Chapter 2
Identifying and Developing Students' Ability to Reason with Concepts and Representations in Biology

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Introduction

Life scientists are highly dependent on the use of external representations (ERs) and symbolic language to research and teach modern biology (e.g., Tsui & Treagust, 2003), particularly at the submicroscopic level in areas such as biochemistry, physiology, molecular biology, and immunochemistry. At this level of cellular organization, the abstract nature of molecules and cellular processes necessitates the use of ERs or visualization tools such as physical models, diagrams, micrographs, computer images, animations, and other symbolic language to help learners and researchers construct meaningful mental models (or internal representations within the *mind's eye*) of biological concepts and phenomena (Schönborn & Anderson, 2006).

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However, the frequent use of misleading symbolism, the great variation in ER design quality, and the poor methods of teaching and learning with ERs often lead to conceptual, visual, and reasoning difficulties that can seriously affect students' understanding of biology (Schönborn & Anderson, 2010). Thus, there is an urgent need to investigate such problems so that student difficulties can be prevented or remediated and so that better quality and more standardized ERs become available to biology education practitioners and researchers.

In this chapter, we describe a conceptual-reasoning-mode (CRM) model (Schönborn & Anderson, 2009) of seven factors affecting students' ability to interpret and learn from ERs. Using the model, we classify various reasoning abilities described in the literature and illustrate how the model can guide student interpretation of an ER. We also show how the model can guide the design and validation of assessment tasks aimed at developing (formatively) and assessing (summatively) students' reasoning ability. We then describe various student difficulties and show how the model can be used as an analytical tool for identifying the nature and source of the difficulties and for designing potential remediation strategies for addressing the difficulties. We conclude by discussing the implications of our research for improving learning and teaching with ERs in biology.

Description of the CRM Model

Our research has empirically identified a predictive model of seven factors that affect students' ability to interpret, visualize, and learn from ERs in a biochemistry context (Schönborn & Anderson, 2009). We have shown that the factors are interdependent in nature and meaningfully expressed as a Venn diagram (see Fig. 2.1).

The conceptual factor (C) represents a student's conceptual knowledge of relevance to an ER, whereas the reasoning factor (R) represents all the reasoning (sense-making) abilities necessary for interpreting an ER. The representation mode factor (M) characterizes the external nature of the ER, including its constituent symbolic markings. As depicted by the Venn diagram (see Fig. 2.1), these three factors are interdependent generating four further interactive factors. This is because students cannot engage their repertoire of reasoning abilities without something to reason with, that is, with the ER (represented by factor R-M) and/or with their conceptual knowledge (factor R-C). In addition, all ERs represent some form of scientific propositional knowledge represented by factor C-M of the model. Finally, interpretation of an ER through engagement of all these factors can be represented by the C-R-M interactive factor.

In this chapter, we demonstrate how the CRM model can be used by biology instructors as a very useful guiding framework and analytical tool in a variety of important applications, particularly with respect to the identification, the development and assessment of student reasoning, and the remediation of any related difficulties.

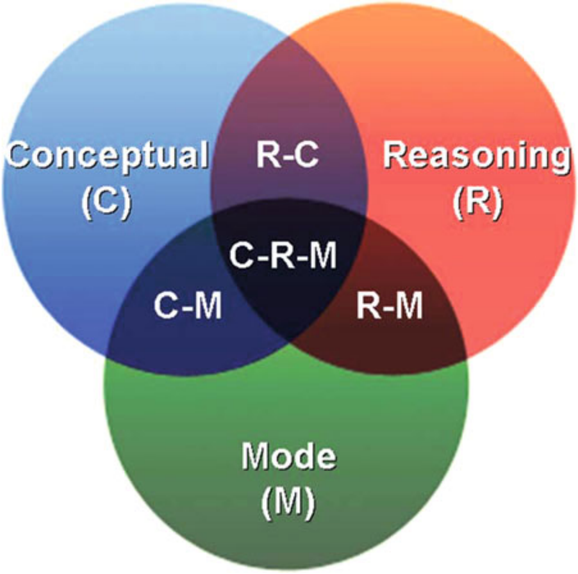


Fig. 2.1 The CRM model of seven factors affecting students' ability to interpret and visualize ERs in biology (Adapted from Schönborn & Anderson, 2009)

Using the CRM Model to Classify Expert Ways of Reasoning

In a recent synthesis of the literature (Anderson & Schönborn, 2008; Schönborn & Anderson, 2010), we identified several key ways of reasoning employed by experts in the practice of biology. In Table 2.1, we classify these cognitive skills according to the CRM model, that is, according to whether they, in our view, correspond to factors R-C or R-M.

There are several important points to note regarding the skills and their classification. First, this is far from an exhaustive list of reasoning abilities, as the literature describes numerous others, particularly those abilities concerning the practice of biological experimentation such as designing experiments, testing hypotheses and using appropriate controls, or technical and practical skills (e.g., Quentin-Baxter & Dewhurst, 1992). Second, research has shown that some of the listed skills are at different levels of inherent difficulty for students. For example, students find memorization of information (see Table 2.1, A1) much easier than transfer and application of knowledge (A3) (Mayer, 2002), and decoding symbolism in a single diagram not as difficult as horizontal translation across multiple representations of the same phenomenon (Schönborn & Bögeholz, 2009). Third, clearly not all the skills (see Table 2.1) can be exclusively classified according to only one factor, as several of the skills may be applied both in the *mind's eye* (R-C) in the absence of an ER, and directly to an external representation (R-M). For example, experts can reason analogically (A4) both with or without an ER, whereas integration of knowledge (A2) can involve linking concepts

