International Journal of Engineering Education Vol. 28, No. 5, pp. 1068–1077, 2012
Printed in Great Britain

0949-149X/91 $3.00+0.00

Student Understanding of Nanoscience through the Gecko's Surface to Surface Interactions*

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Nanoscience education requires learning in a meaningful context. In the NanoLeap unit *Investigating Static Forces in Nature: The Mystery of the Gecko*, high school students were introduced to an interdisciplinary approach in nanoscience. As a summative assessment, 100 high school students wrote essays responding to the question, 'How does the gecko adhere to a ceiling?' Using design based research and qualitative theme analysis, researchers analyzed 100-student essay using the original scores given by their teachers. The findings supply four major themes and five subthemes that highlight trends in student understanding. Expectedly, students accurately described physical characteristics of the gecko, surfaces, and the coinciding principles of force at the nanoscale level. With language, more students used colloquial terms to describe scale than used references to numbers. Unexpectedly, almost half the students used words to describe their sense of wonder and value of nanoscience to understanding their world.

Keywords: nanoscience; assessment; qualitative; essay assessment; science writing; science assessment, high school

1. Introduction

How does a gecko stick to surfaces, even if upside down? High school students learning about nanoscience investigated this question. Teaching nanoscience for understanding provides complications since students cannot make natural ocular observations. Like much of science, pedagogical tools employed overcome this conundrum [1]. Tools included but are not limited to 'making thinking visible' [2], using metaphors [3], embedding concepts in a meaningful and familiar context [4], and the strategy of inquiry based learning [5]. Using these pedagogical tools [6], the Physical Science NanoLeap unit was conceived (http://www.mcrel.org/nanoleap/). The unit anchored student investigations surrounding the mystery of the gecko since a gecko could adhere to surfaces in natural circumstances [7]. The unit entitled *Investigating Static Forces in Nature: The Mystery of the Gecko* reflected the context in which the student learning would occur. This research analyzes the results of student responses to summative essay questions in order to ascertain how *young teenagers think* about nanoscience after a unit of teaching within a high school physical science course.

1.1 Challenges and opportunities surrounding scale and interdisciplinary nature of Nanoscience

Learners find comprehension challenging with objects smaller than human eye can perceive [8–11] since there are no common reference points from which learners can relate the new knowledge. Gaining a concept of scale takes mental 'landmarks' when the learner can relate the new information to something known. This is true regardless of size as immense as the universe or as small as the nanoscale 10^{-9} [12]. Tretter [12] found that experts used precise mathematical language to identify size. Middle school students did not use mathematical language, but instead, they used common experiences—referencing concepts formed outside of school. This finding demonstrates the developmental need of young adults and the need of teachers to relate common experiences to scaffold student understanding [8, 13, 14].

Student understanding is also developed through understanding the interdisciplinary nature of nanoscience [9, 10, 15], which both increases and decreases the challenges for teaching content in a high school setting. On the one hand, students learn best when content is interconnected. The interconnectedness encourages content taught in meaningful contexts, which can increase retention of

* Accepted 1 June 2012.

knowledge [16, 17]. On the other hand, the interdisciplinary nature of nanoscience demands that both the teacher and the students cultivate knowledge beyond that of traditional content [18]. For example, the most basic understanding of nanoscience involves scale, mathematical knowledge in traditional education, but to cultivate a sophisticate understanding of nanoscience, it is critical to understand scale [8, 19]. Though science and math are inextricably connected, it is typical that students do not experience in-depth interconnectedness until advanced science.

1.2 Essay assessment in science

Science assessment is a contentious issue [20] as teachers prepare for standardized tests and a single teacher arduously assesses 120-150 students in USA traditional high schools. Despite the challenges of assessment, multiple types of assessment provide valuable formative and summative data that informs teaching practice [21, 22]. Science assessment needs to focus beyond that of examining content/factual knowledge and delve into student understanding so that a teacher can appropriately scaffold learning [23]. In this section, we will specifically address essay assessment as a way to address student understanding.

