Solving Problems Using Problem Solving

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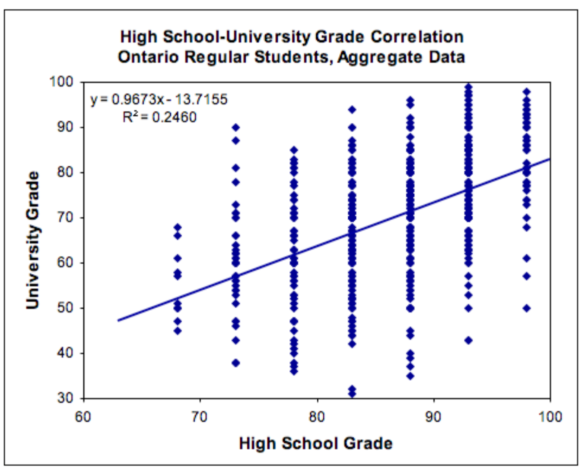
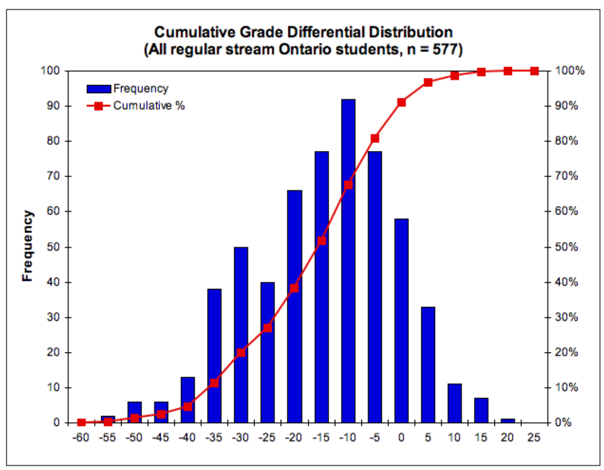
A big problem:

- There is **very little correlation** between high school grades and subsequent performance in university, even when the course content appears to be simple 'review' of the high school curriculum...
- 25% of students see their grade **drop by 30-60 percentage points** in first year undergraduate chemistry compared to high school, irrespective of the high school grade earned...
- The best studies to date can only explain <40% of the variation in student achievement in first year chemistry (or other science subjects)...
- Students who struggle lack confidence, are often weak in algebra, and tend to approach learning as an exercise in memorisation without understanding...





So what do the ones who struggle get wrong, why, and what can we do about it?

Self-Test/Assessment Questions

The following are all taken from 1st and 2nd-year university multiple-choice student self-assessment tests. The distractors in some of the questions were deliberately chosen based on known errors that students commit; this enables highly specific feedback to be provided to the students based on their choices for each question. Such an approach is not recommended for high-stakes tests or exams!

1. Given the expression A/B = X/Y, then B is equal to:
   a. XY/A
   b. AY/X
   c. X/AY
   d. Y/AX

2. When correctly expressed in SI units, a density of 1.23 g/cm^3 is:
   a. 1.23×10^{-3} g/m^3
   b. 1.23×10^{-3} kg/m^3
   c. 1.23 g/m^3
   d. 1.23×10^{3} kg/m^3

3. Consider the following balanced chemical reaction:
   $$2\ MnO_4^- + 16\ H^+ + 15\ I^- \rightarrow 2\ Mn^{2+} + 5\ I_3^- + 8\ H_2O$$
   What volume of 0.0525 M iodide would be required to exactly react with 20.0 ml of 0.0125 M permanganate?
   a. 0.63 ml
   b. 4.76 ml
   c. 35.7 ml
   d. 84.0 ml

4. A solution of known iodine concentration may be prepared by mixing solutions of iodate and iodide under acidic conditions:
   $$a\ IO_3^- + b\ I^- + c\ H^+ \rightarrow p\ I_2 + q\ H_2O$$
   When correctly balanced, the stoichiometric coefficients in this reaction equation are:
   a. $a = 1, b = 1, c = 6, p = 1, q = 3$
   b. $a = 1, b = 5, c = 6, p = 3, q = 3$
   c. $a = 3, b = 3, c = 6, p = 3, q = 3$
   d. $a = 5, b = 1, c = 6, p = 1, q = 5$

