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Author: McGoey, Jon P.

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Contact Information (correct as of 12-23-2010):

Web: www.mlrg.org

Email: info@mlrg.org

Pairing and Compiling Discrepant Events to Help Generate Understanding of Kinetic Molecular Theory

Jon P. McGoey
John Paul II Secondary
London, Ontario, Canada
jmcgoey@quark.physics.uwo.ca
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Abstract

A central aspect to conceptual change strategies relies on introducing events which are discrepant to the students' existing conceptual framework. Discrepancies to existing theory however are dealt with by people in a variety of ways. Most frequently we reject, ignore, or explain away anomalies rather than alter our pre-existing models. This is crucial to meaningful learning since a person must accept the discrepancy's validity as part of the restructuring process. In a classroom, a range of conceptual frameworks exists and by extension, there is a range of responses to any experimental or conceptual evidence presented to the students. This study looks at using a classroom of 25 grade 9 students (age 14) as they construct kinetic molecular theory (KMT). The general approach is identify pre-existing notions, at times group students accordingly, assign (or have students design) experiments to test their models, and to share a vast array of ideas and findings in order to come to some common ground. The common ground to all the events, discrepant or otherwise, is what we eventually call theory. Under traditional tests, students learning under these conditions perform no differently than their peers. Under other measures of understanding, these students performed significantly better than their counterparts. It would seem then that there is little to lose and much to gain by adopting this type of conceptual change strategy.

Introduction

Conceptual change strategies using “cognitive conflict” involve having students explain events which cannot be assimilated by their existing cognitive frameworks. According to Posner, Strike, Hewson & Gertzog (1982), the principles at play are: (a) existing conception must be deemed unsatisfactory; and (b) the new conception must be intelligible, internally consistent, plausible, parsimonious and useful. One problem with these strategies is that classroom teaching involves dealing with 25 individuals, each of whom possess idiosyncratic variations on any given conceptual framework. How can we respond to the wide array of conceptual frameworks? Also, a fundamental aspect of science is our theories -- and students’ and scientists’ theories are remarkably immune to change -- we don’t readily deem our theories unsatisfactory. Lastly, the notion of “conceptual framework” has, subsumed under it, predictive, explanatory and organisational structures. It begs the question of Posner *et al*’s principle: *Useful fine, but useful at what*? Surely a well-contextualized common-sense principle serves our predictive needs far better theory. In addition, explanatory frameworks have the luxury of 20-20 hindsight and the curse of being self-referential. Therefore, if (new) theory is less fruitful or useful than pre-existing constructs, and if explanatory constructs have the odour of rationalisation, the only other usefulness theory can serve is to provide a cohesive or organising framework to subsume other classes of knowledge students are expected to learn.

Recent philosophers of science (e.g., Kuhn, Lakatos, Laudan, etc.), critical and historical analyses all have helped dethrone theory from its roost as the solitary ruling monarch of the epistemological realm. The new order has been called Kuhn’s paradigm, Lakatos’s research programme, and Laudan’s research tradition, all of which distinguish themselves from Popper’s ‘science by falsification’ by declaring theory to be just one component within a larger (and at times, anarchistic) network. These philosophies give us ways to rationalise why ‘attacks’ to theory by anomalous data or discrepant events are so often condoned well before significant restructuring of theory takes place. Root-Bernstein claims we *judge* theory on four bases: logically, empirically, sociologically and historically (summarised in Duschl, 1990). Theories must be:

1. internally consistent or logical, and bounded in such a way that they are falsifiable;
2. testable, verifiable, involve reproducible data, and “provide criteria for the interpretation of data as facts, artefacts, anomalies, or as irrelevant.”
3. able to resolve problems or things which other theories describe as anomalous, pose new problems and offer a new paradigm for their resolution, and be of benefit to others.
4. able to meet or exceed all previous criteria, be able to explain all previous data gathered under other theories, and be consistent with all pre-existing valid ancillary theories.

If these are the ways by which we judge theory to be *adequate*, it may be fruitful to investigate the excuses we construct when we explain away evidence which runs contrary to existing theory. In other words, on what grounds do we judge these data to be *inadequate?* Chinn and Brewer (1993) created 7 classifications of the ways by which people cope with discrepancies (see Table 1). To paraphrase Winston Churchill:

“People regularly stumble over truth and spend most of their time getting up and acting as if nothing had happened.” Ironically, if the little trip-ups are consistent and predictable enough, I suspect they become ‘contextual landmarks’ which let us construct *ad hoc* clauses as a simpler way to restructure our thinking. Wittrock (1994) said, “Students easily finesse discrepant events, rather than use them as occasions to construct meaningful relations between the event and their knowledge and experience which would lead to a revised and improved conception.” Lakatos (1970) said, “There is no such thing as a Popperian quick-kill” by which he meant anomalies alone are never enough to induce practising scientists to restructure core beliefs. We live in a nether world between the power of parsimonious theory and the comfort and predictability of the idiosyncratic. If there are no magic bullets or killer-experiments, perhaps we need to remember that it is the accumulation of straws which *collectively* breaks the camel’s back. Before students judge theories to be inadequate, they must first judge anomalous data to be *adequate.* Once an (over)abundance of acceptable evidence is in place, we can move onto reconstructing theory and conceptual frameworks.

Table 1: Responses to anomalous data (from Chinn & Brewer, 1993)

Type of Response	The person ...	Pre-existing theory remain intact?
Ignoring	does not even talk about or explain away the anomalies.	yes
Rejecting	expresses reasons why the data should be rejected. Most commonly anomalies are rejected by arguing that there were methodological flaws or random fluctuations.	yes
Excluding	declares the anomaly to reside outside the realm of the theory	yes
Abeyance	accepts the veracity of the data and promises to deal with it later. For example, the motion of Mercury’s orbit was anomalous to Newtonian gravitational theory, but physicists were happy that later on, the anomaly would be explained within the existing theoretical framework.	yes
Reinterpreting the data	decides upon re-examination, that what was first seen was not the whole picture -- certain features were omitted from the earlier observations.	yes
Peripheral Change	invokes or makes a minor change to a peripheral theory which in turn digests the anomaly and keeps the core beliefs intact.	peripheral belt
Theory Change	one or more core beliefs are changed.	core change

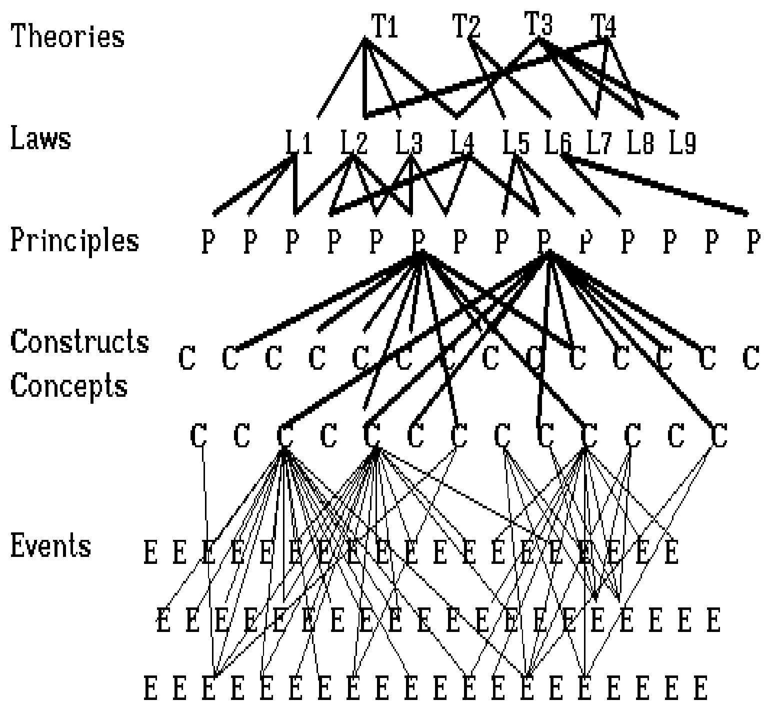


Figure 1: The epistemological relationship between theory, law, principle and construct

