POINT LOMA NAZARENE UNIVERSITY

Scaling Ability and Atom and Cell Conceptions

and Their Implications for Understanding Cellular Functions

by Middle School Students

A thesis submitted in partial satisfaction of the

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by

Casey Vogel

Committee in charge:

Dr. Dianne Anderson, Chair
Dr. April Maskiewicz
Dr. Mike Dorrell

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The thesis of Casey Vogel is approved, and it is acceptable in quality and

form for publication:

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                                                                 Chair

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I dedicate this thesis to my husband, Robert Barber

who supported me with love through the process.

I couldn't have done it without you.

And to my parents, sister and friends, who waited for me.

I'm ready to play now.

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Abstract of the Thesis

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Because students in middle school through high school demonstrate persistent alternative conceptions regarding atoms and cells and their functional relationships, it is important to investigate ways in which to refine and correct these ideas so that students have a stronger foundation upon which to build concepts about cellular biology. Research has also shown that people generally have difficulty scaling objects outside of the macro scale. This study demonstrates the ability of middle school students to improve their ability to scale objects in the macro, micro and nano scales and use the improved sense of scale to better understand the relationships between atoms and cells, two concepts that are currently taught in isolation in California middle schools. Using both quantitative and qualitative methods, student improvement in atom and cell concepts were measured. Students who could not rank an atom smaller than a cell in a size-ranking activity after receiving instruction in size and scale skills performed lower than those who could in overall understanding of atom/cell relationships. Additionally, student interviews revealed that students who developed a more expert understanding of the relationship between atoms and cells also gained a much stronger and deeper grasp of protein synthesis as exhibited by their more articulate and detailed oral descriptions of the process. This research can help inform the development of learning progressions in middle school science, particularly in a time when new standards such as Common Core and Next Generation Science Standards are being introduced.

Introduction

An understanding of the relationships between atoms, molecules and cells is important to the understanding of concepts in cellular biology such as DNA, transcription and translation, and photosynthesis and cellular respiration. Unfortunately, many middle school students exhibit unscientific and fragmented conceptions of atoms, cells and the relationship between the two although they have received instruction in both cell theory and atomic theory (Harrison & Treagust, 1996; Roland, 2009; Sewell, 2002). These two topics are frequently taught in isolation. In California, where this study takes place, the Science Content Standards for California Public Schools places cell theory in grade 7 and atomic theory in grade 8 (California Department of Education, 1998). It is typically left up to the student to create connections between the ideas of atoms and cells.

Both atoms and cells are objects with which students have limited (cell) or no (atom) direct experience, and both must be described using models since they are not of the macro scale. People typically have difficulty scaling, particularly in scales of the very small as compared to the very large (Tretter, Jones, & Minogue, 2006b). Without scaffolding the concept of scales between the nano, micro and macro worlds, it is not surprising that student conceptions of small scale objects become fragmented. Even after receiving instruction in both cell theory and atomic theory, students' alternative conceptions regarding relative sizes of invisible objects persist (Harrison & Treagust, 1996, Sewell, 2002, Roland, 2009). They may estimate cells as being only three times larger than an atom or describe DNA as being larger

than cells (Vogel, 2012). This will, in turn, affect how they understand the relationships between these objects both structurally and functionally.

It has already been shown that use of visual aids (Jones, Taylor, Minogue, Broadwell, Wiebe, & Carter, 2007) and scaffolding using analogies (Magana, Brophy, & Newby, 2008) can improve students' abilities to understand different scales. Since many biology concepts concern processes occurring in both the micro and nano scale, it seems that a student's ability to visualize objects in these scales would not only improve their understanding of relationships between atoms, molecules and cells, but also promote scientifically accurate development of concepts. Studies have shown that middle-school students are capable of developing and applying scaling skills when interventions are put in place. However, it remains to be documented how improving scaling skills might further affect student understanding of related cellular processes which require students to integrate their conceptions of both cells and atoms. The purpose of this study is to determine if explicit instruction in scaling of objects between the macro, micro and nano worlds will aid students in understanding the relationships between atoms, cells and molecules; and also to determine if such an improvement correlates with students' understanding of cellular processes occurring on the nanoscopic level. In this study, I will specifically investigate student understanding of protein synthesis following a scaling intervention.

Literature Review

Theoretical Perspective

Learning occurs in the minds of individuals when they assimilate and accommodate new ideas from observations and interactions with the world around them into existing mental constructs (Piaget, J., 1964). As Piaget described, more sophisticated concepts are first formed as schema and are then refined, modified and reorganized through additional observation and experience including mental problem solving and interaction with people and things. All prior knowledge affects future knowledge and can provide either useful foundations for, or impediments to, emerging, sophisticated ideas (Smith, diSessa & Rochelle 1993). In Taber's typology of learning impediments (Taber, 2004), he identified fragmentation as a barrier to constructing complex ideas. The organization or "chunking" of knowledge often takes place at the subconscious level. This compartmentalization of knowledge can lead to fragmentation of understanding where the learner does not see relevance between material they hold in their cognitive structure and new material being presented. Unrefined or fragmented concepts may impede, but do not preclude development of expert ideas; but for expert ideas to develop, a foundation of correct supporting prior knowledge is necessary. When incomplete or fragmented conceptions are identified and further developed and interconnected by educators, they can aid in establishing a foundation upon which to build more sophisticated and expert knowledge (Hammer, 1996).

Alternative Conceptions Related to Cells and Atoms

Alternative conceptions are constructs of partial or incomplete knowledge,

sometimes misapplied in a given context, and are resistant to instruction (Smith et al., 1993). Research shows that many unscientific, alternative conceptions exist regarding aspects of cells and atoms, including the relationship between cells and atoms (Harrison & Treagust, 1996; Roland, 2009; Sewell, 2002). Common non-scientific ideas include the following (Vogel, 2012):

1) atoms have cells in them

2) cells are made of protons, neutrons and electrons

3) cells are found only in specific parts of the body

4) atoms are alive

5) atoms can be viewed with a light microscope.

Table 1 includes additional examples. Clearly, these ideas show that the students hold some partially correct conceptions. For instance, students know that cells are building blocks, but then they misapply this idea (#1 above) and determine that cells can be building blocks of atoms. They know that cells are "found" in the body, yet their conception (#3) remains incomplete when they don't expand that idea to all parts of the body. Additionally, they know that atoms make things and cells make things, but they then confuse the characteristics and roles of each as illustrated by conception #4. An Australian study with year 9-12 students showed that non-scientific concepts about the relationships between atoms and cells were not resolved as students progressed through more advanced science classes (Sewell, 2002). Harrison and Treagust (1996), also in Australia, investigated students' mental models of atoms and molecules in grades 8-10 and discovered that some students confused atoms with cells and described atoms as being alive. Elizabeth

Roland (2009) carried out a study in Kentucky examining conceptions of atomic and cellular structure and relationships between atoms and cells, and found results consonant with the Australian studies. At the conclusion of her study of high school students' ideas about atoms and cells, which showed some similar alternative conceptions, Roland pondered, "It leaves one questioning how students make sense of photosynthesis or genetics, which utilize molecules and specific elements in the process, if they do not identify atoms inside of cells" (Roland, 2009, p.182).

Table 1 is a list of student conceptions from my 2012 pilot study designed to characterize 8th grade students' conceptions about the relationship between atoms and cells, including size relationships. Results for this table were obtained using the same Atom/Cell relationship pretest as appears in the appendix of this paper, but with students from the previous year. Students clearly have many correct ideas about these topics, but fragmented and erroneous ideas still exist alongside them, even though all participating students had received instruction the previous year in cell theory and the same year in atomic theory (Vogel, 2012). The pilot study showed student ideas similar to those shown in other studies (Harrison & Treagust, 1996, Sewell, 2002, Roland, 2009) as noted in the final column.

Table 1.
Student Conceptions of Atoms and Cells
Eighth grade students' conceptions about atoms, cells and their relationships. Students (n=44) were divided into high, middle and low academic achievement groups. In the final column, it is noted for incorrect conceptions whether each was also identified in another study: (H = Harrison & Treagust, 1996; S = Sewell, 2002; R = Roland, 2009)

		High	Mid	Low	Total	Other Studies
ATOM		n=15	n=15	n=14	N=44	
correct	atoms are building blocks of matter (not energy)	6	3	6	15	
	building blocks of cells	15	8	7	30	
	building blocks of things including living things	14	8	8	30	
	building blocks of things	15	15	12	42	
	nucleus w/ protons & neutrons, electrons outside	8	2	4	14	
	something in the center, other parts around it	15	12	9	36	
	cannot be seen with microscope	13	12	8	33	
	smaller than cells	14	11	8	33	
	not alive	11	11	10	32	
incorrect	make up heat and light	7	7	3	17	R
	are alive	4	3	3	10	H
	make up only living things	1	2	0	3	R
	can be seen with a microscope	3	2	3	8	H S
	equal in size to cell	0	1	2	3	S R
	larger than cells	0	2	3	5	S R
	some non-living matter exists that is not made of atoms	2	9	6	17	H
CELL						
correct	building blocks of living things	13	13	7	33	
	Found in living things	15	14	11	40	
	contain nucleus	15	9	6	30	
	can be seen with a microscope	9	9	5	23	
incorrect	building blocks of all things (except energy)	1	0	0	1	S R
	drawn as an atom	3	1	1	5	S
	make up random things	1	1	5	7	R
	can't see with a microscope	7	6	8	21	

RELATIONSHIP BETWEEN ATOMS AND CELLS						
correct	both make up living things	13	11	8	32	
	both are in living things	15	11	9	35	
	cells only in living things	13	11	7	31	
	cells made from atoms	14	8	7	29	
incorrect	cell and "atom" used interchangeably	1	1	0	2	
	atoms do not make up living things	0	1	2	3	S R
	atoms do not make cells	0	7	4	11	S R
SIZE RELATIONSHIPS						
correct	water molecule smaller than cell	5	5	1	11	
	water molecule smaller than DNA	7	3	4	14	
	DNA bigger than atom	9	6	8	23	
	DNA smaller than cell	7	7	4	18	
	ALL ITEMS RANKED CORRECTLY	3	0	0	3	
incorrect	DNA smaller than atom	3	8	3	14	
	DNA bigger than cell	6	9	7	22	
	water molecule bigger than DNA	4	12	7	23	
	water molecule bigger than cell	6	11	9	26	
	water molecule smaller than atom	2	4	4	10	
	atom bigger than DNA	3	8	3	14	
	cell nucleus and atom nucleus similar in size	1	7	3	11	

Difficulties With Scale

Studies have shown that scaling objects outside of the macro scale is difficult for many people. In a 2006 study, Castellini et al. conducted a public survey of 491 people at a shopping mall with ages ranging from 7 to 91 years. While 45% of respondents could correctly rank a series of small, familiar objects according to size,

such as a grain of salt and an eyelash, only 7% could correctly rank the invisible objects: cell, bacterium, atom and water molecule (Castellini, Walejko, Holladay, Theim, Zenner & Crone, 2006).

Research has illustrated possible reasons for difficulties in the ability of people to scale objects in a number of ways. There is evidence indicating that very small scales present more difficulty for people than very large scales. In one study, accuracy of scale declined in a consistent manner for very large scale objects (such as mountains, continents, planets and interstellar distances), but small objects were ordered by participants with a high degree of accuracy until they were beyond the realm of the visible at which point accuracy dropped "precipitously" (Tretter et al., 2006b). For many people, there is little differentiation in the realm of the small, and small things are just lumped together as "small" (Tretter et al., 2006a). Some of these results may be attributable to the lack of experience people have with objects outside the macro scale. Tretter et al. (2006a) showed a correlation between how people scaled objects and their direct experience with those objects.

Studies in recent years have uncovered some of the strategies people, including science experts, use in scaling objects accurately. In a 2009 study, Jones and Taylor interviewed working adults, including experts in science fields, to determine strategies they used for scaling objects in the course of their jobs. Participants recalled using their bodies as rulers for rough measurement. They tended to have one or more anchor points or size references they used routinely in their work. For example, the chemist and zoologist in the study both noted they knew the size of a micron because the red blood cell is 7 micrometers across (Jones

& Taylor, 2009). Like Jones and Taylor's anchor points, Tretter also showed that a common strategy used in scaling is to use significant size landmark objects with which a person is familiar. Some of the common landmark objects used were the self, athletic fields and driving distances. A lack of familiar landmarks with which to scale very small objects may contribute to this difficulty at the very small scale. Though sizes of objects exist along a continuum, Tretter et al. (2006b) has shown that a strategy that experts use in scaling is to mentally "jump" to a new scale and create a mental context in which to think about a phenomenon. Experts have familiar landmarks within different scales which novices lack.

In the scale of the very small, it is often impossible to have direct experience with objects. This is particularly true with middle school students who may be exposed to ideas of atoms and cells for the first time and whose resources do not include technologically advanced equipment beyond a common light microscope. However, it has been shown that symbolism is another important vehicle to providing a clear understanding of nanoscale objects (Batt, Waldron, & Broadwater, 2008). In the absence of direct experience, familiar representations of nanoscale objects do contain information about said objects and can provide a mental landmark that can aid a person in jumping between scales. However, these representations lack realistic scale and thus present a different set of problems when students need to conceptualize how such objects are integrated into larger objects. For instance, the iconic symbol for an atom with a nucleus and elliptical orbits surrounding it, though inaccurate, does provide some accurate information about atoms and is universally recognized.