5. A 500 mL sample of a solution contains 0.375 moles of HNO_3 in pure water. What is its pH?
   a. pH 0.125
   b. pH 0.426
   c. pH 0.727
   d. The pH cannot be less than 1

Write your own question (groups of ~3). Once written, swap with another group to evaluate the question for *validity*: content accuracy, clarity of wording, lack of ambiguity, and only one correct answer. Please hand this page in afterwards; questions will be shared via the website http://www.chem.utoronto.ca/~dstone/teachers/ afterwards.

Algorithmic questions with two or more step calculations:

Many students do *not* know how to layout and present calculations, check units, use the correct number of significant figures, or sanity check the final answers! This is a key *process* that must be taught, and needs constant reinforcement.

Draw a process worksheet or flow-chart for calculating a concentration either (a) from a mass and volume when making a standard solution, or (b) from a volumetric titration:

Structured, Diagnostic, and Conceptual questions

This question is an example of conceptual vs. algorithmic ("algebraic") problem solving, and can be asked in one of three ways. Source: Lillian Bird, *J. Chem. Ed.*, **2010**, *87(5)*, 541-546.

Structured example:

A flask is first evacuated, then filled with 0.200 g of methane gas (CH_4) and stoppered.

a) The molecular mass of methane is 16.0 g/mol. How many moles of methane are contained in the flask?
b) The flask containing the methane is held at a constant temperature of 298 K. What is the pressure if the flask has a volume of 1.00 L? The value of the gas constant R = 0.0821 atm L/(mol K).
c) A second flask is filled with 0.200 g of carbon dioxide gas (CO_2, molecular mass of 44.0 g/mol). How many moles of carbon dioxide are contained in the second flask?
d) The flask containing the carbon dioxide is also held at a constant temperature of 298 K. What is the pressure in this flask if it also has a volume of 1.00 L? The value of the gas constant R = 0.0821 K/(mol L).
e) Compare your answers to b) and d). How does the pressure in each flask relate to the molecular weight of the gas within it, given that both have the same volume and are at the same temperature?
f) Use this information to predict whether a 1.00 L flask containing 0.200 g of nitrogen gas (N_2, molecular weight 28.0 g/mol) at 298 K would have a higher or lower pressure than the flask containing the carbon dioxide. Explain your reasoning.

Diagnostic example:

Individual 0.200 g samples of each of the following gases were placed in four separate 1.00 L stoppered flasks at 298 K. In which flask do you expect the gas to exert more pressure? *Explain your answer.*

Flask:	1	2	3	4
Gas in flask:	CH_4	CO_2	N_2	Ne
M_m (g/mol)	16.0	44.0	28.0	20.2

Lillian Bird notes that of 106 students: 36% calculated the pressure for each gas and justified their answer solely on these values; 42% similarly did all the calculations but then derived the principle and used that as justification; 26% gave the correct answer solely in terms of principles.

Concept text example:

Four identical sealed containers are each filled with a different gas (as indicated below) until each contains exactly the same mass. If all four are held at the same temperature, which flask contains gas at the greatest pressure?

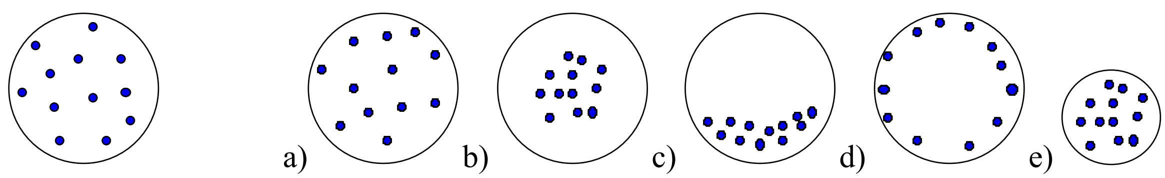
This can be provided with or without the same table as before; students can only provide a solution if they can manipulate the concepts and equations *without* the benefit of a concrete calculation, since the mass, volume, and temperature are never stated!

Conceptual *versus* Algorithmic (Algebraic) Thinking

Mary Nakhleh and others have adopted a diagnostic approach using *paired* questions: the first usually requires a fairly straight–forward calculation that can be done simply by following a memorized procedure (algorithmic or algebraic thinking); the second explores a student's *conceptual* understanding of the same phenomenon. A number of the alternate conceptions test questions use the same structure.

Gas laws example:

1. 0.100 mole of hydrogen gas occupies 600 mL at 25 °C and 4.08 atm. If the volume is held constant, what will be the pressure of the sample of gas at –5 °C?
   a) 2.98 atm
   b) 3.67 atm
   c) 4.08 atm
   d) 4.54 atm
   e) 6.00 atm
2. The diagram on the left represents a cross-sectional view of a rigid sealed tank filled with hydrogen gas at 20 °C and 3 atm pressure. The dots represent the distribution of hydrogen molecules within the tank. Which of the diagrams (a) through (e) illustrates one possible distribution of the hydrogen gas molecules in the tank if its temperature is lowered to –5 °C? The normal boiling point of hydrogen is –252.8 °C.

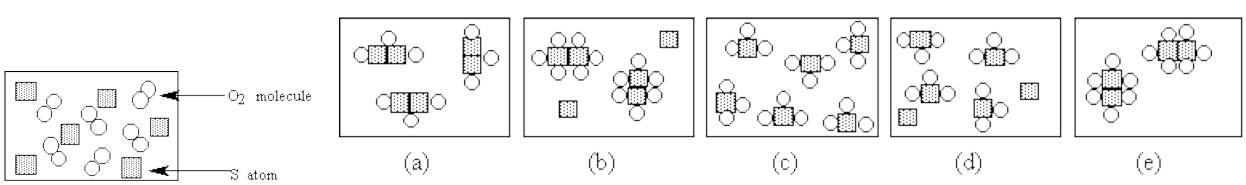


Limiting reagent example (actually three related questions):

1. Which is the limiting reagent when 2.0 mol of CO_2 reacts with 2.0 mol of S_2 to form COS and O_2?
   a) CO_2 b) S_2 c) COS d) O_2

2. Atoms of three different elements are represented by ⊗, ⊕, and ∅. Which is the limiting reagent when two ⊗⊗ molecules and two ∅∅⊕ molecules react to form ⊗∅⊕ and ∅∅?
   b) ⊗⊗ b) ∅∅⊕ c) ⊗∅⊕ d) ∅∅

3. The diagram on the left represents a mixture of S atoms and O_2 molecules in a closed container. Which diagram on the right shows the results after the mixture reacts as completely as possible according to the equation $2S + 3O_2 \rightarrow 2SO_3$?



4. When a match burns, some matter is destroyed – True or False?
5. What is the reason for your answer to question 7?
    a. This chemical reaction destroys matter.
    b. Matter is consumed by the flame.
    c. The mass of ash is less than the match it came from.
    d. The atoms are not destroyed, they are only rearranged.
    e. The match weighs less after burning.

6. A 1.0-gram sample of solid iodine is placed in a tube and the tube is sealed after all of the air is removed (see diagram). The tube and the solid iodine together weigh 27.0 grams. The tube is then heated until all of the iodine evaporates and the tube is filled with iodine gas. Will the weight after heating be:
    a. Less than 26.0 grams.
    b. 26.0 grams.
    c. 27.0 grams.
    d. 28.0 grams.
    e. More than 28.0 grams.
7. What is the reason for your answer to question 6?
    a. A gas weighs less than a solid.
    b. Mass is conserved.
    c. Iodine gas is less dense than solid iodine.
    d. Gasses rise.
    e. Iodine gas is lighter than air.

8. 100 mL of water at 25°C and 100 mL of alcohol at 25°C are both heated at the same rate under identical conditions. After 3 minutes the temperature of the alcohol is 50°C. Two minutes later the temperature of the water is 50°C. Which liquid received more heat as it warmed to 50°C?
    a. The water.
    b. The alcohol.
    c. Both received the same amount of heat.
    d. It is impossible to tell from the information given.
9. What is the reason for your answer to question 8?
    a. Water has a higher boiling point then the alcohol.
    b. Water takes longer to change its temperature than the alcohol.
    c. Both increased their temperatures 25°C.
    d. Alcohol has a lower density and vapor pressure.
    e. Alcohol has a higher specific heat so it heats faster

References:

- Mary B. Nakhleh, "Are our students conceptual thinkers or algorithmic problem solvers?" *J. Chem. Ed.*, 1993, *70(1)*, 52-55
- Mary B. Nakhleh and Richard C. Mitchell, "Concept Learning versus Problem Solving: There is a difference" *J. Chem. Ed.*, 1993, *70(1)*, 190-192
- Susan C. Nurrenbem and Miles Pickering, "Concept Learning versus Problem Solving: Is there a difference" *J. Chem. Ed.*, 1987, *64(6)*, 508-510.

The following two questions appear back-to-back on the University of Guelph 1st-year chemistry student evaluation test. The results obtained are consistent year-over-year...

10. The geometry of a water molecule is:
    a. angular or bent
    b. linear
    c. pyramidal
    d. tetrahedral

11. The geometry of a molecule in which the central atom is bonded to 2 H atoms and has 2 lone pairs is:
    a. angular or bent
    b. linear
    c. pyramidal
    d. tetrahedral

The following tables summarises student response rates for each option in the preceding multiple-choice questions. Correct answers are in bold font.

Question	**a**	**b**	**c**	**d**	**Comment**
10	**88.8%**	4.5%	4.6%	2.1%	
11	15.9%	**53.0%**	13.9%	17.2%	

Advantages of multiple choice + explain:

- Can easily see if the student is *surface learning* (blind use of memorized procedures)
- Gives insight into *concrete* versus *formal* operational development (Piaget)
- Explanation gives insight into thought processes & potential errors/misconceptions
- For some students, having to explain helps develop that deeper insight
- For others, having to explain helps clarify conceptual leaps ("it is ∴ evident that…")
- Need to teach "what to do when you're stuck" strategies:
    - *Draw* pictures
    - *Highlight* known values
    - *Write* symbols for unknowns
    - *Identify* any constants or constant values
    - *Jot down* relevant equations

Sketch an example of how a student might work the conceptual gas laws question if they do not find it intuitively obvious. Again, group work, share, hand in…

There are no bad questions (or are there?)

Sometimes, you can create problems where none existed. At other times, you can create opportunities for thought, discussion, and reflection. As an example, consider how *your* students would likely respond to the following two questions, posed in this exact sequence, on a test or exam:

1. What is the pH of an acid?

2. What is the pH of 1.0×10^{-8} mol/L of HCl?

Following up a simple recall/algorithmic question with a request to *represent* the answer differently can be useful (see earlier m/c paired concept questions, for example) but again you need to pay careful attention to the wording:

1. Balance the following equation for the production of ammonia: $N_2 + H_2 \rightarrow NH_3$

2. Represent the balanced reaction using circles with letters in the centre to depict the atoms:

3. What do the following symbols indicate?
    a. H
    b. H_2
    c. H^+

4. Sketch a diagram to represent the metallic bonding present in a block of solid copper:

Other ways of framing conceptual questions for easy marking (!) & diagnosis:

Many weak students seem to have a hard time (a) identifying key information and (b) identifying relevant information that actually answers the question (rather than merely being a true but irrelevant statement). One way around this is to get them evaluating statements in these terms.

In the following questions, mark each provided explanation (or observation) as either

• (T) True	• (E) Explains
• (F) False	• (D) Does not explain
• (I) Irrelevant	• (I) Irrelevant

1. Many compounds of the transition metals Sc through Zinc have characteristic colours, both as solids and in solution. This is attributed to splitting of the 3d atomic orbitals. For example, aqueous $CuSO_4$ is a cyan colour because:

   ( ) When an electron drops down from an upper to a lower 3d orbital, the emitted photon has a wavelength in the blue region of the spectrum

   ( ) When an electron is excited from a lower to an upper 3d orbital, the absorbed photon has a wavelength in the red region of the spectrum

   ( ) The increased size of the cation caused by the splitting makes it large enough to scatter blue light out of solution, much like particles in the atmosphere

Roll your own question T/F/I or E/D/I question in your group; share, evaluate, hand in!

Mole Concept Test (From Duncan & Johnstone, *Education in Chemistry*, 1973, 213-214)

1. Given that $Mg + S \rightarrow MgS$, what mass of Mg would react completely with 32 g of S?
    a) 12 g
    b) 24 g
    c) 32 g
    d) 56 g

2. Given that $2\ NaOH + H_2SO_4 \rightarrow Na_2SO_4 + 2\ H_2O$, how many moles of H_2SO_4 are required to react with 1 mole of NaOH?
    a) ½ mole
    b) 1 mole
    c) 2 moles
    d) 4 moles

3. Given that $2\ SO_2 + O_2 \rightarrow 2\ SO_3$, what mass of SO_2 would react with 32 g of O_2?
    a) 32 g
    b) 64 g
    c) 96 g
    d) 128 g

4. Given that $C + O_2 \rightarrow CO_2$, what mass of O_2 is required to react with 3 g of carbon?
    a) 8 g
    b) 16 g
    c) 64 g
    d) 128 g

5. What is the correctly balanced form of the equation $Al + O_2 \rightarrow Al_2O_3$?
    a) $2\ Al + O_3 \rightarrow Al_2O_3$
    b) $Al_2 + 3\ O \rightarrow Al_2O_3$
    c) $4\ Al + 3\ O_2 \rightarrow 2\ Al_2O_3$
    d) $Al_4 + 6\ O \rightarrow 2\ Al_2O_3$

6. Given that $N_2 + H_2 \rightarrow NH_3$, how many moles of H_2 would react completely with 1 mole of N_2?
    a) 1 mole
    b) 2 moles
    c) 3 moles
    d) 4 moles

7. A molar solution of HCl contains
    a) 1 mole of HCl dissolved in 1 mole of water
    b) 1 mole of HCl dissolved in 1 litre of water
    c) 1 mole of HCl dissolved in 1 litre of solution
    d) 1 mole of water dissolved in 1 litre of HCl

8. Which solution of NaCl is most concentrated?
    a) 200 mL of a solution containing 2 moles of dissolved NaCl
    b) 500 mL of a solution containing 4 moles of dissolved NaCl
    c) 750 mL of a solution containing 8 moles of dissolved NaCl
    d) 1000 mL of a solution containing 6 moles of dissolved NaCl

9. Which of the following solutions of HCl is most concentrated?
    a) 500 mL of 2 M HCl
    b) 1000 mL of 3 M HCl
    c) 300 mL of 4 M HCl
    d) 800 mL of 5 M HCl

10. Which of the following solutions contains the most NaCl?
    a) 500 mL of 2 M NaCl
    b) 1000 mL of 3 M NaCl
    c) 250 mL of 4 M NaCl
    d) 200 mL of 5 M NaCl

Notes and comments on questions 1–10 from the original study of Scottish high school students: Facility value (FV) is the percentage answering the question correctly; discrimination power (DP) is the difference in FV values between the top and bottom third of the students when ranked by overall score (for large classes, upper and lower quartiles can be used instead).

Num.	Answer	FV(%)	DP(%)	Comment
1	b	80	42	
2	a	51	55	Deviation from 1:1 stoichiometry causes problems
3	d	37	57	Similar comment
4	a	72	41	
5	c	55	39	Balancing equations problematic
6	c	37	29	Almost half chose answer (a)
7	c	55	22	Students unaware of finite volume of *solute* in solvent!
8	c	>66%	n/a	
9	d	42	15	Low DP implies even best students making mistakes
10	b	39	10	Most ignored the volume in the problem

Additional Note:

Half of 2nd-year undergraduates in an analytical chemistry course incorrectly chose b for question 7 on a self-assessment test

Additional conceptual questions can be found on the J. Chem. Ed. Question Bank web site at:

http://jchemed.chem.wisc.edu/JCEDLib/QBank/collection/CCInventory/index.html

Problem Solving

John Hayes: "Whenever there is a gap between where you are now and where you want to be, and *you don't know how* to find a way to cross that gap, you have a problem" (emphasis added; as cited by Bodner, 2003).

Polya's model of problem solving (ok for routine exercises but...) *C.f.* "GRASS"

- Understand the problem
- Devise a plan
- Carry out the plan
- Look back

The Anarchistic Route, or "How an *expert* solves problems" (Wheatley, as cited by Bodner):

- **Read the problem**
- Now read the problem again
- Write down what you hope is the relevant information
- **Draw a picture**, make a list, or write an equation or formula to help you begin to understand the problem
- Try something
- Try something else
- See where this gets you
- Read the problem again
- Try something else
- See where this gets you
- Test intermediate results to **see whether you are making any progress** toward an answer
- Read the problem again
- When appropriate, strike your forehead and say, "son of a..."
- Write down 'an' answer (not necessarily 'the' answer)
- **Test the answer to see if it makes sense**
- Start over if you have to, celebrate if you don't

Problem solving group activity:

- Get into groups of about 3 or 4, and have one person volunteer to act as an observer. Turn to one of the following problems and solve it as a group.
- The observer should take notes on how the group goes about solving the problem, any difficulties they encounter, and how they resolve them.

  Note: if the problem is one you have seen before, volunteer to be the observer!

Observer Notes:

The Waterfall Problem

The Horseshoe Falls are 49 m high. Assuming that all the potential energy of the water is converted into heat, how much warmer is the water at the bottom of the falls than at the top? Comment on the magnitude of your answer. The flow of water over the falls is reduced at night as more is diverted through the hydroelectric generating station. What affect will this have? Give reasons for your answers.

Relevant Data:

> Potential energy $E_p = mgh$ where m is mass (kg), g = 9.81 m s^{-2}, and h is height (m); the specific heat capacity of water s = 4.179 J/(g °C).

The Pizza Problem

We all know that if you try and eat pizza too soon after it comes out of the oven you can burn your mouth. Is this because of the crust, the cheese, or the tomato sauce? Use your knowledge of the different phases of matter, kinetic molecular theory, and thermochemistry to justify your answer.

Some relevant data:

- Assume that a 50 g slice of pizza consists of 25 g crust, 20 g cheese, and 5 g of sauce. Approximate values of the specific heat capacity are: Cheese = 3.0 J/(g °C); Crust = 2.0 J/(g °C); Sauce = 4.0 J/(g °C). The heat capacity of water = 4.2 J/(g °C).
- Pizza is cooked at ~ 450 °F (230 °C). Assume that, by the time it reaches your table, the pizza has reached a uniform temperature of about 150 °C. The soft tissue on the inside of your mouth (which has a very high water content) is 37 °C. Cheese melts at around 40 °C. The latent heat of fusion of milk fat ΔH_{fus} = 84 kJ/kg.

The Water and Wine Problem

You have a glass of water and a glass of wine. Assume that both are pure, homogeneous substances. (If it helps, consider the wine to be pure ethanol!)

1. Transfer exactly one teaspoon from the glass of water to the glass of wine and mix thoroughly.
2. Transfer exactly one teaspoon of this contaminated wine to the glass of water and mix thoroughly.

Consider the amount of water in the glass of wine, and the amount of wine in the glass of water: Which of the following statements is *true*?

a) The amount of water in the wine is greater than the amount of wine in the water
b) The amount of wine in the water is greater than the amount of water in the wine
c) The amount of water in the wine is equal to the amount of wine in the water

The Xenon Fluoride Problem

A sample of a compound comprising only xenon and fluorine was confined to a bulb with a pressure of 24 torr. Hydrogen was added to the bulb until the pressure was 96 torr. Passage of an electric spark through the mixture produced Xe and HF. After the HF was removed by reaction with solid KOH, the final pressure of xenon and unreacted hydrogen in the bulb was 48 torr. What is the empirical formula of the xenon fluoride in the original sample?

The Train Problem

Two trains are stopped on adjacent tracks. The locomotive of one train is 1000 yards ahead of the locomotive of the other. The end of the caboose of the first train is 400 yards ahead of the end of the caboose of the other. The first train is three times as long as the second. How long are the trains?

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