

A STUDY OF UNDERSTANDING:  
ALCHEMY, ABSTRACTION, AND CIRCULATING REFERENCE IN TERTIARY SCIENCE EDUCATION

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## ABSTRACT

### A STUDY OF UNDERSTANDING: ALCHEMY, ABSTRACTION AND CIRCULATING REFERENCE IN TERTIARY SCIENCE EDUCATION

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Understanding is widely touted to be of paramount importance for education. This is especially true in science education research and development where understanding is heralded as one of the cornerstones of reform. Teachers are expected to ‘teach for’ understanding and students are expected to ‘learn with’ understanding. This dissertation is an empirical study of the concept of understanding. After analyzing various constructions of understanding in current U.S. education literature, I suggest that understanding is defined by five distinct features—they are *knowledge (or knowledge base)*, *coherence*, *transfer*, *extrapolation*, and *cognition*—and that these features are heavily informed and shaped by the psychological sciences. This relationship is neither good nor bad, I argue, but it means that teaching for and learning with understanding are not heavily informed and shaped by, for example, the natural sciences. Drawing from historical, philosophical, and anthropological perspectives of science, but especially from the work of Bruno Latour, I enact a radical revision(ing) of psychological notions such as “abstraction” and “transfer.” The two main purposes of this re-visioning are (1) to draw critical attention to particular characteristics of a cognitive learning theory that emphasizes abstract concepts, and (2) to align many of the principles and tools used in science education more closely with those used in empirical scientific research. Finally, by bringing some examples of teaching and learning from an

undergraduate biology classroom into conversation with both psychological and empirical practices and perspectives, I suggest that problematizing the current construction of understanding creates much needed room in mainstream science education for more empirical forms of learning and styles of teaching. A shift to such forms and styles, I conclude, should prove to be more inclusive and less constraining for both students and teachers.

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For the always feisty and festive Cleo C., and for the always caring and supportive Sarah P...  
I am forever grateful to have known both of you.

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## INTRODUCTION

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### The Case of the Mutant Spinach Plant

I spent six years between 2004-2009 in and around a number of different undergraduate biology courses in the Great Lakes region of the United States. During this period, I gathered a wide range of experiences in STEM education. For instance, I logged over 240 hours of observation in undergraduate biology classrooms and another 50 hours in undergraduate biology laboratories; I attended no fewer than 200 lectures and had the opportunity to watch the interactions between a handful of college professors and almost 2000 undergraduate science majors; I sat through no fewer than 12 midterm and final exams; I trained a cohort of professors in the use of an instructional technology, iClickers<sup>®</sup>, a real-time technology designed to assess student learning and increase student engagement during class; I worked with an interdisciplinary team on the use of lexical analysis software to analyze student responses to open-ended questions pertaining to key science concepts; I spent nearly 40 hours interviewing undergraduate students about scientific concepts and principles; I recorded no fewer than 88 lectures on videotape; I logged well over 60 hours in planning meetings and discussions with course instructors outside of their classes; finally, I collected hundreds of digitally and non-digitally formatted instructional artifacts produced by the course instructors. Many of these hours were spent observing the day-to-day practices of two professors and nearly four hundred students in a cellular biology course, Biological Science 101 (hereafter “Bio101”).

## About Bio101

Bio101 is a large-enrollment, introductory-level science course required for science majors. All students wishing to major in biological, chemical, physical, earth, space or environmental sciences must successfully complete Bio101 in order to earn their bachelor degrees. At this university, Bio101 is also a required course for students enrolled in the university's preservice science teacher training program, as well as for undergraduate students enrolled in other 'pre-' programs, for example, pre-medicine, pre-veterinary, pre-nursing and pre-dentistry.

The presence of preservice science teachers in Bio101 is one of the main reasons I came to be involved in the course. In the early stages of my Teacher Education Ph.D. program, I received financial support from an initiative connected to the Carnegie Foundation's *Teachers For a New Era* (TNE) project. One of the guiding principles behind the TNE project was to encourage "top-level collaboration between university faculty in the arts and sciences with the school of education faculty to ensure that prospective teachers are well grounded in specific disciplines."<sup>1</sup> Working with diverse and experienced faculty from both the College of Education and the College of Natural Science, I participated in an grant-derived initiative whose explicit goal was to find and/or develop ways of improving teaching and learning in introductory-level undergraduate science courses in which preservice science teachers were known to be in attendance. The underlying question that motivated the TNE-supported initiative was this: In

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1. Michigan State University College of Education, "A New Model for Teacher Education," iii.

what ways can introductory-level undergraduate science courses more positively contribute to the preparation and production of a higher-caliber of K-12 science teachers?

It was under the auspices of the TNE-supported initiative that I first stepped into Bio101 with research responsibilities in fall 2004. And it was in that fall course that I first met the professors, both of who were veteran faculty members and experienced research biologists. My presence in Bio101 continued during summer 2005, where I worked with one of the professors in a truncated, six-week version of the course. In addition to continuing with research responsibilities, I was also the course teaching assistant and technology coordinator. In fall 2005 I again joined the two professors during the fifteen-week version of the course. Once again, I had responsibilities that included research and technological coordination. In fall 2006 I joined the professors for yet another fifteen-week instantiation of the course, but this time working in a tripartite capacity as researcher, technology coordinator, and laboratory section instructor. In fall 2007 I returned to the co-taught course for a final time with my responsibilities limited to research and instructional technological support. In total, I spent substantial time in five different instantiations of Bio101 between 2004-2007, with the most sizeable and continuous blocks of time occurring in summer 2005, fall 2006, and fall 2007.

Despite the occurrence of enough interesting moments around which one could assemble an entire career of research, for me there was one particular type of moment that stood out against the broader backdrop of this biology course. In this dissertation, I will simply refer to it as the *application moment*. The case of the mutant spinach plant is an instance of the application moment that occurred in fall 2006.

## The Application Moment

The most recognizable feature of the application moment is rather straightforward: Usually on high-stakes assessments (e.g., test or exams), but sometimes during class and on homework assignments, teachers or professors pose questions to students—application questions—whose defining feature is that they describe some sort of problem, situation, or phenomenon that students are likely to find entirely new, novel, or unfamiliar. The inclusion of these novel elements is both deliberate and purposeful. It is by design. Sometimes known in the trade as “twists,” “tweaks,” or “curveballs” (an American baseball reference), these unfamiliar elements are meant to make students hesitate, scratch their head, and even stumble (intellectual speaking). These elements are supposed to make answering the application question a less straightforward affair. Their intent is to purposely nudge students toward intellectual discomfort.

An example of an application question used in Bio101 appeared on Exam 2 as question “52.” The full text of the question can be seen in Figure 1.

52) Suppose you discovered a mutant strain of spinach in which the thylakoid membranes were slightly permeable to  $H^+$  ions, thus allowing a slow leakage (remember that in normal membranes,  $H^+$  is not permeable at all). What change in the reactions of photosynthesis might occur in compensation for this defect?

- A) cyclic photophosphorylation would increase
- B) non-cyclic photophosphorylation would increase
- C)  $O_2$  production would decrease
- D) cyclic photophosphorylation would decrease
- E) non-cyclic photophosphorylation would decrease

*Figure 1.* Question “52,” the Mutant Spinach Question, from Bio101 Exam 2 (fall 2006).

I came to know this particular application question through my conversations with the two Bio101 professors and their colleagues as “the Mutant Spinach Question.” Not having been present in the course, readers will have a difficult time recognizing the unfamiliar element, but nevertheless it, or rather *they*, are there. The unfamiliar elements are collectively held by the two phrases, “mutant strain of spinach” and “slow leakage.” Neither of these phrases had ever been used in the lectures, assigned readings, or homework assignments leading up to Exam 2. One of the Bio101 professors made this fact quite clear in a statement made to students just two days after the exam: “You’ve never heard about spinach with leaky membranes before. Right? I made that up...and I presented to you...and I’m asking you to apply your newfound scholarship to that, OK?”<sup>2</sup>

Here, we see one of the main reasons why I have decided to call the Mutant Spinach Question and others like it application questions (within application *moments*): the term comes straight from the language of the professors themselves.<sup>3</sup> In these moments, the Bio101 professors use specially designed questions that ask their students to apply their newfound scholarship to situations and problems defined by new, novel or unfamiliar elements. In the many hats I’ve worn in science education—teacher, instructor, teacher educator, professional development leader, curriculum designer, and researcher—I’ve heard these same questions called a half dozen or so names by their users and creators, for example, “real-world” questions, “transfer” questions, “reasoning” questions, “critical thinking” questions, “higher-order thinking” questions, “challenge” questions, “analytical” questions, “weeder” questions, and more.

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2. Lecture Transcript (October 18, 2006): 00:20:44 - 00:21:43.

3. One use of term *application question* can be traced back to the work of the American psychologist Benjamin S. Bloom (1913-1999) (see Bloom et al. 1956).

Although others are free to choose differently, my decision to call them application questions—instead of using one of those other aliases—is because I want to ground them in the language of the users, that is, in the speech of those in whose classroom I was ever-present.

One of the more interesting functions of many of the application questions used in Bio101, including the Mutant Spinach Question, is that the professors and their colleagues often used them to identify and classify certain kinds or types of students. For example, they sometimes used students' performance on application questions during their informal conversations with one another to talk about those students who 'got' the material or 'grasped' a concept versus those who didn't. On at least one occasion, the classificatory functionality of the Mutant Spinach Question was coupled with a predictive one: I once heard one of the Bio101 professors say of the Mutant Spinach Question, "I would love to know, could I just ask that question and give away our 4.0s?"<sup>4</sup> Although the professor made the statement to his colleagues with a full measure of humor in it, he also bestowed it with an equal measure of seriousness. He and others in the room genuinely wondered if there was in fact a strong correlation between those students who answered the Mutant Spinach Question correctly on Exam 2 and those who a) earned a top mark on Exam 2, and b) would end up earning a top mark in the course. More formally, the professors and their colleagues used students' performance on carefully crafted and/or selected collections or "clusters" of application questions to facilitate the grouping of Bio101 students into different categorical schemes. One such categorical scheme involved the diagnosis of students as having one of three types of difficulties: a) when "students interconvert matter and energy," b) when "students lose track of

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4. Instructor Interview (June 2007): 00:81:18-00:83:53.

matter when it becomes a gas,” and c) when “students do not follow matter and therefore do not catch obvious errors in their thinking.”<sup>5</sup>

For their part, the Bio101 students had their own names for such questions, including “hard,” “difficult” and “challenging,” and sometimes “tricky,” “unfair,” and even “deceitful.” This was certainly the case with the Mutant Spinach Question, a fact of which the professors were made only too aware of by way of a statistical exam report provided to them by a university scoring office. According to the report, eighty percent of the nearly four hundred Bio101 students present for Exam 2 in fall 2006 answered the Mutant Spinach Question incorrectly—only *twenty percent* of the students had selected the *correct* answer. Understandably so, this kind of statistic earned the Mutant Spinach Question some degree of notoriety and distinction among the instructors and many of their interested colleagues. It was the most missed question on Exam 2 and one of the most missed questions on any of the four semester exams. When the professors first saw that eighty percent of their students had missed the Mutant Spinach Question their disappointment was clearly visible. I could see in the expressions on their faces that they not only wanted more from their students—for example, more effort, more commitment, more studying, more hard work—but also more from themselves. And yet, they seemed rather unsure of exactly what to do in their role as facilitators, as experts, as teachers, as instructors...as professors. They were unsure as to how to go about trying to raise the percentage of their students able to answer the Mutant Spinach Question correctly.

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5. Wilson et al., “Assessing Students’ Ability,” 323-331.

A few months later, the professors knowingly and generously agreed to meet with me and revisit their disappointment to make it audible. In June 2007, I held a joint interview with them. The Mutant Spinach Question came up repeatedly during the interview, sometimes at my prompting, but more frequently because of their interest and volition. It was apparent to me by the end of the interview that both professors were still at a loss to explain with any confidence the high failure rate precipitated by the Mutant Spinach Question. At one point in the interview they explicitly asked me for help. More specifically, they asked for help in finding ways to improve student performance on these types of questions in the future. They said it was the one thing they wanted most out of their involvement and participation in a number of teaching- and learning-related research projects in which their course had assumed a central role. Once asked, I must admit I have felt duty-bound to try and honor it. At the time, I understood their request—as I still do—as a call for help to find ways to improve students' ability to apply existing knowledge to novel situations and unfamiliar events. Although the professors may not recall the moment with the same clarity and force as I do now, it should be clear to them and others that I took their request seriously. The work presented in dissertation is the culmination of the better part of six years of time and energy devoted to their request.

As a science educator, science teacher educator, and science education researcher, I am expected to pay close attention to moments in classrooms when things go poorly for teachers and/or students. Without a doubt, question "52" was a clear-cut case of an application moment gone wrong. Although the Mutant Spinach Question was just one of many application questions used by the Bio101 professors throughout the semester, it was one of the more dramatic examples of a instance in which learning did not unfold as planned. As such, the Mutant



Spinach Question assumes a significant role within this dissertation, but it is admittedly just one of many questions that could have assumed a starring role.<sup>6</sup> Although the Bio101 instructors invented the Mutant Spinach Question, they did not invent application questions. I know this because I have seen them used again and again in classrooms and curricula since first becoming involved in science education in the early 1990s. I have seen application questions used in primary, secondary, and tertiary science education; in preservice science teacher programs; and in professional development programs for more experienced science teachers. I've seen them used with rural, urban, and suburban students; with public and private school students; and with students from six continents. In other words, application questions are *trans-age*, *trans-discipline*, *trans-experience*, *trans-community*, and *trans-continental*. They are a well-established feature of an educational landscape that extends well beyond the practices found in an undergraduate biology course. Clearly, application questions are part of something much bigger, more layered, more interesting, and more complex.

In pursuit of the goal of finding ways to help the professors improve student performance on application questions in the future, I trusted that the professors would point me in the general direction this bigger, more layered, more interesting, more complex *something*. Whenever they discussed the results of application questions with students in the classroom, and whenever they discussed them with colleagues (as well as with me) outside of

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6. In the discourse of the Bio101 instructors and their colleagues, a number of these questions, like the Mutant Spinach Question had their own unique identifiers. For example, there was the "Two Viruses Question," the "Jared Question," the "Grape Question," the "Maple Tree Question," the "Radish-in-the-Dark Question (as well as the "Radish-in-the-Light Question"), and the "Corn Question."

the classroom, they almost always turned in their conversations to something they routinely called “understanding.”

### Overview of Remaining Chapters

This dissertation is a study of a concept, specifically, the concept of *understanding*. It is not a study of a classroom, a teacher, or a student. It is not a study of teaching or learning. Following an approach developed by Bruno Latour and others working in Science Studies, my approach to the study of a concept is to observe and describe that concept in action. I take the first steps in following the concept of understanding in **Chapter 1** (“Understanding is All the Rage”), where I chronicle how six contemporary science education texts define and describe understanding. I take a particular interest in the notion of *learning with understanding*, which seems to have enlisted many supporters in science education over the past 25 years. In **Chapter 2 (A Distinct Horizon of Expectations)**, I make the case that learning with understanding is predominantly informed by the psychological sciences through a process Popkewitz calls, “the alchemy of school subjects.” Although unavoidable, the alchemy transforms how scientists learn with understanding into something different by the time this set of practices makes its way into classrooms. The alchemy is neither a good nor a bad thing, but a psychological alchemy gives a distinct shape to what it means to learn with and teach for scientific understanding. In **Chapter 3 (A Horizontal Shift)** and **Chapter 4 (A Scientific Horizon)**, I aim to disrupt the tenets of a predominant psychological learning theory—abstract conceptual learning theory—by familiarizing readers with the anthropological and philosophical work of Latour, who offers us vital empirical insight into how scientists confront unfamiliar phenomena. This disruption is meant to prepare the ground, so to speak, not only for a radical revision of

psychological notions such as “abstraction” and “transfer,” but also for the specific purpose of trying to make abstract conceptual learning theory more inclusive and less constraining for teachers and students. The general form of my contention is that abstract conceptual learning theory doesn’t have to be so individualized, secretive, clandestine, rationalistic, and universalized. In other words, the historically and culturally specific formulation of abstract conceptual learning theory is not inevitable. It can be different. It can be otherwise. More specifically, it can be more inclusive, visible, material, empirical, and perhaps even more scientific. **Chapter 5 (Horizons In Action)** and **Chapter 6 (New Horizons for Scientist Teachers)** takes the concepts and sensibilities developed in Chapters 3 and 4 and embeds them within an example of instruction in an undergraduate biology course. Here, two distinct styles of science teaching and learning—one psychological and the other empirical—are contrasted in an experiment called a “bioeducational assay.” The function of this assay is to evaluate the two styles according to traits or characteristics such as relative purity, composition, activity, and potency, but it also allows us to make statements about the overall effectiveness of the styles relative to some important aims and goals of U.S. science education.

**CHAPTER 1**  
**UNDERSTANDING IS ALL THE RAGE**

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Understanding is a tricky thing to get one's mind around. We want students to be able to employ knowledge in flexible and novel ways, to develop coherent networks of concepts, to use what they learn in school to understand the world around them, and to develop an interest in lifelong intellectual pursuits. But to help students achieve such understanding is no mean feat.

—Rebecca Simmons, *Educational Leadership* (February 1994)

Four Centuries of Enthusiasm

For those readers attuned to Western intellectual history and the Modern Age (hereafter Modernity), the naming of understanding by the Bio101 professors will come as little to no surprise. In this simple act, the professors are vocalizing a construct to which many historical figures have given substantial attention. In fact, understanding has forged a visible trail through Western culture for at least the past four hundred years. Western philosophers, in particular, have taken a keen interest in it. During the Enlightenment, a number of the most noted natural philosophers wrote extensively about the notion of human understanding including Descartes (1596-1650), Locke (1632-1704), Leibniz (1646–1716), Hume (1711-1776) and Kant (1724–1804) among others.<sup>7</sup> More recently, and perhaps more relevant to the

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7. For example, see Descartes's *Rules for the Direction of the Mind* (1684), Locke's *An Essay Concerning Human Understanding* (1689), Leibniz's *New Essays Concerning Human Understanding* (finished in 1704 but not published until 1765), Hume's *An Enquiry Concerning*

concerns of contemporary science educators, the American philosopher, psychologist, and progressive educator John Dewey (1859-1952) heaped praise upon understanding at the start of the 20th century by way of a warning to all Americans as to the steep price of failing to acquire it. As Dewey once wrote, “To grasp a meaning, to understand, to identify a thing in a situation in which it is important, are thus equivalent terms; they express the nerves of our intellectual life. Without them there is (a) lack of intellectual content, or (b) intellectual confusion and perplexity, or else (c) intellectual perversion—nonsense, insanity.”<sup>8</sup>

A more forceful case for the importance understanding would be difficult to make. In the absence of understanding, Dewey claims, only intellectual confusion, perplexity, and perversion can be expected to thrive in human societies. Devoid of understanding, we see only individuals who are at once nonsensical and insane.

### **Enthusiasm in Contemporary Science Education**

Rather than wane since the early years of the 20th century, education’s enthusiasm for both *teaching for* and *learning with* understanding has significantly waxed.<sup>9</sup> In science education, the case for the importance for understanding has taken a number of forms, but two of most influential documented forms published in the past 25 years are entirely continuous and consistent with the case for understanding articulated by Dewey in the early 1900s. For

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*Human Understanding* (1748), and Kant’s three Critiques: the *Critique of Pure Reason* (1781/1787), the *Critique of Practical Reason* (1788), and the *Critique of the Power of Judgment* (1790).

8. Dewey, *How We Think*, 117.

9. As one observer noted while attending to mathematics education, “The concern for teaching for understanding is as old as the 20th century. The *intuitive rightness of learning with understanding* [...] has led to the widespread importance of developing students’ understanding...” Fennema and Romberg, “Preface,” ix (emphasis added).

example, eighty years after the initial publication of Dewey's *How We Think*, the American Association for the Advancement of Science's Project 2061 put forth a forceful case for the importance of understanding in their landmark reform publication *Science For All Americans*:

Education has no higher purpose than preparing people to lead personally fulfilling and responsible lives. For its part, science education—meaning education in science, mathematics, and technology—should help students to develop the understandings and habits of mind they need to become compassionate human beings able to think for themselves and to face life head on. It should equip them also to participate thoughtfully with fellow citizens in building and protecting a society that is open, decent, and vital. America's future—its ability to create a truly just society, to sustain its economic vitality, and to remain secure in a world torn by hostilities—depends more than ever on the character and quality of the education that the nation provides for all of its children.<sup>10</sup>

Six years after *Science For All Americans* was published, the National Research Council put forward their case for understanding in another landmark reform publication, the *National Science Education Standards*:

Why is science literacy important? First, an understanding of science offers personal fulfillment and excitement—benefits that should be shared by everyone. Second, Americans are confronted increasingly with questions in their lives that require scientific information and scientific ways of thinking for informed decision making. And the collective judgment of our people will determine how we manage shared resources—such as air, water, and national forests.