The parsimonious nature of theory is related to its position in the epistemological hierarchy. This is shown in Figure 1 which is an adaptation of Gowin's Epistemological Vee (Novak and Gowin, 1984). Scientists try to construct the fewest number of theories with the greatest amount of empirical explanatory and predictive power for the widest possible range of phenomena. It is a one-to-many relationship between theory, laws, principles, and constructs and concepts. Theories are broad in context, concepts and notions lower in the hierarchy are contextually rich. Theory is 'powerful,' but I think for most new learners, *theory is far less powerful at predicting than is a set of well-understood principles or locally contextualised patterns or rules. Theory's strength lies in its essential nature: its cohesive interconnectedness of smaller concepts and patterns.* As misconceptions research shows, being able to correctly choose the right rule from among a set of mutually inconsistent but contextually-rich principles gets most people (and science graduates!) through the day just fine. Reciting the rule (and its exception) that "wood floats but ebony doesn't" is more useful at predicting the behaviour of wood in water than by deducing the prediction from kinetic molecular and gravitational theory. Similarly, who among us would explain that apples fall from trees because apples are more dense than the corresponding air they displace? Theory is powerful in the sense it can be used to double-check the veracity of notions subsumed under it. Its greatest usefulness lies in its ability to create logical coherence to a vast array of predictive frameworks.

This paper reports on a minor variation to the conceptual change paradigm. The steps to this modified sequence are:

- *compile many* "exposing" events using predict, observe explain (POE) sequences;
- *compile many* discrepant events to establish the validity of existing constructs and to reveal logical inconsistencies among them;
- *differentiate* or classify existing explanatory constructs within an epistemological framework;
- purposefully *sort students* into groups so that dissonant views must be heard;
- require students to *reconcile* pairs and groups of discrepant events
- *apprentice* students into our way of knowing
- *teach some epistemology*
- *build theory* from students existing constructs and *use it to organise new and pre-existing constructs* into a logical, cohesive, and parsimonious package.

These ideas are not new. POE sequences have been used as a means to teach for understanding. Nussbaum & Novick (1982) used the term "discrepant events" in describing how conceptual conflict is brought about. Tik Liem (Liem, 1982) was a teacher who regularly referred to discrepant events but shared his knowledge within the in-service and professional development circuits. Hewson and Hewson (1983) referred to the need to differentiate conceptions. Dreyfuss, Jungwirth & Eliovitch (1990) differentiated between "experience-bound -- common sense -- knowledge" and cultural knowledge. Designing collaborative tasks to foster interactions based on dissonant conceptual stances has been used by Lumpe & Staver (1995). Concept mapping has a long history of being able to help students learn the relationship among concepts. Lastly, research into metacognition (White & Mitchell, 1994) and "learning how to learn" (Novak & Gowin, 1984) suggests that overtly addressing epistemological issues helps students understand better by giving them a way to see and think about the fundamental underlying structure of a discipline's knowledge.

I wish to offer to this dialogue some field data which supports the following notions: Conceptual change is not a linear process of refutation but instead resembles a paradigm shift (or change of programmes or traditions). Discrepancies 'pile up' until we can no longer ignore the plausibility of an alternative way of thinking. This paper is a report of a grade 9 science class which was learning particle theory. The paper is grounded within a naturalistic tradition and a teacher-as-researcher setting. Student data consists of passages culled from students' writing. I also offer us some quantitative data to assert that these 'digressions' into teaching for understanding are not to the detriment of traditional testing and do in fact bring about deeper understanding of kinetic molecular theory.

Method

The study is based on 26 students from my grade 9 science class. Students ranged from 13 to 15 years of age. Five other grade 9 classes were being taught that semester, two by the same teacher. The school's catchment is broad but draws mostly from the lower-middle SES. Classes are de-streamed (all ability levels) and hand-built to ensure each class is not over-represented by either academic or behavioural extremes. Part way through the course I was joined by an apprenticing teacher (Bart Scollard) who assisted me in record-keeping, debriefing, member-check and negative case analysis. He also taught some lessons which were part of this report.

The data reported herein spanned several months. Several exposing events took place 3 to 2 weeks preceding the 'formal' or continuous group of lessons. Since notions of KMT run throughout so much of western science, it is difficult to argue for instance that "Plants" or "Nutrition" *isn't* dealing with KMT. Spreading the exercises out also eliminates boredom and discourages students from developing algorithms for completing the task.

Results

Our naturalistic data is shown first, followed by our quantitative assessment which shows that our diversion into conceptual change practices did *not* significantly impair students performance on tradition tests but did improve their scores on a (non-traditional?) test of understanding, specifically the latter portion of a (Predict), Observe and Explain sequence. Our naturalistic data is consistent with existing findings into how students think about many physical phenomena.

Naturalistic Assessment

In the section below, I describe each event, the task we assigned to the students, summarise the trends in the class, and provide a summary and interpretation. Students were expected to provide reasoned predictions and to classify their reason as primarily experience or "not-directly-experience". Students wrote reasoned predictions on the top half of their page and their observations and reconciliation's or reviews on the lower half. All events were teacher-demonstrations except where noted. In all events, students were not evaluated for getting the right answer -- however after the fourth event though, students were marked for completeness (i.e., substantiate the reason in some way). N.B.: Each table's title identifies whether we are reporting students' predictive or explanatory constructs.

Exposing Event 1: The Rising Balloon on the Flask

Description: A balloon was stretched over a volumetric flask, massed, and dipped into hot (55 (C) water for a few minutes. The flask was removed, dried and re-massed before the balloon deflated. The task was to provide reasoned predictions on the final mass. This event was done 3 weeks before the continuous block of the Structure of Matter lessons were taught. The current unit involved looking at photosynthesis in microscopic pond life.

