<u>Student Alternative Conceptions in Chemistry</u>

(Originally: Student Misconceptions and Preconceptions in Chemistry)

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"Chemical equations ... it took me ages to pick it up as I found it quite confusing ... but having been taught by a teacher one way I tend to relate to it in the same way but in my own thinking ... in an exam I would probably get it wrong. You see when we are told to swot for a test we have to go swot in our book all the stuff the teacher's way ... we go home and we try to learn that ... but as soon as it hits our eyes it goes in our brain and it goes out the other way ... and so when we come to write it down and we think ... and we write it down all our way ... because of course it still means the same thing ... there is no difference ... but to the teacher there is a distinct difference between our way and the teacher's way ... and the teacher's way is the right way ... that's what I find so hard."

15-year-old science pupil in New Zealand, in Osborne and Freyberg (1985).

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Learning is an active process, and what students do with facts and ideas with which they have been presented depends to a very high degree on what they already think and believe. Being able to recognize and work with these student-held ideas and conceptions is thus a key component of an effective educational strategy. Mulford and Robinson (2002) expressed the problem thus:

> Alternative conceptions play a larger role in learning chemistry than simply producing inadequate explanations to questions. Students either consciously or subconsciously construct their concepts as explanations for the behavior, properties or theories they experience. They believe most of these explanations are correct because these explanations make sense in terms of their understanding of the behavior of the world around them. Consequently if students encounter new information that contradicts their alternative conceptions it may be difficult for them to accept the new information because it seems wrong. The anomalies do not fit their expectations. Under these conditions the new information may … be ignored, rejected, disbelieved, deemed irrelevant to the current issue, held for consideration at a later time, reinterpreted in light of the student's current theories, or accepted [while only making] minor changes in the student's [previously held] concept. Occasionally anomalous information could be accepted and the alternate conception revised.
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> If anomalous new information is presented in a learning situation where the student is rewarded (with grades) for remembering it, the information may be memorized in order to earn the reward, but it is likely to be quickly forgotten because it does not make sense.

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(Appendix 2, Outline of Topics, Cont.)

Introduction

There has been controversy over whether to refer to student conceptions that aren't in accord with those held by scientists as "preconceptions" or "misconceptions". "Misconceptions" seems excessively judgmental in view of the tentative nature of science and the fact that many of these conceptions have been useful to the students in the past. "Preconceptions" glosses over the fact that many of these conceptions arise during the course of instruction. Use of the expression "student alternative conceptions" was finally agreed upon.

The following review of the literature on student alternative conceptions in chemistry, and the compilation that came from it, was begun by participants in the Summer, 2001 Integrated Chemistry and Physics course at Arizona State University, who, on their own initiative, organized an action research team to begin the design of a new chemistry curriculum. Work on it continued during the 2002 and 2004 summer meetings of the Modeling Instruction in Chemistry action research teams and their consultants.

The Modeling Instruction in Chemistry action research team members were largely high school teachers who had been influenced by the Modeling Instruction in Physics workshops (Wells, *et al*., 1995). The Modeling Method of Physics Instruction (described at http://modeling.asu.edu) focuses on scientific models as central units of knowledge. The original modeling program, for first-semester physics, was motivated by the role that major student alternative conceptions play in blocking understanding of Newtonian mechanics. The program uses a patient guided-inquiry approach to leading students into confrontations with the results of experiment, getting them to articulate their thinking, and managing the student discourse as they argue their way to a new interpretation. Dramatically higher levels of success have been achieved in this phase of physics instruction. A key feature of this program is use of research-validated concept tests such as the Force Concept Inventory (Hestenes et al., 1992) to measure student conceptual change during the course of instruction.

In recent years, high school, college and university teachers involved with modeling instruction in physics have been working to apply these insights and methods to other content areas of physics (e.g. Swackhamer, 2001), to AP physics instruction, to middle school and high school physical science instruction, and now to chemistry instruction.

Among the purposes for studying and cataloging student alternative conceptions in chemistry as part of a project to design a new curriculum were the following:

1. Identifying key misconceptions can help in designing curriculum, by identifying where student breakthroughs are needed and alerting designers to pitfalls. Key misconceptions are those which, if left unresolved, have the potential to block or impede further progress.

2. Teachers and curriculum designers need to be aware that instruction can actually foster misconceptions that are later problematic and difficult or impossible to erase. This knowledge may lead to different choices in how initially to teach topics.

3. Understanding student conceptions is essential for designing effective questions and "distracters" for concept evaluation instruments and tests in chemistry and physical science (e.g. Yeo et al. (2001).)

4. An awareness of student alternative conceptions provides teachers with a window into their students' thinking, helping them listen to their students more powerfully, and thereby helping them to more skillfully manage student discourse.

5. We sought to provide teachers, curriculum designers and researchers with a broad bibliography of student alternative conceptions for further research.

6. The process of compiling student alternative conceptions served as a stimulus to discussions about what conceptions and models we most want our students to master, and how to frame them.

If it is true – and we believe it is - that students must construct their own understanding, and must build new understanding out of the conceptions that they already possess, then it is inescapable that students will need to draw on their "alternative conceptions" for pieces that they can rearrange and reuse to form new concepts. Identifying the concepts the students possess contributes to the search for "bridging" concepts. These are concepts initially accepted by students which are close enough to scientifically accepted ideas to be useful in transitioning to the use of the latter, as proposed by Clement (1982) and de Vos (1987). An example of this might be Linn and Songer's use of a heat-flow model similar to the "caloric" theory, but stressing that heat lacks mass, for working with middle-school students. (Linn (1991))

Beneath the expressed student alternative conceptions may lie a set of what Halloun and Hestenes (1985b) call "commonsense concepts", which students may not even be able to articulate. Andrea diSessa has proposed that students can be seen as possessing a large set of *phenomenological primitives* or *p-prisms* (diSessa (1983,1993)), a "rich system of elements that are organized only in limited degree …. relatively simple and usually abstracted from common experiences. For example, 'people expect that greater effort is accompanied by greater results.'" (diSessa and Sherin (1998) p.1177). Other examples include "closer is stronger", and "maintaining agency", meaning a continuing cause that maintains motion. (Hammer (1996)) It is proposed that that these p-prisms are never discarded but are rearranged to form new concepts. That level of analysis is beyond this work, but may help explain the observation that groups of students holding alternative conceptions and struggling with discrepant facts can – with guidance and some appropriate questioning - discuss their way into a very different and stable conception.

The list "Student Alternative Conceptions In Chemistry" in Appendix 2 is certainly not complete. The literature on the subject is extensive and has been far from completely mined. Researchers continue to discover new alternative conceptions by asking new questions. Educators and textbook writers continue inadvertently to generate new misconceptions. Finally our understanding of what alternative conceptions are and what is important about them is changing.

It can be argued with justification that reducing the cited literature to a list of misconceptions strips away much of its value. Teachers and researchers would be well served to find and read the sources. For example, Rozier et al. (1991) in a study of student reasoning in thermodynamics, involving 2000 students and 29 teachers at the University of Paris, explored the following: student difficulties in thinking about situations involving three variables; their difficulty in following their own chain of reasoning in the reverse direction; their appeal to sequential intermediate states to justify their reasoning; and their willingness to consider that systems will obey different laws during a transition between states. Out of this insightful and thought-provoking work I have lifted for this list such student alternative conceptions as I was able to express in one or two sentences.

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Case studies following small numbers of students were not included in this list due to the small sample size. They can offer great insight into student alternative conceptions and how they can evolve over time in response to instruction. For example, Greenbowe and Meltzer (2001) analyze in depth over the course of six weeks the progress of one “typical” student's thinking about calorimetry, looking at the processes of concept formation and maintenance, laying bare the structure of her ideas and the uneven and multi-step process by which she moved from one set of ideas to another.

Alternative conceptions – the problem

Preconceptions in chemistry, as in physics, are extremely persistent. Authors reporting on the evolution of preconceptions describe a rapid evolution in fundamental ideas about chemistry between the ages of 6 and 12, but only very slow change thereafter, in spite of intensive instruction in chemistry. Alternative conceptions present at age 12 are likely to still be present at 18, and may persist throughout life. For example, Ahtee and Varjoli (1998) found that approximately 10% of eighth graders in Finland failed to distinguish between substances and atoms. The same percentage of secondary school students and university students made the same mistake!

Bodner (1991, 1992) and Birk (1999) document the persistence of elementary alternative conceptions into graduate school. Bodner (1991) reported that fully 30% of entering graduate students in chemistry, considering the bubbles in water that had been boiling for over an hour, failed to identify them as consisting of water vapor, and 20% indicated that they contained air and/or oxygen. None was able to correctly describe the reaction of sodium metal with chlorine gas to form Na+Cl- and most held views greatly at variance with what they had been taught. Among his comments: “The research being done to identify the concepts build during their first exposure to chemistry is important … because the misconcepts they build are so resistant to instruction that a significant fraction of the population even after [900 hours of laboratory and lectures continues to hold them]”

Lewis *et al*. (1994, 1996) studied alternative conceptions in thermodynamics in 8^{th} graders, secondary students, college students and a group of "experts" holding advanced degrees in various sciences. They found all held similar misconceptions about the natural world. Only among those with Ph.D.s was the incidence of misconceptions significantly lower.

These preconceptions form the mental framework, the scaffolding, on which students build all subsequent knowledge. New information and ideas which students receive are reinterpreted and rearranged to fit within this scaffolding. Many authors have commented on how clear students are during exit interviews that their answers make sense and are right, even while recognizing sometimes that they don't agree with current scientific thought. Students often acquire a significant ability to solve problems in chemistry courses without understanding the principles the problems were intended to teach. Given that these conceptions exist as actual physical pathways laid down in the brain, and given that the cognitive architecture of the brain, once laid down, cannot be expunged but only overlaid with new paths, it is not surprising that it should be very difficult for students to move beyond them to the scientifically accepted concepts. Students instead graft new knowledge onto a conceptually faulty base.

For example, Nurenburn and Pickering (1987, reported in Mulford (1996)), found that of a selected group of college students who were all successful at solving algorithmic questions, many had a very low understanding of the chemistry involved. Lythcott (1990, reported in Mulford (1996)) found that of a group of high school students who were able to balance an equation, most could not draw a diagram of what was happening. Peterson and Treagust (1989) found that of a group of secondary school students, 74% were unable to answer conceptual questions about electron repulsion in valence shells, but 78% were able to successfully answer test questions designed to test this understanding. Similarly Yarroch (1985) found that of "A and B level" high school chemistry students virtually all could balance the equation

H2 + N2 -> NH3

but half could not draw a correct molecular diagram to explain this result.

Many investigators report on the ineffectiveness of didactic teaching at altering or replacing misconceptions. For example, Herbert Beall (1994) lectured college freshmen on the second law of thermodynamics and the ideal gas laws. After the lecture only 11% were able to correctly predict the effect that opening a cylinder of compressed gas would have on the temperature of the gas. Douglas Mulford (1996) in his dissertation observed that student gains on his Chemical Concept Inventory given before and after their general chemistry courses were marginal, and even students receiving an “A” were able to answer on average only 12.2 out of 22 concept questions correctly. He commented that "a student can earn a high grade ... while still having a high level of misconceptions" and that the gains in concept mastery they made (on the order of one point for the class as a whole), while statistically significant, were of "doubtful educational significance."

Marilia Thomaz et al. (1995), L. Lewis et al. (1994) and Clough and Driver (1985) focus on students' concepts about heat and temperature. Clough and Driver (1985) find the whole subject of student preconceptions on this topic to be a "steaming swamp", a morass of wrong and contradictory ideas that are not worth struggling with. They argue for ignoring preconceptions and focusing on building a new coherent structure. Thomaz et al. argue that this has been proven to be ineffective and that to be able to affect student thinking, teachers “need to go into that swamp” and work with student preconceptions.

Nature and Origins of Alternative Conceptions in Chemistry

Hesse and Anderson (1992) and Tabor (1998) point to the strong preference of most of their subjects for common-sense reasoning, everyday analogies, visible effects and changes, and common (non-scientific) word usage. They observed that students actively rejected the use of scientific vocabulary ("fancy scientific words") in favor of colloquial speech, which led the students into many misunderstandings. They called for teachers to lead students in careful examination of the limits of analogies and metaphors. They predict that some classes of preconceptions will be culturally specific, a product of the analogies and metaphors common in particular cultures or built into particular languages, rather than being universal.

Along this line, Schmidt (1997) discusses how misconceptions form a meaningful and coherent alternative framework in students' minds, which is very robust and difficult to change. He then focuses on the role of everyday meanings of words in fostering misconceptions. He traces some of these misuses of words--for example “oxidation” -- to the way they were historically used in chemistry.

Nakhleh (1992) points out that “words such as ‘atom’ and ‘neutralization’ are actually labels that stand for elaborate cognitive structures stored in the brain … sensible and coherent understandings of the events and phenomena in their world from their own point of view.”

These cognitive structures are not dictionary definitions; they have visual components and many of the investigators reviewed used student drawings (or sculptures!) to explore them. DiSessa (2004) points out that these often appear to be organized in the students’ minds as stories that unfold as the students sketch and explain their ideas.

Tabor (1997) points to anthropomorphic thinking in students' (and teachers’) reasoning about the behavior of electrons in chemical interactions. It was also observed in students' reasoning about chemical reactions. What electrons "want" to do is used as a primitive force concept. (Many teachers and researchers, myself included, still reason this way sometimes, a cause for reflection.)

Harrison and Treagust (1996) classified the kinds of models that can be built of a physical phenomenon, and then observed how students used various models and types of model to build a picture of the phenomenon. They deduced that none of the 48 students completing a chemistry course had come to understand that the models they were using were only models, which "... served the development and testing of ideas, not the depiction of reality." Only one of the 48 seemed to even be "on the verge of achieving this understanding." The authors call for teachers to lead their students in a thorough study of the process of model construction and to an understanding of the limitations of the models so constructed.

Many authors observed that the ways in which students confuse models and images with reality and the ways in which concepts learned (or misunderstood) in earlier grades form the framework for later misconceptions. For example, Harrison *et al*. (1996) discuss at length the model of the atom as being like a living cell with a nucleus that divides, a model which a significant minority of students use as their framework for understanding chemistry throughout their school careers. This can have serious consequences. D. Cros, et al. (1986) noted that university students who used the Bohr model to describe an atom failed to move beyond this picture, and this apparently stunted their development as chemists, causing their understanding of interactions between subatomic particles to fail to grow.

Kmel *et al*. (1998) points to a " ... hierarchy of increasing cognitive demand [in describing chemical processes:]

1. Disappearance
2. Displacement
3. Modification
4. Transmutation
5. Chemical reaction (interaction)."

They observe the gradual progress of students from age 8 through 18 in moving up this hierarchy, which is also a movement away from a "model of matter which is homogeneous, static and continuous."

With some phenomena, nearly all students come to the learning process with one version or another of the same dominant set of preconceptions. The force concept is a classic example of this; see for example Clement (1983), Halloun and Hestenes (1985a and 1985b) and McClosky (1983). With other phenomena, there was no dominant student alternative conception, but rather a whole spectrum of ideas.

Some alternative conceptions are held by non-chemists and may be learned from textbooks in other subjects. For example, "Breaking chemical bonds releases energy." Of a group of high school chemistry students, 48% claimed this (Cachapuz (1987); see also Barker (1985) in Kind (2004) p.64). The role of energy in chemical bonding is a most fundamental issue. The concept of bonds storing energy has an intuitive appeal, makes the story of chemical energy much easier to tell, and is widely used even by biologists.

<u>Difficulties with abstract concepts</u>

Many alternative conceptions may be generated by students as they grapple with information and models presented in school which they are unprepared to imagine or understand.

R. Stavy (1988) followed a cohort of students, and observed that while they were taught atomic theory repeatedly in 4^{th} through 7^{th} grades, when questioned about physical phenomena in 8^{th} grade they still made no reference to atomic theory in their explanations. Only in grade 9, beginning with explanations about gasses, did they start to refer to it. From this, he questions the efficacy of teaching atomic theory before students have fully explored the nature of matter at a macroscopic level. However, Gabel reminds us (Gabel et al., 1987) that we must live with the reality that “the microscopic level is depicted at the elementary level,” so that as a practical matter teachers cannot avoid the atomic theory.

The difficulty here may be that students have difficulty believing in something they cannot see. The student must “overcome immediate perceptions which lead him to a continuous static view of the structure of matter. … Internalizing the model [adopted by scientists] requires overcoming basic cognitive difficulties of both a conceptual and a perceptual nature.” (Novick and Nussbaum, 1981, quoted by Kind, 2004, p.9.)

Writing in 1999, Dorothy Gabel refers to "three levels of expressing matter ... macro, sub-micro (particle models) and symbolic (chemical notation)." She observes that "chemistry instruction occurs predominantly on the most abstract level, the symbolic level", and she presents evidence that this is ineffective.

Erickson (1985, reported in Viennot (1998)) argues that early introduction of the molecular model is unavoidable. Referring to the persistence of students' misconceptions about vaporization, he wrote, "The understanding would seem to require some explanation of what is happening to the liquid at the molecular level in order for temperature invariance to make sense."

There is ample evidence that the particle model is difficult for students to grasp, and, whether it is introduced early or later, there is no doubt that it must be fully mastered at the high school level for students to be fully successful in chemistry. Kind (2004) proposes that the ability to distinguish between elements, compounds and mixtures based on the particle model of matter may largely determine which students can continue with chemistry after age 16. She reports that “about 43% could define ‘element’ and ‘compound’ correctly at the start of a post-16 course and that this figure remained unchanged at the end.” (!) (Barker (1995), in Kind (2004) p.23.) Clearly this is a key conceptual problem and one that poses a major challenge to teachers. Kind proposes a “bridging exercise” of having students observe progressively smaller unseen things, such as insect details, bacteria and viruses, as a way of establishing the reality of the realm of things too small to see, followed by engaging the students in a process of imagining atoms. (Kind, 2004, p.13)

Hong Kwen Boo (1998) emphasizes that students have a difficult time understanding the abstract concept of energy, and urges that more emphasis be given to the concept of the "driving force involving the concept of free energy/entropy," and to the difficulty students have in bridging the gap between “perceptual thinking” and the use of "concepts about particles and their interactions." "Students [failed to] understand the nature of science as a process of construction of predictive conceptual models ... and the nature of scientific concepts and principles ... [i.e.] their applicability across the entire range of [chemical] phenomena." Ricardo Trumper (1993) on the other hand argues that "we can start teaching students about energy in about the 5th grade, since they have good cognitive building blocks associated with a good energy concept."

Viennant (1993a), considering student reasoning about heat transfer along a rod, observed that when more than one factor was considered the students would use sequential reasoning – ordered in time. Driver (1985), Anderson (1986) and Guiterrez and Ogborn (1992) (all reported in Viennot (1998)), Sere (1987), and Mehent (1997) all observed pa reluctance of students at all levels to consider more than one cause for an effect. This shows up as extreme difficulty in working with three-variable relationships such as the ideal gas law. The students would either disregard one variable, or if dealing with two at a time they would imagine them as operating sequentially in time, in what Rozier (1991) calls "linear causal reasoning." This way of thinking, he reported, was "extremely resistant to instruction." It conditioned students to cling to alternate conceptions that require only linear or one-step reasoning.

Another key difficulty students face is the problem of imagining “nothing”. Many writers (e.g. Griffiths 1992, Novick and Nussbaum 1978) have noted that many students cannot imagine “nothing” between atoms or molecules, and either deny that they can be far apart in a gas or propose a variety of possible substances to fill the spaces. This is even true of many university science students. (Benson et al. (1993), in Kind (2004)) As Kind (p.11) puts it:

> Students of all ages find space difficult to imagine and intuitively “fill” it with something. Since students depend on visible, sensory information about solids and liquids to develop their naïve view of matter, their difficulty accepting a model proposing

that there is “nothing” in the spaces between particles is unsurprising.

Difficulty imagining “reversibility” is another stumbling block for students, who come up with many alternative explanations to work around their lack of understanding. Many students fail to see state changes, dissolution and other physical changes as reversible. For example Gensler (1970, in Kind (2004) p.25) observes that students fail to see that re-crystallized sugar is the same stuff which was added to the water originally. This contributes to the students’ difficulty in distinguishing physical from chemical changes. The reversibility of chemical reactions also poses serious conceptual challenges to the students, leading to an inability for example to grasp the reciprocal relationship between acids and bases and the concept of an equilibrium. This to be sure must come in part from the inability to see that “something is happening” at equilibrium when no visible change is occurring, but students in very high numbers in upper grade classes also view the forward and reverse reactions as two separate reactions. (Johnstone et al., 2007) At a still deeper level, inability to grasp reversibility may be related to student difficulties in general with picturing two things going on at once.