Science understanding and ability also will enhance the capability of all students to hold meaningful and productive jobs in the future. The business community needs entry-level workers with the ability to learn, reason, think creatively, make decisions, and solve problems. In addition, concerns regarding economic competitiveness stress the central importance of science and mathematics education that will allow us to keep pace with our global competitors.<sup>11</sup>

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10. American Association for the Advancement of Science (AAAS), *Science for All Americans*, xiii.

11. NRC, *National Science Education Standards*, 11-12.

As did Dewey, both the American Association for the Advancement of Science (AAAS) and the National Research Council (NRC) see the price of not acquiring understanding as infinitely costly. In the absence of properly developed “understanding(s),” “habits of mind,” and “scientific ways of thinking”—the authors of both landmark reform documents forewarn—only indifference, dependence, uninformed decision making, and faint-heartedness can be expected to thrive.

As recently as June 2013, the release of the *Next Generation Science Standards* demonstrates that this same conceptual backbone remains largely unaltered. As its authors communicate in the opening sentence in their Executive Summary:

There is no doubt that science—and, therefore, science education—is central to the lives of all Americans. Never before has our world been so complex and science knowledge so critical to making sense of it all. When comprehending current events, choosing and using technology, or making informed decisions about one’s healthcare, science understanding is key. Science is also at the heart of the United States’ ability to continue to innovate, lead, and create the jobs of the future. All students—whether they become technicians in a hospital, workers in a high tech manufacturing facility, or Ph.D. researchers—must have a solid K–12 science education.<sup>12</sup>

Once again, understanding is seen as preeminent. Without it, the thinking goes, only nonsense, incomprehension, and indecision can be expected to thrive. And so, we see a recurring theme in science education throughout the 1990s, as well as now into the second full decade of the 2000s: individuals, families, and societies, but also governments, economies, and nation states, are widely reported to pay a high price for misunderstanding(s) in the areas of

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12. NRC, “Executive Summary,” 1.

science, mathematics, engineering, and technology.<sup>13</sup> Understanding is widely billed as a phenomenon that is “of paramount importance for education,” and this is especially true in education research and development where understanding is widely heralded as one of the cornerstones of STEM education reform.<sup>14</sup> In other words, in much of K-16 STEM education understanding has been—and still remains—all the rage.<sup>15</sup>

Today’s science students—whether primary, secondary, tertiary, or lifelong—are expected to read, listen, and learn with understanding; science teachers are encouraged to teach and assess for understanding; science curriculum is expected to promote and support understanding; and professional development programs are told to deepen science teachers’ understanding (e.g., of students, content, and pedagogy). In many respects, understanding is educational equivalent of truffles (or bacon): *The taste of everything said to be enhanced by its mere presence.*

### Understanding Understanding

The reach and influence of understanding even gives distinct form to two of the most high-profile constructs in science education reform over the past 25 years: science literacy and scientific inquiry. For example, an important part of science literacy is said to involve “understanding some of the key concepts and principles of science.”<sup>16</sup> In addition, scientific inquiry is said to refer to “the activities of students in which they develop knowledge and

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13. Since approximately 2000, these four disciplines—science, technology, engineering, and mathematics—are often collectively referred to as the “STEM” disciplines.

14. NRC, *How People Learn: Brain, 8.*

15. I thank my advisor and dissertation director, Lynn Fendler, for allowing me to play off of a phrase she uses in one of her publications (see Fendler 2006).

16. AAAS, *Science for All Americans*, xvii.



understanding of scientific ideas, as well as an understanding of how scientists study the natural world.”<sup>17</sup> Thus, at times understanding functions as if it were a web, network, or some sort of electromagnetic field: one can hardly move from place to place in science education without coming into contact with or being affected by at least one of its extensive threads, tendrils, or resonant forces.

Those working within science education research and development must be so acclimated to its almost constant companionship that I suspect it would be rather difficult if they were to try to imagine their profession without it. As one researcher/developer writes, “Almost everyone involved in science education research and development claims 'learning with understanding for all' as our basic goal.”<sup>18</sup> Another contributor points out that many of America’s national goals and standards for science/mathematics curricula and teaching now reflect a deep affection for and commitment to *learning with understanding*.<sup>19</sup> In the next section, I want to draw specific attention the notion of learning with understanding so that we (you and I)—still in the early stages of finding ways to improve student understanding—may come to recognize some of its more defining features.

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17. NRC, *National Science Education Standards*, 23.

18. Anderson, “Designing Systems,” para. 6.

19. As the authors of the NRC’s *Learning and Understanding* write: “Learning with understanding is strongly advocated by leading mathematics and science educators and researchers for all students, and also is reflected in the national goals and standards for mathematics and science curricula and teaching (American Association for Advancement of Science [AAAS], 1989, 1993; National Council of Teachers of Mathematics [NCTM], 1989, 1991, 2000; NRC, 1996).” NRC, *Learning and Understanding*, 118.

## Learning With Understanding

In my tracing of the notion of learning with understanding in the literature, I have noticed that this construct has come to have no fewer than five defining features associated with it. The first of these features is that learning with understanding is routinely associated with the possession of something. Most often, this something is said to include entities such as 'information,' 'skills,' 'previous learning' and 'prior knowledge' (among other entities). I shall endeavor to refer to these entities collectively as a "base of knowledge" or, more succinctly, a "knowledge base." Therefore, students who learn with understanding are said to possess a knowledge base. I will refer to this discursive feature of learning with understanding as the *knowledge base*. The second of these features is that learning with understanding is routinely associated with a knowledge base that is defined by such qualities as 'continuity,' 'coherence,' and 'connectedness' as opposed to, say, 'discontinuity,' 'fragmentation,' and 'isolation.' Therefore, students who learn with understanding are said to possess a certain kind of knowledge base, that is, one that is both deep (in quantity) and rich (in connections). I will refer to this particular discursive feature as *coherence*. The third of these features is that learning with understanding is routinely associated with a deep, rich knowledge base that is subjected to various actions, processes or performances such as 'application,' 'extension' or 'transfer.' Therefore, students who learn with understanding are said to be able to apply their knowledge, extend their skills, and/or transfer their learning. I will refer to this particular discursive feature as *transfer*. The fourth of these features is a corollary to the third. Students who learn with understanding are said to be able to apply, extend, and/or transfer their deep, rich knowledge base to certain types or kinds of situations. Many of these situations are said to be 'new,'

‘different,’ ‘novel,’ ‘unfamiliar,’ ‘unscripted’ or ‘strange.’ In other words, these situations are said to lie just beyond or outside of the plain, ordinary, initial, and/or familiar realm of students’ typical everyday experience(s). To put this differently, students who learn with understanding are said to be able to apply, extend, and/or transfer their deep, rich knowledge base to situations beyond the original context of learning. I will refer to this particular discursive feature as *extrapolation*. The fifth defining feature is that learning with understanding is routinely associated with the mind or brain. In the discourse of learning with understanding, not only is the knowledge base commonly associated with the mind/brain, so too are the various actions, processes, and/or performances students are said to need to perform when demonstrating their understanding. Students who learn with understanding are said to be able to *mentally* or *cognitively* apply, extend, and/or transfer their deep, rich knowledge base to situations beyond the original context of learning. Thus, I will refer to this particular discursive feature as *cognition*.

To summarize, the five features are *knowledge base*, *coherence*, *transfer*, *extrapolation*, and *cognition*.

This characterization should make it clear that in this dissertation I am studying a concept, specifically, the concept of learning with understanding. It is not a study of a classroom, a teacher, or a student. It is not a study of teaching or learning. My overall approach is to study the understanding while it is, so to speak, in action—in this chapter, deployed within six texts that circulate widely among communities of science educators and science education researchers. The six texts presented below are meant to illustrate the consistent use of these five distinct discursive features. Collectively, however, they help us see a particular way in

which the notion of learning with understanding has been constructed during the period of years from 1990-2013. There are at least two sound reasons for limiting the scope of this review to this particular historical period. First, this span of years subsumes the entire period of time during which the Bio101 professors had been teaching the course together, as well as many of the years they taught the course, or one similar to it, separately. If these professors were consulting the literature or their colleagues during this period for insight on learning with understanding, then the six examples presented below typify what they might have read or heard. Second, and perhaps more importantly, this period encapsulates an era that one group of science educators has named, “The Age of Reform in Science Education.”<sup>20</sup> The Age of Reform in Science Education (or Reform Age) began in approximately 1990 when several organizations took the initiative to provide goals, standards, frameworks, and/or curriculum recommendations designed to increase student achievement on a national basis.<sup>21</sup> In limiting my review to literature published during the Reform Age, I am assuming that a) the discursive construction of learning with understanding by those writing within the Reform Age is mostly—but not always—continuous with one another, and b) the discursive construction of learning with understanding by those writing within the Reform Age is mostly—but not always—discontinuous with those constructing it in Ages immediately preceding the Reform Age—for example, the so-called “Age of Crisis” (1970-1989) and “Golden Age” (1950-1969).<sup>22</sup>

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20. This is a wonderful term used by the University of Arkansas’s Project to Advance Science Education (PASE) on their “Interactive Timeline - Science Education in the U.S.A.” As of August 2013, the timeline is still accessible at <http://coehp.uark.edu/pase/itseusa/>.

21. For an accessible history of the Reform Age see DeBoer 1991.

22. The “Age of Crisis” and “Golden Age” are also terms used by PASE on their “Interactive Timeline - Science Education in the U.S.A.” (see note 18 above).

It is important to note that this review of the history of understanding in science education is far from exhaustive. It does not claim to include every individual, group, or organization that contributed to the notion of learning with understanding during the Reform Age. Instead, the selection of texts included below—which is followed by the spoken “text” of the Bio101 professors—are meant to illustrate its five distinct discursive features so that we may see with more clarity and precision the margins and/or boundaries of this notion’s envelope of possibilities, or rather, its *horizon of expectations*.<sup>23</sup>

#### Example #1: Science for All Americans (1990)

*Science For All Americans (SFAA)* is a product of AAAS’s Project 2061. AAAS’s Project 2061 has produced a number of influential publications throughout the Reform Age including *SFAA* (1990), *Benchmarks for Science Literacy* (1993), *Blueprints for Reform* (1998), *Designs for Science Literacy* (2001), and the *Atlas of Science Literacy, Volumes 1* (2001) and *2* (2007).

Project 2061 has been described as “a long-term initiative of the American Association for the Advancement of Science (AAAS) to help all Americans become literate in science, mathematics, and technology. To achieve that goal, Project 2061 conducts research and develops tools and services that educators, researchers, and policymakers can use to make critical and lasting improvements in the nation’s education system.”<sup>24</sup> Project 2061 described *SFAA* in this way,

“This book is about science literacy. *Science for All Americans* consists of a set of recommendations on what understandings and ways of thinking are essential for all citizens in a

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23. For the British historian, philosopher, and educator Stephen Toulmin (1922-2009), *horizons of expectation* are those entities that “mark limits to the field of action in which, at the moment, we see it as possible or feasible to change human affairs.” Toulmin, *Cosmopolis*, p. 1.

24. AAAS, “About Project 2061,” para. 1.

world shaped by science and technology.”<sup>25</sup> The phrase “learning with understanding” is never used in *SFAA*, so we must pursue statements about this notion alternatively through its use of the term *understanding*. Fortunately, *SFAA* uses the term *understanding* in its sixteen main sections no fewer than sixty-eight times.

Although this text claims to convey the “levels” and “contexts” of understanding appropriate for all people, it does not contain an explicit definition of the term *understanding*. Nevertheless, there are instances in the text that communicate what the authors of *SFAA* think understanding is, as well as what they think it is not. An example of one of these instances is found in the Introduction,

So *Science for All Americans* represents the informed thinking of the science, mathematics, and technology communities as nearly as such a thing can be ascertained. It is a consensus, to be sure, but not a superficial one of the kind that would result from, say, a survey or a conference. The process cannot be said to have led to the only plausible set of recommendations on the education in science, mathematics, and technology for all children, but it certainly yielded recommendations in which we can have confidence. *It is an ambitious but attainable vision that emphasizes meanings, connections, and contexts rather than fragmented bits and pieces of information and favors quality of understanding over quantity of coverage.* Is not that precisely the kind of education that we should want for all Americans?<sup>26</sup>

Near the end of this passage we see an example of the second discursive feature of learning with understanding—*coherence* (i.e., students who learn with understanding are said to possess a certain kind of knowledge base, that is, one that is both deep (in quantity) and rich (in connections)). In contrasting “quality understanding” with “quantity of coverage,” the authors of *SFAA* associate understanding with things like “meanings,” “connections” and

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25. AAAS, *Science for All Americans*, xiii.

26. AAAS, *Science for All Americans*, xxiii (emphasis added).

“contexts,” whereas coverage is associated with “fragmented bits” and “pieces of information.” Thus, in this text we see that understanding is not about fragmentation and isolation, it’s about coherence and connectedness.

Example #2: National Science Education Standards (1996)

The National Research Council (NRC) *publishes the National Science Education Standards (NSES)*. The NRC has been described as the “working arm” of the U.S National Academies and is responsible for carrying out the studies endorsed by its three major branching organizations, the National Academy of Sciences (NAS), National Academy of Engineering (NAE), and the Institute of Medicine (IOM). The NRC has published influential group-reviewed reports throughout the Reform Age. They have published many important documents during the Reform Age, but by far one of their most influential documents thus far is the *National Science Education Standards* (hereafter *NSES*) published in 1996. As is the case with AAAS Project 2061’s *SFAA*, the phrase “learning with understanding” is never used in the *NSES*, so we must pursue statements about this notion through its use of the term *understanding*. Fortunately, the *NSES* uses the term *understanding* in its first ten main sections no fewer than four hundred and thirty-five times.

Understanding is defined explicitly in Chapter 2 (“Principles and Definitions”) at the same time as the term *knowledge*:

**KNOWLEDGE AND UNDERSTANDING** [emphasis in the original]. Implementing the *National Science Education Standards* implies the acquisition of scientific knowledge and the development of understanding. Scientific knowledge refers to facts, concepts, principles, laws, theories, and models and can be acquired in many ways. *Understanding science requires that an individual integrate a complex structure of many types of knowledge, including the ideas of science, relationships between ideas, reasons for these relationships, ways to use the ideas to explain and predict other natural phenomena,*

*and ways to apply them to many events. Understanding encompasses the ability to use knowledge, and it entails the ability to distinguish between what is and what is not a scientific idea.* Developing understanding presupposes that students are actively engaged with the ideas of science and have many experiences with the natural world.<sup>27</sup>

In this passage we see examples of four of the five discursive features of learning with understanding. With respect to the first feature, *knowledge base*, we get a precise formulation of the different components thought to constitute a proper knowledge base. According to the *NSES*, “scientific” knowledge includes elements such as “facts, concepts, principles, laws, theories, and models.” With respect to the second feature, *coherence*, we see that the *NSES* stipulates that understanding requires individuals to “integrate a complex structure of many types of knowledge.” With respect to the third and fourth features, *transfer* and *extrapolation*, we see that *NSES* combines them together in phrases such as “ways to use the ideas to explain and predict natural phenomena,” “ways to apply them to many events,” and “the ability to use knowledge.” Each of these phrases speaks directly to the transfer feature (e.g., when drawing from the notion of knowledge ‘application’ or knowledge ‘use’), as well as to the extrapolation feature (e.g., when asking individuals to use/apply their complexly structured knowledge to explain and predict “natural phenomena” and unfamiliar “events”). We do not see the fifth feature, *cognition*, explicitly mentioned in this same section. Nevertheless, a few pages earlier in the same chapter the *NSES* authors define science learning as an “active process,” and then clarify the term *active process* by saying that it “implies physical and mental activity. Hands-on activities are not enough—students also must have ‘minds-on’ experiences.”<sup>28</sup> Here, we can

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27. NRC, *National Science Education Standards*, p. 23 (emphasis added).

28. NRC, *National Science Education Standards*, p. 20 (emphasis added).



see that cognition is a key feature of what the *NSES* authors mean when they talk about learning science. Thus, we might safely presume that the *NSES*'s notion of learning science with understanding would also necessarily, but not sufficiently, include an element of mental/cognitive activity.<sup>29</sup>

Example #3: National Center for Improving Student Learning and Achievement in Mathematics and Science (1995-2004)

The National Center for Improving Student Learning and Achievement in Mathematics and Science (NCISLA) is a collaborative research group engaged in long-term studies and teacher professional development programs in science and mathematics. Its participating members work in six higher education institutions—five in the U.S and one in The Netherlands. First formed in 1995, they were charged by the U.S. Department of Education to assemble a research base about ways science and mathematics instruction can be improved.<sup>30</sup> Although their main focus is to advance effective reform of science and mathematics education mainly at the K-12 level, NCISLA's construction of the notion of learning with understanding is consistent with the constructions of other documents targeting reform throughout both secondary and tertiary science education. I did not query a single NCISLA text for its use of the term *understanding* or for the phrase "learning with understanding." Instead, I queried a number of documents and statements appearing on/in their entire website.

On their website, NCISLA reports the aim of the center's research as,

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29. We can see that the *NSES* define science learning not only as "minds-on," but also as "hands-on." Although I focus exclusively on the minds-on component of their definition here, I will return to the important notion of hands-on science learning in Chapter 6

30. For more about NCISLA (1995-2004) see <http://ncisla.wceruw.org/index.html>.

to identify ways that students can learn mathematics and science with understanding. To this end, researchers designed and evaluated instruction that can enhance *students' abilities to connect ideas and concepts and apply what they know to new situations and phenomena*. Researchers reasoned that these abilities, in addition to students' mastery of basic skills, are vital for students facing an increasingly complex world.<sup>31</sup>

In this short passage we see examples of four of the five discursive features of learning with understanding. The *knowledge base* and *coherence* features are combined within a single sentence. According to *NCILSA*, a proper knowledge base includes “ideas” and “concepts” which are connected. We saw a similar idea in the *NSES*—both constructions emphasize the continuity, coherence, and connectedness of the knowledge base. The *transfer* and *extrapolation* features are also combined within a single sentence. When *NCISLA* uses phrases such as “to connect ideas and concepts and apply what they know to new situations and phenomena,” they speak directly to the active, processual or performative component of learning with understanding (in this instance, knowledge ‘application’), as well as to the situational one (e.g., to apply connected ideas and concepts to “new situations and phenomena”).

We see an example of the fifth feature, *cognition*, in *NCISLA*’s articulation of the conceptual basis for their work,

The conceptual basis for our work at the National Center for Improving Student Learning and Achievement (*NCISLA*) is centered on learning with understanding. It is difficult to define understanding without engaging in circular argument. Because virtually all complex ideas or processes can be understood at a number of levels and in quite different ways, we characterize understanding as emerging or developing. As a consequence, *we choose to define understanding in terms of mental activity that*

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31. *NCISLA*, “Program Overview” (emphasis added).

contributes to the development of understanding rather than as a static attribute of an individual's knowledge.

*We propose five forms of mental activity from which mathematical and scientific understanding emerges:* (a) constructing relationships, (b) extending and applying mathematical and scientific knowledge, (c) reflecting about experiences, (d) articulating what one knows, and (e) making mathematical and scientific knowledge one's own. These ideas are elaborated in more detail in Carpenter and Lehrer (1999), Fennema and Romberg (1999) and specific examples of how they are instantiated in classrooms are described throughout our web site.<sup>32</sup>

In short, NCISLA explicitly associates learning with understanding with “five forms of mental activity.” Relationship construction, knowledge extension/application, experiential reflection, knowledge articulation, and knowledge personalization are all constructed as “mental activities” from which understanding emerges.

If we follow the Carpenter & Lehrer (1999) citation from second paragraph in the passage included above, we can then see all five of the distinct discursive features of learning with understanding woven into a relatively concise and coherent discursive fabric.<sup>33</sup> When making a case for learning with understanding, Carpenter and Lehrer include the following statements in relatively close proximity to one another,

Perhaps the most important feature of learning with understanding is that such learning is generative. When students acquire knowledge with understanding, *they can apply that knowledge to learn new topics and solve new and unfamiliar problems. When students do not understand, they perceive each topic as an isolated skill. They cannot apply their skills to solve problems not explicitly covered by instruction, nor extend their learning to new topics.* In this day of rapidly changing technologies, we cannot anticipate all the skills that students will need over their lifetimes or the problems they will

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32. NCISLA, “Learning with Understanding,” 1 (emphasis added).

