learning. Numerous researchers have shown how modeling can lead to conceptual change (see for example, Clement, 2008c; C. B. Lee et al., 2011; N. Nersessian, 1999).

Evaluating models. Model evaluation is key to conceptual change and growth. Students apply new information during instruction to evaluate the model they generate. The source and timing of new information can vary. Evaluation can be prompted by classroom conversations and discussion during which the teacher asks students to consider hypothetical outcomes of a proposed model (Khan, 2008). Students may also evaluate a generated model by considering other representations and models (Clement, 2008a; Nuñez-Oviedo & Clement, 2008). Some models and simulations may also be run in order to test the model and collect data, thereby evaluating the model (Blikstein & Wilensky, 2009).

Revising models. By encountering new information and evaluating models, students consider revising their models. Revisions provide opportunities to repeatedly test and confirm (or disconfirm) models. For some, revising models involves the important step of revising mental models at the same time (Buckley et al., 2004). Changes that are made serve as a catalyst for re-evaluating or re-testing the model. Thus, the modeling process is cyclical in nature (Buckley et al., 2004; Clement, 2008a). Indeed, evaluating and revising indicates that the model is perpetually taking shape. In effect, this process could be characterized as constructionist process and not merely the act of initially generating a model (Blikstein & Wilensky, 2009).

Modeling and Student-Centered Learning

In practice and in research, model-based learning is closely aligned with the pedagogical goals of student-centered learning; model-based learning practices are consistent with many student-centered practices. Because scientific modeling is a common inquiry practice in science, model-based learning engages students in learning and applying authentic practices. Prior knowledge is initially represented by the learner's mental models during model construction (Buckley, 2000). Providing externalized models affords opportunities to reconstruct individual understanding through interactions, a process deemed most helpful when initial guidance is sufficiently open to promote student-centered activity. Activity support, however, may require a balance of student initiative and expert scaffolding (Clement, 2008b; Nuñez-Oviedo & Clement, 2008). Scaffolds could come in a variety of forms and at a variety of junctures during modeling including the following: (1) how to begin a model. In one effort by the National Technology Leadership Coalition, students were provided with an initial model upon which to base their model and elaborated their construction; (2) how to reason with knowledge during modeling (Davis & Linn, 2000); and (3) how to evaluate models, thereby learning to reason further with the model (Kenyon, Schwarz, & Hug, 2008). Indeed, according to advocates, one of the primary benefits of model-based learning is that it promotes student-centered activity (Clement & Rea-

Ramirez, 2008). Table 3 summarizes how model-based learning aligns with core values and assumptions of student-centered learning.

Table 3. Model-based learning alignment with the student-centered learning core values and assumptions (Land et al., 2012).

Values and Assumptions	Design Implications	Learner Activity	Model-Based Learning
Centrality of the learner in defining meaning	Includes increasingly complex problems built around main concept.	Learner articulates ideas, gathers information, and creates artifacts.	Modeling is a process whereby learners create artifacts, test ideas and refine models (Clement, 2000; Wilensky & Reisman, 2006).
Scaffolded participation in authentic tasks and sociocultural practices	Learning, ideas, and activities are situated in authentic contexts.	Learner encounters new content and applies new skills and content in real-world or simulated contexts.	Modeling is an authentic task is science fields (Lehrer & Schauble, 2006) and can be used to situate to-be-learned content (Lehrer & Schauble, 2005), thus developing content and inquiry practice together.
Importance of prior and everyday experiences in meaning construction	Opportunities provided for students to externalize personal beliefs and ideas. Familiar/local problems can illicit personal ideas.	Learner generates ideas and artifacts that can be communicated, tested and revised.	Designed activities help students elicit prior knowledge through models and model construction (Buckley et al., 1997; Clement, 2008b; Gobert & Buckley, 2000).
Access to multiple perspectives, resources, and representations	Learning environment incorporates multiple views, interactions with teacher and students, and various representations.	Learner shares emerging ideas; structures and applies new ideas gained through interactions.	Learners use models to communicate and share ideas, revise existing models, and they typically encounter multiple models in the curriculum (Buckley, 2000). Modeling can help students integrate knowledge (Linn, 2000) Modeling can help learners transform ideas from multiple representations (Shen & Confrey, 2007).

Scientific Modeling and Young Children

Learning with models has been implemented with children at the elementary school level (see, for example, Baek et al., 2011; Lehrer et al., 2008; Lehrer & Schauble, 2005). For example, children applied modeling skills as a form of inquiry (Lehrer & Schauble, 2006). They constructed model representations of their understanding (Kenyon et al., 2008), evaluated their models, and revised them (Baek et al., 2011).

However, while potentially valuable, modeling as a form of inquiry often requires practice to implement effectively (Lehrer & Schauble, 2006). Schwarz and colleagues (2009) observed that children in one study changed in both the ability to create explanatory models and in their inquiry reasoning with models.

While children have engaged in a variety of model-based activities, associated theories and practices are not easily ported to the elementary classroom. Many skills involved in modeling activities, such as analogic reasoning, representing abstract concepts, and cause and effect reasoning, develop over time and require maturation and practice. Therefore, the design of model-based learning environments and the deployment of models need to be adjusted to align with children's developmental capacity (Lehrer & Schauble, 2005).

Reasoning with Models

While scholars have identified various reasoning activities that learners engage in at different phases of using models (Löhner et al., 2005), some types of reasoning can be implemented throughout the modeling process.

Analogic reasoning in modeling. In order to engage in scientific modeling, learners must engage in analogical reasoning. Students who use models must map connections between features of the models and their real-world referents. Lehrer and Schauble (2006) propose that analogic mapping contributes to model complexity; some models are easier to map due to resemblance or literal similarity to what is represented while other models involve abstract representations. To illustrate, Lehrer & Schauble (2006) studied elementary students using dowels and craft materials to create a model of the elbow. The students' first concern was making something that looked like an elbow. They even incorporated Styrofoam balls to simulate the bumps in the elbow and Popsicle sticks to represent fingers – features which did not enhance the function of the elbow, but did enhance the visual similarity. Later, as students evaluated and compared the model to the motion of their own elbows, they focused on the relations between parts and to designs that represented motion and restricted elbow motion. Lehrer and Schauble described this "shift from literal similarity to mapping relations [as] a hallmark of analogical reasoning" (p. 373).

Relational Reasoning. When students create models, they must also engage in relational reasoning. In other words, they must recognize and consider relationships between objects, either in the real world or in the model: "There has to be a relational reason for including objects, otherwise the model would be random" (Stratford et al., 1998).

Evaluating Models. Through model evaluation, a learner may begin to recognize nuances of the referent or target model. Evaluation can occur in a variety of contexts. Evaluating a model can help the learner come to recognize previously held conceptions as they move toward conceptual change.

While evaluation is necessary, inducements may guide a learner in how and what to evaluate. Students who use computer-based modeling to simulate a process or an event may evaluate the initial model when they execute the program in order to decide whether to change or debug the model (Stratford et al., 1998). In other studies, students constructed models with a teacher who asked frequent questions, encouraging students to evaluate the models they created and to change as needed (Nuñez-Oviedo & Clement, 2008). For instance, in a study (Khan, 2008) involving high school students learning atomic stability, a teacher posed “what-if” questions to prompt students to incrementally change the magnitude of a charged particle. Students then speculated about what would happen and gradually changed the boundaries of their model based on speculative experiments.

Transformative Modeling. When constructing models, students apply existing knowledge and seek new ways to represent that knowledge (Shen & Confrey, 2007, 2010). In one study with elementary school teachers, Shen and Confrey (2007) observed that moving through a series of models, learners engage in successive transformations including the process of constructing models. During a workshop on the Sun, Moon, and Earth system, teachers were involved in a series of transforming representations: They first used raw data to create data tables, then data tables to create 2-D models, followed by spheres and 2-D models to test ideas and create 3-D models. The researchers noted three important transformative modeling functions: (1) Transformative modeling allows the learner to see different aspects of the referent; (2) Making connections and seeking consistency between different representations can support the learning process; and (3) transformations can help detect and resolve inconsistencies between the learner’s understanding and the model. Thus, the act of transforming can prove pivotal in promoting conceptual growth and change.

Among young children, transforming models can prove cognitively demanding as it requires attention to multiple simultaneous representations at once, while simultaneously performing higher-order comparing, contrasting and analyzing. Transformations in student-generated models could represent deeper reasoning than merely reproducing part or all of a model. Furthermore, transformations may reveal inconsistencies between the child's understanding and the target model; detecting those inconsistencies and responding to resolve them would represent a level of careful analysis during modeling.

Contextual reasoning with models. Modeling is necessarily bound in the context in which it takes place. Stated differently, there is no single inherent quality in a model that defines what is or is not a model. Individual interpretation is as important as the qualities of the model. In effect, context becomes central to learning and reasoning with models insofar as aspects of the context play a part in understanding and interpretation of the model. The learner's prior knowledge of the target of instruction will facilitate the learner's mapping and understanding of the model. Furthermore the learner's ability to reason analogically may be influenced by development (Lehrer & Schauble, 2006). Finally, customs and practices in the situation that a model is used may bias or influence the learner's interpretation of the model.

Framework: Student-Centered Model-Based Learning in the Classroom

Student-centered learning provides a framework for constructivist learning in informal as well as formal learning environments. During student-centered activities, the individual engages in authentic practices to define meaning and navigate the learning process. Such activity encourages the learner to draw upon prior knowledge while encountering new ideas through interactions with representations and artifacts of the domain. As such, student-centered activities provide the opportunity for constructivist learning on the part of the learner.

"Degrees" of student-centeredness. While student-centered learning is sometimes treated dichotomously as a contrast to guided instruction (Kirschner et al., 2006) it might be more helpful to think in terms of varying levels. Alfieri and colleagues found that various kinds of scaffolded practice were more effective than no guidance (2011). Further, Perkins (1999) suggests that different domains and contexts can call for different kinds of constructivist instruction. Student-centeredness varies according to the degree of support and guidance (see Figure 1.) And while greater student-centeredness may offer opportunities such as student-initiated discovery and engagement in authentic practice, there are trade-offs as well. For example, less direction may result in students pursuing activity not related to the goals of the teacher and it may take longer for students to complete tasks.

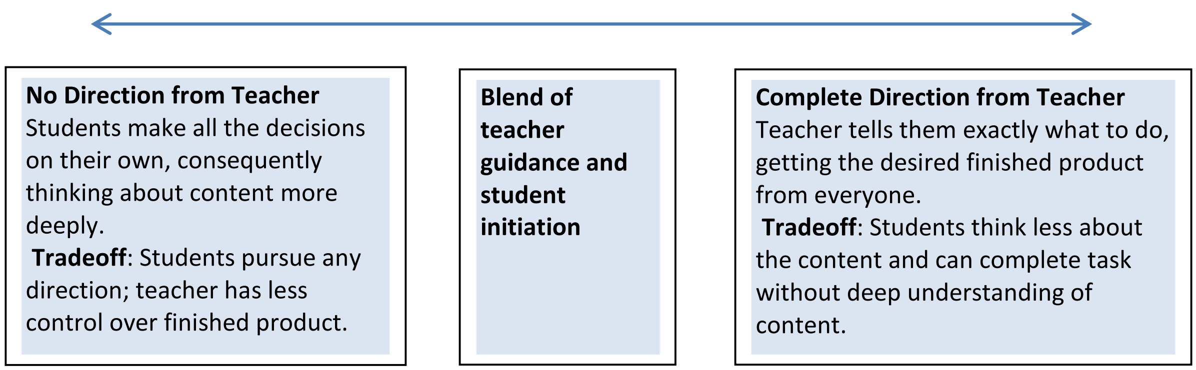


Figure 1. Spectrum of student-centeredness.

Student-centered practice in the classroom. As previously described several practical classroom concerns make it difficult to implement student-centered activities. The breadth of content that teachers are required to cover in order to meet state standards makes it difficult to give sufficient time to student-centered activities. And the amount of content can contribute to students' participating in many instructional activities that appear to be unrelated to each other. The outcome is that student-centered practices come into conflict with the curricular demands placed on teachers. One approach to address that apparent incompatibility is to develop student-centered activities that can be integrated with the existing curriculum.

Model-based learning. Model-based learning provides resources that address these issues. Viewing the various representations of scientific phenomena as models provides a way to integrate curricular representations with the student's own mental models. Furthermore, model-based learning provides methods and practices that are student-centered and promote constructivist learning (Ifenthaler & Seel, 2012). Construction of models is especially critical to the potential of model-based activity as a student-centered learning method. It is during construction that learners draw on prior knowledge to externalize mental-models and create artifacts that integrate to-be-learned content with prior knowledge (Clement, 2008).

In elementary classrooms. To adapt model-based learning as student-centered practice in the elementary classroom, age-appropriate adaptations must be considered. Creating models involves a materials language. Using a computer program to create a model requires knowledge of the computer program's code or a set of available tools (Löhner et al., 2005). Creating models out of materials requires knowledge of a particular craft, whether that be, for example, working with Styrofoam, construction paper and glue or working with electronics kits. Therefore, to use model-construction in the elementary classroom, educators must consider teacher *and* student skills involved and whether those skills are age appropriate.

The materials used to create a model have certain affordances that may suggest what kind of models can be constructed. If students are given a set of Styrofoam balls and told to construct a model of the solar system, the model will most assuredly deal with a limited set of concepts such as position of celestial bodies and relative size. Given a computer program whose primary function is to let users define behaviors of agents, students may focus on different aspects of the solar system such as rotation and orbiting patterns of planets, moons, and meteors. The kinds of materials used to create a model can influence the model-construction process. This has been demonstrated in research with computer programs (Löhner et al., 2005) and can reasonably be applied to other materials as well. Factors that influence what a learner can or will model can be called determining affordances.

Drawing to model. Drawing pictures to model understanding is a particularly relevant student-centered practice for elementary students. Some have argued that drawing is a process of making meaning (Brooks, 2009). Ainsworth, Prain, and Tytler (2011) offer several reasons "why student drawing should be recognized alongside" other key communications in science education (p. 1096) including drawing to reason in science and drawing to learn. Further, drawing is a familiar medium for children; it eliminates some of the difficulty young children may have learning complex or unfamiliar materials, increasing the feasibility of use as a form of model-based learning. And, drawing has fewer determining affordances so, drawing makes both literal and abstract representations possible.

Drawing has proven to be a useful form of modeling for older students and adults to represent beliefs about science (Frankel, 2010). And graphical representations helped students reason differently than the textual representation (Cox, 1999; Löhner et al., 2005). Researchers working with younger children have used drawing as a form of modeling to elicit and analyze science reasoning (Rea-Ramirez, M. A., & Nunez-Oviedo, 2008; Schwarz et al., 2009).

Directions for Research

Much of the past research on reasoning has focused in large part on the reasoning limited to that which is directly related to the model. For instance, Löhner and colleagues (2005) reviewed inquiry and model-based reasoning processes and reduced them to five common categories: orientation, hypothesizing, experimenting, model evaluation, and documentation. This and similar work is helpful in understanding methods to facilitate learning with models, however, in order to study student reasoning more completely, the larger context must be considered. Students may need to construct a model diagram (Hogan & Thomas, 2001) at the onset of modeling work, but if they choose to copy a neighbor's ideas, then this aspect of constructivism is experienced to a limited degree. A student may need to hypothesize while using a model (Löhner et al., 2005), but if the teacher steps in to help by giving the student a hypothesis to work with then that aspect of model-based learning is cut short. Any number of factors in the classroom can influence how a student engages in model-based activity. Additional research into student's reasoning should consider how students strategize and reason as they use models. Such work can help clarify to what extent students are engaging in learner-centered, constructivist learning. And perhaps that work will lead to understanding how facets of a designed intervention promote or diminish student-centered activity.

Development activities and technological research have brought advanced tools and methods for helping students learn through modeling with promising research-based results in the classroom. Understanding basic patterns and behaviors during modeling when contextualized in the classroom will contribute to efforts to integrate model-based learning in the curriculum and to make modeling more student-centered.

CHAPTER 3

METHODS

The purpose of this study was to examine how elementary students reason during student-centered model-construction in science. This study was designed to identify key patterns that can provide resources for expanded studies in follow-up research. I used the following research questions to guide this study:

1. *What characteristics of student-generated models reflect (or do not reflect) constructivist processes?* Students incorporate various features from home and objects from classroom demonstrations used to represent abstract phenomena in their drawings. This question guided analysis of how students incorporated constructivist elements into models. The purpose was to develop indicators and resources for using constructivist models.
2. *How do students reason as they construct personal models?* When students generate models, they decide what to create and they appropriate resources to represent their understanding. Do they simply reproduce teacher/curricular models or is there evidence of unique accommodation with the student's background? The purpose was to identify common activities and exceptional activities that describe reasoning during modeling.
3. *How do the teacher's instructions during model generation and subsequent interactions affect the students' construction of models?* The teacher's implementation of modeling may be a key influence in promoting constructivist

modeling. I analyzed the teacher's implementation and compared that with students' modeling to examine the teacher's impact on modeling.

Operational Definitions

Several terms define specific features of this study:

Enactment – An implementation of the modeling activity with the class, including all of the teacher's instructions and the students' behaviors during model creation.

Constructive Modeling – Modeling that induces constructive reasoning through interaction with the model.

Constructive Elements – The discreet, individual parts of a model used to represent ideas, facts, or phenomena.

Explanatory Models – Models that explain a process or causal relationship in science.

Factual Models – Models that communicate facts, without explanation of processes or causal relationships.

Open-ended prompts – The teacher's instructions which are characterized by being non-specific and leaving open the number of ways one could respond.

Directed prompts – The teacher's instructions which are characterized as being specific or detailed.

Rationale

I conducted the current study in an elementary public school classroom. The setting provided an authentic situation to consider the classroom context and teacher-student interactions. This case study focuses on students and teachers modeling in a bounded system. The setting is also a traditional classroom wherein the teacher relies on a variety of instructional practices, but does not typically engage in model-based instruction per se. While the setting provides the desired authentic, traditional classroom that is important to the study, the tradeoff is that this is different from a model-based learning classroom where modeling is routine practice. This study can help provide resources for transitioning toward a model-based practice in the classroom. Appropriate to studying phenomena in context (Marshall & Rossman, 2006), I used non-participant observations and artifact analysis supplemented by unstructured interviews. I observed the natural setting and all the connected parts as one inseparable context. Consequently, I allowed the teacher to enact the planned modeling events without a script or specific methods. Her judgments and responses were a part of the setting that I observed.

This study is formative and designed to help establish performance patterns in a classroom enactment of student-centered, model-based learning. As such, the methods were designed to find patterns and identify and analyze emerging ideas. Because of the formative nature of this research, I conducted several preliminary studies leading up to the current study. This study is part of a larger effort incorporating elements of design research (Akker, Gravemeijer, McKenney, & Nieveen, 2006) carried out across four years which informed aspects of the current implementation.

To ensure students' rights were protected, this study was approved by the University of Georgia Institutional Review Board (IRB) with permission of the participating teacher, district and school officials. I also obtained signed written consent from students, parents and/or guardians and the teacher.

Preliminary Studies

My research plan included three parts: (a) students constructed open-ended models intermittently; (b) the participating teacher focused on promoting constructivist thinking during modeling; and (c) I observed daily instruction. During design-based studies, I followed this same general plan across four different teachers and classrooms at three different schools in the Southeastern and Western United States on the following science topics: sound and sound waves, constructive and destructive forces in earth science, sound and light, and microorganisms. These preliminary studies enabled me to identify common themes and practices across science topics and contexts and provided background central in the development of the current study.

In the first study, fourth-grade students modeled sound and light waves. I observed that even though drawing was a familiar activity, drawing models was challenging. The autonomy provided individuals produced no evidence of theorizing while drawing; in addition, students required more guidance in both what to model and how to model. In the second study, we focused on teaching students to model before providing opportunities to create models; a different group of fourth-graders also modeled light. Students were able to model with guidance, but as class activities progressed, their models replicated class instruction more.

Still, variations were noted in how students modeled from one enactment to another and evidence suggested that differences were influenced by how the teacher prompted modeling. This suggested that student-centered modeling involved complex interactions between teacher, class environment, and students. Based on those studies, the current study expanded data gathering to focus on how students reasoned during modeling and how the teacher and class instruction influenced modeling. The planned analysis focused on promoting student autonomy via teacher prompts as to how students constructed knowledge and described their theories during modeling.

Current Research Setting

The School. The setting included 26 sixth-grade students in a Western U.S. public school. The number of daily students who participated varied based on attendance. The site was selected because the science topic area was germane to this study and represented typical public school practices, administrative demands, and state performance standards of U.S. public schools. The instructor was a female teacher with 11 years of elementary-school-level teaching experience. Prior to teaching, she was a science major in college who reported feeling comfortable teaching science and the science topic that provided the context for this study. She had not been trained previously in model-based instruction. During meetings she expressed her teaching values of helping students make connections between content and personal life and helping students understand content at a deeper level. We used those values as a basis for understanding the goals of constructivist modeling.

Curriculum. The science curriculum was aligned with state standards (Utah State Office of Education, 2010). The teacher used a variety of sources to choose and develop lesson plans and activities to address these standards. During the study, the teacher focused on 6th Grade Science Standard 5, a unit on microorganisms (see Figure 2). The modeling activities involved students reproducing or re-representing concepts identified in the standards. Thus, the modeling activities provided opportunities to use (or go beyond) specific targeted resources in the creation of their models. The teacher incorporated a variety of hands-on activities and projects, but did not explicitly teach specific modeling or model-based learning methods (see, for example, Gobert & Buckley, 2000; Lehrer & Schauble, 2006).

The primary focus of the microorganisms unit was to understand different kinds of microbes and their effect on humans and the natural world. Students studied four sub-topics: bacteria, fungi, protozoa, and viruses. The teacher used a variety of associated activities and assignments including having students create summaries of class content; having students make creative projects to re-represent facts about microbes; and showing students visuals of microbes from telescopes to videos and web searches. Much of the focus centered on factual information and visual representations of microbes.

5. *Students will understand that microorganisms range from simple to complex, are found almost everywhere, and are both helpful and harmful.*	
Objective 1 *Observe and summarize information about microorganisms.*	*a. Examine and illustrate size, shape, and structure of organisms found in an environment such as pond water.* *b. Compare characteristics common in observed organisms (e.g., color, movement, appendages, shape) and infer their function (e.g., green color found in organisms that are producers, appendages help movement).* *c. Research and report on a microorganism's requirements (i.e., food, water, air, waste disposal, temperature of environment, reproduction).*
Objective 2 *Demonstrate the skills needed to plan and conduct an experiment to determine a microorganism's requirements in a specific environment.*	*a. Formulate a question about microorganisms that can be answered with a student experiment.* *b. Develop a hypothesis for a question about microorganisms based on observations and prior knowledge.* *c. Plan and carry out an investigation on microorganisms.* *d. Display results in an appropriate format (e.g., graphs, tables, diagrams).* *e. Prepare a written summary or conclusion to describe the results in terms of the hypothesis for the investigation on microorganisms.*
Objective 3 *Identify positive and negative effects of microorganisms and how science has developed positive uses for some microorganisms and overcome the negative effects of others.*	*a. Describe in writing how microorganisms serve as decomposers in the environment.* *b. Identify how microorganisms are used as food or in the production of food (e.g., yeast helps bread rise, fungi flavor cheese, algae are used in ice cream, bacteria are used to make cheese and yogurt).* *c. Identify helpful uses of microorganisms (e.g., clean up oil spills, purify water, digest food in digestive tract, antibiotics) and the role of science in the development of understanding that led to positive uses (i.e., Pasteur established the existence, growth, and control of bacteria; Fleming isolated and developed penicillin).* *d. Relate several diseases caused by microorganisms to the organism causing the disease (e.g., athlete's foot -fungi, streptococcus throat -bacteria, giardia -protozoa).* *e. Observe and report on microorganisms' harmful effects on food (e.g., causes fruits and vegetables to rot, destroys food bearing plants, makes milk sour).*

Figure 2. Standard 5 from the 6th grade Utah State Office of Education Core Standards for Science.

Procedures

In the classroom, the teacher began each day by reviewing routine class business and announcements. The teacher agreed to teach all aspects of her lesson as normally done, but introduced the modeling activity (students drawing visual representations of their understanding) four times during the unit. Her implementation helped to maintain authenticity of the everyday classroom teaching, while allowing me to observe modeling activities in a typical classroom with customs and routines familiar to both the teacher and students.

Preparing the teacher. Prior to implementing modeling activities, we exchanged understanding of the principles underlying student-centered learning, constructivism, and model-based learning. I demonstrated examples and shared student models from previous studies to illustrate how students might respond to the modeling activity. I stated that a goal of modeling is for students to generate models on their own, while the teacher supported (scaffolded) students to develop individual models.

Modeling during classroom instruction. During the month-long science unit, the teacher implemented four modeling enactments. An enactment comprised several key components: The students were asked to draw a model related to the current topic; students were given autonomy in choosing how and what to represent; the teacher provided students prompts to create constructivist models. After each enactment, the teacher and I shared observations about how students responded and exchanged possible interpretations. During these exchanges, I reminded the teacher of the goal of helping students use constructive thinking as they created models. She also provided informal evaluations based on her teaching experiences as to whether students engaged in constructive modeling. If she assessed student modeling as lacking constructivist qualities, we discussed ideas to modify the next activity. Then, during each subsequent modeling enactment, the teacher adjusted implementation.

Enactment 1, Day 3 of Unit. After a two day overview of microorganisms, the teacher handed out blank paper and told the students they were going to model what they knew about microorganisms. She framed the activity by asking them to imagine they had been assigned to "explain what microorganisms are or what you know about microorganisms to a fifth grader." In describing how to complete the assignment she asked them to "come up with a model, diagram or picture" to show what they know. She attempted to help them model by emphasizing "There is not a right or wrong answer to this." Twenty-five students completed their models.

Enactment 2, Day 7 of Unit. After studying bacteria in depth for several days, the teacher asked the students to "draw like before" to show what they had learned. She encouraged them to model more than facts. While they were drawing, she emphasized modeling the "how" and the processes of bacterial decomposition, as opposed to merely showing what they are. Twenty-five students completed models.

Enactment 3, Day 13 of the Unit. The class had studied protists (protozoa and algae) after which the teacher handed out blank sheets of paper and asked them to draw a model "of some sort" of protists. During the assignment, several times she asked students to consider how protists affect us and "how they interact with our lives." Eighteen students completed models.

Enactment 4, Day 22 of the Unit. During prior meetings, the teacher noted that students' models were fact-oriented with less focus on personal construction of ideas and she considered a different prompt from the previous three enactments. As students completed a final comprehensive exam on the unit, she took small groups to the back of the room and explained the assignment. She asked students to think of a microorganism that is in or around their house at that moment, then draw a model to show the life cycle. She provided multiple examples of how this assignment could be completed. Eleven students turned in models.

Measures & Observations

I collected data from the following sources:

- Observations of the modeling enactment
- Student-generated models
- Interviews with students
- Interviews with teacher
- Observations of daily class

Data analysis was based on an interpretivist approach (Marshall & Rossman, 2006). I began by organizing and categorizing data based on anticipated data. I connected those themes with elements of the theoretical framework and elements of constructivist modeling and student-centered instruction. I also looked for other unanticipated patterns and themes to extend my analysis.

Observations of enactments. Each modeling activity focused on how students performed within the classroom context. During each enactment, I recorded the teacher's instructions using a voice recorder and observed student behavior. I recorded how students worked and resources they used such as their notes or websites on the screen in front of them. I used a protocol to guide my observations (see Appendix A). These observations provided recordings of the teacher's instructions and notes of student behaviors.

I transcribed teacher instructions to prepare them for analysis and separated individual prompts which I then organized according to enactment. I labeled each prompt as open-ended instruction, directed instruction, or other. *Open-ended instruction* referred to prompts that initiate work without explicitly directing students what to do beyond drawing a visual representation of the science topic. *Directed instruction* referred to prompts that direct students with specific information to complete the task. That information may be presented as an expectation or it may be presented as information that gives students a clearer sense of what to model. Either case is coded as *directed* because it provides specific information that potentially supplants decision-making on the student's part. Prompts labeled as *other* included instructions that were neither open-ended nor directed; this category allowed for analysis of unanticipated themes.

Student-generated models. I collected each student's models as artifacts to determine whether models reflected evidence of constructivist thinking or reproductions of existing models. I used a protocol to guide my analysis (see Appendix A). For evidence of constructivist models, I looked for personal experience and/or representations of understandings not identical to class instruction or representation. For evidence of reproductions, I compared models with the existing models from my prior observation of class instruction and activities. I also recorded general modeling approaches and notable features to capture unanticipated aspects of student models.

Student interviews. After each modeling activity, I analyzed the content of the drawing using the same criteria to identify evidence of constructivist modeling and/or reproductions of models. I then looked for either: (1) common patterns across the class. Common patterns across the class are representations or ideas that were similar to and repeated by more than half of the class; or (2) unique elements. Unique elements were representations that did not appear to represent curricular models. Students with those elements were selected for interview. I conducted interviews during class activities that followed the modeling event to allow four interviews per modeling event. I conducted a total of 16 student interviews.

I used semi-structured interviews with open questions that allowed students to explain their own understanding. I first asked students general questions in order to record their purpose and intentions in their models, then questions more specifically related to the research focus. I recorded and transcribed responses for later comparison with data that emerged from the analysis of the models. Responses provided additional insight into the content of the drawn-models.

Teacher interviews. I used open questions in order to induce responses that reflect her perspective as an instructor. Teacher interviews were held on multiple occasions to document attitudes toward instruction and reactions to the modeling activities. My purpose was to understand her perspective and gain insight into enactment of the activities and to document her perceptions of students' modeling work and how future activities could be modified to help students construct individual understanding and integrate information.

I analyzed interviews by looking for comments related to interpretations of students' modeling behaviors, beliefs about the modeling enactment, and beliefs about classroom instruction in general and to provide more contextual information behind the changes the teacher made from one enactment to the next.

Daily observations. I observed class instruction each day throughout the science unit to document representations that could contribute to students' understanding of the science topic. I recorded audio of all class activity, collected pictures of visual representations, and noted other models or representations such as analogies and metaphors. The resultant data included a list of curricular models used in the class. I analyzed the daily class activities by organizing them into visual representation, metaphors, and analogies based on familiar experiences or prior knowledge to further interpret student-generated models. Table 4 summarizes that data and how each data source addresses the research questions.

Table 4. Research question, data source and rationale.

Research Question	Data Source	Rationale
1. *What characteristics of student-generated models reflect (or do not reflect) constructivist processes?*	Student-generated models; Interviews with students	Analyze models to identify key patterns and elements of constructivist models
2. *How do students reason as they construct personal models?*	Interviews with students; Observations of model generation	Supplement analysis of models with other data to find evidence of *how* students reasoned
3. *How do the teacher's instructions during model generation and subsequent interactions affect the students' construction of models?*	Observation of class; Student-generated models; Interviews with students; Teacher interviews	Compare observations of class with data on models to examine impact of teacher

Data Analysis

Research Question 1: What characteristics of student-generated models reflect (or do not reflect) constructivist processes? Student drawings were analyzed as representations of either non-constructivist elements (i.e. reproductions of class representations) or constructivist elements (representations derived by reasoning or personal application). I first used responses from student interviews to corroborate the analyses of the drawn models.

I then looked for qualitative differences in the various elements identified in the models. Using both anticipatory data reduction and the potential emerging themes, I listed representation types students used to generate models.