Excessive reliance on memorization is a well-known obstacle to student understanding. Bou Jaoude (1992) developed an instrument to divide a high school class into "rote learners" and "meaningful learners". He found similar levels of misconceptions initially in both groups. After instruction the rote learners had failed to progress or even had regressed, while the meaningful learners had made significant gains in concept mastery.

Viennot (1998) notes that students generally confuse rates of reaction and rates of change with final states. This may underlie many alternative conceptions, such as the belief he uncovered that since iron heats faster than sand, it will reach a higher temperature. He suggests that students require two additional essential thinking skills that are “opposed to the common threads of their everyday reasoning:”

1. They must be able to identify the relevant systems as well as their essential characteristics in order to predict transfers of heat.
2. They must be able to clearly sort out what concerns changes on the one hand, and permanent states on the other.

The ability to distinguish between a state and a rate of change can be seen as an underlying or fundamental mathematical ability. Other capabilities whose absence might also block students' ability to grasp chemistry concepts include division, ratio and proportional reasoning, direct and inverse variation, probability, randomness, large and small numbers, and exponential growth. Many alternative conceptions no doubt are developed by students to cope with concepts that are beyond their reach because of such difficulties.

The search for key or central alternative conceptions

Thomaz *et al*. (1995), working with groups of secondary students in the UK, reported that 92% to 97% of the students " ... revealed a great difficulty in accepting that different objects are at the same temperature when in contact with the surroundings for a long time." They focused on this as the core concept in their highly successful project using constructivist methods to teach thermodynamics.

L. Viennot (1997), E. Clough and R. Driver (1985), and J. Solomon (1985) outline the varieties of student misunderstandings about energy. Solomon discusses how the ways in which teachers word their explanations of energy generate new misconceptions.

C. Gayford (1986) and Solomon (1985) outline the ways students confuse energy with the "life force" in biological systems. (This could perhaps be the result of or at least reinforced by using the concept of energy in biology before having properly studied it in physics or physical science.) Kruger (1990) found the same confusion about energy among primary school teachers.
deVos, et al. (1994) identify the key concepts in chemistry as being the "chemical substance" and the "chemical reaction". To them the key difficulty faced by students was "the incoherence and incompleteness of all chemistry curricula studied," and they document many misconceptions that result. They call for a "chemistry curriculum that will lead students on a quest for the hidden factors that determine chemical change and the creation of new substances," with a minimum of imposed definitions and explanations.

Mary Nakhleh (1992) identifies the central misconception of chemistry as being that matter is a continuous medium that is static and space filling.

Arons (1997) identifies the idea that "something (electricity, charge or energy) is used up in electric circuits" as the key misconception on this subject.

Hestenes, Wells and Swackhamer (1992) identify three major "commonsense beliefs" about force: moving objects contain a certain amount of force, force causes motion (force is proportional to velocity) and force is dominance (larger, more “powerful” objects exert more force on smaller and “less powerful” objects than the latter do on the former.) These alternative conceptions may well appear in chemistry as analogies, such as the belief that chemical reactions have "inertia" which will carry them beyond equilibrium (Kesidou 1997), that water requires force to carry it upward in evaporation (Schmidt 1997), the surprisingly widespread belief that atoms are alive (Griffiths,1992), and the common belief that chemical reactions involve an active reagent acting on a passive one (Brosnan,1992).

Kokotas, Vlachos and Kardaidis (1998) and Tabor (1997, 1999) observe that many misconceptions have primitive concepts underlying them such as "conservation of force". This and other such primitive concepts do not appear to be something the students have been taught. Tabor identifies the fundamental student belief underlying their many misconceptions about electrical forces within the atom as being that "force is conserved", that there is a certain amount of force available to be shared between the available particle pairs. Here it is the Coulomb force that is not understood or applied, but the alternative conception being used is that a charged body contains a certain amount of force. Thus oppositely charged ions will “use up each others' force” and lock together into a molecule.

Kokotas *et al*. (1998) suggest that more recently acquired alternative conceptions will be found to have been grafted onto a foundation of more primitive and intuitive preconceptions, such as the view that heat has weight. McCloskey (1983) carries this further with an examination of the similarity of student preconceptions in mechanics to the pre-Newtonian conceptions of Aristotle and of medieval Europe, and suggests that people may naturally come to these views because they are in some way “hard-wired” into us.

Are acquired alternative conceptions really less difficult to deal with and less damaging than older or more fundamental ones? Kind (2004, p.74) argues that they must be taken very seriously, recent or old. Tabor (1997) noted “that students never seem to dismantle old ideas about chemical bonding, but instead prefer to add new thinking…. Of course for many students this results in confusion and poor understanding.” Kind adds, “if students cannot ‘unlearn’ ideas, then we should teach chemistry we really mean them to know right from the beginning.” This injunction should be carefully weighed when evaluating the use of a “bridging exercise”, as discussed elsewhere in this article.

Student alternative conceptions in thermodynamics pose a special dilemma to the compiler. There remains a considerable amount of controversy around the proper interpretation of the second laws of thermodynamics. Many texts and teachers present entropy as a measure of disorder or chaos, while many physicists and physical chemists have abandoned this interpretation (Lambert (1999); Denbeigh (1989).)

Experts are not in agreement on whether to interpret (and teach) the mole as a “number” (Dierks (1981) in Kind (2004) p.50) or as an “amount of substance” or “chemical amount” that corresponds to 12 grams of carbon-12 (Nelson (1991) in Kind). Kind speculates that “This difference may be at the centre of problems associated with the mole – in teaching the concept we may use 'amount of substance' and 'number of particles' synonymously, contributing unwittingly to students’ difficulties by never really explaining what we mean in either case.”

Lists of alternative conceptions that have been proposed as key or central misconceptions by various investigators (Table 1), and by the participants in the Modeling Methods in Chemistry Workshop of 2001 (Table 2) have been provided below.

Implications for Teaching.

When the importance of student alternative conceptions in a subject area has been recognized, what use should the teacher make of this knowledge? There is ample evidence (previously discussed) that instruction that fails to acknowledge and address these alternative conceptions will prove unable to foster real growth in understanding of the subject. Students can still gain "knowledge", in the form of memorizing facts and procedures for solving very limited classes of problems, and teachers may out of frustration become reconciled to settling for this kind of learning, and even to calling it success. But in the words of Mary Nakleh (1992), “knowledge is not understanding.” So how then should the teacher proceed?

First, the teacher shouldn’t design a course around dealing with student alternative conceptions. A course has to be built around positive goals. In particular it should be built around the models or fundamental concepts of chemistry to be mastered and understood by the end of the course. An understanding of student thinking will affect the tactics and even the strategy followed, but the course must be about building, not tearing down. Vanessa Kind’s booklet and the Modeling Instruction Program (links in Appendix 1) offer two of what must by now be many such curriculum outlines available.

A knowledge of student alternative conceptions will be helpful in deciding where to start and what to cover. As Driver and Bell (1986) put it: "We may need to reconsider the assumptions we are currently making about where students start from in their thinking in science courses. … We may be making unwarranted assumptions that students will have [understood the prerequisite topics], and we can therefore take [these] for granted and build on [them] in lessons …."

Should the teacher confront students with the evidence that their ideas are wrong or lacking in predictive value, and then present them with replacement ideas? This is tempting. It is relatively simple to do, and it's fun – for the teacher. Pedagogically however it is a very bad idea. It can be embarrassing and devaluing for the students, whose ideas always, at every time, represent the culmination of a lifetime of trying to make sense of their world, and are therefore held as valued possessions. As Smith et al.(1993) put it, "misconceptions are faulty extensions of productive prior knowledge." The students have spent a lifetime, starting as toddlers, trying to be right, and they get defensive, angry and wary when being made wrong. In any case, they simply cannot just switch off their own ideas and adopt new ones that are presented to them, even if the evidence is clear. Brains don't work that way. As Smith (1993) observes, replacing misconceptions "… is neither plausible nor always desirable; misconceptions thought to be extinguished often reappear."

Hammer (1996) argues that calling a statement a misconception implies that it must be removed from the student's mind. "To construct from useful conceptions without eliminating misconceptions would leave in place knowledge inherently inconsistent with expert understanding." This he argues is impossible, making the entire enterprise of dealing with misconceptions flawed. Yet modern practice shows that new conceptions arrived at over time or through guided inquiry and student discourse are in fact stable and do in fact come to replace old conceptions. (e.g. Francis (1998)) Perhaps this is achieved not by an eradication but by the learners' rearrangement of mental elements at some deeper level.

If a teacher decides to follow this path, he or she should get training in how to manage student discourse and guide student thinking in a non-directive manner. To move beyond their previously held ideas students must construct new ones, in interaction with the results of experiment. For the teacher, especially for veteran teacher, this can be quite challenging and counterintuitive. It is a skill that cannot easily be self-taught. For example, after a lifetime of being the expert who explains everything, you'll have to learn to steadfastly refuse your students (and maybe their parents) when they righteously demand that you do your job and give them "the answer". It is said that we teach the way we were taught. Hesse and Anderson (1992) commented that "it is likely that the same conceptual-change techniques that are employed by the teacher to promote conceptual change within students must also be applied to the present body of practicing teachers."

The Modeling Methods program listed in Appendix 1 is one place to look for this kind of training, but there are surely others.

David Hestenes (1995), commenting on the dismal performance of physics graduate students on their oral exams, points out that students don't really start to master the concepts of physics until they start on their dissertation research. He implies that rich interactive inquiry-focused experiences such as working closely with a professor on a project need to be provided much earlier in the curriculum.

Lewis and Linn (1994) argue for a curriculum that includes everyday knowledge, to encourage integration of knowledge, to engage students in building on their intuitive conceptions, and to make scientific knowledge easier to remember.

Finally, get your principal and your department chair on your side! Any effort to take on a new way of teaching should have their understanding and approval, including an agreement on how you are going to measure the success of your students and of your course. A course based on guided inquiry and discourse aimed at achieving conceptual change will not look like other courses, won't have the same rhythm, and won't be able to cover as many topics. To succeed, you need your administrators to understand it and why it is worth doing.

Organizing the Chemistry Alternative Conceptions

The preconceptions and misconceptions listed in Appendix 2 are categorized by topic. They are divided into essential physical concepts (background), basic chemistry, electrochemistry, thermodynamics and atomic chemistry. For the most part, the essential physical concepts section ("A. ") does not rely on the atomic theory, while the basic chemistry part ("B.) does..

I have tried to edit the list to include only alternative conceptions held by 8-10% or more of a student cohort, ages 12 and above, (except in a few cases where a smaller number shows the persistence or diminution of a conception over time).

The information about cohorts of students among whom the alternative conceptions were observed, and with what frequency, has been reported where it has been preserved. Evaluations from researchers on the importance of the misconception being reported is included in Appendix 2. These and evaluations by the teachers in a modeling workshop are presented separately in Table 1 and Table 2.

The section on chemical equilibrium is structured around the framework of Hackling and Garnett (1985); the section on force is structured around the framework of Hestenes (1992); and the section on energy is structured around the framework of Ricardo Trumper (1990) as reported in Swackhamer (2001). Some topics were restructured to follow the framework given by Kind (2004), or for acids, bases and neutralization that of Hand and Treagust (1988) as reported in Kind.

Rating the Alternative Conceptions

Suggested criteria for rating a conception as key or central:

1. Consider the proportion of students who hold an alternative conception. Also look at all the other reported alternative conceptions around the same question. Do they reflect one or two deeper issues?

2. Consider the alternative conception's persistence over time and in the face of instruction and contradictory information? Which alternative conceptions stand firmly on their own and which are undermined, weakened and finally reinterpreted or left behind as new structures of understanding are built around them?

3. Which alternative conceptions prove fatal to an understanding of a topic, and which prove

less damaging or harmless? Will you leave students behind and lose their willingness to trust the process and its outcomes if they fail to break through on this one, or is this one they can come around on later without serious damage? Perhaps choosing key conceptions could be thought of in terms of choosing your battles.

4. Alternative conceptions that appear to be “primitive”, rooted in the student’s self-taught (and strongly held) system for understanding the world, or rooted in everyday experiences and perceptions, such as “metal is cold”, are likely to be particularly resilient and therefore important.

5. Within a group of related conceptions, there may be one that appears to most simply express or summarize the group, and another that is most likely to be chosen by the students. It is tempting to choose the former, but this is risky until we understand at a deep level what thought process is generating this conception and how it fits into the students’ system of understanding.

6. Selections by veteran teachers should be listened to with an open mind, even though they may not possess all the distinctions that the research community holds. It would have been good to have recorded the modeling workshop teachers’ explanations of their choices.

Some examples of how some student alternative conceptions might be evaluated:

"Anodes are always on the left" is an example of a misconception which is both trivial and non-primitive, a simple artifact of the habit of some textbook writers of always illustrating anodes in this way. This sort of misconception will clear up quickly when students actually understand what an anode is from their own experience, and may disappear when new textbooks come out. An interesting glimpse of what is going on in student learning.

“Chemical bonds store energy” (previously mentioned) is not a primitive misconception in the sense that it refers to a concept (the chemical bond) which is several steps removed from the child's experience of the world. However, whether it is taught in school, picked up from the ongoing conversation about energy in the larger world or arrived at by the student through their own thinking, once the concept has been acquired it becomes heavily used and strongly held. This misconception can become a serious obstacle to further progress in chemistry.

"Heat has the properties of matter" and "heating an object adds mass to it" (Schmidt, 1997) are both important alternative conceptions, widespread, persistent and having significant consequences. Are they redundant? The former appears to be the fundamental statement of the misconception, and would thus rate designation as a key misconception, but the latter would be the example in which a student would recognize their own ideas. The similarity of this conception to the medieval “phlogiston” and early modern “caloric” are clues that its roots may be very deep. My call would be that the first expression is the better choice.

"Temperature is a property of the material from which a body is made" and "two objects in the same environment don't eventually reach a common temperature." Of a group of secondary students, 95% gave each of these responses (Thomaz, 1998). Here we have a misunderstanding that is primitive and fundamental in that it arises inevitably out of observations. It is extremely widespread, extremely persistent and has profound consequences for the student's further progress in chemistry. These are logically equivalent statements. The first summarizes what subjects report, and the second is its expression as a failure to understand a core scientific principle. The first one is the actual alternative conception. However, neither is as fundamental as the conception “metal is cold”. Metal “feels” cold! That is true! Until students can reinterpret this phenomenon (e.g. “what we feel isn’t really how cold or hot something is, but how fast heat is flowing through our skin”), many simply won’t believe their thermometer! This may require first distinguishing heat conductivity from heat capacity and quantity of heat energy.

The previously mentioned model of electrical forces within the atom, "force is conserved," was never actually said by any of the subjects, yet once distinguished, its fingerprints can be seen on a number of other alternative conceptions. It seems to be a good hypothesis about what the students are “really” thinking at a deeper level. I called it Key, but it really needs more testing.

I contributed my own nominations for key alternative conception where I felt the findings of the investigators reviewed pointed strongly to this conclusion but they didn’t actually call it; or where from my own teaching experience I recognized an alternative conception as one I had encountered in my students and had found stubborn, persistent and troublesome, and where no investigator had called out it or any similar conception.

Recommendations

Work remains to be done in reviewing the literature, especially publications since 2004. It would be good to see what has developed out of diSessa’s work with p-prisms, and whether this approach appears to be leading to practical applications. The literature concerning use of student alternative conceptions for “bridging exercises” – step-by-step efforts to lead students to correct explanations starting from what they already believe, as proposed by Clement (1982) and de Vos (1987) - could be surveyed and referenced as part of this list.

Articles reporting case studies which follow student conceptual progress over the course of a lesson, a semester or a childhood, should be included. Concepts representing the scientist’s views, (the “right answers”), labeled as such, could be added to the list, making it more useful to a wider audience. While nearly all entries to the full list in Appendix 2 were taken from the published refereed literature, many are not attributed and annotated. These are primarily from the first summer when our goal was to get a list of misconceptions quickly for the new action research team then beginning the task of designing a chemistry course, mentioned above. This needs to be remedied.

Maps or chains of conceptual growth would be of great value. For this it would be good to collect case study, cross sectional and other data on how conceptions evolve over time – maps of chains of conceptual growth. This could include any information on how and why the transition between steps, and where, how and why chains get blocked by a stubborn alternative conception. Can the time required to progress through this chain be compressed? What steps can be skipped? Is it possible to take a chain of concept development that occurs typically between say the ages of 10 and 18 and lead students through it in a semester, a month or an hour? Can the intermediate concepts – or others discovered by the teacher – be used for bridging exercises? This information of course is closely tied to teaching strategies. These should be included or links to them could be provided. The result would be a kind of atlas of student conceptual growth.

Trevor Anderson and Jennifer McKenzie, in their great CARD (Conceptual and Reasoning Difficulties) website (Appendix 1), have made an impressive start on this. They have built a very large list of student difficulties in chemistry (other sciences and mathematics are being added) with links to references, summaries of the research, and remediation strategies. Each difficulty is rated on a four-level framework described by Grayson, Anderson and Crossley (2001), according to how much is known by the researchers about it. This is of course not the same as a list of key alternative conceptions, but it is potentially a big contribution toward it. Mining their site for contributions to the list of alternative conceptions in Appendix 2 below and for more information about current entries would be a great project for someone with time on their hands.

Arranging for teachers to have online journal access would be a huge step forward in connecting the theory and practice of teaching, and would for example make this article much more useful to them. Most teachers, the primary intended audience of this article, don't have ready access to a great research library. Most of the articles referenced here have already been digitized and put online, but can't in general be accessed by teachers from their homes. Teacher access to these would also allow the interested teacher to pursue the authors' own references and to search for other works by the same author.

Providing teachers with online journal access could be done by teachers' associations, by school districts, by state or provincial education departments, by national departments or ministries of education, or as a service to their neighborhoods by nearby universities or colleges. Journals are always starved for funds and most won't jump forward with offers of free access for teachers, but they could certainly take on actively promoting this idea and offering to negotiate easy terms for entities representing teachers. Perhaps they could agree to offer free access to teachers in poor countries and communities as a public service.

Many concept tests or formative assessments have been or are being developed for many levels of and topics in chemistry. If such a test uses observed student alternative conceptions as distractors (wrong answers), and if it is used as both a pre-test and a post-test for the same class, the resulting data is potentially useful for research. Makers and users of these tests could be identified and invited to join in such projects, particularly for collecting information on the evolution of student conceptions over time.

Alternative conceptions concerning a number of topics have yet to be found or evaluated by us, and also do not appear in the CARD index. These include:

The periodic table of the elements.
The equipartition theorem.
Geometry and polarity of molecules.
The third law of thermodynamics.
Organic chemistry – all of it.

References have been found to misconceptions concerning the geometry and polarity of molecules (Furio Mas,1996). It would be very surprising if there weren't a substantial number of misconceptions concerning the periodic table of the elements, given that students are introduced to this topic in grammar school, long before they are clear about what an atom is.

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Table 1: The expert observers' selection of key student alternative conceptions in chemistry.

These candidates for key (and "important") student alternative conceptions were either chosen by researchers, or else I was able to unambiguously infer from what the researchers wrote that they so regarded them. (In some cases I have preserved their actual words.) Presumably they don't all hold the same criteria for their choices, and each had their own focus and their own framework of ideas, so these choices cannot strictly be compared. It is nevertheless interesting to see how they often made different but related choices, and how seldom two researchers picked the same one. The failure of any one researcher to select any particular alternative conception or to choose from any particular category of alternative conceptions should not be given any significance, as presumably few of them had a complete list of alternative conceptions in front of them to consider, and most were concerned with only a limited subset of chemistry.

For information about the entries in Table 1, see Appendix 2.

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A.1.2	Matter can disappear. [Kind (04): Key]
A.1.4.1	Matter is continuous, but contains particles; matter exists between atoms. [Kind (04): Key]
A.1.4.1a	The space between atoms and molecules is not empty. [Kind (04): Key]
A.1.6	Particles may have macroscopic properties: they may burn, contract, expand or change shape. [Kind (04): Key]
A.2.8	Gas behaviour is explained by attractive or repulsive forces between molecules. [Kind (04): Key]
A.3.1.3	(Mass is confused with density.) [Kind (04): Key]
A.3.2.1.2	The products of chemical reactions need not have the same mass as the reactants. [Schmidt (97): Key]
A.5.1	Collisions between molecules cause heat. [Thomaz (95): Key]
A.5.1.1	Heat has the properties of matter or substance. [Schmidt (97): Key]
A.5.1.1.1	Heat can add weight to the object being heated. [Schmidt (97): Key]
A.5.1.1.2	Heat is a substance residing in a body which can pass from one body to another, like a fluid. [Thomaz (95): Key]
A.5.1.1.2.1	Heat is in the fuel being burned and is not formed during combustion. [Schmidt (97): Key]
A.5.1.4	Heat is something that heats up other things; either the hot object or a substance given off by it. [Viennot (98), Important]
A.5.1.6	Heat is a sensation. [Thomaz (95): Key]
A.5.1.7a	The state of hotness or coldness depends on the material from which a body is made. [Thomaz (95): Key]
A.5.4.2.1	Heating a body always means raising its temperature.[Thomaz (93, 95): Key]
A.6.1.1	Temperature is a measure of a body's heat. [Kesidou (93), Key]
A.6.3	Like heat, temperature is a property of the material from which a body is made. [Thomaz (93): Key]
A.6.3.1	Different materials (flour, nails, water) placed for a long time in a room which is at a certain temperature remain at different temperatures. [Thomaz (95): Key] [Viennot (98), Key]

A.7.2.2	Collisions between particles cause heat. [Viennot (98): "Central misconception"]

Table 1: Expert Observers' Selection, Cont.