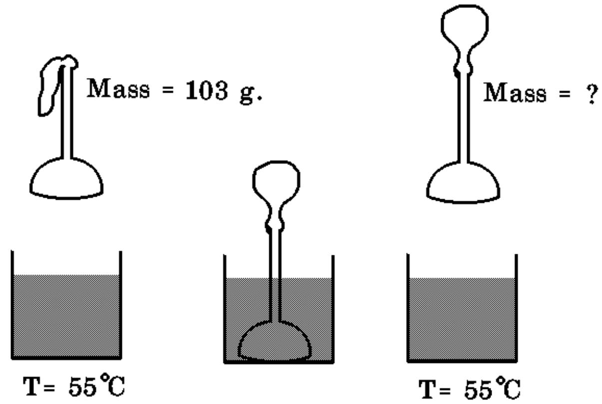


Figure 2: The Rising Balloon on the Flask

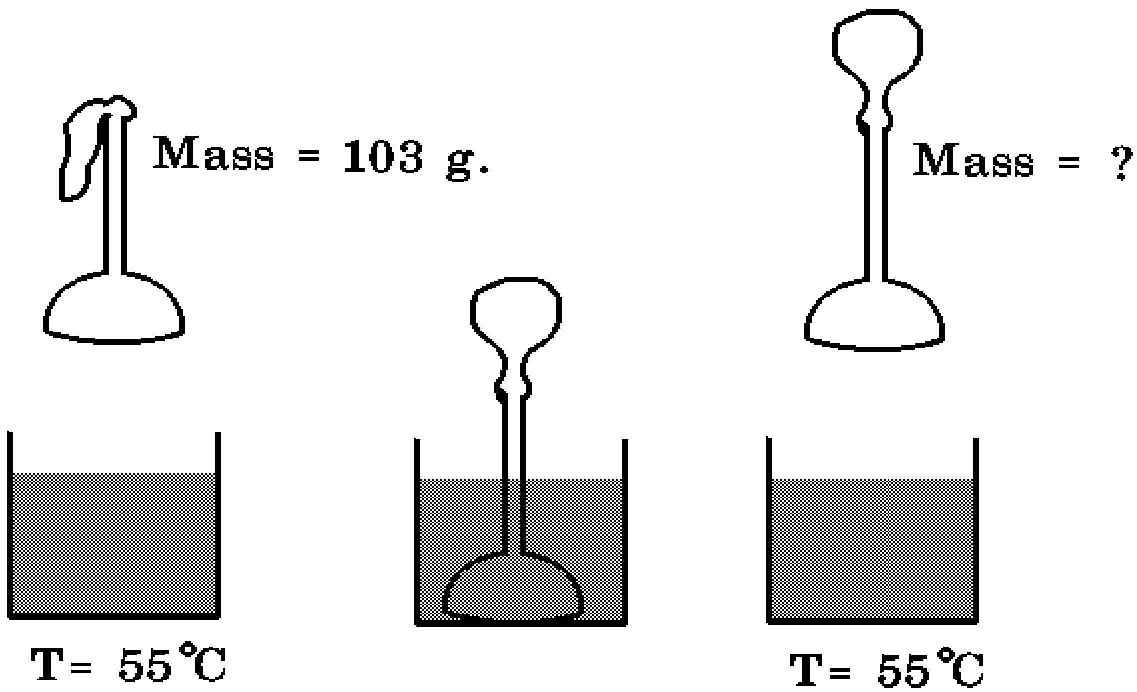


Figure 2: (enlarged)

Results:

Table 2: Explanatory constructs for "Balloon on a flask"

- *Hot air rises (8 of 13)*

  KPH: Because the air in the bottle got hotter and the when air gets hot it rises so the air filled up the balloon.

Students claimed that the air totally exited the flask and moved into the balloon. Most students in this category cited a hot-air balloon as being a similar sort of event.

- *Things get big when they get hot.(6 of 13)*[1]

  MGU: For example in the summer the doors tend to get stuck because of the hot weather. In the winter the doors move easily because of the cold weather.

Most students cited hot-air balloons as similar events; MGU's explanation was unique.

- *Idiosyncratic (1 of 13)*

  AES: ... into the bucket where the beaker was placed and the balloon on top of the beaker. As the water went in, the steam rose up and filled the balloon expanded and the beaker got hotter.

- *Observations-as-reasons (5 of 13)*

  TTR: Because you put hot water in the beaker. Then the balloon fills up with hot air

These students' explanations are really just observations.

Of the 23 students present, one student predicted the mass would decrease, 6 predicted increase, 6 said the same and 10 students recorded no predictions at all. No-one provided any reasons. When explaining or rationalising what happened, all students ignored the question of mass and instead explained the balloon's inflation.

Discussion:

Students' unwillingness or inability to address the question of mass may be because they ignored the data or may be due to the newness of the POE exercise. Both constructs of 'hot air rises,' and 'things get big when they get hot' are resonant with Engel, Clough and Driver's (p. 139) claim that children have an intuitive but unexplainable understanding of the principles. From the standpoint of theory building, these constructs will be subsumed by the principles of buoyancy and thermal expansion, both of which will be consistent with KMT. Note also that students at this stage in this context are not distinguishing between observations and reasons, neither are they referring to air in the particulate or molecular sense. We left this exposing event unresolved for the time being.

[1] The total number of constructs invoked is greater than 13 since some students used more than one construct in their reconciliations.

Exposing Event #2: The three syringes[2]

Description: Three syringes, stoppers and nails were massed. The first was drawn but not capped; the second was drawn then capped, and the third was capped then drawn so a vacuum was formed. All were re-massed. Students gave reasoned predictions on the final masses. The final masses were *not* determined until several days later (see conflict with "Heavy Basketball" below.) This POE marked the first day of our continuous block of 2 weeks of lessons.

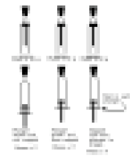


Figure 3: The three syringes

[2] We also did another exposing event the next week during the "Plants." After having seen microscopic pond life, students drew pictures and gave explanations on how single-celled organisms eat. Most students (15 of 22) made references to multi-cellular organs such as "they grab food with their arms" and "food is chewed in their mouths." Food was referred to in the bulk sense.