33. The main reason for following this citational pathway and including it in Example #3 is because the NCISLA website lists Thomas Carpenter as its director and Richard Lehrer as a faculty member at one of the six collaborating NCISLA institutions (Vanderbilt University).

encounter. *We need to prepare students to learn new skills and knowledge and to adapt their knowledge to solve new problems. Unless students learn with understanding, whatever knowledge they acquire is likely to be of little use to them outside the school.*<sup>34</sup>

And then a little bit later,

*We propose five forms of mental activity from which mathematical understanding emerges: (a) constructing relationships, (b) extending and applying mathematical knowledge, (c) reflecting about experiences, (d) articulating what one knows, and (e) making mathematical knowledge one's own. Although these various forms of mental activity are highly interrelated, for the sake of clarity we discuss each one separately.*<sup>35</sup>

Despite the fact that Carpenter and Lehrer write only of “mathematical understanding” within this selection, an analysis of NCISLA’s larger corpus of work shows that these two NCISLA representatives and their many colleagues assume that the mental activities from which mathematical and scientific understanding emerge are *one and the same*.

Example #4: How People Learn (1999, 2000)

Between 1999-2000, the NRC published two texts under the general title, *How People Learn*. The text released in 1999 had the added title, *Bridging Research and Practice*. There are three authors of this document: three co-editors (M. Suzanne Donovan, John D. Bransford, and James W. Pellegrino), one committee (Committee on Learning Research and Educational Practice), and one council (National Research Council). The text released in 2000 had the added title *Brain, Mind, Experience, & School*. There are two authors of this document: one committee (Committee on Developments in the Science of Learning with additional material from the Committee on Learning Research and Educational Practice) and one council (National Research

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34. Carpenter and Lehrer, “Teaching and learning mathematics,” 18-19 (emphasis added).

35. Carpenter and Lehrer, “Teaching and learning mathematics,” 19 (emphasis added).

Council). Both *How People Learn* texts listed the same two authoring organizations: the Board on Behavioral, Cognitive, and Sensory Sciences (BBCSS) and the Division of Behavioral and Social Sciences and Education (DBASSE). *Bridging Research and Practice* (hereafter *Bridging*) mentions the term *understanding* in its first six main sections no less than one hundred and fifteen times (the phrase “learning with understanding” is used four times). *Brain, Mind, Experience, & School* (hereafter *Brain*) mentions the term *understanding* in its first twelve main sections no less than three hundred and sixty-six times (the phrase “learning with understanding” is used seventeen times). Although this review will draw at times from both texts, most of my analytical attention will concentrate on how the notion of learning with understanding is constructed in *Brain*.

In a section titled “Learning with Understanding” (Chapter 1), the authors of *Brain* speak directly to our notion of interest:

One of the hallmarks of the new science of learning is its emphasis on learning with understanding. Intuitively, understanding is good, but it has been difficult to study from a scientific perspective. At the same time, students often have limited opportunities to understand or make sense of topics because many curricula have emphasized memory rather than understanding. Textbooks are filled with facts that students are expected to memorize, and most tests assess students’ abilities to remember the facts [...] The new science of learning does not deny that facts are important for thinking and problem solving. Research on expertise in areas such as chess, history, science, and mathematics demonstrate that experts’ abilities to think and solve problems *depend strongly on a rich body of knowledge about subject matter* (e.g., Chase and Simon, 1973; Chi et al., 1981; deGroot, 1965). However, the research also shows clearly that “usable knowledge” *is not the same as a mere list of disconnected facts. Experts’ knowledge is connected and organized around important concepts (e.g., Newton’s second law of motion); it is “conditionalized” to specify the contexts in which it is applicable; it supports*

*understanding and transfer (to other contexts) rather than only the ability to remember.*<sup>36</sup>

In this passage we see examples of four of the five discursive features of learning with understanding. The *knowledge base* feature is visible in the later half of the paragraph. According to *Brain*, a proper knowledge base includes a “rich body of knowledge about subject matter.” Furthermore, “concepts” are cited as one of the key epistemological elements found in expert knowledge.<sup>37</sup> The *coherence* feature is also visible in the later half of the paragraph, where expert knowledge is said to be “useable,” by which is meant “connected and organized around important concepts” and also “conditionalized.” Once again, we see a construction of the knowledge base that foregrounds continuity, coherence, and connectedness. With respect to *transfer* and *extrapolation*, we see that *Brain* combines them together in phrases such as “[expert’s knowledge] is “conditionalized” to specify the contexts in which it is applicable” and “[expert’s knowledge] supports understanding and transfer (to other contexts) rather than only the ability to remember.” When the authors of *Brain* use these phrases they speak directly to the active, processual or performative component of learning with understanding (in this instance, knowledge ‘application’ and knowledge ‘transfer’), as well as to the situational one (e.g. to apply and/or transfer expert knowledge to “other contexts”).

At least at first glance, examples of the cognitive feature may be hard to see. They never explicitly use the terms *mind*, *brain* or *mental abilities*. On a number of occasions, however, the authors set learning with understanding in opposition to “memory.” Although this doesn’t

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36. NRC, *How People Learn: Brain*, 8-9 (emphasis added).

37. This emphasis on the importance of “concepts” in learning with understanding is one of the likely sources of the notion of *conceptual* understanding.

preclude the possibility that understanding could be associated with entities outside of the mind/brain, that possibility is quickly closed by the authors' explicit use of the term *transfer*. Historically, the notion of transfer belongs to psychology. One of its earliest formal uses in the 20th century was in the work of American psychologists Edward L. Thorndike (1874-1949) and Robert S. Woodworth (1869-1962). Thorndike and Woodworth made use of the phrase "the transfer of practice" in a paper published in the *Psychological Review* in 1901. In it, transfer was described as a "mental function."<sup>38</sup>

We learn even more about what *Brain* means by the term *transfer* in a section titled "Transfer of Learning" (Chapter 10).

A major goal of schooling is to prepare students for flexible adaptation to new problems and settings. Students' abilities to transfer what they have learned to new situations provides an important index of adaptive, flexible learning [...] Transfer can be explored at a variety of levels, including transfer from one set of concepts to another, one school subject to another, one year of school to another, and across school and everyday, nonschool activities.<sup>39</sup>

Here, we see that transfer is associated with problem solving in new settings and also "adaptive, flexible learning." We also see that transfer is a generic term used to describe that which takes place between two different settings or situations: for example, between two sets of concepts (e.g., photosynthesis and cellular respiration); between two school subjects (e.g., biology and chemistry or biology and U.S. history); between two school years (e.g., high school seniors and college freshman); and/or between two activities (e.g., a lab experiment and a walk

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38. See Thorndike, Edward L., and Robert S. Woodworth. "The Influence of Improvement in One Mental Function Upon the Efficiency of Other Functions (I)." *Psychological Review* 8 (1901), 247-261.

39. NRC, *How People Learn: Brain*, 235.

in the woods). This particular use of the term *transfer* has both temporal and spatial components that will be explored in the next chapter, but it does not help us clarify the relationship between transfer and learning with understanding. However, this next selection of text accomplishes this particular goal.

Learning with understanding *is more likely to promote* transfer than simply memorizing information from a text or a lecture. Many classroom activities stress the importance of memorization over learning with understanding. Many, as well, focus on facts and details rather than larger themes of causes and consequences of events. The shortfalls of these approaches are not apparent if the only test of learning involves tests of memory, but when the transfer of learning is measured, the advantages of learning with understanding are likely to be revealed.<sup>40</sup>

Here, a relationship between transfer and understanding is made clear: learning with understanding *promotes* transfer. In other words, learning with understanding increases the likelihood or probability that transfer (i.e., knowledge use, extension or application) will happen successfully. With the clarification of this relationship, as well as with the help of all the quoted passages above, we can finally see an important relationship between knowledge, understanding, and transfer: According to the authors of *Brain*, understanding is the product or result of knowledge that has been mentally *transformed*—in other words, it’s the result of knowledge that has been memorized *and then* organized (e.g., connected, conceptualized, and conditionalized). Knowledge that has been transformed in these particular ways can be described as “a rich body of knowledge” or “expert knowledge.” The authors of *Bridging* offer other useful phrases to describe this particular type of knowledge, including “a strong

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40. Ibid., 236 (emphasis added).



conceptual framework” and “a richly structured information base.”<sup>41</sup> They also call this particular type of knowledge “deep” understanding. Transfer, then, is the subsequent mental application, use, or extension of that deep understanding (i.e., that transformed, rich, expert knowledge) to new contexts characterized by one (or more) of four spatio-temporal levels.

Example #5: Learning and Understanding: Improving Advanced Study of Mathematics and Science in U.S. High Schools (2002)

The NRC published *Learning and Understanding: Improving Advanced Study of Mathematics and Science in U.S. High Schools* in 2002. There are two authors of this document: one committee (Committee on Programs for Advanced Study of Mathematics and Science in American High Schools) and one council (National Research Council). There are three authoring organizations: the Board on Science Education (BOSE), the Board on Testing and Assessment (BOTA), and the Division of Behavioral and Social Sciences and Education (DBASSE). *Learning and Understanding* mentions the term *understanding* in its first thirteen main sections no less than two hundred and twenty-three times (however, there are three Appendices and four additional Reports which use the term another two hundred and thirty-two times). The phrase “learning with understanding” appears in the main sections thirty-one times. Learning with understanding is first discussed in the Executive Summary.

The concept of “learning with understanding” *is concerned with knowledge and how it is organized*. Effective instruction is focused on enabling learners *to uncover and formulate the deep organizing patterns of a domain*, and then *to actively access and create meaning around these organizing principles*. Learning with understanding also *helps students develop the ability to evaluate the relevance of particular knowledge to novel problems and to explain and justify their thinking*. As students learn and practice these

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41. NRC, *How People Learn: Bridging*, 2.

skills of critical reflection, they become able to *apply knowledge in multiple contexts, develop adaptive expertise, and serve as active members of learning communities.*<sup>42</sup>

In this passage we see examples of four of the five discursive features of learning with understanding. The *knowledge base* and *coherence* features are visible in the first and second sentences of the paragraph. According to the authors of *Learning and Understanding*, learning with understanding “is concerned with knowledge and how it is organized.” In the second sentence, we see an emphasis placed on a particular type of epistemological unit, the “organizing patterns” or “organizing principles” of a domain. Once again, we see a construction of the knowledge base that foregrounds continuity, coherence, and connectedness. With respect to the *transfer* and *extrapolation* features, we see that *Learning and Understanding* combines them together in phrases such as “to evaluate the relevance of particular knowledge to novel problems” and “to apply knowledge in multiple contexts.” When the authors of *Learning and Understanding* use these phrases they speak directly to the active, processual or performative component of learning with understanding (in this instance, knowledge ‘evaluation’ and knowledge ‘application’), as well as to the situational one (for example, to evaluate knowledge relevance to “novel problems” and to apply knowledge “in multiple contexts”).

A bit deeper into the Executive Summary we are made aware of another valued epistemological unit said to help provide additional organization to a knowledge base.

Learning with understanding is facilitated when knowledge is related to and structured around major concepts and principles of a discipline.<sup>43</sup>

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42. NRC, *Learning and Understanding*, 6 (emphasis added).

43. *Ibid.*, 7.

In addition to integrating organizing patterns and principles into their knowledge base, students who learn with understanding also integrate “major concepts” into them. The expectation that students integrate major concepts into their knowledge base goes a long way toward helping explain the large number of appearances of the term *conceptual understanding* in the text. The term appears fifty-six times in the first thirteen major sections and is defined as follows:

Conceptual understanding involves *the creation of rich integrated knowledge structures around an underlying concept*. Understanding is not a static point in learning, but rather *a continually developing mental activity*.<sup>44</sup>

In seeing how *Learning and Understanding* constructs conceptual understanding, one can't help but notice the continuity between this notion and what the previous example—the NRC's *How People Learn*—referred to alternately and equivalently as, “a rich body of knowledge,” “a strong conceptual framework,” “a richly structured information base,” “expert knowledge,” and/or “deep understanding.” One also can't help but notice how the authors construct conceptual understanding as “a continually developing mental activity.” *How People Learn* achieved the cognitive feature by way of associating learning with understanding with the notion of transfer. There is good reason for the presence of these two continuities: the authors of *Learning and Understanding* explicitly reference *How People Learn* just prior to stating their “seven principles of human learning” in Chapter 6 (“Learning with Understanding: Seven Principles”). In fact, the *Learning and Understanding* authors state that it was research summarized in *How People Learn* upon which they decided to base their principles for learning

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44. Ibid., 22n8 (emphasis added).

with understanding. In the text supporting and explaining these principles, we see a number of terms and ideas that also appeared in *How People Learn*. For example, *Learning and Understanding* speaks of “expert strategies for thinking and problem solving,” and knowledge that is “connected,” “organized” and “conditionalized.” Taken collectively, we see complementary constructions of learning with understanding between these two texts.

Despite a few subtleties here and there, the construction of learning with understanding is more or less the same for both texts. Understanding—whether deep or conceptual—is the product or result of transforming knowledge inside of the mind. In *How People Learn*, the transformation is driven by mental actions or processes such as memorization, organization, building connections, conceptualizing, and conditionalizing. In *Learning and Understanding*, organizing knowledge around the deep patterns, key principles, and/or major underlying concepts of a domain or discipline drives the transformation. Once organized in deep, rich, meaningful, structured, principled, patterned, and/or conceptual arrangements, this new knowledge—i.e., the understanding—is deemed fit for its mental extrapolation (application, use, extension, transfer) to novel and, it is hoped, multiple contexts.

Example #6: Grant Wiggins and Jay McTighe (2005)

Prentice Hall publishers released the first edition of Wiggins and McTighe’s *Understanding by Design (or UbD)* in 2000. The ASCD (formerly the Association for Supervision and Curriculum Development) then published a second, expanded edition in 2005. “As the title suggests,” the authors write, “this book is about good design—of curriculum, assessment, and

instruction—focused on developing and deepening understanding of important ideas.”<sup>45</sup>

According to Wiggins and McTighe, *UbD* is not written specifically for science or STEM educators, but rather, it is a book intended for all those “educators, new or veteran, interested in enhancing student understanding and in designing more effective curricula and assessment to achieve that end.”<sup>46</sup> Nevertheless, *UbD* is a widely cited publication in K-16 science education and it is used extensively in science teacher education and professional development programs. *UbD* contains some of the most precise and explicit treatment of understanding of any of the texts selected for this review of texts.

According to the *UbD* authors, “There are different kinds of understanding; we need to be clear about which kinds we are after. Understanding, we argue, is not a single goal, but a familiar of interrelated abilities—six different facets of transfer—and an education for understanding would develop them all.”<sup>47</sup> Two pages later, they expand on this statement, as follows:

The word *understanding* turns out to be a complex and confusing target despite the fact that we aim for it all the time. The word naturally deserves clarification and elaboration, which is the challenge for the rest of this book. For now, though, consider our initial working definition of the term: To *understand* is to make connections and bind together our knowledge into something that makes sense of things (whereas without understanding we might see only unclear, isolated, or unhelpful facts). But the word also implies doing, not just a mental act: A performance ability lies at the heart of understanding, as Bloom (1956) noted in his Taxonomy in discussing application and synthesis. To understand is to be able to wisely and effectively *use*—transfer—what we know, in context; to *apply* knowledge and skill effectively, in realistic tasks and settings. To have understood means that we show evidence of being able to transfer what we

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45. Wiggins and McTighe, *Understanding By Design*, 5.

46. *Ibid.*, 5.

47. *Ibid.*, 4.

know. When we understand, we have a fluent and fluid grasp, not a rigid, formulaic grasp based only on recall and “plugging in.”<sup>48</sup>

Because of the authors’ already existing emphasis within the passage, I have chosen not to add emphasis as I did in the previous three examples. However, I suspect that by now readers will be able to see clearly the backbone of many of the five discursive facets of learning with understanding without my help. In just the third sentence in the paragraph we see elements of the first four features: *knowledge base* (“knowledge”), *coherence* (“to make connections,” “to bind together knowledge”), and *transfer* and *extrapolation* (“to make sense of things”). Many of these same four features can also be identified within the last two sentences in the paragraph (e.g., “to wisely and effectively *use*—transfer—what we know,” and “to *apply* knowledge and skill [...] in realistic tasks and settings”). Although the cognition feature is easy to identify within the fourth sentence (“...a mental act”), Wiggins and McTighe suggest that the notion of learning with understanding also goes beyond mental actions. To clarify what sort of actions lie beyond mental ones in learning with understanding, they cite the work of “Bloom (1956)” and draw explicit attention to two terms—*application* and *synthesis*—that appear in what is now commonly referred to by educators as “Bloom’s Taxonomy” (or “Bloom’s Taxonomy of Educational Objectives”).

Interestingly, the terms *application* and *synthesis* appear in Bloom et al.’s 1956 paper as two of six “levels” that help define learning objectives in the “cognitive domain.”<sup>49</sup> Bloom and his fellow authors were all contributing to the field of educational psychology in the 1950s and 60s. It remains unclear to me as to whether their collective use of the term *cognition* is meant

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48. Ibid., 6-7 (emphasis in the original).

49. See Bloom et al. 1956.

to mean actions beyond or within the mind/brain. However, we gain some clarification as to what Wiggins and McTighe mean by their use of the phrase “not just a mental act” in a chapter titled “Understanding Understanding” (Chapter 2).

In Chapter 2, Wiggins and McTighe write about learning with understanding as having three main dimensions or facets: 1) understanding as meaningful inferences, 2) understanding as transferability, and 3) understanding as a noun. The first of these facets, they explain as follows:

Understanding thus involves meeting a challenge for thought. We encounter a mental problem, an experience with puzzling or no meaning. We use judgment to draw upon our repertoire of skill and knowledge to solve it. As Bloom (1956) put it, understanding is the ability to marshal skills and facts wisely and appropriately, through effective application, analysis, synthesis, and evaluation. Doing something correctly, therefore, is not, by itself, evidence of understanding. It might have been an accident or done by rote. To understand is to have done it in the right way, often reflected in being able to explain *why* a particular skill, approach, or body of knowledge is or is not appropriate in a particular situation.<sup>50</sup>

Here, we see an even sharper focus on the cognitive feature of learning with understanding. Students who learn with understanding are said to be able to mentally apply, extend or transfer their deep, rich knowledge base to situations beyond the original context of learning. The authors talk about understanding fluidly as meeting a “challenge for thought,” as requiring “judgment,” and as encountering a puzzling “mental” problem or experience devoid of meaning. Once again, they cite terms from Bloom et al.’s cognitive domain, but this time they cite four of the six “levels”—*application, analysis, synthesis, and evaluation*—rather than just two of them.

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50. Wiggins and McTighe, *Understanding By Design*, p. 39 (emphasis in the original).

In the second of their three facets of understanding, Wiggins and McTighe continue to construct learning with understanding as a predominant mental activity by making repeated use of the term *transfer*. As I noted in a previous example (Example #2: *How People Learn*), transfer is a concept that historically belongs to psychology. Here is how the authors of UbD use the term:

Understanding is about *transfer*, in other words. To be truly able requires the ability to transfer what we have learned to new and sometimes confusing settings. The ability to transfer our knowledge and skill effectively involves the capacity to take what we know and use it creatively, flexibly, fluently, in different settings or problems, on our own. Transferability is not mere plugging in of previously learned knowledge and skill. In Bruner's famous phrase, understanding is about "going beyond the information given"; we can create new knowledge and arrive at further understandings if we have learned with understanding some key ideas and strategies.<sup>51</sup>

The *UbD* authors then elaborate upon the notion of transfer. Once again, they relate their ideas about understanding, and now transfer, to work of Bloom:

Transfer is the essence of what Bloom and his colleagues meant by application. The challenge is not to "plug in" what was learned, from memory, but modify, adjust, and adapt an (inherently general) idea to the particulars of a situation:

*'Students should not be able to solve the new problems and situations merely by remembering the solution to or the precise method of solving a similar problem in class. It is not a new problem or situation if it is exactly like the others solved in class except that new quantities or symbols are used. . . . It is a new problem or situation if the student has not been given instruction or help on a given problem and must do some of the following. . . . 1. The statement of the problem must be modified in some way before it can be attacked. . . . 2. The statement of the problem must be put in the form of some model before the student can bring the generalizations previously learned to bear on it. . . . 3. The statement of the problem requires the student to search through memory for relevant generalizations. (Bloom, Madaus, & Hastings, 1981, p. 233)'*

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51. Ibid., 40 (emphasis in the original).



Knowledge and skill, then, are necessary elements of understanding, but not sufficient in themselves. Understanding requires more: the ability to thoughtfully and actively “do” the work with discernment, as well as the ability to self-assess, justify, and critique such “doings.” Transfer involves figuring out which knowledge and skill matters *here* and often adapting what we know to address the challenge at hand.<sup>52</sup>

Since transfer is a term that historically belongs to psychology, we can therefore allow ourselves to see cognitive feature of learning with understanding in the use of terms such as “transfer,” “transferability,” and also “application” (which they claim is the Bloomian equivalent of transfer). Furthermore, we can also allow ourselves to see the cognitive feature in their use of phrases such as “going beyond the information given” and to “modify, adjust, and adapt an (inherently general) idea to the particulars of a situation.” Wiggins and McTighe construct these particular actions as mental performances. They are the kinds of performances enacted when individuals act “thoughtfully.” We also should be aware of the fact that the *transfer* and *extrapolation* features are present too. When Wiggins and McTighe use sentences such as, “To be truly able requires the ability to transfer what we have learned to new and sometimes confusing settings,” and “The ability to transfer our knowledge and skill effectively involves the capacity to take what we know and use it creatively, flexibly, fluently, in different settings or problems, on our own,” they speak directly to the active, processual or performative component of learning with understanding (in this instance, knowledge ‘transfer’ and knowledge ‘use’), as well as to the situational one (for example, to transfer knowledge and skills to “new and sometimes confusing settings,” to use knowledge “in different settings or problems,” and to address “the challenge at hand”).