A.8.2	Force is supplied to things, which contain it and use it up. [Hestenes (92): Key]
A.8.3	Force causes motion. (Force is proportional to velocity.) [Hestenes (92): Key]
A.8.4	Force is dominance; the bigger, faster, more powerful thing in an interaction exerts more force. [Hestenes (92): Key]
A.9.1.1	Energy is the "life force". [Viennot (97): Key]
A.9.3	Energy can disappear. [Kruger (90), Key]
A.9.3.1	Energy is used up in processes. [Kind (04): Key]
A.9.3.3	Energy is not lost but is exhausted in bringing about an effect. [Kesidou (93): Key]
A.9.4.2	Energy is used to create chemical bonds. [Kind (04): Key]
A.9.5.2	Chemical bonds stores energy. [Kind (04): Key]
A.9.5.2.1	Energy is stored in "high energy" bonds such as ATP. [Kind (04) p.66: Key]
A.9.5.2.2	Breaking chemical bonds releases energy. [Kind (04): Key]
A.9.5.2.4	Fuel stores energy. [Kind (04) p.66: Key]
A.9.7.1	Energy is "produced" [Kruger (90): Key]
A.9.9.2	Energy and force are the same thing. [Kesidou (93): Key]
A.10.1.1	There is only one kind of charge. [Arons (97): Important]
A.10.1.1.1	Positive charge is actually a deficit of negative charge. [Arons (97): Important]
A.10.1.3.1	Charge is used up in electric circuits. [Arons (97), Key]
A.10.3.3	(Students fail to recognize that an ideal battery maintains a constant potential difference between its terminals.) [McDermott (92), Key]
A.10.4.1	(Concept of a complete circuit not understood.) [McDermott (92): Key]
A.10.4.2	("Something" is not conserved in electrical circuits.) [Arons (97): Most Important]
A.10.4.2.1	"Electricity" is used up in electric circuits. [Arons (97): C; Key]
A.10.4.2.2.2	Current is used up in electric circuits. [McDermott (92): Key]
A.10.4.2.3	Energy is used up in electric circuits. [Arons (97): Key]
A.10.4.4	Direction of current and order of elements matters in simple circuits. [McDermott (92): Key]
B.1.1.4	Atoms have electrons circling them like planets around a star. [Cros (86): Key]
B.1.2	Atoms have the properties of bulk matter. [Kind (04): Key]
B.1.3	Atoms are alive (because they move.) [Griffiths (89, 92): Key]
B.1.3.1	Atoms are like cells with a membrane and nucleus. [Wheeler (78): Important]
B.1.7.1	(Particles (atoms and molecules) may explode, burn, contract, expand and/or change shape.) [Kind (04): Key]
B.2.1	Molecules are basic, simple, indivisible entities. [CH: Key]
B.2.5	(Failure to distinguish Elements, Compounds and Mixtures in terms of atomic model.) [Kind (04): Crucial; "may largely determine which students can continue with chemistry after age 16."]
B.3.2	(Students confused – and experts divided - about whether to treat a mole as a number or a quantity of matter.) [Kind (04): Key]
B.3.3	(Students unable to visualize, work with mole-size large numbers.)

	[Kind (04): Key]
B.4.1	Solid, liquid and gas are three types of same substance. One disappears as the other appears. [Schmidt (97): Key]
B.4.2	Solid, liquid and gas are different substances. One disappears as the other appears. [Kind: Key]

Table 1: Expert Observers' Selection, Cont.

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B.4.2.2.4	Bubbles from boiling water consist of oxygen and hydrogen gas. [CH: Key]
B.4.3	Freezing and boiling are examples of chemical reactions; a phase change is a kind of chemical reaction. [Ahtee (98): Key]
B.4.3.2	When reversibility of a chemical reaction is observed, it can be explained as phase changes which occur as the temperature fluctuates. [van Driel: Important]
B.4.7.3	Freezing is like drying. [Schmidt (97): Key]
B.5.1	Melting and dissolving are the same thing. [Lee (93): Key]
B.6.1.2	Chemical reactions are reactions which produce irreversible change. [van Driel (98): Key]
B.6.1.2.1	The original substance vanishes "completely and forever" in a chemical reaction. [van Driel (98): Key]
B.6.1.2.2	Fuels are destroyed in burning or changed into something else. [Kind (04): Key]
B.6.1.2.3	Physical changes are reversible while chemical changes are not. [van Driel (98): Key]
B.6.1.4.3	Combustion is a change of state of matter – solid or liquid to gaseous. [Kind (04): Key]
B.6.2.2	Chemical reactions are caused by active agents acting on passive agents. [CH: Key]
B.6.2.2.1	Chemical reactions must be driven by external intervention, e.g. heat. [Cachapuz (87): Key]
B.6.3.1a	Mass is not conserved. The products of chemical reactions need not have the same mass as the reactants. [Schmidt (97): Key]
B.6.3.8	(Role of oxygen in burning not recognized.) [Kind (04): Key]
B.6.4.1.1	Energy is used up in chemical reactions. [CH: Key]
B.6.7.1	Chemical equilibrium and a chemical steady state are static conditions. [Kind (04): Key]
B.6.7.1.3	At equilibrium, most or all chemical reaction ceases. [CH: Key]
B.6.7.2	(An equilibrium reaction is not seen as two separate reactions.) [Kind (04): Key]
B.6.7.4.2	When the amount of a reactant is increased the rate of the forward reaction is increased but the amount of the reverse reaction is decreased. [Hackling (85): Key]
B.6.7.4.6	When a system is at equilibrium and a change is made in conditions the rate of the favored reaction increases but the rate of the other reaction decreases. [Hackling(85): Key]
B.6.7.6	(Le Chatelier's Principle held to always apply.) [Kind (04): Key]
B.7.5	A candle burning is endothermic, since heat is needed to initiate the reaction. [deVos (86): Key]
B.8.1	An acid is something which eats material away or which can burn you.

[Hand (88): Key] [Kind (04): Key]

B.8.1.1 Testing for acids can only be done by trying to eat something away. [Hand (88): Key]

B.8.1.2 The difference between a strong acid and a weak acid is that strong acids eat material away faster than weak acids. [Hand (88): Key]

B.8.2 Neutralization is the breakdown of an acid or something changing from an acid. [Hand (88): Key] [Kind (04): Key]

B.8.3 A base is something which makes up an acid. [Hand (88): Key]

Table 1: Expert Observers' Selection, Cont.

B.8.4 A base/alkali inhibits the burning properties of an acid. [Kind (04): Key]

B.8.5 Hydrogen ions are present in acids, but acids remain molecular in solution. [Kind (04): Key]

C.2.1.2.1 Electrons move through electrolytes by being attracted to positive ions in the solution. [Sanger (99): Important]

D.5.4.2 The "driving force" in a chemical reaction refers to an external causative agent. [Cachapuz (87): Key]

E.1.1.2 Atoms "own" their electrons. [Tabor (98a): Important]

E.1.1.3 Atoms are like cells with a membrane and nucleus. [Wheeler(78)(?) Important]

E.4.1. Atoms "want" or "need" to form bonds. [Kind (04): Key.]

E.4.2.2 Atoms are held together because they share electrons, so sharing electrons is like a force. [CH: Key]

E.4.5 Ionic pairs such as Na^{+} and Cl^{-} are molecules. [Kind (04): Key]

E.4.3 There are only two types of bond: covalent and ionic. [Kind (04): Key]

E.4.7 Covalent bonds are weaker than ionic bonds. [Kind (04): Key]

E.4.5 Atoms are held together because they share electrons, so sharing electrons is like a force. [CH: Key]

E.4.6 The central (first) element in a formula is more powerful, and is responsible for bond formation. [Kind (04): Key]

E.5.2.1 The number of ionic bonds an ion can form is determined by the electronic configuration. [Taber (97): Key]

E.5.2.2 Ionic bonds can only form between the electrons that have donated or contributed electrons. [Taber (97): Key]

E.5.3.1 Ionic bonds can only form between one sodium ion and one chlorine atom, so ion interaction with other ions are "just forces", not bonds. [Taber (97): Key]

E.5.6 Covalent bonds are weaker than ionic bonds, and break first on heating. [Kind (04): Key]

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Table 2: A chemistry teachers' selection of key and important student alternative conceptions.

Of the participants in the action research team that met at Arizona State University and initiated the project of designing and testing a "modeling method" curriculum in chemistry, most were high school chemistry teachers and most of those had become very aware of student alternative conceptions through their participation in and use of the "modeling methods in physics instruction" training. Presumably they had already become good listeners for the ideas of their chemistry students.

The teachers were asked to consider the list of alternative conceptions that had been collected to date, and to rate them as "key misconceptions" (widely and strongly held and representing a serious obstacle to the students acquiring the chemists' viewpoint), "important", and down to "participants doubt anyone believes this". Below are the conceptions which most of the participants, after discussion, agreed were Key or Important.

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A.1.4	Matter is continuous, homogeneous, space filling and static. [mw: Key]
A.1.4.1	Matter is continuous, but contains particles; matter exists between atoms [mw: Key]
A.1.4.1.1a	The space between atoms and molecules is filled with air. [mw: Key]
A.1.4.2	There is no space between molecules in solid objects. [mw: Key]
A.2.1.1	Air has no mass. [mw: Key]
A.3.2.1.1.1	A sealed container with a bit of liquid in it weighs less after the liquid has evaporated. [mw: Key]
A.3.2.1.3	Weight (mass) is lost in dissolving. [mw: Important]
A.5.1.1.2	Heat is a substance residing in a body which can pass from one body to another, like a fluid. [mw: Key]
A.5.1.1.2.1	Heat is in the fuel being burned and is not formed during combustion. [mw: Key]
A.5.1.6	Heat is a sensation. [mw: Key]
A.5.1.7a	The state of hotness or coldness depends on the material from which a body is made. [mw: Key]
A.5.1.12.2	Heating a body always means raising its temperature. [mw: Key]
A.6.1.1	Temperature is a measure of a body's heat. [mw: Key]
A.6.9.1.1	The temperature at which water boils is the maximum temperature to which it can be raised. [mw: Key]
A.7.1.6	Molecules expand when heated. [mw: Important]
A.8.3.1	Water needs a force, heat, to force it upward in evaporation. [mw: Key]
A.8.10.1	Oil doesn't mix with water because oil and water molecules repel each other. [mw: Key]
A.9.5.2	Chemical bonds store energy. [mw: Key]
A.9.5.2.4	Fuel stores energy. [mw: Key]
B.1.1.1	Atoms are hard, like billiard balls. [mw: Key]
B.1.1.2	Atoms are soft and fuzzy. [mw: Key]
B.1.1.4	Atoms have electrons circling them like planets around a star. [mw: Key]
B.1.4.3	Mass is conserved, but not the number or species of atoms. [mw: Key]

B.2.2.1	Molecules are small particles formed by successive partitioning of matter and hence keep their macro properties such as hard, soft, etc. [mw: Key]

Table 2: A High School Teachers' Selection, Cont.

B.2.2.2	The properties of molecules depend on the phase of the material composed of them. [mw: Key]
B.2.2.2.2	Water vapor molecules weigh less than ice molecules. [mw: Important]
B.4.0.2	Water (or alcohol) disappears as it evaporates. [mw: Key]
B.4.0.3.1	A sealed container with a bit of liquid in it weighs less after the liquid has evaporated. [mw: Key]
B.4.2.2.5	Bubbles from boiling water are made of heat. [mw: Key]
B.4.2.2.1	Bubbles from boiling water consist of air. [mw: Key]
B.4.2.2.2	Bubbles from boiling water consist of air and oxygen gas. [mw: Important]
B.4.2.4.2	Molecules of ice are hard and frozen. [mw: Key]
B.4.2.4.3	Water from melting ice is different from running water. [mw: Key]
B.4.3	Freezing and boiling are examples of chemical reactions; a phase change is a kind of chemical reaction. [mw: Key]
B.4.4.1.1	Drops of water on the outside of a cold bottle of water come from inside the bottle. [mw: Key]
B.4.4.1.2	Drops of water on the outside of a bottle are made by the cold. [mw: Key]
B.4.5.3	The temperature at which water (or any substance) boils is the maximum temperature to which it can be raised. [mw: Key]
B.5.1	Melting and dissolving are the same thing. [mw: Key]
B.6.1.2	Chemical reactions are reactions which produce irreversible change. [mw: Key]
B.6.1.2.1	The original substance vanishes "completely and forever" in a chemical reaction [mw: Important]
B.6.1.2.3	Physical changes are reversible while chemical changes are not. [mw: Key]
B.6.1.7.1	Re-crystalized sugar is not the same as the original sugar that was dissolved, so a chemical reaction must have taken place. [mw: Key]
B.6.2.1	Chemical reactions are caused by mixing of substances. [mw: Important]
B.6.2.2.1.2	Coldness causes a nail to rust, drawing the rust out of the nail, like a magnet. [mw: Key]
B.6.3.5.1	A rusting nail won't change weight because the rust was already in the nail. [mw: Key]
B.6.4.2	Chemical bonds store energy. [mw: Key]
B.6.5.1	Reactions between two chemical species in a solution may be analyzed without considering the effects of other species present. [mw: Key]
B.6.5.4.1	Reactions that proceed more rapidly also proceed further (more completely.) [mw: Key]
B.6.6.1.1	Chemical reactions will in general continue until all the reactants are exhausted. [mw: Key]
B.6.6.3	When reversibility of a chemical reaction is observed, it can be explained as phase changes which occur as the temperature fluctuates. [mw: Important]
B.6.7.1.6	The concentrations of all species in a reaction mixture are equal (or have a simple arithmetic relationship) at equilibrium. [mw: Key]
C.2.1.2.1	Electrons move through electrolytes by being attracted to positive ions in the solution. [mw: Important]
E.3.1	Coulomb's law doesn't work inside the atom. It works in physics but not in

chemistry. [mw: Key]

E.3.2.2 Nuclear forces are like tentacles; each one is attached to an electron. [mw: Key]

Appendix 1:

Online Resources

The Modeling Instruction Program web site: <http://modeling.asu.edu> has a password-protected link to chemistry modeling materials, and sponsors training programs in teaching a first-year high school chemistry course. For the password, contact Jane Jackson <jane.jackson@asu.edu>, Co-Director, Box 871504, Department of Physics, Arizona State University, Tempe, AZ 85287. 480-965-8438

CARD, Conceptual and Reasoning Difficulties: Trevor Anderson at the University of Natal and Diane Grayson have developed a very rich website that summarizes a large number of alternative conceptions, especially in chemistry. The URL is: http://www.card.unp.ac.za. The website greets you with: "Welcome to CARD, the Conceptual and Reasoning Difficulties resource for researchers and teachers in science, mathematics and technology education! Currently CARD contains over 5000 references as well as extensive information on chemistry difficulties, and will be expanding to include other areas of science, mathematics and technology." It contains lists of alternative conceptions with links to the research and to teaching strategies, often with materials available. This is a tremendous site.

Kind, Vanessa (2004), (Formerly Vanessa Barker). *Beyond Appearances, Students' Misconceptions About Basic Chemical Ideas", 2nd Edition,* 84 pages, Royal Society of Chemistry, available at <http://www.chemsoc.org/pdf/LearnNet/rsc/miscon.pdf> This booklet is a **must-have and must-read** for anyone teaching chemistry or doing research in chemistry education. Kind categorizes student chemistry alternative conceptions and student difficulties into a set of three to five key difficulties in each of 11 areas of chemistry, and then proposes teaching strategies for addressing (or sometimes for using or preventing the formation of) these difficulties.

Facets of Thinking in Physics, by Jim Minstrell and Pamela Kraus. Jane Jackson wrote of this site: "This is … HUGE …! Jim is a master high school teacher/researcher." A number of alternative conceptions were taken from this site for our list. Unfortunately I don't at this time seem to be able to find it. You can try contacting Jim Minstrell at <jimminstrell@TALARIAINC.com

The Misconception Synthesis Project, William F. McComas, USC Rossier School of Education, mccomas@usc.edu . Currently there are approximately 150 individual misconceptions citations targeting a variety of natural science topics. These misconception studies may be searched using a combination of science key terms and/or the age of the individuals in the study population through an easy-to-use interface to locate information about students' "naive conceptions". http://rsoeweb2.usc.edu/TE/Misconception/index.html

C^3P Project, "Comprehensive Conceptual Curriculum for Physics." Principal Investigator: Richard P. Olenick, Department of Physics, University of Dallas, 1845 E. Northgate Dr., Irving, TX 75062, olenick@udallas.edu. List of preconceptions is available at http://phys.udallas.edu/C3P/Preconceptions.pdf. The list is not annotated, but it covers a lot of ground, much of it overlapping with chemistry. The curriculum it supports is highly thought of in the physics education reform community.

The International Commission on Physics Education, 1997-98. http://www.physics.ohio-state.edu/~jossem/ICPE/C3.html . This informative site contains a review by Viennot (1998) of the literature about student cognition and alternative conceptions in a variety of topics in thermodynamics

"Previous Ideas" website, a review and listing of student alternative conceptions in biology, chemistry and physics, from the Centro de Ciencias Aplicadas y Desarrollo Techologico, Mexico, D.F. A well-organized website without a great deal in it. In English. < http://ideasprevias.cinstrum.unam.mx:2048/presentation.htm >

Learn Net, a site provided by the Royal Society of Chemistry, Great Britain, provides a link to Vanessa Kind's 2004 work, listed separately above; a set of worksheets inspired by that work; a well-thought-out set of lessons for age 11-14 introducing the particle model of matter; and links into a great deal else that the Royal Society has been doing around chemistry education. RSC Education Department, http://www.chemsoc.org/networks/learnnet/miscon2.htm, email: education@rsc.org;

Bibliography – - Students' and Teachers' Conceptions and Science Education (STCSE): Reinders Duit, formerly: Helga Pfundt & Reinders Duit., last revised in 2007. A huge (7700 entries!) bibliography of the literature on alternative conceptions in all branches of science, at < http://www.ipn.uni-kiel.de/aktuell/stcse/stcse.html > Unfortunately it may not be huge enough yet; many of the papers in Appendix 3 below are not included. Very little information is provided about the content papers so it is of limited value as a research resource unless you know what names to look for.

"Chemistry: Common Misconceptions and Fairytales", "a collection of wrong interpretations and beliefs regarding chemistry and its concepts", Edward Lindley, elindly@mediaone.net.

"Bad Chemistry": an entertaining and useful discussion of several misconceptions, from Kevin Lehmann, now at the University of Virginia. < kl6c@virginia.edu >
< http://faculty.virginia.edu/lehmannlab/badchemistry.html >

The Foundational Coalition is working to create concept inventories for specific cognitive disciplines, including chemistry, and contains links to others.
http://www.foundationcoalition.org/home/keycomponents/concept/index.html

Appendix 2:

The Alternative Conceptions in Detail with Notes

Key:

Topics A.8: Force, A.9: Energy and A.10: Electricity, within A. Essential Physical Concepts, are labeled "(limited inventory)". This is a caution that a full search of the student conceptions literature on these topics was not attempted. Only such features of these concepts as bear chemistry and the nature of materials at a level up to mid-college was included.

Parentheses around an item in the list of conceptions, such as (Nature of heat), are to indicate that this is not to be taken as an observed student conception but rather as a category name or as an underlying conception inferred (by the compiler if unattributed) for the family of related specific conceptions that follow.

An asterisk (*) after a listing indicates that the listing was entered under more than one category. An asterisk in parentheses followed by a list-item address indicates that the listing is cross-listed within the category given by that addresses. For example, the following listing appears at address B.1.6.4 and somewhere within A.1.4. (At address A.1.4.1.5, as it happens.)