Specific Implications for Biology Instruction

Duncan et al. (2008) explain the difficulties in understanding the molecular basis for genetics as rooted in the need to interrelate models existing on several levels of scale. They further explain that this is so challenging because it 1) requires understanding of chemical and physical interactions at the molecular level, which requires a fundamental understanding of atoms and molecules and the chemical nature of biological molecules and the interactions between them; and 2) cellular and molecular processes and entities involved are invisible and inaccessible to students (Duncan, Ruppert, Bausch, & Freidenreich, 2008). Marbach-Ad and Stavy (2000) identify three levels of organization: macro, micro and molecular that must be bridged in order for students to gain an understanding of cellular and molecular genetic phenomena. Their disappointing findings showed that, "…less than half of the 12th graders were able to explain the functions of RNA, showing their lack of conceptual understanding of the transcription and translation process. Thus, in spite of the fact that 12th grades had studied both micro and macro levels they still showed difficulty in linking these levels" (Marbach-Ad, & Stavy 2000). Current efforts at mapping learning progressions in genetics document poor student understanding of the actual structure of the molecules involved and their relationship to the processes in which they function. (Duncan, Rogat, & Yarden, 2009; Roseman, Caldwell, Gogos, & Kurth, 2006).

Duncan and Reiser (2007) attribute student difficulties in understanding the molecular basis for genetics partly to the need to reason across ontologically distinct levels. They use the term *hybrid hierarchical* to describe genetic phenomena

meaning that it requires sense-making across organizational levels, namely informational (genes) and biophysical (proteins, cells, etc.) They go on to illustrate their point with an analogy of a player piano. The information necessary to make the music is contained in the scroll, but the physical working of the piano is also required. In order to describe how the piano works, one would have to understand what is happening on both levels. In order for students to understand how genetic information is passed on or manifested, they need not only know the concepts in Mendelian genetics, but also the biophysical mechanisms involving the moving parts: atoms, molecules, organelles. They concluded that, "Without an understanding of proteins, the link between the genetic information and its physical effects remains a black box" (Duncan & Reiser, 2007). Providing instruction in the big, underlying and cross-cutting ideas would be aimed at assisting students in linking their conceptual understandings across levels of organization as well as across disciplines.

Fragmentation in Curriculum and Assessment

It has already been established that students often enter class with inaccurate and incomplete knowledge structures into which they are expected to incorporate and organize their new information. Students' knowledge structures may not be organized frameworks. When ideas are not structured in an organized way, it is difficult for students to apply their knowledge to new situations because of this lack of structure and organization; in other words, ideas are compartmentalized (Taber, 2004).

Some of the disconnect between concepts of atoms and cells may arise from

the placement of curriculum into isolated categories. Similar to California, where this study took place, the Australian Curriculum, Assessment and Reporting Authority (ACARA), places the study of cell theory and atomic theory in separate years; cell theory in year 8 and atomic theory in year 9 (ACARA, 2012). In contrast, in Kentucky, the Core Content for Science Assessment places both the study of cell theory and atomic theory in the 8th grade year (Kentucky Department of Education, 2012). Yet, even with atoms and cells studied in the same year, students were still not understanding how the two are related. The National Science Education Standards, which "are designed to guide our nation toward a scientifically literate society," identify "systems, order and organization" as a unifying concept. They state that, "Types and levels of organization provide useful ways of thinking about the world... Physical systems can be described at different levels of organization – such as fundamental particles, atoms, and molecules. Living systems also have different levels of organization – for example cells, tissues, organs, organisms, populations and communities." (National Research Council, 1996, p.117). Yet, the standards fall short of integrating the physical systems with the biological systems. Within their organization of content standards, the organizational levels of matter and of living things are treated separately. It is promising to note that the American Association for the Advancement of Science has begun to include learning goals addressing size and scale concepts in the 2009 revision of their 1993 Project 2061 Benchmarks for Science Literacy. For example, within the Scale strand of the Benchmark "Common Themes" the following learning goal was added for the end of 8th grade: *Natural phenomena often involve sizes, durations, and speeds that are extremely small or*

extremely large. These phenomena may be difficult to appreciate because they involve magnitudes far outside human experience [AAAS, 2009]. As well, the National Research Council, the National Science Teachers Association, and the American Association for the Advancement of Science have embarked on a two-step process to develop the Next Generation Science Standards projected finished in 2012. The project is based on the Framework for K-12 Science Education, which specifically identifies *Scale, proportion and quantity* as a crosscutting concept, which the authors emphasize need to be made explicit for students in order to provide an organizational schema for interrelating knowledge across science fields into a coherent and scientifically-based view of the world (National Research Council, 2012).

Additionally, the fragmentation of concepts may be inadvertently promoted by current high-stakes testing practices. "Current [standardized] assessments are … derived from early theories that characterize learning as a step-by-step accumulation of facts, procedures, definitions, and other discrete bits of knowledge and skill." (Pellegrino, Chudowsky & Glaser, 2001, p.26). Standardized tests can influence teachers to teach directly to items on the test thereby narrowing the curriculum and limiting learning outcomes. Teaching for success on this type of assessment does not require students to connect currently taught concepts with concepts from the same area or from other science areas that were previously learned. As a result, the traditional curriculum and instruction often focuses on isolated bodies of knowledge. Thus, current assessment and instruction practices

can largely be described as linear and compartmentalized in nature (Stevens, Delgado & Krajcik, 2009).

Analysis of the Third International Mathematics and Science Study (TIMSS) (Schmidt, Wang & McKnight, 2005) found that curriculum coherence is the dominant predictor of student learning. The good news is that the science education community is moving toward a view that students do not achieve proficiency by following one general sequence, but by multiple (often interacting) sequences, and that learning progressions should be organized around core or *big ideas* (Duschl, Schweingruber & Shouse, 2007). For example, Stevens, Sutherland and Krajcik (2009) outline the big ideas of nanoscience and identify Size and Scale "as a *big idea* that spans all disciplines of science." As an illustration, they cite hemoglobin, "… - the component of a red blood cell responsible for carrying oxygen – is a classic example of how changing a single building block of a protein can alter the function…" which in turn, can affect the entire organism (ibid. pg 8). In keeping with these recent developments, I set out in this study to show that integrating big ideas into the currently fragmented curriculum will improve student understanding of more complex ideas.

Placing the study of cells and atoms in a more integrated format may be beneficial in helping students develop an understanding of their relationships. However, considering that scaling is a generally a challenging skill as shown by previous studies, an integration of these ideas may be further advanced by explicit teaching of scaling as a skill, and by scaffolding that skill within the framework of the study of atoms and cells.

Defragmenting Science Concepts Using Scale

Schmidt et al. (2005) suggest that one way to facilitate learning beyond the particulars is by making the inherent logical structure of the discipline more visible to both teachers and students. Other studies proposing learning progressions in science conclude that they should identify and characterize not only the ways in which students develop understanding of the important concepts within individual knowledge domains, but foster connections between ideas both within and across domains. (Stevens et al., 2009; Shin, Stevens, Delgado, Krajcik & Pellegrino, 2007). In their Learning Progression for the nature of matter, Shin, et al. (2007) concur with the AAAS Benchmarks for Science Literacy in that students should develop an understanding of the atomic scale and its relation to other more accessible scales (e.g., macroscopic, microscopic) (AAAS,1993). The understanding of scale is identified in the NRC *Benchmarks* as one of four common themes that have implications throughout all disciplines of science (NRC, 1996). Stevens, et. al (2009) define a "big idea" as an idea considered central or fundamental. They go on to explicitly explain the importance of scaling: "People make predictions based on macroscale experiences…that occur in the "world" that can be adequately explained by classical physics. But as size or mass of an object or material transitions through the nanoscale toward the atomic scale, the ability of classical mechanics to predict the behavior of matter begins to fail" (p.8). Supporting students' ability to navigate within and between scales could help them understand the seeming inconsistencies in the behavior of matter as scales are traversed.

Successful Instruction in Scaling

Although there is abundant documentation of the difficulties people have with scale, there is also research indicating that specific instruction directed at this skill has met with some success. In 2007, Jones, et al. found that students' concepts of relative sizes were more accurate after viewing the film "Powers of Ten" made by Charles Eames. They had middle school girls in grades 7-9 at a summer science camp view the film and their results showed that participants' concepts of relative size were more accurate after viewing the film, and they were more accurately able to match metric sizes in scientific notation (Jones et al., 2007). In a 2009 study, Jones et al. showed that teaching middle school students to use body measurements had a significant influence on their estimation accuracy (Jones, Taylor & Broadwell, 2009). In 2008, Magana, et al. successfully used specific instruction in scaling skills with 7th grade students in a Midwestern middle school setting. They employed analogies and metaphors to scaffold scaling abilities and concluded that with adequate scaffolding, students' understanding of these abstract concepts could be leveraged. Additional work has recently been done to characterize and scaffold size and scale cognition (Magana, Brophy & Bryan, 2012; Magana, Streveler, & Barrett, 2011). My study aimed to build on these successes and to discover if there is a correlation between improving scaling ability and understanding atom/cell relationships, and whether there is further correlation between that understanding and understanding cellular processes.

Research Questions

As discussed in this review of literature, a lack of ability to scale small objects

will likely affect students' ability to construct meaningful concepts of micro and nanoscale objects contributing to incomplete and erroneous understanding of atom and cell relationships. This can only provide a questionable foundation upon which to build understanding of biological processes, which can be inherently difficult to understand. Genetics, as well as other biological processes such as metabolism and photosynthesis, involve concepts at the macro, micro and nano scales. By the end of 7th grade, students have received instruction in cell theory, cell structure and function and heredity. By the end of 8th grade, they have received instruction in atomic theory, atomic structure and basic chemistry. Armed with an understanding of atoms and cells, students are then expected to go on to high school biology and learn about more complex biological processes involving atoms and cells together. Previous studies have already shown that students past the 8th grade and into high school maintain alternative conceptions of both cells and atoms, and these alternative conceptions have been described (Harrison & Treagust, 1996; Roland, 2009; Sewell, 2002). These alternative conceptions regarding the objects involved in biological processes will have a direct effect on student understanding of the processes themselves. Studies have shown that people have difficulty scaling objects that are in the micro and nano scales, though interventions have been shown to improve this ability. The purpose of this study is to answer the following research questions:

1.   Will an improvement in overall ability to scale micro, nano, and macro scale objects have a positive effect on student conceptions of atoms, cells and their functional relationships?

2.　　Will an improved understanding of the relationship between atoms and cells show a positive correlation with students' ability to understand protein synthesis?

Methodology

Research Design

A mixed methods sequential explanatory design was used in this study (Figure 1) and consisted of two distinct phases. The first phase was a sequential triangulation design: data transformation model (Creswell & Plano Clark, 2007), in which both quantitative and qualitative data regarding student conceptions about atoms/cells and their relationship was collected using a pretest. The data was transformed into quantitative data. After an intervention, the same data was collected as a posttest and transformed to quantitative data for analysis. This phase of the design was for the purpose of answering the first research question regarding how students' overall ability to scale small objects (determine which are bigger and smaller relative to one another) affects their understanding of atom/cell/relationship concepts. The second phase of the design was based on the explanatory design: participant selection model (Creswell & Plano Clark, 2007). Results from the atom/cell/relationship portion of the posttests given in the first phase was used to select participants for the second phase. Students from different achievement levels in the first phase were chosen for interviews designed to elicit their understanding of how the protein synthesis process works. Results of these interviews were then analyzed in conjunction with the participants' post test scores to determine if there was a correlation between their atom/cell conceptions and their understanding of protein synthesis.
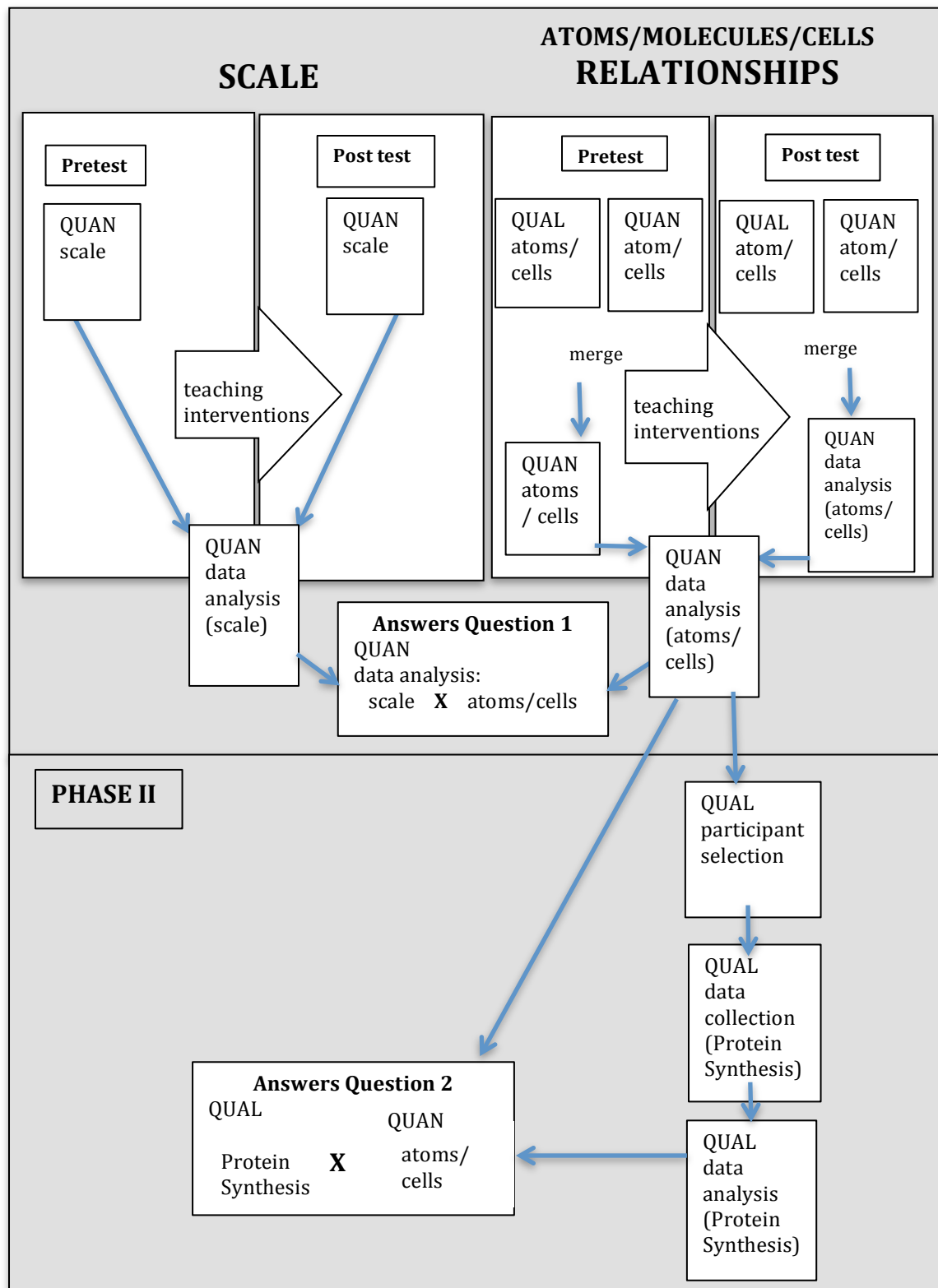
Figure 1. Mixed Methods Sequential Explanatory Design