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52. Ibid., 41 (emphasis in the original).

In the third and final of their three facets of understanding, Wiggins and McTighe remind us that the term *understanding* “has a verb meaning and a noun meaning.”

*To understand* a topic or subject is to be able to *use* (or “apply,” in Bloom's sense) knowledge and skill wisely and effectively. *An understanding* is the successful result of trying to understand—the resultant grasp of an *unobvious* idea, an inference that makes meaning of many discrete (and perhaps seemingly insignificant) elements of knowledge.

A genuine understanding involves another kind of transfer. We go beyond what we see, using big ideas, to make meaning of it [...].<sup>53</sup>

This last facet of understanding, which effectively summarizes the first two, neatly summarizes Wiggins and McTighe’s contribution to the notion of learning with understanding. If we see knowledge transfer (aka. knowledge ‘use’ or ‘application’) as a predominantly mental activity, then the construction of understanding by the authors of *UbD* exhibits all five of the distinct discursive features I outlined at the beginning of this chapter. Furthermore, it does so in a way that very few other texts produced within the Reform Age do. Wiggins and McTighe’s treatise on understanding and its design is more elaborate and more precise than almost all other texts circulating in/through science education. For these and other reasons, it is a text that I shall return to again later in this dissertation. For now, we should be content to remember that for the *UbD* authors understanding is “a mental construct, an abstraction made by the human mind to make sense of many distinct pieces of knowledge.”<sup>54</sup>

### **Teaching For Understanding**

We now turn to the Bio101 professors themselves so as to examine how they construct the notion of learning with understanding in practice. As with the previous six texts, we are

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53. *Ibid.*, 43 (emphasis in the original).

54. *Ibid.*, 37.

looking for the five discursive features of learning with understanding. We are also looking to highlight the continuities and/or discontinuities between their constructions and those presented in the previous six examples.

In a joint summer 2007 interview, one of the professors defined understanding in this way:

**Professor 1:** So I think [understanding is] two components. I think [students] have to know a certain number of facts. I've always felt that an introductory or foundation course [...] is based upon a certain number of facts that the student has to know about a topic, a subject, whatever. So I clearly feel that they have to memorize things or learn things by understanding those facts.<sup>55</sup>

When I asked this professor to clarify what he meant by the phrase "learn things by understanding those facts," he then added,

**Professor 1:** So when I say do they *understand* something...80%...70...60% of it is *facts*...and the rest of it is *trying to integrate those facts in a way that they may have not seen before*.<sup>56</sup>

At which point the other professor picked up the issue:

**Professor 2:** We're really not too far apart on all of that, I mean, I don't think that one can understand without having some *knowledge...so there's this knowledge base...the facts*...and the understanding has to be *built upon really assembling and organizing a lot of facts*. And then being able to *bring* those facts...somehow *use* those facts...*reorganize* those facts in order *to draw explanations*. That to me is the...the understanding part comes in being able *to provide the explanations or predictions*. So that's how we get to these higher order questions that are analytical...the analysis-type questions. And, uh, but I am constantly reaffirmed in my conviction that *the students have gotta know a lot of stuff* in order to make that work.<sup>57</sup>

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55. Instructor Interview (June 2007): 00:12:24-00:14:30

56. Instructor Interview (June 2007): 00:12:24-00:14:30 (emphasis added).

57. Instructor Interview (June 2007): 00:14:31-00:18:21 (emphasis added).

In these two passages, once again, we see examples of four of the five discursive features of learning with understanding. The *knowledge base* feature is clearly visible (“...so there’s this knowledge base...”). In this case, “facts” are cited as one of the key epistemological elements found in the knowledge base. The *coherence* feature is also clearly visible. Within the knowledge base in question, the facts are said to need to be ‘integrated,’ ‘assembled,’ ‘organized,’ and ‘reorganized.’ Once again, we see a construction of the knowledge base that foregrounds continuity, coherence, and connectedness. The *transfer* feature is also clearly visible. The professors say that their students need to be able to “bring” and “use” facts for the purpose of doing things (e.g., “draw explanations,” “provide explanations or predictions”). Although the *extrapolation* feature is less clearly visible, nevertheless, it is present. When the Professor 1 says, “...and the rest of [understanding] is trying to integrate those facts in a way that [students] may have not seen before,” he is pointing directly to new, unfamiliar contextual situations. When the Professor 2 says, “So that’s how we get to these higher order questions that are analytical...the analysis-type questions,” he is pointing directly at questions such as the Mutant Spinach Question and other like it. In other words, he is drawing attention to questions that contain elements students are likely to find new, novel, different, and/or unfamiliar. What we don’t explicitly see in these two passages is the *cognition* feature. In other words, we don’t see any obvious mention of either the knowledge base or the act of using the knowledge base characterized as a mental activity. Professors 1 and 2 never explicitly use terms such as “mind,” “brain” or “mental abilities.” In another portion of the interview, however, as Professor 2 was explaining to me how he thought his students should have answered the Mutant Spinach Question, a connection to the mind/brain was made explicit,

**Professor 2:** So what [students] have to bring is, what *is* going on? And they had to bring in the idea of the membrane which was from 3 to 4 chapters earlier, and they had to bring in the ideas of the ATP synthase, and they had to bring in the idea then of the light reactions and the *different parts* of the light reactions, and they had to put this whole idea of cyclic and non-cyclic photophosphorylation...or, parts of the Z-scheme...and so this is where it gets dicey because the picture—I can imagine the picture they have in their heads of this membrane **[Professor 2 points with his right hand to the right side of his head]** with the ATP, sitting in it, *is different than* the picture they have over here **[Professor 2 points with his left hand to the left side of his head]** of the Z-scheme and the arrow showing cyclic photophosphorylation...even though we say, *phos-phoryl-a-tion* **[Professor 2 pronounces the word slowly]** which ought to trigger, ‘Ding! Ding! Ding! Synthase!’...you know...over here **[Professor 2 again points with his right hand to the right side of his head]** [...] You know...it’s this...going...they...going back and forth on these things very fluidly from representation to representation is another manifestation of being able to tie it together.<sup>58</sup>

In this passage Professor 2 constructs a hypothetical situation in which he describes how Bio101 students might have answered the Mutant Spinach Question. In doing so, he models the strategy as a mental process. He speaks very clearly about “pictures” in the students heads and also about various mental processes—e.g., bringing ideas in, putting ideas together, going back and forth between mental representations with fluidity, and tying ideas together. At this point, this is nothing new. It is the same construction that we have seen throughout all six textual examples. Like so many of their Reform Age colleagues, the Bio101 professors construct the notion of learning with understanding as the ability to mentally apply, extend, or transfer a deep, rich knowledge base to situations beyond the original context of learning.

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58. Instructor Interview (June 2007): 01:21:18-01:23:53 (emphasis in the original).

## Summary

At the beginning of this review, I stated that the Reform Age construction of learning with understanding has come to have no fewer than five defining discursive features associated with it. These five features can be summarized as follows:

**First:** Students who learn with understanding are said to possess a *knowledge base*.

**Second:** Students who learn with understanding are said to possess a certain kind of knowledge base—one that is *coherent*. In other words, one that is both deep (in quantity) and rich (in connections).

**Third:** Students who learn with understanding are said to be able to *apply* their knowledge, *extend* their skills, and/or *transfer* their learning.

**Fourth** (and a corollary to the third): Students who learn with understanding are said to be able to apply, extend, transfer or extrapolate their deep, rich knowledge base to situations *beyond the original context of learning*.

**Fifth:** Students who learn with understanding are said to be able to use *cognition* to mentally extrapolate their deep, rich knowledge base to situations beyond the original context of learning.

The seven examples presented above are meant to illustrate the consistent use of these five distinct discursive features through the K-16 science education continuum. Collectively, they help us see a particular way in which the notion of learning with understanding is constructed during the period of years from 1990-2013. This is not to say that the discourse of learning with understanding has no other distinct features, but rather, only that these five features have achieved a noticeable and traceable density within Reform Age discourse. These

five features help give distinct shape and meaning to what I will call the existing “horizon of expectations” for learning with and teaching for understanding. In other words, these five features help articulate the limits and/or boundaries of what is both possible and probable in science teaching and learning throughout the K-16 continuum.

These five features help shape how teachers act in classrooms, including what they do, what they say, and how they think; they help shape what teachers teach and how they teach it; and they help shape not only who teachers think their students are, but also what they think their students can, and should, do. In other words, these five features help make it both possible and probable for the Bio101 professors to see and approach themselves, their students, and their subject matter in particular ways. In the next chapter, together we will examine a number of the affordances and constraints of this particular horizon of expectations for learning with and teaching for understanding.

## CHAPTER 2

### A DISTINCT HORIZON OF EXPECTATIONS

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Science education is still in the grip of psychology.

— Wolff-Michael Roth & Michelle K.  
Mc Ginn

Understanding something in one way does not preclude  
understanding it in other ways.

— Jerome Bruner, *The Culture of  
Education*

#### A Mental Horizon

As a way of rendering the affordances and constraints of the horizon of expectations for learning with understanding in the Reform Age discourse more explicit, let us consider the first defining discursive feature—that students who learn with understanding must possess a *knowledge base*. If none of the other four defining discursive features are present, then there are many possibilities for what a useable knowledge base can be and where it can exist. For example, untethered from the other four features, a useable knowledge base can take the form of a notebook, a recipe box, a 3-ring binder, a file cabinet, a library, or a laptop computer. Alternatively, it can consist of file cabinets, shelves, books, paper, words, diagrams, photographs, computer chips, electric wires, batteries, and a range of other visible, material items. However, if we constrain the knowledge base with the second feature of *coherence*, then the possibilities for what a useable knowledge base can be and where it can exist are altered. A



useable knowledge base that is both deep in quantity and rich in connections will most likely need to be different than one defined by characteristics such as aesthetics, expedience, or political correctness. For example, a recipe box might need to be bigger in volume to hold more recipe cards, or to fit properly on a shelf. To increase the connectivity, the cards themselves might need to be re-designed so that there would be space where one can record the name of the person with whom the recipe originated. Such a modification in connectedness might better facilitate problem solving when culinary chaos ensues (for example, when bread doesn't rise or when a soufflé collapses). Something similar happens every time another defining feature is added or subtracted. In every instance of layering or addition, the scope—and even the *shape*—of the knowledge base is likely to be in need of alteration.

Not all features are created equally, however, and the *cognitive* feature of learning with understanding embodies this maxim. If we allow the cognitive feature (that students who learn with understanding must be able to mentally apply, extend or transfer their deep, rich knowledge base to situations beyond the original context of learning), then just like before, the possibilities for what a knowledge base can be and where it can exist are altered. In the example I have developed thus far, the same visible, material recipe box might no longer count as a useable knowledge base because such a recipe box is not typically considered a mental object. To be considered useable, it must be transformed into something that counts as mental (or cognitive), for example, into a 'concept,' an 'idea,' or a structured 'framework.' If the recipe box is not transformed into something mental or cognitive, then it won't be able to be *mentally* applied or transferred to situations beyond its original context (e.g., outside of its home

kitchen). To summarize and emphasize the key point: the cognitive feature functions as a kind of prerequisite for the *transfer* and *extrapolation* features.

The cognitive feature helps define the limits and boundaries of the horizon of expectations for learning with understanding in Reform Age discourse more than any of the other features. We might even go as far as saying that the horizon of expectations for learning with understanding in Reform Age discourse is a largely mental, psychological or cognitive one. In other words, because Reform Age discourse demands that students mentally apply or transfer their deep, rich knowledge bases to situations beyond the original context of learning, the expectation is that students need to transform their deep, rich knowledge bases into purely mental forms. How else will students be able to mentally apply them to new, different, unfamiliar, unscripted or strange situations? How else will they be able to transfer them—cognitively speaking—to experiences beyond those commonly considered to be plain, familiar, ordinary, scripted and familiar? This is why the application moment is so important in science education assessments, and the Mutant Spinach Question is an example of assessing the cognitive capacities of the students, especially the cognitive capacities of transfer and extrapolation. The Mutant Spinach Question does not assess perceptions, observation skills, or manipulation of empirical things; it assesses what's inside of students' minds/brains.

Before examining some of the affordances of the construction of learning with understanding in accordance with a mental horizon, however, I want to pause to make an important point. Whether learning with understanding is or isn't mental is *of almost no concern to me*. My major concern in this dissertation amounts to something entirely different. As the analysis in Chapter 1 tries to communicate, science educators and researchers in the historical

period in which I live and work routinely assume that learning with understanding is a mental or cognitive skill/practice. It's true; this is one way to construe learning with understanding. However, in contrast, I wish to raise the possibility that this particular assumption about understanding could be viewed as rather presumptuous based on the fact that it does not align with anthropological accounts of scientific practice produced by scholars in Science Studies.<sup>59</sup> Accounts of scientific practice in Science Studies often show that scientific understanding is typically based on empirical observations and the subsequent inscription of these observations into visible, material forms. Once again, this particular stance should make it clear that in this dissertation I am studying a concept, specifically, the concept of learning with understanding. It is not a study of a classroom, a teacher, or a student. It is not a study of teaching or learning. My overall approach is to study the understanding while it is in action or in practice. In the remaining parts of this chapter, I will draw attention to both the affordances and constraints of constructing learning with understanding according to a mental or cognitive horizon.<sup>60</sup>

### **Some Affordances of a Mental Horizon**

To be sure, there are obvious benefits to be had in constructing learning with understanding primarily as a mental activity. Here are four of them:

#### *Capacity*

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59. I will have much more to say about the domain of Science Studies later in this chapter, but also in Chapter 4.

60. My approach to studying learning with understanding as a concept is primarily inspired by Jonathan Crary's approach to studying "vision" and "attention" (see Crary 1990 and Crary 1999) and Lorraine Daston and Peter Galison's approach to studying "objectivity" (see Daston and Galison 2007), but also Lynn Fendler's approach to constructs such as "teacher reflection" (see Fendler 2003), "community" (see Fendler 2006), and "generalisability" (see Fendler 2006).

The human brain is widely believed to be able to store a sizeable amount of data or information. According to one source, “most computational neuroscientists tend to estimate human storage capacity somewhere between 10 terabytes and 100 terabytes, though the full spectrum of guesses ranges from 1 terabyte to 2.5 petabytes.”<sup>61</sup> This strong belief in the large storage capacity of the brain makes it an ideal location to store the deep, rich knowledge base deemed necessary to carry out learning with understanding.

### *Portability*

As strange as this may sound, the human brain is quite conveniently portable. Other than a regular supply of food, water, and oxygen, the human brain requires little else to sustain it. For example, it does not require its owners to hook themselves up to any external electrical leads. This obvious fact makes it well suited to the task of learning with understanding. When students are asked to mentally apply, extend or transfer their deep, rich knowledge base to new, novel, unscripted and/or unfamiliar situations, some of these situations require travel through space and time—e.g., from one classroom to another (with a single day or week), from one classroom to another (in different school years), or from one classroom experience to an experience outside of school. The portability of the brain ensures that the deep, rich knowledge base deemed necessary to carry out learning with understanding will always be present when needed.

### *Speed*

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61. Wickman, “Your Brain’s Technical Specs,” para. 2.

The human brain is widely believed to be able to process sizeable amounts of stored data or information relatively quickly. At least part of this belief is probably held collectively between and/or among the results of studies attempting to estimate things such as the average number of neurons found in a human brain, the average speed at which these neurons can 'fire,' and the average number of connections found between these neurons. Although the general consensus is that the processing speed of a single neuron is actually quite slow compared to say, the processing speed contained within a common, 1 gigahertz (GHz) smartphone, the sheer number of neurons and their often multiple connections with one another allows us to see the human brain as something capable of performing tasks at great speed. This rather common belief in the brain's processing capacity makes it possible to see the brain as a tool that can function with greater speed (and also efficiency) than many other tools. The ability to think quickly when confronted by new, novel, unscripted and/or unfamiliar situations is highly valued not only in schools, but also in many other aspects of contemporary society. 'Faster' is generally deemed to be 'better.' When this is the case, it's not surprising that educators look to take full advantage of the processing capacity of the brain.

### *Privacy*

Protected by anatomical features such as hair, skin, and bone, as well as often further shrouded by cultural artifacts such as hats, wigs, hoods and/or scarves, the mental activities and processes occurring within the human brain remain mostly hidden from the view of others. In other words, to really 'see' what someone else is thinking is a difficult thing to do. In situations where the abilities of individuals are prioritized, privacy

can be an affordance because it prevents others from easily co-opting or stealing their ideas. The ability to think independently—that is, to think for one’s self, to think on one’s own two feet—is often highly valued in schools. When this is the case, it’s not surprising that educators look to take full advantage of the privacy offered by the brain. Among other things, it helps ensure that individuals will be rewarded for their own hard work as opposed to the hard work of others.

To summarize, although there are surely other benefits not accounted for here, the human brain is widely believed and reported to offer students the affordances of *capacity* (for storage), *portability* (for transport), *speed* (for processing), and *privacy* (for reward). These four benefits—or rather, cognitive affordances—may help explain why science education constructs learning with understanding in accordance with a largely mental/cognitive horizon. When asked to apply or transfer their deep, rich knowledge base to situations beyond the original context of learning, students are told to enlist that which is held within the space of their brains. “Your minds,” students are often told by their teachers, “Are perhaps your greatest ally.”

Describing the four cognitive affordances is a way of providing a reason or explanation for the analytical observation I put forth in Chapter 1—namely, that the notion of learning with understanding has come to be strongly associated with a mental or cognitive horizon of expectations in the Reform Age. When science educators and researchers value qualities such as capacity, portability, speed, and privacy, then a mental/cognitive horizon of expectations for understanding is a reasonable pairing. Before raising critical questions and concerns about this particular historical pairing, however, I first want to merge the cognitive affordances with yet another layer of the Reform Age discourse. This merging exercise is made possible by the

scholarship of the educational theorist Jay Lemke. Lemke's work helps make the key terms and commitments of the mentalist/cognitive horizon more explicit.

### **Abstract Conceptual Learning Theory**

The dominant theory of learning that guides educational practice in our society says what people need to learn are "abstract concepts," which they can then apply to a wide variety of specific situations. Nearly everyone is convinced that conceptual learning is the most powerful form of learning, and the only problem is how to get more people to be able to successfully learn abstract concepts. The way to teach abstract concepts is to demonstrate how they apply to several different situations until the student "catches on" or generalizes and "gets" the concept at an abstract level. The student will then be able to use the concept wherever it is relevant.<sup>62</sup>

From Lemke's description of "[t]he dominant theory of learning that guides educational practice in our society," we can relatively painlessly extract a formal name for a theory that appears to be the lynchpin or cornerstone of the mentalist/cognitive horizon: *abstract conceptual learning theory*. For our purposes, then, the language of abstract conceptual learning theory should be added as yet another layer to our two already existing layers, that is, to the five discursive features of learning with understanding (see Chapter 1) and the four cognitive affordances (see previous section). If we look carefully at Lemke's brief description of abstract conceptual learning theory, we can quickly identify all five of the discursive features at work including the *knowledge base*, *coherence*, *transfer* and *extrapolation*, and *cognition*.

Elaborating abstract conceptual learning theory even further, Lemke helps familiarize us with the types of sensibilities and commitments needed to sustain a mentalist/cognitive

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62. Lemke, "Semiotics and the Deconstruction," para. 30.

construction of learning with understanding. If you ask most science teachers what their main goal is, Lemke explains, they will probably say, “for my students to understand the basic concepts of physics, chemistry, biology, or whatever other field is being studied.”<sup>63</sup>

When they say things like this, Lemke adds, we can be relatively sure that abstract conceptual learning theory is both present and active. “The critical words here are ‘understand’ and ‘concept,’” Lemke writes, “and both of these terms assume a fundamentally *psychological* approach to learning. They belong to the tradition of *mentalism*, in which concepts are mental objects and understanding is a mental process.”<sup>64</sup>

In this particular view of learning, Lemke writes,

a concept exists outside of all language, and indeed outside of all languages, in the sense of representational systems like images, symbols, actions, etc. It exists in some imaginary “lingua mentis” [...] a “language of the mind.”<sup>65</sup>

In this view of learning, he continues, teachers often expect their students to,

be able to “discover” the concept of energy for themselves; they should be able to “generalize” from different instances of energy and “see” the conceptual unity of the various representations [...] It should be possible for them to “leap” to the abstraction because in some sense that abstraction is real, and is always naturally there as a target for their leap.<sup>66</sup>

In this view of learning, Lemke writes elsewhere, teachers “assume that students can learn abstract principles by induction from examples and by descriptions of abstract properties

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63. Lemke, “Teaching All the Languages,” para. 1 (emphasis in the original).