According the National Academies of Science, the updated scientific framework calls for students to write and to illustrate concepts to develop 21st century skills [15]. More specifically, a 12th grade student should be able to do the following:

> Recognize the major features of scientific and engineering writing and speaking and be able to produce written and illustrated text or oral presentations that communicate their own ideas and accomplishments [15, p. 3].

The goal includes students' communication within a scientific community, where essay assessments are considered a means for meeting the goal. In addition, essay assessments have clear standards. Assessment for learning [24, 25] advocates giving clear standards to self assess or peer assess which consists of a scoring guide and specific points which students could answer questions [26]. More specific science standards are addressed in the unit.

1.3 Design of the unit and essay assessment

The USA National Science Foundation, as part of the nanoscience instructional materials development program, funded the NanoLeap project. In 2004, Mid-continent Research for Education and Learning (McREL) in partnership with the Stanford Nanofabrication Facility and Aspen Associates embarked on a four year investigation to determine if nanoscale science could be taught in high school science classes. The name 'NanoLeap' was chosen as to signify that this would be 'one small step' for teachers to determine how nano concepts fit into the physical science curriculum.

The unit engages students actively in the processes of experimental design, while exploring properties of matter. The central question that students consider throughout the unit is: '*What factors affect the strength of the contact forces between interacting surfaces?*' Since nanoscience and technology is an interdisciplinary field requiring the expertise of scientists and engineers from multiple disciplines, the lessons in the unit model the way scientists think as they study a real-life phenomenon by asking the same types of questions that biologists, chemists, and engineers have been asking for years. Indeed, through the investigation of the gecko, students access life science and physical science content and processes in developing an understanding of this phenomenon. This NanoLeap unit motivates students to study a real-world phenomenon and at the same time to give them a better understanding of the role that nanoscale science and technology plays in an ever-changing world. The unit provides students with opportunities to develop skills in experimental design that are often a major emphasis in state science assessments.

The unit presents lessons to be conducted in a sequence to scaffold student learning of the physical science concepts. Each lesson contains a teacher's guide, student journal prompts, and PowerPoint slides to guide investigations along with reflection questions for students to use to connect what they have learned to prior and future learning. Many lessons contain interactive technologies to enhance learning. The unit is organized by a series of questions that provide focus to the learning goals of activities. The following describes the sequence of the unit:

- Lesson 1: How Can a Gecko Walk on the Ceiling?: Students make observations and interpretations of geckos as they adhere to a surface. Students begin to consider different mechanisms for adhesion.
- Lesson 2: What Do We Mean When We Speak About Surfaces in Contact?: Students investigate what is meant by real verses apparent contact between surfaces by studying how much of their shoes are in contact with different surfaces.
- Lesson 3: What Are Your Ideas About Small Sizes?: Students compare objects in different size ranges to have a better understanding of objects at the nanoscale.
- Lesson 4: What Do We Learn When We Look More Closely?: Students conduct a thought experiment in order to explain how size, structure, and scale relate to a surface features and

describe the function of compliant surfaces with regard to adhesion.

- Lesson 5: What Types of Forces Can Hold Objects Together? Students describe what happens when the surface of an object is brought into contact with the surface of another object.
- Lesson 6: How MUCH Force Is Needed to Make an Object Stick? Students make force measurements of the adhesion of transparent tape on a desk surface to explain how the amount of adhesion changes when the conditions of the surfaces change.
- Lesson 7: How Do We Measure Forces at the Nanoscale Level? Students model how instrument probes can be used to characterize surface interactions.
- Lesson 8: How Can a Gecko Walk on a Ceiling? Students return to their initial question and describe how a large number of small forces (van der Waals interactions) at the nanoscale level can add up to macroscopic forces and connect this with how a gecko can adhere to a ceiling by drawing on learning experiences throughout unit. Students demonstrate their learning through responding to an essay assessment.