B.1.6.4 The space between particles contains "a pollutant." (* A.1.4)

Square brackets following a listing: Where all the information is available, the researcher reporting the conception is given, followed by the age or grade of the cohort in which the conception was observed, and the percent (or some other indication of the proportion) of the cohort that gave this response. For example:

A.9.5.1 Energy is a reactant which is added to a reaction. [Thomaz (98), C4: 50%]

This indicates that the researcher or researchers referenced by Thomaz (1998) found that 50% of a group of 4th-year college students (chemistry majors, presumably) held this alternative conception.

Some of the codes used for this categorization:

yo	"years old". e.g.: "13-14yo" means 13 to 14 years old.
P5	Primary school grade 5.
M7-8	Middle school grades 7 and 8.
S	Secondary school students.
S12	Secondary students, 12'th year.
D10	Tenth-graders in Germany (Deutschland).
C	College students
C1	First-year college students.
C4	Fourth-year college students; presumably chemistry majors.
G	Graduate students in chemistry.
GA	Advanced graduate students.

GB	Graduate students in biology.
PT	Primary school teacher
MT	Middle school teacher
ST	Secondary school chemistry teacher.
SB	Secondary school biology teacher.
F	College or university faculty.

"b" and "a" are used to indicate that an observation was made before or after instruction on the topic. For example:

[S12b: 56%] means "Observed in 56% of a group of 12th graders, before instruction."
[17yo,a: 44%] means "Observed in 44% of a group of 17-year-olds, after instruction."

D is used for German ("Deutsch") high school students as it is claimed they have already had three years of chemistry prior to tenth grade and thus might not be comparable to other high school students.

Ratings: When investigators indicated that an alternative conception was central or key, or a major obstacle to student learning of the chemists' understanding, this was indicated by including the word Key (or occasionally a longer statement) within the square brackets, for example:

[Schmidt (97): Key] or [McDermott (92), C1a: 55% (inferred); Key]

In some cases, it is reported that an investigator highlighted an alternative conception as important, although not critical: [Schmidt (97), 12yo: "most"; Important]

In a limited number of cases, where either from reading the literature or from my own experience I was convinced that an alternative conception was crucial, but no one else was saying so, I included my own rating (CH for Chris Horton):

[CH: Key]

The list of alternative conceptions that were tagged as key by one investigator or another was also listed separately in the body of this paper in Table 1 (above).

Conceptions that were chosen as key or important by a group of science teachers that met at Arizona State University in June, 2001 were not noted in Appendix 2, but are listed in Table 2 (above). Items which at least some modeling high-school teachers doubted were misconceptions or thought they were arguably true are labeled: [mw: t] below.

The Alternative Conceptions

A. Essential Physical Concepts

A.0: Size, Volume. (See also B.3, Atomic Scale and Stoichiometry)

A.0.1 **Big means the same thing as heavy.** [CH: very common, S12 and C1]
A.0.2 **Massive means very big.** [Common usage.] [CH: very common, S12 and C1]
A.0.3 **There are 100 cm ^{3} in 1 m^3.** [CH: very common, S12 and C1]
A.0.4 **A lead bar will displace more water than an aluminum bar of the same dimensions.** (* A.4) [CH: very common, S9-S12 and C1]

A.1: Solid, Liquid, Gas, Matter, Substance

A.1.1 **There are more than three kinds of 'stuff'; e.g. solid, liquid, powder, paste, jelly, slime, paper-like, etc.** [Hayes (79) in Kind (04)]
A.1.1.1 **Any solid can be powdered but there is no obvious way to change a powder to a solid.** [Hayes (79) in Kind (04)]
A.1.1.2 **Some solids decompose (change slowly into some other useless substance.)** [Hayes (79) in Kind (04)]
A.1.1.3 **Non-rigid non-hard substances (dough, sponge, sand, steel wool) are not solids.** [Stavy (85) in Kind (04), 12-13 yo. 50%] [Johnson (96), 11-14 yo (in Kind (04) p.27.)]
A.1.1.3.1 **Nails are not solid because not in lumps**. [Johnson (96), 11-14 yo (in Kind (04) p.27.)]

A.1.2 **Matter can disappear**. [Gable (87), PT: "some"] [Kind (04): Key]

A.1.2.1 **When matter disappears from sight (e.g. dissolving, evaporating) it ceases to exist.** [Piaget (74) (in Kind (04))]
A.1.2.1.1 **Matter is not conserved in evaporation: "Gas weighs less than liquid".** (* A.2, B.4) [Stavy (1990), p247 (in Kind (04) p16), 15yo: 50%] [Kokotas (98)] [Russell (89 and 90) (in Kind (04) p. 7), 5-11yo: 45%]
A.1.2.1.2 **Solute (salt, sugar) disappears when dissolved.** * [Prieto (89) (in Kind (04)), 14 yo: 44%]
A.1.2.1.3 **The wax from a burning candle disappears.** (* B.7)
A.1.2.1.4 **The wax from a burning candle becomes energy.** (* B.7, A.9)
A.1.2.2 **Matter can disappear, and its properties (sweetness, smell, etc.) can continue to exist completely without it.** [Piaget (74) (in Kind (04))] [Stavy (90), (in Kind (04) p.7), 10-12 yo: 30%]
A.1.2.3 **Precipitation reaction results in change in mass.** (*B.6.3) [Barker (95 and 99), 16yo: 56%; 18 yo: 70%; (in Kind (04))]
A.1.2.3.1 **Mass increases in precipitation because solid weighs more than a liquid.** (*B.6.3) [Barker(95) and Barker and Miller(99), 16yo: 17%; in Kind(04)]

A.1.3 **Weightless matter can exist.** (*A.3) [Piaget (74) in Kind (04)]

A.1.3.1 **Matter becomes weightless when it evaporates.** (*A.3) [Stavy (90) (in Kind (04) p.8), 14yo: 40%] (Note: this view is not held if vapor is visible.)

A.1.4 **Matter is continuous, homogeneous, space filling and static.**
[Nakhleh (92): "Central Misconception"] [Schmidt (97)] [Kokotas (98)] [mw: Key]

A.1.4.1 **Matter is continuous, but contains particles; matter exists between atoms.*** [Griffiths (92): > 33%] [mw: Key][Kind (04): Key]

A.1.4.1a **The space between atoms and molecules is not empty.** (*B.1) [Kind (04) p.11: Key]

A.1.4.1.1 **Air is everywhere, fills all space, like a thin continuous tissue.** (*A.2) [Krajcik (89), S9: 80%]

A.1.4.1.1a **The space between atoms and molecules is filled with air**. (*A.2, B.1) [Kokotas (98): Important.] [mw: Key]

A.1.4.1.2 **Gas is continuous.** [Schmidt (97), 13yo: 40%; C1: 12%]

A.1.4.1.3 **Copper consists of atoms of copper embedded in a matrix like raisins in bread.** (* A.2, B.1)

A.1.4.1.4 **The space between particles contains "vapour or oxygen"**. (*B.1) [Novick (78) p.276, 16 yo+: 40%. (In Kind (04))]

A.1.4.1.5 **The space between particles contains "a pollutant."** (* B.1) [Novick (78) p.276, 16 yo+: 40%. (In Kind (04))]

A.1.4.1.6 **(There can't just be "nothing" between particles.)** [Kind (04), students all ages. p.11]

A.1.4.2 **There is no space between molecules in solid objects.**

A.1.5 **(Substances, objects, atoms, matter.)**

A.1.5.1 **Substances and objects are the same thing**.

A.1.5.1.1 **Substances prepared in different ways cannot be the same substance; the way of preparing a substance is one of its properties.**

A.1.5.2 **Substances and atoms are different names for the same things.** [M8:10%; S10: 10%; C1a: 10%]

A.1.5.3 **Molecules are "glued together" in substances.** [Schmidt (97), S] [deVos (87), 14-15yo: some]

A.1.5.4 **Grinding is how one makes "matter" from "objects".**

A.1.5.5 **(What a substance is depends on its appearance.)**

A.1.5.5.1 **A flame-blackened copper object is "black copper".**

A.1.5.5.2 **The "skin" of a water drop or a water surface is a different kind of water**.* [Schmidt (97)]

A.1.5.5.3 **Solid, liquid and gas are different substances. One disappears as the other appears.** (*B.4.2)

A.1.5.6 **(Atoms are not conserved.)** * [Gable (87), PT: "some"]

A.1.5.7 **A "pure" substance is one that is in its natural form, hasn't been tampered with or processed. E.g. rock salt is pure, extracted salt is impure.** [Johnson (96), 11-14 yo. (in Kind (04) p.27)]

A.1.6 **(Particles may have macroscopic properties: may burn, contract, expand,**

change shape.) * [Kind (04): Key]

A.2: **Air, Gas, Pressure** (see also D.4.5, Thermodynamics of Gasses)

A.2.0 **Air is alive. E.g. Air always wants to expand everywhere.**
[Sere (86) in Kind (04)]

A.2.1 **Gasses have no mass.** [Schmidt (97), 15-16yo: 40%]
A.2.1.1 **Air has no mass.** [Schmidt (97), 15-16yo: 75%] [mw: Key]
A.2.1.2 **Air can be compressed down to nothing.** [Schmidt (97), 12yo: "most"]
A.2.1.3 **Water disappears as it evaporates.** (*A.1.3, B.4.0) [Kokotas (98)]

A.2.2 **Air is everywhere, fills all space, like a thin continuous tissue**.(* A.1.4)
[Krajcik (89), S9: 80%]
A.2.2.1 **The space between atoms and molecules is filled with air.** (* A.1.4)
[Kokotas (98)]

A.2.3 **Air is different from other gasses: it resembles other invisible quantities such as energy, heat and gravity.** [Schmidt (97), 12yo: 10%]

A.2.4 **Air consists of two types of air, hot and cold.*** [Schmidt (97)]

A.2.5 **Air pressure is a downward influence.** [Olenick]
A.2.5.1 **Weight is caused by air pressure, and disappears in a vacuum.** (* A.3)
[Schmidt (97), S] [Clement (82)] [CH, S12, C1: common]
A.2.5.2 **Fluids exert a bigger pressure downward than upward.** [Olenick]

A.2.6 **Air weighs less when it is expanded.*** [Schnmidt (97). S]
A.2.7 **Air has negative weight.*** [Schmidt (97), 16yo: 25%]
A.2.8 **Gas behaviour explained by attractive or repulsive forces between molecules.**
[Novick and Nussbaum (78,81) 13-14yo "a significant proportion, 16+yo 20%]
[Brook et al. (84), 15yo "a sig. proportion"] [Kind: Key]
A.2.8.1 **Attractive forces between particles in a gas hold them in place.**
[Novick (81), 13-14 yo: many (in Kind (04))]
A.2.8.2 **Repulsive forces between particles prevent them falling to the bottom of a flask.** (* A.8.10) [Novick (81), 16+yo: 20% (in Kind(04))]
A.2.9 **Attractive forces between gas particles help explain air pressure.**
[Brook (84), 15 yo: "a significant proportion"; (in Kind (04) p.12.)]

A.3: **Mass/Weight:**

A.3.1 **(The mass or weight of something depends on properties other than amount and kind of matter.)**
A.3.1.1 **Weight is related to a feeling.** [Schmidt (97), S]
A.3.1.2 **Weight increases with distance above the ground.** [Schmidt (97), S]
A.3.1.2.1 **Weight is caused by air pressure, and disappears in a vacuum.** (*A.2)
[Schmidt (97), S] [Clement (82)]
A.3.1.2.1.1 **Weight is proportional to air pressure, which holds objects down.**
(*A.2) [Olenick]
A.3.1.3 **(Mass is confused with density.)** * [Schmidt (97), S] [Kind (04) p.36: Key]
A.3.1.3.1 **Less dense means weighs less.** [Mulford (96), C1a: 15%]

A.3.1.3.2 **(If reaction products are different density than the inputs, the mass changes.)**

A.3.1.3.3 **A kilogram of lead weighs more than a kilogram of water.** [Krnel (98), S]

A.3.1.3.4 **A gas weighs less than a solid.** [Mulford (96), C1a: 30%]

A.3.1.3.5 **Weight increases if an object is compressed.** [Schmidt (97), S]

A.3.1.4 (**Mass confused with concentration.)** * [Wheeler (78), S]

A.3.2a **Mass is not conserved.** (* B.7) [Furio Mas, 17-18yo: 51%. 12-13yo: 86%]

A.3.2b **Weight is not conserved.** (* B.7) [Furio Mas, 12-18yo: 74%]

A.3.2.1 **The mass or weight changes when a substance changes form.**

A.3.2.1.1 **The weight of a substance changes when it changes phase.** (*B.4.0)

A.3.2.1.1.1 **A sealed container with a bit of liquid in it weighs less after the liquid has evaporated.** (* B.4.0)

A.3.2.1.1.2 **Matter becomes weightless when it evaporates**. (*A.1.3, B.4.0) [Stavy (90) (in Kind(04) p.8), 14yo: 40%]

A.3.2.1.2 **The products of chemical reactions need not have the same mass as the reactants.** * [Schmidt (97): Key]

A.3.2.1.3 **Weight (mass) is lost in dissolving.** * [mw: Important]

A.3.2.1.3.1 **When 1 gram of sugar is dissolved in 20 g of water the solution weighs 20 g or less.***

A.3.2.1.3.2 **Salt disappears in dissolving.** (*B.5) [Mulford (96), C4: 15%] [Lee (93), MS]

A.3.2.1.4 **When the color of something changes, its weight (mass) changes.**

A.3.2.1.5 **Mass is lost in combustion**.* [Mulford (96), C4: 13%] [BonJouade (91), S: 28%]

A.3.3 **(Misc. beliefs)**

A.3.3.1 **Weightless matter can exist.** (* A.1.4) [Piaget (74)]

A.3.3.2 **Air has negative weight.** (* A.2) [Schmidt (97), 16yo: 25%]

A.3.3.3 **Weight and mass are the same thing.** [Common]

A.4 Displacement and Buoyancy, Surface Tension

A.4.1 **Objects float because they are light (without regard to volume or density).** [Krnel (98), S]

A.4.1.1 **A candle will sink in water faster than half a candle.** [Krnel (98), 13-14yo: 40%]

A.4.2 **Fluids, air exert bigger up-forces on lighter objects.** [Olenick]

A.4.2.1 **Air weighs less when it is expanded.** (* A.2.6) [Schnmidt (97). S]

A.4.2.2 **Air (or helium) has negative weight.*** [Schmidt (97), 16yo: 25%]

A.4.2.2.1 **A balloon is lighter if you blow air into it**. (* A.2.7)

A.4.2.2.2 **A tank with no air in it is lighter if you put helium into it.**

A.4.2.3 **Air exerts no upward force on a brick.**

A.4.3 **A paper clip can be made to float on top of water, because it is light.**

A.4.3.1 **A small steel paperclip floats better than a large steel paperclip.**

A.4.4 **Surface tension is like a skin and it is made of something different from water or is made from a different kind of water.**

A.4.5 **(Students unable to explain why steel ships float.)** [Bodner (91) G1: most]

A.4.5.1 **Steel ships float because of surface tension.** [Bodner (91) G1: “surprisingly popular”].

A.4.5.1.1 **Things (e.g. the Titanic) float if they have a larger bottom surface.** [Olenick] [Bodner (91), G1]

A.4.5.2 (**misc. explanations such as “The Titanic was equipped with a flotation device.”)** [Bodner (91), G1: “a surprisingly large fraction”]

A.4.6 **A lead bar will displace more water than an aluminum bar of the same dimensions.** (*A.0) [Krnel (98), 14yo] [CH, S9-S12, C1: very common]

A.4.7 **Things sink if they have holes in them.** [Olenick]

A.5: Heat

A.5.1 (**Nature of Heat)**

A.5.1.1 **Heat has the properties of matter or substance.** [Schmidt (97): Key] [mw:t]

A.5.1.1.1 **Heat can add weight to the object being heated.** [Schmidt (97): Key]

A.5.1.1.1.1 **Heated copper is heavier than cold copper.** [Schmidt (97)]

A.5.1.1.2 **Heat is a substance residing in a body which can pass from one body to another, like a fluid.** [Thomaz (95), S: 45%; Key] [Schmidt (97)]

A.5.1.1.2.1 **Heat is in the fuel being burned and is not formed during combustion.** (* B.7) [Schmidt (97): Key]

A.5.1.2 **Heat is not energy.**

A.5.1.3 **Heat is just energy that is added to something.**

A.5.1.4 **Heat is something that heats up other things; either the hot object or a substance given off by it.** [Viennot (98): Important]

A.5.1.4.1 **Heat is a hot object that heats other things.** [Erickson (85)]

A.5.1.4.2 **Heat is a kind of substance that is given off by heat.** [Erickson (85)]

A.5.1.5 **Hot and cold are different kinds of substance.** [Clough (85), S1]

A.5.1.6 **Heat is a sensation.** [Thomaz (95), S: 34%; Key]

A.5.1.6.1 **The perception of hot and cold is unrelated to energy transfer.** [Yeo (01)]

A.5.1.7a **The state of hotness or coldness depends on the material from which a body is made.** [Thomaz (95), S: 67%; Key]

A.5.1.7b **(Being hot or cold is a "natural property" of a material**.) [Tiberghien]

A.5.1.7.1 **Wool is warm, and warms things**. [Clough (85), S] [Lewis (94)]

A.5.1.7.2 **Metal is cold, and cools things.** [Clough (85), S] [Lewis (94)]

A.5.1.7.3 **Foil is better for keeping things cold than is a blanket, because metal is cold and blankets are warm.** [Lewis (94)]

A.5.1.8 **Heat is conserved.** [Bodner (91), G1: 40%]

A.5.1.8.1 **Heat is everywhere and in everything and it is all the same heat**. [Kesidou (93), D10]

A.5.1.8.1 **A cup of coffee and the room around it have the same heat level.*** [Kesidou (93), D10: 50%]

A.5.1.9 **Collisions between molecules cause heat.*** [Thomaz (95): Key]

A.5.1.10 (**Heat is a force.)**

A.5.1.10.1 **Water needs a force, heat, to force it upward in evaporation.** (* B.4.5)

[mw: Important]

A.5.1.11 **Heat is not a measurable quantifiable concept.** [Reported in Yeo (01).]

A.5.1.12 **Heat and temperature are the same thing.** *

A.5.1.12.1 **A change in temperature is the same thing as a flow of heat.** *
[Beall (94), C1a: 17%]

A.5.1.12.2 **Heating a body (adding heat) always means raising its temperature.**
(* A.6) [Thomaz (93, 95): Key] [Bodner (91), G1: <20%]

A.5.2 **(Heat Capacity)**

A.5.2.1 **Metals hold heat better than wood does**. [Kesidou (93), D10]

A.5.2.2 **Some materials are resistant to heating.** [Kesidou (93), D10]

A.5.2.3 **Metals hold cold.*** [Lewis (94)]

A.5.2.3.1 **Metals absorb more cold than plastic does.** [Clough (85), S]

A.5.2.4 **Two liquids heated with equally hot flames to the same temperature will receive the same amount of heat, regardless of how long they are heated.***
[Kesidou (93), D10: 44%]

A.5.3 (**Insulation and Conductivity**)

A.5.3.1 (**Insulation and Conductivity confused**.)