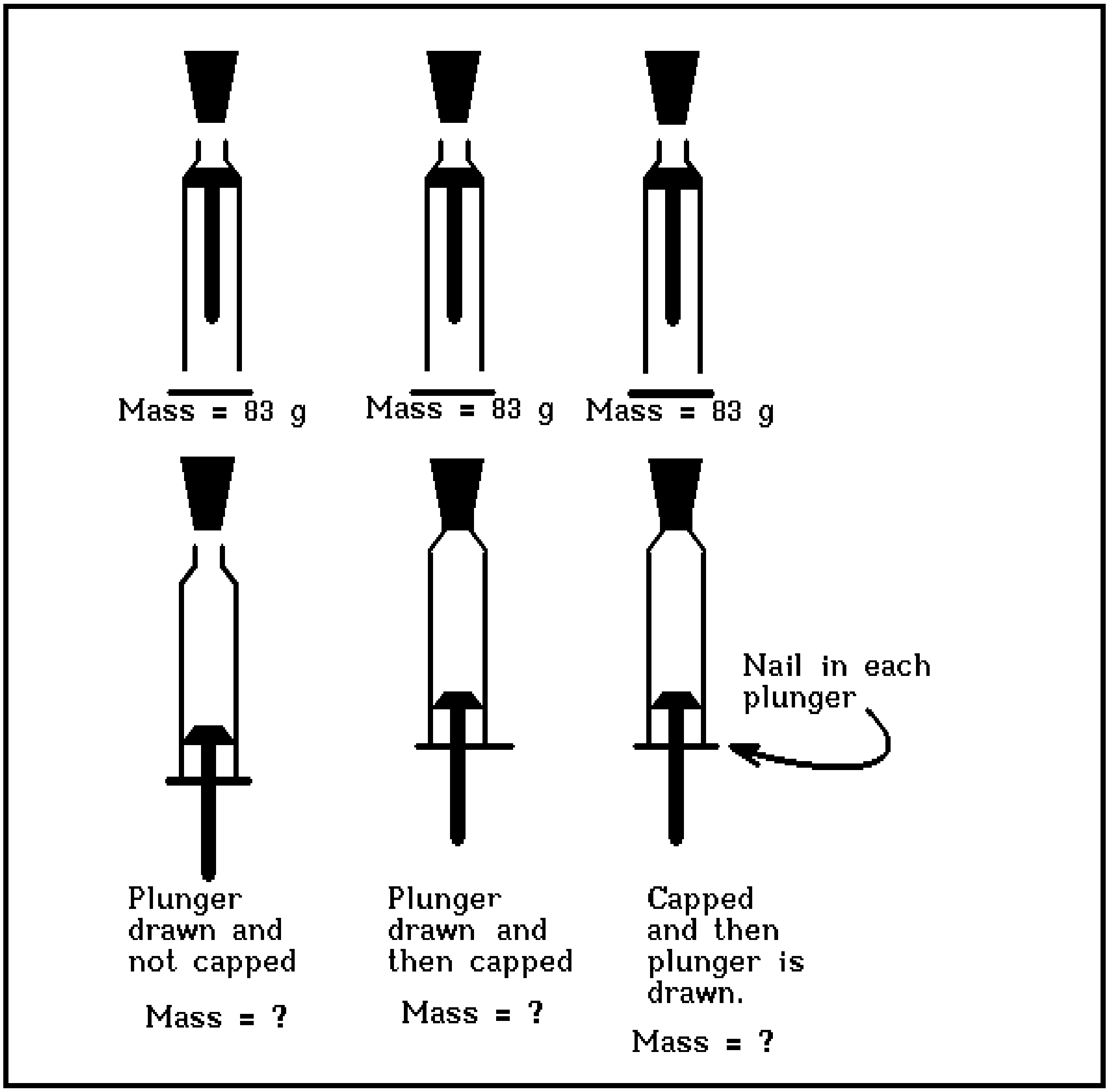


Figure 3: (enlarged)

Results:

Table 3: Predictive constructs used for "The three syringes"

mass will	Predictive construct(s) used
increase	• *Anti air particles have mass or weight(6 of 17)*
not change	• *Air is made of nothing. (8 of 10)*
	Since air is made of nothing, and there is nothing in all three syringes, the masses of all three will be the same.
	• *Size corresponds to heaviness. (2 of 10)*
	The evacuated syringe is the same size as the other syringes so the masses will be the same.
decrease	• *Anti air particles have negative mass or weight (1 of 17)*

Discussion

This notion of anti-air particles is similar to Sere's (cited in Driver 1996) report of children's' claim that air has "negative weight." Except for these students, air was still referred to in the bulk sense (i.e., non-particulate). When compared to the previous event, we can already see a logical inconsistency between the constructs "hot air rising" and "air being made of nothing." How can nothing rise? We decided to conflict this construct (and the anti-air particles construct) against the "Heavy Basketball."

Exposing Event #3: The Heavy Basketball

Description: A basketball's diameter and mass were measured. Air was *added* (pumped in) -- but not enough to measurably increase the diameter. The task was to provide reasoned predictions regarding the new mass.

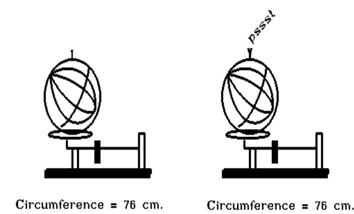


Figure 4: The heavy basketball

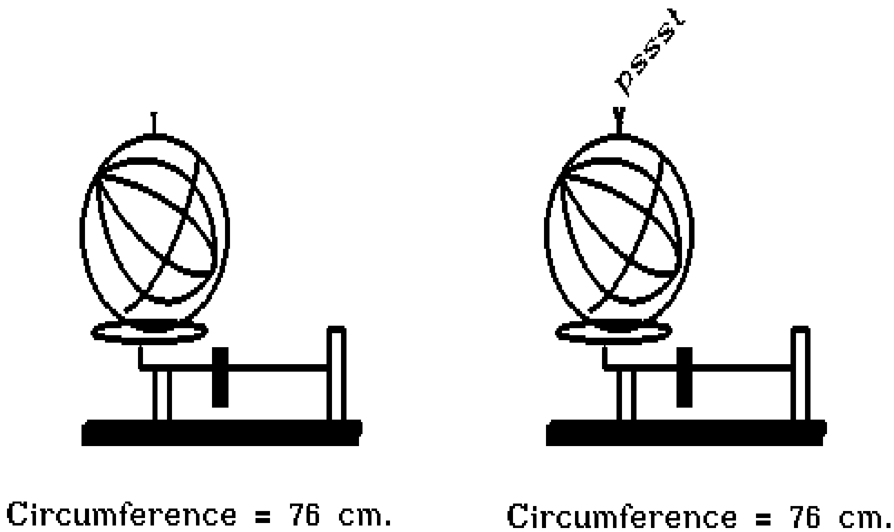


Figure 4: (enlarged)

Results:

Table 4: Predictive constructs for "The heavy basketball"

mass will ...	Predictive constructs
decrease	• *mass = weight, and bounciness corresponds to weight (11 of 13)* SKE: I play basketball and I know that the bouncier ball has more air in it than the flat one. I believe this [prediction] because I played basketball and the ball was not as bouncy as the hard ball with more air inside.
	• *idiosyncratic -- self contradictory (2 of 13)* JMI: My prediction is that the ball will bounce higher because there is more air in it and the ball will weigh more and bounce harder (JMI). [However her drawing showed the mass to go from 600 to 580 g.]
increase	• *mass = weight; heavy things aren't easily thrown or moved (3 of 18)* AKI: When the ball is less bounce-able I think the ball is going to weight heavier because from my experience the ball was heavier to shoot.
not change	• *air is made of nothing (3 of 18)*

Discussion

Several students asked that, before we add air, we drop the basketball several times to determine the average return height. We did this, added the air and the ball dropped again. Several students considered this to be proof that the ball now weighed less. Students are clearly equating mass with weight and weight with carrying.

The obvious cognitive conflicts here are between claims that the basketball weighs less with more air, but that the syringe should weigh the same with less air. This conflict also does not require us to resolve the difference between weight and mass since all items are being measured the same way. Interestingly, the notion that vacuum particles exist cannot be conflicted with the heavy basketball. It is possible to construct an internally logical set of claims that the basketball weighs less with more air and the syringe weighs more with less air since the vacuum particles out-weigh the air particles -- in fact 3 students later would argue exactly that case.

Note that these quotes are *predictive* constructs and not reconciliations. We then paired students with one another so that their predictive constructs for the heavy basketball conflicted with their peers' constructs for the three syringes. Student's worked in twos and threes and the general summary of the discussion is below.

Collaborative Cognitive Conflict: The heavy basketball vs. the three syringes

We next completed the heavy basketball demonstration by finding out whether the mass changed and asked students to prepare new predictions before we set out to find the masses of the three syringes. While students were arguing their cases, I offered the idea that scientists refer to air as "particles" of air and I asked that students try to refer to air in the same fashion.

We should have audio-taped the group debates! As we circulated throughout the group, we found two major ideas emerging. First, many students were acknowledging that *there was some sort of discrepancy between the reasons for their predictions.* Second, many students agreed that *the results of the three syringes event would help resolve the debate.* In Chinn & Brewer's terms, they would hold the data in abeyance until further evidence came in. Also, this shows that the students are committed to internally logical constructs -- which of course is a core belief of our science.