Table 2.1 Selected reasoning abilities classified according to the CRM model, central- to expert-level conceptual understanding and visualization of representations

A. Some examples of reasoning with concepts (classified as R-C)
Understanding a concept means the ability to:
1. Memorize knowledge of the concept in a mindful manner, as distinguished from rote learning
2. Integrate knowledge of the concept with that of other related concepts so as to develop sound explanatory frameworks
3. Transfer and apply knowledge of the concept to understand and solve (novel) problems
4. Reason analogically about the concept
5. Reason locally and globally about the concept (systems thinking)
6. Think metacognitively about the concept
B. Some examples of reasoning with ERs (classified as R-M)
Understanding a representation means the ability to:
1. Decode the symbolic language composing an ER
2. Evaluate the power, limitations, and quality of an ER
3. Interpret and use an ER to solve a problem
4. Spatially manipulate an ER to interpret and explain a concept
5. Construct an ER to explain a concept or solve a problem
6. Translate horizontally across multiple ERs of a concept
7. Translate vertically between ERs that depict various levels of organization and complexity
8. Visualize orders of magnitude, relative size, and scale

Adapted from Schönborn and Anderson (2010), Anderson and Schönborn (2008)

both in the *mind's eye* or while reasoning with a concept map. It is likely though, given the visual nature of biology, that even in cases where no ER is present, at least a mental model is involved in facilitating the reasoning process. Fourth, in some cases there is clearly a logical sequence for using reasoning skills. For example, knowledge cannot be integrated (A2) before key information has been memorized (A1), and both these reasoning processes need to precede higher-order reasoning such as problem solving (A3), analogical (A4) and systems thinking (A5), as well as any metacognitive activity (A6). Finally, and related to the above, it will become apparent, based on the examples of assessment tasks and student difficulties presented in this chapter, that more than one reasoning skill is always simultaneously engaged by biologists when ERs are being interpreted.

So the question arises: What is the purpose of dividing biological reasoning into separate skills? Why not study reasoning as an integrated process as it clearly occurs in this manner? The answer is simple—by distinguishing the different ways of reasoning, we are more easily able to identify the nature and source of specific reasoning difficulties and to devise ways of remediating them. In the following sections, we show how the CRM model, together with knowledge of the different reasoning abilities, can be used as an analytical tool for (1) guiding student interpretation of ERs, (2) identifying the unique nature and source of specific reasoning difficulties with ERs, and (3) devising approaches to remediate and develop student competence in these areas.

Using the CRM Model to Guide the Assessment and Interpretation of ERs

After the identification of the various cognitive skills that we considered central to biologists, the next step was to devise approaches to developing such competencies in students as part of formal biology curricula. In previous studies (Anderson, 2007; Schönborn & Anderson, 2008, 2010), we advocated the idea of assessment-driven development of conceptual understanding, including reasoning with concepts and representations. This idea stemmed from the crucial and reciprocal relationship that exists between the four key components of the educational process, namely, course objectives, teaching, learning, and assessment (Anderson, 2007). In line with this relationship, the *how* and *what* of assessment informs how and what students will focus on during learning—the idea of *learning to the test*! Based on this, we argue that specifically designed tasks, which focus on each of the reasoning abilities, as shown in Table 2.1, could be effective at both developing (formatively) and assessing (summatively) students' reasoning ability in biology. The approach involves giving students repeated practice at performing such tasks that specifically require them to use the particular visual skill that requires improvement.

To ensure that we developed sound assessment tasks—that specifically required students to reveal their conceptual understanding and reasoning ability with concepts and representations—we used (1) the guidelines presented in Anderson and Rogan (2010, p. 56), (2) the cognitive skills listed in Table 2.1 of this chapter, and (3) the CRM model to devise guidelines for assessment design. These guidelines are presented in Box 2.1. The guidelines provide criteria that correspond to each factor of the CRM model that instructors might wish to use to ensure that the tasks are both sound and focus specifically on assessing conceptual understanding and reasoning ability with representations. Establishing whether students have the necessary prior conceptual knowledge (factor C) that corresponds to the scientific propositional knowledge represented by the ER (C-M) is important because research has shown that one cannot assume that what students have studied in previous courses was necessarily learned. It is also essential to ensure that the ER is a sound representation (M) of the intended propositional knowledge (C-M). Also that such knowledge is appropriate for the course being taught and that it is of a suitable standard for the educational level so that it is neither too cognitively demanding for the students nor too easy for them (Anderson & Rogan, 2010). Finally, and most importantly for the present goals, each task must require students to use certain cognitive skills (R) so that a range of intended tasks can be designed to cover all reasoning abilities (see Table 2.1).

We are currently testing these guidelines by developing a wide range of tasks for use in various biological science disciplines, some examples of which are also included in this chapter in the section on student difficulties. We are also classifying and validating the tasks using the CRM model as an analytical tool. This is both from the perspective of expert opinion of what reasoning abilities are being tested and, most importantly, from a student perspective to ascertain if student response data can be coded for both R-C and R-M categories as well as for subcategories of reasoning abilities and any related reasoning difficulties. An example of such a task

Box 2.1 Guidelines for Designing and Analyzing Conceptual Assessment Tasks Involving Representations (ERs) Based on the CRM Model of Schönborn and Anderson (2009)

Factor C:

- Do students have the necessary prior conceptual knowledge to interpret the ER and answer the question?
- Will the task test and reveal evidence of both sound conceptual knowledge and any alternative conceptions in students?