Study Participants and Setting

Participants for this study consisted of all students (N=168) in my six classes of 8th grade science from a large public middle-school in southern California. The school draws students from both urban and suburban neighborhoods and has a total enrollment of 1146 students: 38% White, 46% Latino, 51.6% socioeconomically disadvantaged, and 35.6% language learners. Average science class size was 28.4 students. Science classes were not leveled or tracked, but some classes had resource clusters or greater concentrations of high-achievers due to the leveled scheduling of language arts and math courses, though curriculum remained the same for all classes following the California Science Standards for 8th grade. All students having attended the same school the previous year received instruction in cell theory and heredity in 7th grade, including cell structure and the general function and location of DNA and genes. Seventh grade instruction includesd identification, examination and comparison of plant and animal cells using microscopes as well as identification of visible cell organelles. Organelles invisible with the microscopes were also studied along with their functions. The place of cells in organizational hierarchy of organisms was studied along with differentiation of cells to form different tissues. Students also completed a unit of study on heredity and genetics which included Mendelian genetics as well as the role of DNA and genes in phenotypic expression. Prior to data collection, all 8th graders received instruction on the nature of matter including methods of quantifying matter such as measuring mass, volume and density; and also physical changes in matter including

changes of state. This instruction included discussion of what the particles making up matter will do when energy is added or removed to cause change of state, though no explicit instruction had yet been given on the structure of atoms or molecules prior to the pretests and interventions. One hundred sixteen students completed pretests and posttests and 13 completed interviews. All research was conducted in compliance with the Institutional Review Board of Point Loma Nazarene University.

Data Gathering Tools

   Atom/Molecule/Cell Conceptions and Scaling Pretests and Posttests.
Prior to instruction on atomic theory, as part of regular class activity, students took a paper-and-pencil pretest to assess their conceptions about atoms, molecules, cells, and their interrelationships (Appendix A). The first part of the pretesting consisted of both objective and open-ended questions. This tool was a reformatted version of the one used by Elizabeth Roland (2009) in her doctoral thesis on students' conceptions of atomic and cellular structure and relationships between atoms and cells. The second part of the pretest consistsed of a student activity in which a list of small scale and macro scale objects were provided and students were asked to order them according to size. This tool was based on similar tools used in scaling ability studies (Magana et al., 2008; Delgado, 2007; Magana, personal communication 10/07/2012). The same test was given as part of regular class activity after the chemistry unit which concluded with instruction in carbon chemistry in living things and instruction on protein synthesis. Information on the specific interventions is detailed below.

Protein Synthesis Interviews. Following the lessons on protein synthesis, 13 students were interviewed individually to assess their level of understanding of protein synthesis. Six of the students showed a high level of understanding of the relationships between atoms, molecules and cells as evidenced by their posttest results. The remaining seven students showed persistent alternative conceptions about the relationships between atoms, molecules and cells as evidenced by their posttests. It is understood that some students come to school with various impediments to learning that may result from circumstances outside of the classroom, which can undermine their ability to put forth their best effort. In light of this fact, students with errors so copious as to make their test nonsensical or incomplete were excluded from selection.

At the beginning of each interview, the interviewee was presented with two diagrams, as shown in Appendix D, showing protein synthesis from DNA transcription through translation at the ribosome. The diagrams were similar to diagrams in their science text and other instructional materials when they learned about the process in class. They were given about five minutes to examine the diagrams and were asked to choose one or both to use for the purpose of explaining or "teaching" the process to the interviewer.

Students explanations were analyzed for depth of understanding. Responses were coded for correctly connecting ontological levels within the description of the process, connecting structure of objects to function, attributing correct characteristics to structures, and describing cause and effect relationships between

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steps in the process. I created the interview protocol as well as the diagrams (see Appendix D).

Criteria for Participation in Interviews

There were a number of criteria for choosing volunteer candidates for participation in interviews. Students had to have taken all four parts of the pretest and posttest and had to have been present for both lessons on protein synthesis. Additionally, students from different levels of achievement on the Atom/Cell post-test were invited to participate. Interviews took place in the students' regular science classroom. They could choose to come either before school or after school, and parental permission was required for participation. Since the interviews were an activity beyond the regular school day, students were offered the choice of receiving community service credit or a $5 gift card for their participation. Though the implementation of all the above criteria limited the candidate pool, 13 students were interviewed. The number was limited by the time available remaining in the school year in which interviews could take place. Six students were from the "novice" level of performance on the A/C Part II posttest rubric (Appendix A), one from the "emerging" level, one from the "developed" level and five were from the "expert" level. Efforts were made to include a more even number of students at each level, but not all of qualifying students chose to participate.

Data Analysis

Part I of the atom/cell relationship pretest was scored in two ways. The first part asked students to identify objects as being made by atoms and/or as being

made by cells. This was given a numerical score based on the number of correct identifications. The open-ended questions were then considered along with the choices made in the first part and the overall Part I pretest was given a rubric score. The scaling portion of the pretest was given a numerical score. Beginning with the item listed as the largest, the first two listed items were compared. Beginning with the second item, one point was scored for each item that was correctly ordered as larger than the one before it. In this way, each item was only compared to the one listed directly before it so that an early error did not severely affect the score. Results were analyzed for correlation between improvements in scaling ability and improvements in atom/molecule/cell relationship concepts.

The expectation was that students with more expert understanding of atom, molecule and cell relationships would be able to explain the process of protein synthesis more accurately than those with a novice understanding of atom, molecule and cell relationships. Scores on posttest Part I were compared to the results of the student's corresponding interview by counting the frequency of "higher level statements" in the interview responses. The "higher level statements" consisted of four types of statements: (O)Ontological, showing an understanding of hierarchical structures, (S) Structure/function, showing an understanding of how a particular structure can perform a function, (C) Characteristic, showing knowledge of an object's characteristics rather than just being able to name the object, and (E) Cause and Effect, showing an understanding of how one action causes a particular effect. I selected these categories because they were frequently described as important aspects of student understanding of scientific concepts in the research literature on

science education (Table 2). The posttest Part I scores and interview scores were analyzed for the significance of correlation.

The interview consisted of students examining two diagrams, which I drew, of the protein synthesis process and being asked to explain the process to me. I then asked questions for clarification. It was easy to use the diagram to point out different objects and simply state where the process starts and ends with certain objects moving about in space. As such, the coding sought to identify statements of deeper understanding that showed that students understood that the objects involved were molecules made of smaller parts within a larger cell; that each structure had a particular function and role; that the characteristics of the structures aided them in performing their functions; and that steps did not just happen in an arbitrary order, but that one step leads logically to the next. Each transcript was read and examined for statements indicating deep understanding in each of the listed categories. Those statements were coded on the page with O, S, C or E. If the statement was repeated later, it was marked again, but not counted a second time toward the score. Marks in each category were counted and totaled. Additionally, the transcript was considered holistically and rated according to a rubric I created (see Appendix D) for a general, overall rating of category of understanding.

Table 2.
Categories of Understanding. Examples of science education literature that describe the categories of understanding used to code the interviews.

Categories of understanding	Authors	Topic of study
O=ontological levels S= structure/function, C= characteristic E= cause and effect		
C	Harrison & Treagust, 1996	secondary students' mental models of atom and molecule
O	Marbach-Ad & Stavy, 2000	secondary students' cellular and molecular explanations of genetic phenomena
C	Sewell, 2002	secondary students' conceptions of atoms and cells
O, S, E	Roseman et al., 2006	learning progression for the molecular basis of heredity
O, S, E, C	Duncan & Reiser, 2007	reasoning across ontological levels in genetics
	Shin et al., 2007	learning progression for nanosciences
O, S, E	Mohan et al., 2009	learning progression for carbon cycling
O	Stevens et al., 2010	learning progression for the nature of matter
O, S, E, C	NRC, 2012	K-12 Science Framework

Interventions

Considering that previous research has shown that certain interventions have been successful in improving students' ability to scale, this study made use of those same interventions. Following are the interventions that were used during the atomic theory unit as part of the regular class activities:

Powers of Ten Video. Students participated in a lesson using the *Powers of Ten* video by Charles and Ray Eames (1977). This was a one-day lesson designed by H. Jin and L. Mohan (2009). Students first reviewed magnitudes of ten using millimeter graph paper in a teacher-led lesson. Then they were asked to group twenty objects into scale

categories prior to viewing the movie *Powers of Ten*. After viewing the movie, they were asked to review their choices and make any changes before sharing aloud their reasons for their choices (Appendix B).

Analogy and Metaphor Scaffolding. Following the method used by Magana et al. (2008), students received a three-day lesson in scaling consisting of three 44-minute class periods.

Day 1: Students were asked to order and group according to scale. The objects ranged from the nanoscale to the macroscale, and included molecules and cells. Students were allowed to work independently or in pairs with the interactive computer application "Generation Nano", described below in Day 3.

Day 2: Students were introduced to the idea of nanotechnology. An overview of some different nanoscale and microscale objects were given. Nanometers were specifically defined by the teacher and compared to meters. Students were introduced to a logarithmic number line showing magnitudes of ten using metric units. Students had their own copy to reference while the teacher used one projected on the screen to explain its structure and to show how it is read. Examples were given to show different magnitudes and then proportional analogies were constructed. For example, the diameter of a pencil lead is approximately ten times smaller than the width of an adult's index finger fingernail; similarly, the height of a typical yogurt cup is ten times smaller than the height of a typical three-year-old child. After I provided examples, students identified their own analogies.

Day 3: Students worked in teams of two or three to construct their own analogies, which were shared aloud in class. They had some independent practice using guiding questions

and fill-in-the-blank analogies before constructing some of their own. This activity was based on one used by Magana (personal communication,

Computer Interactive. "Generation Nano" is an interactive computer simulation using a logarithmic number line. Students use it to practice scaling objects on a number line with magnitudes of ten. This was used by students to practice scaling before they constructed analogies with their partner or group. It can be accessed here: http://www.generation-nano.org/ (GenerationNANO, 2012).

Timeline

Students began the normal chemistry unit with 5 class periods of instruction on the history of atomic theory and how we have come to understand the structure of the atom. This was followed by three additional weeks of instruction that included arrangement and classification of elements in the periodic table, identification of elements based on characteristic properties, and physical and chemical characteristics of elements based on electron configurations. At that point, classes were recessed for the two-week winter holiday. Upon resumption of classes, students received two days of instruction reviewing the structure of atoms, which was followed the next day by the intervention.

The intervention began with the Powers of Ten lesson that took one 44-minute class period and approximately 15 minutes of the next class period the following day. The following day, at the conclusion of the Powers of Ten lesson, the remaining class period was spent demonstrating to students how to access and use the Generation Nano web interaction. Students were given the entire class period the next day to explore the Generation Nano web interaction and complete a handout guiding them through the

activities (see Appendix E). Following that lesson, students participated in the *Analogy and Metaphor Scaffolding* three-day lesson.

Following the intervention, students participated in the remainder of the chemistry unit which included sub-units on atomic bonding, chemical reactions, conservation of matter, the nature of acids and bases, and finally a short unit on carbon chemistry. At the end of the carbon chemistry unit, approximately six weeks after the Analogy and Metaphor three-day lesson, students took the post-test. Following the posttest was a two-day lesson on DNA transcription and translation to proteins.