Assessments were embedded throughout the unit as formative assessments. Summative assessments included two essay assessments. In order to maintain focus, this article discusses what we learned from student responses to the second essay assessment. The second essay assessment that assesses students understanding of the entire unit content includes writing prompts, student rubrics and sample anchor papers are included in the teacher guide for lesson eight. Please find the essay question and rubric below:

1.3.1 Student essay assessment task

Student Directions: Essay Assessment: Demonstrate Your Understanding

Write a short essay in response to the prompt below. Base your essay on what you have learned about gecko adhesion throughout the unit. You may refer to your journal to help you plan your response; however, the writing in the essay should be distinct from your journal and be written in your own words (i.e., no copying). Your response to the prompt should not exceed one page. You may use diagrams to illustrate concepts; however, the diagrams should reinforce your written explanations not replace them.

Writing Prompt

Explain how the gecko can adhere to a ceiling. Your written explanation should include the following:

- Describe (with words and/or drawings) the surface-to-surface interactions between gecko 'setae' and a ceiling. Be sure to address the characteristics of both the setae and the surface. Include the shape, number, and size of setae in contact with the surface.
- Describe the variables affecting adhesion: the surface area, the surface contact, and the type of surface.
- Explain how a lot of tiny adhesive forces overcome the force of gravity.
- Describe the electrical forces and their role in gecko adhesion (i.e., interactions of charged particles between atoms of the spatula and the ceiling surface).

Refer to the instructional rubric on the next page to learn of the criteria that will be used to evaluate your writing.

1.3.2 Rational for the essay and rubric

The essay assessment aligns to the National Science Education Assessment Standard 'C' and 'D' [26]. Standard 'C' states that what is claimed to be measured is actually measured. The essay prompt describes variables related to adhesion that were the focus of the unit including an understanding of surface to surface contact at the nanoscale and how many tiny intermolecular forces are more than adequate to overcome the force of gravity.

The assessment standards stipulate authenticity of tasks (i.e., similar in form to tasks they will engage in outside of the classroom). Scientists often must write reports that summarize research or report on findings. Likewise, in the NanoLeap unit students are asked to summarize what they have learned over the three-week unit by responding to the prompt and the subpoints.

Finally, Assessment Standard 'D' states that the process used to assess student achievement must be fair to all students. The essay assessments contain rubrics and anchor paper examples that can be used in order to ensure fair scoring.

The essay assessments in the NanoLeap physical science unit are summative in nature and aligned with the concepts they are intended to measure. Not only do the essay assessments provide a rich set of data about student learning in their own voice, but they also were designed to be valid, authentic and fair.

1.4 Research questions

The research questions are an outgrowth of trying understand students' perspectives so that one can better design instruction.

Primary guiding question: How do high school students think about nanoscience within the context of gecko adhesion?

- Secondary questions: What are qualitative differences between the students who earn a higher score when compared with a lower score?
- What are the qualitative insights gained from essay questions that are less likely to be evident in traditional multiple choice tests in nanoscience?

2. Method

Design-based research (DBR) [27, 28] was conducted throughout the creation of the unit. This iterative approach to research allows the research to be grounded in context, similar to action research [29] but in addition, the work was supported by researchers to 'improve both practice and research in educational contexts' [30, p. 16]. Design-based research takes into account the full design of a learning unit and practical influencing theories in order to examine how students' understand. From an articulated design-base, researchers aim to uncover practical ideas that can inform teaching [31]. A principle of DBR requires teachers and researchers to work together [32]. The following two paragraphs describe the way in which the teachers worked with the researchers.

The first design phase involved ten selected teachers who applied to Mid-continent Research for Education and Learning (McREL) for an opportunity to design the unit. Selected physical science teachers helped to design the unit including the assessment with the input of the NanoLeap team (http://www.mcrel.org/nanoleap/People/index.asp), which included members from McREL and the Stanford University's Nanofabrication Facility within the United States of America.

Culminating the unit, teachers administered essay questions. During the field test of the unit, two evaluators used the rubrics and anchor papers to justify the scores that the student earned for their responses. Although approximately 300 students participated in the first implementation, 100 essays were processed from three teachers. Teachers scored the essays based on a 4-3-2-1 rubric rating (Table 1) as well as established anchor papers. The anchor papers were determined by consensus building among teachers and researchers. A four was the highest score and one was the lowest.