Factor R:

- Will the task test and reveal evidence of students' reasoning skills and difficulties?
- See also subsets, R-C and R-M, below.

Factor M:

- How well or poorly does the ER represent the intended phenomenon?
- Do you think the ER and its constituent symbolism will be clear and not too complex for the students to understand?
- Do you think the ER will help the student to answer the question?

Factor R-C:

- Will the task test students' cognitive skills required for scientific reasoning?
- Will the task reveal evidence of students' cognitive difficulties?
- Which cognitive skills are being tested by the task?

Factor R-M:

- Will the task test students' visual skills (representational competence)?
- Will the task reveal evidence of students' visual difficulties?
- Which visual skills are being tested by the task?

Factor C-M:

- What propositional knowledge is represented by the ER and required for answering the question? That is, what specific concept(s) is the question designed to probe?
- Is the propositional knowledge appropriate for the educational level of the course? That is, is the extent and complexity of the required knowledge not too cognitively demanding?

Factor C-R-M (can students master the assessment task?):

- Does the task test students' conceptual understanding?
- Does the task allow for a range of scientifically correct (creative) answers?

(continued)

Box 2.1 (continued)

- Does the task probe students' ability to interpret, visualize, and learn from the ER?
- If the task reveals student difficulties interpreting the ER, check whether soundness of an ER (M), prior conceptual knowledge (C) or cognitive skill competence (R), is limiting.
- Is the instrument suitable as a formative task for promoting students' conceptual understanding and learning during the course?
- Is the instrument suitable for grading students' conceptual understanding?

is presented in Box 2.2 together with an analysis of the task using the CRM model to suggest, from an expert perspective, what reasoning abilities (see Table 2.1) might be required for students to answer the question.

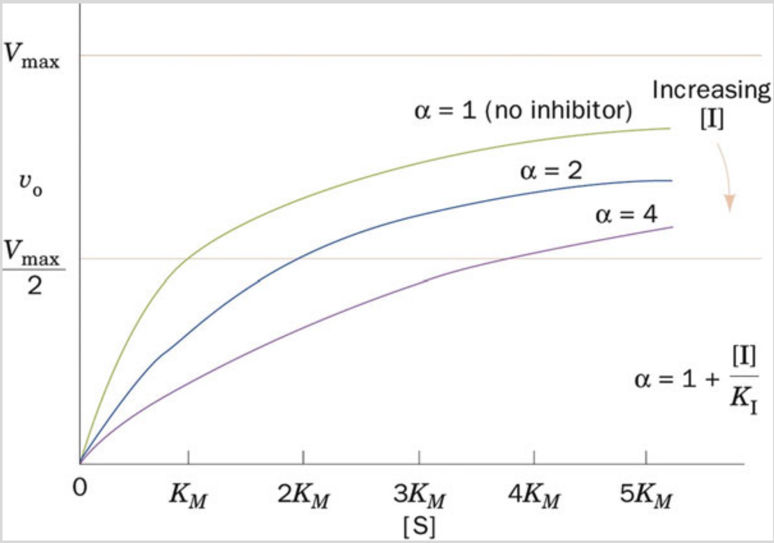
On examining the example in Box 2.2, one is struck by the enormous amount of conceptual, symbolic, and strategic knowledge that we as instructors require students to master in order to merely interpret a single ER. This suggests the importance of clearly explaining ERs to students and giving them sufficient time to interpret them. As can be seen by the structure of the question in Box 2.2, the student is guided to link to all the critical concepts (C-M) that are important for interpreting the graph. Then, they are required to use Table 2.1 to identify which ways of reasoning (R) they think are necessary to use their conceptual knowledge (R-C) to make sense of the ER (R-M). In addition, they need to think of other representations of the kinetic experiment depicted by the graph (horizontal translation) (see Table 2.1, B6) in order to obtain greater insight into the nature and purpose of the experiment and the underpinning molecular processes. They also need to translate vertically (see Table 2.1, B7) (Schönborn & Bögeholz, 2009) to place the kinetic process being studied in the context of a living system. In so doing, they achieve a deeper analysis of the graph.

We have found that using the CRM model as an analytical tool to systematically and separately consider the various critical concepts, ways of reasoning (see Table 2.1) and related representations of relevance to the ER can significantly facilitate student interpretation of ERs. Although this remains to be confirmed by research, in our experience this approach gives students some sort of meaningful structure for making sense of an ER rather than the somewhat random manner used by some students. In this regard, our studies on secondary-level biology students' interpretation of a diagram of the thermoregulation process showed that students often completely ignored certain symbolism (e.g., arrows) or parts of an ER in attempting to interpret an ER (du Plessis, Anderson, & Grayson, 2003). In response to this problem and several other student difficulties with symbolism and ERs, we developed a strategy and tutorial for developing students' ability to interpret arrow symbolism in biology diagrams. Implementation of the strategy and tutorial in a small-scale study involving 18 grade 9 students resulted in significant improvement in the ability of some students

Box 2.2 An Example of the Use of the CRM Model as an Analytical Tool to Guide ER Interpretation

Interpret the graph below in as much detail as possible by doing the following:

1. List (C-M) and explain (C) the biochemical concepts related to the graph.
2. List and explain the experimental and mathematical concepts related to the graph.
3. List other ERs that represent the same phenomenon (e.g., equation, apparatus, models).
4. Use the supplied list of reasoning abilities (R; Table 2.1) to identify which:
   (a) Cognitive skills are required to make sense of the graph (R-C).
   (b) Visual skills are required to make sense of the graph (R-M).
   (c) Explain how you use each reasoning ability (a and b) to interpret the graph (C-R-M).
5. Describe the method a biologist would use to collect the data represented in this graph.