64. Ibid, para. 1 (emphasis in the original).

65. Ibid., para. 23.

66. Ibid., para. 29.



and relations.”<sup>67</sup> Furthermore, Lemke adds, teachers expect students to “‘catch on,’ to formulate abstract generalizations that will then apply to new and unfamiliar examples,” and to “‘transfer’ the abstract principle to new settings.”<sup>68</sup>

The approach of abstract conceptual learning theory is clearly a psychological one. However, as we will soon see later in this chapter and also in Chapters 3 and 4, a psychological approach to learning about science is sometimes not aligned, and sometimes not compatible, with a scientific approach to learning about the world. Furthermore, when Lemke writes about *abstract concepts, abstract principles, and abstract properties and relations*, when he writes about *discovery, generalization, induction, understanding, and conceptual unity*, and when he writes about *application, transfer, lingua mentis, and leaping to new settings, specific situations, and unfamiliar examples*, by now readers should recognize that we are in highly familiar discursive territory. This is precisely the same mentalist/cognitive territory that we encountered when examining the Reform Age construction of learning with understanding in Chapter 1. Because many of the discursive features and commitments of abstract conceptual learning theory are homologous to both the five discursive features of learning with understanding and the four cognitive affordances, we can, with very little effort, see clearly the threads of complementarity between them. Collectively, these three overlapping discursive registers underpin the mentalist attitude; they are part of the same discursive family; and they help constitute the cognitive horizon of expectations. However, a few of important questions still remain: How did this particular horizon come to dominate the Reform Age in Science

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67. Lemke, “Semiotics and the Deconstruction,” para. 37.

68. Lemke, “Semiotics and the Deconstruction,” para. 40.

Education? By what means did it enter the Reform Age and for what purpose? And perhaps more importantly, are there possible horizons of expectations for learning with understanding that are something *other than* mental/cognitive?

To begin the process of generating satisfactory answers to these questions and others, we briefly turn our attention to another educational theorist, Tom Popkewitz, and his concept of “the alchemy.”<sup>69</sup>

### **The Alchemy of School Subjects**

Popkewitz’s concept of the alchemy directs attention to those practices in modern teaching and teacher education that help transform the disciplinary subjects into school subjects. In other words, it directs attention to those practices in schooling that help transform, say, the content of biology into the course “BIO 100” or the content of algebra into the course “MTH 101.” As Popkewitz explains,

An odd thing happens on the way to school. As the sorcerer of the middle ages sought to turn lead into gold, modern teaching and teacher education produce a magical transformation in the disciplines of the sciences, social sciences, and humanities [...] I call this transformation an alchemy.<sup>70</sup>

Popkewitz’s concept of the alchemy draws our attention to what happens to disciplinary knowledge as it is moved from scientific laboratories and into school classrooms. In order to render subject matter knowledge and practices compatible with the realities of schooling—the school timetable, conceptions of childhood, and organizational theories of teaching—they must

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69. What Popkewitz often calls “the alchemy” he also refers to as “the alchemy of pedagogy” (Popkewitz 1998) and “the alchemy of school subjects” (Popkewitz 2002; 2004). In this text, I use all three terms interchangeably.

70. Popkewitz, “Alchemy Makes Inquiry,” 262.

be translated, ordered, reconfigured, transformed, and/or transmogrified. After all, as Popkewitz observes, “Children are not scientists or mathematicians.”<sup>71</sup> For Popkewitz, then, the alchemy of school subjects is unavoidable. The practical reality is that there must be *some* kind of alchemical activity that takes place as the disciplines are transported and integrated into classrooms because alchemy is “a necessary part of schooling.”<sup>72</sup>

But how does the concept of the alchemy help us account for the construction of learning with understanding as largely mental/cognitive? According to Popkewitz, the stark reality of modern schooling is that the governing principles of the alchemy are no longer those of science or mathematics “but those of pedagogy.”<sup>73</sup> To put this differently, Popkewitz claims that the transformation of disciplinary fields such as biology and chemistry are more likely to be determined by disciplinary tools from *outside* biology and chemistry. These tools—or what Popkewitz sometimes calls “translation tools”—include but are by no means limited to disciplinary assumptions, commitments, concepts, and theories. In other words, Popkewitz suggests that the ‘hard(er)’ sciences are more likely to be disciplined by ‘soft(er)’ sciences as they make their way into school and classrooms rather than their own disciplines. These circumstances are neither inherently good nor bad, Popkewitz notes, but it practice it means that the governing principles of science are not the governing principles of science education—instead, they are the governing principles of, for example, social sciences such as psychology.<sup>74</sup>

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71. *Ibid.*, 262.

72. Popkewitz, “The Alchemy,” 4.

73. *Ibid.*, 4.

74. For a provocative and insightful account of the historical intersection of psychology and teacher education, see Fender 2012.

And when this happens, Popkewitz observes, events transpire and practices emerge which are at the same time both “magical” and “odd.”<sup>75</sup>

### **Abstract Conceptual Learning Theory: A Tool for Translation**

Now, let us together consider abstract conceptual learning theory when cast in light of the alchemy the school subjects.

At the end of Chapter 1, we saw that learning with understanding in the Reform Age is often conceptualized as follows: To learn with understanding is to be able to mentally demonstrate the ability to apply, extend or transfer a deep, rich knowledge base to situations beyond the original context of learning. When seen through the lens of the alchemy, we should see this particular definition as the result or product of an alchemical transformation. This product presupposes that there is something outside of schools and classrooms that we might recognize as ‘authentic’ scientific learning with understanding. In other words, the alchemy asks us to assume that there are actual moments or practices during which scientists can be seen applying, extending or transferring their existing scientific knowledge to new problems, strange events, and/or unfamiliar phenomena. In reality, there are such moments and practices. We in science education commonly recognize them in both formal and informal conversation as scientific “research,” “inquiries,” and perhaps even as “investigations.” The alchemy asks us recognize these authentic moments and practices as the starting or ‘raw’ material for a necessary alchemical transformation in large part because the realities of research science and scientists are different from those of classroom teachers and students.

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75. Popkewitz, “Alchemy Makes Inquiry,” 262.

What I want to suggest here, then, is that Lemke has identified for us one of the main translation tools for this alchemy. Abstract conceptual learning theory—which Lemke identifies as a “fundamentally *psychological* approach to learning,” as belonging to “the tradition of *mentalism*,” and as a “*cognitive* model of science education”<sup>76</sup>—is precisely what helps transmogrify the raw material of how scientists learn with understanding into the refined product of how science students learn with understanding in the Reform Age. Not only that, but abstract conceptual learning theory also helps give distinct shape and focus to how science professors and teachers teach for understanding. When considered in the light and shadows cast by the alchemy of school subjects, it is no great surprise that students are expected to demonstrate the ability to apply, extend or transfer a deep, rich knowledge base to situations beyond the original context of learning in ways deemed and described as mental/cognitive. It is also not surprising that in teaching science for understanding, professors and teachers spend a great deal of instructional time and energy trying to target and improve their students’ mental and cognitive abilities. As is the case with every exercise of the alchemy, the translation tools in use make some actions, perspectives, and pedagogies more likely while simultaneously rendering others less so. An alchemy using abstract conceptual learning theory and the concepts of application and transfer as its main translation devices will produce certain kinds or styles of teaching for understanding. However, there is no guarantee that those psychological styles will always resemble scientific styles. For example, translation tools such as application and transfer make it more likely that teachers will ask their students to apply or transfer their deep, rich knowledge base to situations beyond the original context of learning with the help of

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76. Lemke, “Teaching All the Languages,” para. 1 (emphasis in the original).

mental or cognitive faculties *instead of with the help of other types of faculties*. These particular translation tools also make it more likely that teachers will ask their students to enlist mental or cognitive allies during learning *instead of recruiting other types of allies*. In other words, these particular translation tools make it more likely that teachers will limit or bound their pedagogical designs, decisions, and other actions according to the possibilities articulated by a mental or cognitive horizon *instead of those articulated by other types of horizons*.

In practice, the use of abstract conceptual learning theory as a tool with which to translate scientific learning with understanding into classroom learning with understanding makes it extremely difficult to conceive of learning with and teaching for understanding as something other than psychological, mental, and cognitive. In other words, when abstract conceptual learning theory is directing and disciplining the alchemy of scientific learning with understanding, a mental horizon appears as though it is logical, reasonable, commonsensical, and perhaps even inevitable. It communicates the unnecessary impression that psychology, mentalism, and cognition are part of a 'natural' order of things or 'fundamental' state of affairs.

If there is one thing we learn from the Popkewitz's concept of the alchemy, however, it's that alchemists have a choice when it comes to selecting their translations tools. One of the great values of Popkewitz's concept is that it helps make possible the following 'What if...' questions:

What if...

- Science educators were to choose a different kind of tool of translation for the alchemy of how scientists learn with understanding?

- Science educators were to move away from the governing principles, concepts, and theories of psychology, mentalism, and cognition?
- The notion of mentality was temporarily removed from the Reform Age definition of learning with understanding?
- Science students were able to demonstrate the ability to apply, extend or transfer a deep, rich knowledge base to situations beyond the original context of learning without having to do so mentally?
- The governing principles, concepts, and theories of, say, scientific research were allowed to inform and infuse our notion of learning with and teaching for understanding?
- Science education allowed scientific tools to be the basis for a new alchemy?

In accordance with the original goal stated in the Introduction, if we want to try and help science professors and teachers find ways to improve student performance on application or transfer questions in the future—in other words, *to learn with understanding*—then one course of action would be to disturb or disrupt the possibilities articulated by a mental or cognitive horizon. To do so would have the effect of distracting us—at least for the moment—from maintaining too strong or sharp of a focus on mental faculties and allies. The next major section of this chapter is devoted to the negative, critical task of such a disruption, distraction, and provocation. Once readers are left feeling satisfactorily disrupted, distracted, and provoked, only then can I begin the positive, constructive task of exploring new possibilities for the alchemy of learning with and teaching for understanding.

## A Critical View of the Mental Horizon

In the previous section, we saw that learning with and teaching for understanding in the Reform Age has come to be associated with a mental/cognitive horizon of expectations. We saw that this construction is a product of an unavoidable alchemy of school subjects that transforms how scientists learn with understanding into something different. Finally, we saw that this alchemy relies on psychological and cognitive translation tools such as abstract conceptual learning theory and concepts such as “understanding,” “application,” and “transfer.” These tools give a distinct shape to what it means to learn with and teach for understanding. They help actively limit or bound the thoughts, speech, and other actions of both teachers and students. Not only do they help define an envelope of possibilities, but they also help define an envelop of probabilities as well, and those probabilities make science more accessible to some students than to others.

In the remaining sections of this chapter, I take a critical approach to this mental/cognitive horizon. Once again drawing heavily from the scholarship of Lemke and Popkewitz, I offer a challenge to the association of learning with and teaching for understanding with a mental/cognitive horizon. In using the term *critical*, I mean to say that I aim to render certain commitments and assumptions of this historically situated discourse explicit. By rendering these elements explicit, they become available to various modes or styles of critique. Among other uses, critique can help a) delineate the existing boundaries of a current cultural practice with increased precision, b) draw attention to various ironies, problems, obstacles, challenges, discrepancies and/or conundrums posed to and faced by the



members of a particular community, and c) remind the members of a particular community that it is possible to think, speak, and act differently.

### **Raising Questions about Cognition**

To ask science educators to distance themselves from a mental/cognitive horizon is to risk professional heresy. Such is the depth of support given to the power and promise of the mind/brain in science education. We already have one sensible reason to take this risk, however, and it comes to us in the form of the Mutant Spinach Question. Let us not forget the fact that eighty percent of the fall 2006 Bio101 students answered the Mutant Spinach Question incorrectly.<sup>77</sup> There is at least one more sensible reason to add to this list of grievances. This one is related to cognition. Despite the aforementioned affordances of the brain, which included capacity, portability, speed, and privacy, there are at least two widely acknowledged cognitive constraints shackling this so-called ‘super’ organ. First, the human brain’s working or short-term memory is widely reported to be capable of holding somewhere between five to seven “chunks” of information depending on the category and features of the chunks.<sup>78</sup> This characteristic of the brain could be seen as a constraint on students’ ability to learn with understanding. Depending on the size, structure, and integrity of a chunk (a construct that is still hotly debated among cognitive scientists), this characteristic could hinder

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77. Because the Mutant Spinach Question was a multiple-choice question, the Bio101 professors openly acknowledged that there was no way of knowing how many of the twenty percent of students who answered the Mutant Spinach Question correctly got it right “for the right reasons.” In other words, they were fully prepared to concede that the twenty percent of students who answered question “52” correctly—and for the right reasons—was in reality probably something less than twenty percent.

78. See Miller, G.A. "The Magical Number Seven Plus or Minus Two: Some Limits on Our Capacity for Processing Information." *Psychological Review* 63, no. 2 (1956): 81–97. (Re-published in *Psychological Review* in April 1994.)

students' ability to efficiently access and make use of the deep, rich knowledge base deemed necessary to carry out learning with understanding. Second, a new generation of high-resolution neuroimaging techniques has prompted some researchers to claim that the human brain's complexity is beyond both imagination and belief.<sup>79</sup> The task of mapping the brain so as to better display its many levels (and layers) of both structural and functional complexities is seen as so challenging, that a Nobel Prize winning brain researcher, Eric Kandel, had this to say of U.S. President Barack Obama's 2013 announcement of the BRAIN project (Brain Research through Advancing Innovative Neurotechnologies): "Going to the moon – I don't mean to in any way minimize it – was in part an engineering project. This [BRAIN project] is going into the unknown. This is like Columbus discovering America, if you will."<sup>80</sup> This particular characteristic of the brain could be seen as a constraint on students' ability to learn with understanding. Such complexity could hinder the ability of researchers in science education to know with precision where in the brain the many facets of learning with understanding occur (not to mention how).

Admittedly, our list of grievances is rather short—in fact, we now have two. Most science educators, however, will require a lengthier list of grievances before they begin to consider distancing themselves from such a long-standing mental/cognitive horizon. For

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79. Stephen Smith, a professor of molecular and cellular physiology described the brain's complexity this way: "One synapse, by itself, is more like a microprocessor—with both memory-storage and information-processing elements—than a mere on/off switch. In fact, one synapse may contain on the order of 1,000 molecular-scale switches. A single human brain has more switches than all the computers and routers and Internet connections on Earth." Moore, "Human Brain," para. 7 (see inset). This fact is particularly impressive when considering that in the cerebral cortex alone there are roughly 125 trillion synapses.

80. Pathe, "Obama Hopes," para. 5.

assistance in this endeavor I return to the work of Lemke, and later to Popkewitz, who will each help us populate the list with additional grievances.

### **Raising Questions about Abstract Conceptual Learning Theory**

Let us quickly review what Lemke said about abstract conceptual learning theory (hereafter ACLT). First, ACLT is the dominant theory of learning that guides educational practice in our society. It says that what people need to learn are abstract concepts, which they apply or transfer to a wide variety of specific situations. Second, nearly everyone is convinced that abstract conceptual learning is the most powerful form of learning. Therefore, the problem of teaching can be formulated as follows: how can we get even more students to successfully learn even more abstract concepts? Third, because ACLT foregrounds both “concepts” and “understanding,” it assumes a fundamentally psychological approach to learning. It belongs to the tradition of mentalism, in which concepts are mental objects and understanding is a mental process. In more contemporary terms, it belongs to a cognitive model in science education. Fifth, in this view of learning, concepts exist outside of all language. They exist in some imaginary “*lingua mentis*” [...] a “language of the mind.”<sup>81</sup>

In practice, Lemke reports that this particular construction of ACLT produces a style of science teaching in which:

- Teachers teach abstract science concepts by demonstrating how they apply to several different situations until their students catch on or generalize and get the concept at an

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81. Lemke, “Teaching All the Languages,” para. 23.

abstract level. Once this happens, they assume their students will then be able to transfer that knowledge, that is, to use the concept wherever it is relevant.

- Teachers expect their students to be able to a) *discover* science concepts for themselves, b) *generalize* from different instances of the concepts, c) *see* the conceptual unity of a science concept among its various representations, and d) *leap* to the abstraction because in some sense that abstraction is real, and is always naturally there as a target for their leap.
- Teachers assume that students can learn abstract principles by induction from examples and by descriptions of abstract properties and relations.
- Teachers expect students to a) catch on, b) formulate abstract generalizations that will then apply to new and unfamiliar examples, and c) transfer the abstract principle to new settings.

When reading these statements, we should see that ACLT tends to push entities such as *knowledge, thinking, concepts, abstraction, reasoning, logic, and understanding* (as well as other entities) into an existence defined largely by qualities such as invisibility and immateriality. Qualities such as these tend to render entities such as knowledge and understanding incredibly difficult for students, teachers (including teacher educators), and researchers to see and touch. In some ways, these particular qualities tend to render highly valued entities as individualized, secretive, clandestine, undocumentable, and universal (among other renderings). And yet, knowledge, thinking, reasoning, and understanding are some of the most celebrated and promoted allies in the movement to reform all of science education.

To take a mentalist approach to entities such as knowledge, thinking, reasoning, and understanding is to make a choice that privileges individuality, secrecy, clandestinity, undocumentability, and universality over other qualities. In other words, to take a mentalist approach to these entities is to be selective and exclusive. It limits our conceptions of what these entities can be to a culturally and historically specific set of values, ethics, assumptions, and beliefs. Lemke helps us contextualize this line of critique explicitly within science education:

Of course students do independently construct some kinds of [conceptual] similarities between situations on their own. These may agree with those constructed by the discourses and practices of science or they may not. The odds are not in the students' favor. When students do effectively and more or less independently recapitulate the history of modern European science, it is largely because they are so positioned within contemporary society that they have already begun to construct some of the higher-order patterns that characterize how our *dominant cultural tradition* approaches certain kinds of problems. This will be much more commonly the case for students of *upper-middle class cultural background* than for students who are not daily immersed in *the dominant subculture of our society*, the one that dictates the curriculum. It is not evidence of superior intelligence, but of *privileged cultural positioning*.<sup>82</sup>

For Lemke, the set of values, ethics, assumptions and beliefs that define—and thus place limits on—our current approach to entities such as knowledge and understanding are mostly those of “upper-middle class” cultural backgrounds. According to this logic, those students from backgrounds outside of the upper-middle class are more likely to struggle in educational moments in which knowledge and understanding are defined exclusively as mental and cognitive. On the other hand, this same logic also makes it possible to formulate a reverse argument: those students from backgrounds outside of the upper-middle class are more likely

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82. Lemke, “The Missing Context,” para. 22 (emphasis added).

to find greater success in moments in which knowledge and understanding are defined as something other than mental/cognitive.

To define entities such as knowledge and understanding as something other than mental or cognitive requires a disruption of abstract conceptual learning theory. To disrupt ACLT one needs to revise the psychological notions of the “concept” and “abstraction.” Only then can ACLT be made more inclusive and less constraining for teachers and students. If ACLT can be given permission to value other styles of learning, including and especially non-psychological or empirical styles of learning, then we will have succeeded in making learning with and teaching for understanding more inclusive educational practices. Abstract conceptual learning theory doesn’t have to be so individualized, secretive, clandestine, rationalistic, and universalized. This historically and culturally specific formulation of ACLT is not inevitable. It can be different. It can be otherwise. More specifically, it can be more inclusive, more empirical, and more scientific.

### **Raising Questions about Psychology**

The histories of psychology and science education are entangled in complex ways. Fortunately, Popkewitz has already done a fair bit of disentangling for us—at least enough to allow us to continue to raise doubts about the suitability of the use of translation tools from psychology.

When speaking earlier of the alchemy of school subjects, it was said that because so many of the translation tools used in science education originate in the psychological sciences, science education frequently ‘minds’ the gaps between scientists’ science and school science. Another way of saying this is that when it comes to science teaching and learning, the

mind/brain is still the primary object of interest and affection. For Popkewitz, however, we should perceive this practice of minding the gap between disciplinary fields and school subjects from at least two viewpoints.

First, we must recognize that the use of psychological tools to translate disciplines like science is neither inherently good nor bad. Instead, the use of such tools should be viewed as having certain affordances and constraints. Whether or not a particular psychological tool is an affordance or a constraint can depend largely on a variety of issues including pragmatic (what is the desired outcome?) and socio-political (who benefits? who doesn't?) concerns. For example, Popkewitz goes to great lengths to show how the governing principles of psychological and social psychological concepts and tools are well suited to the tasks of normalization and division.