Results

Quantitative Results

The first part of this investigation attempted to determine if there was a relationship between students' ability to scale and their understanding of atom/cell relationships in regard to atoms being the structural units that make up molecules and in turn make up cells. Tests were administered to 168 eighth grade science students, but all parts of the two sets of pretests and posttests were taken by only 116 students due to absences from class on one or more of the days when tests were administered. One test set was designed to test scaling ability of objects ranging from the macroscale to the nanoscale, and the other test set was designed to test understanding of atom and cell relationships. In the first test set, students were given a list of items and were asked to rank them according to relative size. From this point forward, this test will be referred to as the Scaling test. The second test set was divided into two parts. There was an objective portion where students identified items on a list as being made of cells and items on a list as being made of

atoms. There was also a subjective part with open-ended questions about the nature of atoms and cells. From this point forward, these two parts will be referred to as the Atom/Cell or A/C pre/posttest Part I (objective) and Part II (open-ended). The Scaling tests and A/C Part I were given numerical scores based on number of items correct. A/C Part II was scored with a rubric. These tests and associated rubrics are included in Appendix A. Both pretests were given over the course of two separate days in the first trimester of the school year. The posttests were given over two separate days in the second trimester of the school year, sixteen weeks later. For the purposes of this discussion, scores for students who did not take any one or more parts of the test were excluded from analysis unless otherwise noted. As well, any students obtaining the highest rubric score (6) in the Atom/Cell pretest were excluded as they were unable to show improvement between pretest and posttest. Seven of the 123 students who took both pretest and posttest of the Atom/Cell test were in this category, so they were excluded from later analysis.

Improvement in Scaling Scores. For comparison between Scaling pretest and post-test scores, all students were originally included who took both parts of both the tests. Results are shown for 123 students in Table 3. Mean score for the Scaling test improved 2.01 points from 8.98 to 10.99 out of a possible 15. There was a statistically significant difference between the pretest and posttest scores (paired t-test with $t_{(122)}$= 8.19, p < 0.01). Effect size was 0.46 showing a medium effect size. Though not a large effect size, there was improvement in scaling ability. When students scoring 6 points on the Atom/Cell Part II test were excluded, the results were similar (paired t-test with $t_{(116)}$ = 8.19, p < 0.01) with effect size of 0.47. This

indicated that a strong prior understanding of atom/cell relationships did not affect

improvement of scaling ability within this sample.

Table 3.
Results for Scaling and Atom/Cell Relationships pretests and posttests. Asterisk indicates significant change, *p<.01.

	Scaling (maximum 15) *inclusive of students with rubric score of 6 on Atom/Cell pretest* N=123	Scaling (maximum 15) *excluding students with rubric score of 6 on Atom/Cell pretest* N=116	Atom/Cell part I (maximum 26) N=116	Atom/Cell part II rubric score (maximum 6) N=116
pretest	8.98	8.87	15.53	2.8
post-test	10.99	10.91	20.13	4.3
average change	+ 2.01*	+2.04*	+4.6*	+1.5*

Improvement in Understanding of Atom/Cell Relationship. In a

comparison between the pretests and posttests of Atom/Cell Part I to measuring

student understanding of atom/cell relationships, the score change between pretest

and posttest was +4.6. When submitted to a paired two-tailed t-test, the results $t_{(116)}$

= 7.23, p< 0.01, indicated a statistically significant difference. There is a medium

effect size of 0 .43. For the rubric score for Atom/Cell Part II, the average score

increase was 1.5 points on a six point rubric, which indicated a significant

improvement in scores ($t_{(116)}$ = 8.07, p<0.01). The results show that there was an

improvement in ability to scale objects including items spanning from macroscale to

nanoscale, and there was also an improvement in student understanding of

atom/cell relationships.

Correlation of Improvement in Scaling Ability and Improvement in

Atom/Cell Relationship Understanding. This study aimed to determine if an

increase in the ability to scale objects would correlate with students' understanding of the relationship between cells and atoms. The change in scores between Scaling pretests and posttests was compared to the change in scores between the objective part, Part I, of the Atom/Cell Relationship pretests and posttests resulting in a Pearson correlation coefficient of $r_{(115)} = 0.225$, $p < 0.05$ indicating a statistically significant relationship between students' ability to rank objects according to size and their ability to identify what objects are made from atoms and made from cells. Results are shown graphically in Figure 2.
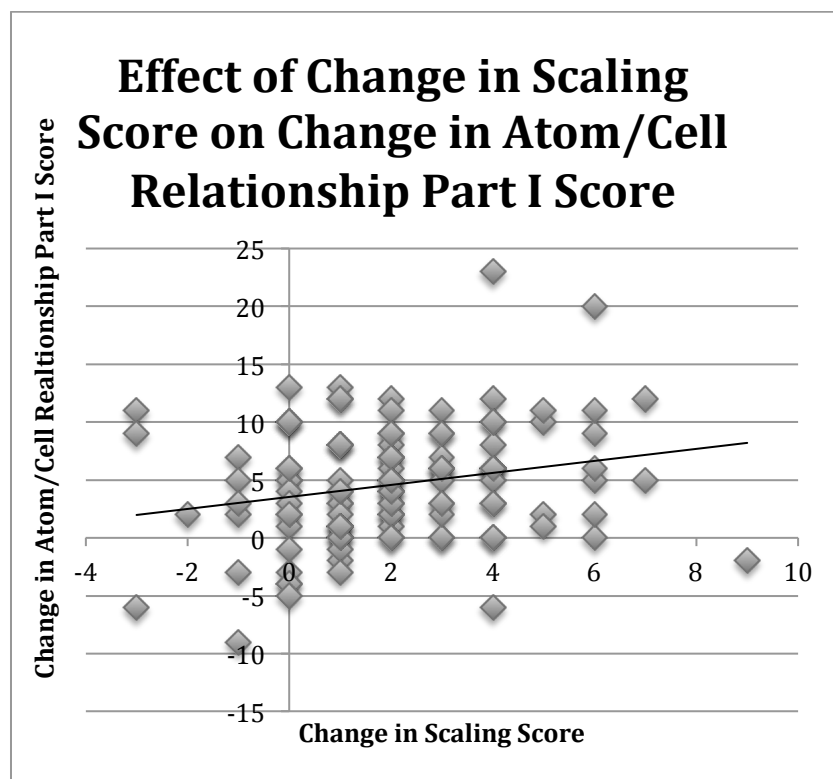

Figure 2: Comparison of score changes from pretests and posttests between the Scaling test and the A/C Part I test.

When the same comparison was made between change in Scaling scores and change in scores of Part II of the Atom/Cell Relationship tests, the Pearson correlation

coefficient was $r_{(115)} = 0.122$, $p > 0.05$. This compares the students' ability to rank objects according to size with their open-ended statements regarding atom/cell relationships. The correlation here does not show significance.

Scale Ranking of Atom v. Cell Compared to Atom/Cell Posttest Rubric Score. Considering that the Scaling test had some shortcomings (discussed later), another way of looking at the data would be to look at the students in the Scaling posttest who ranked atom and cell either "cell<atom" or "not rated", and compare that to the change in the A/C part II rubric score. This would eliminate the effect of incorrect student ideas of some of the materials listed in the scaling part of the test and only relate understanding of atom/cell size relationship to an overall understanding of how atoms and cells are related functionally. Results of this comparison are shown in Table 4 below. These results show that those who understood the correct size relationship tended to have an improved understanding of the overall atom/cell relationship in their posttest. Overall, 72% of students ranking "atom<cell" in the Scaling Posttest improved their A/C Part II rubric score, compared to only 54% for students who ranked "cell<atom" or who did not compare the two items. Of the 54% of students who did not make the correct ranking but did improve their scores, 46% improved their rubric score by one or two points while only 8% increased by three or four points. In comparison, of the 72% of students who made the correct ranking and also improved their rubric score, 36% improved by one or two points, while 41% improved by three or four points. So, a much lower percentage of students were able to make three to four point rubric improvements showing gains in their overall understanding of

atom/cell relationships when they were unable to correctly rank the size

relationship.

Table 4
Comparison of change in students' Atom/Cell rubric scores between those who did not have the
correct Scaling post-test atom<cell ranking and those who did.

Scaling post-test ranking of atom vs. cell		Change in Atom/Cell rubric score from pretest to posttest			
		-1 or 0	+1 or +2	+3 or +4	N
	cell<atom or not ranked	11 (46%)	11 (46%)	2 (8%)	24
	atom<cell	21 (23%)	33 (36%)	38 (41%)	92

Additionally, we compared changes in Atom/Cell rubric scores between groups of

students who did not change from the incorrect ranking or no ranking on the

pretest and those who made a change from an incorrect ranking or no ranking on

the pretest to a correct ranking on the posttest as shown in Table 5.

Table 5
Comparison of change in students' Atom/Cell rubric scores between those who did not make a
change to the correct Scaling post-test atom<cell ranking and those who did.

Changing scaling post-test ranking of atom vs. cell		Change in Atom/Cell rubric score from pretest to posttest			
		-1 or 0	+1 or +2	+3 or +4	N
	cell<atom or not ranked	11 (46%)	11 (46%)	2 (8%)	24
	Changed from incorrect or not ranked to atom<cell	9 (20%)	15 (34%)	20 (46%)	44

If we look even more closely at the rubric scores, it becomes obvious that the

students making positive changes to their atom<cell ranking on the scaling post-test

improved their overall rubric score more than those who did not. As shown in Table

6 with the data further disaggregated, only 17% of students who did not make the

34

change improved their rubric score by more than 1 point, while 59% of those who

made the change improved their score by more than 1 point. This shows that when

students corrected their understanding of the size relationship between atoms and

cells, they more often also improved their understanding overall of how atoms and

cells are related. This suggests connection between size ranking and an overall

understanding of how atoms and cells are related.

Table6
Comparison of change in students' Atom/Cell rubric scores between those who did not make a
change to the correct Scaling post-test atom<cell ranking and those who did.

		Change in Atom/Cell rubric score from pretest to post-test						
		-1	0	+1	+2	+3	+4	N
Changing scaling post-test ranking of atom v. cell	cell<atom (18 students) or not ranked (6 students)	4	7	9	2	2	0	24
					17%			
	Changed from incorrect or not ranked to atom<cell	4	5	9	6	12	8	44
					59%			

Problems with the Scaling Test That Affect Analysis. The scaling tool I

chose was based on the scaling tools used in previous research (Delgado, et al.,

2007; Magana, Brophy & Newby, 2008). In retrospect, there were several items on

the scaling activity that students had limited experience with—mitochondria,

bacterium, virus—and thus, I would have little expectation of them being able to

scale these items properly. Several of the items, though not completely unfamiliar to

students, may have been cause for confusion or guessing. All items on the list have

been part of the students' curriculum at my school. I know that students learned

about viruses and bacteria last year, but I have little reason to believe they would

have made any considerable size comparisons to cells or other nanoscale objects.

After seeing the number of errors in ranking, I looked back at the 7th grade textbook

used at this school. It does not make any significant size comparisons. In fact, there

is nothing in the text that would give any reasonable indication of size relationships

between viruses, bacteria, mitochondria or cells. Given that the 8th grade curriculum

does not cover cell structure and function, my curriculum was restricted to a brief

review of cells before discussion of scale. Furthermore, bacteria come in a wide

variety of sizes as do viruses. It would likely have been better to leave mitochondria,

virus and bacteria out of the scaling activity.

I examined the Scaling post-test results for students who took both pretest

and posttest and then created an inventory of items most commonly missed as

shown in Table 7. Virus topped the list with 80 incorrect rankings in the 116 tests,

followed by water molecule, protein molecule, DNA diameter and mitochondria. The

carbon atom trailed with 38.

Table7
Number of incorrect rankings in Scaling post-test by item.

item	virus	water molecule	protein molecule	DNA diameter	mitochondria	carbon atom	bacteria	atom nucleus	red blood cell/skin cell	cell nucleus	ant	hair diameter	sunflower seed	chicken egg	child
Number of incorrect rankings	80	64	58	57	53	38	35	26	23	19	10	4	3	1	0

Also of interest is that although the actual diameter of the DNA falls between

the water molecule and the protein molecule, with water molecule and protein

molecule listed adjacently 50 times. Of those adjacent listings, 22 listed protein

molecule right before water molecule. Proteins are orders of magnitude bigger than

water molecules leading one to wonder if students merely listed the two

"molecules" together without thinking about their relative sizes. Similarly, 11 of the

23 errors involving red blood cell and skin cell were with skin cell being listed

directly before red blood cell. The term "skin cell" is vague in that it does not specify

a particular type of cell that makes up the skin, which is made of various types of

cells of different sizes. Though a red blood cell is considered small at about seven

micrometers when human cells can range from tiny, two micron platelets to 100

micron adipose cells, there is little reason to believe an eighth grade student would

have this type of detailed knowledge. A better tool would have omitted virus,

protein molecule, bacteria and red blood cell. This would simplify the ranking and

give a clearer view of the basic hierarchy of relative sizes.

Qualitative Results

   Problems with the Atom/Cell Test. A contributing factor to the lack of

evident significant correlation between change in Scaling scores and change in Part

II of the Atom/ Cell Relationship test may be due to the nature of the second part of

the Atom/Cell relationship test. This part of the test was open-ended, and though

some students were able to perform very well in indicating which objects were

made of atoms and which were made of cells in the objective portion of the test, they

may have misinterpreted the questions in the open-ended portion (Part II) or had

difficulty articulating their ideas. For example, one student, NiC (pseudonym),

scored a very high 25/26 on Part I of the Atom/Cell post-test indicating that she

could correctly identify objects made of cells and objects made of both atoms and cells. However, her answers on the open-ended portion indicated possible misinterpretation of the questions. Here is an excerpt from NiC's A/C Part II post-test with a rubric score of 4 in which she replies to various questions:

3. Explain as clearly as you can what an atom is.
They are stuff that takes up objects.
...
5. Are atoms and cells similar? If so, explain.
Yes, they are both in living things and are small
6. Are atoms and cells different?
Yes, atoms can be in non-living things and cells can't.
7. Are atoms and cells related to each other?
No.

