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From Nanometers to Kilometers and Beyond: Teaching Physical Properties Across Multiple Scales

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Abstract

The importance of science students being able to reason across many orders of magnitude of size and time is referred to as scale literacy and has been highlighted as an important skill which enables students at all levels to communicate across disciplines and think more clearly about the implications of many scientific principles. We are developing an online instrument designed to assess students' senses of scale and thereby identify the developmental stages of scale literacy among different student groups. We report here the initial results of this instrument and highlight a number of ways it will be refined to increase its sensitivity and precision.

Keywords: sense of scale, cross-cutting concepts, logarithmic reasoning, nanoscience

Introduction

In 1986, the American Association for the Advancement of Science (AAAS) initiated a long-term program to improve science education through the development of learning goals and curriculum, the creation of new assessment tools, and the formation of programs for teacher development. In 1989, the association published a document entitled Science for All Americans (AAAS, 1989) wherein it identified four common themes in science education. In 1993, it published its Benchmarks for Science Literacy (AAAS, 1993) wherein it reiterated and developed these four principal areas for science literacy: models, constancy and change, systems, and scale. The scale concept invites students to understand physical phenomena across all scales of size (cosmological to quarks) and time (geological to electron motion). When it comes to the issue of size scaling, the Benchmarks publication points out that our everyday experience centres on our own body dimension (meters) and that most people are able to visualize sizes within ±3 orders of magnitude. Outside of this range, however, most people do not have a natural ability to comfortably assess and measure dimensional features of objects and processes.

The AAAS (1993) study was followed by the National Research Council's Board of Education (2011) issuing a framework surrounding science literacy, which identified seven core areas, namely patterns, cause and effect (mechanism and explanation), systems and system models, energy and matter (flow, cycles, and conservation), structure and function, stability and change, and scale, proportion, and quantity. These same features have been adopted into the new Next Generation Science Standards, developed by the National Science Teacher Association (2013) being implemented across the United States into what are called "cross-cutting concepts". These have value in science education "…because they provide students with connections and intellectual tools that are related across the differing areas of disciplinary content and can enrich their application of practices and their understanding of core ideas" (p. 223). Coming out of these reports was a recommendation that science education be organized around three principle approaches: (a) practices involved in science and engineering, (b) cross-

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cutting concepts (one of which is scale) that unify across the fields of study, and (c) the core content that helps define a particular physical science discipline. A recent update (Holme, Luxford, & Murphy, 2015) to the General Chemistry Anchoring Concepts Content Map published by the American Chemical Society's Exam Institute increased more than 5-fold the number of "nodes" – discrete conceptual items – relating to the anchoring concept "Visualization and Scale."

The importance of scale – and being able to reason across many scale ranges – can be appreciated when we consider the very large and the very small. Understanding the structure of the world in which we live requires the appreciation of many geologic processes. But thinking of the long-term consequences of continental drift where North America is drifting towards Europe at a rate of about 1.6 cm per year (UNAVCO, 2015) is challenging when the student realizes that that amounts to only about 160 meters of movement in the last 10,000 years as the last ice age concluded. Similarly, the cosmological distances relating to the motion of galaxies can be difficult to evaluate when human travel distances are generally experienced on the scale of kilometers. These scale challenges can manifest themselves in a student's difficulty in conceptualizing organismal and cosmological evolutionary processes and thereby impact on their academic achievement. At the other end, we have observed individuals who have expressed concerns about human health due to one's proximity to electrical power lines. The argument put forth is to consider how the magnetic fields accompanying these power lines will pull the body's molecules back and forth 60 times per second (being the 60 Hz frequency of our AC power grid). When one then appreciates that every molecular bond is already vibrating in the range of 1 to 100 trillion times a second (100 THz), this 60 Hz "threat" should become less worrisome. An inability to appreciate THz motion, however, leaves such a person with a belief in a false public health concern. Students' reasoning across many orders of magnitude is important if they are to become scientifically literate. Scale literacy is important beyond schooling and continues to develop throughout one's working adult life (Jones & Taylor, 2009). We see a need for educators to be able to assess students' scale-perception skills and develop interventions to help build their success in this area.