We massed the 3 syringes on an electronic balance and the evacuated one had noticeably lost mass. Consistent with Chinn & Brewer, some people decided that the values were either inaccurate, imprecise or methodologically false (i.e., I "did something" to make the results that way). We now had seen students ignore, reject, exclude,and hold data in abeyance. We felt we were getting close to theory.

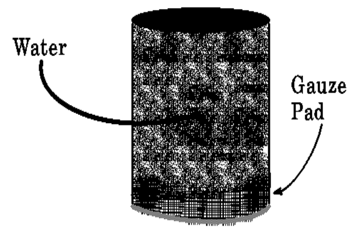
The class and I reviewed the constructs and agreed that:

1. hot air rises
2. air is made of something -- mass or weight, whichever it is that the balance measures.
3. hot things get big
4. vacuum particles (might) exist
5. "bounciness" is not a good measure of mass -- certainly not for things which hold air.

We next decided to allow students to do their own designing and experimenting with pairs of somewhat disparate events. Our intent was to compile more confounding experiences which we would collate into a larger framework. We also thought that by allowing students to design and run the experiments, they would be less inclined to rejecting discrepancies on statistical or methodological grounds.

Student exploration: "Magic gauze" and "Sticky streams"

We did an "Observe and Explain" sequence using the "Magic gauze" event and invited students to cite previous classroom events in their reasons. Students then designed and ran their own experiments and wrote reconciliations regarding the magic gauze event. The next day we followed the same sequence using the "Sticky streams" event. After the students had experimented with both events, they wrote a reconciliation of *both* the sticky streams and magic gauze. Note that the top of the can is open for the sticky streams event.



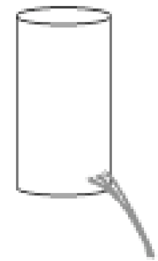


Figure 6: Sticky water

Figure 5: Magic gauze

Description: We ran water from a tap through some gauze, citing some magical incantations, and then used the gauze to cover a full glass of water. We inverted the glass and asked to explain why the water did not pour out.

Description: We punched and reamed three holes about 0.25 cm apart into the base of an empty pop can or PTE bottle. We filled the contained and asked students to explain why the streams of water combined.

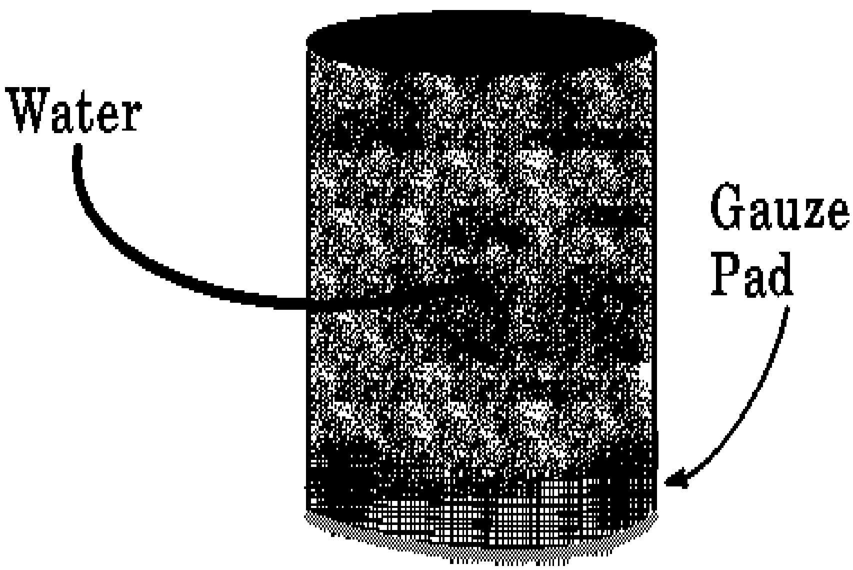


Figure 5: (enlarged)

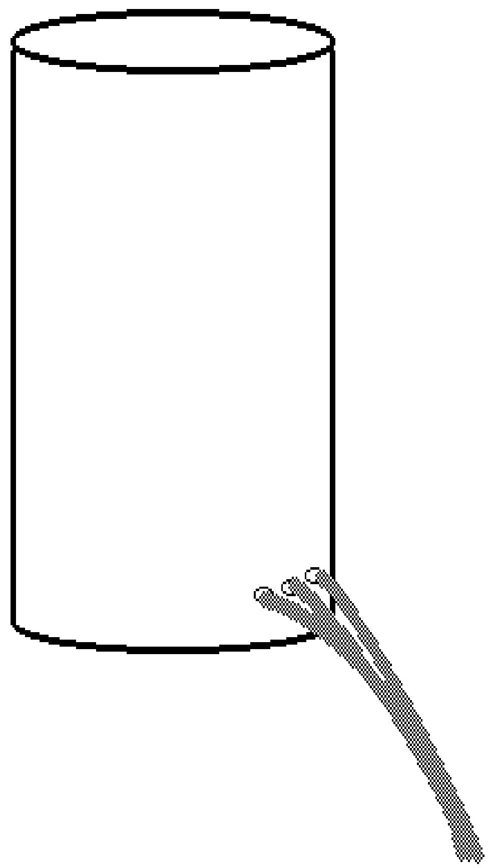


Figure 6: (enlarged)

Results

Table 5: Predictive and explanatory constructs for "Magic gauze"

- *Displacement (12 of 22)*
  TCL: ... the water will stop before all the water is out because no more air could get into the glass.
  AGA: ... because the air couldn't get up the glass because the water was covering the holes.
- *Observation as Reason -- not enough air in the jar (4 of 22)*
- *Water and air pressure and air displacement (3 of 22)*
  JAZ: The water did not come out because there is so much water pressure at once not all of the water can come out a once. The holes can only fit so much.
- *Semi-permeable membrane (2 of 22)*
  EPE: ... I think [the water will slowly leak out] because the cloth is semi-permeable and water goes through it.
- *Particle Theory (1 of 22)*
  SKE: All of the water wants to get out at the time because of gravity. All the water's being pulled down at the same force, so therefore being pushed or stuck together.

Table 6: Predictive and explanatory constructs for "Sticky streams"

- *Pressure makes the water go out. (9 of 18 responses).*
  CZI: the water will come out because the air pressure from the top will push the water out.
- *Streams coalesce because of the closeness of the holes. (7 of 18, 2 from the previous group of 9)*
- *Particles Attract (2 of 18)*
  WSZ: I think the water particles will come out of the holes because it is only logic... the water combined because it is almost like magnet.
  CZI: I think that the water came together because the water particles electrically react with each other and create static.
- *Idiosyncratic: (1 of 18) Baffle 'em with words*
  SKE: The water stuck together because of gravity, friction, and pressure.

Discussion

Notions surrounding displacement of air, air, air and water pressure are all part of the predictive and reconciling frameworks. Note that 1/3 of the class equated observation with reason (closeness of the holes).

Reflective Phase: Apprenticing the students into our way of knowing

If I were to help structure ideas, I felt I had to find some way to resolve displacement and pressure in some way which was consistent with the students' previously summarised constructs. Since air is made of something, then what does that something *do*? I suggested that particles are always pushing in every direction, and that gravity just tends to pull the particles downwards. I suggested that we could explain why water flowed out of the three holes but not the glass by:

> Magic gauze: air pushes up, water gets pulled down; result = no flow.
> Sticky streams: air pushes up, water gets pulled down, but in addition, air from above goes into the container and pushes water out; result = flow.