An example of a possible (brief) answer:

1. Biochemical concepts include enzyme, substrate, inhibitor, active/binding sites, and affinity.

(continued)

Box 2.2 (continued)

2. Mathematical/graphical concepts include V_{max}, K_m, K_{cat}, K_i, dependent and independent variable, constant, concentration, reaction velocity, and saturation curve versus linear relationship.
3. Other related ERs: experiments, equipment (macro level), double reciprocal plot, table of plotted data, Michaelis-Menten equation and formulas, visual competitive inhibition models, animation of enzyme substrate interaction, and qualitative illustration of near-equilibrium (reversible) reactions versus far-equilibrium (irreversible) reactions.
4. (a) Memorize, analyze, transfer, integrate, systems thinking, and analogical reasoning.
   (b) Decode, horizontal/vertical translation, construction, interpretation, transfer, and apply.
   (c) This is a graph depicting the effect of increasing concentrations of a competitive inhibitor (as compared to no inhibition) of an enzyme-catalyzed reaction occurring at constant enzyme concentration. The kinetics profile is typical of all competitive inhibition situations occurring in cells.
5. Set up the enzyme assay under optimal conditions of temperature, pH and ionic strength. Set up tubes with a range of concentrations of substrate up to 5 times the value of the enzyme's K_m for that substrate. Add a fixed concentration of enzyme to each tube, mix gently and incubate for a fixed time period. To determine the initial velocity, measure the disappearance of substrate, or the appearance of product, at two early time periods, for example at 15 and 45 secs. Plot the results on a Michaelis-Menten curve. Repeat the experiment but at 2 different inhibitor concentrations and plot these data on the same curve.

to interpret arrow symbolism in a nitrogen cycle diagram (du Plessis & Anderson, 2009). This strategy contained several similar elements of the proposed CRM-guided strategy in that students are required to systematically analyze each part of a diagram and identify and interpret the meaning of all the constituent symbolism.

Using the CRM Model to Analyze Student Difficulties for the Nature and Potential Source of Unsound Reasoning

In this section, we present some selected examples of student reasoning difficulties to provide further support for the importance of formally teaching scientific reasoning as part of all biology curricula. These examples were identified by our research group in different areas of biology and classified according to the CRM model and the reasoning abilities presented in Table 2.1.

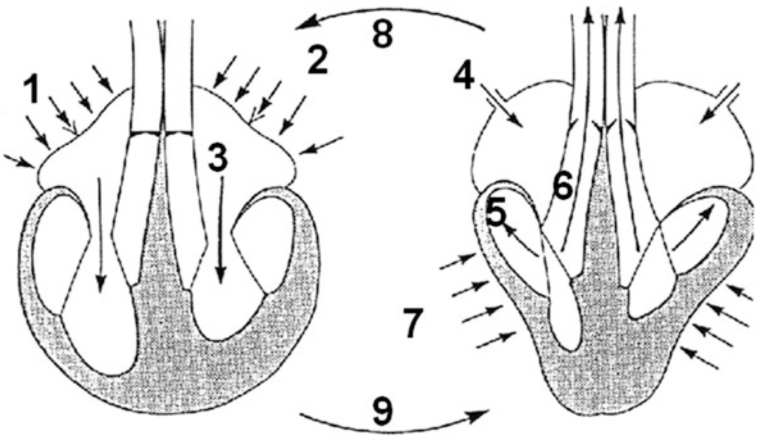


Fig. 2.2 A stylized diagram of the cardiac cycle (Wright, 1989, p. 55) (Reprinted with permission)

Reasoning Difficulties with an ER of the Cardiac Cycle

The following diagram (see Fig. 2.2; Wright, 1989) depicting the cardiac cycle was used in a study by our group to investigate secondary-level students' interpretation of arrow symbolism (du Plessis et al., 2003). The diagram, without its labels and caption, had previously been used in a biology examination at a secondary school in South Africa.

Extensive data obtained from open-ended and multiple-choice questions, as well as student-generated diagrams and clinical interviews, revealed evidence of a range of major student difficulties with their interpretation of the various arrows in the diagram. Regarding arrow 1, 39% of students interpreted it as blood entering the atrium rather than its intended purpose (as in the case of arrow 2) of indicating that blood could not flow into the closed atrium. In addition, 41% of students thought that the cluster of arrows on either side of arrows 1 and 2 represented pressure being applied to the outside of the atria causing them to contract, rather than simply indicating that the muscular wall of the atria was contracting. Regarding arrows 1 and 4, 36% of students did not see any difference in their intended purpose, suggesting that they thought both arrows show blood entering the atrium. Furthermore, many students did not recognize arrows 1 and 2 as being separate from their perceptual unit of similarly styled arrows. Whereas arrow 5 is intended to show blood pushing against and closing the tricuspid valve, 24% of students interpreted it instead as blood flowing out of the heart. Finally, 14% of students suggested that arrows 8 and 9 were part of blood flow.