Many types of experiments have been developed including card sorting, absolute length assignments, pairing-item test, relative length assignments, and interviews (Jones, Tretter, Taylor, & Oppewal, 2008; Gerlach, Trate, Blecking, Geissinger, & Murphy, 2014a; Gerlach, Trate, Blecking, Geissinger, & Murphy, 2014b; Tretter, Jones, Andre, Negishi, & Minogue, 2006a). These studies have found that people tend to accurately estimate the lengths of items within about three orders of magnitude of themselves: from millimetres to the range of kilometres. At distances longer than kilometers, accuracy begins to taper off, with more experienced individuals (when considering students in the range from grade five through to PhD students), and also people who receive higher chemistry grades, performing better. At distances longer than 10^9 m, only 20% of PhD students in science/science education could estimate sizes accurately within one order of magnitude, and most were over two orders of magnitude away.

In the region of the very small – in what can be called the "invisible region"– a similar, effect occurs: there is a quick drop in length estimation accuracy that changes very little within the 10^{-9}-10^{-6} m range. The portion of people whose estimates of items in this regime are within one order of magnitude of accepted values hovers (Tretter et al., 2006b) between 3-19% for students in Grades 5-9, with no significant improvement through that range. Of the "gifted seniors" (Grade 12 students in the top 8 percentile of the population, based on aptitude test scores), 20-40 % estimated sizes of invisible objects within one order of magnitude; 30-60% of PhD students did the same. This indicates that improvement of sense of scale does occur through schooling, often without intentional focus in that area.

There has also been work in developing a framework to understand the progression of understanding that students proceed through (Swarat, Light, Park, & Drane, 2011). Four distinct levels of sorting were discovered: fragmented, linear, proportional, and logarithmic. A fragmented understanding of scale describes a student who, while quite possibly competent in regimes around himself/herself, has limited understanding of scale in the invisible regime and cannot link the visible and invisible regimes. Students thinking linearly also struggled with invisible items, as a linear scale does not allow for meaningful differentiation between very small objects when visible objects are differentiated. Students showing proportional thinking linked items by a ratio of sizes (e.g., the length of an ant is 100 times larger than the width of a hair), but used inconsistent ratios across different items. A logarithmic-level of understanding was considered the highest level, where the student considered items' sizes relative to each other, using a consistent ratio (usually 10). Of the students tested, 13% thought in a fragmented system, 32% linearly, 33% proportionally, and 9% logarithmically.

Card-sorting tasks have been well-established in the literature as an effective way of determining students' sense of length scale. Thus far, these have all been administered individually by a member of the research team. The current project has developed a digital version of a card-sorting task that can be administered to many students without the supervision of an expert.

Instrumentation

Nanosz Sense of Scale (Nanosz SoS) was developed to be a digital, scalable version of previous workers' card-sorting tasks (Gerlach et al., 2014a). In this version, participants log on to the site and are presented with nine items indicated by both a written and pictorial representation of each object arranged in no particular order in a grey lobby area. Students click to drag the items onto a length scale lower on the page. A dashed, red, vertical line appears when items are dragged onto the length scale, indicating precisely where the item is being placed. Once placed, the line becomes grey, with the exception of items that are dragged to the extremes of the length scale, which remain red. Students are able to continue to move items around after placement. Once all of the items had been moved from the lobby onto the length scale, the option to continue appears. Figure 1 shows all of the items in a sample arrangement and the program ready to move on to the next stage.