In accordance with DBR [31] the expertise of the teachers was valued as the teachers scored the essays. After scoring, the researchers looked for commonalities and patterns among the answers [31]. The researcher did not attempt to re-score student essays, but deferred assessment decisions to the teachers. Rather, the researchers used the essays to better understand the students thinking [31]. Therefore, though the authors used the data to analyze student conceptual understanding, the anonymous teachers completed the initial phase of analysis, which was used as the basis for further development.

2.1 Theme development

Theme development and agreement among researchers was nested in the principles of DBR with themes and systems relevant to teaching [3]. The authors read the essays and parsed the responses into the first three themes to reflect the

Table 1. Instructional rubric for essay assessment used by students while answering the prompt

Criteria	Advanced (4)	Proficient (3)	Partially Proficient (2)	Novice (1)
Writing Style and Mechanics	**Concise, clear, and engaging explanations** with **flawless** spelling, punctuation, and grammar.	**Concise and clear** explanations with **minor errors** that do not interfere with communication.	**Appropriate writing** format. Writer does **not appear to have carefully proofread**.	**Demonstrates little or no attention** to the writing format. Has great difficulty communicating.
Understanding of Content	• **Explanations** are complete* and **detailed, demonstrating a sophisticated** understanding of surface-to-surface interactions and forces affecting adhesion. • Writes in **own words** using **common & scientific language.** * Responses include answers to all four bullet points in the prompt.	• **Explanations** are **complete*** demonstrating an understanding of surface-to-surface interactions and forces affecting adhesion. • **No clear inaccuracies** or misconceptions. • Mostly writes in **own words** using **common & scientific language.** * Responses include answers to all four bullet points in the prompt.	• **Explanations demonstrate a basic** understanding of surface-to-surface interactions and forces affecting adhesion. • **May contain inaccurate** or **incomplete** information. • Writes using **scientific language** only, **not always writing in own words**.	• Explanations are **missing important information.** • **Does not demonstrate a basic understanding** of surface interactions and forces affecting adhesion and/or **contains inaccuracies.** • Writing is **not in own words**.

essay requirements (See Writing Prompt). From the themes, subthemes emerged based on patterns or trends demonstrated by students in their answers. The last theme emerged fully on the basis of the analysis with no preconceived notion of essay requirements. The first author completed the primary analysis. The second and third authors confirmed, questioned, and ultimately, validated findings. Inter-rater reliability was based fully on consensus since agreement was necessary for moving forward. Consensus was reached through the following: designers created the question and rubric, ten teachers implemented the essay question and rubric, two designers determined anchor papers, and three researchers parsed the essays based on teacher established ratings. This thorough collaboration of ratings between teachers and researchers, analysis of the findings was triangulated [30, 31] and allowed for insights into understanding student thinking for practical purposes [31].

2.2 Limitations and opportunities

Both the research design and analysis have particular limitations and opportunities. In the design, the initial scoring of the essays goes unquestioned since the teachers completed the ratings. This allows for increased researcher objectivity with qualitative researchers, but also, can decrease the validity of the essay scoring [30].

Looking for patterns within essays carries with it limitations. General writing ability, student motivation, and question comprehension all influence the essay quality, which may or may not reflect the student's comprehension of scientific principles [15, 33, 34] or more specifically, the nanoscience concepts. Students could have a greater or lesser comprehension based on the assessment type. All assessment yields an estimation of student learning. The strength of essay assessment is that one can gain insights into the way a student thinks. When students put ideas into their own words, language patterns emerge that are relevant to understanding the student's conception, not the teacher's conception, of nanoscience and technology.

3. Findings of essay characteristics

3.1 Theme One: Surface-to-surface interactions between the gecko 'setae' with characteristics of both the setae and the surface

3.1.1 Subtheme: Students accurately describe the characteristics of the setae and surface

Students were able to accurately articulate the characteristics of the gecko foot and the surface despite student rating. In the following examples, a

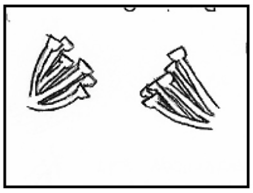

Fig. 1. Student 4A drawing of spatula shape tip of seta.