Analysis of the above difficulties according to the CRM model suggests a problem with both the diagram or representation mode (M) and student reasoning (R). In the case of the diagram, the arrows are drawn in the same style but represent several purposes, including direction of flow (arrows 3, 4, and 6), direction of flow stopped by closed valves (arrows 1 and 5), alternating processes (arrows 8 and 9), and contraction (arrow groups 2 and 7). Similar problems have been noted by various authors (e.g., Ametller & Pinto, 2002) who reported that confusion can result when similarly styled arrows are used for different purposes (synonymy) or differently styled arrows for the same purpose (polysemy) (cf. Strömdahl, 2012). Thus, the issue of synonymy (corresponding to factor M of the model) as well as the number of arrows clearly contributes to the complexity of the diagram, and this was evident in various reasoning difficulties shown by students. Such difficulties probably included incorrect decoding of arrow symbolism (R-M; see Table 2.1, B1), incorrect interpretation of the ER (R-C; B3), inappropriate application of their knowledge of the cardiac cycle (A3), and inappropriate analogical reasoning (R-C and R-M; A4) about the ER—an analogical model of heart function. In addition, spatial reasoning (R-M; B4) might have been a problem in cases where students included arrow 1 together with the neighboring arrows as one perceptual unit.

Using the CRM model to classify the difficulty in the above manner leads to greater insight into the nature and possible source of the difficulty and permits the design of a more informed remediation strategy that specifically targets those reasoning abilities with which students have problems. Clearly in the above case this strategy would need to include ways of familiarizing students with the issue of synonymy and developing their ability to recognize and interpret diagrams with this problem, that is, to also improve students' ability to evaluate the quality and limitations (see Table 2.1, B2) of ERs. Alternatively, a different ER could be used to teach the cardiac cycle, but this will not solve the problem of the numerous other ERs with the same problem of synonymy.

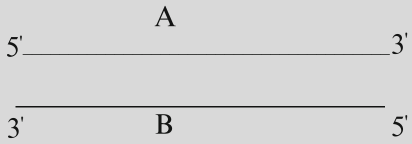
Reasoning Difficulties with Symbolism in Molecular Biology

Gupthar and Anderson (2003) investigated student difficulties associated with DNA-strand symbolism and function. Double-stranded DNA is composed of two antiparallel strands which are complementary in terms of base sequence and *run* $5' \rightarrow 3'$ in opposite directions. The two strands are labeled either *coding* or *template*, depending on their respective function. The coding strand is the strand of DNA within a gene whose nucleotide sequence is identical to that of the transcribed RNA with the replacement of T by U in RNA. The template is defined as the strand of DNA within a gene whose nucleotide sequence is complementary to that of the transcribed RNA (Scism, 1996). During transcription RNA polymerase binds to, and moves along, the template in the $3' \rightarrow 5'$ direction, catalyzing the synthesis of RNA in a $5' \rightarrow 3'$ direction. In DNA replication, which occurs semiconservatively, each DNA strand serves as a template for complementary DNA synthesis. The result is two molecules of double-stranded DNA, each of which contains one of the template strands. A typical question given to biochemistry students to probe understanding of this topic is presented in Box 2.3.

The following difficulties, coded as R-C (with italics font) or R-M (with regular font), based on student interviews, revealed that some students interchanged the DNA-strand labels and thereby failed to differentiate between the functions of the template and coding strands:

Box 2.3 An Example of a Typical Probe for Symbolism in Molecular Biology

The following is representative of double-stranded (ds) DNA:



1. Name strands A and B and explain why you named them as such.
2. (a) Which strand(s) is/are implicated in:
   (i) Replication?
   (ii) Transcription?

   (b) Explain why in each case.

> A is the leading strand. *Replication occurs in a 5′→3′ direction within a replication bubble or fork*. There is a problem with the polarity of B, *resulting in the formation of Okazaki fragments*, thus B is the lagging strand.
>
> A is the leading strength [strand] *because nucleotides move from a 5′→3′ direction*. B is the lagging strand *because nucleotides move from a 5′→3′ direction.*
>
> A – leading strand. It begins from 5′→3′ left to right. B – lagging strand. It forms in the opposite direction to the leading strand and therefore it is from right to left in the 5′→3′ direction.

Analysis of these difficulties with the CRM model revealed various reasoning difficulties. First, the reference to *leading strand, lagging strand*, or *Okazaki fragments* clearly demonstrates a substitution of DNA-strand labels with nomenclature associated with DNA replication intermediates. This suggests a problem with decoding the symbolism (R-M; see Table 2.1, B1). Furthermore, students failed to transfer (R-C, A3) the appropriate knowledge to each strand to identify its function, thereby failing to correctly interpret (R-M, B3) the ER.

Reasoning Difficulties with an ER of the Structure of Immunoglobulin G (IgG)

We have reported elsewhere a wide range of difficulties shown by biochemistry students when interpreting textbook diagrams of immunoglobulin G (IgG), which included the following ER (see Fig. 2.3) (Schönborn, Anderson, & Grayson, 2002).