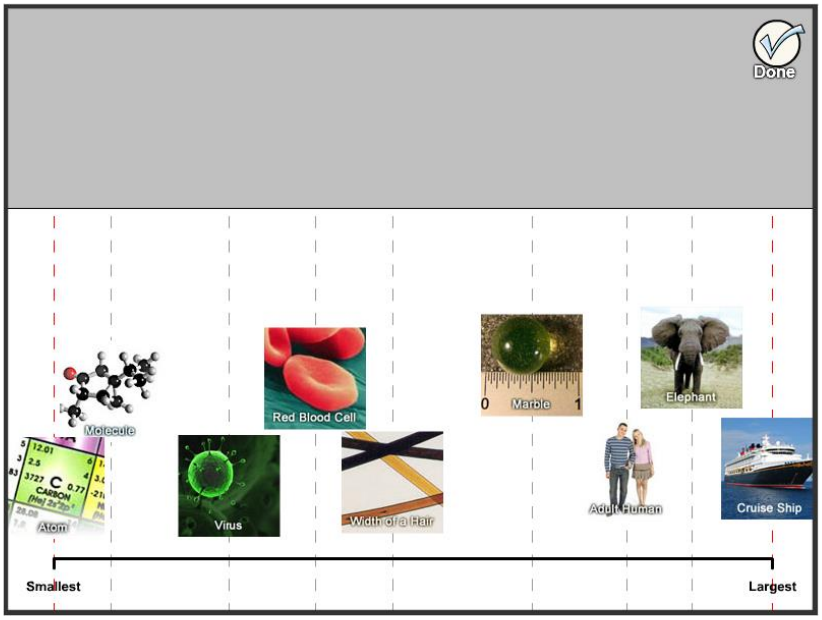

Figure 1. Nanosz SoS interface. The student has dragged items out of the lobby (grey section, top) and onto the length scale. Since all items are on the length scale, the “Done” button is clickable.

After clicking “Done,” students were asked to explain how they decided where to place the items; they enter this explanation into a textbox on the page. Once they have submitted the explanation of their thought process, they are given an opportunity to revise the placement of the items and a final explanation of why they made any changes. This completed the assessment. Both their initial and final item arrangements are recorded.

Recruitment

First and fourth year undergraduate students in the B.Sc. Nanoscience major at the University of Guelph were invited in-class to participate in this research project and were given a link to the study via email. No remuneration, either financial or grades, was offered. Fourteen fourth-year students and 13 first-year students completed the task. Participation or lack thereof had no effect on the students’ standing in their respective courses. This project received approval from the university’s Research Ethics Board.

Data Cleaning

Students’ placements of all items on the length scale were quantified between 0-1, with 0.001 increments. First, any placements by students who did not order the items by length scale (based on their comments) were removed. The remaining students’ placements were then scaled to fill the 0-1 range, expecting that the typically small variation in the placements of the extreme items were due to students not realizing they had not placed the item in the most extreme position.

Results

Seven of the 12 first-year students and 13 of the 14 fourth-year students placed the items in sequence with no mistakes. The most items any student incorrectly ordered were two, and the virus and molecule items were the only items incorrectly placed by more than one student, occurring thrice.

Comparing each student's placements with the correct placements of the items (on a linear and logarithmic scale), 13 of the 14 fourth-year and all of the 12 first-year students ordered the items most closely to the logarithmic model. The one student who attempted to order the items linearly did so with the understanding that a linear model was likely not the most useful, saying, "I'm trying to use a linear scale to emphasize the drastic size difference between the objects. The smallest objects are probably not very accurate."

While previous work (Sawart et al., 2011) has indicated that logarithmic ordering indicates the highest order thinking on this kind of task, one should interpret our finding with caution. Based on the items, and amount of space provided, a student simply ordering (not giving meaning to the relative spacing between the items) would have been categorized as a logarithmic thinker. To differentiate between students who ordered the items roughly evenly and those who were truly thinking logarithmically, the standard deviation of the differences between an item and the next smallest item (across all items) was taken for each student. This value was 13% for the items placed perfectly, and for relatively even spacing between items, this value would be very low.

Four first-year students' placements yielded these standard deviations of under 1.3% and did not exhibit any obvious trends in their difference values, implying that they were ordering the items, rather than positioning them on a scale. While this is not conclusive evidence that the remainder of the students were intentionally placing the items logarithmically, rather than only ordering (they may have only considered the order and placed the items unevenly), it does suggest that the instrument is measuring a difference in the performance of different students.

