

## 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 4<sup>th</sup>-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 <sup>th</sup> 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 12<sup>th</sup> 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<sup>3</sup> in 1 m<sup>3</sup>.** [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.\* [Schmidt (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.**  
[Krnell (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).**  
[Krnell (98), S]

A.4.1.1 **A candle will sink in water faster than half a candle.**  
[Krnell (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) [Schmidt (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) [Krnell (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]

A.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% to 10% 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 causative 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* 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 resistors 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<sub>2</sub>O 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  $6 \times 10^{23}$  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. \*** [Krncl (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.**  
[Krncl (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)** [Krncl (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<sub>2</sub> bonds are not broken in forming H<sub>2</sub>O.** [Mulford (96)]
- B.6.1.5.2 **(Additive view of chemical reactions) In a chemical equation, 3N<sub>2</sub> 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. (Weights 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)]

**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  $\{\text{energy} + \text{CaCO}_3(s) = \text{CaO}(s) + \text{CO}_2(g)\}$  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<sub>3</sub>O and OH to distilled water results in neutral water.**
- B.8.7 **A base is an OH<sup>-</sup> 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<sub>2</sub> 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 amorphous 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 syllabus.]

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 its 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  $\text{Na}^+$  and  $\text{Cl}^-$  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  $\text{Na}^+\text{Cl}^-$  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  **$\text{H}^+$  and  $\text{Cl}^-$  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<sup>+</sup>.** [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<sup>+</sup> and Cl<sup>-</sup> 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<sup>+</sup>Cl<sup>-</sup> 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 CH<sub>4</sub> 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 pairs 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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