This student clearly has some understanding of how atoms and cells both play a role in living things. However, the statement: "*They are stuff that takes up objects*" is unclear. What is meant by "takes up objects"? Does she mean "makes up" objects? In the first objective part of the test, every object she marked as "Made of one or more CELLS" she also marked as "Made of one or more ATOMS"; however when asked if atoms and cells are related to each other, she simply answers "No." This lack of clarity limits her score on the rubric.

Another example is student JaD who scored 23/26 on Part I of the Atom/Cell post-test with the following responses to the open-ended Part II:

1. Explain as clearly as you can what a cell is.
A cell is part of your organism.
2. You just identified some items that you said were made of at least one or more cells. How did you decide which items were made of cells and which were not?
by deciding which ones were alive or dead between objects
3. Explain as clearly as you can what an atom is.
an atom is a positive negative charge that makes everything
4. You just identified some items that you said were made of at least one or more atoms. How did you decide which items were made of atoms and which were not?

everything has atoms
5. Are atoms and cells similar? If so, explain.
they are similar by how they make stuff
6. Are atoms and cells different?
there different by shape and size and atoms make everything
7. Are atoms and cells related to each other?
no they aren't related to each other

Here again, we have a student who states that atoms and cells both make up things,

correctly identifies those things in the objective portion, makes a distinction

between cells being part of living things and atoms being part of everything, but

then, when asked if they are related, says that they are not. It is possible that

students are interpreting the question about relationship in different ways that may

lead to confusion.

Regardless, the highest rubric scores were reserved for students making the

clearest statements about atoms making up all objects including cells, and cells

making up living things. Students such as JaD above, could not score a 6 on the

rubric due to the lack of clarity in their responses even though they made numerous

correct statements about the nature of both objects. Although there were

shortcomings to the open-ended form of assessment, there were definite changes in

rubric score between the pretest and the posttest on that portion. Those changes

can be used to look at the data in a different way as shown in the following section.

Quantification of Qualitative Interview Data

Identifying a Correlation Between Improved Atom/Cell Relationship

Understanding and Understanding of Protein Synthesis. In addition to seeking a

correlation between scaling ability and understanding of atom/cell relationships,

this study proposed to identify a correlation between understanding of atom/cell

relationships and understanding the process of protein synthesis. Following the

classroom unit of lessons on carbon chemistry and macromolecules, students were

given a two-day lesson on protein synthesis in cells. Following those lessons,

interviews were conducted in order to determine student understanding of the

complex process of protein synthesis.

Examples of Scoring for Higher-Level Statements. As mentioned earlier in

the methodology section, given the nature of the interview, it would not be difficult

for participants to explain the diagram by pointing out each object in the order in

which it is involved in the process. This may indicate knowledge of the correct order

in which steps take place, but would not necessarily indicate understanding of the

process or even understanding of what happens at each step. For example, below is

an excerpt from an interview that resulted in a rating of one, the lowest rating:

> Ro (psuedonym): The protein synthesis steps, first a DNA passes
> through an RNA polymerase and um unzips to get the code *(points to*
> *polymerase and DNA)*, then it, RNA gets a code, no makes…gets a code
> to form a copy, right here *(points to mRNA)*…like…I think. *(pointer*
> *follows along mRNA leaving nucleus and out to ribosome)* then it
> attaches to a ribosome, and the tRNA attaches to amino acids, and
> um…another one does the same, too *(pointing vaguely to and near*
> *tRNA and ribosome complex)*…another tRNA, and… I think that's all I
> remember.

The statement portion, "…first a DNA passes through an RNA polymerase and um

unzips to get the code *(points to polymerase and DNA)*, then it, RNA gets a code, no

makes…gets a code to form a copy, right here *(points to mRNA)*…" was counted as an

E (cause/effect) statement as well as an S (structure/function) and a C

(characteristic) statement. The E was because the student indicated a cause and an

effect – the DNA passed through the polymerase as part of a process. It unzipped it

to make a copy. The S was because he indicated that the polymerase had a particular function, and in order for it to work, the DNA had to pass *through* its structure and get unzipped, indicating the double-stranded nature of the DNA. The C was for indicating the characteristics of DNA as being double stranded so as to need unzipping and having a code inside it. After that statement, the student's description deteriorates into a series of objects attaching to other objects in a series. There is no further elaboration regarding characteristics of the objects, how their structure follows their function or the logical connection between steps. No further statements are counted from that excerpt.

Later in the interview, I asked Ro some questions to prompt further elaboration:

Interviewer (I): okay, um can you tell me what some of the things that are in the picture and what their jobs are?

Student(S): This is an RNA polymerase *(points to RNA polymerase)*. It unzips the DNA *(points to DNA)* to get the code for the RNA *(points to RNA)*. This is the ribosome *(points to ribosome)*...um...no, wait...um...this is tRNA *(points to tRNA)*, it transfers the RNA from places, um, and well...this is the nucleus *(points along nuclear boundary)* of the cell, which first it needs to go through in order for this *(points generally to ribosome complex and surrounding items)* to happen...and... I think...that's all I know.

At this part of the transcript, the statement, "...It unzips the DNA *(points to DNA)* to get the code for the RNA *(points to RNA)*..." is identified C and E for the same reasons above, but those are not counted toward the total because they are a repeat of what the student has already stated. However the remainder of the statement rates another S and an E because Ro indicates that there is the process performed by the

RNA polymerase must happen in the nucleus (S-nucleus houses DNA and replication process) first *in order for* (E) the process at the ribosome to occur.

Though Ro is given a number of subsequent prompts to elicit greater detail, he can tell little else about the process:

> I: Okay, you told me that thing is an RNA polymerase, um, can you tell me about it, anything else about it? What…you told me what it did.
> S: It unzips the DNA to get the code.
> I: But, what is it?
> S: It's like…um… *(very long pause)*
> I: If you're not sure, that's okay, just tell me you're not sure
> S: I'm not sure
> I: Um, so, do you know where that RNA polymerase might come from?
> S: um…it comes from atoms, that's all I know.

This excerpt gets a point for O because Ro states that the polymerase comes from atoms, but he can offer little else. He is unable to describe the origin of the polymerase as the same process he is describing. In the excerpt below, a different student, Co, who ultimately scored a four— the highest possible— in the Protein Synthesis rubric, makes a statement indicating that the polymerase is a protein made by the same process that is being described in the diagram.

> I: okay, do you know anything about how it makes you you?
> Co: is that, …it has certain orders that it kind of…has specific details from like, parents and stuff, um…hmmm…
> I: okay, …
> Co: it gives orders, I guess. Like, it has instructions.
> I: oh, okay. So, it has instructions, and, um, what's DNA made out of? Do you know?
> Co: um…nucleic acids. I forgot what the D stands for.
> I: deoxyribo - it's not important. So, it's made of these nucleic acids, and what are nucleic acids made out of?
> Co: um…macromolecules
> I: okay
> Co: It's a type of macromolecule, um
> I: Wait, the nucleic acid is? or the DNA is?

Co: the nucleic acid is a macromolecule, and it, um and nucleic acid is made out of atoms ...

I: okay, what's that yellow thing that's on it? *(pointing to RNA polymerase)*

Co: it's, um, RNA polymerase...no, it's not...

I: yeah, it's labeled right there, but what is it?

Co: um... it – like, what's its function?

I: sure

Co: It makes the copy of the uh...messenger RNA.

I: Do you know what the polymerase might be made of?

Co: um...the ones that went through the same process of the proteins.

I: It's made out of proteins?

Co: It's ...yes, I think so.

[Later in the interview, Co indicates that proteins are also made of atoms.]

Although Co is not very confident, his response shows a deeper understanding of the protein synthesis process in that it not only makes proteins for the cells to use, but it makes proteins that become part of the cell and that the cell will even use some of them in continuing this very process.

The highest rubric score (four) was reserved for an overall explanation that matched the following description:

(4) Process is described as a series of steps for the purpose of building a polymer protein composed of a chain of smaller parts. The purpose of the protein is to aid in the functioning of the cell or as part of the cell itself. It is clear that the process is driven by the code found in the DNA, and the code is preserved through the steps by the various molecules involved so that the protein is created correctly. Objects involved in the process have certain attributes that aid their function. Steps are describes in terms of one step leading logically to the next.

While the lowest scoring explanations fit the following description:

(1) Process is described as occurring in one or more cells for the purpose of building something. Purpose of the product is unclear. Description is a series of steps without elaboration regarding the purpose of the steps or description of objects involved.

Results of Comparison Between Improvement in Atom/Cell

Relationships and the Understanding of the Process of Protein Synthesis. In

Table 8, both the pretest and posttest rubric scores are indicated along with code

letters identifying different participants. A score such as 2-3 indicates a pretest A/C

part II rubric score of two and a post-test A/C part II rubric score of three. A score of

3-3 in the first column shows that the pretest and posttest scores were the same.

Again, the highest score on this rubric was 6. The table also shows the rubric scores

obtained from the protein synthesis interviews where a four-point rubric was used

with 4 being the highest score obtainable. The remaining columns show the total

number of higher level statements made by each participant in the interview and

then further breaks those down by category. Since the first part of this study was

considering the effect of understanding scale on understanding the ontological

hierarchy between atoms and cells, there is also a column showing the total of

higher-level statements without consideration for levels of hierarchy removing that

as an assumption for understanding the process.

Table 8
Summary of scores for protein synthesis interviews showing number of each type of higher-level statement type used by participants in the course of the interview. Students obtaining only a novice level of understanding are on the top half of the table. Students obtaining an expertlevel of understanding are on the bottom.

student code with A/C part II rubric pretest and posttest scores	interview rubric score	number of higher level statements made in interview	higher level statements minus O (ontological levels)	O - ontological levels	S - structure/function	C - characteristic	E - cause and effect
2-3 Jo	1	9	8	1	4	1	3
2-3 Ma	1	3	3	0	1	1	1
3-3 Ro	1	8	5	3	2	1	2
4-3 Sh	3	14	12	2	4	3	5
3-3 Al	2	12	10	2	5	2	3
2-3 SaL	1	7	4	3	2	1	1
4-4 Da	2	8	7	1	4	0	3
averages	**1.57**	**8.71**	**7.00**				
4-5 Me	4	25	16	9	3	6	7
3-6 Mi	4	29	20	9	10	3	7
3-6 Ha	4	28	19	9	7	6	6
3-6 SaN	4	21	15	6	8	3	4
2-6 Li	3	18	13	5	6	2	5
3-6 Co	4	26	17	9	4	3	10
averages	**3.38**	**24.5**	**16.7**				

From this point forward, all students in the interview group who did not progress further than novice level (rubric score of 3) in the Atom/Cell posttests will be referred to as the novice group. The remaining students will be referred to as the expert group. From the novice group data, it is clear that students from this group who remained at the novice level of atom/cell relationships also made fewer higher-level statements showing understanding of the process of protein synthesis (Table 8, top half). This is shown graphically in the charts below (Figures 3 and 4). Figure 3

shows the number of statements showing higher-level understanding made by individual students interviewed. Pretest and posttest Atom/Cell part II rubric scores are shown above the identification code for each student along the x-axis. Students are arranged along the x-axis such that students with lower A/C Part II scores are on the left and students with higher scores on the right. Figure 4 shows the number of statements, omitting those referring to ontological levels, showing higher-level understanding made by individual students interviewed. Pretest and posttest Atom/Cell Part II rubric scores are shown above the identification code for each student along the x-axis.
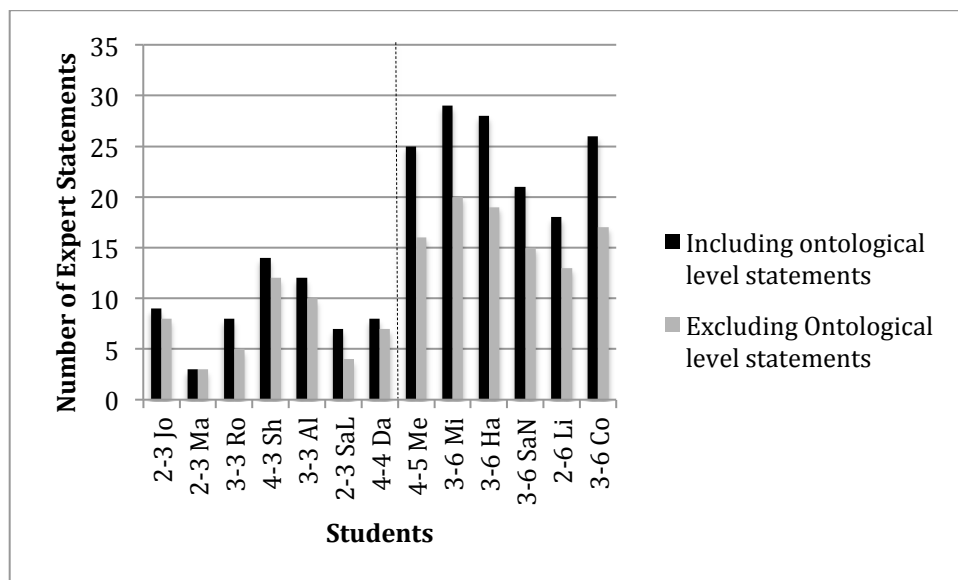

Figure 3. Number of higher-level statements made by students in the protein synthesis interviews. The dashed line indicates the division between students obtaining only a novice level of understanding of atom/cell relationships on the left, and those obtaining an expert level of understanding on the right as per their A/C Part II rubric score. Pretest and Posttest rubric scores are noted above the letter codes identifying each student.