The overall performances showed several key differences between the two groups of students. Mean errors ($\bar{E}$) were determined by the average of the absolute differences between each of the student's placements ($P_{student}$) and the ideal placements (P_{ideal}) on a logarithmic scale (equation 1). The ideal spacing of the items on linear and logarithmic scales is shown in Figure 2.

$$\bar{E} = \sum_{n}^{1} \frac{|P_{student} - P_{ideal}|}{n} \qquad (1)$$

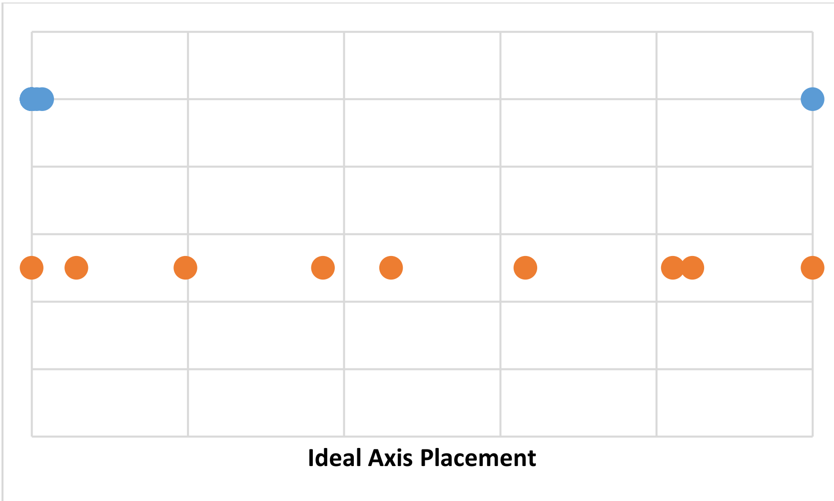

Figure 2. Ideal placements of the items on a linear (top) and logarithmic (bottom) scale, increasing to the right. The items, from left to right, are an atom, a molecule, a virus, a red blood cell, the width of a hair, a marble, an adult human, and a cruise ship.

These errors can be summed over the entire set of items or any subset. Here we studied two subsets: the visual range (that which can be observed with the eye) and the invisible range (that which is smaller than human vision can perceive). They were then averaged over each group of students. The results of this analysis are summarized in Table 1.

Table 1

Summary of Student Placements of Items Compared to Ideal Placements of Items

	First-year Students		Fourth-year Students		Difference
	Mean error	*SD*	Mean error	*SD*	*p* value
Overall	0.12	0.07	0.05	0.03	< 0.01
Invisible ($<10^{-4}$ m)	0.09	0.05	0.05	0.05	0.05
Visible	0.06	0.02	0.05	0.01	0.13

First-year students' results showed greater mean errors than the fourth-year students' placements. The overall results (consisting of placements for all nine items) revealed that first-year students' item placements are more than twice as far from ideal placements ($p < 0.01$) and have more variation (*SD* of 0.07 for first-year students, compared to 0.03 for fourth-year students).

Since the literature consensus has shown that the invisible regime has often caused participants the greatest problems, two subsets of the data were specified; the atom, molecule, virus, and cell were categorized as invisible; and the marble, human, elephant, and cruise ship as visible. While the first-year students did only slightly worse on placing the visible items ($p = 0.12$), the major performance difference occurred in the invisible regime, where first year-students' placements deviated almost twice as much from ideal placements as fourth-year students' placements ($p = 0.05$).

A comparison of the senior students' scale performances with their grade in a third-year nanoscience course focusing on lithography is summarized in Figure 3. There is a slight trend of better performance in the course with increased error in the sense of scale task. The negative correlation is weak and suggests this is not an appropriate validation marker and that the instrument and/or the validation process still need considerable refinement.