A.5.3.1.1 **A conductor is something that keeps things cold**. [Lewis (94)]

A.5.3.1.2 **Conductors (metal) conduct heat more slowly than do insulators, so heat builds up in them faster.** * [Lewis (94)]

A.5.3.1.3 **Insulators don't feel hot because "heat leaves them so quickly."**
[Lewis (94)]

A.5.3.2 (**Some things attract cold or heat.)**

A.5.3.2.1 **Metals attract heat better than wood does.** [Kesidou (93), D10]
[Lewis (94)] [Clough (85), 12yo, 14yo, & 16yo: ~22%]

A.5.3.2.2 **Metals attract cold.** * [Lewis (94)]

A.5.3.3 (**Final heat a function of conductivity.)**

A.5.3.3.1 **Metals are cold because heat passes through them faster.**

A.5.3.3.2 **Iron heat faster than sand, so it gets hotter (in the same oven). ***
[Viennot (98), S]

A.5.3.3.3 **Sand doesn't get as hot as the oven because it heats slower**.*
[Viennot (98), S]

A.5.3.4 **(Some things resist heating, others don't.)**

A.5.3.4.1 **Sand will not heat because "Sand cannot heat".**
[Tiberghien (85), “adolescents”: 33%]

A.5.3.4.2 **Foil is better for keeping things cold than is a blanket, because metal is cold and blankets are warm.** (* A.5.2)

A.5.3.5 **(Insulation seen as a barrier phenomenon.)**

A.5.3.5.1 **Metals let heat in or out more easily than plastic.**
[Clough (85), 12yo: 33%, 14yo: 27%; 16yo: 4%]

A.5.3.6 **Substances which insulate hot objects won't insulate cold objects.**

A.5.3.7 **Electrical and heat conductivity are the same thing.** (* A.10.8)

A.5.4 **(Heat Transfer)**

A.5.4.1 **Bodies cool spontaneously without another body being present.** [Kesidou (93), D10] [CH: arguable]

A.5.5 **Heat rises, only travels upward.**

A.5.5.1 **Water needs a force, heat, to force it upward in evaporation.** (* B.4.5) [Schmidt (97)] [mw: Important]

A.6 Temperature

A.6.1 **No difference seen between temperature and heat.** (* A.5.1) [Erickson(85), all ages:25%] [Viennoit (97)]

A.6.1.1 **Temperature is a measure of a body's heat.** [S: 35%] [Kesidou (93), Key] [Thomaz (93), S]

A.6.1.1.1 **Temperature is the "intensity" of heat or degrees of heat** [Kesidou (93), D10: >50%]

A.6.1.2 **Temperature is the amount of heat in a space. It tells you the hotness of the stuff in that space.** [Engels(82)] [Viennoit (97)]

A.6.2 **A change in temperature is synonymous with a flow of heat**. (* A.5.1) [Beall(94, 95), C1: 15%, C1a: 17%]

A.6.2.1 **Heating a body (adding heat) always means raising its temperature.** (* A.5.1) [Thomaz (93, 95): Key] [Bodner (91), G1: <20%]

A.6.3 **Like heat, temperature is a property of the material from which a body is made.** [Thomaz (93), S: 95%][Kesidou (93), D10: 53%] [One of them: Key]

A.6.3.1 **Different materials (flour, nails, water) placed for a long time in a room which is at a certain temperature are at different temperatures.** (* 6.8.3) [Tiberghien(85), "adolescents": "a majority"] [Thomaz (95), Sa: 95%, Key] [Beall (95), C1a: 11%] [Viennot (97,98): Key]

A.6.3.2a **Water is at same temperature as room because "water takes on the temperature of its surroundings."** [Tiberghien (85): "adolescents"] …

A.6.3.2b **Water " is in equilibrium with its surroundings."** [Viennot (98), S]

A.6.4 **The temperature of a body depends on its size.**

A.6.5 **(Rate of heating or conductivity and final temperature are confused.)** [Viennot (98), S]

A.6.5.1 **Iron heat faster than sand, so it reaches a higher temp. (in the same oven a long time).*** [Viennot (98), S] [Tiberghien (85), "adolescents"]

A.6.5.2 **Sand (flour) doesn't reach as high a temperature as the oven (long time) because it heats slower.*** [Viennot (98), S] [Tiberghien (85), "adolescents"]

A.6.5.3 **Metals are cold because heat passes through them faster**. (* A.5.3)

A.6.6 **The boiling/vaporization temperature is the highest temperature a substance can reach.** [Viennot (97)] [Thomaz (93, 95)] [Anderson (79)]

A.6.6.1 **(When a substance such as zinc reaches its melting temperature and the temperature rise pauses, students have a hard time believing it will**

resume rising when all the zinc has melted.) [Tiberghien (84, 85), S: 70%]

A.6.7 **Different sensations mean different temperatures.** [Thomaz (93, 95)]

A.6.8 **("Temperature dynamics")**

A.6.8.1 **Raising two bodies to the same temperature requires the same amount of heat.** [Mulford (95), C4: 22%] [Kesidou (93) D10: "Many"]

A.6.8.2 **Temperature is something which can be transferred from one body to another.** [Thomaz (93, 95), S: 17%]

A.6.8.3 **Two objects sitting in the same environment for a long period of time don't necessarily reach the same temperature.** (* A.6.3.1) [Thomaz (95), Sa: 95%] [Beall (95), C1a: 11%] [Viennot (98), Key]

A.6.8.3.1 **Temperature change continues after two bodies reach the same temperature due to "heat inertia".** [Kesidou (93), D10: 18%]

A.6.8.4 **The sum of the temperatures of two bodies placed in contact must remain the same.** [Kesidou (93), D10]

A.6.8.5 **A jar of water in the oven reaches the same temperature as the oven because water is in equilibrium with its surroundings.** (* A.5.3) [Viennot (98), S]

A.6.9 **(Temperature scale)**

A.6.9.1 **The temperature of a phase transition is seen as the maximum temperature that a substance may have.** [Thomaz (93)]

A.6.9.1.1 **The temperature at which water boils is the maximum temperature to which it can be raised.** * [Thomaz (95)] [mw: Key]

A.6.9.2 **10 C is twice as cold as 20 C.** [Normal, pre-instruction – CH]

A.6.9.3 **There is no limit on the lowest temperature.** [Normal, pre-instruction.-CH]

A.6.9.4 **(Students have a very hard time with melting or vaporization at very high or very low temperatures. High and low temperatures difficult to visualize.)** * [Viennot (98)]

A.7: Molecular model of heat

A.7.1 **(Static forces, descriptive responses used to explain behavior of particles in gasses.)**

A.7.1.1 **When heating a gas, "particles are forced apart", or a repulsive force acts on them**. [Novick and Nussbaum (81), 16+ yo: 60%. (In Kind (04))]

A.7.1.2 **Increasing forces between particles causes an increase in tire pressure during a journey.** [Brook, et al.(84), 15 yo: 12%. (in Kind (04))]

A.7.1.2 **Decrease in gas volume on cooling is due to increased attractive forces.** [Novick and Nussbaum (81) p.192: S: "many". (In Kind (04))]

A.7.1.3 **Cooling of air leads to (partial) liquefaction, clumping of molecules.** [Novick and Nussbaum (81), inferred, 13 yo thru C: 70%. (In Kind (04))]

A.7.1.4 **Cooling of gasses: particles "shrink", "condense", "sink" or "settle".** [Novick and Nussbaum (81), any age: 50%. (In Kind (04))

A.7.1.5 **Molecules expand when heated.*** [S12: >50%] [Mulford (96), C1a:10%] [Lee (93)] [Griffiths (92)] [Kesidou (93), D10]

A.7.1.7 **Water molecules in steam are larger than those in ice.**

[Griffiths (92) (in Kind (04)), 18yo: 50%]

A.7.2 **(Friction acts between particles)** [CH: S12, C1: Common]

A.7.2.1 **Particles in solid bodies will slow down and eventually stop, due to inertia or friction.** [Kesidou (93), D10] [CH, S12, C1: common]

A.7.2.2 **Collisions between particles cause heat.** [Viennot (98): "Central misconception"]

A.7.2.2.1 **Gasses, objects at higher pressure have higher temperatures because their molecules collide more often.** [Beall (94), C1a: 17%]

A.7.3 **The inertia of particles is different in the three states of matter.** [Kesidou (93), D10]

A.7.3.1 **It is harder to get particles in solid bodies into motion.** [Kesidou (93), D10]

A.7.3.2 **Particles in solid bodies are slower.** [Kesidou (93), D10]

A.7.4 **(Molecules have a temperature.)**

A.7.4.1 **Molecules in a hot liquid are hotter than molecules in a cold liquid.** (*B.2) [deVos (87), 14-15yo: some]

A.7.4.2 **Temperature is transferred from one molecule to another by heat conduction.** (*B.2) [Kesidou (93), D10]

A.7.5 **At equilibrium, vapor and liquid molecules have different kinetic energies.** (*B.4) [Johnstone (77), Sa: >50%]

A.8: **Force** (limited inventory) (See also A.10.2: Electrical Force, and E.3: Atomic Structure: Electrical Force)

A.8.1 **Force is conserved.**

A.8.2 **Force is supplied to things, which contain it and use it up.** [Hestenes (92): Key]

.8.2.1 **Something has a certain amount of force available to or in it.**

A.8.2.1.1 **Nuclear force gets spread over a number of electrons; none is left over to attract another electron.** (* E.3)

A.8.2.2 **Vibrating molecules use up their force and stop.***

A.8.3 **Force causes motion. (Force is proportional to velocity.)** [Hestenes (92): Key]

A.8.3.1 **Water needs a force, heat, to force it upward in evaporation.** (* A.5) [Schmidt (97)]

A.8.4 **Force is dominance; the bigger, faster, more powerful thing in an interaction exerts more force.** [Hestenes (92): Key]

A.8.4.1 **Water has the force to dissolve salt.** *

A.8.4.2 **When Mg is placed in aqueous HCl, Mg is the driving force. It is very reactive and drives the reaction.** (* D.5.4) [Cachapuz (87), S12a: 27%]

A.8.4.3 **When Mg is placed in aqueous HCl, the acid is the driving force, because it is very strong.** (* D.5.4) [Cachapuz (87), S12a: 9%]

A.8.5 **(Energy and force are the same thing.)** *

A.8.6 **(Pressure is the same as force.)** [Olenick]

A.8.7 **(What electrons or other physical entities "want" to do is used as a primitive force concept.)** [Tabor (97)]

A.8.8 (**Gravity seen as a significant force at the atomic scale.)**
A.8.8.1 **Atoms are attracted by gravity.*** [Arons (97), C]
A.8.8.2 **Electrons are kept in orbit by gravity.** [Arons (97), C]

A.8.9 **(Sharing electrons is like a force.)** (* E.6.1) [CH: Key]
A.8.9.1 **Atoms are held together because they share electrons.** (* E.6.1)

A.8.10 **(Molecules can repel each other.)**
A.8.10.1 **Oil doesn't mix with water because oil and water molecules repel each other.** (*E.7, B.5) [Lehmann, C: “almost universal”; F: “some”]
A.8.10.2 **Repulsive forces between particles prevent them falling to the bottom of a flask.** (* A.2) [Novick (81), 16+yo: 20% (in Kind(04))]

A.9: **Energy** (limited inventory)

A.9.1 (**Anthropocentric: energy is associated with human beings.)** [Trumper (90), S9, S10, S11:100%])
A.9.1.1 Energy is the “life force”. * [Kruger (90), PT] [Viennot (98), MT: Key]
A.9.1.1.1 **Energy is caused by life, animal activity, human activity.** (*A.9.3) [Viennot (98), MT; Important]
A.9.1.2 **Energy is liveliness.** [Viennot (97), MT] [Kruger (90), PT]
A.9.1.3 **Energy is produced from certain types of reactions that take place in living things.** * [Gayford (86), SB: >44%]

A.9.2 (**Depository: some objects have energy and expend it.)** [Trumper (90), S9, S10, S11: 100%])
A.9.2.1 **Energy is not really energy until it has been "released".** [Solomon (85), S9]

A.9.3 **Energy can disappear.** [Kruger (90), PT; Key]
A.9.3.1 **Energy is used up in processes.** [Kesidou (93), D10: 33%] [Kind (04) p.66: Key]
A.9.3.2 **Battery running out is an example of energy not being conserved.** [Solomon (85), S9. (In Swackhamer (01)]
A.9.3.3 **Energy is not lost but is exhausted in bringing about an effect.** [Kesidou (93), D10: Key]

A.9.4 (**Energy is “needed” for something to happen).** [Trumper (90), S9: 96%; S10,S11: 100%]
A.9.4.1 **All energy forms cause actions and effects**. [Kesidou (93), D10]
A.9.4.2 **Energy is used to create chemical bonds.** [Gayford (86), SP: 78%]

[Kind (04) p.66: Key]

A.9.5 (**Ingredient: energy is a dormant ingredient within objects, released by a trigger.)** [Trumper (90), S9: 12%]

A.9.5.1 **Energy is a reactant which is added to a reaction.*** [Thomaz (98), C4: 50%]

A.9.5.2 **Chemical bonds store energy.** (* E.4) [Ross (93), 15yo] [Kind (04) p.66: Key]

A.9.5.2.1 **Energy is stored in "high energy" bonds such as ATP.** [Gayford (86), "typical biology texts", SB: 74%] [Kind (04) p.66: Key] [Originally stated by Lipman (41), according to Gayford (86)]

A.9.5.2.2 **Breaking chemical bonds releases energy.** (* E.4) [Cachapuz (87), S12a: 48%] [Kind (04) p.66: Key]

A.9.5.2.3 **Bond making requires energy.** [[Tabor (98b), C] [Cachapuz (87), S12a: 48%]

A.9.5.2.4 **Fuel stores energy.** [Ross (93), 15yo] [Kind (04) p.66: Key]

A.9.6 (**Activity: energy is an obvious activity.)** [Trumper (90), S9: 75%; S10, S11: 100%]

A.9.6.1 **Work is a form of energy.**

A.9.6.2 **Something not moving can't have any energy.** [Olenick]

A.9.7 (**Product: energy is a by-product of a situation or a process.)** [Trumper (90), S9, S10, S11: 100%])

A.9.7.1 **Energy is "produced".** [Kruger(90), PT: Key] [Trumper (90)]

A.9.7.1.1 **The wax from a burning candle becomes energy.** (* B.7, A.1)

A.9.7.1.2 **Charge becomes energy in a light bulb and is given off.** (*A.10) [CH: S12, C1]

A.9.7.1.3 **Energy is produced from certain types of reactions that take place in living things.** (* A.9.1) [Gayford (86), SB: >44%]

A.9.7.1.4 **Energy is caused by life, animal activity, human activity.** (*A.9.1) [Viennot (98), MT: Important]

A.9.7.2 **Energy can suddenly "erupt" from something that doesn't have energy.** [Solomon (85), S9: "many".]

A.9.7.2.1 **Uranium doesn't have any energy. It's just "a rock".** [Solomon (85), S9]

A.9.7.3 **Energy comes from the sun. (not just for photosynthesis.)** [Kruger (90), PT]

A.9.8 (**Functional: energy is seen as a very general kind of fuel associated with making life comfortable.)** [Trumper (90), S: 9:6%; S10: 13%]

A.9.8.1 **Conservation of energy means using less energy.** [Tabor (98a), C]

A.9.9 (**Energy is Force)**

A.9.9.1 **The amount of energy needed to bring about an effect depends on the resistance met.** [Kesidou (93), D10: common]

A.9.9.2 **Energy and force are the same thing.** (* A.8) [Kesidou (93), D10: 35%] [Trumper(90)] [One of them: Key]

A.9.10 (**Flow transfer: energy is seen as a type of fluid transferred in some process.)** [Trumper(90), S9:75%; S10: 30%; S11: 56%])

A.9.11 (**Energy does not degrade - inferred.)**

A.9.11.1 **Energy from a golf ball which bounces to a halt is still available for use in the system.** [Solomon (85), S9: 35%, in Swackhamer (01)]

A.9.11.2 **Energy can be recycled.**

A.9.12 (**Energy is not associated with motion.)**

A.9.12.1 (**Kinetic energy of an object does not depend on the speed of the object.)** [Viennot (97), MT]

A.9.12.2 **Energy is not a property of stationary systems.** [Viennot (97), MT] [Kruger(90), PT]

A.9.13 (**Energy as the transfer of something we are keeping track of from one system to another, "accepted scientific concept", not used.)** [Trumper (90),. S9: 25% of students used in 2% to10% of instances; S10: 40% used in 7% to 12% of instances; S11: 67% used in 1% to 11% of instances.]

A.9.13.1 **(Conservation of energy not used.)** [Brook et al. (84), 15yo: 95%] [Finegold and Trumper (89), 14-17yo: 80%]

A.10**:** **Electricity** (limited inventory) (See also C: Electrochemistry and E.3: Atomic Structure/Electrical Force)

A.10.1: **(Electrical Charge.)**

A.10.1.1 **There is only one kind of charge.** [Arons (97), C: Important]

A.10.1.1.1 **Positive charge is actually a deficit of negative charge.** [Arons (97), C: Important]

A.10.1.1.2 **Positive charge is actually no charge at all; negative charges are attracted to uncharged bodies.** [Arons (97), C: Very common]

A.10.1.1.3 **A charged body has only one kind of charge.** [Olenick]

A.10.1.2 **Designation of + and – are absolute.** [Olenick]

A.10.1.3 (**Charge is not conserved)**

A.10.1.3.1 **Charge is used up in electric circuits.** [Arons (97): Key]

A.10.1.3.1.1 **Charge becomes energy in a light bulb and is given off.** (*A.10.4, A.9) [CH, S12, C1]

A.10.2 **(Electrical Force.)**

A.10.2.1 **Forces exist at a point without a charge there.** [Olenick]

A.10.2.2 **Electrical fields don't exist unless there is something to detect them**. [Olenick]

A.10.2.3 **The electrical force is the same as the gravitational force.** [Arons (97), C] [Olenick]

A.10.2.4 **An electrical charge will always move along a field line.** [Olenick, paraphrased]

A.10.3 (**Electrical potential.)**

A.10.3.1 (**Students fail to treat potential difference as the driving or causitive influence in a circuit.)** [Cohen(83), S11a and S12a: a large proportion and very strongly rooted.]

A.10.3.2 (**Students don't distinguish between current and potential difference.)** [McDermott(92), C1 –C4; "often"] [Not really an alternative conception – CH)

A.10.3.3 (**Students fail to recognize that an ideal battery maintains a constant potential difference between its terminals.)** (* A.10.5) [McDermott (92), C1 –C4: Key] [Not really an alternative conception – CH)

A.10.3.4 (**Students fail to distinguish between potential difference and potential.)** [McDermott (92), C1a: ~20%] [Not really an alternative conception – CH)

A.10.3.5 **What potential difference *is* is given by V = IR.** [Cohen (83), S11a and S12a: "many"]

A.10.4 (**Electrical Current and Circuits)**

A.10.4.1 (**Concept of a complete circuit not understood.)** [Not really an alternative conception – CH) [McDermott (92), C1a: 55% (inferred); Key]

A.10.4.1.1 **Electricity "charges" a light bulb but doesn't pass through it.** [Steinberg (95)] [CH: common]

A.10.4.2 **(Something is not conserved in electrical circuits.)** [Arons (97): Most important misconception]

A.10.4.2.1 **"Electricity" is used up in electric circuits.** [Arons (97), C: Key]

A.10.4.2.2 **Charge is used up in electric circuits.** [Arons (97), C: Key]

A.10.4.2.2.1 **Charge becomes energy in a light bulb and is given off.** [CH, S12; C1: common]

A.10.4.2.2.1.1 **The Electric Company supplies the electrons for your household current.** [Olenick]

A.10.4.2.2.2 **Current is used up in electric circuits.** [McDermott (92), C1a: "many", inferred; Key]

A.10.4.2.3 **Energy is used up in electric circuits.** [Arons (97), C: Key]

A.10.4.3 (**Current not voltage is the primary concept.)** [Cohen (83), S11a and S12a]

A.10.4.4 **Direction of current and order of elements matters in simple circuits.** [McDermott (92), C1 –C4: Key]

A.10.5 **Batteries and cells have electric charge stored in them.** [Steinberg (95)] [CH, S12, C1: common]

A.10.5.1 **Batteries and cells use up their charge in use.*** [Steinberg (95)]

A.10.5.2 **Batteries and cells can be revived by recharging them, which involves putting charge back into them.*** [Steinberg (95)]

A.10.5.3 **A battery is a constant current source, regardless of resistance of circuit.** [McDermott (92), C1a – C4: "most pervasive and persistent difficulty".]