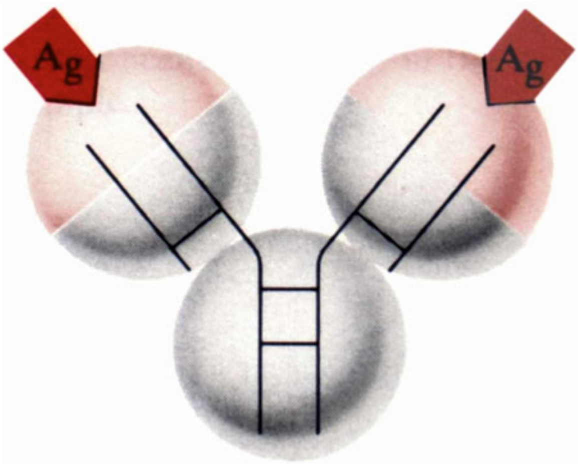


Fig. 2.3 Stylized diagram of the three-dimensional structure of an IgG antibody molecule (Reprinted with permission from Pearson Education, Inc., Upper Saddle River, NJ 07458, USA)

The following are selected examples of difficulties identified in interviews related to the interpretation of Fig. 2.3 which we coded in italics font for R-C and in regular font for R-M:

> *Heavy and light chains and [with] H-bonds between them.*
>
> Black lines [are] some form of bond or attachment holding the 3 cells together- *blood cells, biconcave type shape.*
>
> The colored (grey) region represents *different amino acid residues attached to the backbone* (black line) *of the antibody.*
>
> *Cell (C), cell division takes place, two cells (V) are formed. Cell C old mature structure attaches 2 cells with black lines or bonds. Young immature cells (V) are attacked by Ag.*
>
> This is meant to represent *a DNA molecule, leading strands and a lagging strand of DNA...*
>
> It looks like *a new replicating strand of DNA. Ja [yes]... it is nucleotide synthesis...*

Analysis of these difficulties using the CRM model as a guide suggests that the major problem was an incorrect decoding of the symbolism (R-M; see Table 2.1, B1) in the diagram, incorrect interpretation (R-M, B3), as well as inappropriate transfer and application (R-C, A3) of knowledge from biological domains concerning blood cells, cell division, and DNA replication (R-C, A3; and R-M, B6). In addition, there is also an analogical reasoning problem (R-C, A4) stemming from a diagram that poorly represents the intended protein structural information. Once again a remediation strategy would be designed to specifically address these reasoning difficulties so that students would improve their ability to evaluate the quality and limitations (R-M, B2) of ERs.

Reasoning Difficulties with Metabolic Pathways Occurring in Cells

Hull (2004) performed a study in our group on students' mental models of various biochemical processes. Data collection consisted of audiotaped interviews as well as

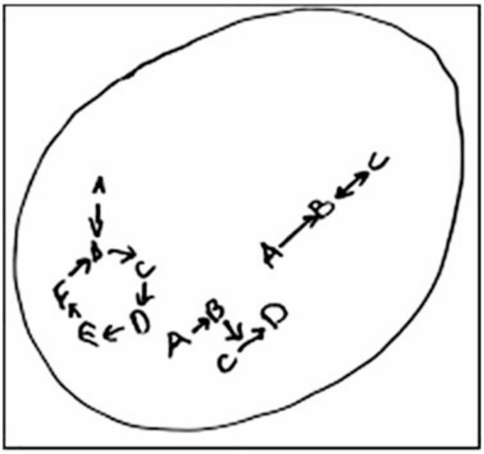


Fig. 2.4 A biochemistry student's representation of various biochemical processes occurring in vivo

student-generated diagrams in which students were asked to draw what they were visualizing. All interviews were in English and transcribed verbatim. The following are examples of such data which we have coded in italics for R-C and regular font for R-M:

I: Ok, let's say that we're sitting in the cytoplasm and we can see a cyclic process, for example the TCA cycle, happening in front of us, describe what you think that will look like.

S: Aah, I think they [metabolic constituents] would be going in a circle in front of me *and you'll have products and various substances going off into the rest of the cell* and ja [yes], it would be going round and round.

I: Ok, and what about a linear process?

S: Linear processes occur in a straight line. Linear processes occur at 180° in any direction... and occur vertically or horizontally.

I: Ok, let's come out of that cell and imagine we're looking at that same cell through a very powerful microscope, draw a rough outline of the cell and the processes you saw in the cytoplasm.

S: [draws cell outline in Fig. 2.4].

The above data represents a clear case of inappropriate horizontal translation (R-M; see Table 2.1, B6) from a typical textbook ER of metabolic pathways to how students imagine such processes would look in the cell. It is a typical case of literal interpretation (R-M, B3) and incorrect decoding (R-M, B1) of diagrams and demonstrates that students with this difficulty did not transfer (R-C, A3) their earlier acquired chemical knowledge of collision theory and kinetic energy of molecules to the cellular scenario. This led to the construction (R-M, B5) of an inappropriate ER based on an unsound mental model. Vertical translation (R-M, B7) was also a problem as students attempted to *move* from the molecular level to the cellular level. Thus, in summary, any remediation strategy would need to focus on developing a range of reasoning abilities in students—including the transfer and application of knowledge; the decoding, interpretation, and construction of ERs; and the horizontal and vertical translation across such ERs.

The above examples of student difficulties with representations, alongside numerous other examples in the literature, constitute strong evidence for the importance of addressing such difficulties, either through the devising of remediation strategies or by improving or replacing a specific ER. That is, in our view, course curricula, teaching and assessment approaches, learning activities, and pedagogical content knowledge need to be informed and shaped by the representations we use to educate biology students. Possible approaches are discussed in the next three sections.

Application of the CRM Model to the Design of Remediation Strategies

Since students in our studies showed such a wide range of conceptual, reasoning, and visualization difficulties with representations, there is clearly an urgent need to address the remediation and/or prevention of such difficulties in course curricula. In this section we present an example of three related difficulties in the context of metabolism and briefly show how we used the CRM model to both analyze them and design a remediation strategy that successfully addressed the difficulties.

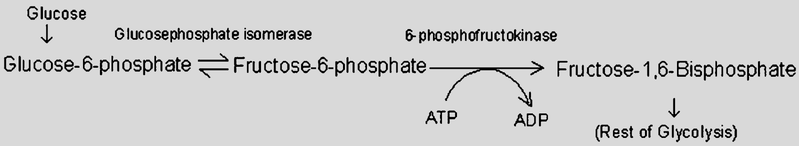
Box 2.4 contains an example of a typical question which we gave to biochemistry students to probe their reasoning difficulties with metabolism (Grayson, Anderson, & Crossley, 2001). In this particular study, we also used more focused probes and interviews to delve deeper into the nature of the difficulties.

The expert response (Box 2.4) was analyzed by the CRM model and the results used to guide the coding of student responses with respect to the types of reasoning we could expect when answering the question. Clearly all questions require memory (R-C; see Table 2.1, A1) of numerous critical concepts concerning the functioning of metabolism which students need to transfer from various contexts (mainly chemistry) and apply (R-C, A3) to the context of metabolism. They also need to integrate (R-C, A2) such concepts in order to establish a sound explanatory framework for interpreting the ER (R-M, B3) and answering the question. In addition, question 2 requires systems thinking (R-C, A5) in that there is a need to consider the influence of the inhibition on other reactions in the pathway. Furthermore, questions 1 and 3 require horizontal translation (R-M, B6) from the equation of the inhibited reaction to an ER of its mechanism in order to fully understand the effect of enzyme inhibition on the reaction. Question 1 also requires horizontal translation (R-M, B6) to activation energy diagrams to realize the key function of the enzyme as a catalyst under cellular conditions. Finally, analogical reasoning (R-M, A4) is also important in that the diagram is an analogical model of the real process occurring in cells.

The expert response and the above classification, using the CRM model, were used as a standard to code student responses with respect to sound and unsound ways of reasoning. The following are selected descriptions (quotes not shown) of three difficulties, revealed by the question in Box 2.4, which we termed Essential

Box 2.4 An Example of a CRM-Guided Assessment Task

Consider the following part of glycolysis functioning in a cell:



If 6-phosphofructokinase is totally and irreversibly inhibited by a toxic substance, explain what effect this would have on:

1. The conversion of fructose-6-phosphate to fructose-1,6-bisphosphate
2. The relative concentrations of intermediates before and after the inhibited reaction
3. The half-reaction for the conversion of ATP to ADP
4. The overall flux through glycolysis

Example of expert response:

1. The reaction will stop because the enzyme is an essential catalyst in the mechanism of the reaction, by stabilizing a high energy intermediate so that the reaction can occur under cellular conditions.
2. Both G-6-P and F-6-P will increase, while intermediates after the *point* of inhibition will deplete in concentration.
3. ATP will not be converted to ADP unless the enzyme facilitates the transfer of the phosphate from ATP to F-6-P in the active site.
4. The flux will decrease to zero as neither glucose is used nor pyruvate produced, because F-1,6-BP is no longer produced as a substrate for the next reaction.

Summary of CRM analysis of expert response:

R-C: Memory (A1), integrate (A2), transfer/apply (A3), systems thinking (A5), analogical reasoning (A4)

R-M: Decode (B1), interpretation (B3), horizontal (B6) translation

(E) Nature Difficulties due to students not being able to appreciate the indispensable nature of enzymes as key participants in the mechanism of metabolic reactions:

E_1: The inhibited reaction will proceed without enzyme, but at a slower rate.

E_2: One of a pair of half-reactions, coupled in parallel, can occur without the other.

E_3: An inhibited enzyme-catalyzed reaction will proceed because other factors override the effect of inhibition, such as whether the inhibited reaction is spontaneous (E_{3a}) in nature or is displaced from equilibrium (E_{3b}).

Analysis of students' written quotes that corresponded to the above descriptions revealed evidence of several different reasoning difficulties. First, students with E_1 difficulties had clearly rote learned (R-C, A1) the basic definition of an enzyme as a catalyst but did not remember its essential role in the mechanism of the reaction. Nor did they translate horizontally (R-M; see Table 2.1, B6) to activation energy diagrams to realize the key function of the enzyme. Thus, integration (R-C, A2) of the concept of an enzyme with other critical concepts—such as mechanism, kinetics and, in the case of E_2 with the concept of parallel coupling, bi-substrate reactions, and, for E_3 with equilibrium, Le Chatelier's principle, spontaneity, and exergonicity—was clearly poor, while their transfer and application (R-C, A3) of such concepts and principles to solving the problems was in many cases inappropriate. When using the diagram or representation mode (M) to answer the questions, some students incorrectly decoded the meaning of the straight arrow/curved arrow symbol used to depict parallel coupling and thought that ATP cleavage was not essential (E_2) for the reaction to occur. But the major reasoning difficulty across all three difficulties was a failure to translate horizontally (R-M, B6) to ERs concerning the enzyme catalytic mechanism of the reaction.

Thus, based on the above CRM-informed analysis of the difficulties, our remediation strategy was designed to specifically target the following reasoning difficulties: memory (see Table 2.1, A1), integration (A2,), transfer/application (A3), decoding of symbolism (B1), ER interpretation (B3), and horizontal translation (B6). The strategy was structured as a tutorial that included questions and tasks that specifically focused on the following:

- Critical concepts (e.g., spontaneity, chemical energy, chemical equilibrium)
- Integration of critical concepts composing an explanatory framework
- The essential nature of enzymes.
- The mechanisms of enzyme catalysis

In presenting the tutorial and the constituent tasks, we attempted to create a conceptual ecology and status that favored conceptual change as discussed by Duit and Treagust (2003) and others. In brief, we attempted to expose students to sound metabolism concepts and principles in the hope that they would find their new conceptions intelligible, plausible, and fruitful. Since students' lack of understanding and integration of the critical concepts was generic to all three difficulties, step 1 of the strategy was to address this problem with a concept-mapping task (cf. Schönborn & Anderson, 2008). The concept map (not shown) included the following concepts which we considered critical to the functioning of metabolism: *spontaneity*, *metabolic reactions*, *substrate*, *kinetics*, *coenzyme* or *cofactor*, *coupling*, *inhibitor*, *equilibrium*, *mechanism*, *thermodynamics*, *enzyme*, *energy*, and *ATP*.

Step 2 of the strategy was designed to specifically target the E_1-type difficulty by addressing integration (see Table 2.1, A2), transfer/application (A3), and horizontal translation (B6). This step required students to respond to tasks requiring them to:

- Determine which components (e.g., enzyme, coenzyme, cofactor, substrate) are essential for occurrence of metabolic reactions

Table 2.2 Results showing the effect of the remediation strategy on the incidence of student difficulties over a period of four consecutive years

Type of difficulty[a]	Percentage incidence and fraction of students showing each difficulty				
	No remediation		Before remediation	After remediation	Prevention[b]
Year	1	2	3		4
E_1	51%	48%	31%	2%	5%
	44/86	52/108	29/95	2/98	4/89
E_2	27%	53%	44%	1%	0%
	23/86	55/103	43/97	1/98	0/89
E_{3a}	30%	20%	34%	4%	1%
	26/86	23/118	32/94	4/98	1/89
E_{3b}	44%	16%	11%	1%	2%
	38/86	19/118	10/94	1/98	2/89

[a]See text for descriptions of each type of difficulty

[b]The remediation strategy was incorporated into the normal teaching process in an attempt to prevent the development of the student difficulties

- Determine what role each component plays in the mechanism of the reaction from analysis of various diagrams and an animation of an enzyme mechanism
- Use the kinetic graph (see Box 2.1) to compare the effect on reaction rate of reducing enzyme concentration to zero versus decreasing enzyme activity to zero by means of an inhibitor

Finally, step 3 targeted both E_2- and E_3-type difficulties by addressing reasoning concerning integration (A2), problem solving (A3), decoding (B1), and horizontal translation (B6) by requiring students to perform the following:

- E_2 tasks predicting the mechanism of reactions coupled in parallel (i.e., single mechanism)
- E_{3a} and E_{3b} tasks requiring application of knowledge of spontaneity, exergonicity, chemical energy, and equilibrium to metabolic reactions

As shown in Table 2.2, the revealed incidence of the difficulties was high for three consecutive years, whereas implementation of this strategy in the third year almost totally eliminated all the difficulties, while in the fourth year we were able to *prevent* the difficulties, rather than having to *cure* them.

In summary, our results suggest that the CRM model is a very useful analytical tool for identifying the nature of student reasoning difficulties and for developing more informed and better designed remediation and prevention strategies to address such difficulties. Since it might not always be feasible to design such a strategy for every difficulty, future work should focus on identifying more generic strategies that might be useful in addressing a range of related reasoning difficulties. Indeed, such strategies, if successful, could be incorporated into instructors' pedagogical content knowledge so that many of the difficulties are addressed in instruction rather than in remediation.

Conclusion

In this chapter we have shown that the CRM model can be extremely useful to biology education practitioners and researchers as a guiding framework and analytical tool for various aspects of the educational process. This includes using the model to guide the classification and assessment of reasoning abilities and to develop students' problem-solving strategies for interpreting ERs in biology. In addition, the CRM model is a valuable analytical tool for identifying the nature and potential source of students' reasoning difficulties with ERs and thereby for informing the design of remediation strategies for addressing the difficulties.

Like all models, the CRM model has limitations. In particular, the CRM-guided coding approach has revealed the following two problems concerning the analysis of quotes from student interviews: (1) the quotes do not reveal situations where students lack certain ways of reasoning and (2) the quotes do not always reveal all the types of reasoning being engaged by students, as this depends on the extent of their responses and therefore, to some degree, on the nature of probe design. Both these problems, though, can be minimized, respectively, by comparing student responses to multiple coded expert responses and by delving deeper into student reasoning during clinical interviews. The application of the presented examples of coding is also highly dependent on a complete list of reasoning abilities, whereas the nature of the reasoning displayed in students' quotes is not always lucid, which means that the coding is often subjective and requires validation by several experts.

Despite these limitations, we believe that the CRM model could become an important component of a biology education practitioner's and researcher's pedagogical toolkit, particularly in the area of scientific reasoning and visualization of external representations. Future work will focus on testing and validating reasoning tasks that could be used to both assess and develop reasoning in our students while at the same time yield data that enables instructors to monitor student progress. Ultimately, we believe that the teaching, learning, and assessment of reasoning ability should be integrated into all biology course curricula. Given that practical and technical skills are explicitly taught in all biology courses, there is no reason why we should not place the same emphasis on reasoning skills. This is because instructors cannot simply assume that these central skills will be automatically acquired through informal interactions with scientists and other students.

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