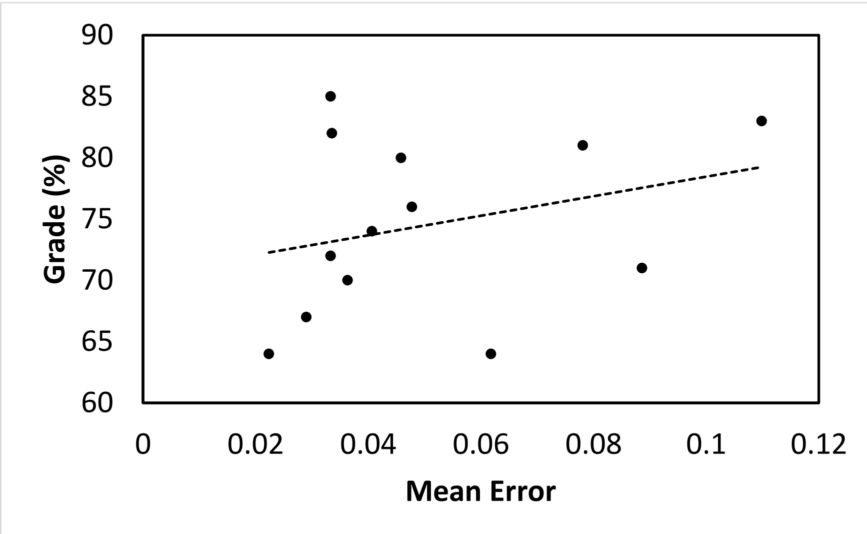

Figure 3. Fourth-year students' mean errors on a sense of scale test correlated with their grade obtained in a previously completed third year nanoscience course.

Previous literature has shown that the correlation of success in chemistry courses and sense on scale tasks have been sensitive to the topics covered in the course. For example, there was little correlation with a chemistry course focusing on stoichiometry, but a large correlation with a course focusing on molecular structure (Gerlach et al., 2014b).

Future Work

There were three aspects of the Nanosz SoS instrument that will be adjusted as a result of this study. First, one student listed the largest item, the cruise ship, as 0.365, while still ordering all items correctly. His/her reasoning did not address this uncommon behaviour. We speculate that this could have been either for technological reasons (e.g., the working space was cut off by the monitor/mobile device) or because s/he felt that a cruise ship was not the largest item they could imagine. In the beginning of this task there is introductory text, part of which explains, "At one extreme exist galaxies whose dimensions are measured in light years," yet the largest item in the test is a cruise ship. In future iterations of this instrument, the explanatory text will be made consistent with the items being tested to avoid priming students from using only small parts of the length scale. While we intend to ultimately develop an instrument that will be able to autonomously assess student's sense of scale, we may require oral interviews during further development to gain additional insight into students' rationale as this will likely be helpful in adjusting the instrument's design and implementation.

In interviews, some students expressed concern about ordering molecules and viruses, and sometimes even atoms and molecules, because there are exceptions to the accepted ordering. The largest molecules synthesized are larger than typical viruses, an iodine atom has a greater van der Waals radius than a hydrogen molecule, and an ostrich egg (which can weigh up to 1.5kg) is a single cell. In the future, generic items such as “cell” will be replaced with more specific ones, such as “red blood cell.”

The instructions of the test will be changed to avoid students only ordering and not considering the proportional spacing between items. In this investigation, the instructions read “In this exercise you will order nine common objects from smallest to largest by dragging them into position along a scale.” The use of the word “scale” was intended to have students consider proportionality. While 100% of the fourth-year students appeared to have considered relative spacing, only nine of the 13 first-year students did. Replacing the word “order” with “place,” and being more specific (without priming students to think linearly, logarithmically, or otherwise) is expected to mitigate this kind of misunderstanding.

In this iteration of the instrument, students were allowed to place items anywhere within a two-dimensional space, with the vertical space provided only so that students could avoid overlapping pictures if desired. Only the x-axis placement was considered in analysis. In the next iteration of Nanosz SoS, the items will be arranged along a top banner, and students will connect the images to where they feel those items would be on the scale. The items will reorder as necessary, but stay within the upper banner, as to not concern the student with overlapping pictures or significance of vertical space.

