Investigating levels of conceptual understanding: A case study from thermal and transport science

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CONTEXT

How do students come to understanding important concepts in engineering science? Is the process a "Eureka, I have it!" event of sudden illumination? Or is the process much fuzzier, with students going through phases of uncertainty before full understanding of a concept is reached?

The research reported in this paper expands upon work to measure engineering undergraduates' conceptual understanding of difficult concepts in thermal and transport science through the development of a concept inventory (Streveler, et al, under review). The focus of the paper is the reanalysis of data collected in a senior chemical engineering transport class where students were asked to explain fundamental concepts in fluid flow and heat conduction using their own words and no equations.

Preliminary findings for this work were reported in an unpublished AERA paper (Miller et al., 2003) and provided evidence that even advanced engineering students may simultaneously hold more than one model of fundamental engineering sciences at the same time. This paper will present reanalysis of this data using the liminality construct a lens for analysis.

RESEARCH QUESTIONS

This paper will investigate the following research questions:

1. What models do students use to explain molecular processes like momentum transfer and heat conduction?
2. How can the idea of 'liminality' be used to help explain the results?
3. Can Chi's theory of emergent vs. direct properties be useful in explaining how students explain fluid flow and heat conduction?

THEORETICAL FRAMEWORKS

Two theoretical frameworks inform this work. First, Meyers and Land (2006), originators of theory of threshold concepts idea, have introduced a construct called 'liminality' which describes an in-between stage of understanding. During liminality a person

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simultaneously holds different mental model of a single phenomenon. We will investigate the concept of liminality as they pertain to our results.

Our second framework is Chi's theory of emergent vs. direct processes. Chi (2005) proposes that a lack of understanding of emergent phenomenon underlies many robust misconceptions in science. She has proposed that emergent processes (which arise from the simultaneous system interactions) can be contrasted to direct cause-and-effect actions.

METHODOLOGY

Preliminary findings

Students in a senior-level transport phenomenon course were asked to explain in their own words, with no equations, the following two questions.

1. *How momentum is transferred through a fluid via viscous action? If you'd like, use a specific application (such as laminar flow in a circular pipe) for your explanation.*

2. *How energy is transferred via conductive action? If you'd like, use a specific application (such as heat flow through a solid plate) for your explanation.*

Each question was asked prior to discussion of that topic in the course. Question 1 was posed on the first day of class, question 2 about midway through the semester. Students were given a sheet of paper to write their answers to each question. 39 students answered question 1. 32 students answered question 2.

Preliminary analysis of the data was conducted to answer two research questions.

- What models do students use to explain these phenomena?
- Is students' use of models consistent across sampling times?

Rubrics were developed which classified mental models of momentum transfer (Table 1) and heat conduction (Table 2) as macroscopic, microscopic, molecular, or mixed. Responses were coded "non-responsive" if the student did not attempt to answer the question.

Three researchers coded responses to the momentum transfer question. These three people were joined by an additional researcher to code the heat conduction question. Coding was compared and discussed until consensus was reached.

Table 1. Macroscopic, Microscopic, Molecular, and Mixed Descriptions of Viscous Momentum Transfer in Laminar Pipe Flow Used as Scoring Rubric for Student Responses from Miller et al. (2003)

Macroscopic Description The pressure at the pipe inlet is increased (usually by pumping) which causes the fluid to move through the pipe. Friction between fluid and pipe wall results in a pressure drop in the direction of flow along the pipe length. The fluid at the wall does not move (no-slip condition) while fluid furthest away from the wall (at the pipe centerline) flows the fastest, so momentum is transferred from the center (high velocity and high momentum) to the wall (no velocity and no momentum).
Microscopic Description Fluid in laminar flow moves as a result of an overall pressure drop causing a velocity profile to develop (no velocity at the wall, maximum velocity at the pipe centerline). Therefore, at each pipe radius, layers of fluid flow past each other at different velocities. Faster flowing layers tend to speed up slower layers along resulting in momentum transfer from faster layers in the middle of the pipe to slower layers closer to the pipe walls.
Molecular Description Fluid molecules are moving in random Brownian motion until a pressure is applied at the pipe inlet causing the formation of a velocity gradient from centerline to pipe wall. Once the gradient is established, molecules that randomly migrate from an area of high momentum to low momentum will take along the momentum they possess and will transfer some of it to other molecules as they collide (increasing the momentum of the slower molecules). Molecules that randomly migrate from low to high momentum will absorb some momentum during collisions. As long as the overall velocity gradient is maintained, the net result is that momentum is transferred by molecular motion from areas of high momentum to areas of low momentum and ultimately to thermal dissipation at the pipe wall.
Mixed Description Students use more than one model in their description.