Figure 3 shows that students who scored a five or six (Developed or Expert) score on the posttest rubric for atom/cell relationships, on average included 25.5 expert statements in their protein synthesis interviews. That is an average of 15.79 more expert statements than students who scored a four (Emerging) or lower. The number of expert statements in the interviews overall ranged from three to 29 per interview. One focus of this study was to determine influence of scaling abilities on student understanding of atoms, cells and subsequently a cellular-level biological process. For that reason, statements that show that the student is connecting concepts across ontological levels was included and counted as a higher level statement. To avoid a possible circular argument—that improvement in ability to scale across levels will improve ability to link ideas across levels—I also looked at the data after removing the ontological level statements. Even with the ontological statements excluded from the data (as shown in Figure 4), students with final A/C rubric scores of five or six had an average of 16.7 expert statements, or 9.7 more than the other students, with total expert statements per interview ranging in number from three to 20.

Student "Li" who began with an A/C rubric score of two and improved it to six, was able to outperform the students who did not develop their atom/cell relationship understanding beyond the novice level. Students who began with a lower level understanding of atom/cell relationships at the outset may have had greater difficulties developing their understanding in the same amount of time as the other students. However, if we take only the four students ending at Novice level who began at the same levels as those who ended at Developed or Expert, and

compare them with those six students ending at Developed or Expert level, the

Novice students still only averaged 10.5 expert statements overall in their

interviews as compared to the average 25.5 expert statements made by the

advanced students.

Additionally, the interviews were scored according to a rubric that

considered a more holistic view of the student's explanation (see Appendix D).

Students who were able to improve their understanding of atom/cell relationships

from novice to expert were able to give more thorough and detailed explanations of

protein synthesis as indicated by their interview rubric scores shown in Table 8.

Those with only a novice level of understanding averaged a score of 1.57 out of 4,

while those with an expert level of understanding averaged 3.38. All but one of the

six expert students scored a 4/4 on the rubric (see rubric description in section

titled: Quanitfication of Qualitative Data), whereas among the students who only

reached a novice level of understanding of atom/cell relationships, only one scored

a 3/4 on the rubric with the others scoring 2 or 1. These low end descriptions met

or fell short of the following description:

(2) Process is described as a series of steps for the purpose of building a polymer
protein composed of a chain of smaller parts. The purpose of the protein is to aid in the
functioning of the cell.

1. I feel like I'm left hanging with this last bit of evidence. You talk about a holistic
rubric, but then I don't get to see those overall results. Or did I miss that somewhere.
Those findings need to be in a figure also, yes?

2. I needed it to be more clear where you left your results for your first research Q
and came to the results for the second research Q. You'll see where I say that you
need a better subtitle. See https://owl.english.purdue.edu/owl/resource/560/16/

Conclusions

Answers to Research Questions

This research sought to discover whether or not an improvement in student scaling ability would correlate with an improvement in student understanding of atom/cell relationships. Students did show improvement in both scaling and understanding atom/cell relationships as shown by the scores from their pretests and posttests. Based on those scores, there was significant correlation directly between scaling ability as measured by the Scaling pretest and posttest and student understanding of atom cell relationships as measured by the first part of the atom/cell relationship pretest and posttest where students identified objects made of atoms and objects made of cells. However, students frequently had difficulty articulating ideas clearly in the open-ended portion of the atom/cell relationship pre and posttests, and there was no clear correlation between the scaling scores and atom/cell relationship rubric scores. In addition to the overall scaling scores, I specifically parsed out the *size* relationship between atoms and cells from among the other items on the Scaling test. There was a sizeable increase in overall atom/cell relationship understanding among students who changed from an incorrect size ranking or no size ranking between atom and cell to a correct ranking. A greater percentage of students (59% v. 17%) were able to make a 3 to 4 point improvement in atom/cell relationship understanding as shown by their A/C II (rubric) scores if they learned the correct size relationship between atoms and cells as compared to those who did not. This shows that students who understood the

size relationship did have an overall better understanding of the nature of atoms and cells. This evidence does suggest that scaling skills may contribute to understanding of how atoms and cells are related. When students could scale more accurately, they also did a better job at correctly identifying which objects were made of atoms and which were made of cells; and if they correctly described the atom/cell size relationship, they also scored better on the rubric. This suggests that scaling skills help students to understand how atoms and cells are related, but to confirm that, a future study would need a more objective atom/cell relationship test that could more deeply probe student understanding without the ambiguity of the open-ended responses.

The second goal of this research was to determine if a better understanding of the relationship between atoms and cells would correlate to a students' ability to understand protein synthesis. In the student interviews explaining protein synthesis students who had a more expert understanding of atom/cell relationships also gave a much more thorough and detailed description of the protein synthesis process. A typical interview on protein synthesis given by a student with expert atom/cell relationship understanding began like this:

> S: Well, this is protein synthesis. And, it starts out where the DNA goes through the RNA polymerase - that (points), and this unzips the DNA, which makes a copy of it, so now there's like two of the DNA. So, now there's and extra. It's the messenger RNA. So it leaves the nucleus and goes into the cytoplasm. And, the messenger RNA travels to the ribosome, and once it's there, it goes through, and these, tRNAs, the little blue things, they collect amino acids on the top of them, and they go through and they connect with the R, with the messenger RNA, and the amino acid they collected goes, and they make bonds to form a little chain…as they go through… and…as they go through, they match up

> *with the RNA so they go in a specific order to form the right chain. Then*
> *after this has been, or after this has had all the pieces put together, it*
> *goes through and is formed into the right shape so it can be used as a*
> *protein in the cell.*

whereas a typical start to a novice student's explanation began like this:

> *S: Oh, well there's this DNA. It's like splitting. Like, you can see it…*
> *I: okay (prompting)*
> *S: and then…there is where the um, tRNAand um, ribosomes they like*
> *bond together…*
> *I: okay (prompting)*
> *S: cause they're right there, and… …um…the mRNA comes into this, wait,*
> *what is this called again?*

Though the sample size was small, the expert students gave consistently more

developed explanations for the process of protein synthesis including more remarks

about the ontological nature of the objects involved in the process, the

characteristics of those objects, their structure and function and the causes and

effects of various actions within the process. In addition, they generally gave more

detail and description from the outset with less prompting and fewer questions

asked by the interviewer. Of the students giving interviews who began at the same

level of atom/cell relationship understanding, those who improved that

understanding to an expert level could better explain protein synthesis, but given

the small sample size, it is impossible to apply a statistical test that would give

meaningful support to indicate causation. Considering the many factors that

contribute to a student's success, it is not possible to make generalizations. It is

possible that the students who were more successful at learning atom/cell

relationships were also more successful at learning protein synthesis because they

had better study habits. It would be interesting to expand a study such as this over a larger group of similar students.

Confirmation of Previous Research

Though the work of Tretter et al. (2006a) and Castellini et al. (2006) show that conceptualizing size across scales is difficult, the results of this study confirm previous research claims (Jones et al., 2007; Magana et al., 2008) that classroom interventions can improve students' ability to scale macro, micro and nanoscale objects. Even with the shortcomings of the scaling test, students showed significant improvement in their scaling abilities. These results also confirm those of other studies (Harrison & Treagust, 1996; Sewell, 2002; Roland 2009) that find that atom/cell misconceptions are persistent as shown by 17% of students still unable to correctly rank atoms and cells by size in the Atom/Cell Part II posttest.

Limitations

As with most qualitative research, there exists a level of ambiguity in the assessment and scoring of participant responses. For example students' improvement in their understanding of the relationship between atoms and cells was shown more by part I than by part II of the Atom/Cell test because of the lack of clarity in written answers which led to ambiguity in scoring. An attempt was made to mitigate this by considering agreement in responses to the first part with remarks in the second part when creating the rubric score, but there always remains an element of subjectivity when evaluating open-ended answers to questions.

There was no actual control group that received the same instruction as the other students but without the interventions for improvement in scaling. Having such a control group would have been highly desirable, but was decided against for a variety of reasons. First, the only other teacher on the campus who teaches the same subject does not teach in the same style or with the same lessons that I do. Dividing my own six classes into an experimental and control group would have made the group sample sizes very small. The students included in the analysis already had to meet the criteria of having taken all test portions and attended all protein synthesis lessons. Meeting these criteria already had reduced the number of students available to me from 168 to 123. As well, the six classes were clustered with various levels, which would have made it impossible to have two similar groups. Finally, after reading the convincing research of others showing the effectiveness of the tools used to teach scale, I could not exclude half of my students from that instruction with good conscience.

Limited by the factors elaborated above, the sample size for the interviews is small – thirteen interviews. With a sample this small, it is impossible to control for a variety of factors. There are a number of factors that can affect the success of a student's interview beyond their grasp of the topic being explained, such as English language deficiencies, or difficulty with articulating ideas verbally or shyness when being recorded. There is no way to control for a student's motivation level, or how they are feeling that day. It would have been desirable to have a much larger interview pool. Anecdotal evidence can be drawn from the interviews, but with only thirteen, it is not possible to make broad generalizations.

Additionally, there were some problems with the scaling tool. If this study were to be repeated, the scaling tool would have to be revised according to the criteria elaborated above.

Implications for teaching and education

Based on the data in this study, there is enough evidence to support the integration of scaling skills in the teaching of life and physical science topics. I will continue to include lessons on size and scale in my eighth grade curriculum to support my students' conceptions of atoms as the building blocks of all matter including living cells. Unfortunately, there is nothing in the current state standards of California that address scale, and consequently, no real support in California textbooks that address scale. Though the Next Generation Science Standards do include Size and Scale as a crosscutting concept, corresponding curricular materials or learning progressions that integrate this concept into curriculum have not yet been developed. Though many teachers are capable of doing so, few have the time, in addition to their other teaching duties, to develop comprehensive curriculum. Future research should focus on the development of learning progressions and curriculum for the Next Generation Science Standards that integrate the crosscutting ideas such as Size and Scale to ensure that they are actually taught in the classroom.

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Appendix A: Atom and Cell Pretests/Posttests

Cells and Atoms Pretest   Name _____ per _____

1.Explain as clearly as you can what a cell is.	3.Explain as clearly as you can what an atom is.

	Put an X in one of the columns for each item.	Made of one or more CELLS	NOT made of any cells.	I don't know.			Put an X in one of the columns for each item.	Made of one or more ATOMS	NOT made of any atoms.	I don't know
a	animal cell					a	animal cell			
b	bacteria					b	bacteria			
c	banana					c	banana			
d	cloud					d	cloud			
e	diamond					e	diamond			
f	skin					f	skin			
g	heat					g	heat			
h	light					h	light			
i	mushroom					i	mushroom			
j	paper clip					j	paper clip			
k	plastic cup					k	plastic cup			
l	leaf					l	leaf			
m	muscle					m	muscle			

2. You just identified some items that you said were made of at least one or more **cells**. How did you decide which items were made of **cells** and which were not?	4. You just identified some items that you said were made of at least one or more **atoms**. How did you decide which items were made of **atoms** and which were not?

5. Are atoms and cells similar? If so, explain.

6. Are atoms and cells different? If so, explain.

7. Are atoms and cells related to each other? If so, explain.

Living/non-living

	Put an X in one of the columns for each item.	can be alive	canNOT be alive	I don't know
8a	copper			
b	atom			
c	lettuce			
d	element			
e	oak tree			
f	protein			
g	rabbit			
h	spider			
i	virus			
j	heat			

9. Explain how you chose which items could be alive and which could not.

Circle the best answer for question 10 and 11.
10. The size of an atom is _____ a cell
a. larger than
b. equal to
c. smaller than
d. an atom and a cell are the same thing.
e. I do not know the answer.

11. Using a standard classroom microscope, which of the following can be observed by a person?
a. atom
b. cell
c. both an atom and a cell
d. neither an atom nor a cell.

Part II: Ranking items by size

Look at the list of 16 items below. Read through it carefully. If there is anything on the list with which you are not familiar, or you really can't remember anything about it, draw a single line through it to cross it out. ~~Like this.~~

- water molecule
- DNA (diameter)
- bacterium (1 bacteria)
- protein molecule
- mitochondria
- cell nucleus

- atom nucleus
- ant
- virus
- skin cell
- carbon atom
- sunflower seed

- chicken egg
- average first-grade child
- human hair (diameter)
- red blood cell

Now that you have gone through the list and removed anything unfamiliar, look at each item and think about how big it is compared to all the other items. List them beginning with the smallest item, and ending with the biggest item. Use the blank space below to work out your ideas.

When you have decided what order to list the items, record your list in the chart. If you crossed anything off the list, you will have some blank spaces at the end, which is okay.