The relocation of school subjects into psychology inscribes *divisions* that locate the child who does not have the dispositions and sensitivities inscribed in the alchemy. The *deviant child* is the child who does not learn the alchemy, does not follow the conduct of the alchemic problem solving, and thus needs to be rescued through better management and self-management. Few notice that the evidence of teaching school subjects, pedagogical content knowledge, and curriculum standards are about the psychological well-being or *the deviancy of the child*.<sup>83</sup>

In the field of education, most influences of psychology are regarded as authoritative and beneficial. However, Popkewitz's analysis helps open a possibility in which it is possible to recognize the limitations and exclusions of psychological approaches to teaching and learning. One limitation of abstract conceptual learning has already been mentioned: its privileges some

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83. Popkewitz, "Alchemy Makes Inquiry," p. 265 (emphasis added). See also Popkewitz 1998; 2004.

students while excluding others.<sup>84</sup> An example from my own experience in science education research might illustrate more clearly how psychological tools are effective tools for particular ends such as normalizing and sorting students.

### **In Pursuit of Model-Based Reasoners: An Example of the Alchemy in Action**

As a member of a university research team trying to improve teaching and learning in undergraduate biology courses, my team looked to research accounts of disciplinary science for tools and concepts commonly used by scientists in their daily practices. “Scientific models,” it was decided, were representational tools that seemed to do much of the intellectual heavy lifting in science.<sup>85</sup> In the process of bringing scientific models to the forefront of teaching and learning in introductory-level biology courses, we translated our initial ideas about scientific models into a taxonomy similar to Bloom's Taxonomy of Educational Objectives.<sup>86</sup> Bloom's Taxonomy, with its division of educational objectives into three "domains"—affective, psychomotor, and cognitive—has obvious roots in psychology. Each domain is subsequently divided into various "levels." Our taxonomic tool also included levels that we called "categories," which we then used to classify and group multiple-choice exam questions.<sup>87</sup> Our taxonomy helped us classify and order existing exam questions in used the course as Category 1, 2, 3 or 4 questions corresponding to the following descriptions:

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84. Another limitation, one that will be developed and discussed further in Chapters 3 and 4, is that abstract conceptual learning is not even the preferred style of inquiry for most scientists.

85. For example, see Rudolph 2000 and Giere 2004.

86. See Bloom et al. 1956.

87. See Richmond et al. 2010.



Category 1: Not directly associated with features of the specific photosynthesis teaching model as presented

Category 2: Describe or reproduce the specific model

Category 3: Manipulate the photosynthesis model in context

Category 4: Apply the model in situations beyond the original context

With the aid of additional translation tools such as statistics, we evaluated a longitudinal data set containing student performance on the four categories of exam questions. The results of our statistical analysis eventually helped us divide students into two new types or kinds of students: “model-based reasoners” and “non model-based reasoners.” In the language of the research group, those students who regularly answered the Category 4 questions correctly on exams were said to reason “more like scientists,” while those students who regularly answered the Category 4 questions incorrectly on exams were said to reason “more like students.”

The alchemical path on which our research group traveled should by now be evident. We subjected scientific models to an alchemical reaction by way of the use of translation tools from both psychology and statistics. Along the way, we created an efficient means of normalizing and sorting both the exam questions (into four categories) and the students (into two categories). As a result of this particular alchemy, new potentials were created for the governing of each of these two entities. If they wanted to, the professors could exert new forms of governance on the test questions. For example, they could select certain questions for deletion, revision, or promotion based solely on their “Category” status. If they wanted to, the professors could also exert new forms of governance on the students. For example, they could identify certain students as candidates for either “advanced study” or “remediation” based

upon their newly earned status as either model-based or non model-based “reasoners.”<sup>88</sup> In other words, one of the outcomes of our study was that we created a new reality in which certain questions with particular traits and certain students with particular traits could be subjected to educational practices that they had never previously encountered.<sup>89</sup>

More generally, when tests ask students to display knowledge they have never been explicitly taught, it suffices to say that those test questions privilege some students and exclude others. Those whose cultural experiences match those of the instructors will have prior knowledge that puts them at an advantage. The test questions assume a trajectory of inference that is particular to a specific historical and cultural subgroup. This assumption of abstract conceptual learning, then, functions to normalize and to sort—it includes some styles of thinking and excludes other styles.

One may be inclined to label Popkewitz's work as anti-division, anti-normalizing, and anti-governance. To that charge, however, Popkewitz explicitly states that psychological concepts and theories “are not necessarily bad and may have importance in the governing of schooling.”<sup>90</sup> Thus, Popkewitz is open to the possibility of the there being strong social and

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88. This anecdote offers us a way of understanding the concept of *governmentality* that is somewhat different from Foucault’s use of the term. That is, when the means of crossing a gap between scientists' science and school science is conceptualized primarily as the 'minding' of it, one of the end results is that researchers and teachers gain in their ability to direct the minds of a student or group of students towards certain ends—in other words, they gain in their ability to *govern* their students' *mentality*.

89. Another way to describe what my research group did with the scientific models is that we engaged in the practice of “psychological reductionism” (see Popkewitz 2004, 27). That is, we took a complex cultural practice that enables scientific knowledge production and reduced it to a psychological concept—*model-based reasoning*—that we then used to divide, normalize, and govern students.

90. Popkewitz, “Alchemy Makes Inquiry,” p. 265.

political reasons for undergraduate science students to learn, for example, how to be "model-based reasoners" and how to improve their "model-based reasoning skills." The problem is that psychological concepts tend to govern teaching and learning to the exclusion of other approaches, and this narrow limitation has the effect of making science more accessible to some students than to others.

This last point, which addresses the potential desirability for students that can engage in a certain type of reasoning, finally brings us to the second of the two viewpoints that are critical for understanding Popkewitz's critical position on the minding the gap between disciplinary fields and school subjects. To recapitulate, his first viewpoint is that we must recognize that the use of psychological tools to translate disciplines like science is neither inherently good nor bad. His second perspective is that we must also recognize that the use of psychological tools may have functions originally designed for purposes other than translating disciplinary fields into school subjects. Or, as Popkewitz explains, "The psychologies of childhood, learning, and cognition are inventions that have different purposes from those of understanding and translating disciplinary knowledge into pedagogical problems."<sup>91</sup>

At this point, one might be tempted to reach the conclusion that Popkewitz is anti-alchemy. On the contrary, he writes, "The fact that an alchemy exists in schools is not surprising."<sup>92</sup> Furthermore, Popkewitz writes, "Alchemy is a necessary part of schooling."<sup>93</sup> Instead, what Popkewitz finds surprising and unnecessary is the "peculiar" school alchemy that relies on psychological/social psychological concepts and tools in its transformation of the

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91. Ibid., p. 265 (see also Popkewitz 1998).

92. Ibid., p. 262.

93. Popkewitz, "The Alchemy," 4.

disciplines for use in schooling to the exclusion of all other approaches. In its construction of pedagogies, Popkewitz argues that schooling has turned repeatedly toward psychologies of instruction, which he sees as intellectual tools that have little to do with the practices found in disciplinary fields such as science and mathematics.

Instead, he suggests an "unthinking" of the alchemy by turning to fields other than psychology. One candidate field he finds promising is Science Studies—a field constituted by a collection of sociologists, historians, economists, political scientists, philosophers, and anthropologists of science and technology. A consideration of Science Studies as a resource for the alchemy, Popkewitz explains,

requires different intellectual tools and strategies for thinking about and ordering the practices of an academic field than are found in current curriculum models [...] This alternative reading would focus on relations or assemblages that construct disciplines, historicizing how the subject is constructed and changes over time, and on the epistemes or the systems of thought that make possible particular types of knowledge in a field. That is, pedagogy needs intellectual tools that consider the relation between the knowledge (concepts, generalizations) and the cultural practices that enable the production of that knowledge.<sup>94</sup>

For Popkewitz, to engage Science Studies as a resource for pedagogical alchemies does not eliminate the problem of alchemy because disciplinary fields must undergo some sort of transformational processes on their way into the spaces of schooling. Additionally, it does not deny a place for psychology/social psychology in curriculum construction. Rather, as Popkewitz writes,

it suggests that in constructing pedagogies we should turn to fields of scholarship concerned with interpreting the intellectual styles, rules of thought, and practices through which knowledge is generated in academic disciplines. The psychologies of

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94. Ibid., 27.

instruction in standards-based reforms are inventions to normalize the child and thus are inadequate for purposes of translating mathematics, science, or other academic fields into curriculum projects.<sup>95</sup>

To summarize, Popkewitz's problematization of the performance of psychological alchemies in contemporary education is twofold. First, he states that while the alchemy of school subjects may be unavoidable, a psychological or social psychological alchemy is a choice. Even though disciplinary fields must undergo some sort of transformation for use in schools, the governing principles of the alchemy need not be those of psychology/social psychology. There are other options. There are other pathways one can chose. In other words, the alchemy does not require minding the gap between disciplinary fields and school subjects. Second, there are ways to unmind—or, as Popkewitz writes, to "unthink"—the gap. Much research in Science Studies examines the practices through which knowledge is generated the sciences. This discipline can also provide translation tools for the alchemy. Rather than being well suited to normalizing, dividing, and governing individuals, however, Science Studies offers concepts and tools designed for other purposes (I will discuss some of these purposes in Chapter 4).

What we should take from this brief (and limited) summary of Popkewitz's position is this: historically, the psychological sciences weren't intellectual practices designed for the purpose of understanding, say, fields of practice such as science and mathematics. Instead, they were concerned with the interior of individuals, as well as the rules and standards of "reason" that enabled human progress and self-betterment. In other words, historically the psychological sciences weren't concerned with the practices of scientists trying to learn with understanding. They were concerned with refashioning a new type of citizen who would be more 'fit' to the

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95. Ibid., 27.

current (and future) times—individuals who would be more aware of their individual, subjective selves—including their desires, affects, attitudes, and bodily practices.<sup>96</sup>

### Summary

And so we return to a question I raised earlier in the chapter: Is it possible that our current assumptions about understanding might produce obstacles and/or undesirable effects for those teachers trying to teach for understanding, as well as those students trying to learn with understanding? My simple answer is, *Yes. Absolutely. Without a doubt.* ACLT privileges some ways of thinking about science and excludes other ways of thinking about science, so a mentally- or cognitively-committed ACLT is not a productive theory or model to meet the widely heralded goal of ‘science for all Americans.’ If science educators were serious about the goal of science for all, they would give serious consideration to ways of including more students and excluding less of them. One way they might do this is by considering an alchemy of scientific understanding that is not informed by the psychological sciences. Instead, they might consider an alchemy that is informed by Science Studies.

Consider for a moment the simple observation that every day the Bio101 students come into the classroom they see things, touch things, do things, and leave with things in their arms, hands, and book bags. On the day of the exam, however, what they can see, touch, and do in class and what they can bring with them to class is much more constrained. This is because learning with understanding is enacted by its participants as if it were a mental or cognitive practice and not a physical or material one. At the same time this construction of understanding draws attention to entities that are both invisible and immaterial (e.g.,

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96. For Popkewitz, people’s desires, affects, attitudes, and bodily practices count as the “soul.”

knowledge, concepts, reasoning, etc.), it effectively draws attention away from entities with more visible and material constitutions (e.g., handouts, notes, textbooks, etc.).

Question “52,” the Mutant Spinach Question, is an excellent example of a mental/cognitive horizon of expectations in action. When nearly eighty percent of the students answer the question incorrectly on the test, the professors immediately seek agents for the widespread failure in the mind/brains of their students. They talk about things such as “misconceptions,” “misunderstanding,” and “procedural display.” Unfortunately, attempting to penetrate the minds/brains of almost four hundred undergraduate students is too daunting of a task. The instructors quickly become frustrated because they don’t seem to know what their students were *thinking* and how they were *reasoning* during the exam—it’s no wonder, the entire class sat in almost complete silence during the exam. “If only we could get inside of their heads,” one of the Bio101 professors once lamented to me after the exam, “If only we could see what they were thinking during the exam.” In this instance, the professors locate their students’ lack of understanding in a space that the professors have little empirical access to—that of the mind/brain. Understanding, which is so often discussed as one of the more paramount phenomena in contemporary science education reform, is treated as if belonged exclusively to the domain of psychology. However, psychology studies the inner world, which is a different kind of empirical work compared to studies in say, biology and anthropology. Could not a biologist help render a organismal horizon of expectations? Could not an anthropologist help render a cultural horizon of expectations? What might happen to learning with understanding if it were to undergo an alchemical transformation that was something other

than psychological? What might happen to teaching for understanding if it were to undergo an alchemical transformation that was something other than cognitive?

In the next chapter, we will try to confront these issues and more by following an anthropologist into the classroom while he studies the application moment. He happens to be an anthropologist of science, which allows him to make some interesting comparisons between how learning with understanding unfolds in a classroom (during a pedagogical expedition) and in Brazil (during a scientific expedition).



### CHAPTER 3 A HORIZONTAL SHIFT

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Since the turn of the century, scores of men and women have penetrated deep forests, lived in hostile climates, and weathered hostility, boredom, and disease in order to gather the remnants of so-called primitive societies. By contrast to the frequency of these anthropological excursions, relatively few attempts have been made to penetrate the intimacy of life among tribes which are much nearer at hand.

—Bruno Latour & Steve Woolgar,  
*Laboratory Life*

Science can teach us [...] no longer to look around for imaginary supports, no longer to invent allies in the sky, but rather to look to our own efforts here below to make this world a fit place to live in.

— Bertrand Russell, *Why I Am Not a Christian*

As mentioned in the introduction, the main purpose of this dissertation is to help professors find new ways to improve students' ability to apply their existing knowledge to novel situations and new, unfamiliar events—in other words, to help them find new ways to improve students' ability to acquire meaningful, conceptual, and/or enduring understanding. To begin this daunting task, I've created a thick description of the application moment in the style of anthropology. I am not an anthropologist, but describing the application practice in an anthropological style helps me render certain features of the application moment more readily visible to readers than they might be rendered in other styles (e.g., sociology or psychology). Once visible, these selected features can then be subjected to a variety of scholarly practices

such as analysis, synthesis, reflection, and critique (among others). Thus, this chapter aims to destabilize how understanding is often understood in mainstream science education discourse and to create an initial opening for new alliances and different possibilities.

### An Anthropologist in the Classroom

Rather than penetrating deep forests, living in hostile climates, and weathering hostility, boredom, and disease in order to gather the remnants of so called primitive societies, an anthropologist attempts to penetrate the intimacy of life among tribes which are much nearer at hand.<sup>97</sup> Looking for research opportunities near or within his own university, he succeeds positioning himself as an observer in an undergraduate biology course. The two veteran instructors, both professors and both microbiologists, generously grant him almost unlimited access to their course. As well as the thrice-weekly classes, for example, the professors also invite him to attend their weekly meetings in which they often plan and discuss—frequently joined by other science educators and researchers—course-related issues about teaching- and learning-related issues.

The anthropologist is particularly interested in moments in which the professors expect their students to extend or apply existing knowledge to novel situations or new, unfamiliar phenomena. The reason why he is interested in these moments is because they are of great interest to the professors. But it's not just the two professors who express a deep interest in them. As it happens, a sizeable portion of a broader group of science educators is interested in them too. For example, the professors and their colleagues give the anthropologist copies of

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97. The wording of this opening sentence is inspired by two sentences written by Bruno Latour and Steve Woolgar in *Laboratory Life* (see Latour and Woolgar 1986, 17).

many articles and books in which a consistent message is present: U.S. science students need to learn how to apply their existing knowledge to novel situations and new, unfamiliar phenomena. It's almost always part of something the texts mention when they discuss terms such as "science literacy" and "scientific inquiry." It's also an important part of something the texts mention when they discuss "learning with understanding" and "the transfer of learning." In these texts, the future health and well being of the students—as well as that of their nation—is repeatedly said to depend on students' ability to learn with "deep," "rich," "meaningful," "conceptual" and/or "enduring" understanding.

As far as the anthropologist can tell, this is what teaching for and learning with understanding looks like in this particular course: For approximately three to four weeks, students report three times per week to a large, auditorium-styled meeting space. Under the tutelage of their professors, they embark on a pedagogical expedition. During much of their expedition together, students and instructors spend the majority of their time in class looking at and talking about "figures." During one stretch of three continuous class periods that the professors call "the topic of photosynthesis" (or sometimes just "photosynthesis"), the professors display for their students no less than 45 different figures—an average of one figure every 3.33 minutes. "Figures" are what the professors call the visible displays—including illustrations, equations, drawings, diagrams, graphs, photographs, etc.—that they project onto a large, theater-sized projection screen located at the front of the auditorium. Many of the students happen to possess full color reproductions of these figures on the pages of a textbook that many, but not all of them, bring to class. By the end of each fifty-minute class period or "lecture," many of the students have highlighted, marked on, underlined, and/or otherwise

annotated the figures in their textbook in ways that are similar to those shown on the projection screen by the professors. Those students not producing a figure-laden textbook during class often attempt to draw the annotated figures in their notebooks from scratch.

If there is some sort of marketplace or financial exchange operating within the confines of classroom, the anthropologist feels that the figures are likely one of the most highly valued, highly traded commodities. As it happens, there is no such visible marketplace, but nevertheless the professors bring new figures to class with them to almost every day. They take great care when selecting, sequencing, and displaying them to/for their students. The anthropologist sees evidence of this care in “lecture outlines” given to him by the professors. These outlines make it clear that the professors spend substantial portions of time outside of classroom thinking about, selecting, and ordering the different figures they show to students in the lectures. For their part, the students go to great lengths during class to either recreate the figures presented by the professors or to annotate them if the figures are already contained within the textbook they possess. Quite noticeably, although the students leave many items behind them on the auditorium floor (e.g., newspapers, food wrappers, and drink containers) they rarely ever—at least purposely—leave any figures behind.<sup>98</sup>

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98. On at least one occasion the anthropologist runs into a group of students from the class at the university library. Recognizing him from his presence in the lectures, they stop him as he’s walking by the room they’ve reserved for something they call their “Bio 101 Study Group.” He enters the windowed room to say hello and immediately notices that the large conference table around which the students are all seated is littered with figures from the course. On the wall is a chalkboard. This surface, too, is cluttered with crudely drawn reproductions of many of the figures strewn across the table (as well as some that are not).

Approximately, every three or four weeks, the professors and students typically set aside a day to depart from this routinized routine in which figures are presented, collected, and annotated. This departure is called a “midterm exam,” and on these days the routine practices of the participants take a turn for the different. There are a total of four exams during each fifteen-week semester—three “midterm” and one “final” exam. Of particular interest to the anthropologist is the fact that each of the exams contains items (or “multiple-choice questions,” as the professors and students call them) in which students are given the opportunity to prove to their professors that they’ve “mastered the course material.” Some of these questions ask students to apply their existing knowledge to novel problems or new, unfamiliar situations. Many of these questions even have unique names given to them either by the professors themselves or by some of their colleagues. For example, there is the “Virus Question,” the “Jared Question,” the “Radish-in-the-Light” question (as well as the “Radish-in-the-Dark question”), and the “Grape Question,” among others. One common feature uniting these questions is the fact that the professors have deliberately withheld mention of certain elements contained within them during the three- to four-week instructional phase of the course. For example, on the second of the three midterm exams the professors put before students a question about a “mutant strain of spinach” whose salient defect is the production of a set of “slightly permeable” membranes within its leaves. The professors and their colleagues know this question as the “Mutant Spinach Question.” By the professors’ own admission, in all of the classes and homework assignments leading up to the exam the students were never told about mutant spinach plants with malfunctioning or “leaky” membranes. Despite this deliberate omission, however, the questions are still posed to the students on the exam. According to the

professors, the Mutant Spinach Question tests whether the students “really, truly *understand*” the concept of photosynthesis.

As they did during the lectures, many students bring book bags and backpacks into the classroom on examination days. However, one of the major differences between lectures and examination days is that much of what students have in their bags and backpacks is never removed from them. The only empirical allies students are allowed to remove from their bags and put to use during the exams include *paper* (in the form of an inscribed paper exam given to them by the professors), a *pencil* (only No.2 pencils, however), a *wristwatch* (but there is also a clock for use on the classroom wall), and a university-issued *photographic ID*, but that is all.