We eliminated the closeness of the holes as an acceptable reason, leaving the issue of why the streams coalesced somewhat open. Some students wheedled until I gave in, and I said that maybe it just showed that water particles stick together. I said, "Maybe air particles don't stick together and that's why they're always flying around so much instead of getting pulled toward the ground."

To re-address the notion of epistemology, I sketched on the board and gave a decidedly abbreviated description of epistemology. The description in essence was "theories and laws were things which applied to all the other littler ideas" and that, "theories are made of statements which are true for all the littler ideas. If we take the commonalties of all the principles we use to predict, those ideas are called theory." We then reviewed the experiments and the student constructs and discussed whether the ideas belonged near the bottom or top of the epistemological pyramid.

Event: The Bouncing Stopper

Description: We put a lightweight stopper (or Ping-Pong ball) on a flask's mouth and immersed it in hot water. Students prepared reasoned predictions of what would happen.

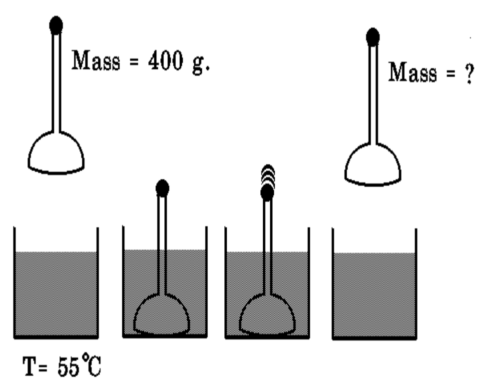


Figure 7: The bouncing stopper

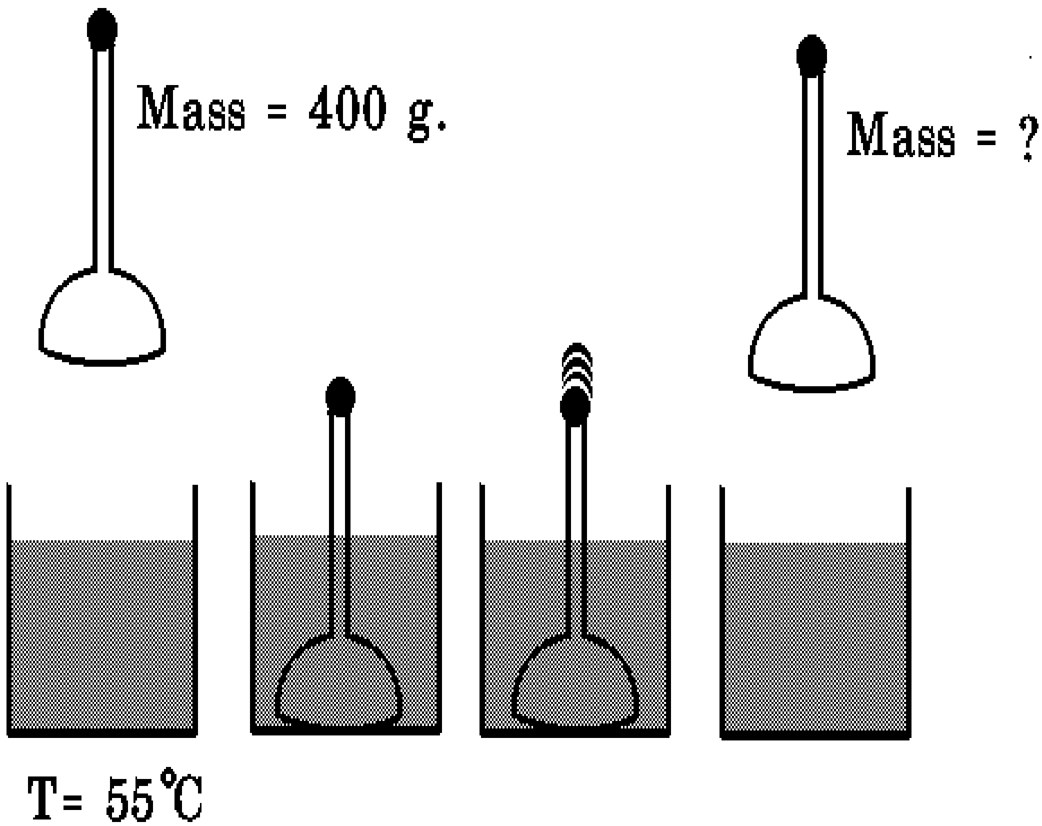


Figure 7: (enlarged)

Results

Table 7: Predictive and explanatory constructs for "The bouncing stopper"

- *Mix and match Pressure, Hot Air Rises, Hot Air Gets Big (16 of 18)*
  JAZ: ... my predictions were right because the hot air did rise and made the top pop up.
  JMI: After the water is added the lid will fly off and the air particles will expand.
  AMA: ... because the hot water gave some the air some pressure to push the lid up but not enough pressure to make the lid come off.
- *Particle Theory (partial) (1 of 18)*
  EPE: I think the air particles in the bottle will expand when the water is poured in the beaker.
- *Particle Theory (partial) (1 of 18)*
  BVA: When the water cools, the air particle inside the beaker will move back closer to each other. None will want to get out so the lid doesn't have to move to let the water out. It's like when telephone wires over roads get hot (in summer) the wires get longer, when they get cold the wires get shorter. The air particles took up more space so the ones that couldn't fit in the beaker left thorough the opening.

Discussion

Most students (14 of 18) used particle-based reasons, but the most common misconception was
that particles themselves get bigger when substances are heated. This notion is difficult to prove based on logic alone since there the notion of molecules is essentially invisible. The question which could be put to students is, "If we cool particles a whole lot, do they disappear? This notion of particles expanding also can be used against the earlier notion some students had regarding vacuum particles.

Event: Disappearing Volume and Mass (Part I) Water and sand

Twenty grams of salt were put in one graduated cylinder and 100 g of water in another. Students predicted what the final volumes and mass would be after the salt was dissolved. Consistent with existing research (Driver 1996, p. 84), about 1/4 of the class predicted that the mass would decrease. Typical answers were that the salt "went away." The rest of the class predicted the mass would remain the same since the salt particles had not left the container, they had only appeared to have "gone away."

Event: Disappearing Volume and Mass (II) Methanol and water

Description: 50 ml of water were massed and added to 50 ml of methanol which had been massed. The students were to reason out the final volume and mass.