A.10.5.3.1 **The current through the battery is independent of the rest of the circuit.** [McDermott (92), C1–C4: Key]

A.10.6 **Protons flow in metallic conductors.**

A.10.6.1 **"Conventional current" is the flow of protons.**
A.10.6.2 **Electric current is different in physics and chemistry (because the current flows in opposite directions.)** [Garnett (92), S12]

A.10.7 **(Students don't distinguish between flow rate and speed.)**

A.10.7.1 **Current flow is how fast electricity flows.** [Olenick] [Common]
A.10.7.2 **Electrons flow at the speed of light in electrical circuits.** [Common]

A.10.8 **(Students don't understand the role of resistance.)**

A.10.8.1 **Resistors are an obstacle to current.** [Iona (79)]
A.10.8.1.1 **Two resisters in parallel will not "draw" more current because resistors don't "draw" current.** [Cohen (83): "many"]
A.10.8.2 **Students fail to see meters as specific resistive circuit elements.** [McDermott (92), C1b: 50% - 85%; C1a: unchanged (!)]
A.10.8.3 **More devices on a series circuit means more current in it because devices "draw" current.** [Olenick]
A.10.8.4 **Electrical and heat conductivity are the same thing.** (* A.5.3)

A.10.9 (**Students fail to see circuits as a whole with every element possibly affecting the functioning of the whole, and try to solve problems locally.)** [McDermott (92), C1 –C4] [Cohen (83), "many"]

A.10.10 (**Electrical Power)**

A.10.10.1 **For two light bulbs in series, something ("power") is available and the higher-wattage bulb will take more of it.** [Cohen (83): "many"]

A.10.11 **An electrical circuit drawing represents a spatial relationship.** [McDermott (92), C1 –C4]

B. Basic Chemistry

B.1 Atoms (See also E.1: Atomic Structure)

B.1.1 **What atoms are like is given by a particular model or diagram; there is only one valid model of an atom.** [Wheeler (78), S]
B.1.1.1 **Atoms are hard, like billiard balls.** [Wheeler (78), S: 54%]
B.1.1.1.1 **Atoms have a definite volume and density**.
B.1.1.2 **Atoms are soft and fuzzy.** [Wheeler (78), S: 38%]
B.1.1.3 **Atoms are like building blocks.**
B.1.1.4 **Atoms have electrons circling them like planets around a star.***

[Cros (86), C1: ~10%; C4: ~10%; Key]

B.1.1.5 **Atoms have shells, like onions.***

B.1.2 **Atoms have the properties of bulk matter.** (* B.2.2) [Kind (04): Key]

B.1.2.1 **Copper atoms have the properties of bulk copper.**
[Schmidt (97), S10: ~50%] [BenZvi, S10: 46%]

B.1.2.1.1 **Copper atoms have the density of bulk copper.**
[Mulford (95), C1a: 70%] [Ben-Zvi (86), S10: 46%]

B.1.2.1.2 **Gold atoms are gold in color.**

B.1.2.4 **Atoms in solids have properties different from atoms in vapors.**
[Ben Zvi (86), S10: 66%]

B.1.2.4.1 **Mercury atoms are liquid.** [Schmidt (97)]

B.1.2.4.2 **Molecules of ice are hard and frozen.** (* B.) [Lee (93)]

B.1.3 **Atoms are alive (because they move.)** [Griffiths (89, 92), S12: ~50%; Key]

B.1.3.1 **Atoms are like cells with a membrane and nucleus**.*
[Wheeler (78), S: 10%; Important]

B.1.3.1.1 **Atoms can reproduce after the nuclei divide.** (* B.1.4)
[Wheeler (78), S: <10%]

B.1.4 (**Atoms are not conserved.)** [Gable (87), PT: "some"]

B.1.4.1 **Atoms can disappear (decay).** [Olenick]

B.1.4.2 **Atoms can reproduce after the nuclei divide**. (* B.1.3)

B.1.4.3 **Mass is conserved, but not the number or species of atoms**.

B.1.5 **Collisions between atoms affect their size.** [Griffiths(89), S12:>50%]
[CH: True at high energies]

B.1.6 **Matter exists between atoms. The space between atoms and molecules is not empty.** (*A.1, A.10) [Griffiths (92): >33%] [Kind: Key]

B.1.6.1 **The space between atoms and molecules is filled with air.** (*A.2, A.1.4)
[Kokotas (98): important.]

B.1.6.2 **Copper consists of atoms of copper embedded in a matrix like raisins in bread.** (* A.1.4)

B.1.6.3 **The space between particles contains "vapour or oxygen".** (*A.1.4)
[Novick (78) p.276, 16 yo+: 40%. (In Kind (04))]

B.1.6.4 **The space between particles contains "a pollutant."** (*A.1.4)
[Novick (78) p.276, 16 yo+: 40%. (In Kind (04))]

B.1.7 **Particles can change form or shape.** [Kind (04): Key]

B.1.7.1 **(Particles (atoms and molecules) may explode, burn, contract, expand and/or change shape.)** (* [Kind (04) p.13: Key]

B.2. Molecules

B.2.1 **Molecules are basic, simple, indivisible entities.** [Tabor(98a), C] [CH: Key]

B.2.1.1 **$N_2 + O_2 \rightarrow 2NO$ is not allowed because N_2 and O_2 can't be decomposed.**

B.2.1.2 **Molecules are conserved in chemical reactions.** [Mulford (96), C1a: 34%]
B.2.1.3 **H_2O represents a single indivisible particle.** [Schmidt (97): 64%]

B.2.2 **Molecules have the properties of bulk matter composed of them.**

B.2.2.1 **Molecules are small particles formed by successive partitioning of matter and hence keep their macro properties such as hard, soft, etc.** [Kokotas (98), D10]
B.2.2.2 **(The properties of molecules depend on the phase of the material composed of them.)**
B.2.2.2.1 **Molecules change shape with phase changes.** [Griffiths (89), S12: >50%]
B.2.2.2.2 **Water vapor molecules weigh less than ice molecules.*** [Griffiths (89), S12: >50%]
B.2.2.2.3 **Molecules of solids are hard, molecules of gasses are soft.**
B.2.2.2.4 **Gas molecules are round, molecules of solids are cubes.** [Schmidt (97), S]
B.2.2.2.5 **Molecules of solids are biggest, molecules of gas are the smallest.**
B.2.2.2.6 **Glue molecules have sticky surfaces.** [deVos (87), 14-15yo: some]

B.2.3 **Properties of molecules depend on the pressure, temperature, etc., of the material**. [Schmidt (97), S]

B.2.3.1 **Molecules expand when heated**.* [Mulford (96), C1a: 10%] [Lee (93)] [Griffiths (89), S12: >50%] [Griffiths (92)] [Kesidou (93), D10]
B.2.3.1.1 **The size and shape of a water molecule is affected by temperature.**
B.2.3.2 **Pressure affects the shape of a molecule.** [S12: >50%]

B.2.4 (**Molecules have a temperature.)**

B.2.4.1 **Molecules in a hot liquid are hotter than molecules in a cold liquid** . (*A.7) [deVos (87), 14-15yo: some]
B.2.4.2 **Temperature is transferred from one molecule to another by heat conduction.** (*A.7) [Kesidou (93), D10]

B.2.5 (**Failure to distinguish elements, compounds and mixtures in terms of atomic model.)** [Kind (04): Crucial; may largely determine which students can continue with chemistry after age 16.]

B.2.5.1 **Any diagram that contains different symbols for atoms, whatever their location, represents a mixture.** [Briggs and Holding (86), 15 yo: 50%]
B.2.5.2 **Molecules are something that a substance "has".**
B.2.5.2.1 **Water is something different from H_20 molecules.** *
B.2.5.2.2 **There is matter between molecules.** (* A.1)
B.2.5.2.3 **The space between molecules contains air.** (* A.1)
B.2.5.3 **Chemical reactions between gasses are simply mixing.** (*B.6) [Schmidt (97), 13-14yo: ~35%]

B.2.6 **(Failure to understand the model that all molecules in a pure substance are the same.)**

B.2.6.1 **Water molecules contain components besides O and H.**

B.2.6.2 **Water molecules are not all composed of the same atoms.**

B.2.6.3 **Water molecules contain different numbers of atoms.**

B.2.6.4 **Molecules in the same substance come in different sizes.** [Griffiths (89), S12: >50%]

B.2.7 **Water molecules are composed of two or more spheres.** [Griffiths (89), S12: >50%]

B.2.8 **A chemical formula represents a single molecule rather than a quantity of similar molecules.** [Ben-Zvi (86)]

B.2.9 **Molecules with the same numbers and species of atom are isomeric only if they belong to the same class of compounds.** [Schmidt (95), Grade 12 and 13 elementary course: about half; Grade 12-13 Advanced Course: about 1/3]

B.3 Atomic Scale and Stoichiometry

B.3.1 **(Size of atoms is greatly overestimated.)** [Griffiths(89), S12: >50%] [Wheler(78), S]

B.3.1.1 **Atoms can be seen with a microscope.** [Griffiths (89), S12: "many"] [Griffiths (92), S] [Wheler (78), S] [Olenick]

B.3.1.2 **Atoms can be seen with an electron microscope.** [S]

B.3.1.3 **Water molecules can be seen with an optical microscope.** [S]

B.3.1.4 **Water molecules are heavy enough to be weighed individually in a high school lab.** [S]

B.3.2 **(Students confused about whether to treat a mole as a number or a quantity of matter.)** [Kind (04) p.49-50: Key] [BouJaoude (00)] [Nelson (91)] [Dierks (81)]

B.3.3 **(Students unable to visualize, work with such large numbers.)** [Kind (04) p.49-50: Key]

B.3.3.1 **A 2-mm-long line of atoms contains 6x10^23 atoms.** [Mulford (96), C1a: 70%]

B.3.4 **(Students unable to use ratio and proportional reasoning needed for molar problems.)** [Shayer (70)]

B.3.4.1 **(Students fail to apply reacting mass reasoning, assume all inputs will combine.)** [Barker (95), 16-17 yo: 32%; after 2-yr course: 16%]

B.4 Phase Changes

B.4.0 **The weight or mass of a substance changes as it melts or evaporates. Mass not conserved.** (*A.1.3, A.2, A.4) [Schmidt (97), S12: 91%; 18 yo: 54%]

[Kokotas (98)] [Stavy (90) 15 yo post instruction: 50%. (In Kind (04) p.16)]
[CH: Key]

B.4.0.1 **Mass not conserved because "gas weighs less than liquid".**
[Stavy (90) (in Kind (04))]

B.4.0.2 **Water (or alcohol) disappears as it evaporates.** (* A.4) [Kokotas (98), D10] [Lee(93)]

B.4.0.3 **If ice is melted the resulting water will weigh less.** * [Krnel (98), S]

B.4.0.3.1 **A sealed container with a bit of liquid in it weighs less after the liquid has evaporated.** (*A.4)

B.4.0.3.2 **Water molecules are largest and heaviest when in the solid phase.**
[Krnel (98), S12: >50%]

B.4.1 **Solid, liquid and gas are *three types of same substance*. One disappears as the other appears**. [Schmidt(97), S; Key]

B.4.1.1 **Water is "modified" into vapor.**

B.4.2 **Solid, liquid and gas are *different substances*. One disappears as the other appears.** (* A.1.5) [Kind: Key]

B.4.2.1 **In evaporation, molecules turn into something else; water (or alcohol) "becomes" vapor.** [Schmidt (97), S] [Kokotas (98), D10] [Lee (93)]

B.4.2.1.1 **Water molecules are largest and heaviest when in the solid phase.**
(*B.4.0) [Krnel (98), S12: >50%]

B.4.2.1.1.1 **Water vapor molecules expand as they evaporate.**
[Gabel (87), PT: some]

B.4.2.1.2 **Alcohol turns into air on evaporation.** [Lee (93), MS]

B.4.2.2 **Vapor is something different from water.** [Lee(93), MS]

B.4.2.2.1 **Bubbles from boiling water consist of air.** [Schmidt(97), S]
[Osborne(83), 12 yo: 30%; 17 yo: 20%]

B.4.2.2.2 **Bubbles from boiling water consist of air and oxygen gas.**
[Bodner (91), G1b: 20% (!)] [Schmidt(97), S]

B.4.2.2.3 **Bubbles from boiling water consist of hydrogen gas**.
[Bodner (91), G1b: 5% (!)]

B.4.2.2.4 **Bubbles from boiling water consist of oxygen and hydrogen gas.**
[Osborne (83), 12 yo: 25%; 17 yo: 40%] [Mulford (96), C1a: 55%]
[Schmidt (97), S] [Kokotas (98), D10] [CH: Key]

B.4.2.2.4.1 **Water evaporating from a dish is converted to oxygen and hydrogen.** [Osborne (83): S12: ~30%]

B.4.2.2.6 **Boiling water becomes smoke.** [Schmidt (97), S]

B.4.2.3 **Atoms in solids have properties different from atoms in vapors**.*
[Ben Zvi, S10: 66%]

B.4.2.4 **Atoms in solids have properties different from atoms in liquids**.

B.4.2.4.1 **Water from melting ice is different from running water.**

[Schmidt (97), S]

B.4.2.4.2 **Molecules of ice are hard and frozen.** (* B.1) [Lee (93)]

B.4.2.4.3 **When butter melts, water is formed.** [M]

B.4.2.5 **(State changes not seen as reversible processes.)**

B.4.2.5.1 **Students have difficulty accepting that the energy exchange involved in freezing and melting has the same magnitude.** [CH: C1]

B.4.3 **Freezing and boiling are examples of chemical reactions; a phase change is a kind of chemical reaction.** (* B.6.1) [Ahtee (98), C1: 8%; Key] [Gensler (70): arguably true. (In Kind(04) p.25)]

B.4.3.1 **Intra-molecular bonds are broken when substances change phase.** (*B.6.1) [Boo (86)]

B.4.3.1.1 **(Bonds are broken in melting, boiling; so phase changes are related to chemical reactions; students confused by this.)** [Gensler (70), (In Kind (04) p.25)]

B.4.3.2 **When reversibility of a chemical reaction is observed, it can be explained as phase changes which occur as the temperature fluctuates.** (* B.6.1) [van Driel, S10: "most"; Important]

B.4.4 **(Water in the air is not recognized.)**

B.4.4.1 **(Water in air not mentioned when discussing condensation.)** [Schmidt (97), 15yo: 100%] [Mulford (96), C1a: 62%] [Osborne (83): 65%]

B.4.4.1.1 **Drops of water on the outside of a cold bottle of water comes from inside the bottle**. [Schmidt (97), S] [Kokotas (98), D10]

B.4.4.1.2 **Drops of water on the outside of a bottle are made by the cold.** [Schmidt (97), S] [Osborne (83), 12-17 yo]

B.4.4.1.3 **Drops of water on the outside of a cold bottle are from hydrogen or oxygen combining.** [Osborne (83), 12-17 yo.; 16-17 yo: 33%] [Mulford (93), C1a: 28%]

B.4.5 **(Vapor and liquid at equilibrium cannot be at the same temperature.)**

B.4.5.1 **At equilibrium, vapor and liquid molecules have different kinetic energies.** (* A.4.1) [Johnstone (77), Sa: >50%]

B.4.5.2 **Molecules in solids are slow, molecules in liquids faster, and in a gas they just zip around.** [Johnstone (77): taught in Scottish elementary schools.]

B.4.5.3 **The temperature at which water (or any substance) boils is the maximum temperature to which it can be raised.** *

B.4.5.4 **Steam is always at more than 100 deg C.**

B.4.5.5 **(Failure to understand that ice and water stay at the same temperature while the ice melts.)** [Abraham (92), MS: 98%]

B.4.6 **(Freezing and melting of substances other than water not seen as the same process.)**

B.4.6.1 **(Students have a very hard time with melting or vaporization at very high or very low temperatures. High and low temperatures difficult to visualize.)** (*A.7) [Viennot (98)]

B.4.6.2 **Freezing must occur at "cold" temperatures, boiling at "hot" temperatures, without regard for the substance involved.** [Kind (04), p.20]

B.4.7 **(Misc. difficulties)**

B.4.7.1 **(Difficult for students to believe that once the transition from solid to liquid is complete the temperature of the liquid will start rising again.)** [Tiberghien (84) (85)]

B.4.7.2 **Ice is at 0 deg and cannot change temperature.** [Common]

B.4.7.3 **Freezing is like drying.** [Schmidt (97), S; Key]

B.4.7.4 **Bubbles mean boiling.**

B.5 Dissolution, Solutions, Precipitation

B.5.1 **Melting and dissolving are the same thing.** [Lee (93), MS: Key]

B.5.1.1 **Salt becomes liquid salt when it dissolves**. [Kokotas (98), D10]

B.5.1.2 **Dissolving sugar melts, becomes liquid sugar.** [Abraham (92)]

B.5.2 **(Dissolution is a mechanical process; dissolutions and colloidal fluids not distinguished.)**

B.5.2.1 **Things dissolve by crushing and mixing them in water.**

B.5.2.2 **Salt is not hard (or dense) enough to resist dissolving**. [Kokotas (98), D10]

B.5.2.3 **Chalk won't dissolve because it is too heavy (or hard)**. [Schmidt (97), S]

B.5.2.4 **Water has the force to dissolve salt.** (* A.8) [Kokotas (98), D10]

B.5.3 **(Things become each other in solution.)**

B.5.3.1 **When sugar is dissolved in water the water takes on properties of the sugar**. [Schmidt (97), S]

B.5.3.2 **When sugar is dissolved in water it takes on properties of the water.**

B.5.3.3 **Sugar becomes water on dissolving.** [Lee (93), MS: "some"]

B.5.4 **Weight is lost in dissolving, solution weighs less than ingredients.** (*A.3) [Mulford (96), C1a: 26%] [Lee (93), MS: 33%] [Driver (85), 9-14 yo: ~67%] [Andersson (84), 15 yo: >50%]

B.5.4.1 **Sugar becomes a liquid in dissolving, and so weighs less.** [Andersson (84), 15 yo]

B.5.4.2 **Dissolved sugar has no mass.** [Andersson (84), 15 yo]

B.5.4.3 **Salt, sugar disappears in dissolving.** (* A.3) [Mulford (96), C1a: 15%] [Lee (93), MS]

B.5.5 **(Concentration and quantity not distinguished.)**

B.5.5.1 **(A strong solution of a salt contains more of that salt than a weak solution, without regard to the quantity of solution.)**

B.5.6 **(Saturation not understood or used.)**

B.5.6.1 **The concentration of salt in a saturated solution will increase when water evaporates.** [Mulford, C1a: 65%]

B.5.7 **Sugar dissolving in water is a chemical change.** (* B.6.1)
[Schollum (81), 14yo: 48%; 16 yo: 55%]

B.5.8 **Diluting fruit juice by adding water is a chemical change**. (* B.6.1)
[Schollum (81), 14yo: 70%; 16 yo: 50%]

B.5.9 **(Some molecules repel each other.)** [Common in biology texts.]
B.5.9.1 **Oil doesn't mix with water because oil and water molecules repel each other.** (*E.7, A.8) [Lehmann, C: “almost universal”; F: “some”]

B.5.10 **Lowering of the equilibrium solvent vapor pressure of a solution is caused by nonvolatile solute molecules partially physically blocking the escape of solvent molecules from the surface of the solution.** (* B.4.7)
[Lehmann: “many textbooks”]

B.6 Chemical Reactions

B.6.1 **(What is a chemical reaction?)**

B.6.1.1 **The product of a chemical reaction consists of one of the reagents.**
[deVos (87), 14-15yo: common]

B.6.1.2 **Chemical reactions are reactions which produce irreversible change.**
[Very common, taught in MS texts.] [van Driel (98), S10: Key]
B.6.1.2.1 **The original substance vanishes "completely and forever" in a chemical reaction.*** [van Driel (98), S10:"most"; Key]
[Very common, taught in MS texts.]
B.6.1.2.2 **Fuels are destroyed in burning or changed into something else.**
[Kind (04) p.44: Key]

B.6.1.2.2.1 **Mass lost in burning because petrol is changed into gas, heat or kinetic energy.** [Andersson (86) p.555, 15yo]
B.6.1.2.3 **Physical changes are reversible while chemical changes are not**.
[van Driel (98), S10: "most"; Key] [Taught in middle schools.]

B.6.1.3 **Chemical reactions between gasses are simply mixing.**
[Schmidt (97), 13-14yo: ~35%]

B.6.1.4 **(Chemical reactions are phase changes.)**

B.6.1.4.1 **When reversibility of a chemical reaction is observed, it can be explained as phase changes which occur as the temperature fluctuate.** (* B.3) [van Driel (88), S10: "most"; Important]

B.6.1.4.2 **Freezing and boiling are examples of chemical reactions.** (*B.3) [Gensler(70) argues that this is not a misconception, as freezing involves formation of inter-molecular bonds. (In Kind(04) p.25)]

B.6.1.4.3 **Combustion is a change of state of matter – solid or liquid to gaseous.** (* B.7) [Schmidt (97)] [Kind (04) p.44: Key]

B.6.1.4.3.1 **A candle burning is described as wax melting.** [Meheut (85), 11-12 yo: 25%. (In Kind (04)]

B.6.1.4.3.2 **Candle decreases in size because wax evaporates.** [BouJaoude (91), 14yo. (In Kind (04))]

B.6.1.4.3.3 **Candle flame is caused by the wick burning**. [BouJaoude (91), 14yo: “some”. (In Kind (04))]

B.6.1.4.4 **Intra-molecular bonds are broken when substances change phase.** (*B.3) [Boo (86)] [Peterson (86)] [Gensler (70): True. (In Kind(04) p.25)]

B.6.1.5 (**In chemical formulae, the atoms or reactants are simply tacked together.**) [Yarroch (85), Sa] [Lythcott (90)]

B.6.1.5.1 **The H_2 bonds are not broken in forming H_2O**. [Mulford (96)]

B.6.1.5.2 **(Additive view of chemical reactions) In a chemical equation, $3N_2$ can be represented as NNNNNN**. [Anderson (86), 12-15 yo: "many"] [Yarroch(85), S:~50%]

B.6.1.6 **Diluting fruit juice by adding water is a chemical change.** (* B.4.3) [Schollum (81), 14 yo: 70%; 16 yo: 50%. (In Kind (04))]

B.6.1.7 **Sugar dissolving in water is a chemical change.** (* B.4.3) [Schollum (81), 14 yo: 48%; 16 yo: 55%. (In Kind (04))]

B.6.1.7.1 **Re-crystalized sugar is not the same as the original sugar that was dissolved, so a chemical reaction must have taken place.** [Gensler (70), 11-14 yo.; consistent with what they observe. (In Kind(04) p.25.)]

B.6.2 **(What causes a chemical reaction?)**

B.6.2.1 **Chemical reactions are caused by mixing of substances**. [Strong (70): Essential but not sufficient. (In Kind (04) p.26.)]

B.6.2.1.1 **Chemical reactions between gasses are simply mixing**. (* B.6.1) [Schmidt (97), 13-14yo: ~35%]

B.6.2.2 **Chemical reactions are caused by active agents acting on passive agents**. [Brosnan (92), S: common] [CH: Key]

B.6.2.2.1 **Chemical reactions must be driven by external intervention, e.g. heat.** [Cachapuz(87), S12a: 85%; Key] [Bairal (92), S10: "many"]

B.6.2.2.1.1 **The fire in a candle came out of the match and went to the candle**.* [CH: very common]

B.6.2.2.1.2 **Coldness causes a nail to rust, drawing the rust out of the nail, like a magnet.** [Hesse (92), Sa: Important]

B.6.2.3 **Rusting is something the nail draws out of the air**.
[Anderson (86), 12-15 yo]

B.6.2.4 **Reactions are caused by atoms trying to fill shells.** (* E.2)
[Tabor (98a), C]

B.6.2.5 **(Vitamin C dropped into water-producing gas.) (No student explained that the gas formed by rearrangement of atoms to form new substances.)**
[Schollum (81 and 82), 11-17 yo: 100%; (summarized in Kind (04) p.35.)]

B.6.3 **(Conservation of matter in reactions)**

B.6.3.1a **Mass is not conserved. The products of chemical reactions need not have the same mass as the reactants.** (*A.3)
[Furio Mas (87), 12-18yo: 69%; 17-18 yo: 51%] [Schmidt (97): Key]

B.6.3.1b **Weight is not conserved.** (* A.3) [Furio Mas (87), 12-18yo: 74%]

B.6.3.1.1 **New products, totally different, are produced in chemical reactions and mass is not conserved.** [Schmidt (97)]

B.6.3.1.2 **Mass is lost in combustion.** * [Mulford (96), C1a: 13%]
[Bou Jouade, S: 28%] [Basili (91), 73% (inferred by Mulford)]

B.6.3.1.3 **A rusting nail will lose weight (not due to scaling)**.
[Bodner (91), G1: 10%] [Mulford, C1a: 38%] [BouJaoude, Sa:12%]
[Osborne (83)]

B.6.3.1.3.1 **Rust "eats away" the metal.**
[Brook (85),15yo:30% (in Kind (04))]
[Andersson (90) in Kind (04)].

B.6.3.1.4 **When steel wool burns inside a closed flask, its weight or mass changes.** [BouJaoude: ~80% (inferred)]

B.6.3.1.5 **A nail will be heavier after rusting by adding something (not due to a reaction): water, rust, oxygen, oxygen and water.** [Brook (85)]
[Andersson (84) in Kind(04) p.34.]

B.6.3.2 **Substance is not conserved in reactions.** [Furio Mas, 12-18yo: 43%]

B.6.3.2.1 **The wood in a burned match, wax from a burning candle disappears.**

B.6.3.2.1.1 **The wax from a burning candle becomes energy.**

B.6.3.3 (**Number of atoms in a chemical change is not conserved.)** [Schmidt (97)]

B.6.3.4 (**Species of atoms change.)**

B.6.3.4.1 **In rusting, iron turns into other elements.** [Anderson (86), 12-15 yo]

B.6.3.5 **A rusting nail won't change weight**. [Bodner (91), G1: 6%]
[Mulford (96), C1a:11%] [BouJaoude, Sa: 24%]

B.6.3.5.1 **Rusting nail won't change weight because the rust was already in the nail.** [Schollum (81) p.13, in Kind (04) p.38] [Andersson (90)]

B.6.3.5.1.1 **"The iron had only reacted with the oxygen in the air which does not weigh anything."** [Driver, et al. (85) p.163]

B.6.3.6 **Mass of steel wool will decrease after burning in open.**

[Driver (85), 15yo,a: 40%]

B.3.6.1 **Mass would decrease because gas or smoke is driven off. (Oxygen not mentioned)** [Driver (85), 15yo, post 2 yrs chem. instruction: 19%]

B.3.6.2 **Mass would decrease because ash weighs less than steel. (Oxygen not mentioned)** [Driver(85), 15yo, post 2 yrs chem. instruction: 10%]

B.6.3.7 **Precipitation reaction results in change in mass.** (*A.1.2) [Barker(95) and Barker and Miller(99), 16yo: 56%; 18 yo: 70%; in Kind (04)]

B.6.3.7.1 **Mass increases because solid weighs more than a liquid.** (*A.1.2) [Barker (95), (99), 16yo: 17%; in Kind (04)]

B.6.3.8 **(Role of oxygen in burning not recognized.)** [Kind (04) p.44: Key]

B.6.3.8.1 **Exhaust gasses from burning petrol weigh the same or less than the petrol burned.** [Barker (95), (99), 16yo: 86%; 18 yo: 60%]

B.6.3.8.2 **The petrol going into the flame must equal what comes out. (Weighs the same.)** [Barker(95), Barker and Millar(99), 16yo: 44%; 18 yo: 30%]

B.6.3.8.3 **Petrol is converted to light, heat or energy.** [Barker (95), (99), 16yo,18 yo: small proportions.]

B.6.3.8.4 **Exhaust gasses from burning petrol weigh less than the petrol because “gas is lighter”.** [Barker (95), (99), 16yo, 18 yo: small proportion.]

B.6.4 **(Energy in Chemical Reactions)** (See also A.9: Energy)

B.6.4.1 **(Energy not conserved in chemical reactions.)**

B.6.4.1.1 **Energy is used up in chemical reactions.** (*A.9.3) [Kesidou(93), D10:33%]

B.6.4.1.1.1 **Energy is a reactant which is added to a reaction.** (* A.9.4) [Thomaz (98), C4: 50%]

B.6.4.1.2 **Energy is created in chemical reactions.**

B.6.4.1.2.1 **Gasoline causes energy, but does not contain it.**

B.6.4.1.2.1.1 **Energy from gasoline is not really energy until it has been released.**

B.6.4.2 **Chemical bonds store energy.** (* A.9.4) [Gayford (86), SB: 74%]

B.6.4.2.1 **ATP contains "high energy bonds" which release energy when they are broken.** (* A.9.4) [Common belief, found in Biology texts.]

B.6.4.3 **(Kinetic barriers to a chemical reaction not understood.)** [Johnstone (77), Sa: >50%]

B.6.4.4 **The internal energy of the system goes to zero at equilibrium.** (*B.6) [Thomas (98)]

B.6.4.5 **Energy is a reactant which is added to a reaction.** * [C: 50%]

B.6.5 **Reaction dynamics.**

B.6.5.1 **Reactions between two chemical species in a solution may be analyzed without considering the effects of other species present.** [mw:,t]

B.6.5.2 **The "lowest stoichiometry" in a chemical reaction gives the limiting reagent**. [Huddle (96)].

B.6.5.2.1 **Lowest molar amount of reagents is the limiting reagent.** [Huddle (96)]

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B.6.5.3 **Chemical reactions will continue until all the reactants are exhausted.** [Hackling (85), S: 33%] [van Driel (98), S10]

B.6.5.4 (**Students unable to distinguish between how far a reaction goes and how fast it goes.)** [Wheeler (78), S]

B.6.5.4.1 **Reactions that proceed more rapidly also proceed further (more completely.)**

B.6.5.4.2 **The reason temperature affects equilibrium composition is that temperature affects the rate of reaction.** (* D.5)[Thomas(98),C4:25%]

B.6.6 **(Reversibility of Chemical Reactions)**

B.6.6.1 **Students fail to distinguish between reactions that proceed to completion and those that don't.** [Hackling (85), S12a: many]

B.6.6.1.1 **Chemical reactions will in general continue until all the reactants are exhausted**. [Hackling (85), S: 25%] [van Driel (98), S10] [mw: Key]

B.6.6.1.2 **Products of combustion are so changed that the reaction is not reversible.** (*B.7) [Schmidt (97)] [Common]

B.6.6.2 **Very slow reactions must be reversible.** [Johnstone (77), Sa]

B.6.6.3 **When reversibility of a chemical reaction is observed, it can be explained as phase changes which occur as the temperature fluctuate.** [van Driel, S10: "most"]

B.6.6.4 **The change in internal energy from heating and work is not reversible**. [C: 88%]

B.6.7 **(Chemical Equilibrium)** [Finley(82): Rated "most difficult [topic] for students to understand"]

B.6.7.1 **Chemical equilibrium and a chemical steady state are static conditions.** * [Maskill and Cachapuz (89), 15yo,b: 76%; 15yo,a: ~76%] [Kind (04): Key]

B.6.7.1.1 **Processes are driven by their seeking a state of equalization or rest.** (*D.5) [Kesidou (93), D10: "common"]

B.6.7.1.2 **The rate of reaction tends to zero as equilibrium is approached (because Delta G approaches 0)** *. [Johnstone (77), Sa: inferred, "probably common"] [Hackling (85), S12a: common]

B.6.7.1.3 **At equilibrium, most or all chemical reaction ceases.** (*D.5.3) [CH: Key]

B.6.7.1.4 **The internal energy of the system goes to zero at equilibrium.** [Thomas (98)]

B.6.7.1.5 **The Reverse reaction rate is the same as the forward rate from the beginning.** [Hackling (85), S12a: 17%]

B.6.7.1.6 **The concentrations of all species in a reaction mixture are equal (or**

have a simple arithmetic relationship) at equilibrium.
[Hackling (85), S: 50%] [Thomas (98), C4: 31%]

B.6.7.2 **An equilibrium reaction not seen as two separate reactions.**
[Kind (04) p.72; Key]

B.6.7.2.1 **Students view the two reactions as separate and independent events.**
[Johnstone et al. (77), in Kind (04) p.69: 16-17yo: 80%]
[Gorodetsky (86), 17-18yo: 1/3] [Cachapuz and Maskill (89), 14-15 yo.]

B.6.7.3 **(Not understanding approach to equilibrium)**

B.6.7.3.1 **Forward reaction rate increases as the reaction "gets going".**
[Hackling (85), S12a: 23%]

B.6.7.3.2 **Rate of forward reaction increases with time from the mixing of the reactants until equilibrium is established.**
[Hackling (85), S12a: 25%; "One of most significant misconceptions."]

B.6.7.4 **(Changing equilibrium conditions.)**

B.6.7.4.1. **If the *amount* of a reactant is increased, its concentration remains the same**. [Hackling (85), S12a: 17%]

B.6.7.4.2 **When the *amount* of a reactant is increased the rate of the forward reaction is increased but the amount of the reverse reaction is decreased**. [Hackling(85), S12a: 43%; Key]

B.6.7.4.3 **When the temperature is increased the rate of the reverse reaction is increased but the rate of the forward reaction is decreased.**
[Hackling (85), S12a: 57%]

B.6.7.4.4 **When the volume is decreased the rate of the forward action is increased but the rate of the reverse reaction is decreased.**
[Hackling (85), S12a: 63%]

B.6.7.4.5 **After changing the *concentration* of a reactant, after equilibrium is reestablished, the rates of the forward and reverse reactions will be equal to those at the initial equilibrium.** [Hackling (85), S12a: 40%]

B.6.7.4.6 **When a system is at equilibrium and a change is made in conditions the rate of the favored reaction increases but the rate of the other reaction decreases.** [Hackling (85): Key]
[Banerjee (91), C: 35%; F: 49%]

B.6.7.4.6.1 **After changing the *temperature*, after equilibrium is reestablished, the rates of the forward and reverse reactions will be equal to those at the initial equilibrium.**
[Hackling (85), S12a: 27%]

B.6.7.4.6.2 **After changing the *volume or pressure* of the system, after equilibrium is reestablished, the rates of the forward and reverse reactions will be equal to those at the initial equilibrium.**
[Hackling (85), S12a: 27%]

B.6.7.5 **(Le Chatelier's Principle (LCP) held to always apply.)**
[Wheeler and Kass (78) 17-18yo: 95%] [Quilez-Pardo and Solaz-Portoles(95), "students": 70-90%; "teachers": 70%] [Kind (04) p.72: Key]

B.6.7.6 **Position of equilibrium affected by amount of reactants.**

B.6.7.6.1 **The amount of pure solid affects the position of homogeneous equilibrium.** [Thomas (98), C4: 55%]

B.6.7.7 **Increasing the concentration of a reagent increases the value of K when equilibrium is re-established.** [Hackling (85), S12a: 20%]

B.7 Combustion

B.7.1 (**Combustion isn't a reaction; it is a release of heat which destroys things.)**

B.7.1.1 **Heat is in the fuel being burned and is not formed during combustion.** (*A.5.1)
B.7.1.2 **Colors in a flame were present in one of the reactants.** [Schmidt (97)]
B.7.1.3 **Smoke formed during combustion was already present in the wood.** [Schmidt (97)]

B.7.2 **Combustion is a change of state of matter – solid or liquid to gaseous.** (*B.6.1) [Schmidt (97)]

B.7.2.1 **If water appears during burning it was present in the wood or candle**. [Schmidt (97)]

B.7.3 **(Air is a passive participant in reactions.)**

B.7.3.1 **Air above a flame is the same as air going into the burner.** [Schmidt (97), all ages: 50%]
B.7.3.1.1 **Only air is above the flame.** [Schmidt (97), 40%]
B.7.3.2 **Oxygen aids combustion but does not participate.** [Schmidt (97)]

B.7.4 **Mass is lost in combustion.** * [Mulford (96), C1a: 13%] [Basili (91), 73% (inferred by Mulford)]

B.7.4.1 **The wood in a burned match disappears.**
B.7.4.1.1 **Match burned inside sealed container; system weight not conserved.** [BouJouade (92), "meaningful learners", Sb: 50%, Sa: 29%; "rote learners", Sb: 56%, Sa: 72%]

B.7.4.2 **The wax from a burning candle disappears.** *

B.7.4.3 **The wax from a burning candle becomes energy**. *

B.7.5 **A candle burning is endothermic, since heat is needed to initiate the reaction.** [Very common and robust, all ages.] [deVos (86): Key]

B.7.5.1 **The fire in a candle came out of the match and went to the candle**. [Very common all ages]
B.7.5.2 **The energy shown in {energy + $CaCO_3$(*s*) = CaO(*s*) + CO_2(*g*)} is an activation energy.** [Thomas 1998, C4: 31%]

B.7.6 **Combustion of alcohol, wood, or a candle are different phenomena.** [Schmidt (97) , 13-14]

B.7.7 **Combustion is a color change.** [Schmidt (97), 13-14: 33%]

B.8 (Acid-Base Reactions)

B.8.1 **An acid is something which eats material away or which can burn you.** [Hand (88) p.55, 16yo; Key] [Kind (04) p.47: Key]

B.8.1.1 **Testing for acids can only be done by trying to eat something away.** [Hand (88) p.55, 16yo; Key]
B.8.1.2 **The difference between a strong acid and a weak acid is that strong acids eat material away faster than weak acids.** [Hand (88) p.55, 16yo; Key]
B.8.1.3 **(Particle ideas not used with acid-base reactions.)** [Hand (88) p.55, 16yo]

B.8.2 **Neutralization is the breakdown of an acid or something changing from an acid.** [Hand (88) p.55, 16yo: Key] [Kind (04) p.47: Key]

B.8.3 **A base is something which makes up an acid.** [Hand and Treagust (88) p.55, 16yo: Key]

B.8.4 **A base/alkali inhibits the burning properties of an acid**. [Kind (04) p.47: Key]

B.8.5 **Hydrogen ions are present in acids, but acids remain molecular in solution.** [Kind (04) p.47: Key]

B.8.6 **Mixing an acid with a base (without regard to quantities) neutralizes the base resulting in a neutral solution.** [Common]
B.8.6.1 **In neutralization all the H and OH ions are canceled.** [Common]
B.8.6.2 **Mixing equal molar quantities of H_3O and OH to distilled water results in neutral water.**

B.8.7 **A base is an OH^- donor. (Old definition)** [Cros (86,88), C1, C2: many]

B.8.8 **When Mg is placed in aqueous HCl, the acid is the driving force, because it is very strong.** (* A.8) [S12a: 9%]

B.9 Oxidation, Reduction and Oxidation States

B.9.1 **Oxidation is the addition of oxygen in a reaction.** [S: common] [Garnett (92)]

B.9.1.1 **Reduction is the removal of oxygen in a reaction.** [S: common] [Garnett (92)]
B.9.1.2 **If a reaction includes oxygen, then it is an oxidation reaction.** [S: common]
B.9.1.3 **Sometimes a reaction can be both oxidation (because it includes oxygen) and reduction (because an electron is donated.)** [Schmidt (97)] [S]
B.9.1.4 **If a reaction doesn't involve oxygen it is not oxidation.** [Schmidt (97)]

[Common]

B.9.2 **Oxidation and reduction operations can occur independently.** [S]

B.9.3 **Changes in the charges of polyatomic species can be used to identify oxidation or reduction equations.**

B.9.3.1 **Changes in the charges of polyatomic species can be used to determine the number of electrons removed from or gained by reacting species.**

B.9.4 **The oxidation state of an element is the same as the charge of the monatomic ion of that element.**

B.9.5 **Oxidation numbers or states can be assigned to polyatomic molecules and ions.**

B.9.5.1 **The charge on a polyatomic species indicates the oxidation state of the molecule or ion.**

C. Electrochemistry (See also A.10: Electricity)

C.1 (Electric Cells and Batteries – General)

C.1.1 **Batteries and cells have electric charge stored in them**.

C.1.1.1 **Batteries and cells use up their charge in use.**
C.1.1.2 **Batteries and cells can be revived by recharging them, which involves putting charge back into them.**

C.1.2 **Dry cells are fundamentally different from wet cells.**

C.1.3 **Anodes are positive (negative) and cathodes are negative (positive) by definition.** [Taught in middle schools.]

C.1.4 **Anodes, like anions, are always negatively charged and release electrons; cathodes, like cations, are always positively charged, attract electrons**. (* C.3) [C1a]

C.2 (Electric Current in Electrolytes)

C.2.1 **Electrons flow in electrolytes**.

C.2.1.1 **Electrons can flow through aqueous solution without assistance from the ions.** [C1a]

C.2.1.2 **Electrons move through solution by being attracted from one ion to another.**
C.2.1.2.1 **Electrons move through electrolytes by being attracted to positive ions**

in the solution. [Sanger (99): 6 of 10 textbooks; Important]

C.2.1.3 **When an electrolyte conducts a current, electrons move onto an ion at the cathode and are carried by that ion to the anode.**

C.2.1.3.1 **There is a high electron concentration at the anode, because electrons go there.**

C.2.1.3.2 **There is a low electron concentration at the cathode, because electrons are drained from there.**

C.2.1.3.2.1 **Electrons move from high concentration region at the anode to low concentration region at the cathode.**

C.2.1.4 **Ions in solution can accept or deposit electrons at the electrode surface without undergoing any chemical change.** [Sanger (99): 6 of 10 textbooks.]

C.2.2 **Free protons flow in electrolytes, whether acidic, base or neutral**.

C.2.3 **In a cell the anions and cations attract each other and this affects the movement of ions to the electrodes.** [S12: Important]

C.2.3.1 **Electrons move through electrolytes by being attracted to positive ions in the solution.** *

C.2.4 **The movement of ions in a circuit does not constitute an electric current.**

C.3 **(Galvanic Cells)**

C.3.1 **Anodes, like anions, are always negatively charged and release electrons, and cathodes, like cations, are always positively charged and attract electrons**. (*C.1) [C1a]

C.3.1.1 **The anode is positively charged because it has lost electrons. The cathode is negatively charged because it has gained electrons.** [C1a]

C.3.2 **Electrons enter the solution from the cathode, travel through the solutions and the salt bridge, and emerge at the anode to complete the circuit.** [C1a]

C.3.2.1 **Only negatively charged ions constitute a flow of current in the electrolyte and the salt bridge.** [C1a]

C.3.2.2 **Electrons can flow through aqueous solution without assistance from the ions.** (* C.2) [C1a]

C.3.3 **Cations and anions move until their concentrations are uniform.** [C1a]

C.3.4 **Half-cell potentials are absolute in nature and can be used to predict the spontaneity of the half-cells.** [C1a] [Sanger (99): "many" textbooks.]