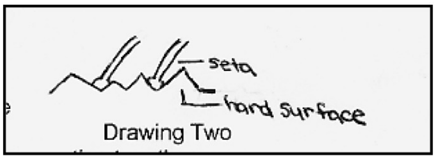

Fig. 2. Student 4A drawing of seta interacting with the surface.

student rating of a 4, 2, and 1 demonstrate similar features with few content errors.

The first example illustrates an essay that was rated a 4. Using accepted terminology with images to illustrate ideas:

> Geckos have about one million hair-like seta on their feet. Seta can only be seen with a microscope, because they are at the nanoscale level. Each seta has up to one thousand spatulas branching off the end off of it (Fig. 1). The gecko can stick to the ceiling because the tiny spatulas get into the bumps on the surface of the surface (Fig. 2). Even if the surfaces look flat, at nano level it is full of bumps resembling small hills (Student 4A).

In this essay portion, the student noted what *could not* be seen with the naked eye—the setae, spatula and surface, all of which demonstrate a need to observe at the nanoscale. However, the response contained a factual error in scale: seta is at the nanoscale level.

In contrast to an essay rated a 4, the 2 rated essay elaborates less, and there are more content errors:

> The gecko to climb on the roof of the ceiling uses its hair fibers. A gecko has 1 million seta -1 billion spatulas and 100-1000 spatulas per gecko. The gecko uses plenty much of its spatulas to stick to the ceiling. Using the 'AFM' (Atomic Force Microscope) you can see the gecko's tiny fibers (spatulas) on slide into small places (student 2Z).

It is interesting that the essay rated a 2 still used accepted terminology related to the concepts of scale and tools. However, this student seemed to 'mix up' facts by writing that the gecko has '100-1000' spatulas per gecko, rather than per seta.

Regardless of score, students used colloquial language as well as accepted content language to describe characteristics. For example, many students wrote words such as 'nooks and crannies' to describe the surface of materials. These semantics are probably influenced by unit lessons, which use metaphors so that students can relate to the information. Also, students used the word setae and spatula correctly. The commonality of words is expected especially when referring to the nanoscale or small.

3.1.2 Subtheme: Students use colloquial semantics to identify the meaning of nano-size

In order to describe nano-size, students used the words small, tiny or little regardless of their rating (Table 2). Students that score a four or three use the term 'nano' or 'micrometer' more than the 2 and 1, but all reverted to familiar language to convey meaning.

In this four rating, the student refers to a number, but also uses the word 'little': 'It has spatulas on its feet, little flat platforms on the underside of its toes and millions of seta branches on those spatulas' (Student 4D). The term 'little' was used to refer to a seta.

In the example of a 3, the student uses 'small' to refer to the spatula, 'The spatulas are so small they fit in between the rough surface on the Nano scale level' (Student 3F). The term nanoscale was also used to more specifically identify small.

The sample from a 1 uses the word tiny and small: 'Then, there's smaller hairs on that tiny hair' (Students 1A). Similar to the other examples, the students refers to the setae and spatula shaped tips, but there is no mention of the accepted content terminology when referring to scale. Interestingly, it was *rarely* mention that nano refers to 10^{-9} meters nor did students refer to numbers in the context of gecko or surface characterization.

3.2 Theme Two: Variables affecting adhesion—the surface area, surface contact, and the type of surface

In this theme, the findings indicate that most students grasp particular principles but at the same time, there is greater differentiation between those that earn a 4 and a 2 rating on the overall scoring of the essay than in Theme One. In the examples, students show a general understanding that the surface *is not* as smooth as it appears. The student score differences exist within the description of how the gecko adheres to the surface. In the examples below, portions of the students' essays will exemplify accuracies, inaccuracies and variations with the answers.

3.2.1 Subtheme: The surface area is not what it appears to be

Most students described the surface materials beyond what the naked eye could see. This is an example from a student who earned a 4 rating: 'The gecko's setae comes in contact with a surface by which the gecko adheres to the ceiling, the setae gets into all of the nooks and crevices of the surface to increase surface contact for better adhesions'(Student 4E). This general principle, that things are not what they may appear, is confirmed with a student who earned a lower score.

The student who earned a 2 rating writes, 'The ceiling may look flat, but it is not' (Student 2D). The difference between the students' answers resides in the level of detail. The student who scored the 4 wrote in greater detail than the student who earned a 2. In the next example of a 2 rating, the student relates the surface characteristics to gecko adhesion, though the reasoning is not fully acceptable. 'The surface always has little tiny cracks in them and little tiny setae go in between those cracks to hold it up' (Student 2F). Student 2F demonstrates knowledge of the surface, but the reasoning behind the gecko adhesion may be misunderstood since it is not clear from the student description how the setae 'hold it up.'

3.2.2 Subtheme: The amount of surface-to-surface interaction is critical for adhesion

Similar to the subtheme above, many students, regardless of essay rating, were able to identify the need for greater surface-to-surface interaction for adhesion. In the following 4 rated example, the student discusses principles of surface-to-surface interaction and the way it relates to gecko adhesion:

> Adhesion is affected by the surface area the gecko has because the gecko tries to reach the maximum surface area using its setae to touch every part of the surface. The surface contact affects adhesion because if there isn't enough surface contact the gecko would not be

Table 2. Number of student essays that use colloquial words compared to the number of essays that use mathematical terms

	4 Rating	3 Rating	2 Rating	1 Rating	Total
Number of essays	6	40	34	20	100
Use small/little/tiny	5	33	27	10	75
% Using the words small/little	83%	83%	79%	50%	75%
Use number or mathematical terms	3	15	16	4	38
% Using number or mathematical terms	50%	38%	47%	20%	38%

Note: Regardless of rating, students used colloquial words such as small or tiny to indicate scale rather than a number or mathematical language to indicate scale. Almost twice as many students used colloquial language. This table supports the qualitative *Subtheme 3.1.2.*

> able to adhere very well or even at all. The more surface contact the better the gecko will adhere (Student 4E).

This student clearly describes how surface area, surface contact and type of surface affect adhesion. In contrast, the following sample 2, nominal words were used, 'They (geckos) make a lot surface contact' (Student 2C). The student did not articulate the relevance of the surface contact, though the student knew of its importance. In 3 ratings, students more clearly articulate: 'The gecko has the ability to stick to walls and ceilings, because of the amount of surface contact' (Student 3I). Many students discussed surface area in relation to the gecko. Fewer students described a complete relationship between surface interactions and gecko adhesion similar to the 4 rating. Most students describe surface interactions similar to the 2 and 3 rating.

3.2.3 Subtheme: Variables affecting adhesion were variable according to student rating

Unlike the two other sub-themes, descriptions of variables affecting adhesion revealed misconceptions that probably impacted the overall student essay rating. In the following example the student earned a 4 with no content errors:

> The type of surface does not really matter for a gecko. The more rough the surface the setae the gecko must use to adhere. The surface can be wet, smooth, slippery or rough and the gecko may still adhere with ease (Student 4E).

In this example, the student describes several variables including the large amount of surface contact between the setae and the 'nooks and crevices' in a seemingly smooth wall. The student lists several other variables that may or may not affect the ability of the gecko to adhere. In another 4 rating, the student writes about a variable, 'If the surface is dirty, it also affects the adhesive force making it not very strong'(Student 4B). Similarly, the student describes how this is not a gecko concern because it 'cleans its feet.'

Students who score below a 4 hardly focus on describing variables that effect adhesion, and student misconceptions arise. A student confuses the variable with the gecko sticking, 'If the table is rough it (*gecko)* won't stick as good as if it were dry (Student 2D). In another 2, the student described adhesion mechanisms (as variables) as these mechanisms were considered in a previous lesson as potential explanations for answering the essential question of the unit. 'The variables affecting the adhesion are friction, suction, capillary wet adhesion and interlocking'(Student 2Aa). When an essay was rated a 2, and the response did address the variables, it was unlikely that the essay connected the variables to the gecko adhesion.

3.3 Theme Three: Tiny adhesive forces overcome the force of gravity including the electrical forces for gecko adhesion

This theme deals with a principal of static forces within the context of gecko adherence. Within the three themes, this theme reflects the greatest qualitative difference between students who rated a 4 and those that rated a 2 or 1. The following examples review answers from a 4, 3, 2, and 1 which are reflective of the qualitative differences.

A student that earned a 4 rating, describes the reason why a gecko can walk on the surface. The following is a sample, also from 4 rated essay with student describing only with words:

> Tiny adhesive forces like van der Waals attraction are not affected by gravity because the tiny forces are too small to be affected by gravity. Nano things are too small to be affected by gravity because of their size. Nano patches are not affected by gravity. The electrical forces that allow the gecko to adhere to do with van der Waals attraction. Geckos setae has the opposite type of electrical charges than the surface the gecko's setae is adhering to the attraction between the surface and the gecko setae are not very strong, but with millions of setae the gecko has enough attraction to hold itself to the ceiling with one toe (Student 4E).

In this sample, the students identifies van der Waals force and the properties that change at the nano scale, but it is not clear that the student understands the temporary nature of these forces due to the electron cloud.

In the following example of 3 rated essay, the student uses more common language to describe a complex phenomenon. Cleaning the gecko's feet provides an important context to describe electrical force:

> The way it cleans its feet after only five steps, or so is, because it can put negative or positive repulsion, through its feet. The little spatula shaped seta may also have negative and positive attraction because opposites attract, because if the gecko has a positive charge and the surface has a negative charge, they would attract (Student 3D).

Though syntactically awkward, the student is able to convey the abstract idea. The student relates the information to what is commonly known, 'opposites attract,' but the student does not address the idea of many temporary small electrical forces adding up to a force large enough to suspend the gecko.

Students who were rated a 2 or 1 often minimally described the complexity of electrical forces. In essay 2Z the student writes the following: 'When the gecko walks a charge goes to its seta (Fig. 3), and then to the spatulas which makes them stick to the ceiling using static electricity' (Student 2Z). The student *did not* identify the electrical force correctly, but conveys more in the drawing than in words. The

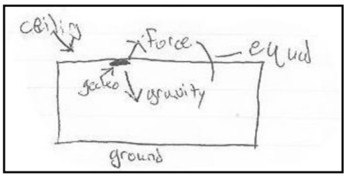

Fig. 3. Student 2Z drawing of electrical forces equaling the downward force of gravity.

drawing indicates the principle that gravity forces pull down on an object, and intermolecular force hold up the object.

The examples from essays that scored a 1, gave nominal but correct information. Student 1A wrote, 'Then the molecules of the surface attract making a charge. So that is how they can walk on the ceiling.' The student was terse in response.

Students often mentioned molecules or van der Waals forces with positive and negative electrical interactions occurring: a complex concept not often addressed in high school. However, the expressions of details vary. The largest difference seems to be with a small word. Not as many students indicate a great number of *small fo*rces increasing the ability to adhere to the surface, but students mention the electrical charge variation.

3.4 Theme Four: Wonder of scientific concepts learned within the unit

Science education aims to instill a love for discovery through logical explanation for concepts that are naturally mysterious (Table 3). In the samples below, the students that rated a 2, 3 or 4 indicate their marvel at concepts, spanning the gamut of the physical nature of the gecko and to the electrical force understood at nanoscale.

Expectantly, a student remarked about the gecko's ability to adhere, 'The gecko is a lizard that seems to defy the laws of gravity' (Student 4D). The student uses the word 'defy,' which means the example caused an intellectual dissonance that needed to be resolved. The quote from a student who earned a 2, integrates the wonder of the gecko with understanding force:

> Geckos are amazing how they stick to everything. The way that they stick, they have very small things that are called setae, then, on the surface they are spatulas that help even more to stick. This is called the van der Walls force (Student 2P).

Amazement of the gecko was integrated with van der Waals forces. Another student who earned a 3 writes, 'Van der Waals is absolutely unique' (Student 3F). Often science principles do not exhibit admiration from students. This did.

Another student identifies realities learned about surfaces, 'The ceiling may look flat, but it is not' (Student 2D). In greater detail, the next quote reflects what appears to be and what actually is when dealing with the surface of objects:

> Some people (think) that a table top is very smooth, when in fact, if you were to look at the same surface under a microscope, you would notice that it is very bumpy and rough (Student 3C).

The student noted that the observation tool, a microscope, modified understanding of reality.

Approximately half of the responses indicate that they found the learning interesting. Though this theme does not necessarily illustrate one of the big ideas of the unit, it does reflect a global goal. Science education aims to create students who are lifelong learners of science, which means students need to be interested first.

4. Discussion

Responses to the students' essays require one to look into the characteristics of the students' arguments and how the students think about the nature of science [12, 33]. The findings from the essay questions confirm and question that of other studies, and shed light on future investigations into science goals, nanoscience and education.

In relation to the language of size and scale the findings are loosely supported with Tretter et al. [12]. There was differentiation between the language sophistication used among the students who were rated 4 or 3 compared to a 2. Students rarely used the mathematical language, but rather talked about nanoscale in terms of colloquial language as 'tiny' and 'small.'

In the multiple-choice test [34, p. xi], there were gains in understanding scale at the nanoscale. However, only seen in essays, student did not use the mathematical language naturally, when prompted to write. Tretter et al. [12] noted that novices relied

Table 3. Total number of essays compared to the number of essays that indicate wonder or interest in content learned

	4 Rating	3 Rating	2 Rating	1 Rating	Total
Number of essays	6	40	34	20	100
Number indicating wonder	5	14	21	6	46

Note: This table shows the distribution of the student ratings on their essays compared to the number that indicated wonder. In total, almost half of the students indicated wonder in their essays, which supports the qualitative *Theme Four*.

on their experience outside of formal education to make sense of scale. As supported by the National Framework [15], students need to write scientifically to become comfortable within the content.

The greatest *common* understandings were characteristics of the gecko—the setae and spatula, even at nano-scale. The greatest *misconceptions* arose when writing about the static forces at the nano-level. This makes sense. The students would have little past experience with knowledge of electrical forces and the principle of force is more abstract than the physical characteristics of the gecko. Students saw images of the gecko's setae and spatula. The images of electrical forces are models, not actual images for which the students can relate.

Educational research has focused primarily on concept of scale in nanoscience. Unexplored within the field of teaching nanoscience lies the range of misunderstanding and those concepts that are generally understood and valued by students. Since nanoscience is interdisciplinary by nature, the task is much larger than with traditional high school physics or chemistry.

Most importantly, student essays declared the wonder of what learned. According to the NanoLeap student surveys, reported by Palmer [35], participation in the NanoLeap physical science and chemistry units did not increase students' interest and/or engagement in science [35, pp. v–vi]. Yet, almost half the student essay responses voluntarily, and sometimes subtly divulged their feelings of wonder about science content they had learned. This is an example of how multiple measures provide a more complete picture of student perceptions.

5. Conclusion

Jules Henri Poincaré (1854–1912) French mathematician:

> *Science is facts; just as houses are made of stone, so is science made of facts; but a pile of stones is not a house, and a collection of facts is not necessarily science.*

The students responses delineate student understanding, especially the facts of principles as they apply to nanoscience. But, student learning about nanoscience needs to be more than a collection of facts. It will only have memorable meaning when bound within a context. From the students' essays, learning about nanoscience within the context of gecko adhesion increased the probability of a memorable context. A student who earned a rating of a 2 wrote,

> Nanoscience gives us great advantages to understand things like surfaces, how a gecko is able to stick to things that people can't stick to, like the ceiling (Student 2Q).

The student noted a 'great advantage' of understanding, and found it valuable to know why we cannot 'stick to ceiling' but something else can. This is the voice of a young teen that wonders and enjoys learning about the seemingly ordinary with extraordinary implications.

Acknowledgements—The late Marni Goldman Ph.D. supplied the initial idea of tantalizing students with the mystery of the gecko. The National Science Foundation program officers for this project were Carole Stearns and Robert Gibbs. The content matter experts were from Stanford University's Nanofabrication Facility Team. Sylvent Otieno scanned images and transcribed students' essay responses.

This material is based on work supported by the National Science Foundation Division of Elementary, Secondary and Informal Education award # ESI-0426401.

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