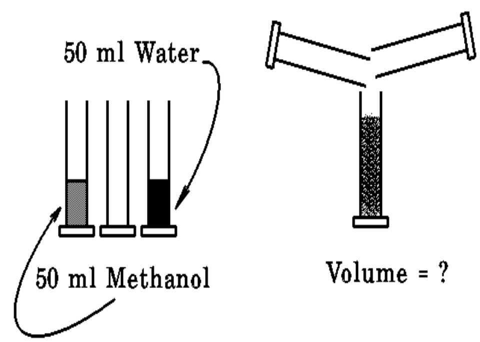


Figure 8: Disappearing volume (methanol and water)

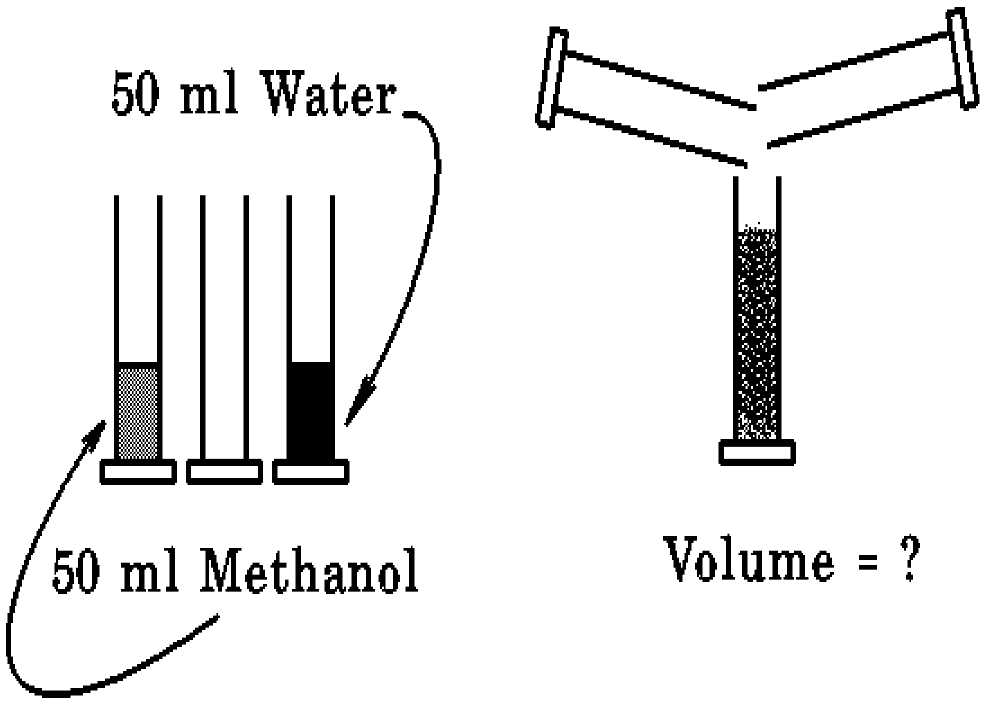


Figure 8: (enlarged)

Results

Table 8: Explanatory constructs for "Disappearing Volume (II)

- *Particles Disappear*
  AGA: When the alcohol was poured in the beaker with the water, there were alcohol particles that disappeared because the particles consumed.
  EPE: I think this happened because the air particles in the water were taken over by the particles in the methanol.
- *Particles or Spaces Shrink*
  JFO: When the water particles get mix with the water particles the water particles shrink and it takes less room. The water particles are smaller than the water particles.
  EKN: the spaces in between the particles get smaller and the particles try to move faster but the particles can't.

Apparently this student has fixated upon the notion of fast moving particles for some reason.

- *Particle Theory*

  AMA: The methanol particles (which are smaller) sunk between the water particles (which are bigger).

Interestingly, this is a student who routinely is way off-base. It appears that something here "clicked."

Discussion

A significant issue for students to resolve is the notion of the indestructibility of the particles. Some students spoke of particles being “taken over” or being “destroyed” by other particles. The greatest problem with dealing with this misconception is that in chemistry, molecules really are “destroyed” in chemical reactions! By this time, we believed that most students were using most of the ideas of the KMT.

Summative Phase: Teacher review of all previous events

In order to show that the notions of the KMT were consistent for every event demonstrated, we prepared around the room all the experiments and demonstrated each one. The postulates of the KMT were written on the blackboard and we referred to the postulates as we made each prediction and explanation. In addition, after each demonstration, we recalled the predictive and explanatory constructs the students had used and, wherever possible, rephrased them in terms of KMT. Much to our pleasure, when we re-did the “Balloon on the flask” event, all the students correctly addressed the notion of conservation of mass.

To offer our apprentices one last chance to try their knowledge out, we gave them one last POE event:

Event: Hot water, big water

Description: An Erlenmeyer was overfilled with cool water. A one-holed stopper with glass tubing was jammed into the flask (so some water displaces up the tubing) and the whole thing was placed in hot water.

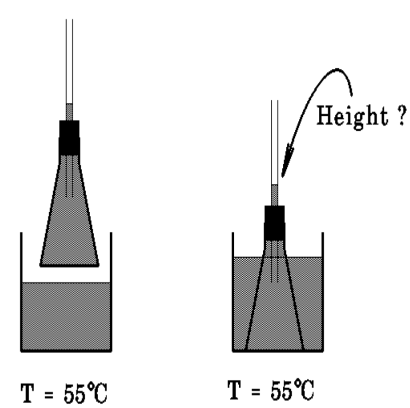


Figure 9: Hot water, big water

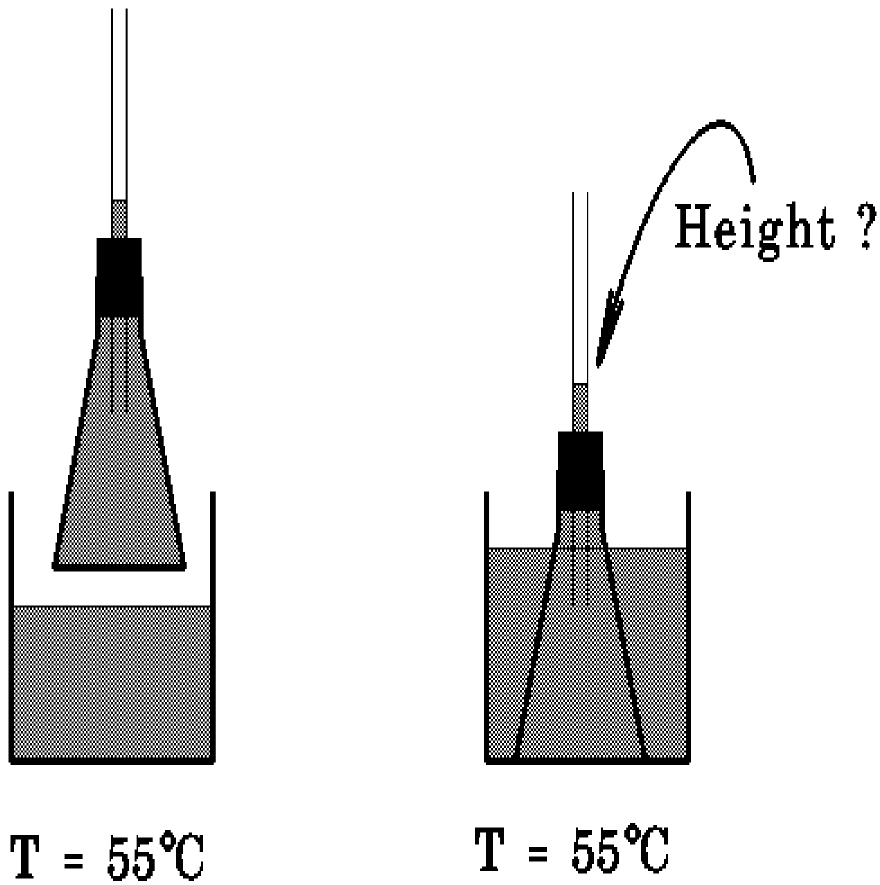


Figure 9: (enlarged)

Results

Table 9: Predictive constructs for "Hot water, big water"

- *(Partial) Particle theory. (9 of 18)*

Students said the particles of water would get hotter and move faster and push their way up the flask.