While the students are allowed to use the paper, pencils, and wristwatches during the examination, they typically don't use the photographic ID until after they complete the exam. It turns out that the professors don't trust their own mental faculties to remember the names and faces of their nearly four hundred undergraduate students—including a handful of who only occasionally show up for classes in person. So, in an effort to ensure the integrity of the end-of-semester course grades, at the end of every exam the professors ask each of their students to prove their identity by means of triangulation. In other words, each student's true identity is held between three visible, material objects: (1) the *photographic ID* (which contains a photograph of the student, their legally established name (first and last), and a one-of-a-kind “student number” (a unique 9-digit alphanumeric code)), (2) a paper “*class roster*” provided by the university Registrar's office (which lists each student's legal name and university student number), and (3) the *face of the student* (the instructors concern is mainly for their students from the neck 'up'). Besides these three allies, any student attempt(s) to enlist other empirical

allies—e.g., enlisting other students or a personal notebook—is strictly forbidden. In fact, right before distributing the paper exams to their students, the professors often remind the students to place all their unapproved empirical allies safely away underneath chairs and/or into folders, purses, shoulder bags, backpacks, etc. As a final way of dissuading individual students from enlisting any *other* student’s exam paper as a potential exam ally, the professors tell students to, “Remember, be sure to keep your eyes on your own exam.”

A few days after the second midterm exam (“Exam 2”), the anthropologist is present when the professors receive a statistical summary of the Exam 2 results from the university scoring office. The anthropologist sees that the performance results of question “52”—the Mutant Spinach Question—immediately grabs the attention of the professors. As it happens, it turns out that nearly eighty percent of the students answered question “52” incorrectly. This percentage makes it the most missed question on the entire exam. Over three quarters of the undergraduate students failed to apply their existing knowledge to the novel phenomenon as the professors had hoped they would. In other words, the professors see this as a clear indication that—when given the opportunity to do so on the exam—more than three-quarters of the undergraduate students failed to demonstrate that they had learned the concept of the “light reactions of photosynthesis” with understanding.

### **Postscript to the Classroom Study**

Months later, sitting comfortably in his office and reading through his field notebooks, the anthropologist outlines a recurring practice he witnessed throughout the fifteen-week course. When asked by their professors to demonstrate that they could apply their existing knowledge to new situations or novel, unfamiliar problems—in other words, when asked to

demonstrate that they had learned important scientific topics or concepts “with understanding”—students were consistently put into moments or events in which they were required to place nearly all of their trust in their own *mental faculties*. Reminded by his field notes detailing the densely populous presence of visible, material “figures” in the lessons leading up to the examinations, the anthropologist is struck by the almost complete invisibility of these figures during the exam events.

A quick glance through the paper exams themselves—which, because he doesn’t fully trust his own memory, the anthropologist collected and archived during his fieldwork—confirms that the exams contained almost no visible, material figures within them. Eager to hear how the professors explain this absence, the anthropologist requests a follow-up interview with the professors. In it, he asks them about the absence of these empirical allies. During the interview, the professors are quick to draw the anthropologist’s attention to a *different* class of allies. Rather than bring empirical allies to exams, they tell him, their expectation is that students bring with them an almost unlimited number of mental allies for use. According to the professors, such allies go by names such as “logic,” “reason,” “facts,” “concepts,” “induction,” “deduction,” “analytical skills,” “critical thinking skills,” and “abstract thinking skills,” among others. Satisfied that he now has a more nuanced understanding of the various allies available for student use during exams—both *empirical* and *mental*—the anthropologist thanks the professors for their time and concludes the interview. He then records the following entry in his notebook:

In this undergraduate biology course, one of the ways that teaching for and learning with understanding can be described is as a series of three- to four-week progressions *from the empirical to the mental*. During the weeks leading up to an examination,



students and teachers typically gather around and devote much of their collective energy toward an almost continuous presentation of visible, material “figures.” These figures are at the center of much of what goes on in the classroom on a daily basis. On exam days, however, these same empirical figures must be kept out of sight, but not *out of mind*. In fact, it is the professors’ expectation—as well as their genuine hope!—that their undergraduate students find ways to efficiently and effectively internalize the once visible, material figures. Thus, within the context of this biology course, teaching for and learning with understanding can be described as a set of practices whose ultimate trajectory is the successful transformation (or *transfiguration*) of vast numbers of empirical allies into mental ones.

### An Anthropologist in the Field

Not more than a year after spending a semester in an undergraduate biology course, an anthropologist has the opportunity to study a team of research scientists working in a remote forest in the Boa Vista region of Brazil.<sup>99</sup> The scientists are there because they are confused by the distribution of plants species in the region. In this area, a particular species of fire-resistant tree has stopped adhering to the law of the land: instead of restricting its presence to the open savanna (its natural habitat) and the areas along the savanna/forest boundary (the edge of its natural habitat), one of the scientists, a local botanist, has also found this *same species* of tree as many as ten meters into the forest. In other words, she has found them living some distance away from its natural habitat. As the four scientists—a botanist, two pedologists (soil scientists), and a geomorphologist—record observations and collect representative samples of the area’s plants and soils, much as he did the previous year in the college biology course, the anthropologist records representative observations and collects representative artifacts as the scientists go about their daily work.

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99. See Latour 1999.

On the night before their first day in the field, the anthropologist is struck by an interesting parallel between the situation in Brazil and the one he encountered a year ago at the American university. Like the undergraduate science students, these scientists are also facing a novel problem. They are confronting a situation that is entirely new to all four of them. Like the students, these scientists need to apply their existing knowledge to an unfamiliar event. The anthropologist can hardly believe his dumb luck! Here, in the Boa Vista region of Brazil, he has the opportunity to witness how a group of research scientists engage in the construction of scientific knowledge. Whether or not it will result in enduring scientific understanding is something only time will be able to tell.

One of the things the anthropologist notices almost immediately is that this team of research scientists consistently *distrusts their own mental faculties*. Case in point: while watching the botanist at work, the anthropologist notices that she fixes little “tin tags” to the horizontal branches of individual trees.<sup>100</sup> Each tin tag has a number inscribed in it as shown in Figure 3.1.

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100. This anthropological account is taken from Latour 1995 and Latour 1999 (see esp. Chapter 2).



*Figure 3.1.* Photograph of a small tin tag affixed to the horizontal branch of a tree found within a field site in Brazil. Figure 11.3 (Latour 1999). (Reprinted with permission by the copyright holder.)

Why does the botanist deploy the small tin tags?

There are many reasons, but one is that *she does not trust her own memory* to reliably and accurately organize the objects found within her field site. She does not trust her mental faculties to remember the exact placements and identities of individual trees after leaving the study site. With over two hundred and thirty-four individual trees to remember it's no wonder

she distrusts her mind!<sup>101</sup> For this botanist, as well as for many research scientists on expeditions and in laboratories, too much reliance on mental abilities such as memory increases the potential for lasting doubt and uncertainty. Instead of (or in addition to) her mental faculties, this scientist places the bulk of her trust in wooden trees, tin tags, paper maps, and a grid of Cartesian coordinates inscribed into her field notebook. That is, in order to increase her understanding of the novel phenomenon she takes deliberate steps to *shift* the weight of responsibility from her mental faculties—which are less reliable, as well as more difficult for others to see and/or grasp—to a *more visible, more material, more mundane* ‘network’ of objects outside of her mind. In other words, she creates an empirical form of insurance. As the anthropologist learns over the course of the scientists’ fifteen-day expedition, given the choice between (on the one hand) firmly affixed tin tags plotted against a Cartesian grid created by the use of maps, notebooks, and surveying instruments and (on the other hand) nothing but their own cognitive faculties, uncertain research scientists like the botanist and her colleagues will choose former *every time*. Thus, the anthropologist concludes that in scientific practice it is not from mental allies that research scientists acquire certainty; it is not in cognitive allies in which they place their trust. Instead, she gains these value commodities from building and maintaining *a well-coordinated network of empirical allies*.

### **Postscript to the Field Study**

Months later, sitting comfortably in his office and reading through his field notebooks, the anthropologist reflects on the events he witnessed during the fifteen-day scientific

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101. Recall that the university classroom professors also distrusted their mental faculties when needing to verify the identity of nearly four hundred undergraduate students at the conclusion of the exams.

expedition. Satisfied that he now has a more thorough understanding of the work of a team of research scientists, he records the following entry in his notebook:

On this scientific expedition, one of the ways that scientists learn with understanding can be described as a fifteen-day engagement with empirical allies. Although it would be silly to deny that the scientists are engaged in thinking and reasoning, it is unnecessary to consider these important actions *as mental practices*. When confronted by a phenomena on the boundary of the Brazilian forest and savanna—a phenomena which they could not understand at first glance (or, for that matter, at second, third or fourth glance)—the team of scientists chose to apply their existing knowledge to a perplexing situation by deliberately shifting the weight of responsibility from their internal, mental faculties to a network of empirically observable objects and practices. It wasn't only the botanist who enacted this strategy. Her two pedologist colleagues enacted a similar strategy when looking at the characteristics of the soil beneath the trees. Rather than tin tags, they used shovels, core samplers, small, open-ended cardboard cubes, a modified wooden suitcase to organize the soil-stuffed cardboard cubes, and a number of other empirical objects—including some of the maps and notebooks used by the botanist. In practice, it appears as though the scientists' expectation of one another is that they find ways to efficiently and effectively externalize the perplexing natural phenomenon. Thus, within the context of this expedition, scientific learning with understanding can be described as a set of practices whose ultimate success depends almost entirely upon the coherent and careful coordination of *a vast army of empirical allies*. In the heat of an epistemological engagement, the scientific mantra amounts to this: mental allies can't be trusted.

Later, when comparing his accounts of the pedagogical and scientific expeditions, the anthropologist is struck by at least two differences between (one the one hand) those practices enacted by scientists to understand an unfamiliar phenomenon and (on the other hand) those enacted by two college professors and their students. First, when compared to the empirical allies enlisted by scientists in Brazil, the number and kind of empirical allies available for enlistment by students in the classroom appears relatively depauperate. Second, whereas research scientists shift the weight of responsibility from their mental faculties to a network of

empirical allies, science professors demand that their students shift the weight of responsibility from a network of empirical allies to their mental faculties. In other words, the practice of learning with understanding in science appears to be *the inverse* of learning with understanding in science education.

### Contrasting Approaches to Learning with Understanding

The two anthropological vignettes above chronicle two expeditions: one scientific and one pedagogical. Admittedly, there are vast differences to be considered when speaking of the goals, aims, audiences, and purposes of scientific research and science education. And yet, despite these vast differences it should now be clear that they share at least one vital thread of continuity: In both accounts, the two groups of protagonists confront moments in which they are required apply or extend their existing knowledge to an unfamiliar phenomenon. In other words, both scientists and science students endeavor to learn with deep, rich, and meaningful understanding.

One thing this juxtaposition of vignettes is meant to show is the existence of two distinctly different approaches to learning with understanding: one that relies on *mental cognition* and another that relies on *empirical perceptions*. In the first vignette, which is inspired by a two-year classroom study I carried out in 2006-2007, we see one envelope of possibility for learning with understanding. This envelope is defined by traits such as *invisibility, immateriality, intangibility, and internality*. In other words, the envelope in which the two professors and their nearly four hundred students engage in learning with understanding is one that is largely defined by a shift from empiricity to mentality. In the second vignette, much of which is based on the work of anthropologist of science Bruno Latour, we see another envelope of possibility

for learning with understanding.<sup>102</sup> Among others, this particular envelope is defined by traits such as *visibility*, *materiality*, *tangibility*, and *externality*. In other words, the envelope in which the four research scientists engage in learning with understanding is one that is largely defined by a shift from mentality to empiricity. Bathed in the light of these inverse practices, let us briefly consider the end result of these respective expeditions.

### **The *Telos* of the Scientific Expedition**

At the conclusion of their fifteen-day scientific expedition, the research scientists publish a scientific report. In it, they write about a growing need to detach themselves from certain foundational assumptions within classical pedology. You see, if *only* botanical observations are taken into account, then these scientists must conclude that the Brazilian forest is advancing on the savanna. However, if *only* pedological observations are taken into account, then these scientists must conclude that the Brazilian savanna is advancing on the forest. By combining their differing perspectives, however, their observations force them to ask an entirely different question: What can explain the fact that the predominantly sandy soils found underneath the portion of savanna immediate next to the edge of the forest appear as though they are becoming enriched with clay? Classical pedology instructs them to answer, “In accordance with the laws of thermodynamics, the clay enrichment can be explained by a process known as *neoformation*.” However, *neoformation* requires a source of Aluminum to carry out a known geochemical reaction and the scientists can find no such source within the soils in question.

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102. In particular, see Latour 1999 (Chapter 2).

One of the main reasons they are now in the position to ask this intriguing question is due to the extensive empirical network of objects and practices they cast over the Brazilian forest and savanna throughout their fifteen-day expedition. All four scientists will be the first ones to admit that their mental faculties were never enough to address the problem. To better understand this unfamiliar phenomenon they needed to shift the weight of responsibility from their mental faculties to an eclectic cast of empirical allies. At the conclusion of the expedition, most of these allies are invisible, not because they are mental, but because they are now packed safely away inside of luggage, crates, duffle bags, shipping containers, and the back ends of a fleet of four-wheel drive vehicles. Some of these empirical allies will return to Brazil if and when the scientists can procure funding for a follow-up expedition. At their departure, they are confident they will do so because they see the results of this particular expedition as a great success. Through a collaborative approach to an entirely perplexing phenomenon, they have successfully challenged a number of assumptions widely held in classical pedology. As a result, this team of scientists now understands that their next expedition must focus not on the botanical or the pedological, but instead on the zoological...on *earthworms*. Sometime in the future, they plan to invade the forest-savanna boundary with a new army of empirical allies (as well as some old ones), and the genuine hope is that this alliance of new and old allies will help them make the routine actions of the earthworms—which are presently invisible actors beneath the soil—visible to others. At least one thing is certain: it is not the scientists' individual or collective mental powers that will bring the actions of the earthworms to the surface for all to see—no matter the prestige of their degrees, awards, and various accolades—but a shovel might.



## The *Telos* of the Pedagogical Expedition

At the conclusion of a four-week pedagogical expedition, two college professors receive a published report from the university scoring office. In it, they are made aware of the results of question “52.” In the pages of the report, they learn that eighty percent of their students could not successfully demonstrate that they could apply their existing knowledge to a problem defined by the presence of a couple of unfamiliar elements. In other words, they learn that over three-quarters of their students had not learned with understanding. The mutant strain of spinach with the slow leaking membranes remains *unfamiliar* to most of the students; it is as strange a phenomenon to them now as it was before the four-week pedagogical expedition. The professors and their colleagues in science education have ways of describing the unsuccessful students. For example, some students are said to lack “basic knowledge,” while others are said to possess “misconceptions.” Of some students it is said that they lack “understanding,” while of other students it is said that they lack certain (mental or cognitive) “abilities.” Some students will simply be said to be “unmotivated” and/or “lazy.” For the most part, all of these explanations are *psychological* in character. That is, they relate to objects and processes said to occur inside of the minds/brains of individual students. One of the professors underlines this fact in conversation with the anthropologist. After seeing the results of question “52,” he says that he wished he knew more about “what students were thinking when tackling the Mutant Spinach Question.” He also says that he wished he had some way of knowing “what was happening inside of their minds” as they tried to answer it.

## Scientific Research: A Resource for a Different Alchemy

Here, at this moment, we have arrived at a position in which it is now possible to consider seriously the following proposition: much of the *success* of a team of research scientists in Brazil is attributable to their practice of shifting from mental to empirical allies. To give this notion more clarity, we might claim that in pursuit of greater understanding of a perplexing natural phenomenon (in this case, a previously unencountered distribution of fire-resistant trees) one of the main reasons why scientists tend to keep written notes is because the conventions of scientific practice dictate that they refuse to trust their mental faculties. At the very same moment, we have also arrived at a position in which it is now possible to seriously consider a second proposition: much of the *failure* of group of college students is attributable to their practice of shifting from empirical to mental allies. To give this notion more clarity, we might claim that in pursuit of greater understanding of a perplexing natural phenomenon (a ‘mutant’ strain of spinach), one of the main reasons why students do not use their written notes—many of which contain heavily annotated “figures”—is because the conventions of pedagogical practice dictate that they must place almost exclusive trust within their mental faculties.

One of the benefits of an anthropological style should now be evident because at least one of the ironies of pedagogical practice should now be visible: science professors require students to shift from empirical to mental allies when confronting unfamiliar situations *despite the fact* that they often don’t trust their own mental faculties when engaging in work as both professors and as scientific researchers. Recall that the professors did not trust their own mental faculties when it came to remembering the names and faces of their undergraduate

students during the semester examinations. To counteract this distrust, on each of these four occasions the professors behaved like research scientists. That is, they shifted their trust from mental to empirical allies. That is, they shifted their trust from *internal allies* (for example, memory) to *external allies* (including paper lists, photographic IDs, the actual faces of students, and alphanumeric codes). We can reasonably assume that this shift came as second nature to these two professors because, in addition to their role as professors at their university, they are also both scientists. That is, at the same time they are teaching “Biological Science 101: Cells and Molecules,” both of them are actively engaged in scientific research in microbiology.

Therefore, let us now give permission for ourselves to entertain the following question: What if learning for understanding in classrooms was more aligned with a shift from mental to empirical allies rather than—as is the case in Bio101—a shift from empirical to mental allies? In other words, what if pedagogical expeditions in Bio101 were more like scientific expeditions when it came to understanding unfamiliar events? In (yet) other words, what if professors extended to their own undergraduate students sets of empirical tools and strategies similar to the ones they use in their own work as both research scientists and supervisors of examinations?

If such a shift were to be enacted, would students more frequently find themselves in positions in which it could be said of them that they learned with understanding? Would they more regularly find themselves in situations in which it could be said of them that they had successfully applied their existing knowledge to the novel and/or unfamiliar? Furthermore, what new possibilities for science teaching might be created if science professors, as well as science teachers throughout the K-16 continuum, were given permission to uncouple learning

with understanding from its present mental moorings? Would not students and teachers—including professors and teacher educators—effectively double the ways in which it was possible for them to approach learning with understanding? Would not scores of students who struggle to learn with understanding when aligned with a mental or cognitive horizon of expectations stand to gain from being allowed to demonstrate understanding in other ways? These are some of the overarching questions considered in the remaining chapters of this dissertation.

Before going further, however, let me briefly pause here so as to address one potential misunderstanding of what I am suggesting thus far. Understandably so, some readers may construe my suggestion to shift the emphasis in classrooms from mental to empirical allies as joining an already established vocal and influential chorus of science education reformers calling for more ‘hands-on’ or more ‘inquiry-based’ instruction in college science courses. These same individuals and groups may be tempted to use the stance I have communicated thus far as a way of legitimizing their demands for college science professors to engage their students in more authentic, experiential, real-world, inquiry-based modes of instruction. Despite my genuine affection and enthusiasm for these various instructional approaches, that’s not actually what I’m suggesting. In other words, I am not saying that the solution to the problem of learning with understanding is to start taking four hundred undergraduate students on research expeditions to Brazil. Conversely, I am also not saying that the solution to the problem of learning with understanding is to transform the interiors of lecture halls into replicas of Brazilian forests/savannas—in other words, to fill college auditoriums with soil, fire-resistant trees, and hyperactive populations of earthworms.

To be sure, these would be two solutions to the problem of learning with understanding—and in my opinion interesting ones! However, for reasons practical, structural, economic, and even medical, I cannot see an immediate future in which large universities begin seriously restructuring their existing undergraduate science education programs along either of these particular lines of reform. As those working within it already well know, change is notoriously slow in higher education and—at least in the near future of large, research-oriented universities—I fully expect that many undergraduate science courses will continue to resemble those that I was present in as a researcher from 2004-2009 in at least three distinct ways: (1) undergraduate science courses will continue to meet in largish spaces defined primarily by the presence of fixed student seating, audio-enhancing equipment, and large projection screens; (2) such courses will continue to have sizeable teacher to student ratios (e.g., one instructor for every two hundred or so students); and (3) when it comes to assessing student learning, one of the most important criteria used in selecting modes of assessment in these courses will continue to be those modes that can be graded or otherwise evaluated relatively expediently. In light of these three near-future expectations for undergraduate science education—and compared to the thrilling visions of placing students in the midst of thick tropical forests or promoting the growth of thick tropical forests inside of university auditoriums—I must knowingly disappoint many readers by preemptively warning them that what I will eventually suggest in this dissertation is far less ambitious, much less exciting, and much more mundane. Nevertheless, what I'm about to suggest has at least one key advantage over these two other exciting visions...it is much more realistic.

## **Toward an Ecological View of Learning With and Teaching For Understanding**

I want to suggest that one productive means of expanding the ways in which students approach and demonstrate learning with understanding is to redefine and reconsider the ways in which K-16 science teachers approach teaching for understanding. Rather than taking students and relocating them into earthly forests or taking earthly forests and relocating them into classrooms, one of the keys to expanding the ways in which teachers can approach teaching for understanding rests in the existence of—or, perhaps more precisely, in the acknowledgement, critical examination, and subsequent coherent coordination of—two agents/actors already present inside of many college science classrooms. In other words, my proposed solution to the problem of teaching for and learning with and understanding doesn't require acts of relocation because much of what is needed in order to expand the envelope of existing possibilities is already in the classroom. Although much more attention will be given to these two agents in the chapters that follow, let me at least identify them and give them brief consideration here.