	Item		Item
1.	(smallest)	9.	
2		10.	
3		11.	
4		12.	
5		13.	
6		14.	
7		15.	
8		16.	(biggest)

Atoms/Cells Rubric

6 Expert	**Hierarchical relationship** Cells are the basic unit of living things. Atoms make up all matter including cells. Atoms are not living, and make up all matter. **Atoms are smaller than cells and make up cells.**	Clear articulation of these ideas. Choices on charts do not contradict written statements.
5 Developed	Cells and atoms are **both** structural units of other things. They both are in living things. Atoms are in both living and non-living things. *Atoms are smaller than cells. *Hierarchical relationship is unclear.	These responses sound like an expert response, but are not articulated clearly enough to make a definitive link between cells and atoms, rather it is strongly implied.
4 Emerging	At least **one** of the items has a structural purpose. They **both** are in living things. **Atoms are in both** living and non-living things. *Size relationship is unclear. Atoms same size or bigger. *Hierarchical relationship is unclear.	Cells make things, but atoms are just in things. OR Atoms make things, but cells are just in things. Atoms can make cells, but where atoms are consistently found is unclear or where cells are consistently found is unclear.
3 Novice	**Cells and atoms are not found in the same things.** Cells are in living things. Atoms are in non-living things only.	Atoms and/or cells are only in living things – indication that atoms or cells are not structural, but just found within objects. Relationship unclear. **X-choices in the chart on the first page contradict explanation.**
2 Unclear	Both are in the body, but different places. Contradictory answers. Nonsensical answers. **Some attempt at explanation using relevant vocabulary.**	Responses include remarks such as: *Cells make up everything.* *I don't know what an atom is.* "Cell" and "atom" seem to be used interchangeably.
1	I don't know/ not sure/ written response, but no attempt at an answer.	
0	no answers/blank	

Appendix B: Powers of 10 Activity

General Overview:

Introduction: What does "scale" mean? See Powers of 10 on a grid	~ 15 minutes
Grouping Items Pre-viewing: student worksheet	~ 10 minutes
Whole class: Powers of 10 video remove front matter	~ 15 minutes
Individual/small groups: Revise ideas for grouping objects	~ 10 minutes

Estimated Time: 45 minutes

Purpose:

This lesson introduces students to the idea of using multiple scales to describe and connect systems. Students at the middle school level are likely aware of different scales, but possibly resort to describing systems and processes at the macroscopic scale because it is visible. This activity begins to teach students about 4 benchmark scales and the Powers of Ten. The lesson begins by eliciting students' understanding of atomic-molecular, microscopic/cellular, macroscopic, and large-scale systems. The students then watch the Powers of 10 DVD (17 minutes), a video that shows the relative size of systems, from galaxies to subatomic particles. The video is approximately 17 minutes, but if time is an issue, the introductory material at the beginning of the video can be skipped (view video ahead of time to determine whether or not to use the full 17 minutes). The video should be used as a starting point for 1) revising students ideas about scale, 2) showing how systems can be viewed from multiple scales, and 3) providing students with a Powers of 10 framework for comparing different systems. After the video, the students have the opportunity to revise and modify their understanding of scale and systems. At this point, the main objective for middle school students is to start establishing 4 "benchmarks" for thinking about scale: atomic-molecular, microscopic/cellular, macroscopic, and large-scale. Students will build on these benchmarks in Activity 2 and then connect the benchmarks to Powers of Ten in Activity 3 when they use Powers of Ten as a tool for comparing systems.

Materials:

Powers of 10 DVD
Student copies of *Zooming In and Out*

Advance Preparation:

- Watch Powers of 10 DVD (17 minutes) and determine how much of the video to use
- Get equipment to play DVD
- Run copies of *Zooming In and Out* (if not provided by MSU)

Procedures:

Introductory discussion: Systems and Scale   ~15 minutes

1. Before watching the video, it is important that students have some understanding of 'scale'. Spend the first 10 minutes developing a reasonable definition for these terms with your students. Some possible discussion questions might include:

b.   What does the word "scale" mean to you? (try to cue students to move beyond measuring scales, such as weight scales).
c.   Possible definitions to use (you can use these before the video or wait until the discussion after the video, but at some point the class needs to have a common working definition for the terms 'systems' and 'scale' to use throughout the unit)
ii.   Scale: the **range of measurement** used for considering a particular system. You can use scale and measurement to compare the relative sizes of systems.

Macro Scale discussion:

Look at the handout with the grid. Notice that it is one big square.

Along one edge of the big square, you can see that it has been divided into ten smaller squares. Each of the sides on the smaller squares is **one order of magnitude, or ten times smaller** than the sides of the big square.

Look closely at each of the smaller squares. If you look along just one edge, how many smaller squares have they been divided into? **10**

Each side of the tiny square is **one order of magnitude or ten times smaller** than each of the small (medium) squares.

How many tiny squares are along the length of one side of the big square? **100**

Each side of the tiny square is **two orders of magnitude or 100 times smaller** than the side of the big square.

If we were to take these big squares and put ten of them together end to end, they would be 1 meter long. That meter would be **1 order of magnitude** or **10 times larger** than the big squares.

Now look at the table at the bottom of the page. The right side shows orders of magnitude and how they would be written in scientific notation.

If something is **1 order of magnitude** larger than something else, we would say that it is **ten times larger.** We would write that as $1x10^1$.

If something is **2 orders of magnitude** larger, we would say that it is **100 times larger**, and we would write that as $1x10^2$.

If something was **3 orders of magnitude** larger, we would say that it is **1000** times larger, and we would write that as 10^3.

What if something was a **million** times larger? **6 orders of magnitude and 10^6.**

Zooming In & Out: What Can You See?   **~10 minutes**

1.   Pass out the Zooming In and Zooming Out student worksheet. Read the instruction with students and tell students that the list of things at the beginning of the worksheet are different objects that were included in the video. Tell them that one way of thinking about scale is to group things in terms of 4 broad categories. These include atomic-molecular (things we cannot see or use a microscope to see; need a really powerful microscope to see), microscopic/cellular (we cannot see but can use a microscope to see), macroscopic (things we can see with our eyes), and large-scale (things that are too large to see with our eyes, but we can use representations and models to see, like a globe representing the Earth- the Earth being large-scale, the globe a macroscopic representation of Earth). Encourage the students to dissect the words, for example, discussing what "scopic", "micro", and "macro" means and

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develop a set of working definitions for each of these benchmarks scales. Tell students to look through the list on their handout and think about the video. Then have the students classify each system or component into 1 of the 4 broad benchmark categories.

Powers of 10 video   **~20 minutes**

2. Explain to students that they will watch a short film looking at how the same location can have many different systems at different scales. Students might want to take mental notes of what they see in the video, because images will change quicker than most will be able to write notes down. The DVD can be paused to allow students to further discuss particular images, but this can also wait until Step 4 below.

Zooming In & Out: What Can You See?   **~10 minutes**

3. Now, have students go back and look at their list and see if there is anything that they want to change. If you want to move something, draw a line through the item listed in the first column and write it into the space where you think it should go in the second column.

Reflective Discussion: Systems and Scale   **~next day 10 minutes**

4. The reflective discussion can take a variety of forms depending on the available class time. Have students share where they placed each item and give a reason for why they chose each scale. Prompt for reasons such as:
   You can't see it even with a microscope.
   You can see it with a microscope.
   It is smaller than (something you can see with a microscope).
   It is too big to see the whole thing at once.

Powers of Ten Grid
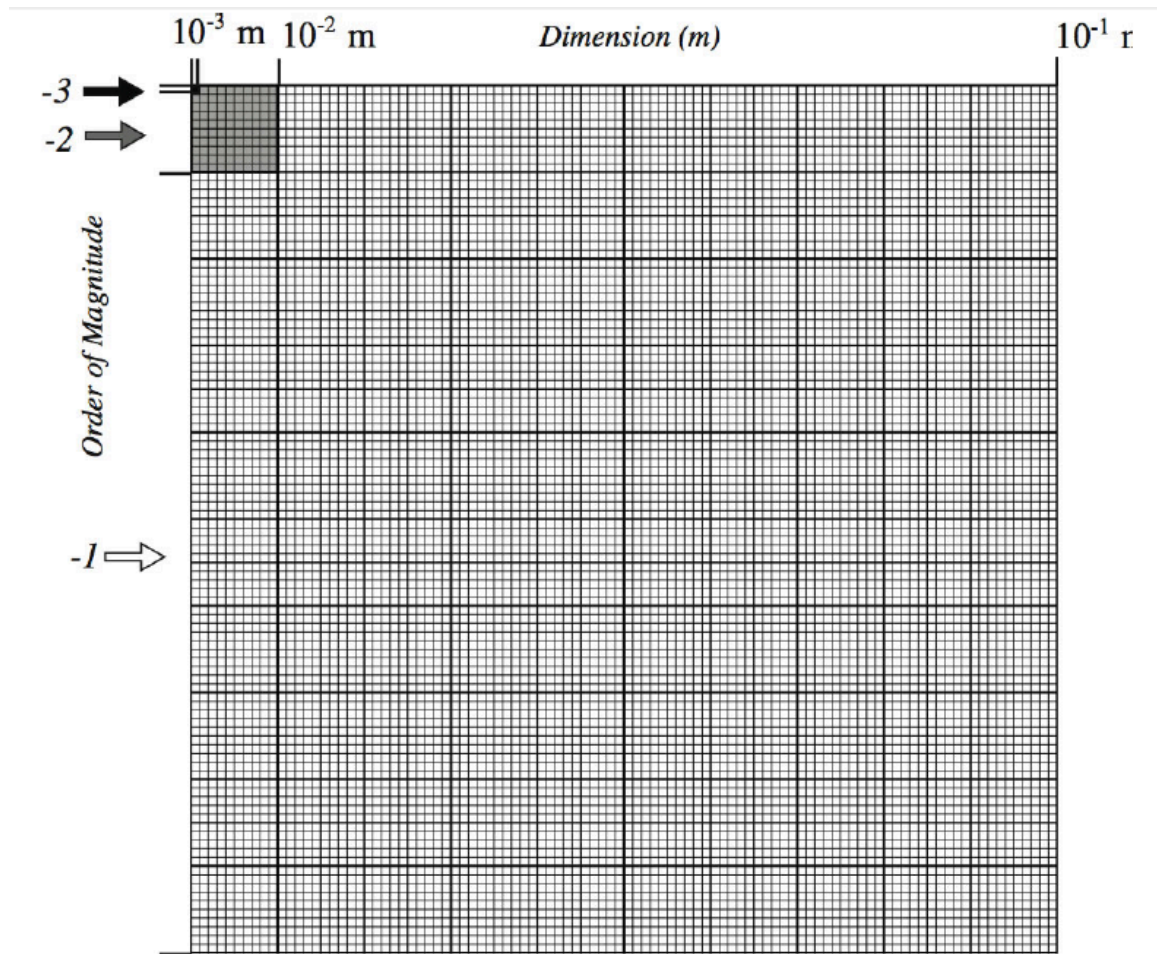
Figure 8.2 Orders of magnitude -3, -2, -1

Table 8.3 Decimal and Scientific Notation

Decimal Notation	Scientific Notation	Order of Magnitude	Decimal Notation	Scientific Notation	Order of Magnitude
.001	1×10^{-3}	-3	10	1×10^{1}	1
.01	1×10^{-2}	-2	100	1×10^{2}	2
.1	1×10^{-1}	-1	1,000	1×10^{3}	3
1	1×10^{0}	0	10,000	1×10^{4}	4

Name: _____ Per: _____

Zooming In and Out

When thinking about different scales we can generally group objects into one of four groups: 1) **nanoscopic:** atomic-molecular (things we <u>cannot</u> see or use a microscope to see; need a really powerful microscope to see), 2) **microscopic:** microscopic/cellular (we cannot see with our eyes, but can use a microscope to see), 3) **macroscopic** (things we can see with our eyes), and 4) **large-scale** (things that are too large to see with our eyes).

The following is a list of systems included in the Powers of Ten video. Try to sort these systems into one of the four categories described above.

Universe	Man or Woman	Cell Nucleus	United States
Hand	Earth	Lake Michigan	DNA molecule
Skin	Carbon Atom	Picnic Blanket	Galaxy
Capillaries	Skin Cell	Quarks	Chicago
City Park	United States	White Blood Cell	Solar System

Before Viewing	After viewing
What systems would you see at the atomic/molecular or **nanoscopic** level?	What systems would you see at the atomic/molecular or **nanoscopic** level?
What systems would you see at the **microscopic** or cellular level?	What systems would you see at the **microscopic** or cellular level?
What systems would you see at the **macroscopic** level?	What systems would you see at the **macroscopic** level?
What systems would you see at the **large-scale** level?	What systems would you see at the **large-scale** level?
Are there any systems that you are unsure about?	Are there any systems that you are unsure about?

Appendix C: Lessons: Scaffolding Size and Scale Using Analogies

Day 1

Students will be asked to order objects according to size and classify them in three different categories (see activity below graciously provided by Dr. Alejandra Magana of Purdue University). The labels of the categories will be defined by the students. After finishing this assignment, they will be given time to work independently with the scaling activity on the interactive activity on the . http://www.generation-nano.org/ website.

1.Order the objects according to its size from the smallest to the biggest.

a) Write the number of the object in the corresponding box.