C.3.4.1 **There is no need for a standard half cell.** [C1a]

C.3.4.1.1 **Cell potentials are obtained by adding individual reduction**

potentials. [C1a]

C.3.5 **The identity of the anode and the cathode depends on the physical placement of the half-cells.** [C1a]

C.3.5.1 **The anode is always on the left.** [C1a]

C.3.6 **Standard reduction potentials list metals by decreasing activity.** [C1a]

C.4 Electrolytic Cells

C.4.1 **In electrolysis, the direction of the applied voltage has no effect on the reaction or the site of the anode and cathode.** [C1a]
C.4.2 **In electrolytic cells with identical electrodes connected to the battery, the same reactions will occur at both electrodes.** [C1a]
C.4.3 **In electrolytic cells, oxidation occurs at the cathode and reduction at the anode.** [C1a]
C.4.4 **In electrolytic cells, water is unreactive toward oxidation and reduction.** [C1a]
C.4.5 **No reaction will occur if inert electrodes are used.** [C1a]
C.4.6 **Inert electrodes can be oxidised or reduced.** [C1a]
C.4.7 **The calculated cell potentials in electrolytic cells can be positive.** [C1a]
C.4.8 **There is no relationship between the calculated cell potentials and the magnitude of the applied voltage.** [C1a]
C.4.9 **Electrolytic cells can force non-spontaneous reactions that do not involve electron transfer to happen.** [C1a]
C.4.10 **In electrolysis of water the entire tube of water has been changed to hydrogen.** * [S] [Naive observation, common]

D. Thermodynamics

D.1 Heat (See A.5: Heat)

D.2 Temperature (See A.6: Temperature)

D.3 Molecular model of heat (See A.7: Molecular model of heat)

D.4 (First Law of Thermodynamics)

D.4.1 (Heat, enthalpy and internal energy)

D.4.1.1 **Heat is energy that is added to something.** * [Thomas (98), C4: 42%]
D.4.1.2 **Enthalpy is the heat contained in the system.** [Beall (94)]
D.4.1.3 **The enthalpy change, Delta H, is the same as the internal energy change,**
Delta U. [Thomas 1998, C4: 38%]
D.4.1.4 **Reactions in solution: chemical change involves simply a transfer of energy between the water molecules (non-bonding energy) to the bonds**

being formed, and the resulting temperature of the water depends on the amount of non-binding energy left. [Cachapuz (87), S12]

D.4.2 **(Energy transfer and work)**

D.4.2.1 **The work done depends only on the initial and final states of the system. (Work is a state variable.)** [Meltzer (01), C1a: 20%]

D.4.2.2 **Heat absorbed is independent of process, depends only on the initial and final states.** [Meltzer (01), C1a: 22%]

D.4.2.3 **No heat is transferred under isothermal conditions.** [Thomas (98), C4: 60%]

D.4.2.4 **(Students fail to see that work done by a reaction comes at the expense of heat released.)** [Johnstone (77), Sa: >50%]

D.4.3 **The internal energy of the system goes to zero at equilibrium.** (* B.6, D.5) [Thomas (98), C4: 38%]

D.4.4 **(Conservation of Energy)**

D.4.4.1 **Energy is conserved if the initial and final internal energy of the system is the same.** [Thomas (98), C4: 25%]

D.4.4.2 **Delta E = 0 for any isothermal process. (True only for ideal gas.)** [Granville (85), S11a: common]

D.4.5 **(Reversibility)**

D.4.5.1 **The change in internal energy from heating and work is not reversible.** [Thomas (98), C4: 88%]

D.4.5.2 **Thermodynamic reversibility is equivalent to a reaction being able to proceed in either direction.** [Thomas (98), C4: 69%]

D.4.5.3 **Thermodynamic reversibility is equivalent to returning a system to its initial state after it has already proceeded to equilibrium.** [Thomas (98), C4: 50%]

D.4.6 **(Thermodynamics of gasses)**

D.4.6.1 **Compressed gas expanding against the atmosphere is in free expansion.** [Beall (94), C1a: 17%]

D.4.6.1.1 **Compressed gas expanding against the atmosphere does no work and undergoes no temperature change.**

D.4.6.2 **Compressed gas expanding against the atmosphere becomes cold, like a CO_2 fire extinguisher.** [Beall (94), C1a]

D.4.6.3 **Compressed gas expanding against the atmosphere fails to come into equilibrium with the atmosphere.** [Beall (94), C1a: 11%]

D.4.6.4 **All ideal gas processes are isothermal.** [Beall (94), C1a]

D.4.6.5 **Gasses at higher pressure have higher temperatures because their molecules collide more often.** (* A.7) [Beall (94), C1a: 17%]

D.4.6.6 **(Mean distance between particles and mean kinetic energy of particles conflated)** (* D.4.6) [Rozier (1991), inferred.]

D.4.6.6.1 **In solids, such as glass and plastics, molecules are squashed against each other and cannot move.** [French textbook, in Rozier (91)]

D.4.6.6.2 **When cooling down a liquid, particles become motionless without any order; it is an amorphic solid.** [French printed university material, in Rozier (91)]

D.4.6.6.3 **Particles need more room to move faster.** [French popular science book, in Rozier (91).]

D.4.6.6.4 **The same amount of heat transferred to the same number of particles of a perfect gas will produce less temperature increase if they are in a larger volume.** [Rozier (91), C: 37%]

D.5 Second Law of Thermodynamics, Entropy and Equilibrium

D.5.1 (What is Entropy?)

D.5.1.1 **Entropy is a measure of disorder.** [Johnstone (77): taught in Scottish sylabus.]

D.5.1.1.1 **A messy room is an example of high entropy.** [Very common in texts] [Lambert (99)]

D.5.1.1.2 **Things move spontaneously toward chaos and disorder.** [Common in texts] [Lambert (99)]

D.5.1.1.3 **Dissolving of a crystalline solid into water represents an increase in entropy.** [Lambert (02): many texts.]

D.5.1.2 **Entropy is a measure of chaos.** [Lambert (99)] [Denbigh (89)]

D.5.2 (Entropy Change in Processes)

D.5.2.1 **According to the second law the entropy of the system must increase.** [Thomas (98), C4: 44%]

D.5.2.2 **"Delta S" = 0 for any adiabatic process.** (True only if process is reversible.) [Granville (85), S11a: common]

D.5.2.3 **Delta S for the system must be positive for any spontaneous process.** [Granville (85), S11a: common]

D.5.2.4 **An increase in entropy means an increase in temperature.** [Johnstone (77), inferred]

D.5.2.4.1 **As a rubber band relaxes and it's entropy increases its temperature must increase.** [Johnstone (77), Sa: ~50%]

D.5.2.5 **Entropy of a gas is inversely related to density.**
[Lambert (02): many students.]

D.5.3 **(Determinants of Equilibrium.) See also B.6: Equilibrium**

D.5.3.1 **The amount of pure solid affects the position of homogeneous equilibrium.**
[Thomas (98), C4: 55%]

D.5.3.2 **The standard change in entropy and enthalpy are not mentioned as factors that determine the value of equilibrium constants.**
[Thomas (98), C4: 94%]

D.5.3.3 **Pressure affects the value of the equilibrium constant.**
[Thomas (98), C4: 38%]

D.5.3.4 **At equilibrium, most or all chemical reaction ceases.** (*B.6.7)
[Thomas (98), C4: 31%] [CH: Key]

D.5.3.5 **The reason temperature affects equilibrium composition is that temperature affects the rate of reaction.** [Thomas (98), C4: 25%]

D.5.3.6 **Processes are driven by their seeking a state of equalization or rest.** *
[Kesidou (93), D10: "common"]

D.5.3.6.1 **The Gibbs energy of the system goes to zero at equilibrium.**
[Thomas (98), C4: 44%]

D.5.3.6.2 **The internal energy of systems in general goes to zero at equilibrium.**
[Thomas(98), C4: 38%]

D.5.4 **Driving Force**

D.5.4.1 **Processes are driven by their seeking a state of equalization or rest.**
(* D.5.3) [Kesidou (93), D10: "common"]

D.5.4.2 **The "driving force" in a chemical reaction refers to an external causative agent.** * [Cachapuz (87), S12: Key]

D.5.4.3 **The addition of energy as a reactant is the driving force behind the reaction.** [Thomas (98), C4: 50%]

D.5.4.3.1 **Heat supplied or absorbed is the driving force in a burning candle.**
[Cachapuz (87), S12a: 81%, Important]

D.5.4.4 **One of the reactants in a reaction (the dominant reactant) is the driving force.** [Bou (98)]

D.5.4.4.1 **When Mg is placed in aqueous HCl, Mg is the driving force. It is very reactive and drives the reaction.** (* A.8) [Cachapuz (87), S12a: 27%]

D.5.4.4.2 **When Mg is placed in aqueous HCl, the acid is the driving force, because it is very strong**. (* A.8) [Cachapuz (87), S12a: 9%]

D.5.4.4.3 **When lead nitrate reacts with aqueous sodium chloride, sodium replaces lead because it is more reactive.** [Cachapuz (87), S12a: 50%]

D.5.4.5 **Reactions are caused by atoms trying to fill shells.** * [Tabor (98a), C]

D.6 **Spontaneous Change and Gibbs free energy.**

D.6.1 **Delta G is the thermal energy transferred into or out of the system.** [Thomas (98), C4: 25%]

D.6.2 **(Gibbs free energy treated as an absolute value.)**

D.6.2.1 **Delta G is not identified as being at std. conditions, const. pressure.** [Beall (94), C1a:99%]

D.6.2.2 **Conservation of mass is not considered in looking for the free energy in a process.** [Thomas (98), C1: 100%]

D.6.3 **Endothermic reactions cannot be spontaneous.** [Johnstone (77)] [Thomas (98), C4: 75%; C1: 75%]

D.6.4 **Whether a chemical change will be spontaneous can be determined from chemical kinetics.** [Thomas (98), C4: 25%]

D.6.5 **"Delta G" < 0 for any spontaneous process.** (True only for isothermal, constant pressure changes.) [Granville (85), S11a: common]

E. Atomic Structure and the Chemical Bond

E.1 **(Atomic Structure) (See also B.1: Atoms)**

E.1.1 **There is only one correct model of an atom.** * [Olenick]

E.1.1.1 **Atoms have electrons circling them like planets around a star.** * [Olenick]

E.1.1.1.1 **The wave function describes the trajectory of an electron.** [Olenick]

E.1.1.1.2 **Electrons can be in any orbit they want.** [Olenick]

E.1.1.2 **Atoms "own" their electrons.** [Tabor (98a), C1: Important]

E.1.1.3 **Atoms are like cells with a membrane and nucleus.** * [S: 10%; Important] [Wheeler (78), S]

E.1.1.3.1 **Atoms can reproduce after the nuclei divide.** [S: <10%]

E.1.1.4 **The size of an atom depends on the number of protons it has.** [S12: >50%]

E.1.1.5 **Hydrogen is a typical atom.** [Olenick]

E.2 **(Atomic shell and electron cloud models.)**

E.2.1 **An electron shell is like an eggshell or clamshell, thin and hard.** [Wheeler (78), S]

E.2.1.1 **The electron shell protects the nucleus, like an eggshell and a yolk.**

E.2.2 **The force attracting electrons in the first (inner) shell would be much greater**

if

the other shells of electrons were removed. [Tabor (97), C: 70%]

E.2.3 **The electron shell is a matrix of some kind of stuff with electrons embedded in it.** [Wheeler (78), S]

E.2.3.1 **The electron cloud is like a rain cloud, with electrons suspended in it like droplets of water. The cloud contains the electrons but is made of something else.** [Wheeler (78), S]

E.2.4 **Reactions are caused by atoms trying to fill shells**. (* B.6.2) [Tabor (98a), C]

E.3 **(Atomic Structure: Electrical force)**

E.3.1 **Coulomb's law doesn't work inside the atom. It works in physics but not in chemistry.** [Tabor (97), C]

E.3.2 **Force is conserved in the atom**. (* A.8) [Tabor (97), interpretation]

E.3.2.1 **A charged body gives rise to a certain amount of force which is available to be shared among oppositely charged bodies around it.** (* A.8) [Tabor (98b), C]

E.3.2.1.1 **Nuclear force gets spread over a number of electrons; none is left over to attract another electron.** (* A.8) [Tabor (97, 98b), C: 72%]

E.3.2.1.2 **If there are fewer electrons than protons the attraction felt by each electron increases.** [Tabor (98b), C] [Tabor (97), C: 79%]

E.3.2.1.3 **As electrons are removed from an atom the net nuclear charge acting on the remaining electrons will increase.** [Tabor (98b), C] [Tabor (97), C: 69%]

E.3.2.1.4 **Because a negative ion has more electrons than protons, the effective nuclear charge attracts the electrons more and pulls them in closer to the nucleus.** [Tabor (97), C (paraphrased)] [Tabor (98b), C]

E.3.2.1.5 **The second ionization energy is greater than the first as there are fewer electrons in the shell to share the attractive force of the nucleus.** [Tabor (98b), C]

E.3.2.1.6 **The nucleus attracts all electrons around it equally.** [Tabor (98b), C]

E.3.2.2 **Nuclear forces are like tentacles; each one is attached to an electron.**

E.3.3 **Electrons are kept in orbit by gravity.** (* A.8) [Arons (97), C]

E.4 The nature of the chemical bond

E.4.1. **Atoms "want" or "need" to form bonds.** [Taber (96), "students and teachers": extensive. (In Kind (04) p.55)] [Kind (04) p.61: Key.]

E.4.2 **The chemical bond is a physical thing made of matter.** [S12a: common]

E.4.2.1 **Molecules (atoms) are glued together.**

E.4.2.2 **Atoms are held together because they share electrons, so sharing electrons is like a force.** (*E.6, A.8) [CH: Key]

E.4.3 **There are only two types of bond – covalent and ionic.** [Kind (04) p.61: Key]

E.4.4 **Bonds store energy.** (* A.9) [Ross (93)] [Kind (04) p.66: Key]

E.4.4.1 **Breaking chemical bonds releases energy.** (* A.9) [Cachapuz (87), S12a: 48%] [Kind (04) p.66: Key]
E.4.4.2 **Bond making requires energy.** [Tabor(98b), C] [Cachapuz (87), S12a: 48%]

E.4.5 **Ionic pairs such as Na^+ and Cl^- are molecules.** * [Cachapuz (87), S12a] [Tabor (98a)] [Kind (04) p.61: Key]

E.4.6 **The central (first) element in a formula is more powerful, and is responsible for bond formation.** [Kind (04) p.61: Key]

E.4.7 **Covalent bonds are weaker than ionic bonds.** [Kind (04) p.61: Key]

E.5 **Chemical Bonds: Ionic**

E.5.1 **Ionic bonds form molecules.** [Kind (04) p.61: Key]

E.5.1.1 **Ionic compounds form neutral molecules, such as Na^+Cl^- molecules, in water.** (* E.4) [Cachapuz (87), S12a] [Butts and Smith (87), 17yo,a] [Barker (94), 17yo,b: 28%; 17yo,a: 40%] [Tabor (98a)]
E.5.1.2 **H+ and Cl- ions form molecules in HCl solution.** [Cachapuz (87), S12a]

E.5.2 **(Ionic bonds seen as covalent bonds.)**

E.5.2.1 **The number of ionic bonds an ion can form is determined by the electronic configuration.** [Taber (97): Key]
E.5.2.2 **Ionic bonds can only form between the electrons that have donated or contributed electrons.** [Taber (97): Key]
E.5.2.3a **(A key factor in ionic bond formation is the generation of “full electron shells.”)** [Kind (04) p.58; inferred.]
E.5.2.3b **(The octet rule drives the chemical reaction.)** [Bodner (91), G1: “by far the most common (misconception)”]
E.5.2.3.1 **Chlorine wants to obtain another electron.** [Bodner (91), G1]
E.5.2.3.2 **Every element wants to obey the octet rule.** [Bodner (91), G1]
E.5.2.3.3 **The driving force** is for Na and Cl to have a filled octet. [Bodner (91), G1]
E.5.2.3.4 **Sodium metal is very unstable, it wants to give up electrons badly to become Na+.** [Bodner (91), G1]
E.5.2.3.5 **The electron affinity for Cl is greater than the energy required to pull an electron off of Na. Therefore Cl can remove an electron from Na.** [Bodner (91), G1]

E.5.2.4 **(Ionic bonds not seen as three-dimensional.)** [Butts (87), 17yo,a]
E.5.2.5 **(Students unable to describe ionic bonds in terms of transfer of an**

electron.) [Barker (94), ~17yo,a: ~66%]

E.5.3 **Both covalent and ionic bonds between Na^+ and Cl^- are present.** [Butts (87), 17yo,a]

E.5.3.1 **Ionic bonds can only form between one sodium ion and one chlorine atom, so ion interaction with other ions are "just forces", not bonds.** [Taber (97): Key]

E.5.3.2 **Na^+Cl^- bonds are not broken in dissolving; only inter-molecular bonds are broken**. [Cachapuz (87), S12a]

E.5.3.3 **Bonds within "ionic molecules" are stronger than inter-molecular forces.** [Cachapuz (87), S12a]

E 5.4 **Ionic charge determines the polarity of the bond.** [Birk (99), C1: 12%]

E.5.5 **Ionic bonds can't be broken by heating.** [Barker (95), 17yo,b:13%; 18yo,a: 15%]

E.5.6 **Covalent bonds are weaker than ionic bonds, and break first on heating**. (* E.6) [Barker (95), 17yo,b: 24%; 18yo,a: 14%] [Kind: Key]

E.5.7 **Covalent bonds have lower boiling points, so require less heat to vaporize.** (* E.6) [Barker (95), 17yo,b:22%; 18yo,a: 31%]

E.6 Chemical Bonds: Covalent

E.6.1 **Atoms are held together because they share electrons, so sharing electrons is like a force.** (* E.4, A.8) [Tabor (98a), C] [CH: Key]

E.6.2 **Atoms form bonds in order to satisfy the octet rule.** [Tabor (98a), C]

E.6.2.1 **Atoms lend and borrow electrons to satisfy the octet rule.**
E.6.2.1.1 **Electrons know which atom they came from.** [Tabor (98a), C]
E.6.2.1.2 **Atoms know who owes them an electron.** [Tabor (98a), C]

E.6.2.2 **Atoms "need" a certain number of bonds.**
E.6.2.2.1 **Methane has the formula CH4 because "C needs four bonds".** [Barker (94), 16yo: 56%; 18yo: 61%; in Kind (04) p.55.]

E.6.3 **Sharing an electron means one atom donates an electron which is shared by both atoms. *** [Cachapuz (87), S12a; Key]

E.6.4 **Electron pars are equally shared in all covalent bonds.** * [Birk (99), C1a: 52%; C4: 18%; Ga: 20%] [Peterson (89a), 17yo: 23%]

E.6.5 **Shape of the molecule is due to repulsion between electrons.** [Peterson (89a), 17yo: ~25%]

E.6.5.1 **The shape of a molecule is due only to repulsion between non-bonding electron pairs.** [Birk (99), AG: 27%; F:14%]

E.6.5.2 **The shape of a molecule is due only to repulsion between bonding electrons.** [C1: 17%] [Birk (99), C1: 14%]

E.6.5.3 **Bond polarity determines shape of molecule.** [Birk (99), C1]

E.6.6 **Covalent bonds are weaker than ionic bonds, and break first on heating.** (* E.5) [Barker (95), 17yo,b: 24%; 18yo,a: 14%] [Kind (04): Key]

E.6.7 **Covalent bonds have lower boiling points, so require less heat to vaporize.** (* E.5) [Barker (95), 17yo,b: 22%; 18yo,a: 31%]

E.7 Intermolecular Bonds

E.7.1 **The strengths of covalent bonds and intermolecular forces are similar.** *

E.7.2 **Van der Waals force bonds aren't really chemical bonds, they are really just a force.** [Tabor (98a), C]

E.7.3 **(Some molecules repel each other)** (* A.8, B.5)

E.7.3.1 **Oil doesn't mix with water because oil and water molecules repel each other.** (* A.8, B.5) [Lehmann, C: “almost universal”; F: “some”]

E.7.3.2 **Repulsive forces between particles prevent them falling to the bottom of a flask.** (* A.2, A.8) [Novick (81), 16+yo: 20% (in Kind (04))]

E.7.4 **Hydrogen bonds between water molecules are “liquid” or “weak” bonds.** [Barker (95), 17yo,b: 20%; 18yo,a: 8%]

E.7.5 **Hydrogen bonds are “an attractive force, not a bond.”** [Barker (95), 17yo,b: 8%; 18yo,a: 24%%]

E.7.6 **Intermolecular bonds are within a covalent molecule.** [Peterson (89a), S12: 23%]

E.7.7 **Silicon carbide has a high melting point because of “strong intermolecular forces.** [Peterson (93), C1: 36%]

E.7.8 **Strong intermolecular forces exist in a continuous covalent network.** [Peterson (89a), S12: ~33%]

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Appendix 3: References

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