> JFO: Water particles are going to rise up the tube because the water particles are hot and hot particles move faster than cold particles.
>
> AGA: The water particles are going to move faster because of the hot water and so the water particles are going to rise up the tube.

- *More Complete PT (9 of 18)*

> (ENE): The particles will rise in the thermometer will rise because when particles are heated, they move faster and push up on the air. The spaces will get bigger and the particles will move away from each other [this student claimed what was happening here was the same as how a thermometer works].
>
> SKE: Since the water particles can't get out of the sides or bottom of the flask, the water particles push towards the top and the water particles rise (SKE).

Discussion

Every student was able to use the ideas of particles moving faster when heated. Their pictures also all showed all water particles to be identical. Half the students invoked additional notions that there were competing collisions between air particles and water particles. All students asserted that the mass of the water would not change.

The last step was to check our class against their peers who were learning in a more traditional mode; that quantitative assessment is included below.

compares our students with their peers the traditional practical test (See Appendix A). Our class does not stand out significantly from their peers, suggesting that students learning under our approach are not hindered as viewed by traditional testing. show the results of the "Observe and Explain" assessment. The (^{2} value indicates that our students performed significantly differently (and better) than their peers. Specifically, our students correctly invoked more KMT postulates in order to explain what they saw. I have included to show which aspects of the KMT were most cited. The least commonly cited postulates the notion that molecules move faster and further apart when heated. The two most frequently pairing of postulates were that particles have mass and that air exists inside and outside an open container.

Table 10: Summary for Traditional[a] Assessment

	Others (N=131)		JM (N=25)	
Score	Observed	*Expected*	Observed	*Expected*
0	15	*15.1*	3	*2.88*
1	35	*33.6*	5	*6.41*
2	28	*31.1*	9	*5.93*
3	26	*26.0*	5	*4.97*
4	17	*16.0*	2	*3.04*
5	10	*9.2*	1	*1.76*
				$\chi^2 = 3.089$

Notes: (a) Appendix A has the actual questions used. χ^2 value for JM is 3.089. Twenty degrees of freedom were used since there were 5 classes all together. For 20 *df,* χ^2 value ($p<0.01$) = 37.6 .

Table 11: Summary for non-traditional “Observe and Explain” assessment

	Others (N=129)		JM (N=25)	
# of postulates	Obs.	Exp.	Obs.	Exp.
0	83	72.04	3	13.96
1	20	16.75	0	3.25
2	6	7.54	3	1.46
3	13	19.27	10	3.73
4	6	9.21	5	1.79
5	1	4.19	4	0.81
				$\chi^2 = 50.50$

Note: use N=129 because 2 students were absent for the O & E assessment. For 20 degrees of freedom, χ^2 value (p<0.01) = 37.6

Table : Specific KMT Postulates Cited for Observe and Explain Assessment

	Others (N=129)[a]	JM (N=25)
Particles have mass	28	21
(Air) Particles exist inside and outside the flask.	19	17
Heat causes particles to move faster.	17	14
Particles move further apart.	12	11
Particles collide with and push lid up.	20	13

Notes: (a) According to , the total number of postulates invoked by the control group should be 100. Results in total to 96 because some responses were disregarded because of some ambiguities in language.

Closing Thoughts

Several critiques need to be addressed in closing. First, it may be claimed that our class did well because we trained them to answer our questions a certain way. This is certainly valid issue, but one which applies to every teacher and every class. Therefore the question is, what type of response should we be training? If not KMT, then what? Second, it may appear that we taught KMT by using a paltry 10 or so demonstrations and in doing so, are dangerously close to advocating induction of grand theories based on too small a sample size. This is not the case. Like all naturalistic investigations, much more than is reported here took place since ultimately virtually every physical event done in the classroom relates to KMT. Chemistry is essentially KMT in origin, therefore two other units taught this semester (photosynthesis and chemical change) would have an impact on generating understanding of KMT. Additionally two other units, Cells and Nutrition, have molecular origins which again would help generate KMT theory. Furthermore, in each of these units, attention was specifically drawn to KMT postulates wherever appropriate. When we connect such diverse contexts into one cohesive understanding, we have built theory. Third, it may appear that I am advocating that teachers undertake a specific series of demonstrations and labs which magically in the end causes most students to understand the KMT. I don't believe that the sequence is important *per se*, at least insofar as pre-planning is concerned. However as learning evolves, the nature of learning from discrepant events requires that a teacher (or school system) be ready and able to respond to individual and group needs. Furthermore, when students in the same class are doing different experiments but all working on the same theory, the constructed theory is strengthened because of the diversity rather than in spite of it. Many students "get the picture" early on, some take longer to learn. As a teacher, I cannot be overly concerned with the specifics of why and how the understanding was generated. I leave those specifics up to the theoreticians from which I get my ideas. My contention is only that in a group setting where teachers cannot monitor every conceptual element, there is value in overkill -- provided that the overkill is broad in context and the target is theory.

Theory change in science has never been a neat and singular process. As many researchers and philosophers have pointed out, in retrospect we can always point to a single event or experiment which turned the tables. Also, significant experiments can be refutations or supporting experiments. Either way, a single event exists in combination with many other related events. Proving what is already believed to be true is hardly difficult -- accepting the validity of something which runs against the grain (i.e., accepting the validity of refuting data) is the challenge. Teachers must be prepared to wait out the students as they run the gamut of responses or excuses we all construct before acknowledge that maybe, just maybe, their thinking needs re-working.

Theory's strength is its ability to cohesively structure and subsume student's everyday predictive constructs. Rather than look for a single magic bullet, it seems fruitful to pursue theory-change as being facilitated by an overabundance of valid and discrepant data from a variety of contexts. That, and the desire to make sense of it all into one big picture, are two things we have found useful in helping students generate understanding.

Acknowledgements:
I wish to thank and congratulate the efforts of Mr. Bart Scollard who was apprenticing with me during a large part of this project. I also promised to thank the students of my 1995 science class all of whom signed the forms, got the permissions, wrote legibly, and gamely set off into the unknown. There is perhaps no better measure of a scientist than a student (or student teacher!) who is willing to "find out." For that, all these young men and women deserve our thanks and praise.

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Appendix 1: Questions from Practical Exam

Part 1 (Traditional)

On the lab desk there is a block of wood.

1. Find the mass of the wood.
2. Calculate the volume the block. Show your work and use the correct units.
3. What is the density of the block? Show your work and use the correct units.
4. If you had a larger block of the same material, what would the density be? Give reasons for your answer.
5. If you had a different substance of the same volume, would it have the same mass? Explain your answer.

Part 2: (Non-traditional: Observe & Explain using Aspects of the KMT)

The Bouncing Lid

(For this examination question, a teacher placed a plastic eye-dropper lid upside down on a volumetric flask. S/he then submerged the flask in a beaker of steaming hot water which had been poured from a kettle recently off the boil. Students were told to:

1. Describe in words the observations you made about the demonstration.
2. What would you predict the final mass to be? Give reasons for your answer.
3. Draw pictures to explain what happened. Use words to describe what you mean with your pictures.

Before the hot water was poured	**While the lid was bouncing**	**After the lid had stopped bouncing**
(For the exam, this table alone occupied a full sheet of 8 1/2” by 14” paper.) Description:	Description:	Description: