Supplemental Material

CBE—Life Sciences Education

Hubbard *et al.*

How question types reveal student thinking: experimental comparison of multiple-true-false and free-response formats
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Supplementary Material 1. Details of experimental MTF×FR question development.

For ease of presentation, we use a question with a short prompt and short T/F statements as an example. We start by showing three examples of student answers to the FR homework question, and then provide the list of conceptions and their frequency from 100 coded answers. Finally, we show three examples of exam answers and how they were coded. Conceptions are color coded such that the final T/F statement can be mapped back to a student answer.

2014 Homework Question:
Explain what happens when a chemical reaction reaches equilibrium.

Student 1: ..., the forward and backward reactions will occur at the same rate. When a reaction in an isolated system reaches equilibrium, it can no longer do work. The reason for this is because systems that are at equilibrium have a minimum value of free energy (G) and when a cells reaches metabolic equilibrium the cell is now dead. A way for a cell to not reach equilibrium is by allowing a constant flow of materials into and out of a cell.

Student 2: ..., there is essentially a "balance" between the reactants and products. This does not necessarily mean that the concentrations of reactants and products will be equal. However, for every reaction there is a point at which both the reactants and the products will maintain constant (though not necessarily the same) concentrations. Basically, the forward reaction and the reverse reaction will be simultaneously occurring at the same rate.

Student 3: ... the forward and reverse reactions are going at the equal rates. This means the concentrations of products and reactants stay constant, but there are still reactions going.

Table 1. Student generated conceptions present in more than one student answer.

Conception	# students
Rate of the forward reaction is equal to the rate of the reverse reaction	10+
It can no longer do work; when cells reach metabolic equilibrium, they die	10+
Concentrations of products and reactants are stable	10+
Free energy is at its lowest possible value	9
Concentration of products and reactants are equal	7
Neither the forward or reverse reaction has stopped	7
To avoid death, cells allow a constant flow of material in and out [1]	6
It is at maximum stability	3
The concentration of products increases while the concentration of reactants decreases	2
The reaction does more work	2
The reactants and products are equal in charge and energy	2
It stops	2
All the forces or influences are balanced out	2

[1] This conception does not answer the question and was not included as a potential T/F statement

Initial MTFxFR question:

MTF: When a chemical reaction reaches equilibrium:

- **A.** T/F the concentration of reactants and products are equal
- **B.** T/F the reactants have all been converted to products
- **C.** T/F free energy is at its lowest possible value
- **D.** T/F the concentration of the reactants and products does not change
- **E.** T/F the rate of the forward and reverse reaction are equal
- **F.** T/F forward and reverse reactions stop

FR: Explain what happens when a chemical reaction reaches equilibrium.

Final MTFxFR question:

(after discussion between J.K.H. and B.A.C. and determining desired T/F balance)

MTF: When the following exergonic reaction reaches equilibrium:

Sucrose + Water ↔ Glucose + Fructose

- **A.** T/F the concentration of reactants and products are equal
- **B.** T/F forward and reverse reactions stop
- **C.** T/F the rate of the forward and reverse reaction are equal
- **D.** T/F the reactants have all been converted to products

FR: Explain what happens when the following exergonic reaction reaches equilibrium.

Sucrose + Water ↔ Glucose + Fructose

Eliminated options and the reason they were eliminated:

T/F free energy is at its lowest possible value – determined this was not adequately covered in the current semester

T/F the concentration of the reactants and products does not change – getting at a similar concept as final statement C

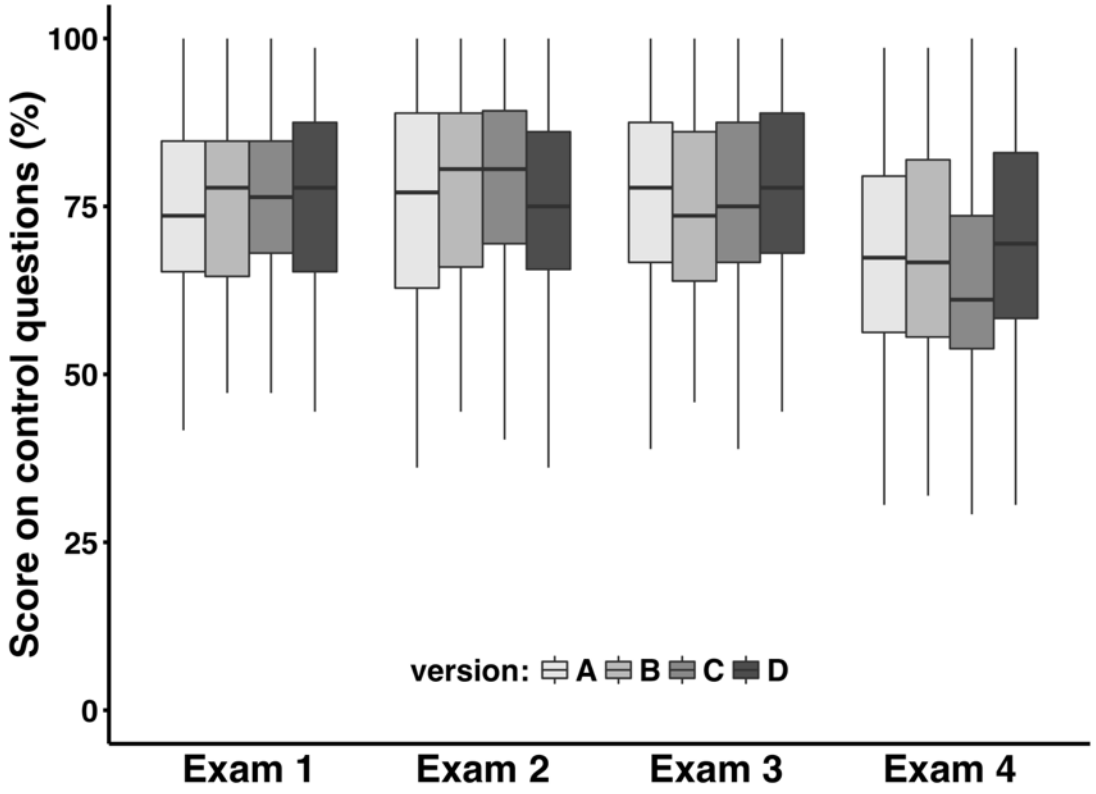
Table 2. Student exam answers were coded for each conception (1 = correct, 2 = incorrect, 3 = unclear/not included). 1 indicates the student would have correctly answered the T/F statement, 2 indicates the student would have incorrectly answered the T/F statement, and 3 indicates that a determination could not be made.

Student Exam Answers	**A**	**B**	**C**	**D**
..., both the reactants and the products are equal. So that means the sucrose and water = the glucose and fructose.	2	3	3	1
..., both the forward reaction rate and the reverse reaction rate will be equivalent. The exergonic reaction is spontaneous and will release free energy while occuring. The reactants will have higher free energy at the start of the reaction as well. However, the chemical reaction will not stop just because the reaction reaches equilibrium, there will be equal movement of molecules back and forth.	3	1	1	1
..., the products and reactants will equal each other. The reaction will not be occuring anymore. Not to say particles won't be moving still, but they will move in sync with each other that the reaction will stay equal.	2	2	3	1

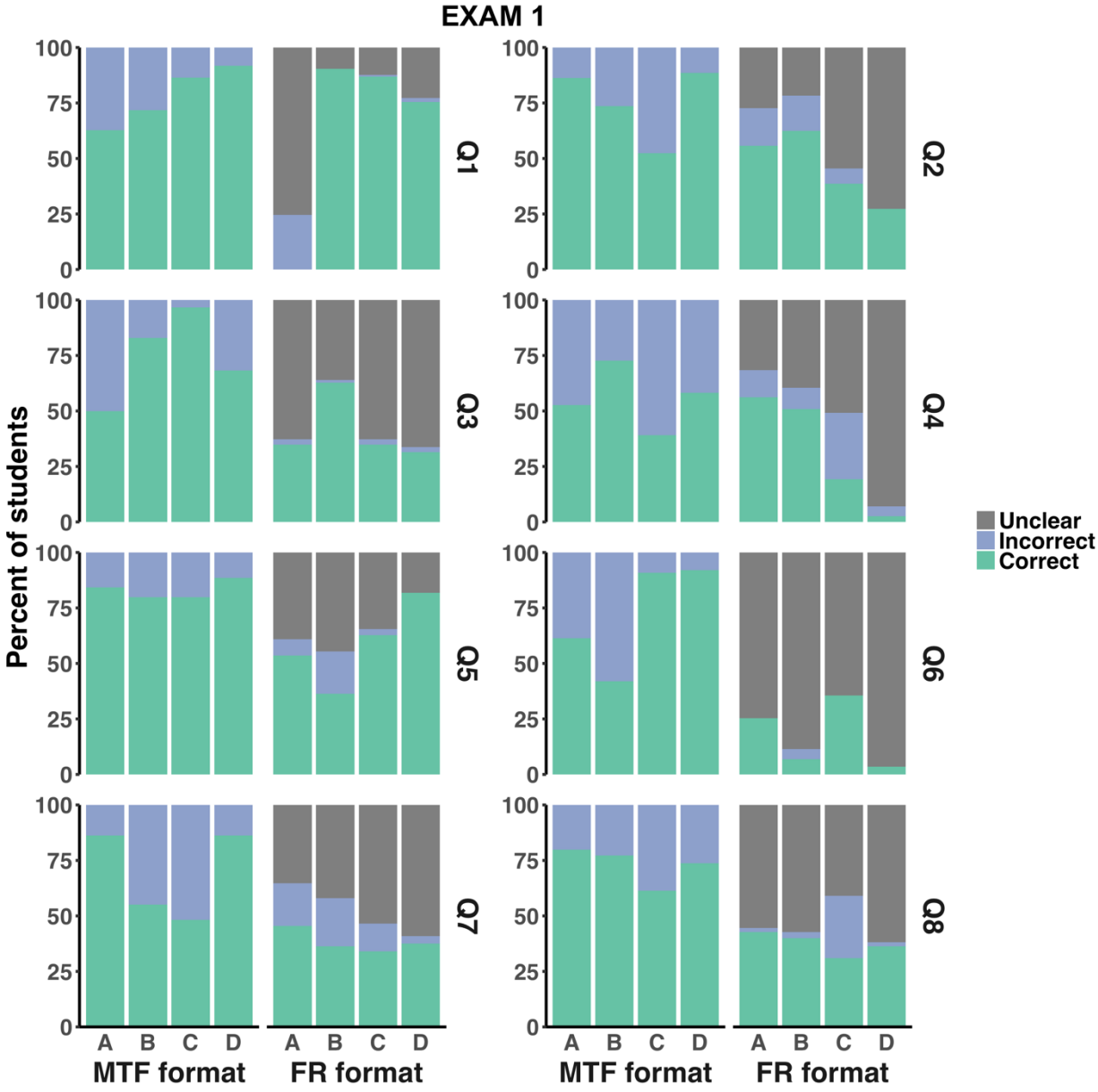
Additional notes:

- A T statement could often be changed to be F, when needed. For example, statement B could read: “forward and reverse reactions continue.” This was particularly useful when statements include directionality (i.e., greater than, increase, etc.).
- In some instances, when the students did not directly address a conception, the coders could infer their answer. For example, in the above examples, the first student states, “the reactants and products are equal.” From this, the coder inferred a correct response to statement D because the presence of both reactants and products indicates that not all reactants have been converted to products.

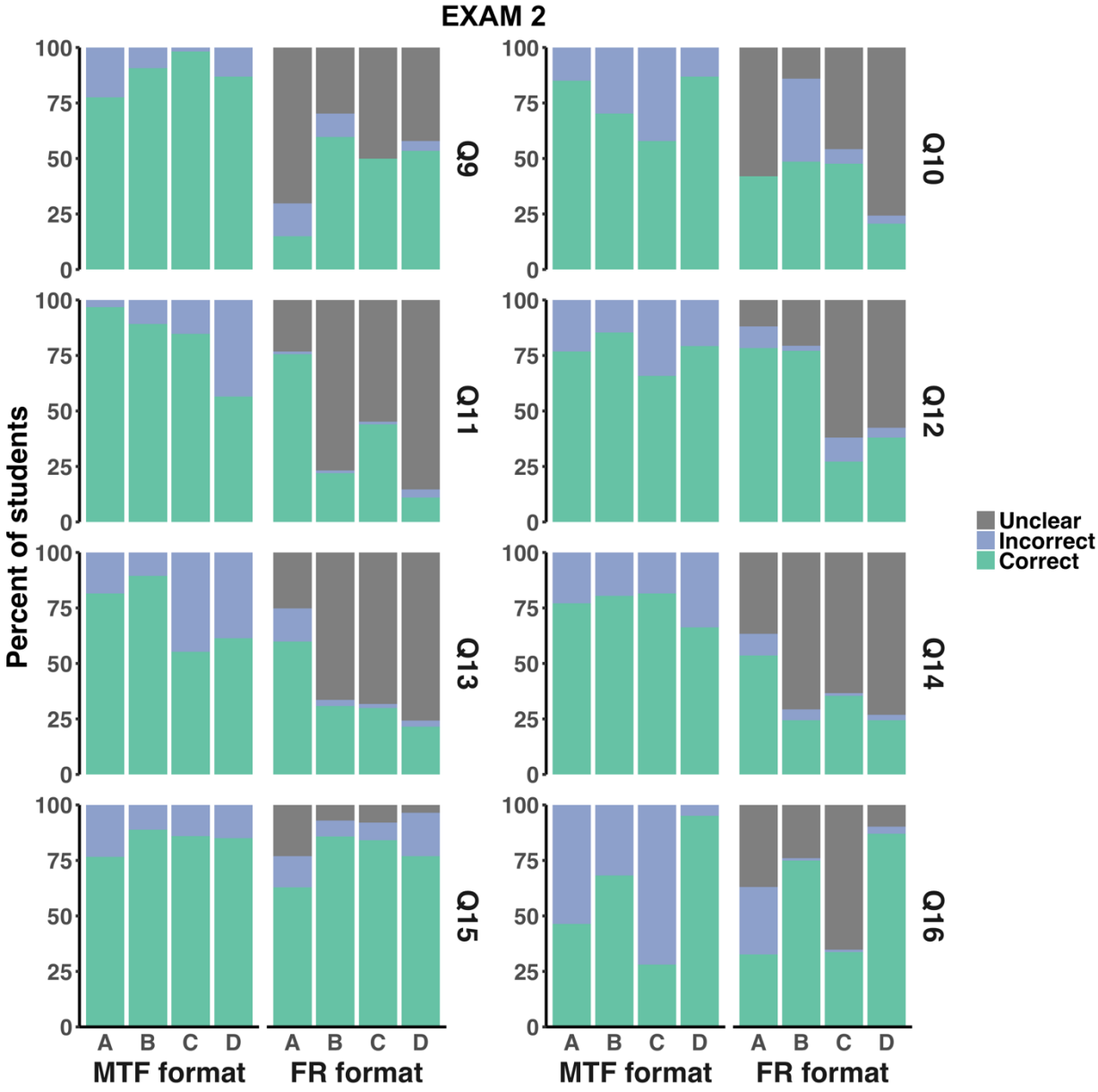
Supplementary Figure 1. Student performance on control questions across exam versions (A-D) for each of the four unit exams. Central bars represent medians, boxes represent inner quartiles, and whiskers represent the 5th and 95th percentiles.



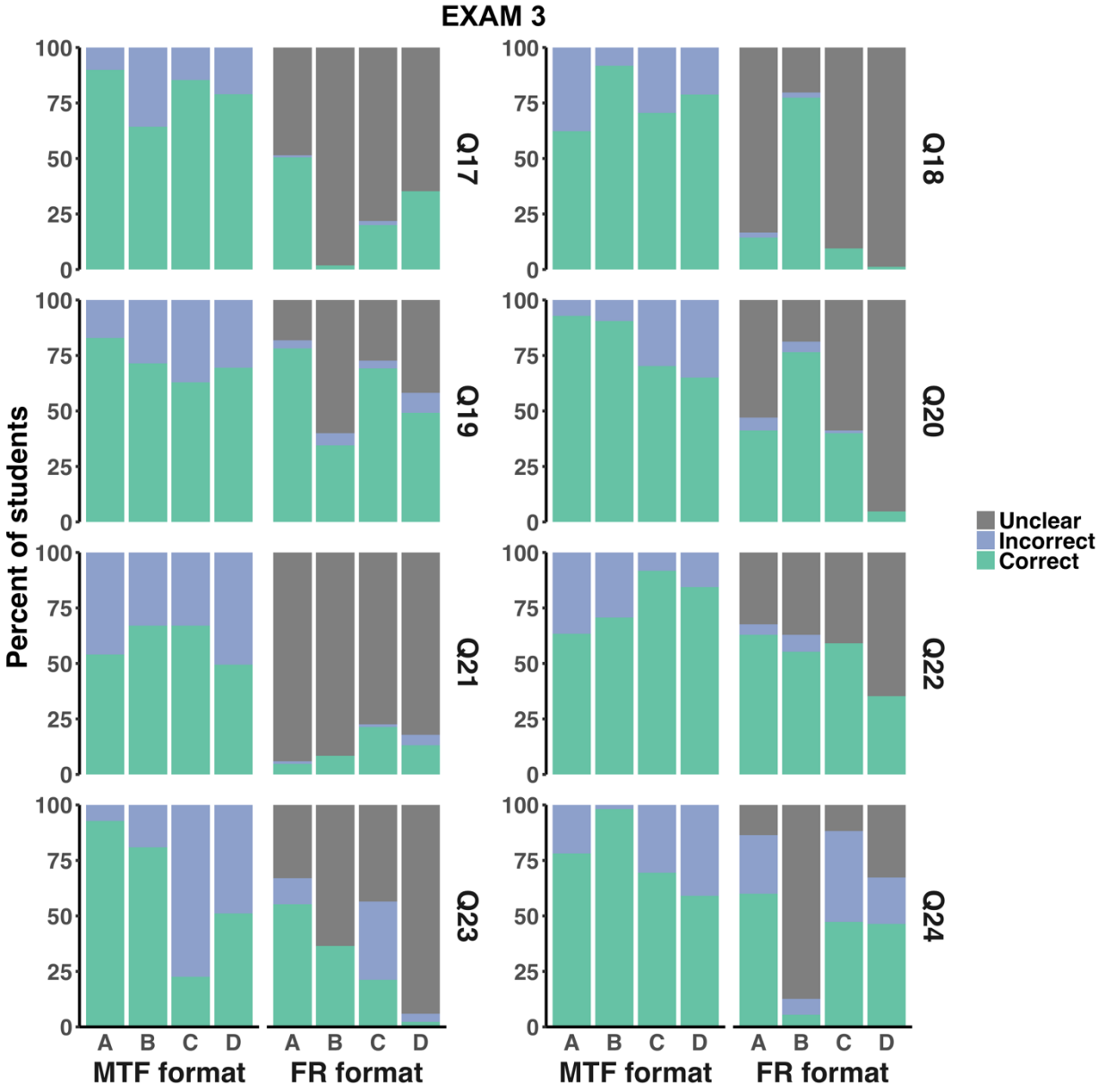
Supplementary Figure 2. Side-by-side comparisons of student responses in MTF and FR format for all the experimental questions that appeared on exam 1.



Supplementary Figure 3. Side-by-side comparisons of student responses in MTF and FR format for all the experimental questions that appeared on exam 2.



Supplementary Figure 4. Side-by-side comparisons of student responses in MTF and FR format for all the experimental questions that appeared on exam 3.



Supplementary Figure 5. Side-by-side comparisons of student responses in MTF and FR format for all the experimental questions that appeared on exam 4.