After these adjustments, we intend to use this instrument to probe several variables currently missing (or only touched on) in the literature. First, these tests have always been done with items that were best sorted with a logarithmic scale, and students exhibiting logarithmic thinking were considered to have achieved the highest order of item scaling. It has been assumed that students who think logarithmically could think linearly (if the items were best sorted in that way) but never tested. When the set of objects span only two orders of magnitude, a linear scaling is probably more revealing than logarithmic, though beyond that a logarithmic scale may be more appropriate. As such, the instrument will be augmented to be able to provide a variety of item sets that will probe a student’s flexibility in thinking either linearly or logarithmically as influenced by the set of objects provided.

Going forward, we will be seeking to study the sense of scale of a more varied group of students depending upon their academic programs. It may prove instructive to observe any differences in performance when comparing arts students with STEM students, to develop a sort of baseline of what level of sense of scale is developed through daily life, versus intentional study. The comparison between biology, chemistry, engineering, physics, and nanoscience students would be interesting to determine whether students in these areas show areas of greatest sense of scale relating to the regime that their discipline focuses on. Furthermore, if the precision of the instrument can be refined, working with younger children may help to clarify the points at which sense of scale begins to develop. This information regarding the development of this central skill of reasoning across many orders of magnitude of scale may point out ways in which new interventions might help with that development. The knowledge of when different stages of scale sense develop and the decoupling of development due to daily activity, versus intentional practice, could better inform the timing of teaching about items outside of the visible regime.

References

American Association for the Advancement of Science/AAAS (1989). *Science for all Americans*. Retrieved from http://www.project2061.org/publications/sfaa/online/sfaatoc.htm

American Association for the Advancement of Science/AAAS. (1993). *Benchmarks for science literacy*. Retrieved from http://www.project2061.org/publications/bsl/online/index.php

American Association for the Advancement of Science/AAAS (2015). *Project 2061*. Retrieved from http://www.aaas.org/program/project2061/publications

Gerlach, K., Trate, J., Blecking, A., Geissinger, P., & Murphy, K. (2014a). Investigation of absolute and relative scaling conceptions of students in introductory college chemistry courses. *Journal of Chemical Education*, *91*(10), 1526-1537.

Gerlach, K., Trate, J., Blecking, A., Geissinger, P., & Murphy, K. (2014b). Valid and reliable assessments to measure scale literacy of students in introductory college chemistry courses. *Journal of Chemical Education*, *91*, 1538–1545.

Holme, T., Luxford, C., & Murphy, K. (2015). Updating the general chemistry anchoring concepts content map. *Journal of Chemical Education, 92*, 1115-1116.

Jones, M. G., & Taylor, A. R., (2009). Developing a sense of scale: Looking backward. *Journal of Research in Science Teaching, 46*, 460-475.

Jones, M. G., Tretter, T., Taylor, A., & Oppewal, T. (2008). Experienced and novice teachers' concepts of spatial scale. *International Journal of Science Education*, *30*(3), 409–429.

National Research Council. Board of Science Education. (2011). *A framework for K-12 science education: Practices, cross-cutting concepts, and core ideas.* Washington, DC: National Academies Press.

National Science Teacher Association. (2013). Next generation science standards. Retrieved from http://nextgenscience.org

Swarat, S., Light, G., Park, E. J., & Drane, D. (2011). A typology of undergraduate students' conceptions of size and scale: Identifying and characterizing conceptual variation. *Journal of Research in Science Teaching*, *48*(5), 512-533.

Tretter, T. R., Jones, M. G., Andre, T., Negishi, A., & Minogue, J. (2006a). Conceptual boundaries and distances: Students' and experts' concepts of the scale of scientific phenomena. *Journal of Research in Science Teaching*, *43*(3), 282-319.

Tretter, T., Jones, M. G., & Minogue, J. (2006b). Accuracy of scale conceptions in science: Mental maneuverings across many orders of spatial magnitude. *Journal of Research in Science Teaching*, *43*(10), 1061–1085.

UNAVCO, University NAVSTAR Consortium. (2015). Tectonic plate motion calculator. Retrieved from http://www.unavco.org/software/geodetic-utilities/plate-motion-calculator/plate-motion-calculator.html