Research Question 2: How do students reason as they construct personal models? I analyzed models and student interviews and looked for evidence of reasoning. Using data from the content analysis of models and interviews data, I organized content into two categories: reproductions and original content. Another set of categories emerged during analysis: the models were either factual models or explanatory models. Factual models were those which only state or list facts. Explanatory models explain processes and causal relationships. I then used statements from the interviews to look for insights into how students reasoned with either type of model.

Research Question 3: How do the teacher's instructions during model generation and subsequent interactions affect the students' construction of models? To examine the influence of the teacher's actions on student modeling, I analyzed her instructions and combined that analysis with findings from research questions one and two. The teacher's instructions were coded as open, directed, or uncategorized to examine changes across the four modeling enactments. Each enactment was compared using the number of statements in each category. I also compared the 4 enactments qualitatively to identify possible unanticipated differences.

Triangulation. I arranged the data and findings that resulted from the analysis of drawn models, student interviews, and observations by enactment to create a systematic description of each modeling enactment. These within-enactment comparisons were used to identify differences between enactments by treating each modeling enactment as a separate case. I then compared that data with changes in the teacher's instructions across cases to determine whether changes in teacher instructions and support influenced students' modeling.

CHAPTER 4

FINDINGS

This study examined four enactments of teacher-led constructive modeling wherein students drew models to represent their understanding of science content. The primary focus was on how students responded to teacher-led modeling. Three research questions were examined: Research questions one and two focused on student's modeling and question three examined the teacher's role and influence on student models. Throughout this report, student drawings are referenced by number. The first number represents the enactment and the second represents the student ID (for example, 3-02 refers to enactment 3, student 02).

Research Question 1: What characteristics of student-generated models reflect (or do not reflect) constructivist processes?

As shown in Table 4, a total of 79 student models were collected across four separate phases: 44 provided at least one constructivist element (a representation that was either personal or original) and 35 provided no evidence. During the first three enactments, approximately half of the models included evidence of constructivist elements. During the fourth and final enactment, a total of 11 models were produced, of which nine included constructivist elements and two showed no evidence of constructivist elements.

Analysis by individual student reveals that most class members included constructivist elements in models at least once (see Table 6). Sixteen students completed three or more models; seven included constructivist elements in at least three models; and five of those seven included constructivist elements in every model they created. Seven other students did not include constructivist elements in any of their models; five of those seven did not complete a model after the first two. Only student numbers 4 and 16 included constructivist elements in all four models, and one student did not include constructivist elements in any of the four models.

Table 5. Total student-generated models with constructivist elements.

	Enactment 1	Enactment 2	Enactment 3	Enactment 4	Total
Number of Models	25	25	18	11	79
Models with no constructivist elements	12	12	9	2	35
Models with constructivist elements	13	13	9	9	44

Characteristics of Constructivist Models

Form. Form situated model setting, format, or logical organization of drawn models. The decision to include different forms included whether to make the model visual, verbal, or a combination. Some students created visual models and chose to add text (see, for example, Appendix B, 1-06; and Appendix C, 2-21), while other students chose textual models with supporting pictures (see, for example, Appendix B, 1-14; Appendix C, 2-09). Only a few models were entirely visual (Appendix B, 1-12 and 1-23; Appendix D, 3-15) or textual (Appendix C, 2-18; Appendix D, 3-13; 3-17; Appendix E, 4-30). Models varied in how form combined visual and/or textual material. Some students' visual models used text labels to clarify the images, while others' text models used simple pictures to re-represent the content, essentially adding visual detail without augmenting information. And still others incorporated complementary text and visuals. In these models, text and visual materials differed from models in which text supported visual or visuals repeated text as each provided separate information.

Table 6. Individual students and their inclusion of constructivist elements.

Student ID	Enactment 1	Enactment 2	Enactment 3	Enactment 4	Constructivist/Total Models
03	X	X	X	-	3/3
04	X	X	X	X	4/4
05	0	0	-	-	0/2
06	X	0	X	-	2/3
07	0	0	-	-	0/2
08	0	0	X	-	1/3
09	0	X	X	X	3/4
10	X	X	-	-	2/2
11	X	0	0	X	2/4
12	0	X	X	-	2/3
13	0	X	0	X	2/4
14	0	X	0	X	2/4
15	X	X	0	-	2/3
16	X	X	X	X	4/4
17	0	0	0	0	0/4
18	0	0	-	-	0/2
19	X	X	0	-	2/3
20	0	0	-	0	0/2
21	X	X	X	-	3/3
22	X	X	-	X	3/3
23	X	X	0	X	3/4
24	0	0	-	-	0/2
25	X	-	0	-	1/2
26	X	0	-	-	1/2
27	0	0	-	-	0/2
28	-	0	X	-	1/2
Unidentified 1	-	-	0	-	NA
Unidentified 2	-	-	-	X	NA

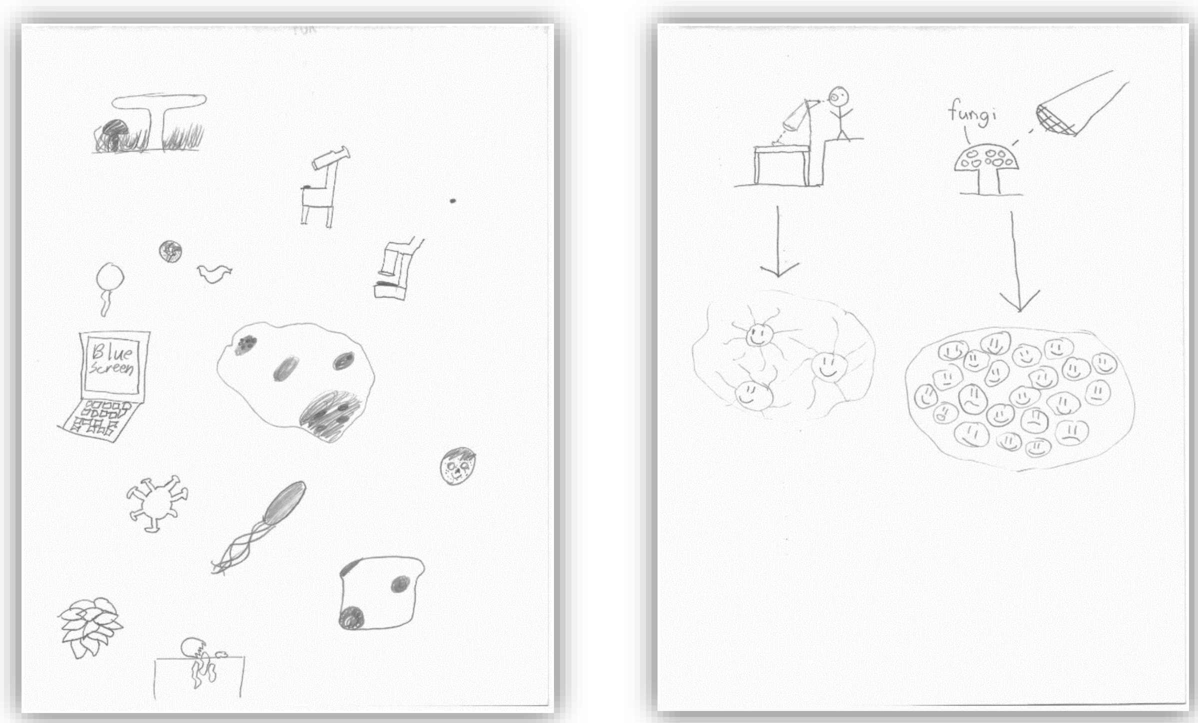
X= At least one constructivist element present
0 = No constructivist elements present
- = No model submitted

Another form characteristic was the information representation. Some models were collages of facts with no indications of relationships between facts. Other models focused on organizing information, employing lists, charts or other visual forms of organization. Finally, a few models focused on describing processes.

Elements. Constructivist aspects were noted in the choice of elements used to represent scientific phenomena. For example, when representing bacteria consuming nutrients, opportunities for constructivist thinking were evident in how to represent the organic materials consumed: students chose leaves in their yard, fruit, and general trash. One model depicted using plastic bags to show that bacteria could not consume inorganic material (see Appendix C, 2-20). Another example of constructivist elements arose from the teacher's repeated statement that bacteria "can live anywhere." Students' models consistently depicted this science principle. When creating models of bacteria, several students drew a collage of pictures representing various places and climates. One boy drew small characters representing bacteria on a camp fire, on a snow flake, on a cactus, in a rain storm, and in an underwater ecosystem (Appendix C, 2-19). Another student drew a rock, a penguin, and a pair of palm trees with the label "they can live anywhere with nutrients" (Appendix C, 2-12). And another student drew an underwater scene, a desert, and outer-space (Appendix C, 2-20). When asked where she learned bacteria can live in those places, she responded, "I thought of it myself."

In some cases students included original objects of personal significance, but unrelated to scientific meaning. For instance, one student began to draw a chicken with viruses which he described to represent chicken pox (Appendix B, 1-19). A different student, triggered by the teacher's describing bacteria as a "pioneer organism," included an isolated drawing of a bacteria made to resemble a western pioneer from the 1800's (Appendix C, 2-19). Another student represented several facts about viruses using a picture of a computer with the label "blue screen of death" (Appendix B, 1-25), a reference to computer crashes which can result from a computer virus. A fourth student drew a mushroom in two of his models and each time included a drawing of a toadstool character from the Nintendo *Mario* video game franchise (Appendix C, 2-22; Appendix E, 4-22).

Combining elements. Students' models combined facts and representations into a single model, with varying results. Some student models included a collage of isolated facts combined into a single model, but the model not did include evidence of fact integration. Others constructed relationships to integrate elements in the model. For example, the model on the left in Figure 3 represents assorted concepts: shapes of some microorganisms, a microscope is needed to see microorganisms, common foods in the house that contain microorganisms, and chicken pox is caused by microorganisms. However, while indicating grasp of factual science concepts, in isolation none depict a shared representation. When the student explained this model she named each item and identified facts about each with no reference or connection to other items in the model. The model on the right in Figure 3 represents many of the same facts– that microorganisms are too small to see, they have a shape, and they are found in a familiar object – in a cohesive model that uses arrows and parallel representations to represent relationship of facts.



Non-integrated facts (1-25) Cohesive, integrates facts (1-21)

Figure 3. Comparison of cohesive, integrated facts and non-integrated facts in models.

Some models included personal elements combined with facts learned in class, but the facts were not integrated cohesively. One student drew a pond with different kinds of algae (Appendix D, 3-25), stating that her family traveled to Sweden and visited a lake where types of algae covered the water. She represented the two kinds of algae she saw beside other facts about algae and protozoa, but did not integrate personal knowledge with class content in her model.

Transformations of representation. While choosing model representations, a few students transformed aspects from a class model to their personal model. For instance, the teacher taught that many bacteria are good and some are bad. While many students represented this fact by representing good and bad next to each other, one student drew the good and bad bacteria in a pie chart to capture a ratio relationship as well (see Appendix C, 2-15). In another case, the teacher emphasized differences between protozoa and algae by comparing and contrasting them. Several students created side-by-side charts for direct comparison of characteristics of each microorganism (see Appendix D, 3-12; 3-11; 3-13; 3-16).

Erroneous information. Another characteristic in some models was the presence of incorrect and unrelated information. One student depicted that bacteria were the first living thing on earth, having lived even before dinosaurs, yet her picture landscape included plants (Appendix C, 2-03). The incongruity of drawing the first living bacteria alongside living plants seemingly had not occurred. Another student inaccurately depicted the process of a virus reproducing, erroneously re-appropriating web-based information for his model. However, inclusion of erroneous information was comparatively rare. Of the 79 student models, only four contained information that was initially naïve or erroneous.

Research Question 2: How do students reason as they construct personal models?

Replication. Across all four modeling events, many students replicated form, themes, and elements of the teacher's curricular models. For instance, during the first three days of instruction the teacher led a discussion in which the class broke down the word *microorganisms* to define constituent parts, gave an overview of the five types of microorganisms, and sent students to a website (Smith, n.d.) to generate notes. The web activity centered on six key items as sources of microorganisms (Figure 4): yogurt, bread (representing yeast), raw meat, a pile of leaves, moldy fruit, and a sick girl with the chicken pox. Students examined each item and read descriptions of the microorganism.

Figure 4. Web activity used during class instruction.

Students then generated their first models. More than half the students included the class definition of *microorganism* and many listed the five types of microorganism with a visual representation of each type. Among students who used real-world examples, the majority included the same items used in the website. The few real-world examples students used other than the website included mushrooms (used as an example by the teacher) and moldy bread.

When creating models, most students combined multiple curricular representations. For instance, one student recreated the setting of the web activity – the kitchen – with slight variation, adding mushrooms and a microscopic view of viruses (Figure 5). These replications did not contain evidence of personal ways of reasoning indicative of constructivist thinking.

Figure 5. Student replicates common class models.

Another example of replication occurred during the third enactment following a week of instruction on protists. During instruction the teacher drew a diagram on the whiteboard to explain that protists were divided in two classes: protozoa and algae (Figure 6). During the modeling enactment that followed several students drew similar diagrams to represent the classification (Appendix D, 3-11; 3-12; 3-13; 3-16; 3-23).

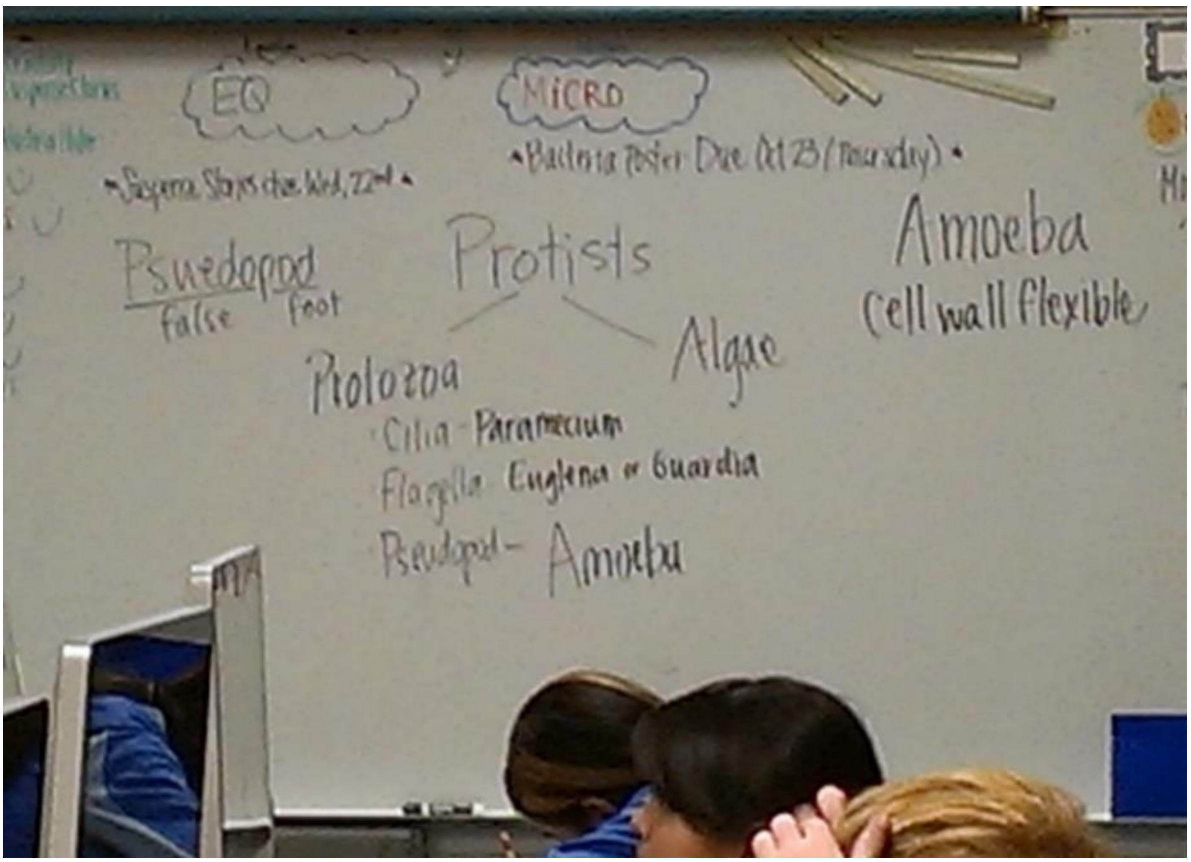


Figure 6. Teacher's protists diagram classification that was replicated or elaborated in student models.

However, the diagrams varied somewhat as some students transformed the diagram into a side-by-side comparison of algae and protozoa (see Figure 7) including facts not included in the teacher's diagram. One student explained that her chart represented both how they were similar and how they were different. When questioned, she stated that the organization was her own way of thinking, indicating replication of curricular models including elaboration and personal thinking processes.

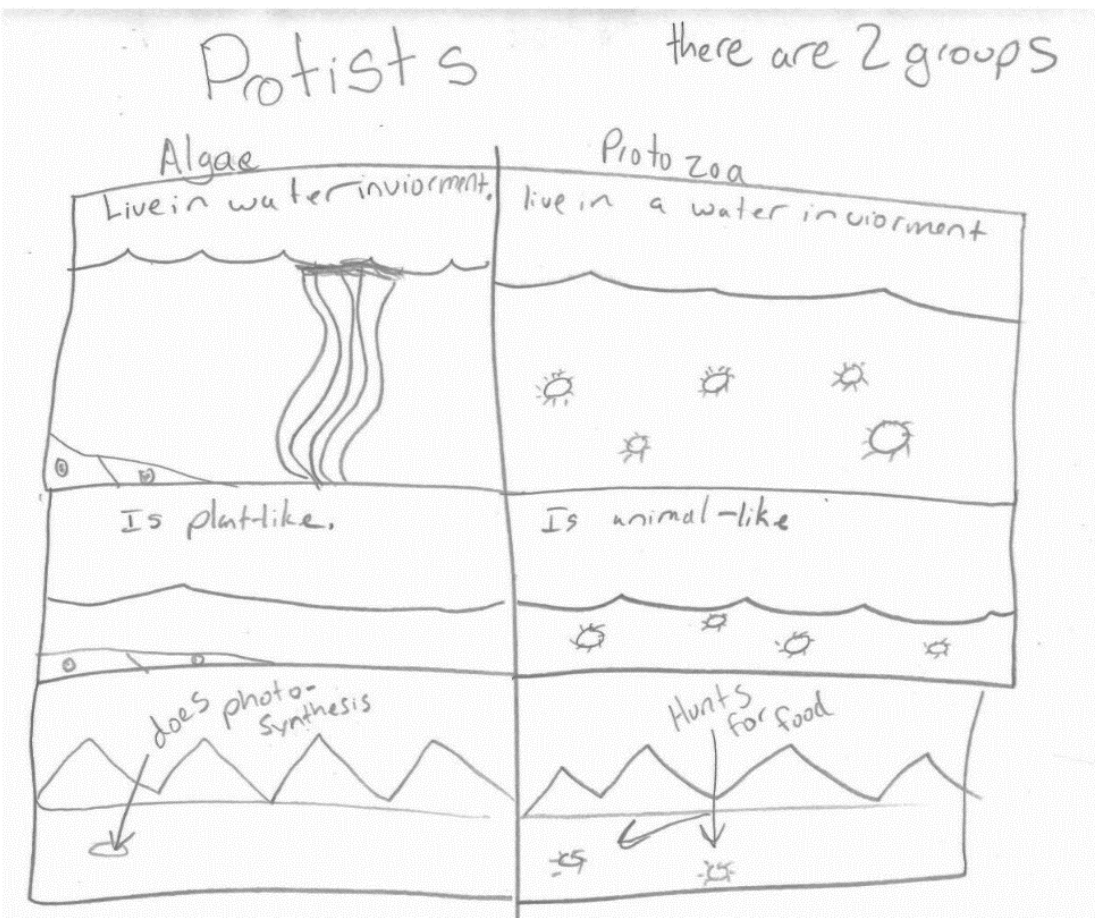


Figure 7. Student elaboration of teacher's diagram (Appendix D, 3-16).

Modeling with facts. One characteristic that emerged was a difference between factual models and explanatory models: Factual models depicted only one or more facts; explanatory models represented a process or a causal relationship. Of the 79 models produced, 63 were factual. After the microorganism unit introduction, most students depicted categories of microorganisms (bacteria, fungi, protozoa, algae, and viruses). This process, though primarily replication for most, reflected differential experiences for some including opportunities for knowledge construction.

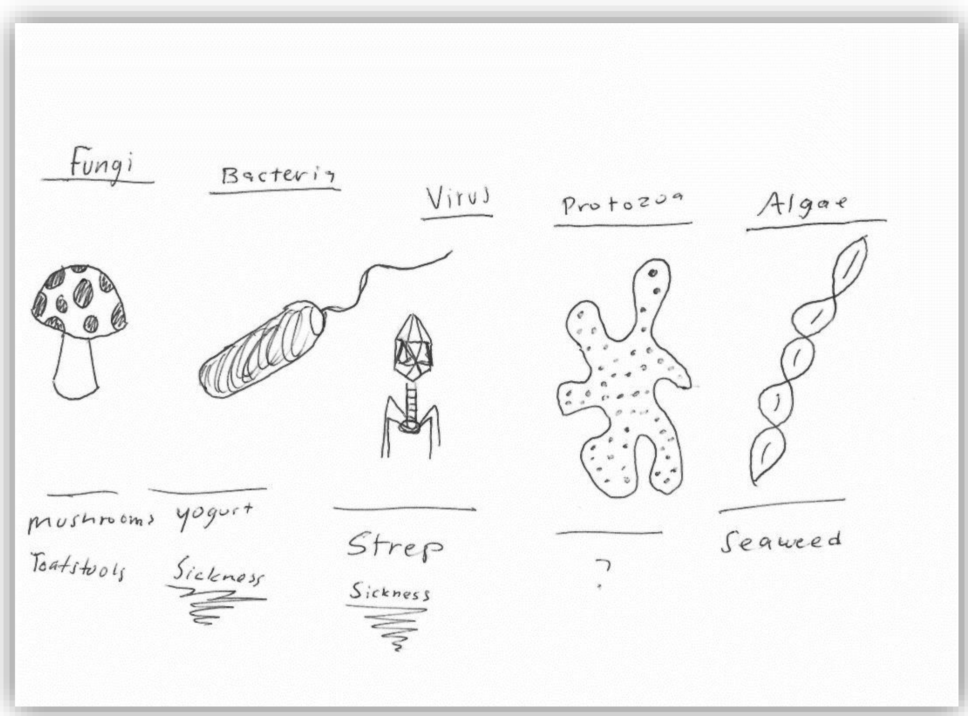


Figure 8. Student adding information about protozoa (Appendix B, 1-11).

One student represented each category with a label followed by a picture of the microorganism (Figure 8). While explaining his model, he stated “I don’t know anything about protozoa, but I just made a blob with polka dots all over it.” The model generation process apparently prompted him to create a visual representation that included gaps he did not recall. With help from his teacher, he continued to build on his model.

Teacher: You gave us a good list of what they are and what they do. What does that help you understand about them?

Student: Umm, it shows how small they are. Like viruses are really small so they can live in your cells, which is kind of scary.

He first reasoned by filling in gaps he was aware of, then, as he explained his model he went beyond simple recall of facts with scaffolding from the teacher.

Other students applied facts in their depictions of real-world environments. One student modeled four types of microorganism, placing each in context: virus and sick person, algae in an aquarium, bacteria growing on fruit, and fungi as a mushroom in the grass (Figure 9).

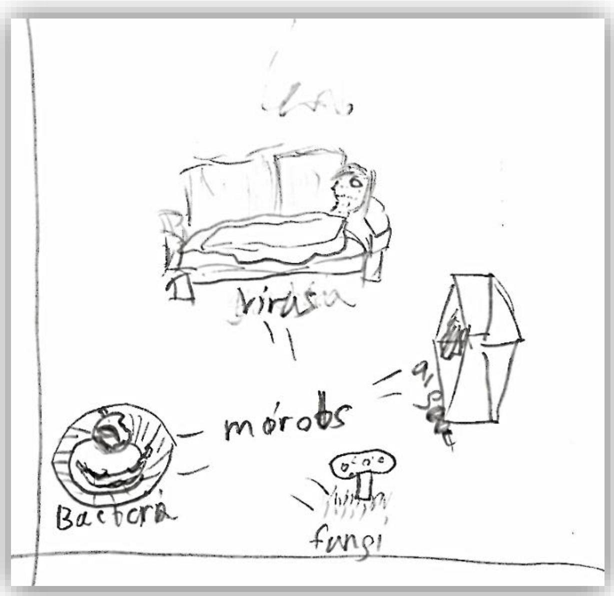


Figure 9. Student model situating microorganisms in a real-world context (Appendix B, 1-10).

A different girl used factual information to consider meaning in the real-world. She depicted three facts the teacher taught: microorganisms are too small to see, humans interact with microorganisms regularly, and microorganisms have distinct shape. She then imagined what it would look like to enlarge a space where microbes live; showed the result of interaction with a virus; and included the purpose of parts of a microorganism (Figure 10).

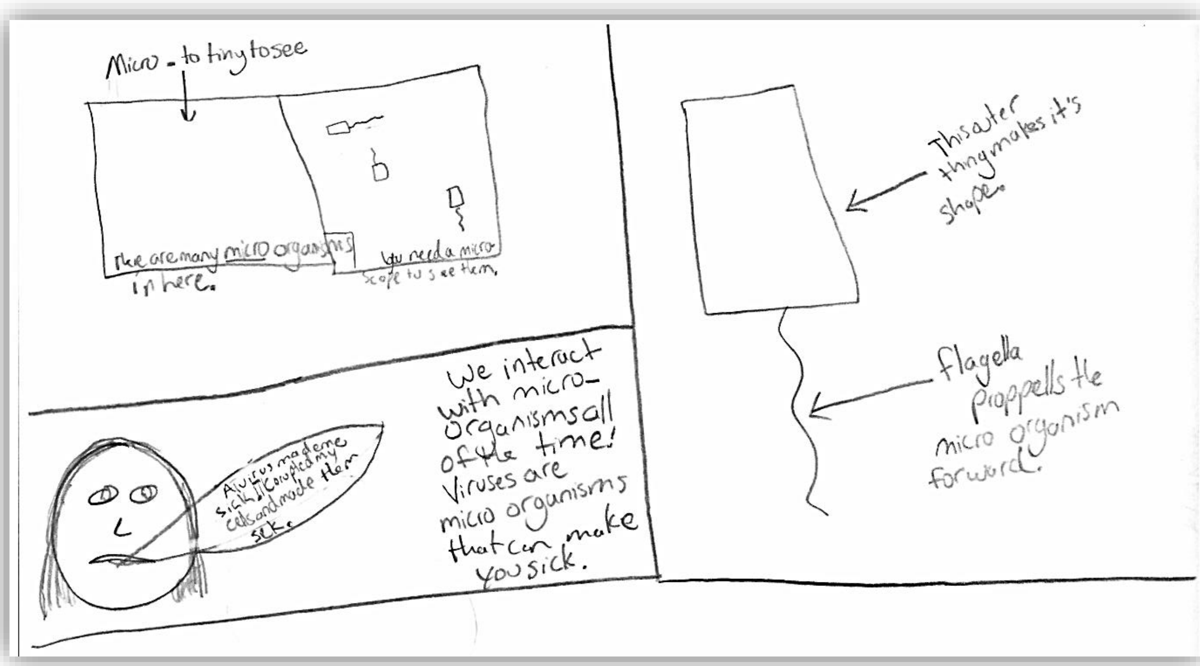


Figure 10. Student model showing how learned facts relate to real-world activity (Appendix B, 1-16).

Factual models also appeared to present opportunities for organizing information. For instance, one student listed the categories of microorganisms, but created a category labeled moss (Appendix B, 1-09). The teacher previously used moss as an example during discussion, but did not represent it as a category of microorganisms. This detail represented the student's re-construction of information as she organized content from discussion.

Reasoning with explanatory models

Whereas factual models presented various opportunities for reasoning, explanatory models included reasoning with procedural information. One student depicted a virus using a cell to reproduce (Figure 11). The image resembles depictions available online and may have been encountered during web searches, but it had not been presented during class instruction.

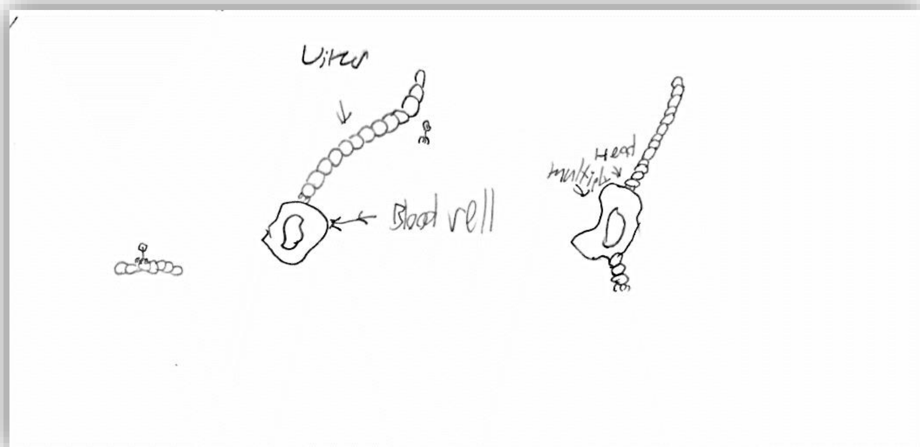


Figure 11. Student model depicting emerging understanding of virus reproduction (Appendix B, 1-06).

As he described the model, he explained, “The viruses are going to the blood cells and biting into them to make them multiply. Like right here, it’s biting, now it’s multiplying.” The description was not entirely accurate, but provided his reasoned explanation of what is happening in the model.

Another student’s explanatory model depicted the life cycle of a fungus (Appendix E, 4-22). He created serial frames that represented what he described as two ways fungus could multiply. He left gaps in his explanation as he moved from a fungal organism being born to the organisms consuming nutrients.

Student: A spore is like, it's basically their way of reproducing. So it's a lot like tiny little dust particles… flying through the wind and trying to settle or something.

Researcher: But what is a spore though? It's a way of reproducing, but what *is it*?

Student: It's like the fungal chain I guess.

Researcher: So do you think that's what it is? Do you think it's like the fungus itself?

Student: It's kind of weird; it's like a seed is a tree.

Researcher: What happens to a spore to make it turn into a fungus?

As we continued the inquiry, he developed his own theory about how a spore works. At this point I returned to his model.

Researcher: So, would you draw anything differently?

Student: Yeah.

Researcher: What?

Student: Should I go get my pencil and, like, draw it right now?

Researcher: Do you want to draw it or would you rather tell me?

Student: I'll go get it.

When he returned he drew in several more frames. As he drew he explained what was happening and added details based on what he was saying.

Student: (drawing as he speaks) Rains on it… give it a little… I should draw a clock… (then shows his model) time!

Researcher: Good job.

Student: Thanks. Give it a little time.

He reasoned through this process of creating an explanatory model, detecting gaps, with help, refining his model, and adding details as he talked through it out loud. Though the model initially emphasized facts, it evolved into an explanatory model.

Research Question 3: How do the teacher's instructions during model generation and subsequent interactions affect the students' construction of models?

Open-ended and directed prompts. The teacher used a blend of open-ended and directed prompts during modeling enactments. Table 7 lists samples of each prompt type, chosen from across all four enactments.

Table 7. Sample teacher prompts during modeling enactments.

Directed Prompts	Open Prompts
• "I don't want you to write a paragraph explaining it to me" • "How would you explain… to a fifth grader?" • "So we're talking about protists right? Remember there are two groups what are the two groups?" • "But it can't be a comic in a silly way." • "You're not telling a story of it, word-wise; you're visualizing the story" • "I want it to be a microbe that is in or around your house right now."	• "Whatever you can do to explain microorganisms" • "It can be if you want it to be" • "You can choose any of the five [microorganisms]." • "You could do whatever it takes for you to really represent" • "There is not a right or wrong answer in how you do this. The only way that it would be wrong is if you don't do anything" • "However you want to represent it"

During the first two enactments the teacher's open-ended and directed prompts were roughly balanced. During the third enactment, a proportional shift was evident toward open-ended prompts while the fourth enactment contained more directed than open-ended prompts. A comparison of direct to open-ended prompts across modeling enactments is shown in Table 8.

Table 8. Directed and open-ended prompts used to lead modeling activity.

	Total Prompts	Directed	Open-ended	Ratio
Modeling Enactment 1	22	11	9	1.2
Modeling Enactment 2	6	3	3	1
Modeling Enactment 3	16	6	10	0.6
Modeling Enactment 4	73	48	25	1.9

Changes in the ratios of prompt types did not appear to influence student modeling; student models were not apparently altered for open-ended versus directed prompts. Furthermore, changes in the number of models with constructivist elements did not appear to vary in relation to open v. directed teacher prompts.

Use of examples. Across all enactments the teacher presented varied examples of ways to model the science concepts. The examples provided additional specificity, as per the definition of directed instruction, yet offered students freedom to create individual models. Because examples added detail to prompts, they were coded separately (different from direct or open-ended). The teacher's examples appeared to influence the student modeling by introducing something to copy to complete the task. This involved replication, described above as a form of reasoning. However, replication of examples during modeling appeared to involve little elaboration.

During the fourth enactment, the teacher presented detailed examples. In response, some students' models followed the examples very closely. With one group of three students, the teacher explained that students could choose any microorganism and then create a representation of its life. She clarified with an example:

> So, this is like the diary of a bacteria or a diary of a virus, or a diary of a fungus… If you choose bacteria in yogurt or something like that, you can be like "it's put in there in the milk at a factory and then it's put in a canister and brought to my house."

Two models closely followed that example. They selected the bacteria that is in yogurt, and focused not so much on the bacteria's life as the teacher directed, but on the process she used in her example of being prepared at a factory, shipped, and arriving at the house (Appendix E, 4-04; 4-23).

During another discussion, one student checked his own understanding of the assignment by offering the beginning of an example which led to a conversation during which the example was elaborated. Through the course of the conversation, the teacher and student constructed a description of bacteria on meat.

> Student: So it can be like, "first they landed in the meat" I guess would be like the…
>
> Teacher: So it gets introduced into the meat somehow, probably from the animal that it was in, the animal that it came from or it was in the air,
>
> Student: flies
>
> Teacher: flies, something like that...
>
> Student: [inaudible]
>
> Cause before the meat was cooked
>
> Student: [inaudible]
>
> Teacher: Yeah, if somebody didn't wash.
>
> Student: [jokes and laughs]

Teacher: It could…seriously. A fly landed on some food, got some bacteria on it, landed on some meat, got it on the meat, now it's in the meat. What's the bacteria doing while it's sitting in the meat?

Student 1: It's decaying.

Student 2: No, it's reproducing.

Teacher: Well, it is reproducing, but what's it doing before that?

Student: It's making it not edible?

Teacher: So, don't think of them as a whole group of them. Think of one little bacterium. What is he doing? He ended up on the meat, now what's he doing?

Student: [inaudible]

Teacher: He's getting nutrients from the meat, from everything around it. And then he's going to be duplicating his DNA and he's…

Student: And he eats the meat and he starts duplicating?

Teacher: Inside you. OK? So that's a good point, so what happens… it's not just… you know, the meat got into you and now it's making you sick. What's happening? Well, it's because bacteria is reproducing in your body and…

Student: …and bacteria's not good for you…

Teacher: Good. That makes sense?

Following that conversation, the student created a model of all that was elaborated in the example, starting with a fly that picks up bacteria, lands on meat, and a person that ends up sick (Figure 12).

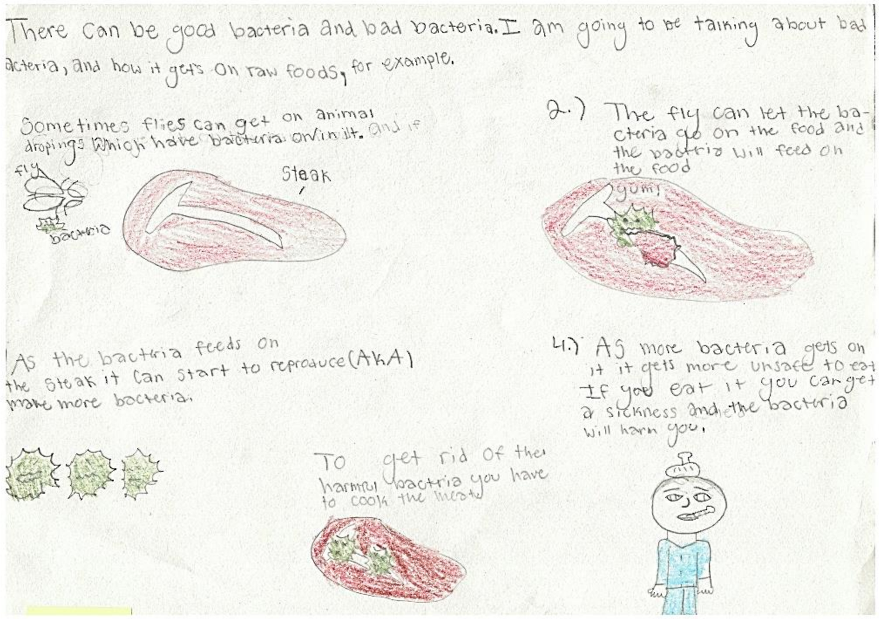


Figure 12. Student model elaborating detailed teacher example (4-13).

Types of Prompts

During all enactments, the teacher did three things that shaped student modeling, though not necessarily in order: (1) framed the assignment; (2) described or referred to the form of the model; and (3) gave guided-thinking prompts to guide students' during modeling. These categories were not preplanned, rather the categories emerged during analysis of the teacher's prompts. Each prompt affected student modeling in different ways; some prompts appeared to influence student models more than others.

Framing the assignment. The teacher framed the modeling activity using a context or problem to give meaning to the assignment. Evidence suggests that the framing of the assignment influenced the types and opportunities for students' constructivist modeling. During the first enactment, she began by saying "imagine you have been assigned to explain what microorganisms are, or what you know about microorganisms, whatever things you have in your head about them, to a fifth-grader." During the second and third enactments, the teacher continued to use the same frame, though mentioning it infrequently. During the second enactment, she referred to the first modeling activity, without repeating the idea of teaching a fifth-grader: “I want you to draw like you did before.” During the third enactment, she referred to the frame once following a longer explanation of the model:

> What is a way that you think about, in your mind, that you think about protists and how would you explain that to a fifth-grader? We’ve done this a couple of times, right? Where I say ‘explain this to a fifth-grader,’ right?

For the fourth modeling enactment the teacher asked students to create a model of the life cycle of a microorganism in their homes. This change in the frame coincided with corresponding changes in student models.

Whereas many models generated during the first three enactments tended to include factual information, the fourth enactment models were more explanatory and process-oriented. Nine of 11 models contained descriptions of processes or cause-effect relationships; Nine of 11 (not the same nine) models had at least one constructivist element (either personal elements or novel ideas that were not a part of class instruction).

Form of the model. The teacher offered students ideas about how to create a model by describing a general form. Student models typically demonstrated a high degree of compliance with form-related prompts. During the first enactment shortly after framing the assignment she said, “You can use a picture.” Students responded, suggesting they considered this to be a meaningful instruction. She then said, “This is more a non-verbal, non-word kind of thing.” During student work as she was offering prompts to help students move forward she repeated, “A picture, a model, a diagram, whatever you can to explain microorganisms.”

During the second enactment, form prompts were few and very general: “You don’t have to use any words if you don’t want to. You can just do it with pictures.” She framed this assignment referencing the first modeling enactment (“…draw like you did before.”) which may have also influenced the form students chose.

During the third enactment, she referred to form only once, but encouraged doing something different without specifying what:

> Choose maybe something, a different way to describe it than we have before. If you’ve used words and diagrams and scientific fact… try a different way this time. See if you can come up with a different way to show your understanding.

Finally, during the fourth enactment the teacher told students they could do what they wanted and illustrated what she meant with examples: “You could do it like boxes, like a photo chart. You can make a life cycle if you want to or some sort of picture.” These prompts were different from previous enactments and fit the assignment to create a life-cycle.

As described previously, evidence did not indicate that form alone influenced constructivist modeling: students varied widely in how they applied the form the teacher requested. However, form was an important characteristic of both student models and the teacher prompts. When form prompts were provided with detail or examples, the students’ and teacher’s models tended to match closely. In the first three prompts students created pictures and diagrams in alignment with how the modeling form was introduced. Even though the third enactment included suggestions to find a different way to model, prompts were less specific and students continued to use the same form. During the fourth enactment, when the teacher changed the form prompts and used specific examples, nine of 11 students used frames and arrows in alignment with the teacher’s prompts.

Some students followed the teacher's form even though they did not address the assignment itself. During the fourth enactment, when students were to create a type of life cycle and told they could use frames and arrows, one student created a model with boxes and arrows; however, the boxes were filled with the same facts used in previous models with no apparent representation by the arrows (Figure 13).

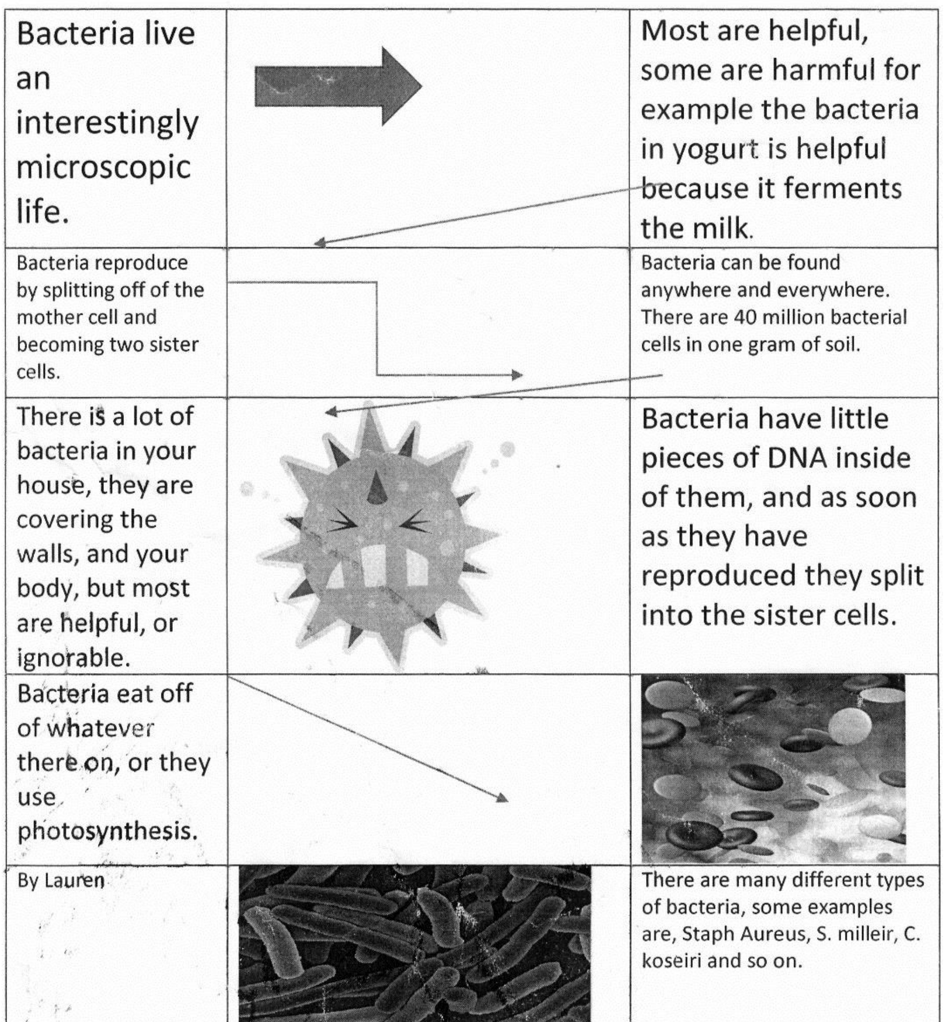


Figure 13. Student model adheres to teacher's form prompts without following assignment (Appendix E, 4-17).

Guided-thinking prompts. During modeling the teacher attempted to guide students' thinking. Prompts in the first two enactments were general, focusing more on *how* students think rather than *what* students think about. The first enactment encouraged students to model their understanding and to think in a personal way about what they were learning. During modeling she prompted, "How is your mind putting together what we've learned with what you already know?" "I'm not looking for specific facts;" "What kind of connections are you making to what you already know…?" "What do you picture in your mind to help you remember and understand what microorganisms are?" In the second enactment she encouraged students to think beyond the parameters of class discussion: "Think about how something works, what it does. Not just what it *is*, but what it *does*, why it matters;" "Why is it important? What does it mean?" Most student models appeared to re-state or reproduce concepts repeated in class such as the notion that microorganisms are small, the idea that some microorganisms are good and some are bad, and the categories of microorganisms.

During the third enactment, the teacher encouraged students to make personal connections or consider processes beyond class content stating, "One of the things we haven't talked a lot about is how [protists] affect us. I want to see if you can make that connection." During modeling she repeated this focus: "How do protists help us work together? How do they affect us? How do they interact with our lives?" Later, to help students who were having trouble modeling, she called out, "So, we're talking about protists, remember? There are two groups of protists, what are the two groups?"

Many models from this round depicted common class ideas: the structure of protozoa; that there are two kinds of protists; that protists live in water; and that some protists are plant-like and some are animal-like. Students frequently included bodies of water in their models.

However, few models included anything related to how protists affect humans: Three students referenced the shell-like structure that is used in human-made products: two drew toothpaste (Appendix D, 3-25; 3-28) and the other drew a rectangle labeled “glass product” (Appendix D, 3-09). One student drew algae labeled “safe seaweed” referring to her personal experience with algae on a family trip. Asked to explain their models, students did not discuss how protists affect humans. When asked, one student said she did not remember the prompt; another said she did not remember, then modified her response to “well, kind of.” A third student said she remembered the prompt, but her model focused entirely on representing the facts about protists (Figure 14).

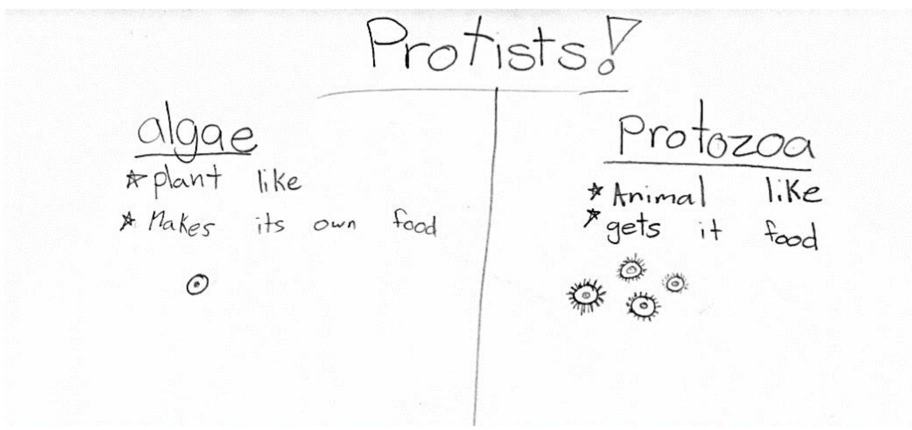


Figure 14. Student model based on protist facts (Appendix D, 3-12).

Some students did not address the prompt despite the ability to do so: Two students did not model the human-protists connection but, later, did so verbally when queried.

During the fourth enactment, the teacher used specific prompts that were coded as directed (as opposed to open-ended). Guided thinking prompts were tied directly to creating a life cycle model of a microorganism: “Information you know about microbes and apply it to your personal life.… I want you to think through: How is it born? Where does it come from? How does it get the food that it needs? How does it get where it's going? How does it get where it is?" This series of questions was intended to guide what students thought about and was repeated several times to small groups of students.

Of the 11 models, four included the form of the life cycle, but were not responsive to the guided-thinking questions (see Appendix E, 4-04; 4-17; 4-20; 4-23). Four models addressed guided questions; however, the questions may not have been interpreted as prompts to guide thinking, but instead as assignment requirements. One simply listed the questions and answered each one (see Appendix E, 4-22).

Influence of Prompts on Individual Student Modeling

As described above, the teacher's prompts changed in terms of guided thinking prompts across the first three enactments and during the fourth enactment the frame and degree of structure changed. These shifts appeared to influence individual modeling, however not all students and not all characteristics of models changed.

Persistence of style. Individual modeling style persisted across all enactments. Students who relied primarily on either textual or visual representations continued to do so even while changing the models in other ways from one enactment to another (for example of text see Student 4 in Appendix B 1-04; Appendix C, 2-04, Appendix D 3-04; and Appendix E, 4-04; for example of visual see Student 3 in Appendix B, 1-03; Appendix C, 2-03 and Appendix D 3-03).

Responses to structured, directed guidance. During the first three enactments, when students were prompted to model by explaining to another student, many models lacked a strong sense of relational reasoning (Stratford et al., 1998) and integration; in other words collages of facts. During the fourth enactment when the teacher provided more specific frame and prompts, many students created models that were more cohesive and integrated. For example, during enactments one through three student 14 created models that listed multiple, loosely related facts. During enactment four, that student used a variety of facts as the parts of a detailed process (Appendix B 1-14; Appendix C 2-14; Appendix D, 3-14; Appendix E, 4-14). Other student models indicate similar shifts from a collage of facts to a cohesive integrated model.

Of the students who created all four models, one student did not display this shift from multiple disconnected facts to an integrated model (Appendix B, 1-20; Appendix C, 2-20; Appendix E, 4-20). While all of her models were carefully drawn and accurate, her fourth model was much like the others.

Individual responses to scaffolding. In addition to structured and directed prompts in the fourth enactment, some students also received detailed thinking and modeling guides in the form of one-on-one or small group conversations. During the first three enactments, some students' models included limited information. The amount of information increased significantly during the fourth enactment. For example, student 13 created early models with one to three facts (Appendix B, 1-13; Appendix C, 2-13; Appendix D, 3-13). During the fourth enactment she and another student engaged in a lengthy conversation about how bacteria form on meat and enter the human body. Her model increased in quality and in amount of information as she modeled this entire process with a very complete model including pictures and labels. Another student whose three previous models provided little information (Appendix B, 1-23; Appendix C, 2-23; Appendix D, 3-23) followed the teacher's prompt to create the life cycle of bacteria in yogurt using his own logic to duplicate her reasoning. The teacher explained

> So this is like a diary of a bacteria or a diary of a virus or a diary of a fungus…. If you choose bacteria in yogurt or something like that you can be like, "It's put in there in the milk at a factory and then it's put in a canister and brought to my house."

He then created a model with more detail than his previous models and described the same yogurt process in his model using his own logic: “Before the bacteria in the yogurt came to my house it was in the store but before that it was in a factory…” (Appendix E, 4-23). The teacher’s scaffolding appears to have helped him create more than previous models and to logically work toward modeling flow of action.

CHAPTER 5

DISCUSSION

This study was designed to examine a constructivist modeling framework in classroom context. The first two research questions examined the models students constructed and evidence of reasoning during model construction. The third research question examined the teacher's role in the modeling process by focusing on the teacher's instructions and interactions related to student modeling processes. Analysis revealed varying elements of constructive modeling as well as changes in student modeling across the four modeling iterations. Some changes coincided with changes in the teacher's instructions, while the strongest incidents of reasoning and elaboration occurred through conversations with the teacher. Patterns of emerging modeling and teacher guidance indicate a framework for continuing research in model-based reasoning in the classroom.

Student Modeling and Reasoning Require Development and Facilitation

Various modeling skills and experiences that are a part of constructivist modeling were incorporated into models with limited evidence of constructivist reasoning. Additional experiences sometimes led to further elaborating an explanation or model. This suggests that reasoning with student models may involve a learned practice that requires development. This is consistent with Schwarz and colleagues (2009) who identified a progression for learning to reason with models. In one study with elementary students developing modeling skills, they reported that while students learned to develop sophisticated models, the challenge was helping students see “model building as a way to generate new knowledge rather than represent what they have already learned” (Schwarz et al., 2009, p. 632).

Emerging elements of models. Students’ models contained emerging elements of constructivist modeling even when more elaborate knowledge construction was not evident. Some models contained what can be termed primitive elements of constructivist modeling: personal associations such as video game characters and puns. These elements may represent personal meaning associated with science concepts. Other models contained multiple representations of scientific information or personal experience, but little integration of science concepts; the models were collages of facts with no apparent relationships. Non-integrated models lacked evidence of constructing relationships between discreet ideas and of using personal background to accommodate new information.

Modeling environment. Evidence suggests that characteristics of the modeling environment may create opportunities for constructing meaning and understanding.

Problems. When students created models they were trying to solve the problem framed for them. In the first enactments, the teacher asked students to create a model that teaches their understanding to another student. Inherent in this assignment is a problem: How to represent information. Students responded with various ways of drawing and labeling their individual models including elements such as applying facts to a real-world setting, transforming a representation, and drawing on personal experiences. During the fourth enactment when the teacher asked students to model the life-cycle of a microorganism, they solved the problem by bringing together and relating various facts. Framing the assignment with a problem created gaps that students filled by applying knowledge and constructing explanations (Jonassen, 1997).

The central role of problems in model-based reasoning is congruous with other work that emphasizes the centrality of problems in learning. Savery and Duffy (1995) call this the "puzzlement" that stimulates activity and identified it as a central proposition of their view of constructivism. They relate this to John Dewey's view that dealing with problems is central to organizing learning.

There was evidence that the kind of problem to be solved influenced how students modeled. During the first enactments, the problem to solve was creating an explanation for other students and most models were based on curriculum-derived facts. The fourth enactment problem asked for students to depict the life-cycle, which resulted in mostly explanatory models. Explanatory models tended to be richer in information, involving students' reasoning about causal relationships and scientific processes. That the nature of the problem influences modeling is corroborated by existing work indicating that the problem used to frame a learning experience can also vary in complexity (Spector, 2012) and in structure (Jonassen, 1997).

Feedback. As students modeled science topics, there was no direct feedback to guide their modeling. This proved to be an important aspect of drawing models. Students often depicted erroneous information without realizing it. One student drew the very first living thing, microorganisms, in a setting with plants. She did not recognize this as an anachronism until it was brought to her attention. Similar experiences were identified in preliminary studies. One student's model of light waves depicted light following a sharply curved path in the air. When an adult showed him the problem he stopped and considered how light would behave then modified his model to reflect his understanding of light.

Science modeling involves different forms of feedback. Because individual drawing per se lacks external feedback, students were able to include erroneous information in their models and retain naïve or incomplete conceptions of science phenomena. Prior researchers described drawing as giving students an opportunity to see and respond to their externalized representations, in essence, creating a dialogue. Donald Schön described learning (and design) as a reflective conversation with the materials one is creating (Bamberger & Schön, 1983; Schön, 1982). He illustrates the process with an architecture student who draws then changes as she observes her representations. Papert states that constructing provides things to think with (Papert, 1980). For example, children building elbow joints were able to detect a problem when their elbows could bend in both directions (Penner, Schauble, & Lehrer, 1998) once their constructions provided feedback. Computer modeling environments allow students to create and test models (Wilensky & Reisman, 2006). In one report, science students were even able to test models using *what if* scenarios in teacher conversation (Khan, 2008). Linn and colleagues directed students to generate models then engage in peer conversations to promote reflection and reasoning with the models (Linn, Clark, & Slotta, 2003; "WISE: Web-based Inquiry Science Environment," 2012). In the present study, students' drawings and reflections were not evident without something or someone to give them feedback.

Cognitive apprenticeship. Students incorporated constructivist elements in models, but there was little evidence that those elements reflected constructivist thinking with the model. Students did, however, extend analytic constructivist thinking via apprenticeship with the teacher. Students elaborated models, deduced strategies to fill in gaps and applied knowledge from models to everyday life. This suggests that they were capable of constructive thinking about science, but required help reasoning with their models.

Clement and colleagues refer to these conversations as co-construction of models that facilitate model evolution (Clement & Rea-Ramirez, 2008). However, in this study the teacher did more than co-create a model with students. The scaffolded-thinking process helped the students to construct models they had not yet conceptualized. As the teacher modeled cognitive processes, the student learned how to model as a cognitive apprentice (Brown, Collins, & Duguid, 1989; Collins, 2006). In one case from the present study involving a conversation about bacteria on meat, the teacher engaged the student in the process of elaborating by asking questions about his model. Starting from a single fact that he generated, she asked questions and used his answers to pose more questions, developing a more complete mental model. Through questions and occasional guides, she modeled both construction and associated reasoning. In this cognitive apprenticeship role, the student engaged in reasoning and model creation with the teacher. Through questioning and apprenticeship processes, students elaborated initial factual models into explanatory models, reasoned details of their models, and made personal connections with their models.

These experiences suggest that for students, constructivist modeling evolves as an emerging skill: some students engaged in aspects of constructivist modeling while others did not. The teacher encouraged students to think through their models and provided prompts, some of which appeared influential while others had minimal influence.

Basic constructivist elements were evident, suggesting students' modeling skills evolve toward model-based construction of meaning. While current science education standards recommend using models to learn, there is less guidance on how to help children develop requisite skills. Patterns observed here and in similar studies could provide guides for helping children develop modeling skills as a form of inquiry and practice in science.

Student Models and Reasoning

There was little evidence that students routinely provided constructivist explanations. Few extra-curricular explanations of phenomena or personal theories were represented in student models; many modeled primarily factual information from the science unit. Rather than using models and examples to construct new ideas, students frequently replicated what was shown in class or reconstructed examples the teacher provided.

Some models, however, incorporated constructivism constituents. Students drew personal items like a pond, a vacation lake, or a video game character, and some refined explanations using their models. Such elements may be necessary to constructing. There were occasional examples of reasoning during modeling, but student reasoning did not reflect either personal constructions or theories. Some students replicated curricular models but incorporated their own variation. Students also went beyond just repeating facts and reasoned with factual models, and provided explanations using science content to develop explanatory models.

In the absence of reasoning during model construction, the modeling task appeared to involve re-representing content. Re-representing content offers opportunities to enrich understanding (Cox, 1999), but may be limited when students rely on prior classroom expectations and seek to produce products and complete assignments in familiar ways. Constructing models to promote reasoning likely requires efforts to establish a class culture that encourages and supports model construction as a process of generating ideas.

Individual differences. Though the study was not designed to analyze individual differences, there was evidence that differences were a factor in modeling. Patterns were evident across both students who incorporated constructivist elements in all models and the student who did not include constructivist elements in any models. Two characteristics may have been influential in this study: (1) tendency to immerse oneself in creating artifacts and (2) depth of understanding.

During daily observations two students were noteworthy for how they interacted during the class. One was excitable and often singled out by the teacher for classroom behavior; when he drew models he was very involved in the process. The teacher stated that he routinely became immersed in all projects, including creative writing and drawing. Given past behavior, the teacher was surprised by his first model because of the details he incorporated, which she interpreted as understanding content. During an interview about one of his models, he wanted to use his pencil and elaborate it according to his evolved understanding, even though he was given the option to verbally explain his new understanding. He was one of only five students who incorporated constructivist elements in every model. His models were rich in detail and included elements such as the Nintendo™ toadstool character, a table to organize information, and what he identified as his own garden (Appendix B, 1-22; Appendix C, 2-22; Appendix E, 4-22).

During daily instruction another girl was noted for her tendency to draw creatively when given the opportunity. As she listened to class discussion she often drew pictures. She responded to discussion, raised her hand, and was involved in class while simultaneously drawing elaborate pictures of, for instance, mermaids, cheerleaders and other objects unrelated to the science instruction. Rather than draw multiple doodles, she took time to develop drawings as each creative drawing occupied all of a class period or discussion. Across the study she drew 3 models and she was one of the five who included constructivist elements in each model. The constructivist elements in her first two models were elaborate scenes, while the third model included a unique representation of algae (Appendix B, 1-03; Appendix C, 2-03; Appendix D, 3-03).

Two cases indicate a difference related to modeling ability and/or science knowledge. One of those involves a student who drew four models and included constructivist elements in all four models (Appendix B, 1-16; Appendix C, 2-16; Appendix D, 3-16; Appendix E, 4-16). Evidence suggests that she had a good understanding of science concepts: Her models were elaborate in detail and used features to explain concepts such as labels and comparisons including both explanations of science concepts as well as visual features to organize information. In contrast' another student drew all four models but did not include any constructivist elements (Appendix B, 1-17; Appendix C, 2-17; Appendix D, 3-17; Appendix E, 4-17). Three models included sparse information and detail. The fourth model was completed on the computer and appeared to have involved research because it included scientific names of microorganisms (Staph Aureus, S. Milleir, and C. Koseiri). However, that model was designed to be a cycle with boxes and arrows, yet there was no relationship expressed by the boxes and arrows; the format was suggested by the teacher, but lacked relatedness and integration. The contrast in these two students across all four modeling events suggests a persistent difference that influenced modeling. However, without measurements of student science knowledge and modeling abilities, one can only speculate on the causes of differences in performance.

Teacher Prompts and Interactions

Based on preliminary studies, the difference between open-ended and directed prompts was expected to be important in promoting constructive modeling. Where directed instructions specify how to complete an assignment, open-ended prompts are believed to minimize students' tendencies to simply comply – a tendency that has been noted in classroom culture (Evertson, Neal, & National Education Association, 2006; McCaslin & Good, 1992). However, there was no evidence that open prompts independently influenced student modeling. Changes in the number or types of prompts did not correspond with changes in models or in the amount of constructivist elements.

In contrast, during initial enactments when the teacher relied more on open-ended prompts, student models were characterized by incorporating facts identical to those presented in class. And students explained models by listing facts and verbally labeling their models, rather than discussing their interpretations, ideas or individual theories. This suggests that when the teacher initially provides either open-ended or ill-structured assignments, students tend to incorporate compliant features in contrast to constructive thinking and conceptual change.

However, observed responses to directed prompts suggest that open-endedness may prove to be important. In preliminary studies instructions were very directed and specific but yielded little variation in student models. In this study, directed instruction via form prompts also led students to comply rather than construct novel interpretations. Additionally, when the teacher provided specific examples for creating a model, some students closely followed the example. These cases suggest that prompts can be so directive that students are able to complete the assignment without reasoning or constructing explanations.

Certain prompts did appear to trigger constructivist student modeling or elements. When the teacher framed the assignment with instructions to consider microorganisms at home, most students situated the model in a personal experience. And when the frame shifted from having students explain what they understood to specific instructions to model the life of a microorganism, students created more explanatory models with integrated information. Prompts that appeared to elicit constructivist modeling framed the assignments and specifically directed the students to incorporate personal elements. Additionally, those prompts appeared to be effective when characterized by specificity and directedness.

Prompts and individual modeling across enactments. The type of prompts and the scaffolding interactions with the teacher helped some students increase important characteristics of the models. The structure in the teacher's framing and guidance led students who were not modeling with many details or with relatedness to add more to their models and integrate information. Students who already created detailed models did not increase the amount of detail, but did increase the relatedness of representations within the model. It seems that in a class where open-ended modeling and reasoning with models is not common, additional structure in the assignment helped struggling students.

Scaffolding. The most productive prompts were given during one-on-one conversations about students' models or ideas. In those cases, students elaborated models, constructed explanations, and integrated ideas. Individuals who previously struggled to create complete or detailed models significantly increase the quality of their models in both amount of information and in incorporating explanatory aspects to the model. The teacher modeled querying and model evaluation and guided students in the detection of gaps in both the individual model and the associated explanations. She modeled an approach to address problems that students solved en route to completing and explaining models.

These findings suggest that with support students were able to create models to elaborate and construct meaning. Furthermore, the teacher implemented mechanisms to support reasoning during model creation such as feedback and reflection.

Designing model-based learning environments

While the exploratory nature of this study does not warrant broad claims about modeling, some important patterns begin to emerge that could prove useful in the design and practice of model-based instruction. As others have asserted (Lehrer & Schauble, 2000; Schwarz et al., 2009), there are basic skills and reasoning to learn as a part of modeling. This study identified elements of constructing in drawn models which may provide a beginning point at which teachers can help students practice modeling. Further research would be needed to make such an effort viable.

Students were most successful reasoning with models when helped by the teacher. That supports other studies which have found that scaffolding and support are helpful in self-directed learning environments (Alfieri et al., 2011). Designers and educators create scaffolds appropriate to the learning environment and the learner. In this and preliminary studies, specific problem areas that framed the modeling activity provided gaps for students to work in; feedback helped students evaluate and revise; and the teacher guided students' thinking during model construction. To help students engage in model-based learning, similar features could be built into other modeling environments. Whereas findings here are formative and not to be generalized, design studies can adapt these mechanisms to different modeling contexts.

Limitations

Task Novelty. Given the exploratory scope of implementation, this study cannot be considered a comprehensive description of teacher and student interactions during modeling. This study introduced a particular approach to constructivist-inspired classroom practice – drawing and reasoning with models – that varied substantially from everyday classroom practices. Furthermore, this study introduced a modeling practice in a non-modeling-based environment. Students responded in conventional ways based on prior experiences in didactic settings. Student responses likely reflected their own evolved habits of mind despite momentary shifts in activities, goals, and teacher guidance. This could partially explain why students often replicated what the teacher said or demonstrated. Following teacher's specific examples and instructions suggests a willingness or desire to respond as they have been expected. Students accustomed to traditional classroom culture may respond to the messy, ill-defined nature of student-centered learning in familiar ways based on their classroom experiences.

Nature of study. This naturalistic study was implemented in a typical classroom setting, to assess external validity but also included limitations. There was limited access to methods for collecting data from students during and after modeling: Observations were limited to the students I could observe and interview at any given moment and the number of students interviewed was determined by available class time. My focus was on the teacher's guidance of and influence on modeling, so it was important that the teacher freely conduct the class in ways expected or required in the school. However, while authenticity was increased, I had less control over the fidelity of constructivist modeling implementation.

Limited implementation. Whereas this study involved implementing a modeling practice in a traditional classroom, there are limitations to conclusions and generalizations. Given students' limited exposure to modeling and reasoning with models in this classroom, broader conclusions cannot be made about model-based instruction where modeling is a part of regular practice and inquiry. And because this study involved using models with only one topic, findings cannot provide broad conclusions about other science topics in other contexts. Instead, findings provide ideas and patterns that should be adapted for further study and development.

Another limiting aspect may be associated with fidelity of enactments. The teacher was supportive of the instructional goals of model-based instruction while also addressing school and state science standards. While motivated and well-versed in emerging national science standards, teachers can enact those differently. Gaps have been identified between espousing learner-centered beliefs and enacting learner-centered practices (Polly & Hannafin, 2011). This possibility suggests that conclusions about classroom model-based instruction are not possible since other classrooms and efforts to enact constructivist modeling will vary by teacher.

Researcher bias. As a researcher, I acknowledge my influence on the selection of target measures and analyses. My interest in student-centered learning and constructivism formed a theoretical lens that informed the study. I began the study with the assumption that constructivism is a useful and current pedagogical approach and therefore worthy of close study. Data collection and analysis focused on teacher strategies and evidence of particular kinds of thinking and learning. Student-centered construction and reasoning were the key goals of the study but significant competing goals and priorities exist in public schools.

Future Research

Studying new approaches to education in traditional environments presents challenges. This study provided some initial evidence for a particular instantiation of student-centered practice. To build on these findings, further research must include more sustained efforts in a classroom. This study examined four enactments in a traditional classroom; sustained efforts need to focus on implementing model-based inquiry across a longer time, examining the apprenticeship process of developing model-based reasoning while also examining patterns and interactions that support constructivist modeling across an extended period.

This study was designed to identify student and teacher patterns in classroom-based modeling. Some teacher prompts influenced student modeling. To understand those, future studies should examine how this and preliminary studies generated seemingly contradictory findings: some directed prompts influenced more conformity, yet certain directed prompts triggered emerging constructivist modeling. Furthermore, findings regarding directed and open-endedness were based on supporting individual modeling and reasoning per constructivist epistemology. In contrast, social science literature focuses on the influence of direct versus minimally guided support (Kirschner et al., 2006). However, there is evidence that in combination a blend of direct and minimally guided support may prove important. Focus on open-endedness in combination with other prompts or practices and in varying contexts is needed to identify when and how approaches can be used in complementary rather than singularly effective ways. Similarly, researchers can closely examine the ways the teacher and everyday classroom learning environments can support constructivist modeling and promote student reasoning.

To make judgments about the influence of student-teacher interactions on constructivist thinking should involve a baseline understanding of how students represent mental models and reason with and beyond constructivist explanations. Though it may seem contrary to the purpose of this naturalistic study, non-naturalistic studies in a controlled environment can more closely analyze modeling behaviors in children with more control over data gathering. Techniques such as think-aloud and student-narrating of recordings of modeling could provide insights into children's representational reasoning to compare modeling in the classroom and beyond the typical classroom settings.

Characteristics of models within students across the length of the study suggest that individual differences influenced modeling and reasoning with models. However, this study was not designed to measure individual differences. In this study some students' modeling style – choice of representation – persisted across all enactments despite other changes. Future research can determine what kind of modeling characteristics are germane to individual differences. If such characteristics exist, it will be important to understand whether germane modeling styles facilitate reasoning with models or whether learning to model with other styles promotes better understanding of subject matter. Research into individual differences and the role they play in modeling will help build classroom practices that build on strengths and support students who need extra support in constructivist modeling.

Conclusion

In this exploratory study I worked with a teacher to implement a science modeling activity during which the teacher guided students to construct models by drawing. In this context, I examined how students modeled and how the teacher influenced modeling. Given findings in preliminary studies, this study was designed to focus on how the teacher might apply open-ended assignments to promote student autonomy while supporting students during model-based learning. Findings suggest that open-ended assignments were not the most important factor to promote constructivist modeling; there are multiple ways a teacher can structure modeling to guide students as they construct individual meaning and understanding. Challenges to conducting this study include that this type of modeling is in many ways foreign to traditional classroom practice. Thus conclusions suggest that distributed cognitive guides were fundamental to students' learning to reason with models.

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APPENDIX A

PROTOCOLS FOR COLLECTING AND ANALYZING DATA

A.1 Modeling Enactments – Observation Guide

A.2 Modeling Enactments – Instrument for Analysis of Instructions and Prompts

A.3 Analysis of Models – Guide

A.4 Analysis of Models – Instrument

Modeling Enactments – Observation Guide

Prepare before beginning:

1) Review research questions – notice other things, but focus on questions.

2) Start recorder and keep it in hand while moving around room.

- Record both teacher's instructions and any conversations she or I have

3) Keep note/observation sheets to keep track of notable events.

- Record time stamp when they occur.

4) Move around room. Stay aware of multiple aspects.

- Teacher's prompts
- Students' actions and responses

During observations – Dual Focus:

Teacher Prompts

- Overall focus of instructions
- Pay attention to notable prompts
    - Triggering previous class instruction
    - Inducements to make personal connections
    - Methods for encouraging autonomy/student-centeredness

Student Actions

- Initial responses (how quickly they begin, staring at blank paper)
- How they draw (thinking, correcting, asking questions, seeking help)

MODELING ENACTMENTS – ANALYSIS OF INSTRUCTIONS AND PROMPTS

Enactment _____ Date___________

General Problem

Open Instruction

Directed Guidance

Other Actions/Helps/Directions

Analysis of Models – Guide

Purpose

1) Focus on general idea, theme or message of the model.
    a. What is the child trying to say?
    b. What are the main methods of saying it?

2) Find artifacts of constructing meaning or understanding.
    a. Personal objects
    b. Ideas or connections that go beyond class instruction and models

3) Find evidence of reasoning and decision-making.
    a. Reproducing class models
    b. Borrowing from notes, neighbors and other resources
    c. Developing personal theories

ANALYSIS OF MODELS INSTRUMENT

Analysis of Model # ________________

Reproductions of class models

Personal/Original Representations

Other

Qualities of the model: Explanation? Factual? What kind?

Overall Summary

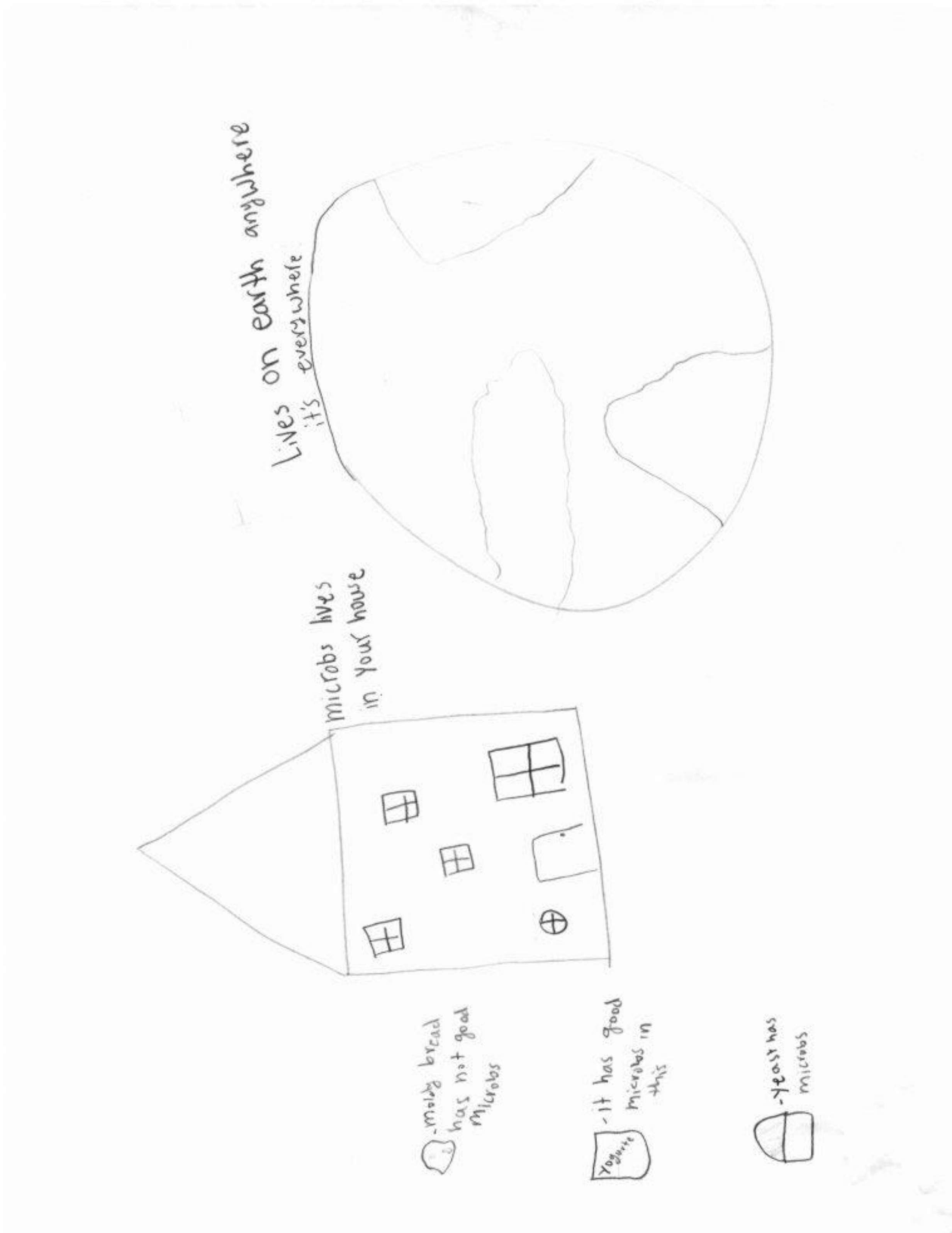
APPENDIX B

STUDENT MODELS OF FIRST ENACTMENT

Student models are numbered by two identifiers: The enactment number followed by the student ID. For example 1-09 means Enactment 1 and Student 09. To view all models within an enactment, view all the models that begin with the same enactment number (1-04, 1-05, 1-06, etc.). To view all models by the same student, view all the models that end with the same number (1-15, 2-15, 3-15, 4-15). Numbers not included mean the student’s model was missing for that enactment.

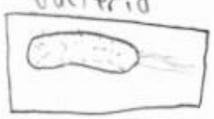
Model 1-03


Virus
Virus
Viruses make our babys sick
Fungi is in moldy fruit
yogurt is a good microb
good microb

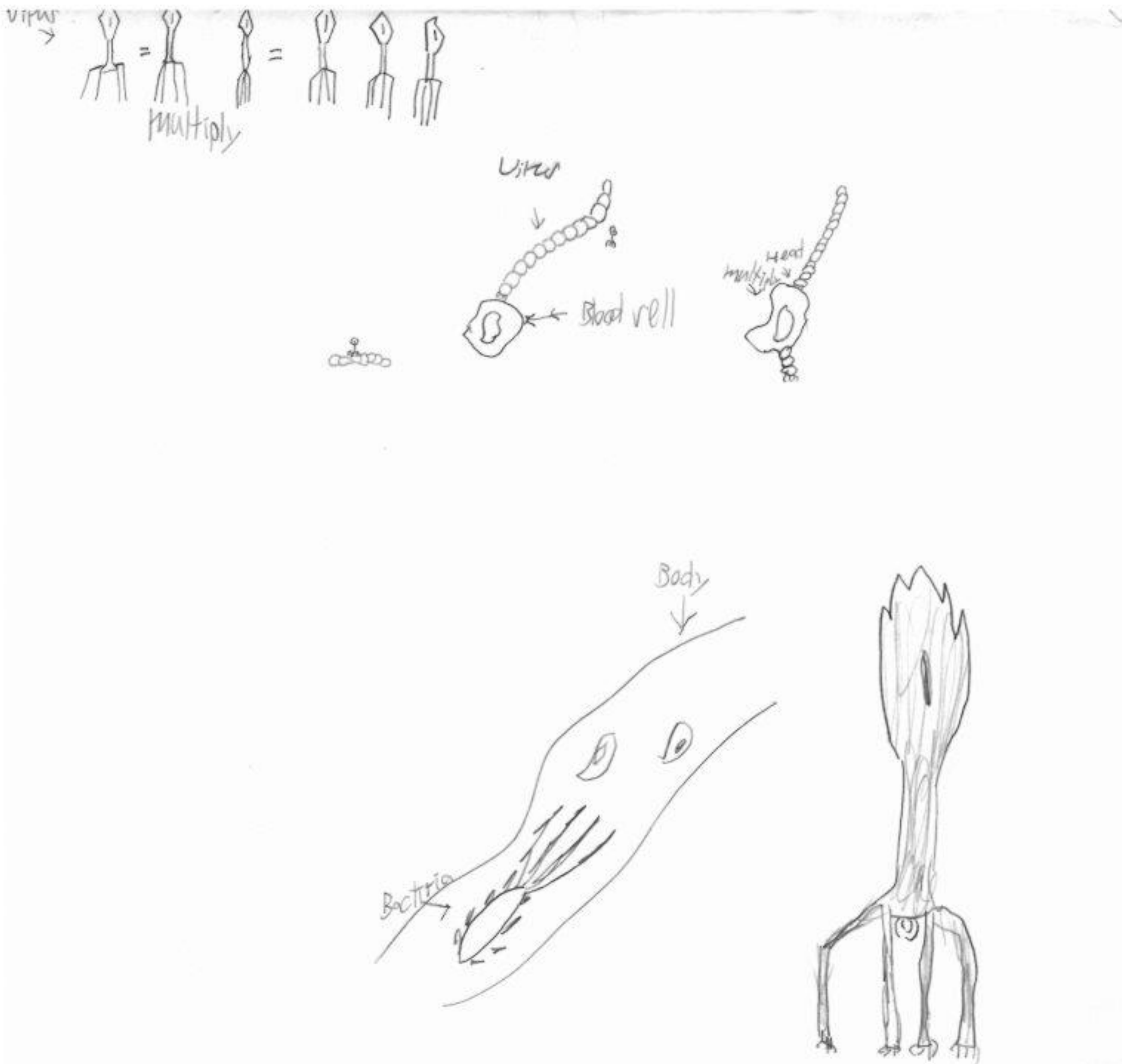

Lives on earth anywhere
it's everywhere
microbs lives
in your house
-moldy bread
has not good
microbs
Yogurt
-it has good
microbs in
this
-yeast has
microbs

Microorganisms are everywhere. Theyre tiny living things that are too small to see without a microscope. One group of microorganisms is bacteria. Bacteria are sometimes thought of as bad and harmful. Sometimes they are, but most of the time theyre not. In fact theyre helpful.

bacteria



P.S. I thought we had like twenty minutes to write a paragraph (well, more) for each kind of microbe. So all I had time to write was bacteria.


multiply
Blood vell
Head
Body
Bactria

Model 1-07

Micro Organisms

I literally dont know ANYTHING about this class.

seriouly.

Fungi Bacteria Protozoa Virus Algae

(mushrooms yeast mold etc.)

micro

organism

Anything

breathing

(not seeable) to naked eye

takes in nutrience

gives off waste

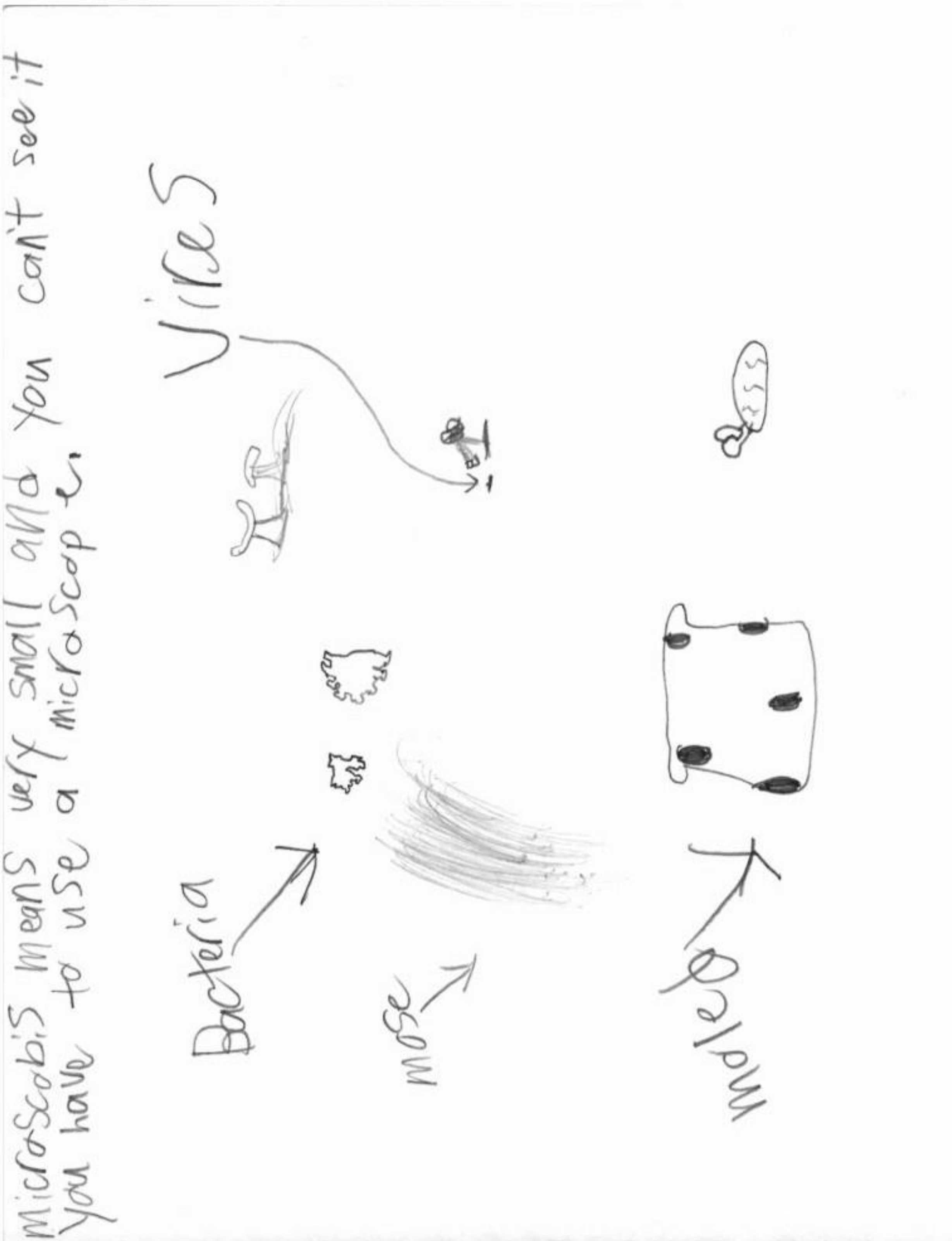
Fungi

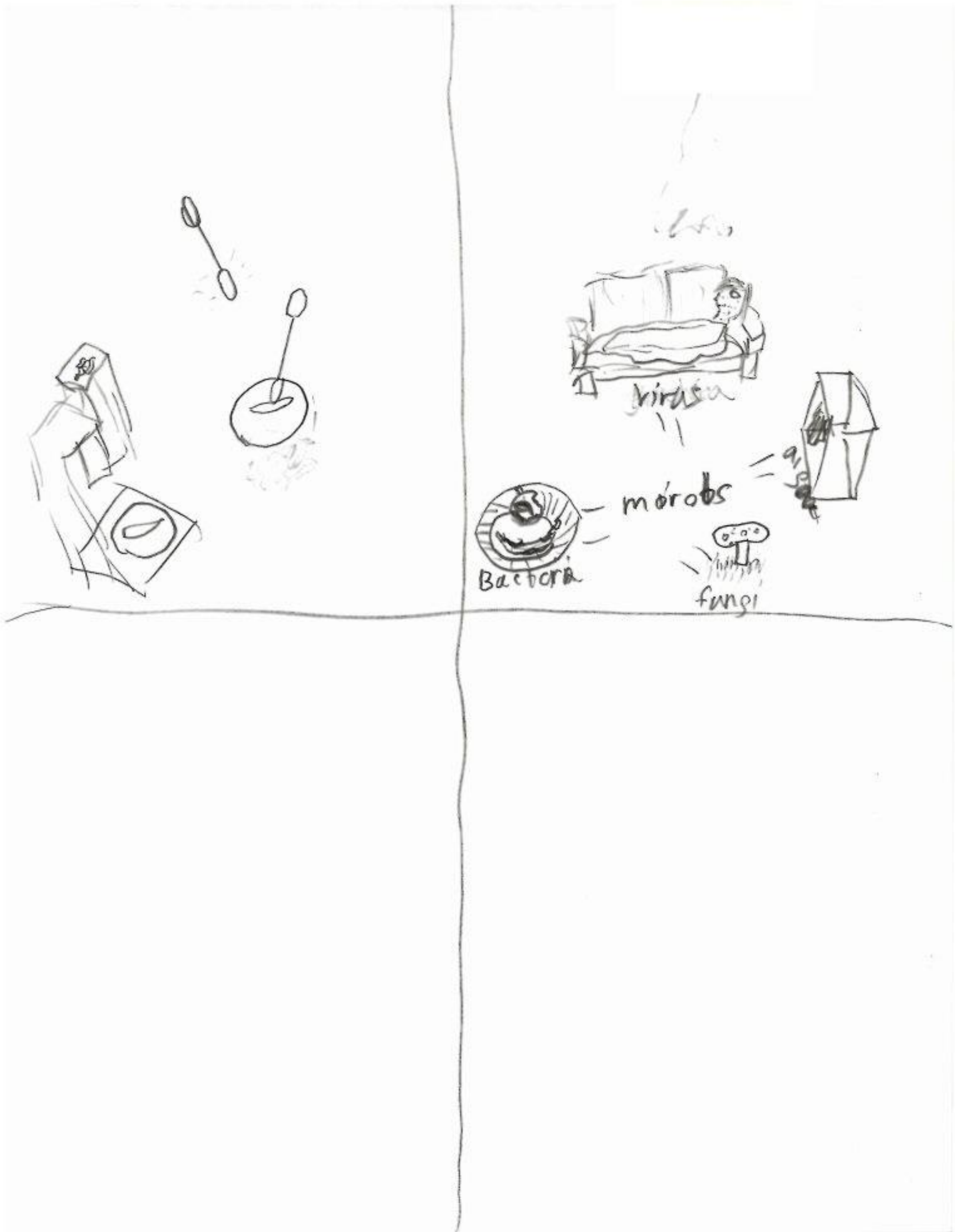
Bacteria

Protozoa

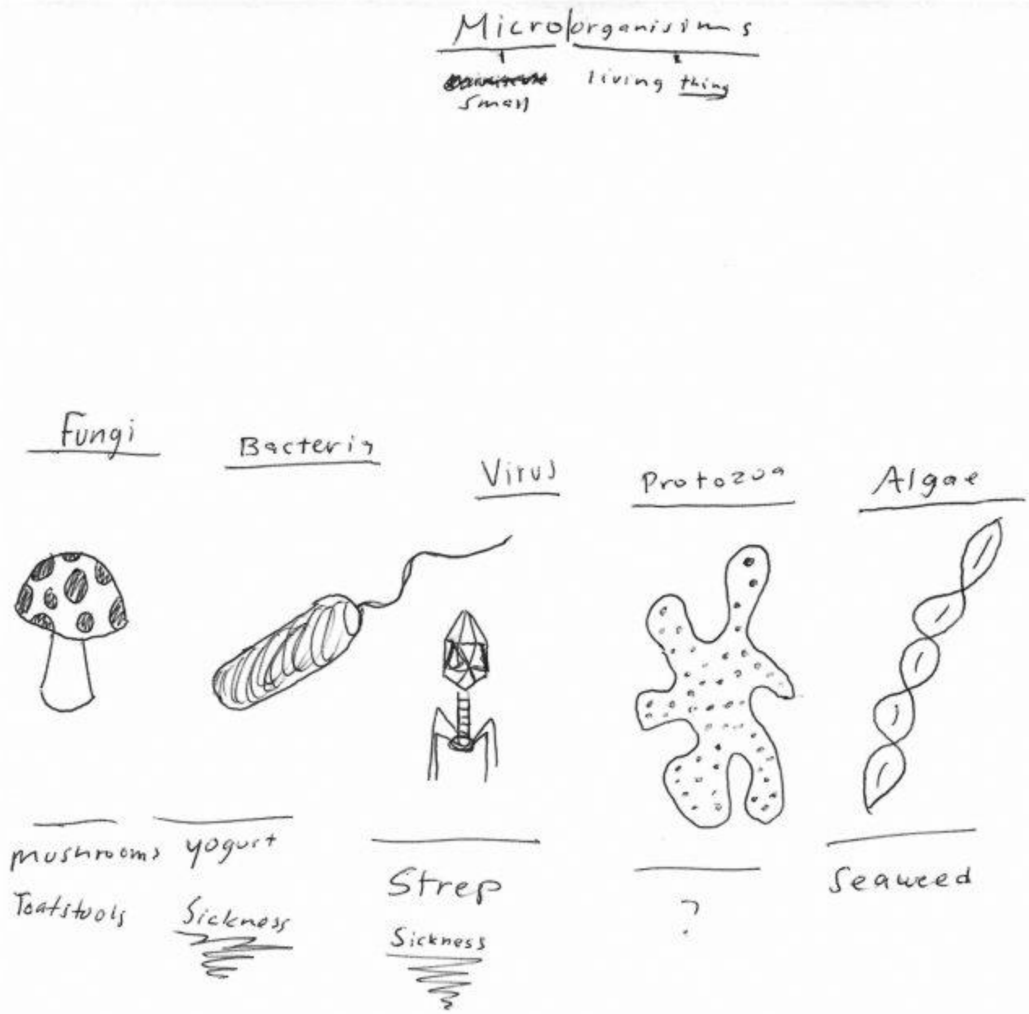
Virus

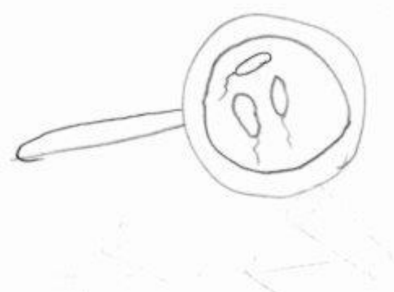
Algae


Microscobis means very small and you can't see it
you have to use a microscope.
Vires
Bacteria
mose
molde


mórobs
Bacteria
fungi

Model 1-11


Microorganisims
small
living thing
Fungi
Bacteria
Virus
Protozoa
Algae
mushrooms
Toadstools
yogurt
Sickness
Strep
Sickness
?
Seaweed




Bacteria can be in humans
Microorganisms

Model 1-14

Microorganism

Bacteria: to small to see with naked eye. 

you can find them anyware

Orginism: living thing, take in oxagin gives off wast

fungi: 

algae: 

mold: mold grows on fruit or other things like 

 =a decaying leaf
(a badiria that helps it regrow)

protozoa: 

virus: muliply & spread. make you sick

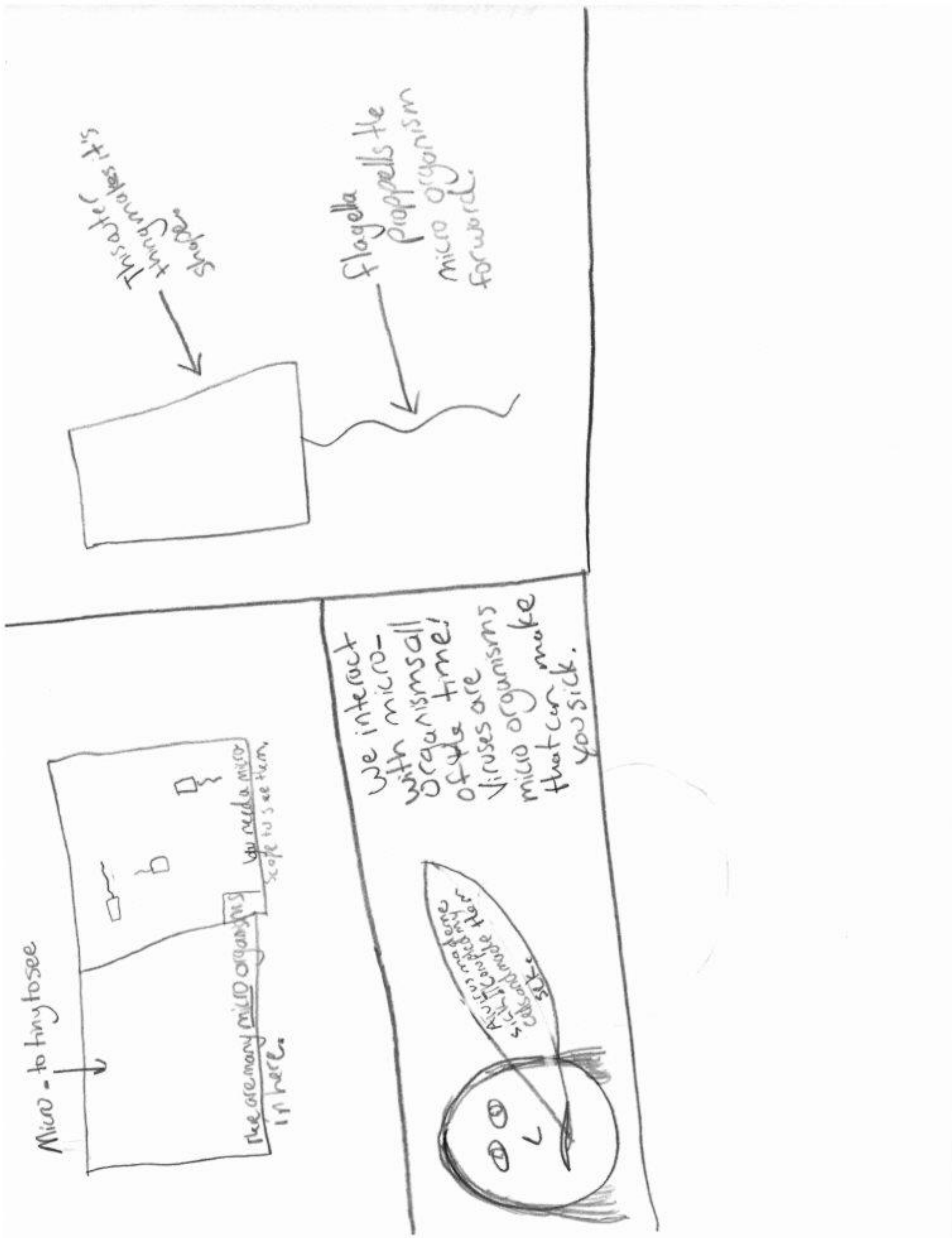
+ = fungi = Yak and
iup

bacteria = and

protozua = ? or mabe

virus = not good and not not bad and

alge = seaweed and


Micro - to tiny to see
There are many micro organisms in here.
You need a micro scope to see them.
This outer thing makes it's shape.
flagella proppells the micro organism forward.
We interact with micro-organisms all of the time! Viruses are micro organisms that can make you sick.
A virus made me sick. It corupted my cells and made them sick.


Bacteria?
Protozoa
Alagae
this stuff in a lake
Fungi
or

Bacteria:  ?

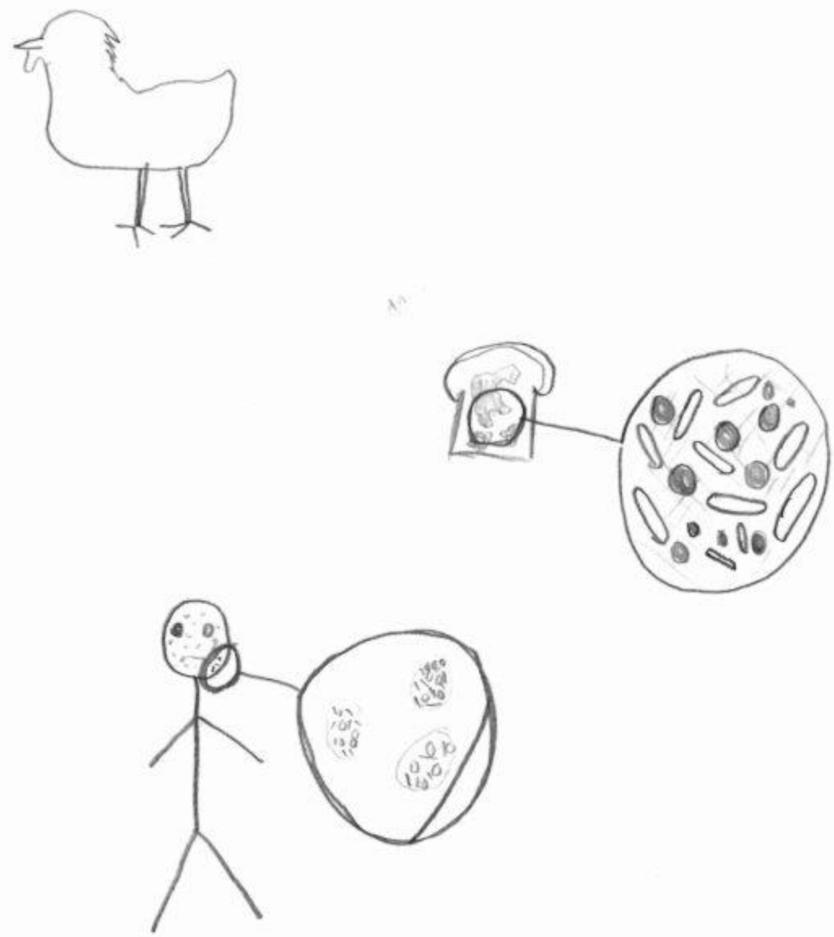
Fungi : comes from mushrooms really Small Sizes and Big too.

Protozoa: ?

Virus: can be bad for you. is Share.

Alage : look like seaweed.

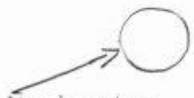
Model 1-19



Microorganis

They are vary small.

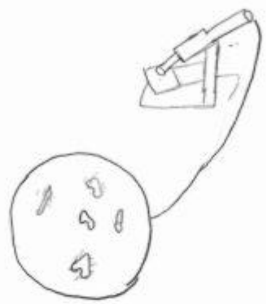
They are also liveing, they move around all the time



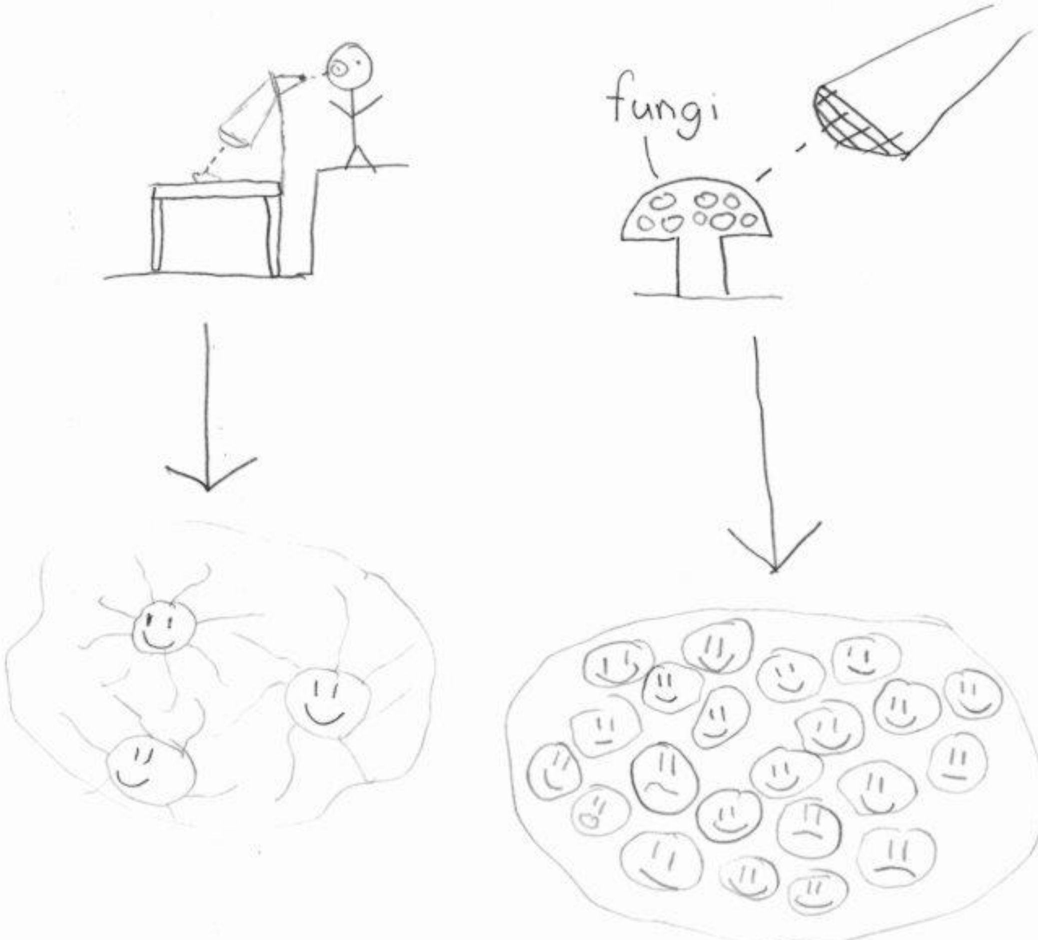
Microborginisms

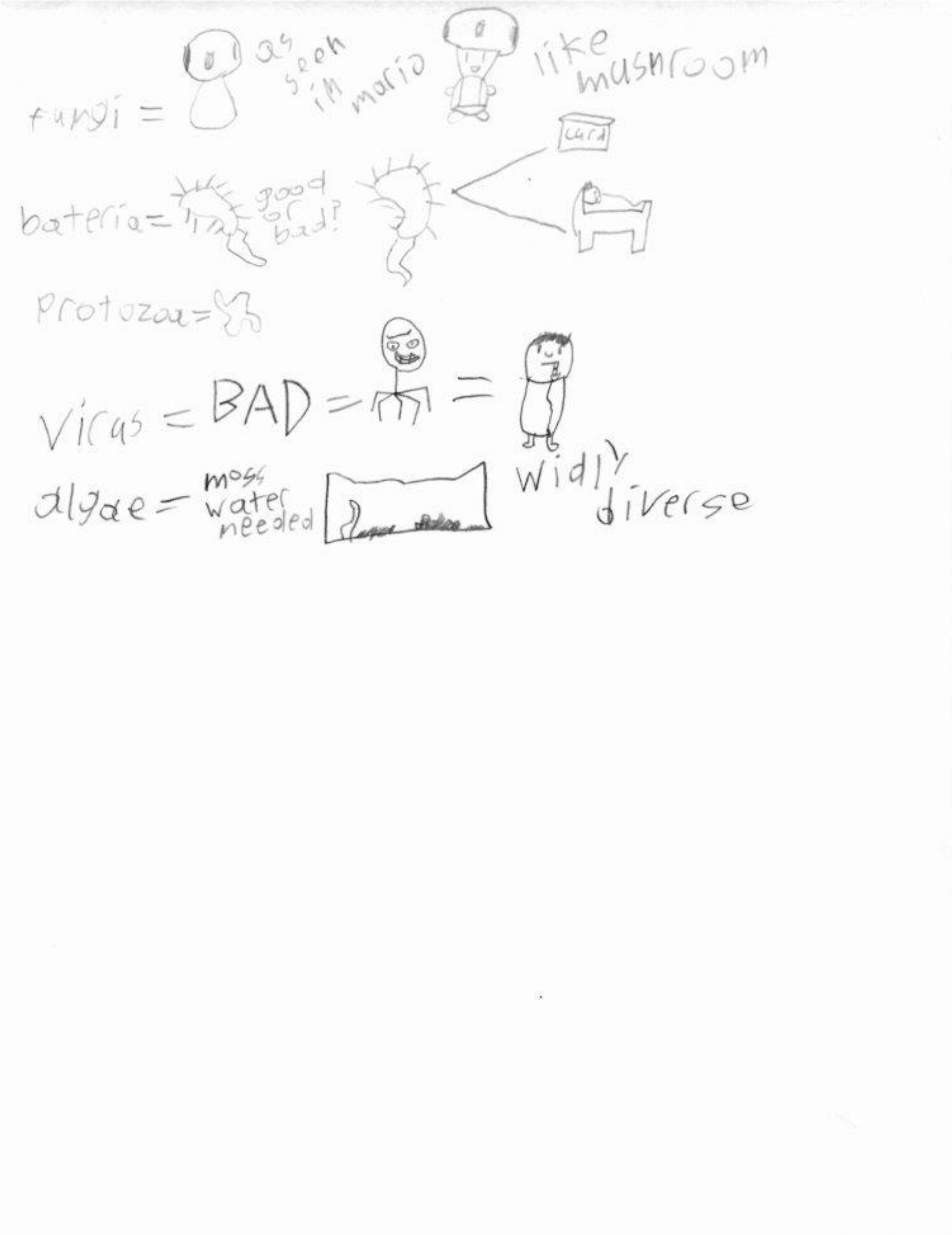
There so small you can't even see it with the naked eye.

microborginisms

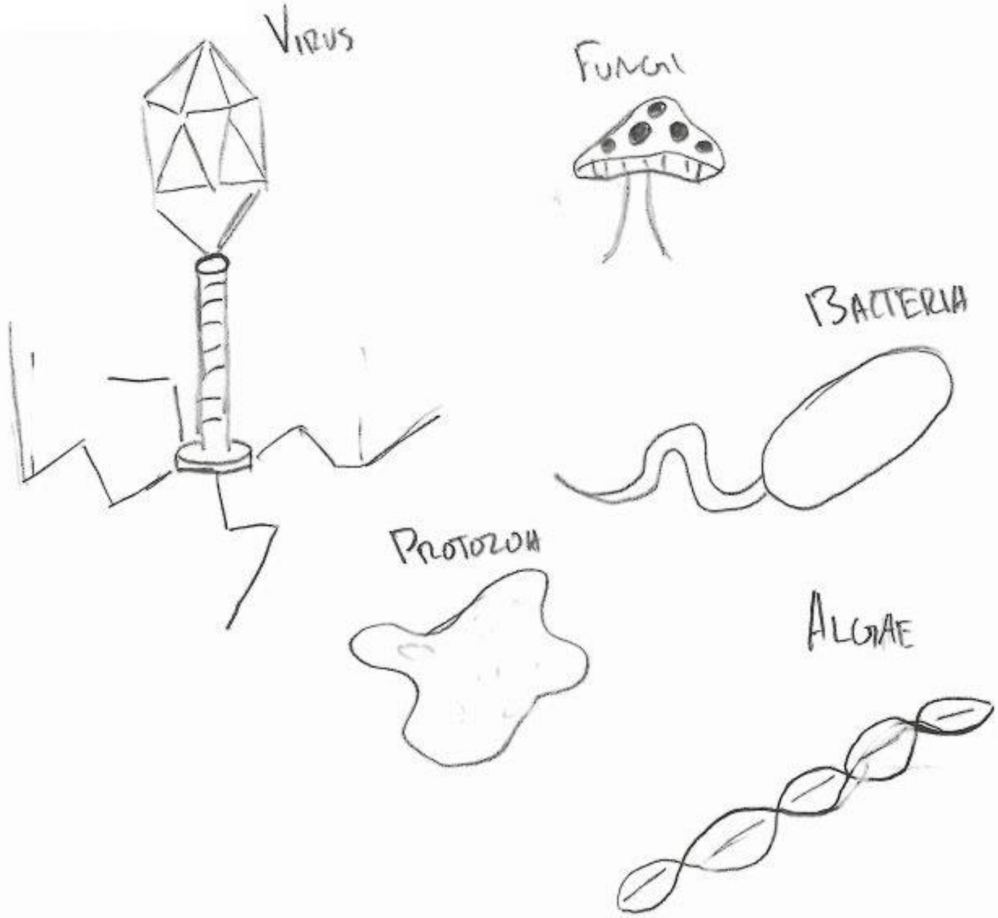


Model 1-21



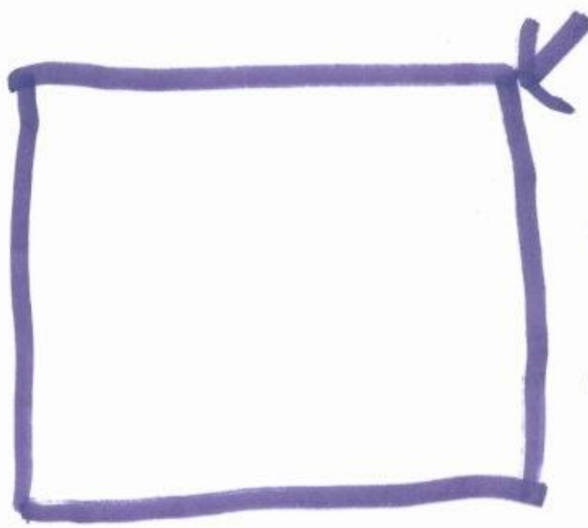

fungi =
as seen in mario
like mushroom
card
bateria =
good or bad?
protozoa =
virus = BAD = =
algae = moss water needed
widly diverse

Model 1-24

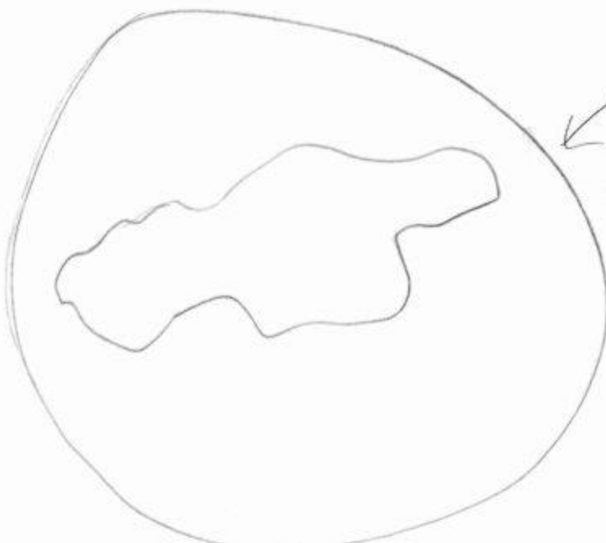


Model 1-25

A mircroorgamis are small liveing things.



In this □ there are lots of microorganisams. You Just can't see it with the nackedeye. You need a microorganisms are small livins things that you can see with the naked eye.



APPENDIX C

STUDENT MODELS OF SECOND ENACTMENT

Student models are numbered by two identifiers: The enactment number followed by the student ID. For example 1-09 means Enactment 1 and Student 09. To view all models within an enactment, view all the models that begin with the same enactment number (1-04, 1-05, 1-06, etc.). To view all models by the same student, view all the models that end with the same number (1-15, 2-15, 3-15, 4-15). Numbers not included mean the student's model was missing for that enactment.

Model 2-03

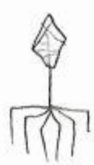

Each cell is bacliera
lergest Cell group
-I live in any enviorment
I have Samonila
I have strep
We are here befor the dinasors
reolly
ya we are the first living
us cells Split & multaply
Good V.S Bad
yogert
V.S
Samonila
yogert wins

Model 2-04


Bacteria
other microbs
I have a fever
bacteria lives anywhere on earth
trash Pile
Bacteria makes them deka
dirt/soil
egg
I ate cookie dow and got Sammll a
Leave Pile has bacteria all over it
yogrutet is a good Bacteria
yougeret
good vs bad
yogret
V.S
egg

Microbes

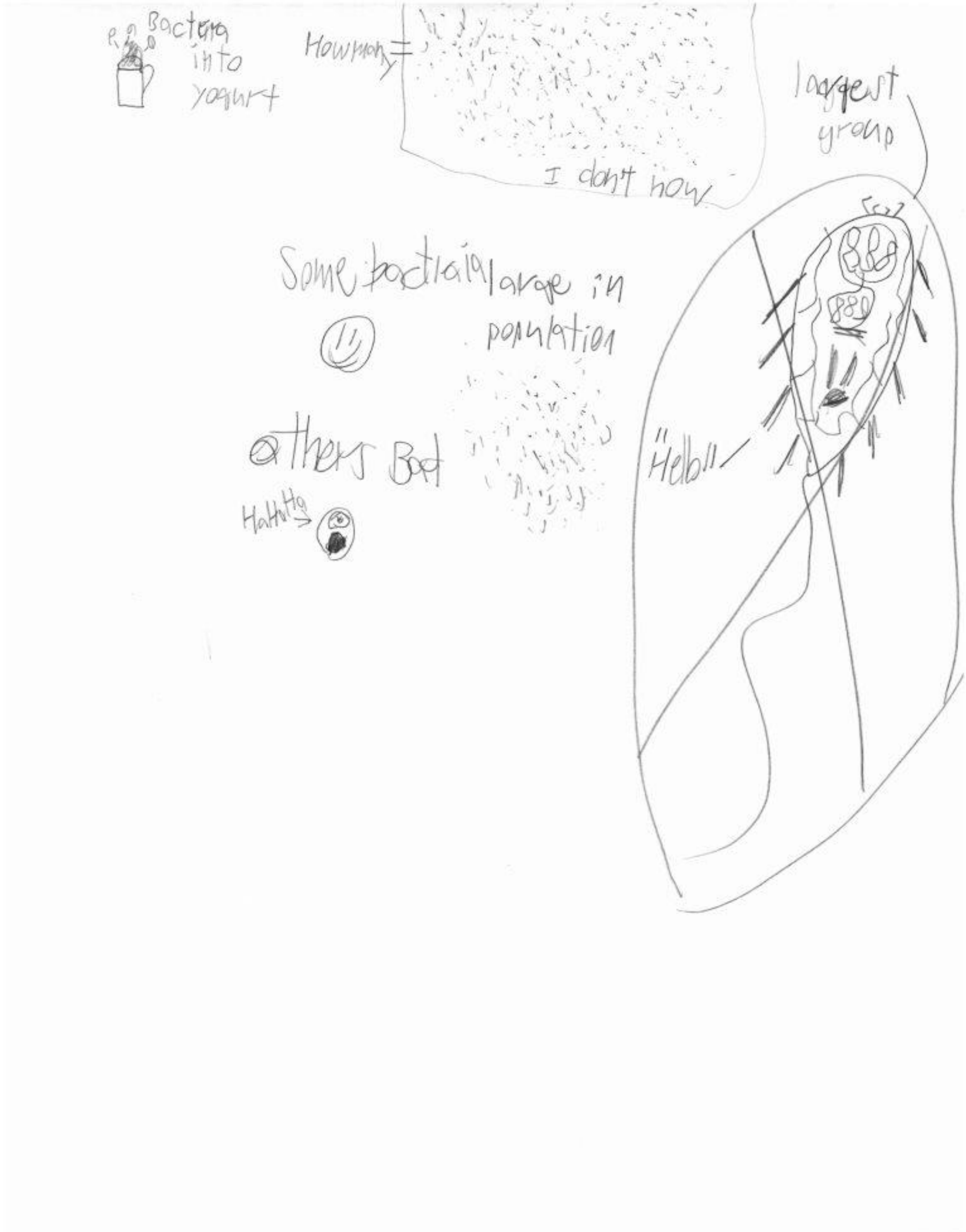
Bacteria:  : Microbe pioneers, most populated group of microbe, mostly helpful, sometimes causer disease

Viruses:  • Smallest microbe in individual • size, causes disease

Fungi:  • Fungi can range in size from • single-celled yeast to multi-celled mushrooms and toadstools. A mushroom is a colony of fungi.

Algae:  : Algae live in really moist enviornments. If there isn't water it won't survive. Algae can come as things like moss. Some Algae, like Green/Blue Algae can be harmful.

Protozoa:  ?: I'm not really sure what Protozoa are. Although I'm sure they're microorganisms.


Bacteria into yogurt
How many =
I don't now
largest group
Some bactiaia large in population
others Bad
Ha Ha Ha
"Hello"

most Bacteria is good for you ♡ (some is harmful)

*Bacteria breaks down food to get the nutrience and to decompose the food in your body

the Bacteria is Largest group of microbes

yogurt

BACTERIA MAKES YOGURT

OVER 4,000 species only 3 shapes!

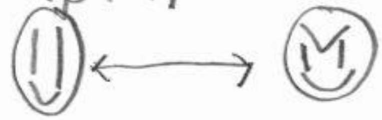
rod

sphere

spiral

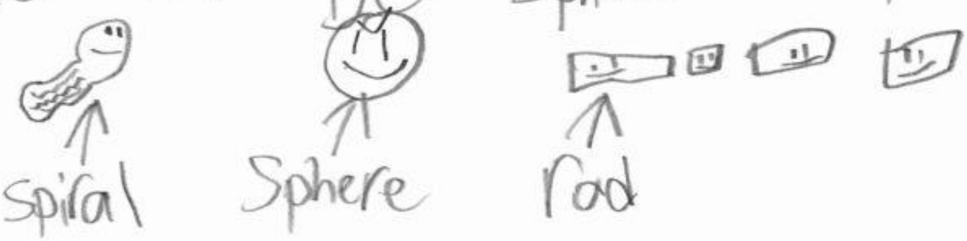
Model 2-08

Bacteria can be helpful or harmful and they can Spread.



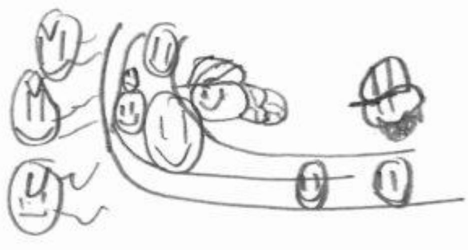
they can get peaple Sick too.

the can Be Sphere or Spirle or rod.

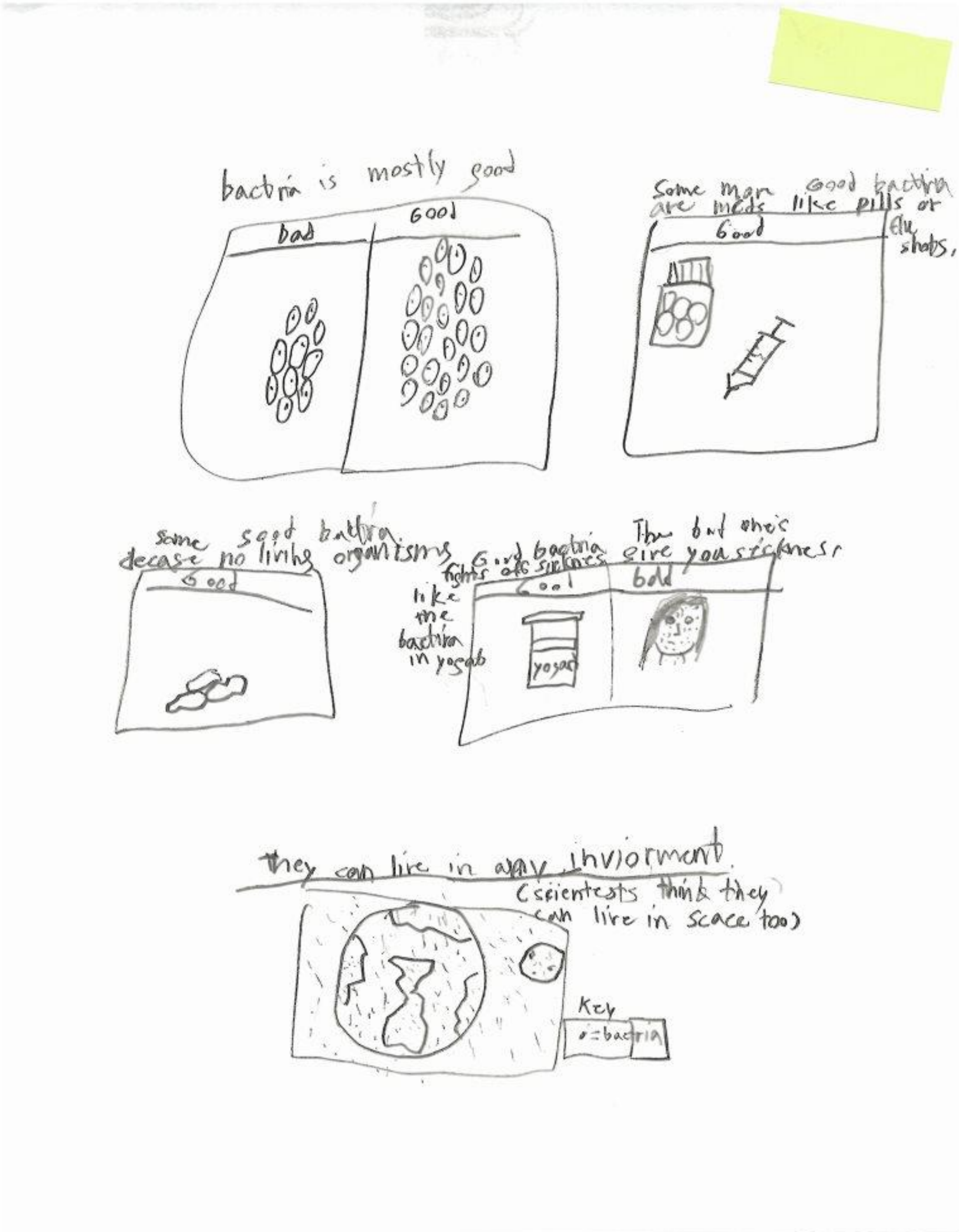


And they can desinigrate.

they take nutrience



Model 2-10


bactria is mostly good
bad
Good
Some man Good bactria are meds like pills or flu shots,
Good
Some good bactria decase no living organisms
Good
Good bactria fights off sicknes like the bactria in yogab
The bad one's give you sicknes,
Good
bad
yogart
they can live in any invironment
(scientests think they can live in scace too)
Key
o=bactria

Bacteria

999 quantillion on your body (10x as many skin cells!)

3 shapes:

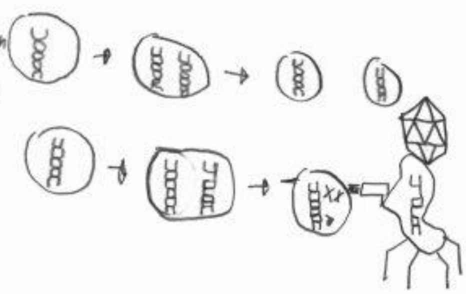
4000+ species!

4000+ Specimences in each!

2nd smallest orginisim.

Reproduction

Mutation



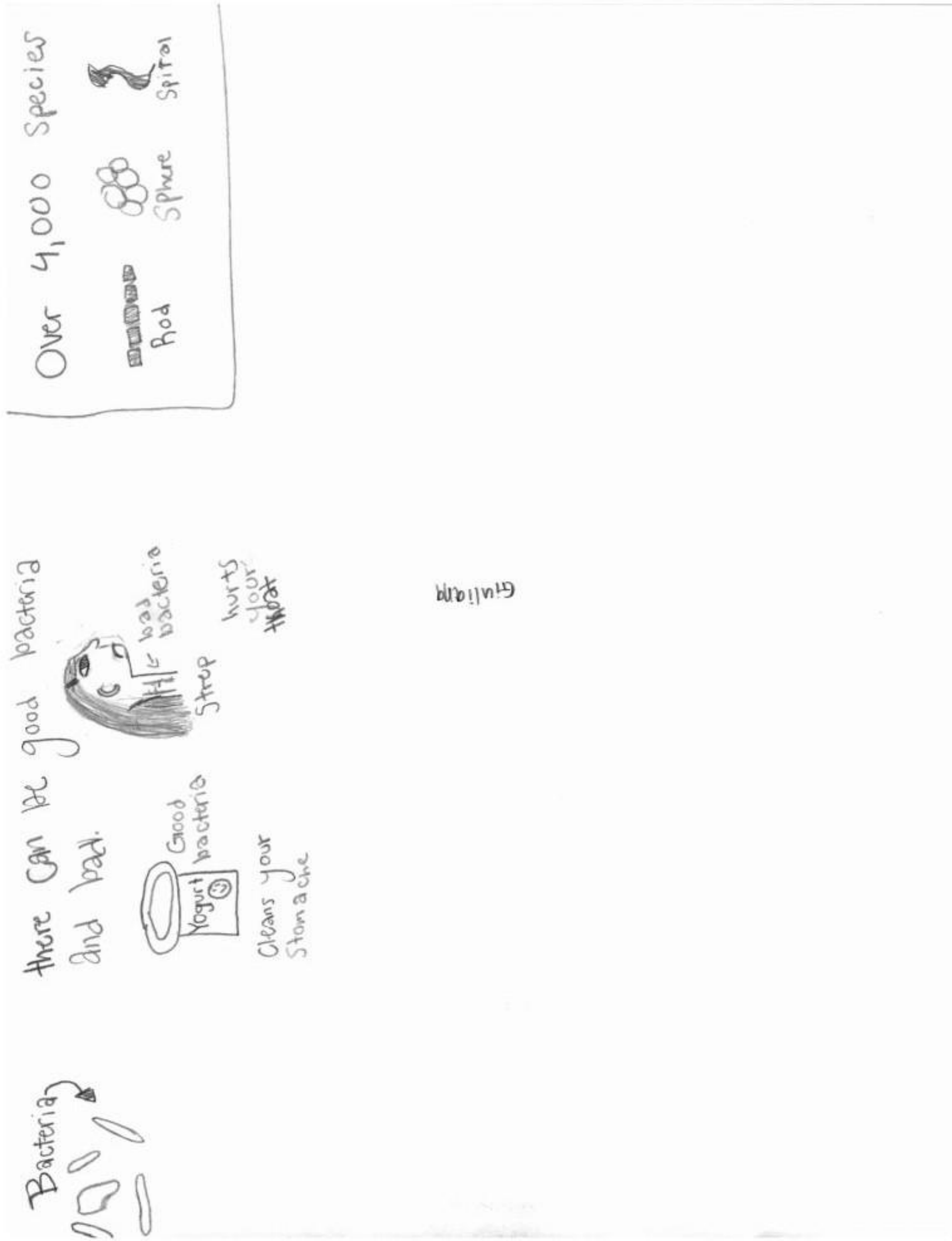
Good + bad

Cure bacteria

Strep

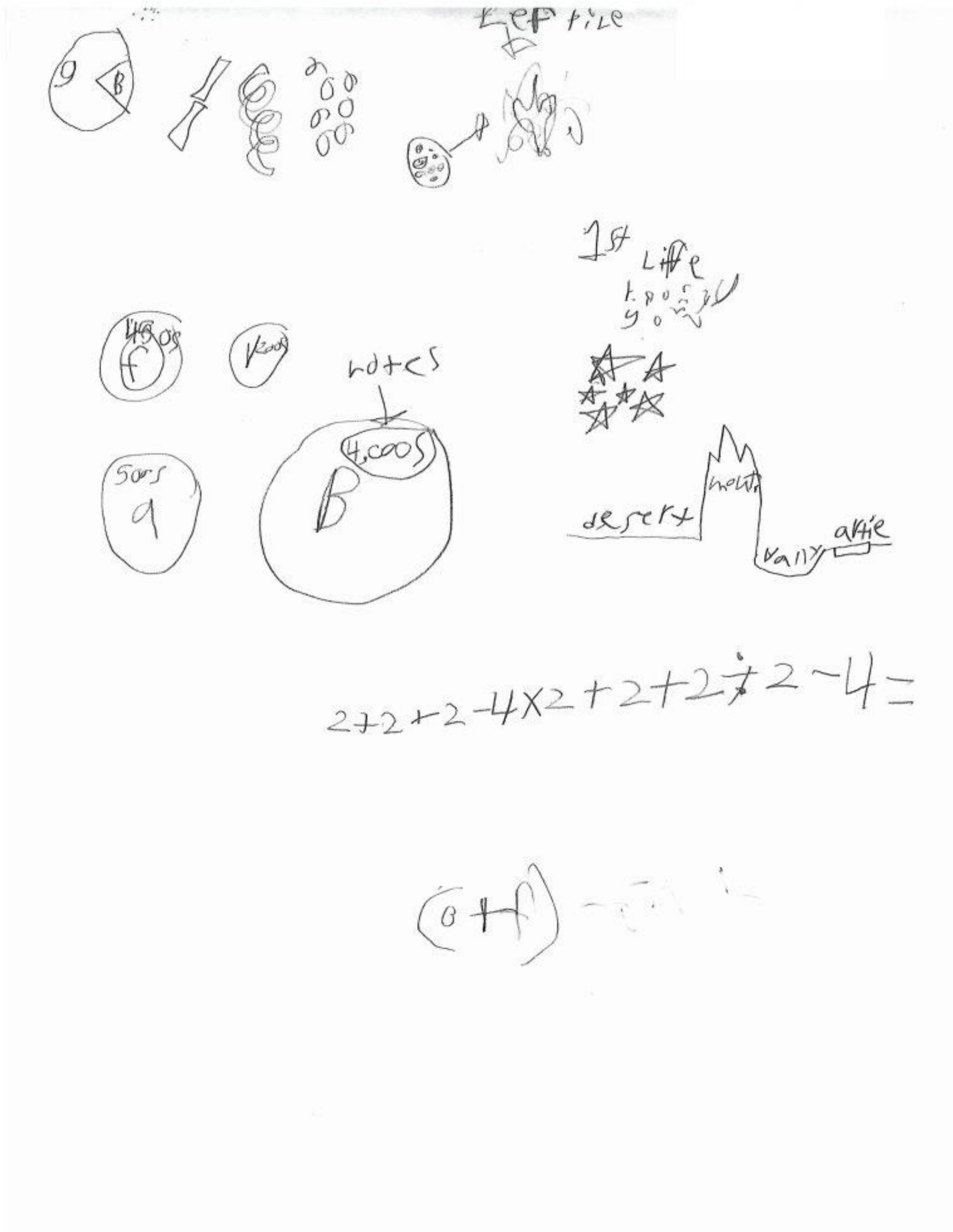

Most bacteria are good
They reproduce by spliting
for every one cell there are 10 bacteria
cell
bacteria
they can live anywhere with nutrients
they help in the process of yogurt
yogurt
3 shapes
rod
sherere
spiral
They are the largest group of microbes
bacteria
virus

Model 2-13


Bacteria
There can be good bacteria and bad.
Yogurt
Good bacteria
Cleans your Stomache
bad bacteria
Strep
hurts your throat
Over 4,000 Species
Rod
Sphere
Spiral

Model 2-14


Bacteria
Own group
(Bacteria)
(Group)
makes you sick
they spread
3 diffrent shapes
(rod, spiral, shere)
in food
yogurt
(it looks like a mouse to me)
Bacteria that looks like a mouse


1st
Life
notes
4,000s
500s
desert
vally
2+2+2-4X2+2+2+2-4=


Bacteria Notes...
Protozoa
Is the largest group in a sine of how many.
Most Bateria is good.
Ex;
Bacteria help decompose, in your intesines.
←intestines
Some bacteria makes you sick.
The doctor saids have strep throut!
I've got typhoid fever!
Bacteria splits to multiply. It copies the same info and then splits in two!
Bacteria can live any whore!
In a
Dessert
In the
Ocean
In a
Forest and cave
from
Deep in the
earth
to
high high
in the sky!
3 different shapes..,
Notes...

★ largest group of microbes

★ most are good, some are bad

good bad

rod shaped

spiral

there in bread, yogurt, mold, old leaves, veggie peelings

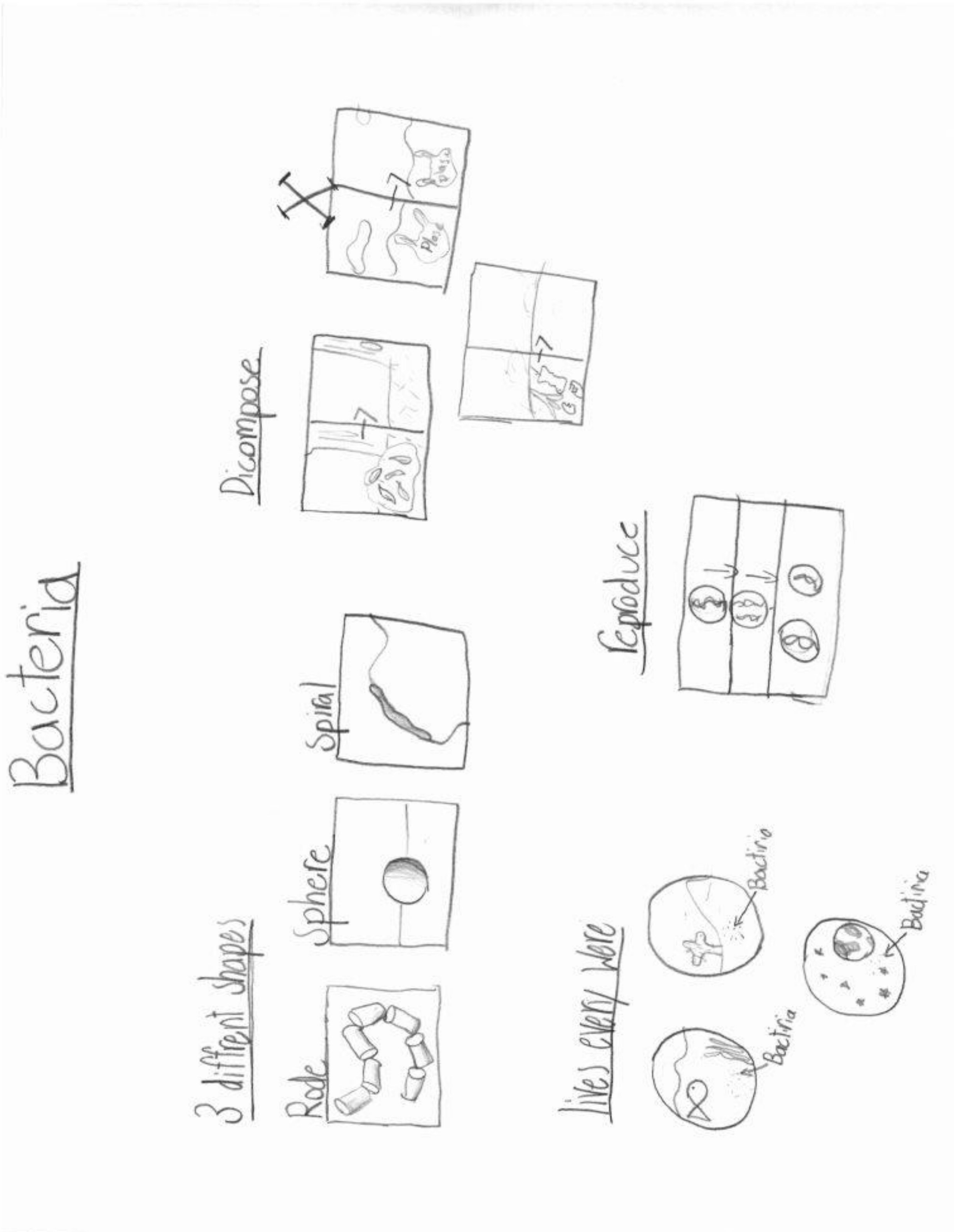
there in your stomach and they help

they are every where

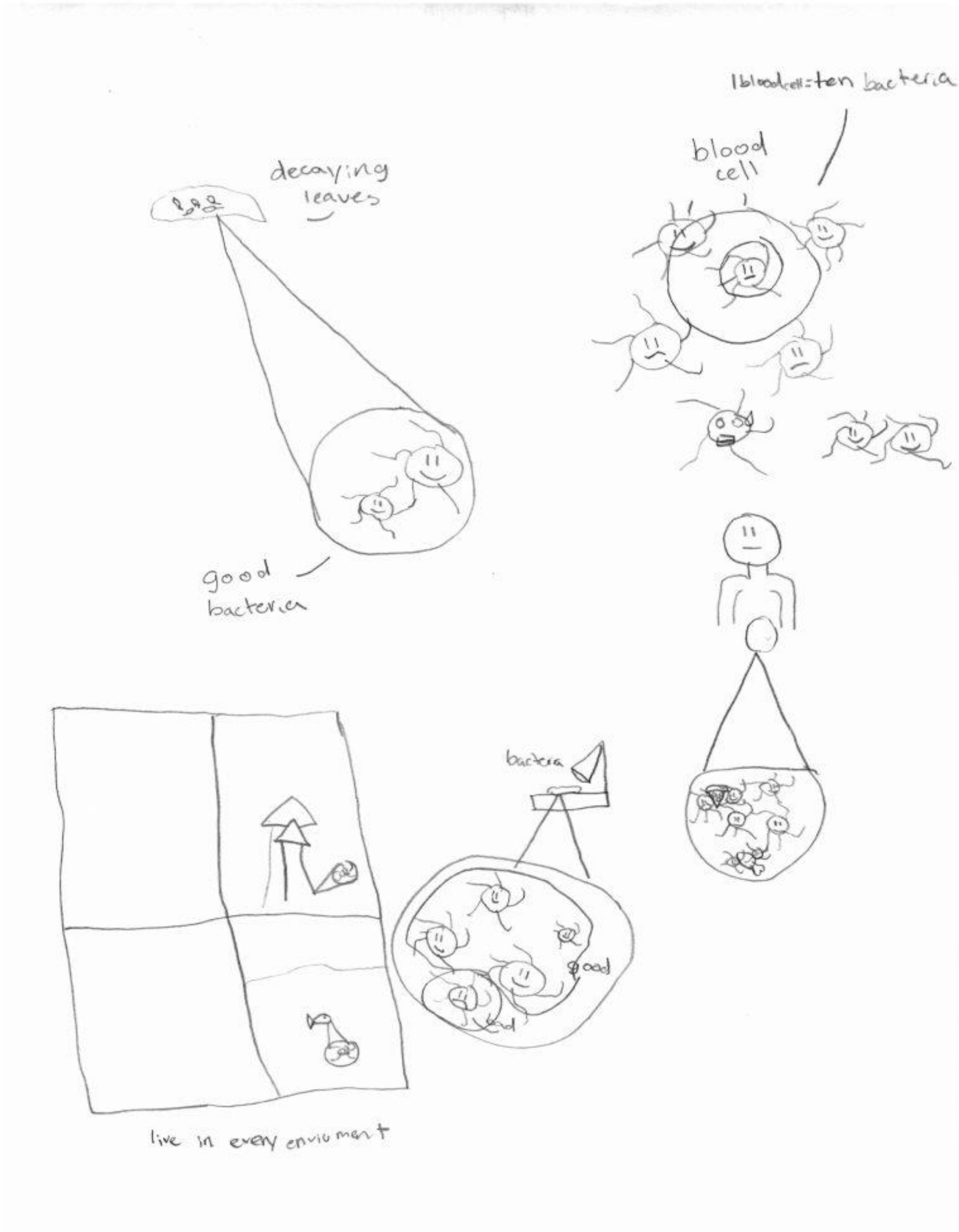
bacteria

Some bacteria can give you diseases and So bacteria is good for you. Some can give you diseaces


= Bacteria


Bacteria
3 diffrent shapes
Rode
Sphere
Spiral
Dicompose
Reproduce
lives every were
Bactiria
Bactiria
Bactiria

Model 2-21


1blood cell=ten bacteria
blood cell
decaying leaves
good bacteria
bacteria
good
bad
live in every enviroment

THE BIG 5

~~notes~~

mind

b	bacteria	algae	fungi	protozaa	Virus
good	curd dairy decompisition curd	water moss	mushroom soup	?	name
bad	silk	spreads alot	grows on organisms	?	every thing about it
pic					
other	most good less bad	very viverse	offten used in video game	?	has a capsule containing virus

Bacteria

Some bacteria helps make yogurt

Some bacteria = 

Some bacteria = 

They're over 4,000 speices of bacteria

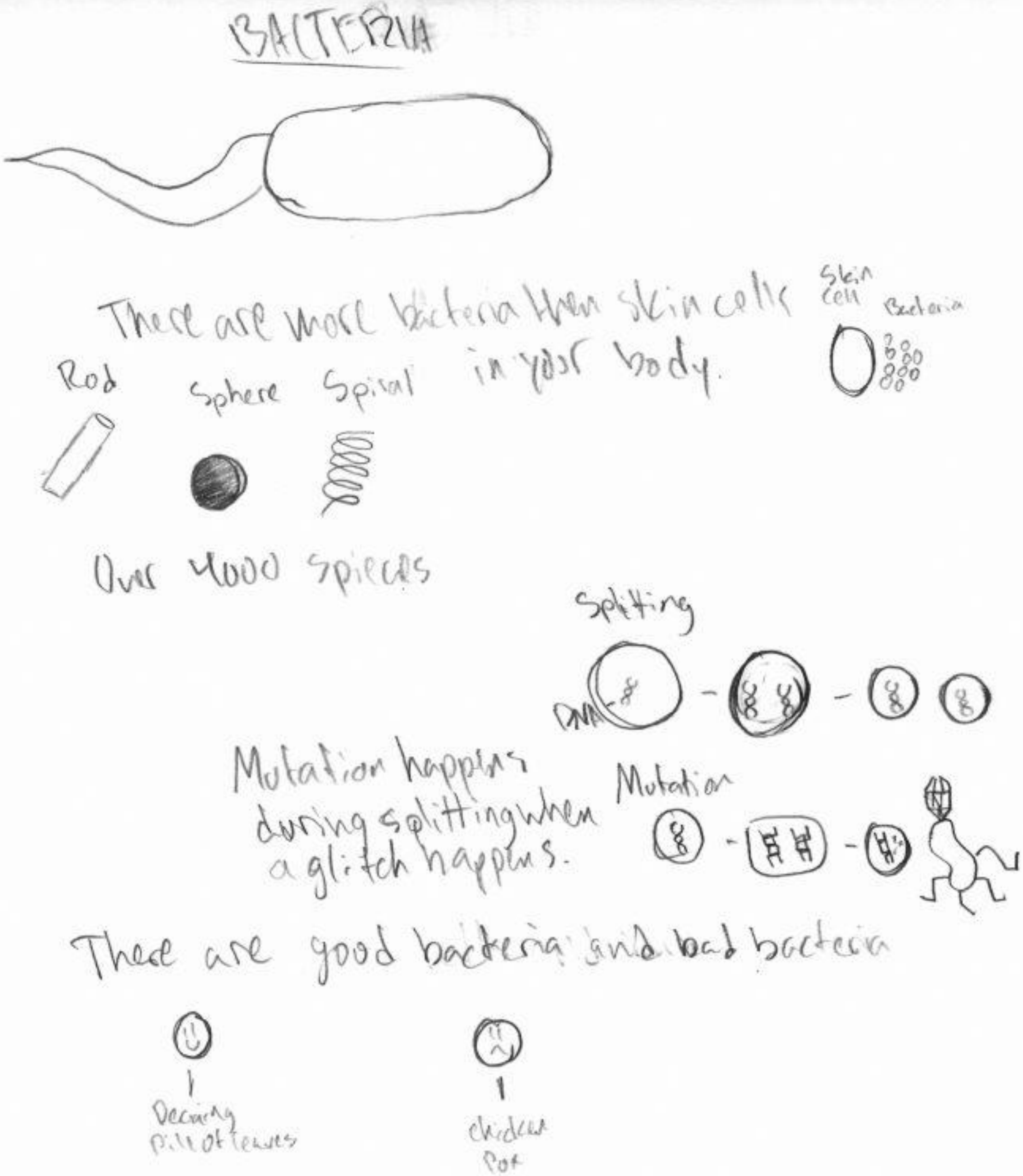
Bacteria can be harmfull and can be helpfull.

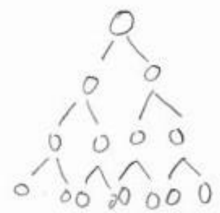
Bacteria can be used to make food. such as yeast.

You don't want bad bacteria. Because bacteria can also be mold.

Bacteria is really small and when you can see it your usely looking through microscope.

Model 2-24


BACTERIA
There are more bacteria than skin cells in your body.
Skin Cell
Bacteria
Rod
Sphere
Spiral
Over 4000 spieces
Splitting
DNA
Mutation happens during splitting when a glitch happens.
Mutation
There are good bacteria and bad bacteria
Decaying pile of leaves
chicken pox

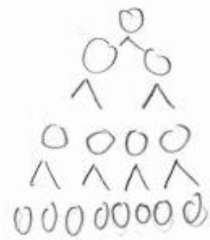


~~Someday~~

· Some are good

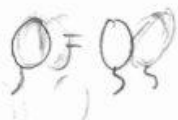
. Some are bad

They can make You sick

- most bacteria are helpful 
- they multiply
- some are harmful 
- you can get sick

bacteria

bacteria multiplys like this by braking in-to towe



they make the exact copy unless mutation happens to make them a new bacteria.

the bacteria brake down things and helps your body that way,

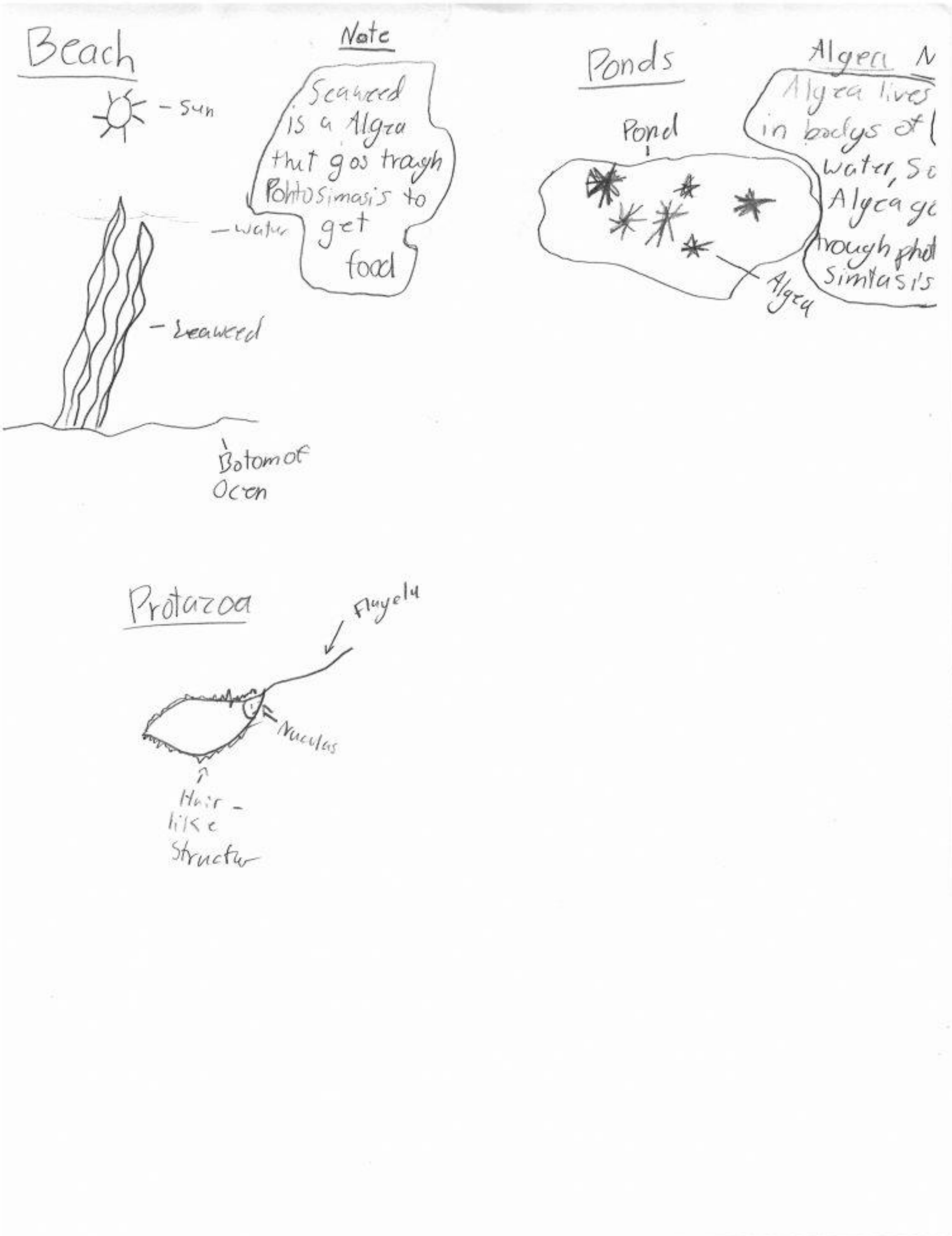
bacteria can also atack your body and it gives you sickness.

bacteria like all micro organisms bacteria gives of wast

APPENDIX D

STUDENT MODELS OF THRID ENACTMENT

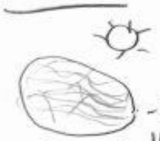
Student models are numbered by two identifiers: The enactment number followed by the student ID. For example 1-09 means Enactment 1 and Student 09. To view all models within an enactment, view all the models that begin with the same enactment number (1-04, 1-05, 1-06, etc.). To view all models by the same student, view all the models that end with the same number (1-15, 2-15, 3-15, 4-15). Numbers not included mean the student's model was missing for that enactment.


Beach
Note
Seaweed is a Algea that gos traugh Pohtosimasis to get food
- Sun
- water
- Seaweed
Botom of Ocen
Ponds
Algea N
Algea lives in bodys of water, So Algea go trough phot simtasis
Pond
Algea
Protazoa
Flugela
Nuculas
Hair - like Structur

Beach

the ocean has protist in it all the Seaweed and Algae.

Pond

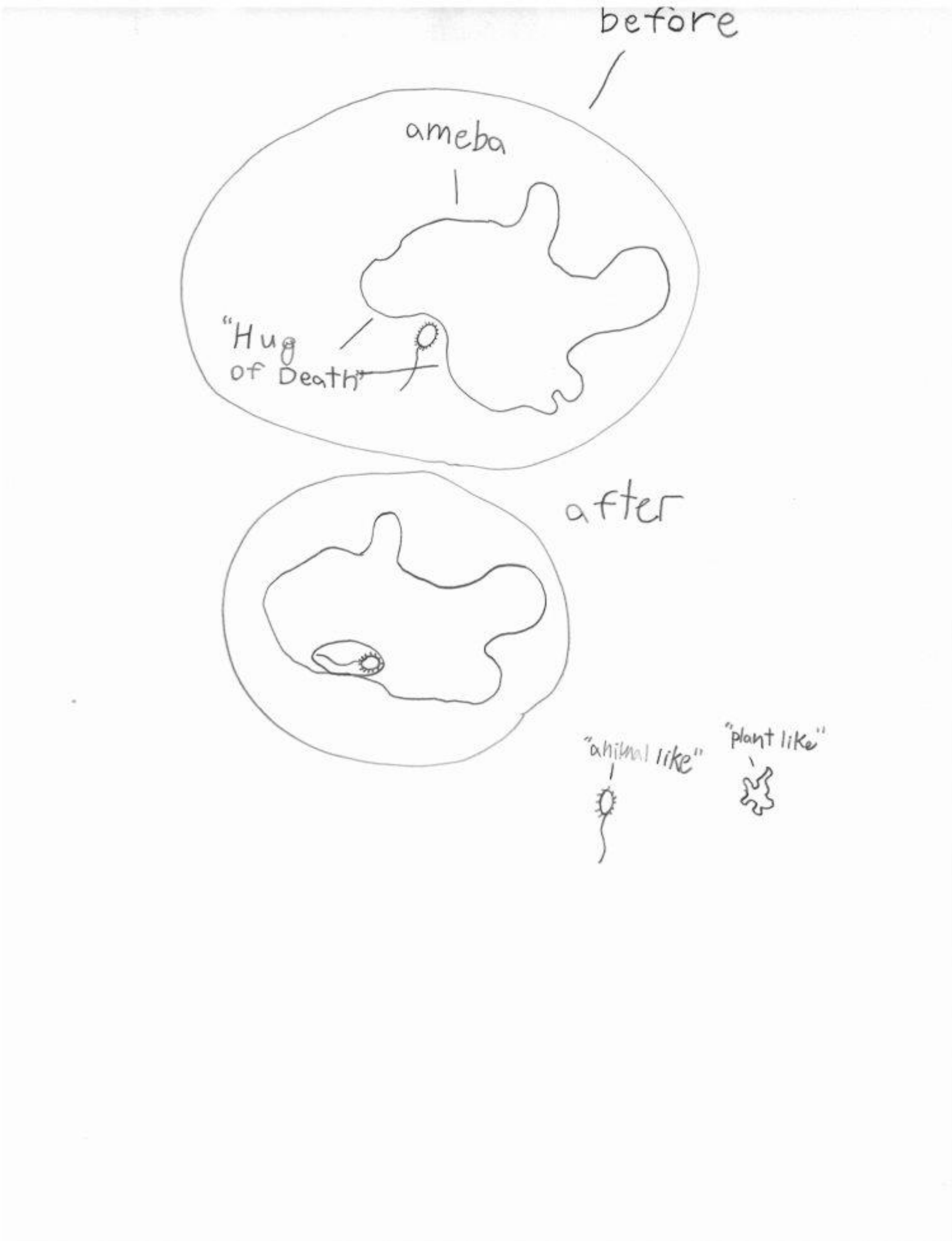


-in the Pond there is tuns of Algae

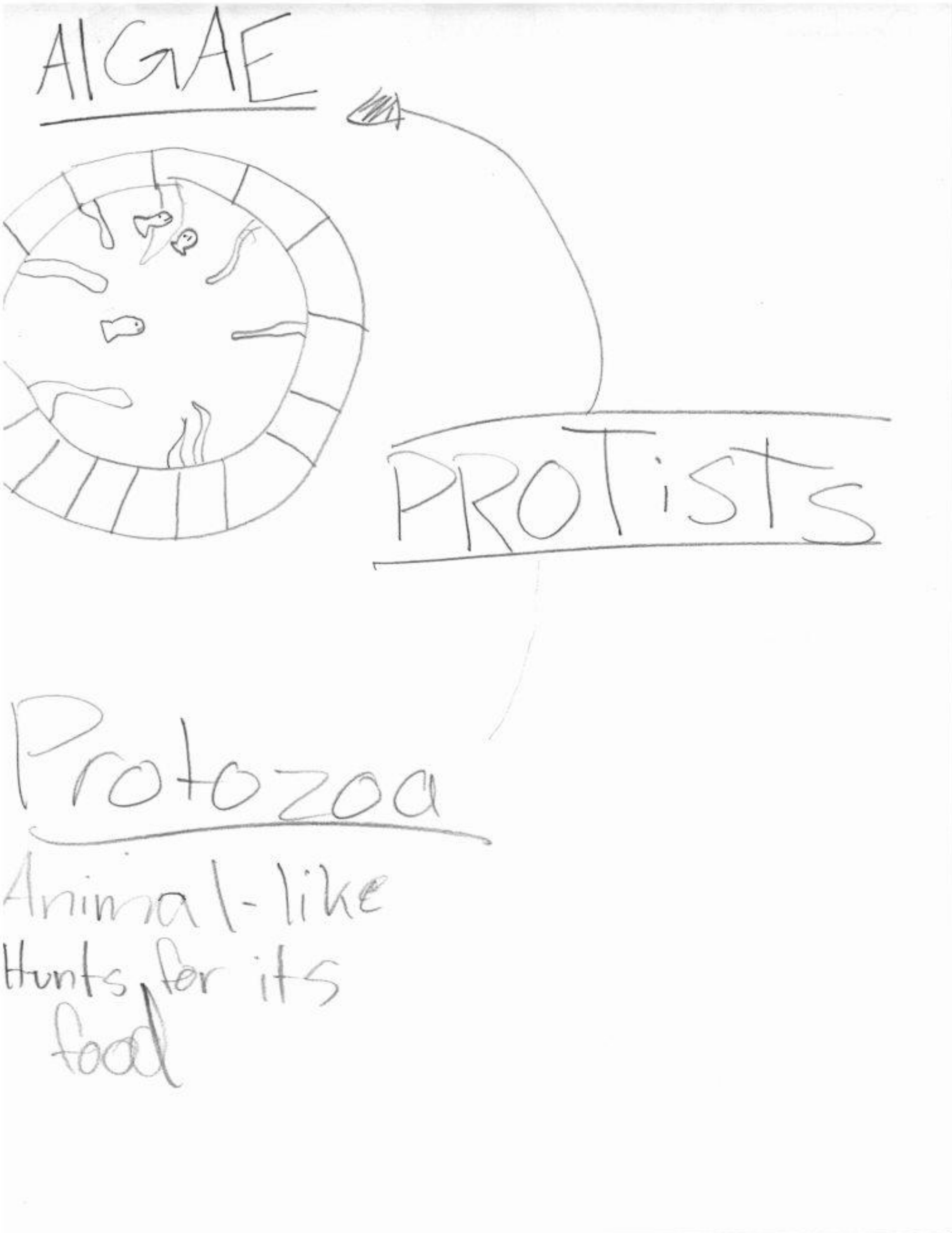
- the Protist and Algae are small
- the Protist and Algae lives in water

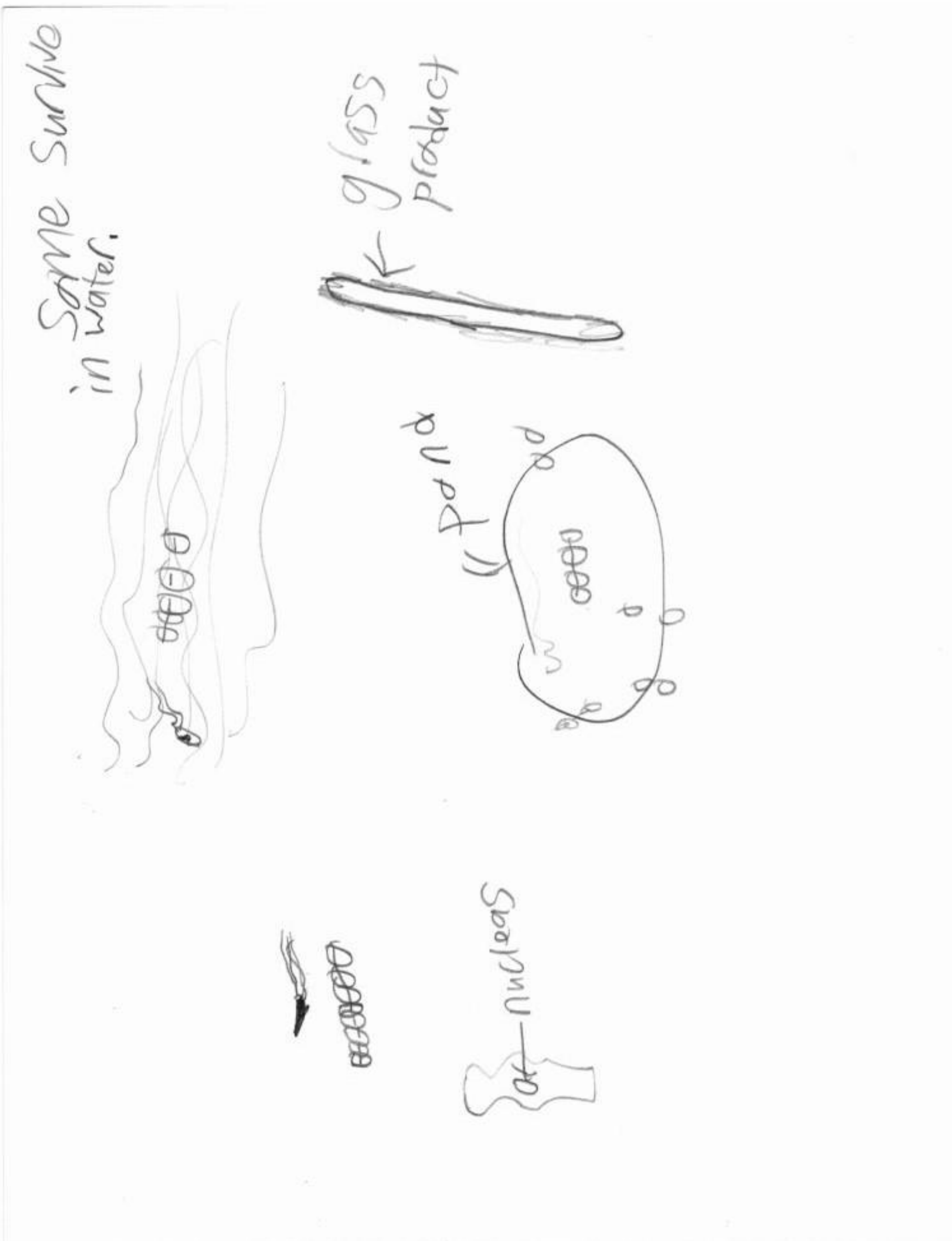
Sea weed is a type of Algae

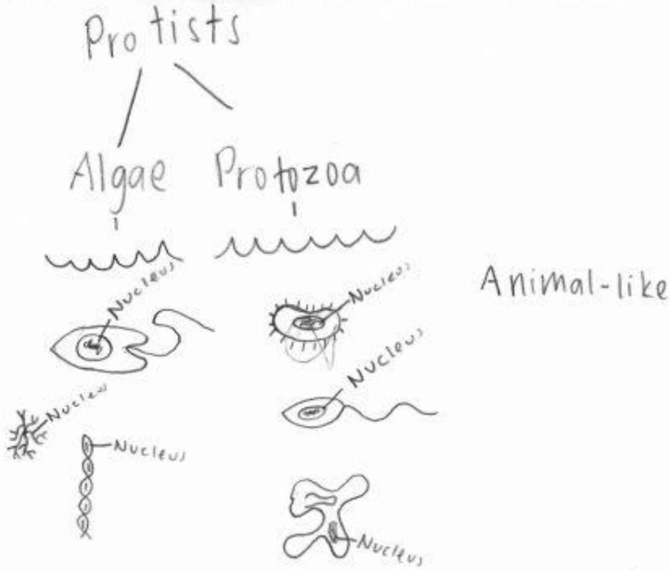
Model 3-06



Model 3-08




Some survive in water.
glass product
pond
nucleas


Protists
Algae
Protozoa
Animal-like
Nucleus
Nucleus
Nucleus
Nucleus
Nucleus
Nucleus
Nucleus

Protists!

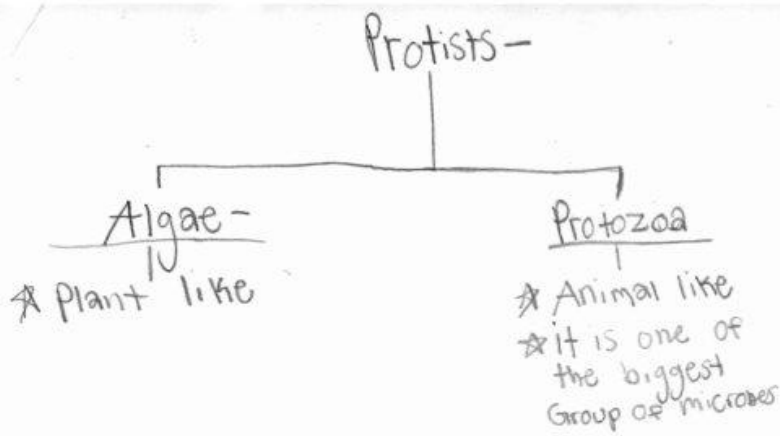
algae

* plant like
* Makes its own food

Protozoa

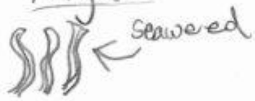
* Animal like
* gets it food

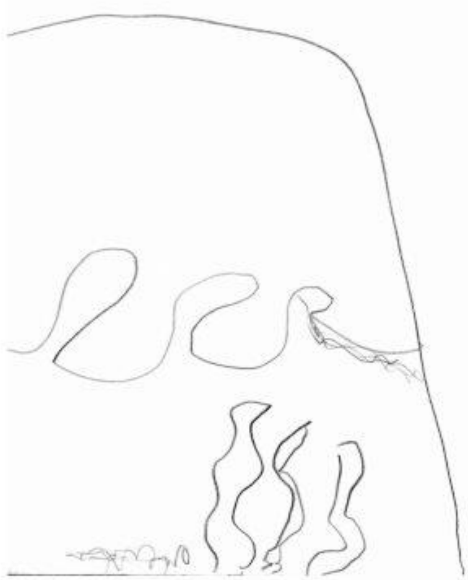
Model 3-13


Protists-
Algae-
* Plant like
Protozoa
* Animal like
* it is one of the biggest Group of microbes

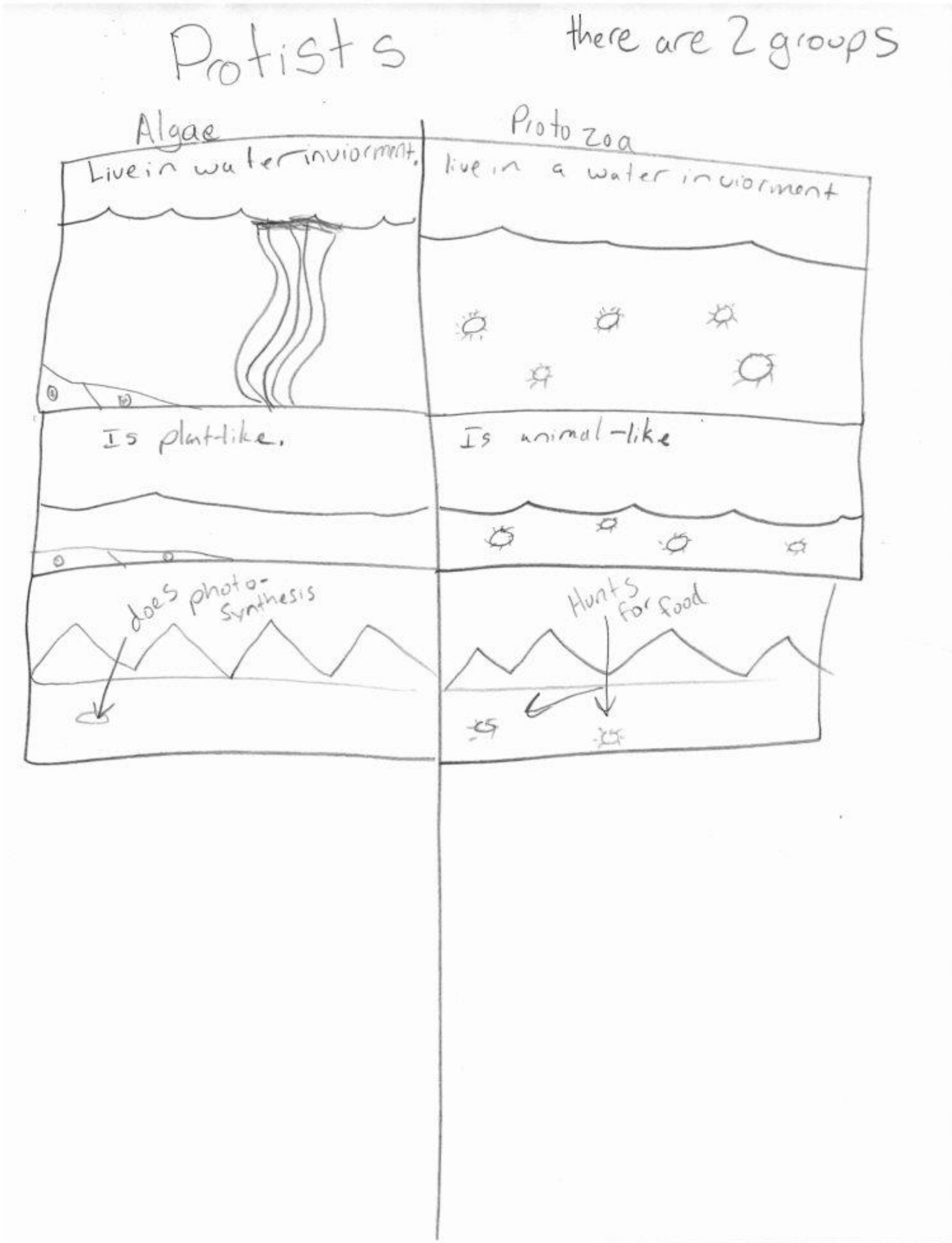
Protist

Algue



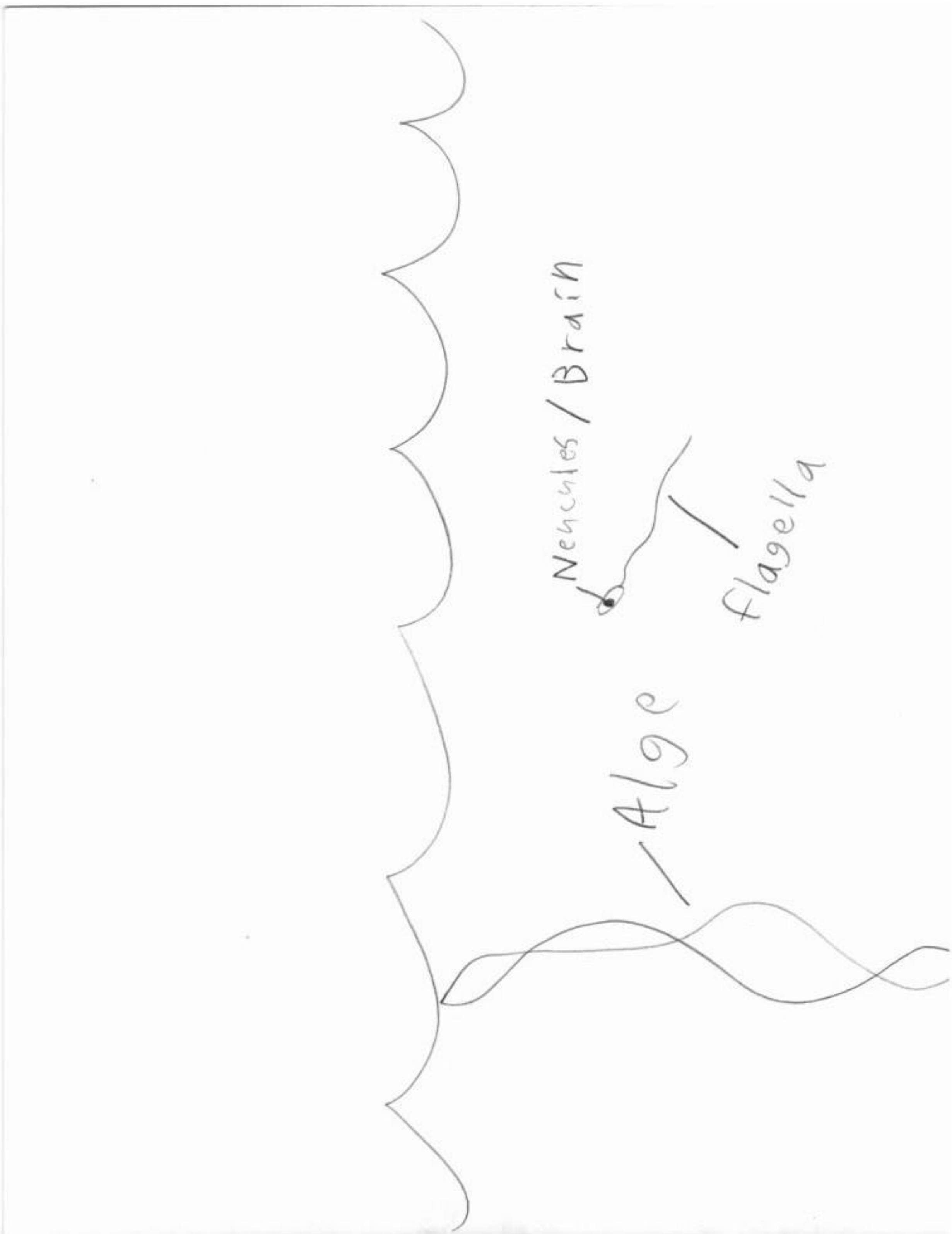


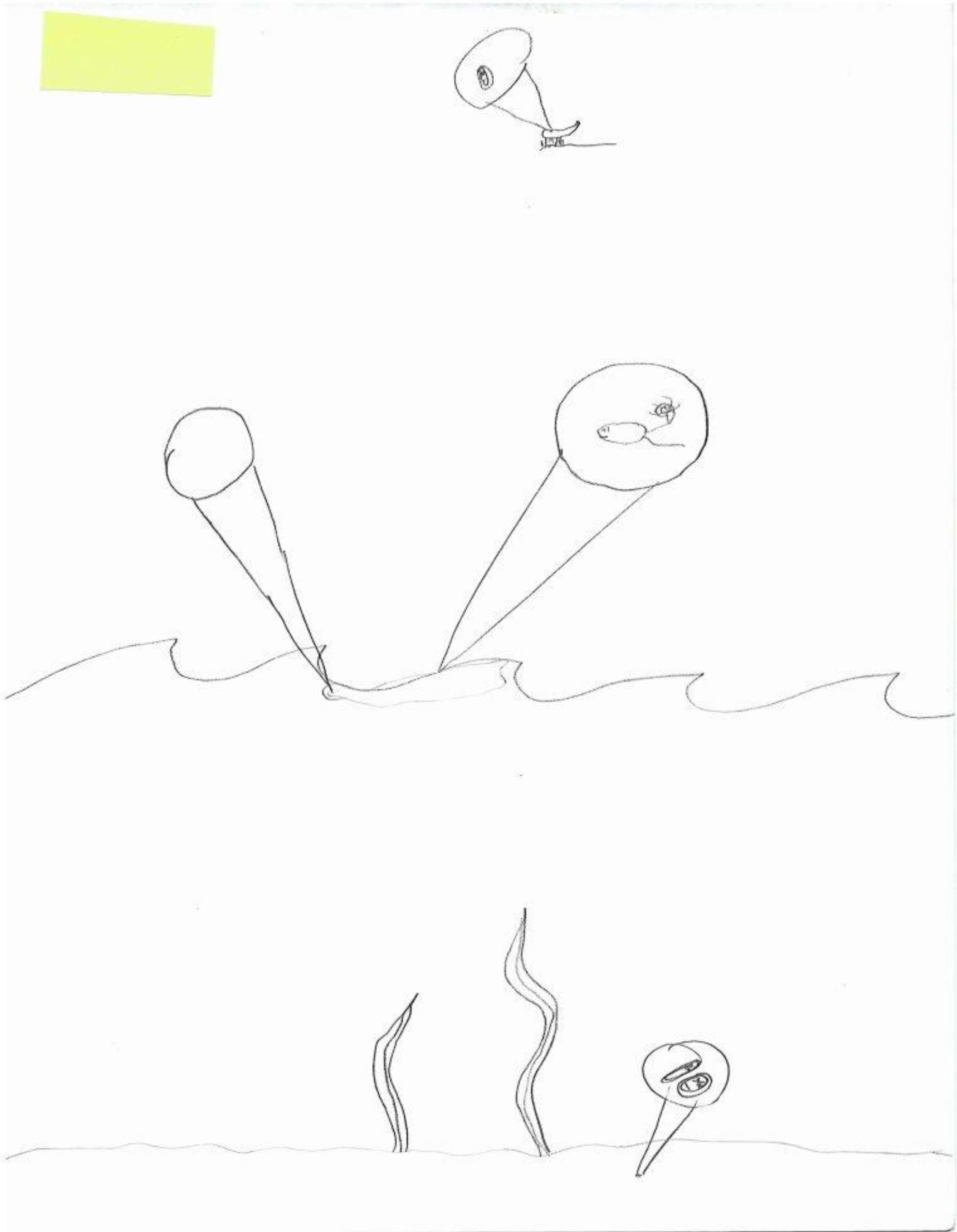
Model 3-16


Protists
there are 2 groups
Algae
Protozoa
Live in water inviorment.
live in a water inviorment
Is plat-like.
Is animal-like
does photo-synthesis
Hunts for food

Protist

There are two main groups of protist, protozoa and Algae
They both live in a warm-water envirOment
Protozoa is animal-like


Nenchtes / Brain
Flagella
Alge



Protists

Protozola

Agae

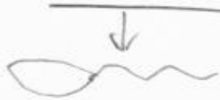
Seaweed

red algae

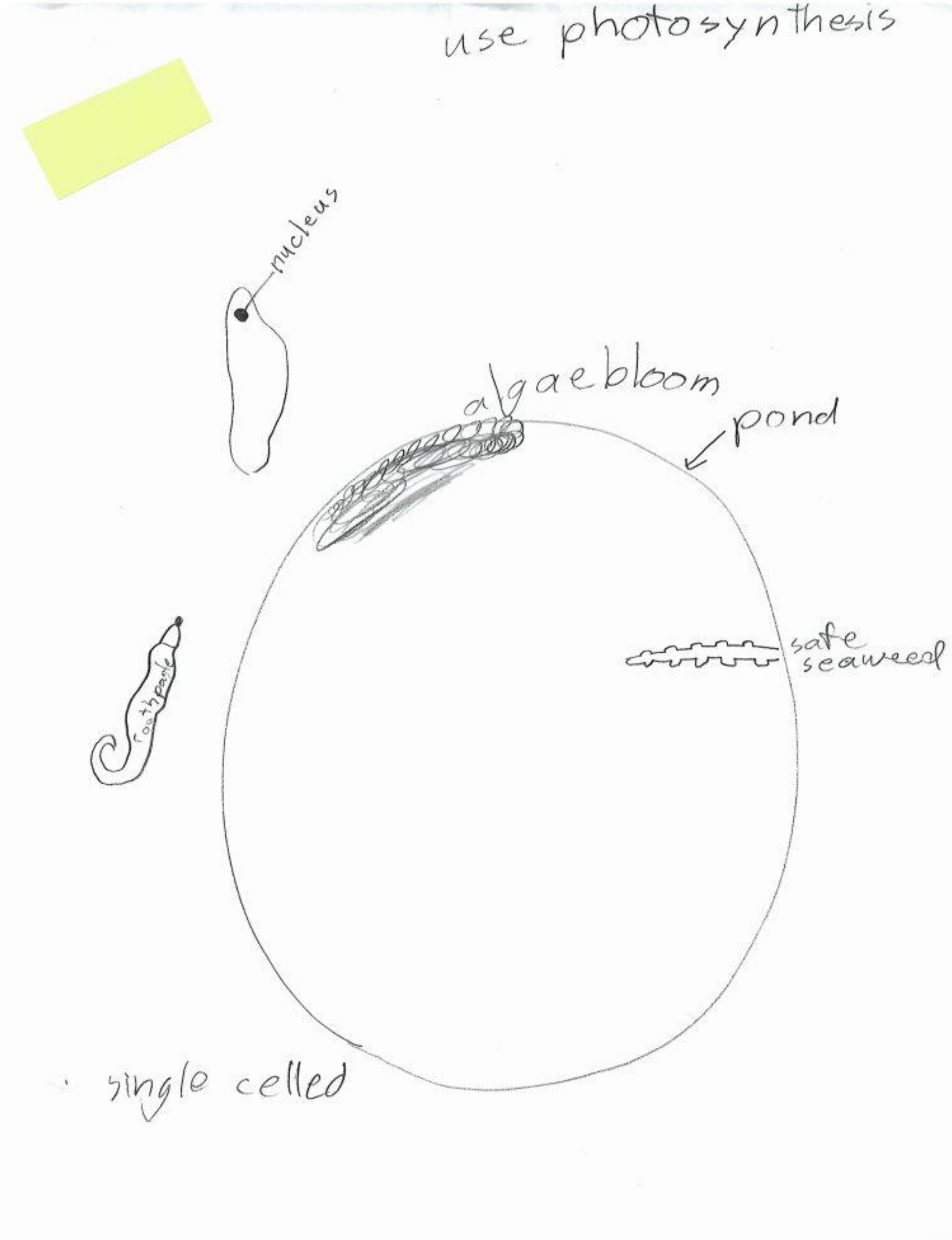
Golden algae

and more

Nuculeas



Model 3-25


use photosynthesis
nucleus
algaebloom
pond
safe seaweed
toothpaste
single celled


glass
like
layer
dead protozila
layer
protozila
layer

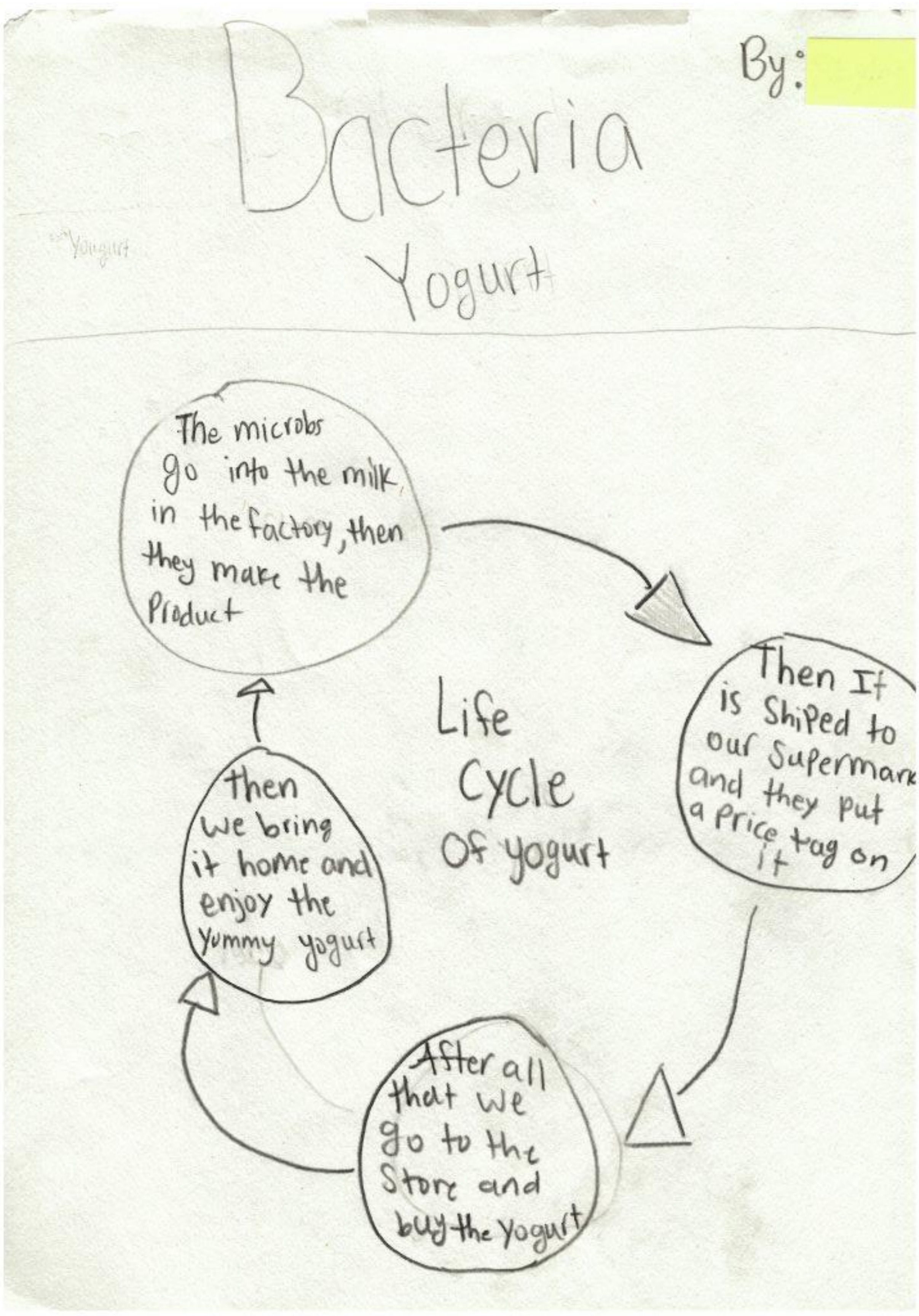
Model 3-29

APPENDIX E

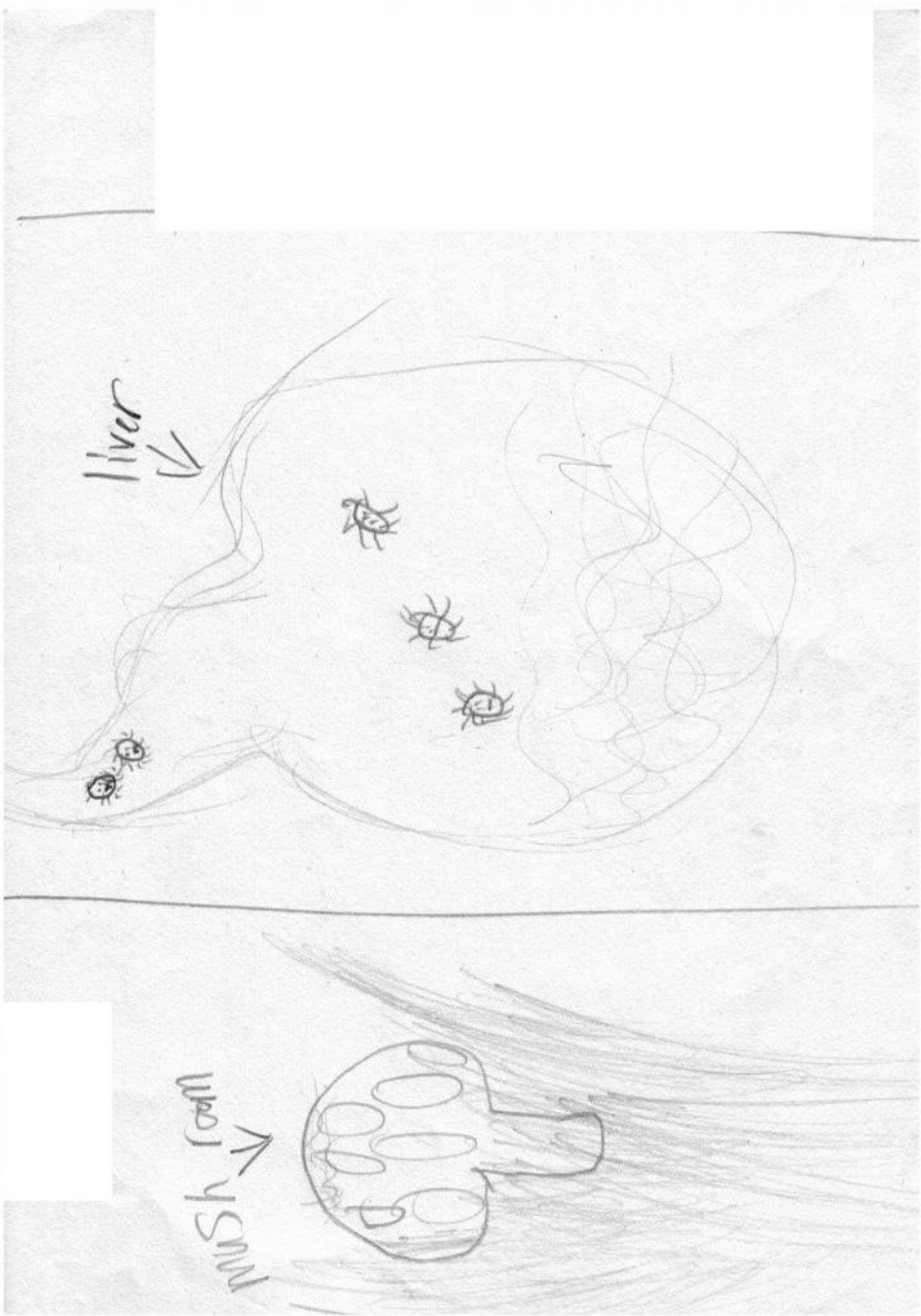
STUDENT MODELS OF FOURTH ENACTMENT

Student models are numbered by two identifiers: The enactment number followed by the student ID. For example 1-09 means Enactment 1 and Student 09. To view all models within an enactment, view all the models that begin with the same enactment number (1-04, 1-05, 1-06, etc.). To view all models by the same student, view all the models that end with the same number (1-15, 2-15, 3-15, 4-15). Numbers not included mean the student's model was missing for that enactment.

Model 4-04



Bacteria
By:
Yogurt
The microbs go into the milk in the factory, then they make the Product
Then It is Shiped to our Supermark and they put a Price tag on it
After all that we go to the Store and buy the Yogurt
then we bring it home and enjoy the yummy yogurt
Life Cycle Of yogurt


liver
mush room

Fungi in my House

In my yard there are mushrooms.

They are Fungi.

I have dead, decomposing leaves, turning into dirt.

That is fungi.

My dad made grape juice. if he leaves it in the pantry. it will ferment into wine.

That is fungi.

There are probably alot more. So watch out for them. They are everywhere...

There can be good bacteria and bad bacteria. I am going to be talking about bad acteria, and how it gets on raw foods, for example.

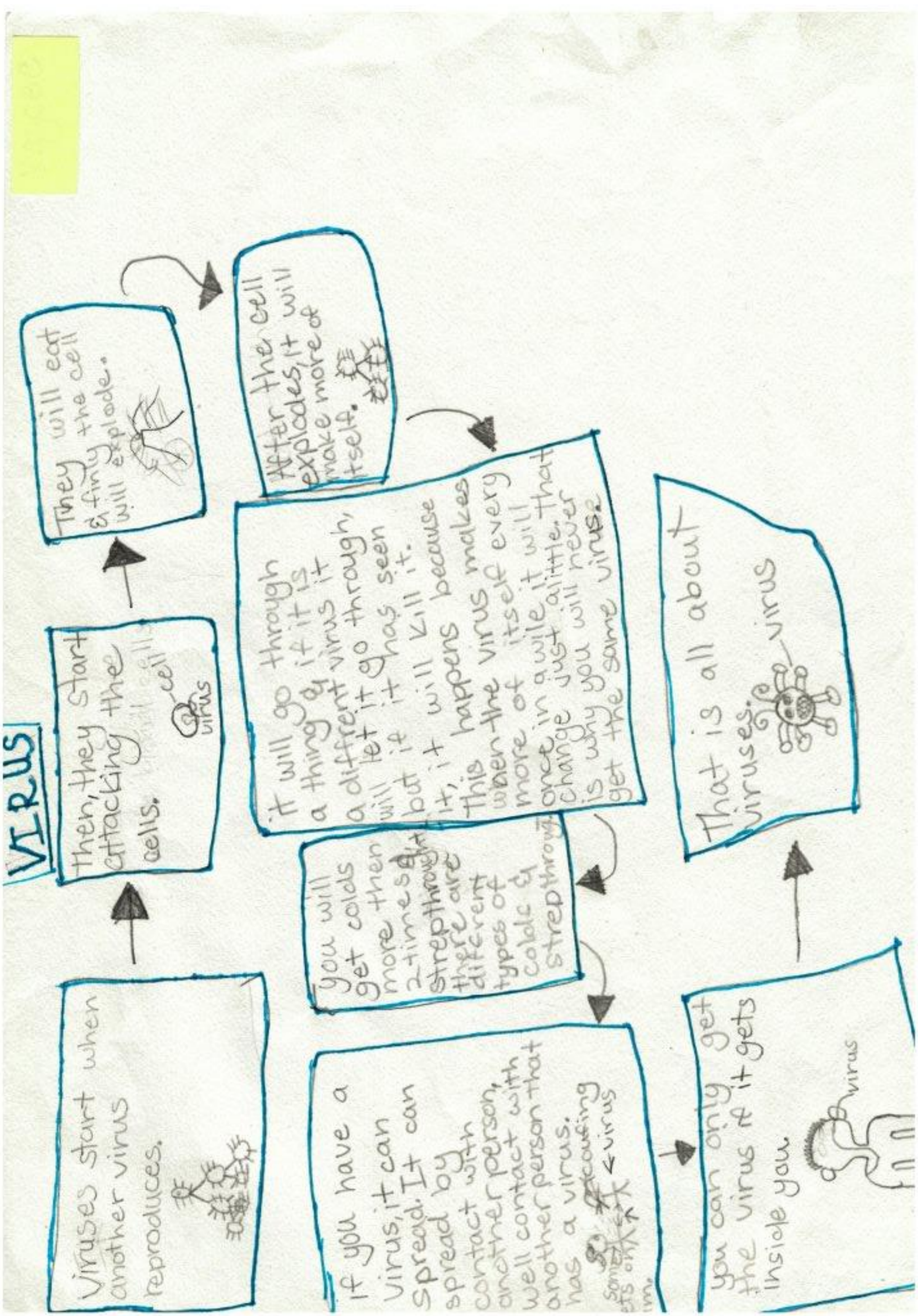
Sometimes flies can get on animal dropings which have bacteria on/in it. and if

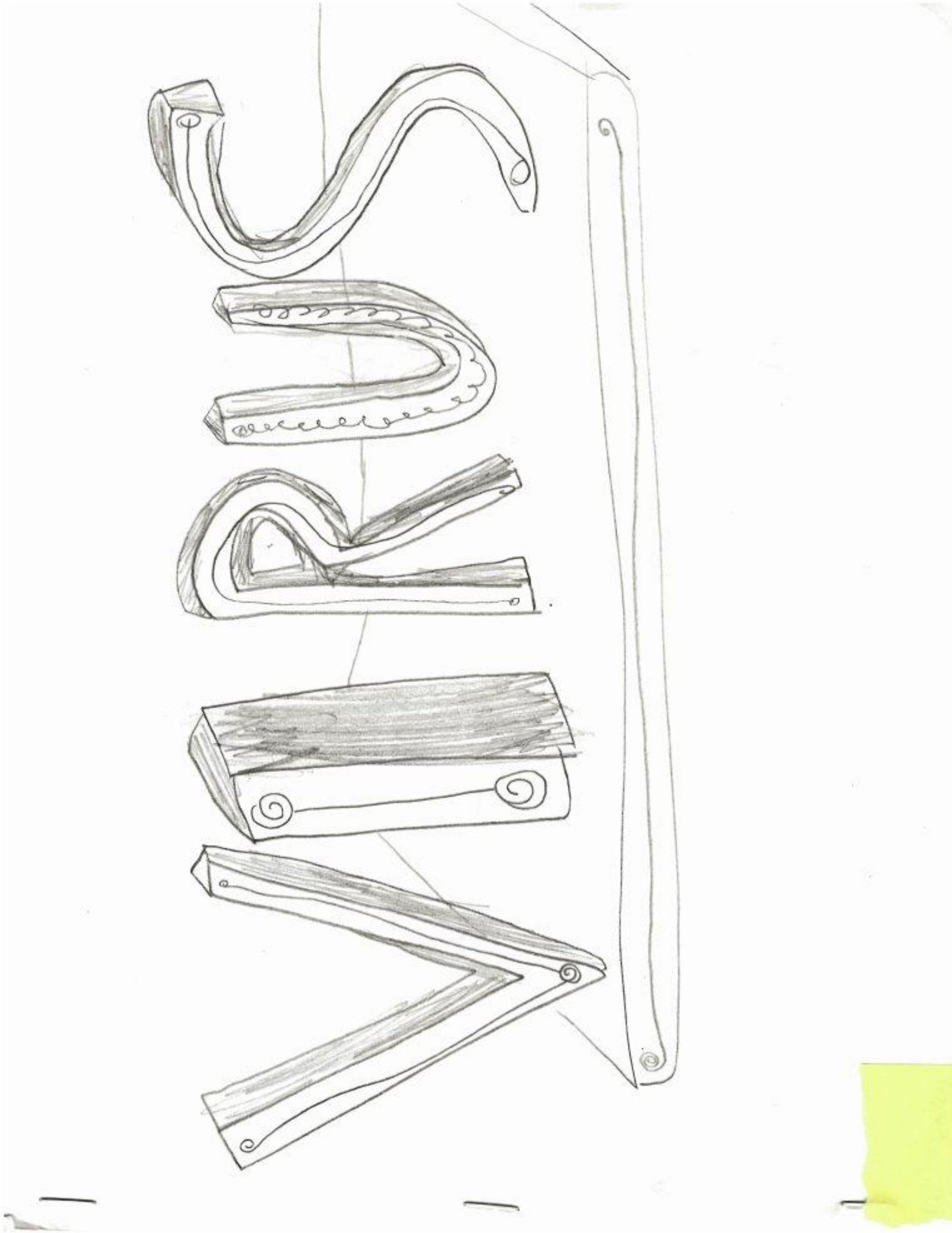
2.) The fly can let the bacteria go on the food and the bactria will feed on the food

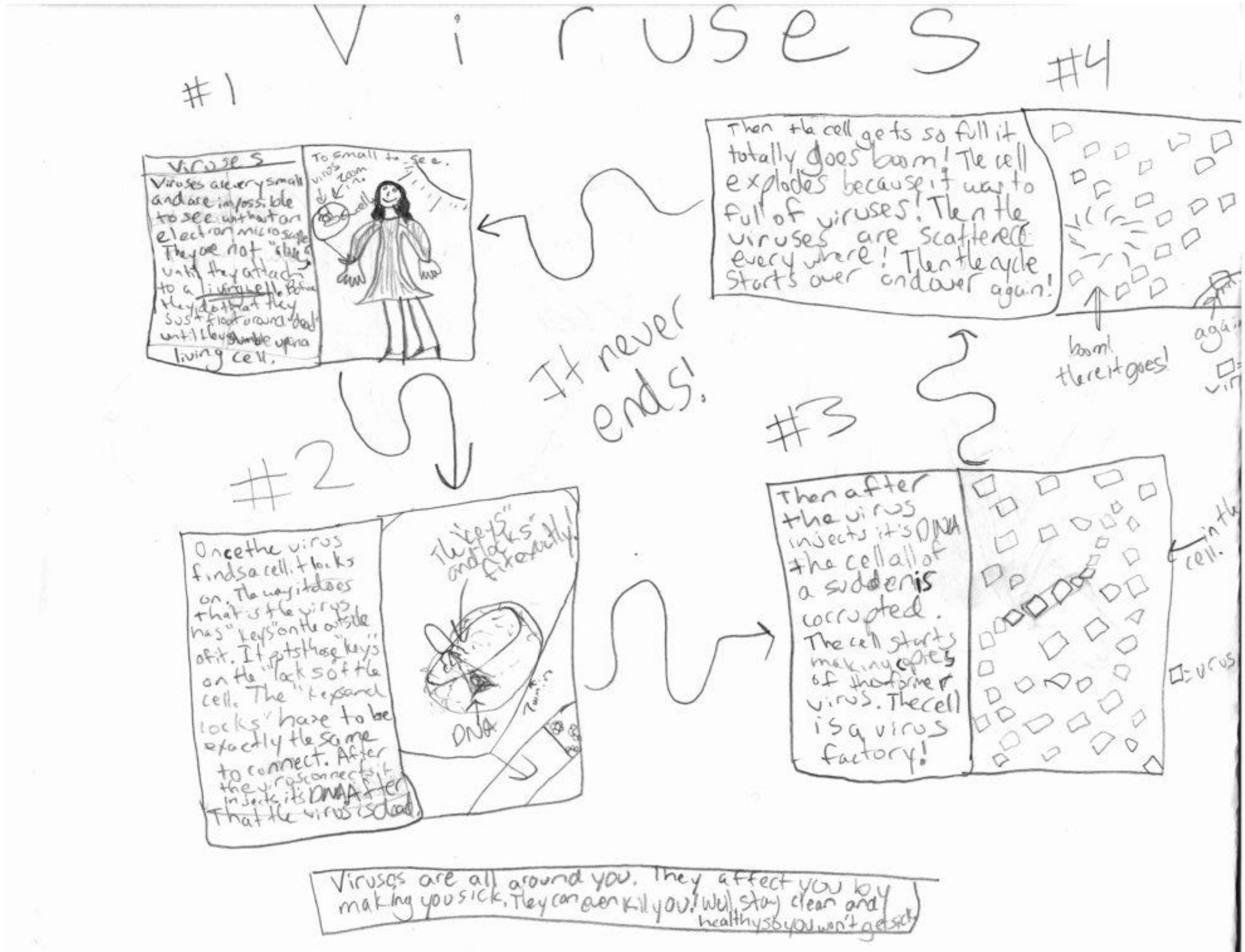
As the bacteria feeds on the steak it can start to reproduce (AKA) make more bacteria.

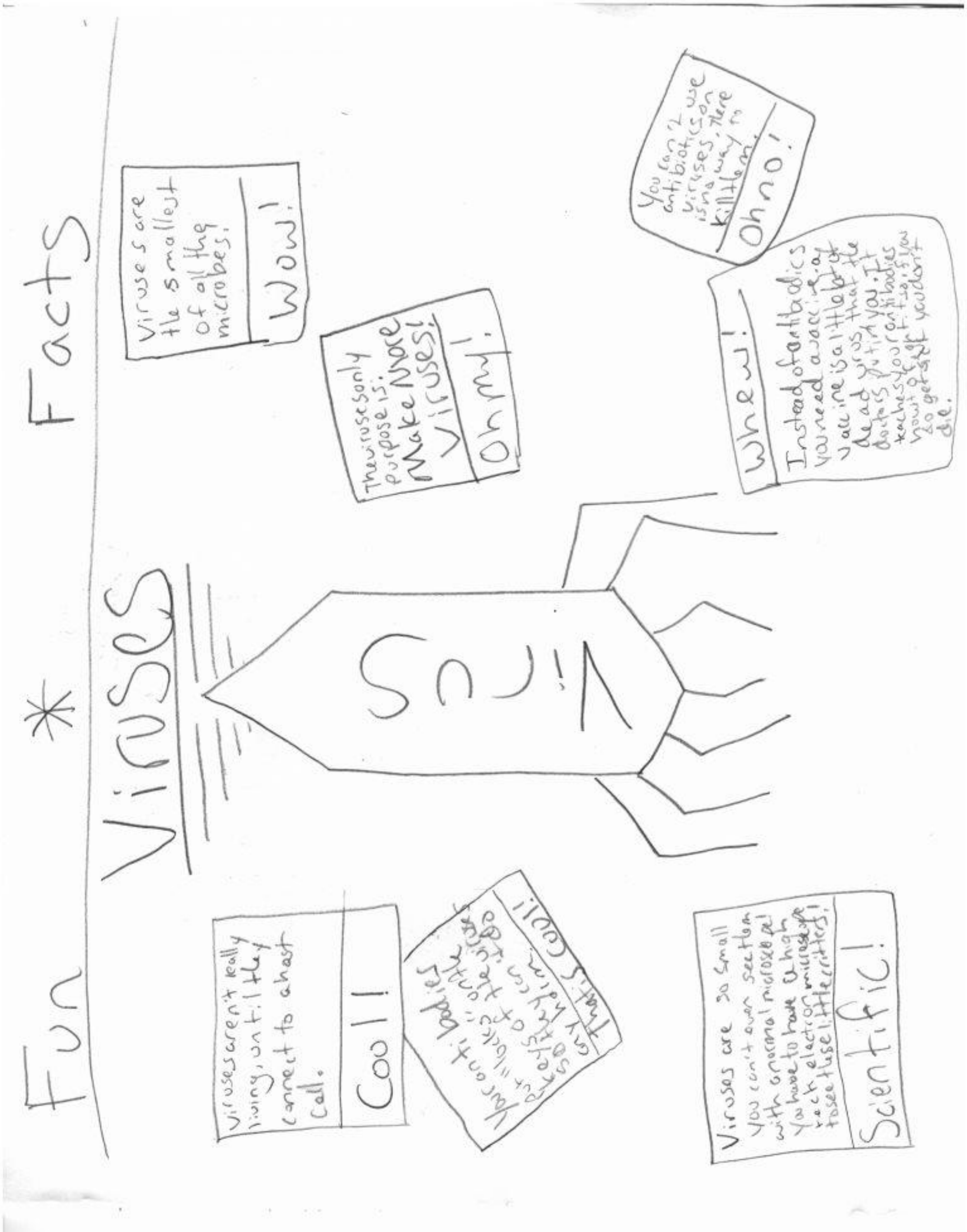
4.) As more bacteria gets on it it gets more unsafe to eat If you eat it you can get a sickness and the bacteria will harm you.

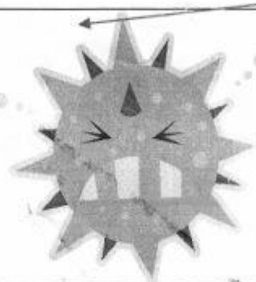
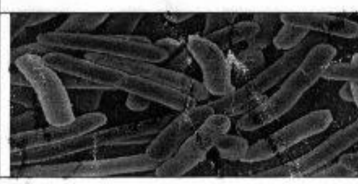
To get rid of the harmful bactria you have to cook the meat

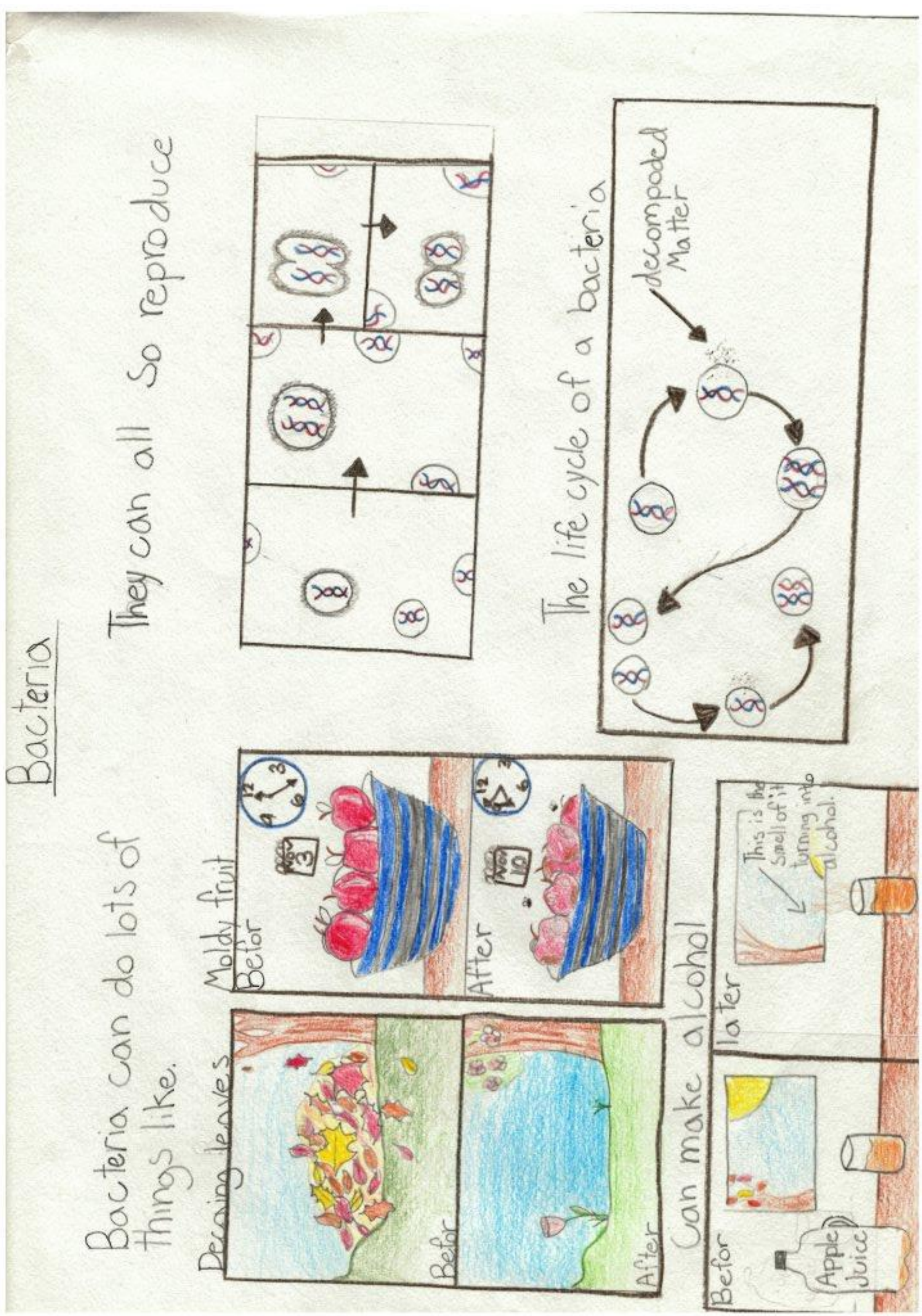

VIRUS
Viruses start when another virus reproduces.
Then, they start attacking the cells.
cell
virus
They will eat & finly the cell will explode.
After the cell explodes, it will make more of itself.
it will go through a thing & if it is a diffrent virus it will let it go through, but if it has seen it, it will kill it. This happens because when the virus makes more of itself every once in a wile it will change just alittle. That is why you will never get the same virus.
you will get colds more then 2 times & strepthrought there are different types of colds & strepthrout
if you have a virus, it can spread. It can spread by contact with another person, well contact with another person that has a virus.
coufing
virus
you can only get the virus if it gets inside you.
virus
That is all about viruses.
virus


VIRUS

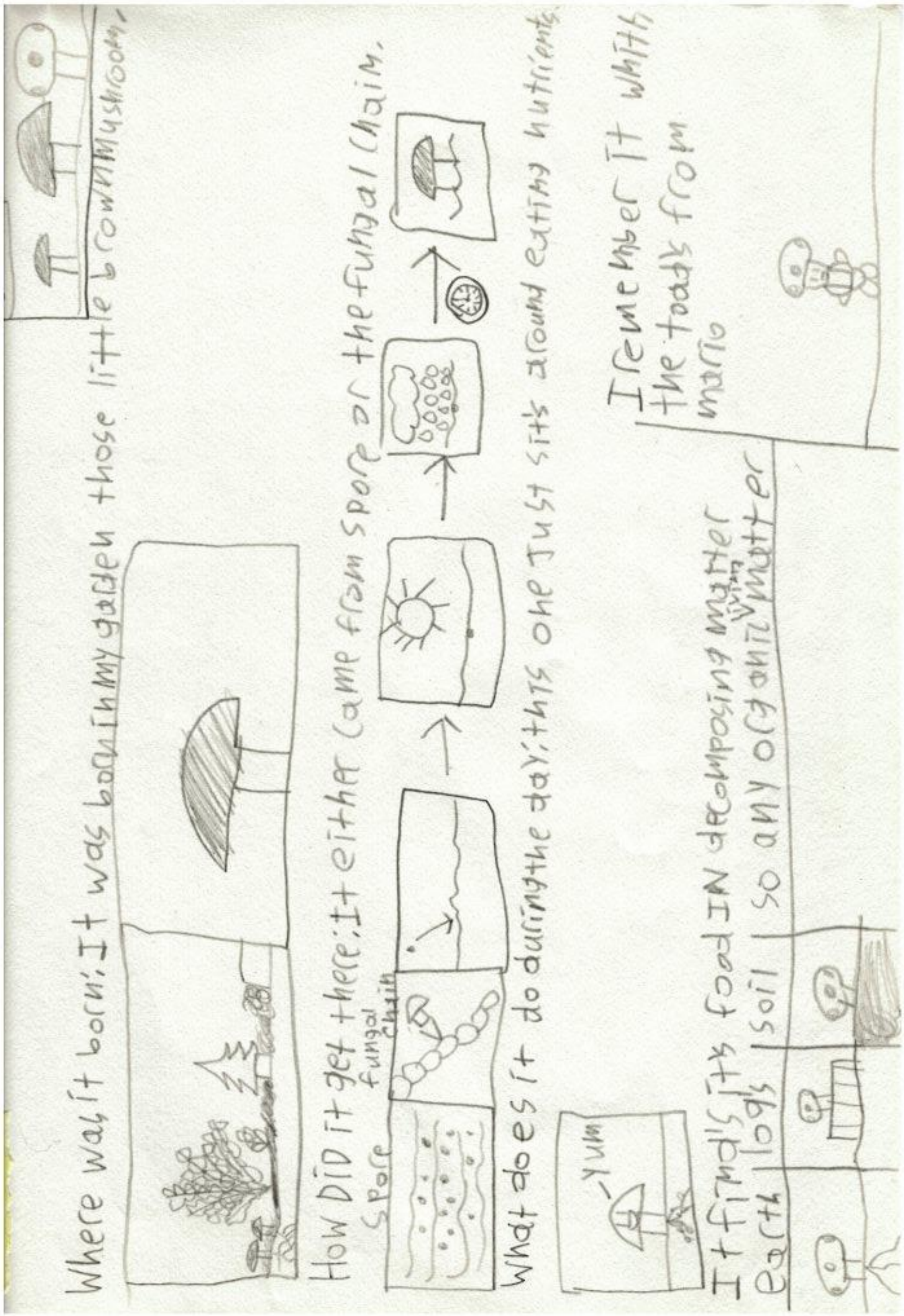

Viruses
#1
Viruses
Viruses are very small and are impossible to see without an electron microscope. They are not "alive" until they attach to a living cell. Before they do that they just float around "dead" until they stumble upon a living cell.
To small to see.
virus
zoom in.
cell
#2
Once the virus finds a cell it locks on. The way it does that is the virus has "keys" on the outside of it. It puts those "keys" on the "locks" of the cell. The "keys" and "locks" have to be exactly the same to connect. After the virus connects it injects it's DNA. After That the virus is dead.
The "keys" and "locks" fit exactly!
DNA
It never ends!
#3
Then after the virus injects it's DNA the cell all of a sudden is corrupted. The cell starts making copies of the former virus. The cell is a virus factory!
in the cell.
□ = virus
#4
Then the cell gets so full it totally goes boom! The cell explodes because it was to full of viruses! Then the viruses are scattered every where! Then the cycle starts over and over again!
boom! there it goes!
again
Viruses are all around you. They affect you by making you sick. They can even kill you! Well, stay clean and healthy so you won't get sick


Fun * Facts
Viruses
Virus
Viruses aren't really living, until they connect to a host cell.
Cool!
Your antibodies put "locks" on the keys of the viruses so they can't do any harm.
That's cool!
Viruses are so small you can't even see them with a normal microscope! You have to have a high tech electron microscope to see these little critters!
Scientific!
Viruses are the smallest of all the microbes!
Wow!
The viruses only purpose is: Make More Viruses!
Oh my!
You can't use antibiotics on viruses, there is no way to kill them.
Oh no!
Whew!
Instead of antibiotics you need a vaccine. a vaccine is a little bit of dead virus that the doctors put in you. It teaches your antibodies how to fight so if you do get sick you don't die.

Bacteria live an interestingly microscopic life.		Most are helpful, some are harmful for example the bacteria in yogurt is helpful because it ferments the milk.
Bacteria reproduce by splitting off of the mother cell and becoming two sister cells.		Bacteria can be found anywhere and everywhere. There are 40 million bacterial cells in one gram of soil.
There is a lot of bacteria in your house, they are covering the walls, and your body, but most are helpful, or ignorable.		Bacteria have little pieces of DNA inside of them, and as soon as they have reproduced they split into the sister cells.
Bacteria eat off of whatever there on, or they use photosynthesis.		
		There are many different types of bacteria, some examples are, Staph Aureus, S. milleir, C. koseiri and so on.

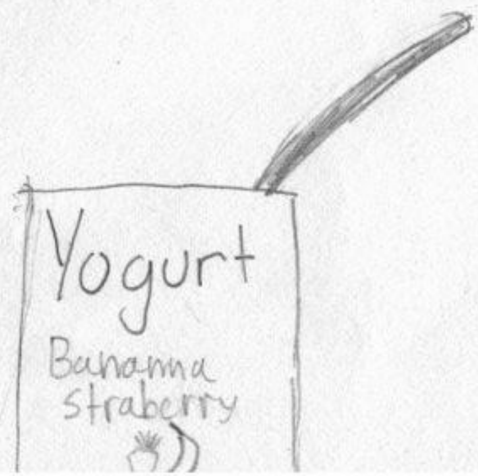

Bacteria
Bacteria can do lots of things like.
Decaying leaves
Befor
After
Moldy fruit
Befor
After
Can make alcohol
Befor
Apple Juice
later
This is the Smell of it turning into alcohol.
They can all So reproduce
The life cycle of a bacteria
decompoded Matter

Model 4-22


Where was it born: It was born in my garden those little brown mushroom,
How DID it get there: It either came from spore or the fungal Chain.
Spore
fungal Chain
What does it do during the day: thats one Just sits around eating nutrients.
Yum
It finds its food IN decomposing matter
living
earth logs soil so any organic matter
I remember It whites the toads from mario

Bacteria

Bacteria is in my house right now. It is in yogurt. Before the bacteria in the yogurt came to my house in was in a store but before that it was in a factory being prosesed and thats were it began. The bacteria was in the milk. They use the milk put with the bacteria in to help make what yogurt is. So if we didn't have bacteria in the yogurt who knows what it would be like. ~~That is how~~ Now you know that there is bacteria in yogurt, but that's not the only place bacteria are they are everywhere



Algae:

Algae is a protist. Protists live under water. That means
Algae can live, in ponds, rivers, lakes, stream, oceans, seas,
and so forth. Algae takes in nutrients by doing photo synthesis.
Photo synthesis is where a plant (or algae in this situation) takes
water and light and mixes it together in this "blender"
and mixes it into nutrients. Then the nutrients goes down
and to the cells to feed it. Algae moves in many ways.
Algae can move by floating on the water and floating around.
Algae can also be floating down or around in the river,
stream and so forth. Algae reproduces by releasing
spores into the water. The spores float around and/or
settle down and grow. Algae likes to grow in colonies.
An algae colony can kind of look like seaweed when
it is out of the water. When it is in the water it looks
puffy as a cloud. Algae is more like a plant because
it does photosynthesis. Algae also has a necleus. The
necleus holds the DNA. Well that
is Algaa!

that is called
algae bloom!

I wasn't super sure about the reproducing. I sorta forgot.