Table 2. Macroscopic, Microscopic, Molecular, and Mixed Descriptions of Conductive Heat Transfer Used as Scoring Rubric for Student Responses from Miller et al. (2003)

Macroscopic Description A temperature change through a material (gas, liquid, or solid) will cause heat to flow. The larger the temperature change, the faster heat will flow. Heat always flows from a high temperature region to a low temperature region. The linear ratio of heat flow per unit area to the temperature difference is called the heat transfer coefficient.
Microscopic Description At any point in the material, a temperature gradient (temperature change per unit length) causes heat to flow from high temperature to low temperature. Total heat flux (heat flow per unit area) is proportional to the temperature gradient.
Molecular Description In liquids and gases, molecules are moving in random Brownian motion. A change in temperature through the fluid will result in a distribution of molecules with different kinetic energies. Energy (heat) will be transferredlocally in 2 ways: 1) diffusion of high energy molecules to regions of low energy molecules, and 2) collisions between molecules in which some energy transfer occurs. The net result is energy (heat) transfer from a hotter to colder region.
Mixed Description Students use more than one model in their description.

Current analysis

The data is being reanalyzed using Chi's framework as a guide (Chi, 2005). The following rubric is being used to score student responses. Two raters are using the rubric to score the written student responses to the two questions posed earlier. (*How momentum is transferred through a fluid via viscous action?*and *How energy is transferred via conductive action?)*

Direct model	Emergent model	Undetermined
☐ distinct	☐ uniform	☐
☐ restricted	☐ random	☐
☐ sequential	☐ simultaneous	☐
☐ dependent	☐ independent	☐
☐ terminate	☐ continuous	☐
☐ additive summing	☐ cumulative summing	☐

FINDINGS AND CONCLUSIONS
From preliminary analysis

As shown in Table 3, only about 15% of students used molecular models to describe momentum transfer and about 40% used molecular models to describe heat conduction. It should be remembered that these students were seniors who had been exposed to the molecular nature of these phenomenon in several courses. Yet only 40% used molecular models even in the middle of the semester.

Table 3. Types of descriptions used by students for momentum transfer (n = 39) and heat conduction (n = 32) from Miller et al (2003)

Description type used in response	Number (and percent) of students for momentum transfer question	Number (and percent) of students for heat conduction question
Molecular	6 (15.38%)	13 (40.65%)
Macroscopic	4 (10.25%)	3 (9.37%)
Microscopic	10 (25.64%)	5 (15.62%)
Mixed	14 (35.89%)	9 (28.12%)
Non-responsive	5 (12.82%)	2 (6.25%)

Even more puzzling is the result that only three students used a consistent model (two students used a molecular model and one student a macroscopic) to explain both phenomenon (see Table 4). These results suggest a high degree of variability and inconsistence in the models advanced engineering students use to describe fundamental engineering science concepts. We argue that this data deserves a second, closer look.

Table 4. Comparison of models used by students for momentum transfer and heat conduction questions (n=28)

Description type used in response	Number of students responding to both momentum transfer and heat conduction questions
Molecular	2
Macroscopic	1
Microscopic	0
Mixed	1
Models not consistent	24

Current analysis

Current analysis is ongoing at the time of abstract submission and will be reported at the conference.

RECOMMENDATIONS

Recommendations will be presented at the conference.

ACKNOWLEDGMENTS

We thank Aidsa Santiago Roman and Tameka Clarke Douglas for their assistance in reanalyzing the data. A special thanks goes to Micki Chi for sharing the draft of her most recent work with the research team.

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