Note: The objects do NOT have their real size

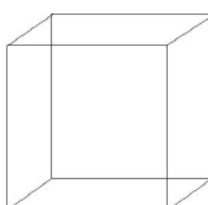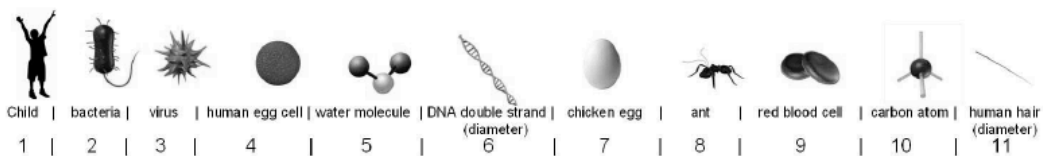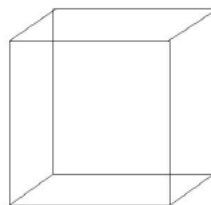| Chicken egg	bacteria	red blood cell (diameter)	DNA double strand (diameter)	human egg cell	water molecule	ant	human hair (diameter)	virus	carbon atom	child
1	2	3	4	5	6	7	8	9	10	11

Smallest _____ Biggest

2.Classify each object on the bins according to **similar sizes**.

a) Write the number of the objects inside the bins. Use as many bins as you require. You don't have to use them all.
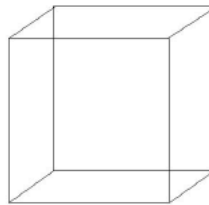
b) **Label** each bin with your classification

Child	bacteria	virus	human egg cell	water molecule	DNA double strand (diameter)	chicken egg	ant	red blood cell	carbon atom	human hair (diameter)
1	2	3	4	5	6	7	8	9	10	11

Label: _____

Label: _____

Label: _____

Day 2

Formal instruction will be delivered with the teacher explaining concepts and the students participating in discussion. The lesson concludes with an exercise consisting of classifying objects according to size. This lesson is titled "Conveying the Difference in Relative Sizes between Microscale and Nanoscale Objects at a Middle-school Level. This lesson was graciously provided by Dr. Alejandra Magana from Purdue University.

In this lesson, students are first introduced to the idea of nanoscience. Then they are shown scale on a number line organized by magnitudes of ten. After being given some examples of the sizes of objects at different magnitudes they are given some proportional analogies of familiar objects, for example the width of a pencil lead is ten times the width of a with of an adult's index finger nail; the height of a typical four-year old is ten times the height of a single-serving yogurt cup. After some examples with familiar objects, a comparison of analogies is set up between macroscale objects and micro and nanoscale objects, for example, the length of a person is one-thousand times the length of an ant, and a single bacterium is one-thousand times the width of a DNA molecule. After other example comparisons are given, students are asked to reassess their choices in the activity from the previous day.

Day 3

On the final day of the lesson, students are asked to work in teams to construct their own analogies which they will then present to the group.

Appendix D: Protein Synthesis Interview With Scoring Rubric

Protein Synthesis Interview

Interview Purpose:
The purpose of the interview is to assess the depth of understanding the student has of the cellular process of protein synthesis. The student will be asked to describe the process and the students responses will be analyzed and coded for the following "expert attributes":

correctly connecting ontological levels within a description (atoms to molecules to cells...)	O
connecting structure with function	Sf
attributing a correct characteristic to a structure	Ch
describe a logical cause and effect relationship between steps in the process	E

Interview Introduction

I am going to show you two diagrams of the cellular process of protein synthesis. Then I am going to ask you to explain the process to me as if you were teaching me and you were using it as a teaching tool. So you will want to look over each one carefully and decide which one you want to use. You may wan to use both. It is up to you. So right now, just take about four or five minutes to look over the diagrams and think about what is going on in them. Don't worry if there are some things you don't remember. This will not affect your grade. (Allow five minutes for the student to examine the diagrams).
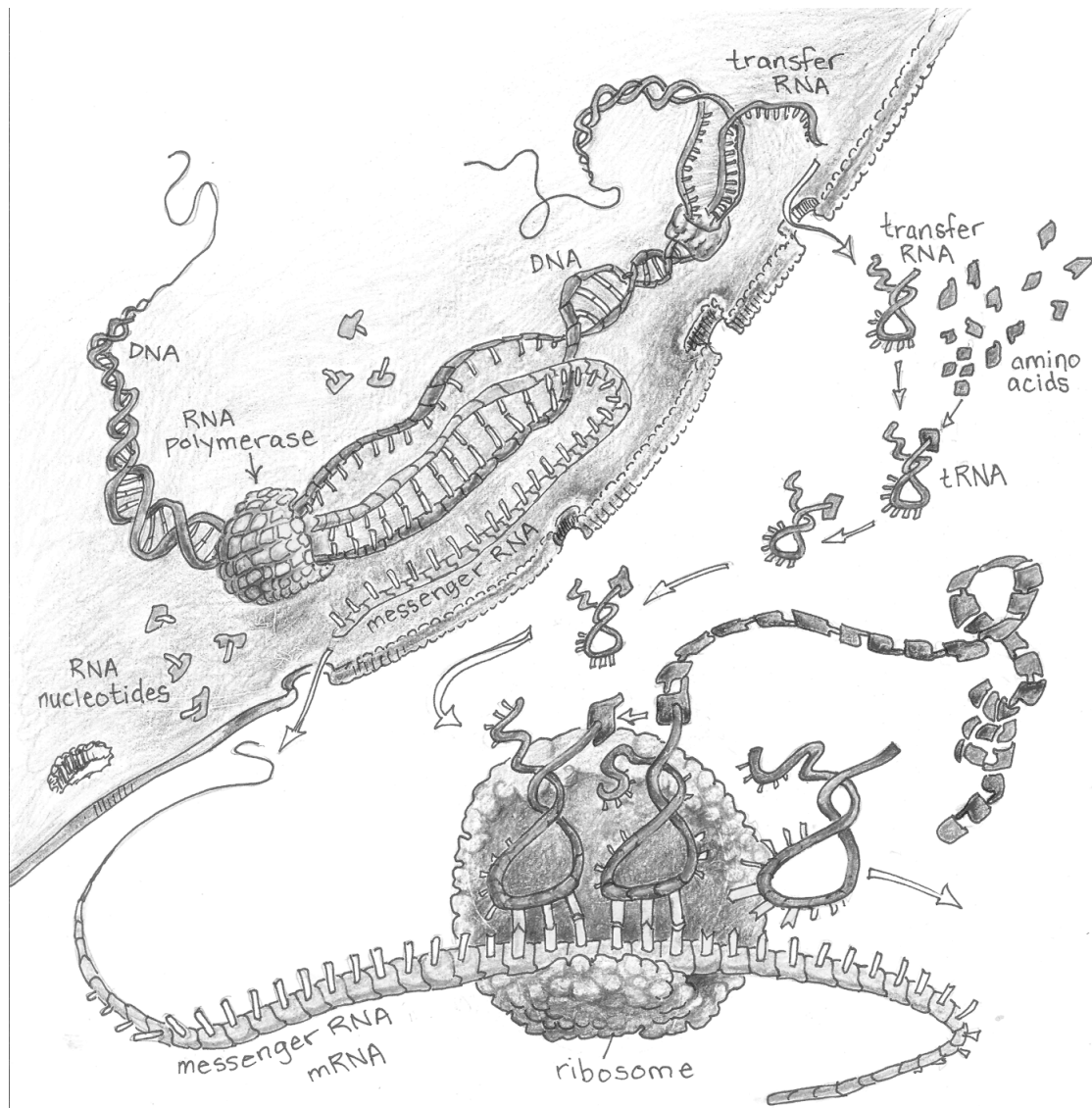
Okay, now that you have had some time to look over the diagrams, you can teach the process of protein synthesis to me. I will occasionally stop you to ask questions. Pretend I am your student, and you really want me to understand this process because I have a big test coming up. But, again, don't worry if there are things you get stuck on or don't remember, just do the best you can. This will not affect your grade.
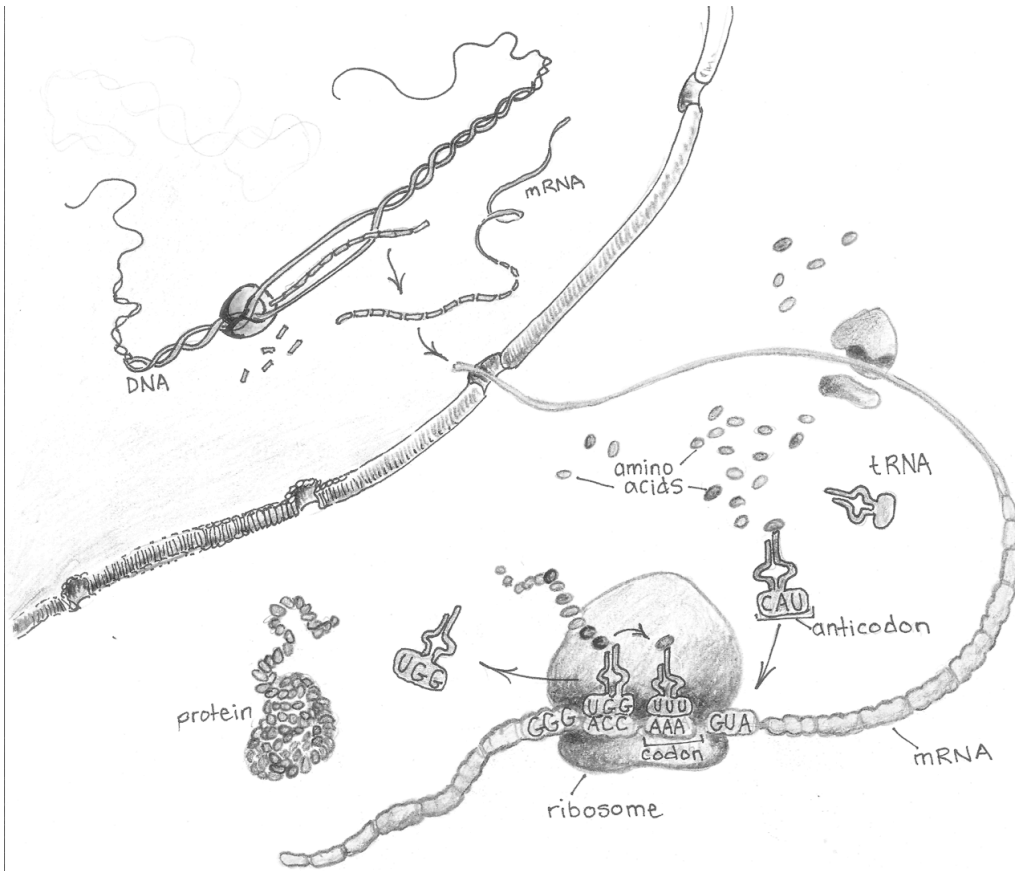
Note Sheet for Interview Responses

Sample questions	Notes on responses	codes
What process or processes are represented in this diagram?		
What is the function/result of that process?		
Where would this process occur?		
All cells?		
Only certain cells?		
What are some of the objects involved in this process?		
What can you tell me about any of these objects?		
What is its function?		

Where would it be found?		
What are they made out of?		
Where do they come from?		
Can you describe the steps in the process and describe what each object is doing?		
What happens first?		
What is the next step?		
What is the product at the end?		
What will it be used for?		

transfer
RNA

DNA

transfer
RNA

amino
acids

DNA

RNA
Polymerase

tRNA

messenger RNA

RNA
nucleotides

messenger RNA
mRNA

ribosome

DNA

mRNA

amino
acids

tRNA

anticodon

protein

UGG

CGG UGG UUU GUA
ACC AAA

codon

ribosome

mRNA

CAU

75

Protein Synthesis Interview Rubric

1
Process is described as occurring in one or more cells for the purpose of building something. Purpose of the product is unclear. Description is a series of steps without elaboration regarding the purpose of the steps or description of objects involved.

2
Process is described as a series of steps for the purpose of building a polymer protein composed of a chain of smaller parts. The purpose of the protein is to aid in the functioning of the cell.

3
Process is described as a series of steps for the purpose of building a polymer protein composed of a chain of smaller parts. The purpose of the protein is to aid in the functioning of the cell. The process somehow includes the code found in the DNA. Objects involved in the process have certain attributes that aid their function. The steps involve matching of codes. Steps are described not just as a series, but in terms of how one thing leads to another.

4
Process is described as a series of steps for the purpose of building a polymer protein composed of a chain of smaller parts. The purpose of the protein is to aid in the functioning of the cell or as part of the cell itself. It is clear that the process is driven by the code found in the DNA, and the code is preserved through the steps by the various molecules involved so that the protein is created correctly. Objects involved in the process have certain attributes that aid their function. Steps are describes in terms of one step leading logically to the next.

Appendix E: Generation Nano Student Handout

Name _____

Per _____

Generation NANO Exploration

Introducing Logarithmic Scale

1. At what unit size can you easily see the individual atoms?
a. nanometer   b. micrometer   c. millimeter

2. About how many microns is a single plant cell?
a. 1   b. 10   c. 100   d. 1000

3. How many times smaller is the single plant cell compared to the whole leaf?
a. 100   b. 1,00 0   c. 10,000   d. 100,000

Your Nano Height

4. What is your height in meters? _____

5. What is your height in centimeters? _____

6. What is your height in nanometers? _____

Sort the Samples/ Learn the Sorting Principles

7. What is the size (about) of a human egg cell? _____

8. How many micrometers (microns) in a meter? _____

9. How many microns in a millimeter? _____

10. Red blood cells and human egg cells are both single cells. How much bigger is an egg cell compared to a red blood cell?
a. 100   b. 1,00 0   c. 10,000   d. 100,000

11. About how many times smaller than a bacterium is the width of a DNA strand?
a. 100   b. 1,00 0   c. 10,000   d. 100,000

When you are finished with the above questions and you have explored all you want to see on the website, go back to the handout from yesterday (Size and Scale Using Analogies – Day 1) and make any changes you wish to make.