The first agent of my interest is human. It is the *professor*. We must remember that at many colleges and universities, the professors who teach undergraduate science courses are also research scientists. To background, forget, overlook and/or ignore this aspect of their professional identity is to lose sight of something critical: when research scientists apply their knowledge to unfamiliar events beyond the walls of their university classrooms they routinely recruit, use, value, coordinate, trust, and align vast numbers of empirical allies. As mentioned previously, one of the reasons why scientists do this is because they tend to distrust their own mental faculties. Thus, in practice scientists tend to find ways to shift their trust from networks

of mental allies over to networks of empirical ones. As most scientists will openly tell you, a scientist's distrust of mental allies is far from a simple matter of personal taste or preference. It's a matter of *professional expectation*. Throughout scientific research communities, scientists tend to value empirical demonstrations over mental or psychological ones. And so, if we draw from this professional expectation instead of backgrounding, forgetting, overlooking and/or ignoring it, then it soon becomes possible to change one of the ways in which we commonly perceive and construct the university science professor. Rather than seeing them as teachers (e.g., when working in the classroom with students) or as scientists (e.g., when working outside of the classroom away from students), it becomes possible to see them as something altogether different. For example, we might begin seeing them instead as *scientist teachers*. Whereas the routine professional expectation of contemporary science teachers is to demand that teachers ask their students to shift the bulk of their trust from empirical to mental allies, the routine professional expectations of *scientist teachers* would be different. Instead of demanding that students go about the work of learning with understanding psychologically, the professional expectation of scientist teachers would demand that professors ask their students to go about things more *scientifically*—in other words, they would ask their students to shift the bulk of their trust in certain situations from mental to empirical allies.

Such a shift in the professional expectations of one's peers brings us to the second agent of interest in this dissertation, a non-human one. It is the "figure." In all of the undergraduate biology courses I observed between 2004-2009, nearly all of the day-to-day activities in the weeks leading up to the examinations revolved around the almost constant display of empirical figures to and for students. An example of one of these figures is shown in Figure 3.2.

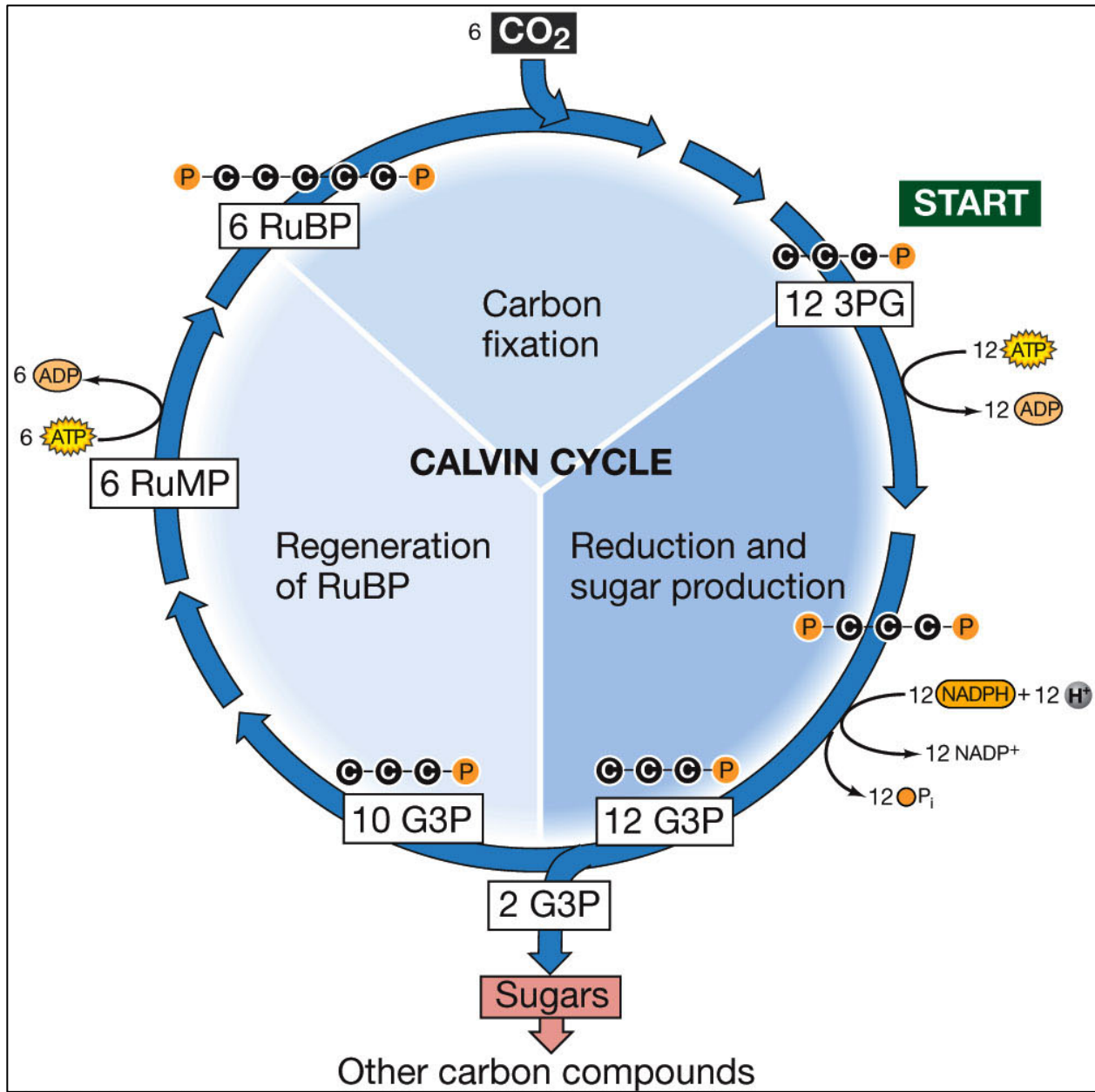


Figure 3.2. The Calvin Cycle. A figure shown to students during a photosynthesis unit in an undergraduate biology course. Figure 8.13 (Part 2) (Sadava, Heller, Orians, Purves, and Hillis 2007). For interpretation of the references to color in this and all other figures, the reader is referred to the electronic version of this dissertation. (Reprinted with permission by the copyright holder.)

We must recall, however, that in the space of the classroom the biology professors I witnessed routinely denied their students the use of these figures on examinations. To clarify,



while the biology professors denied their students the recruitment and use of empirical figures, they strongly encouraged their students to recruit and use mental or psychological figures.

What sort of professional expectations could make such a denial and like-for-like substitution possible? logical? favorable? preferable?

One professional expectation that would make this particular practice possible is the expectation that science teachers enact a theory or mechanism of correspondence. If and when science educators assume that an empirical figure and a mental figure can be simultaneously one and the same thing, it then becomes both possible and logical to see the empirical figure shown in Figure 2 not only as something that can be found on a theater-sized projection screen during a lecture, but also as the very thing that can be found inside of the minds/brains of students. When empirical and mental figures are construed as identical reflections of one another—in other words, when they are construed as *mimetic*—it becomes possible to see the substitution of one for the other as entirely unproblematic. In other words, it becomes possible in practice for science teachers to deny their students the enlistment of an empirical figure on an exam because in principle the mental figure is thought to possess exactly the same traits and benefits as its empirical ‘twin.’

But what if we choose not to see empirical and mental figures as identical? What if we choose not to see them as the corresponding sides of a two-faced coin? What if we choose not to articulate the relationship between an empirical figure of the Calvin Cycle and a mental figure of the Calvin Cycle as mimetic? If and when these denials are permitted, new kinds of professional expectations become possible, logical, favorable, and even preferable. What

resources might begin to help us create these new kinds of professional expectations? Well, we might consider looking in the direction of scientists and scientific research.

Since the 1970s, a diverse and loosely organized group of scholars and researchers including anthropologists, sociologists, historians, economists, philosophers, and political scientists (among others), have turned science and scientists into legitimate objects of interest. One of the most interesting results of their work—and in particular the work of Bruno Latour—is the observation that scientists engaged in research never seem to rely on correspondence theory to articulate the relationship between the world of nature and the world of ideas (or, as Latour writes, the relationship between what’s “out there” and what’s “in there”).<sup>103</sup> Although philosophers of both science and language have long argued the opposite to be true, Latour’s anthropological studies of professional scientists in both laboratories and on field expeditions show that in practice correspondence theory plays almost no functioning role in scientific research.<sup>104</sup> According to Latour, the primary means by which research scientists actually articulate the relationship between the world of nature and the world of ideas is dictated by an entirely different mechanism altogether. Rather than by correspondence, Latour describes a mechanism dictated by actions such as “reference” and “circulation.”<sup>105</sup> Rather than by mimesis, Latour claim is that in practice much of the heavy lifting of scientific discovery is instead accomplished by a scientist’s ability to enlist vast armies of empirical allies—including both human and non-human allies—into a “network” of stable but fragile relations. Thus, for

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103. Latour, *Pandora’s Hope*, 14.

104. See in particular Latour 1986; 1995; and 1999.

105. Latour, *Pandora’s Hope*, 69.

Latour, scientific thinking is not something that is accomplished with the mind or brain, but rather with “eyes and hands.”<sup>106</sup> In other words, for Latour, the cognition of scientists can be described more accurately, adequately, and interestingly as *logistical* practices rather than as logical ones.<sup>107</sup>

### Summary

In this chapter, we have seen that scientists and science students can experience a common dilemma. That is, there are occasions in both research and education when collections of individuals are confronted by novel, perplexing phenomena. How they confront these situations, however, is quite different. Research scientists tend to shift the weight of responsibility from their mental faculties to a network of empirical allies; science professors demand that their students shift the weight of responsibility from a network of empirical allies to their mental faculties. In other words, the practice of learning with understanding in science appears to be the opposite of learning with understanding in science education. This statement of contrast is made possible by the anthropological (but also philosophical) work of Latour, who manages to draw our attention away from the mind/brain and towards the hands/eyes. The logics of science, Latour claims, can be satisfactorily accounted for by a logistics of science.

I will have much more to say about the work, vocabulary, concepts, claims, motivations, and resources of Latour in Chapter 4, but for now suffice it to say that Latour offers science educators something different than a set of mental or psychological resources with which to set about improving the work of teaching for and learning with understanding. Instead of mental

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106. See Latour 1986.

107. See Latour 1987 (Chapter 6).

resources—which, if one prefers, are already available in ample abundance in science education—Latour offers science educators something that might be more accurately described as *ecological*. I use this descriptor because first and foremost Latour is interested in the relationships formed by an immense variety of humans and non-humans including both living (biotic) and non-living (abiotic) things. To put this differently: Latour is as interested in scientists as he is in earthworms, beakers, trees, rocks, shovels, tin tags, cardboard cubes, notebooks, maps, figures, and scientific publications. Rather than a singular focus on humans, Latour generously gives permission for non-human actors to populate a scene. Rather than serve as ‘mere’ props or backdrops to and for human actors, however, Latour grants an equality of agency to these non-human actors such that they too can possess and exercise both practical and theoretical relevance.

In the next chapter, we will begin to learn how to ‘speak’ Latour in the hopes of cultivating a particular type of ecological sensibility—one that grants us needed permission to pay attention to both humans and non-humans in the space of science classrooms. By the end of Chapter 4 we should be more ready to see professors and figures *differently*. If we can take a positive step in that general direction, then we will succeed in substantially increasing the possibility that we can meet one of our original goals: To increase number of ways in which it is possible to conceive of teaching for and learning with understanding.

## CHAPTER 4

### A SCIENTIFIC HORIZON

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When you hear someone say that he or she ‘masters’ a question better, meaning that his or her mind has enlarged, look first for inventions bearing on the mobility, immutability or versatility or the traces; and it is only later, if by some extraordinary chance, something is still unaccounted for, that you may turn towards the mind.

— Bruno Latour, *Science In Action*

Memory is often, and wrongly, conceived of as an act of consciousness and associated with what can be called the mind [...] We don’t analyze the movements of icebergs by studying the bit that appears above the surface of the sea; nor should we study memory in terms of that which fires a certain set of neurons at a determinate time. We as social and technical creatures engage in a vast span of memory practices, from the entirely non-conscious to the hyperaware.

—G.C. Bowker, *Memory Practices in the Sciences*

In this chapter I begin the work of trying to reassemble the existing notions of concepts and understanding around something new and different. More specifically, I draw from Latour’s work regarding what he has called the “logistics” of science and “thinking with eyes and hands.” According to Latour, many social scientists have long explained knowledge gain and knowledge use in the Western natural sciences as primarily the result of individuals with supreme mental abilities. Despite more recent movement toward the social and cultural explanations—which I happen to think suffers from a set of problems similar to those encountered by a belief in the

power of the individual—we see a similar trend in science education. That is, when push comes to shove in classrooms, for example, during high-stakes exams, individual mental abilities still reign supreme. Counter to this explanation, Latour offers a body of empirical and philosophical work that allows us to see the past, present, and future work of natural scientists differently. Latour offers us a new, fresh view of scientific knowledge production and knowledge use (or knowledge *application*) in which humans are demoted, so to speak, in their roles and importance. In a Latourian calculus, humans must share their long-coveted and carefully cultivated plane of immanence with others.

Of particular interest to me is that Latour makes room for the full participation of material, non-humans in science. This enlistment of non-human entities (or “actors,” as he sometimes calls them) creates an entirely new horizon of possibilities for what it means to produce and extend scientific knowledge. I propose that we in science education consider a similar enlistment. In other words, I propose that we allow material, non-human actors to flood our descriptions of classroom science teaching and learning so that we may see things like concepts and understanding from new, different, and fresh perspectives.

I am using a Latourian methodology to investigate two classroom common practices in an undergraduate science course: knowledge gain and knowledge application. This is to say that I’ve deliberately limited my observations and data collection to aspects of these two practices that are both visible and material—to things occurring *outside* of the minds/brains of teachers and students. If aspects of the practices I was studying ever became invisible or immaterial, they were no longer considered to be of interest to me. This rule of method drew much of my initial attention to the use of what the Bio101 instructors often referred to as “figures.” During

a four-day unit on photosynthesis, for example, the instructors displayed nearly forty-five visual images to/for their students at an average rate of one new figure shown every 3.33 minutes. In their attempts to help the Bio101 students gain and apply scientific knowledge, the display of visible, material figures appeared central to these two classroom activities.

My analysis of the use of these classroom figures is informed by a prolonged engagement with the ideas of anthropologist Bruno Latour, as well as by other scholars belonging to the loosely organized domain of Science Studies.<sup>108</sup> In work published over a period of over 30 years between 1979-2013, Latour and others offer an empirical account of the production of figures routinely appearing in research reports, articles, and other scientific manuscripts. I decided on the use of a Latourian framework for my analysis of the use of classroom figures for two main reasons. First, Latour's account is empirical. Regarding the investigation of knowledge gain and application in classrooms, many of the tools and concepts available to science educators and researchers are psychological, that is, they are centrally concerned with products and processes—often in isolation—occurring in the minds of students and teachers. A Latourian analysis of knowledge gain and application demands a central focus on empirically observable products and practices occurring *outside* of minds/brains. Second, increased 'authenticity,' by which is often meant that science education should be *more like*

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108. Besides Latour, the work of a number of other scholars work in Science Studies have informed this dissertation. A short list would include—but would by no means be limited to—the work of Michael Lynch, John Law, Michael Callon, Steve Woolgar, Lorraine Daston, Peter Galison, Ian Hacking, and Michel Serres.

research science, is one of the major goals of early 21<sup>st</sup> century science education reform.<sup>109</sup>

This makes a comparative study of knowledge gain and application as they occur both inside and outside of science classrooms not only timely, but also useful. Such a comparative account stands to offer rich, empirical descriptions of the ways in which knowledge gain and application in contemporary classrooms is visibly and materially continuous and discontinuous with research science. In other words, such a comparison will offer science educators, teacher educators, and education researchers an empirical platform—which is very different from a psychological one—upon which the practices of science education can be re-imagined and re-shaped into practices more proximate to what we might call *scientific* education, *scientific* teaching, and/or *scientific* learning. Such an expansion of the resources available to/for educators, teacher educators, and researchers—but also to/for students—should prove highly desirable.

Of particular interest and use to me in this analysis are Latour's notions of:

- ***Inscriptions***—inscriptions were ever-present in Bio 101. Every lecture was structured around the continuous display, explication, and annotation of visible, material inscriptions (or what the professors called “figures”).
- ***Material or “circulating” reference***—inscriptions have visible, material, historical trajectories. As Latour and others have shown, these trajectories can be described in great empirical detail. The practices of circulating reference are a direct challenge the

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109. I am aware that there are at least three ways in which the term *authenticity* is used in science education research. For example, Buxton describes three different models of authenticity in operation in research (see Buxton 2006). I am interested in what he calls “canonical” authenticity, i.e., making school science more like scientists’ (or research) science.



notion of a direct, one-to-one correspondence between the 'world' and the 'word.' It is not anti-realist, however; on the contrary, in Latour's own words it's a more *realistic* form of realism.

One advantage of looking to Latour is that abstract conceptual learning theory can become something different. For example, it can become something that is more visible, tangible, material, historical, and local. In addition, it can become more empirical and more disciplinary. In other words, it can become more like *science*. This is because the Latourian concepts were derived from empirical studies of science/scientists in action and not from psychology or the alchemy of school subjects. One interesting thing that distinguishes Latour's work from psychology or abstract conceptual learning theory is that in Latour, there is no such thing as transfer. There is only "transformation with deformation" because transformation without deformation is simply *transportation*.<sup>110</sup> Thus, Latour's theory is not a psychological one; it does not rely on mental processes as the primary allies of understanding.

I know some will have questions about the appropriateness of looking to Latour for ways to replace and/or reconstruct science education. For instance, some readers may have reservations about an account of science education derived from studies of science and scientists. *Scientists have different goals compared to science teachers*, they might say, *Scientists have different facilities, audiences, purposes, equipment, etc.* However, I have anticipated these objections and have put together some pretty compelling reasons for taking a Latourian route instead of others. They are included throughout the chapter.

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110. The authors of *How People Learn* actually incorporate the notion of transportation: "The most effective learning occurs when learners *transport* what they have learned to various and diverse new situations." NRC, *How People Learn: Brain*, 238 (emphasis added).

The two main purposes of this chapter are:

(1) To outline a Latourian account of how knowledge is gained and applied in science.

- Across much of his work, Latour draw special attention to the production and use of scientific figures or “inscriptions.” Latour’s empirical interest in inscriptions intersects with the highly visible use of material inscriptions in the undergraduate classrooms I observed. I use this intersection as my main point of departure.

And,

(2) To connect—both empirically and conceptually—the classroom figures I routinely saw displayed to/for students in Bio101 with the scientific figures Latour routinely saw displayed to/for other scientists in reports, articles, and other types of scientific manuscripts.

- This is an important connection to forge, for it helps to narrow the theoretical and practical distance often seen as standing between the world(s) of science and science education.

Once again, I must lean heavily into vocal and ongoing calls for increased authenticity in K-16 science education. A major goal of contemporary science education reform is to make science education more like research science (to make *school science* more like *scientists’ science*). In this dissertation, I do not intend to take a stand as to whether such a vision should be considered good or bad, desirable or undesirable. Instead, my dissertation is an exploration of both the possibilities and the perils of enacting such a vision of authenticity when the vision is grounded empirically instead of psychologically. To put this in terms first introduced in

Chapter 2, I want to engage in an alchemical transformation, but one that takes its measure from empirical studies of scientific research rather than from psychological studies of it.

In the next four sections (Sections A-D), I will explicate four different readings of two classical figures of the Calvin Cycle. Read with Latourian sensibilities, the four readings illustrate relationships between scientific figures and classroom figures.

#### Section A: Science in Action

Empirical studies of science have led to new ways of conceptualizing how scientific knowledge is gained in laboratories and on field expeditions. Since the 1970s, researchers from a variety of disciplines have committed to following research scientists at-work across the globe. Their main object of interest has been the mundane, day-to-day practices of scientists in action or “science in the making.”<sup>111</sup> This dissertation brings forward the work of anthropologist Bruno Latour (and others) and in particular his empirical descriptions of how scientists gain and apply scientific knowledge.

#### **Knowledge Gain**

For Latour, scientific knowledge gain usually starts in some sort of *center*—i.e., physical spaces where scientists accomplish work. Centers can be university offices, company and government laboratories, field stations, museums, etc. How do we know when a physical space is a center of science? It’s likely full of but by no means limited to instruments and equipment, maps and protocols, bookshelves and furniture, cabinets for paper files, cages for live specimens, collections, scientists, technicians, and secretaries. Centers of science are places

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111. See Latour 1987, Introduction.

where scientists typically begin (and end) important aspects of their work such as inquiries, experiments, expeditions, and investigations.<sup>112</sup>

From centers of science, many scientists embark on “cycles of accumulation.”<sup>113</sup> That is, they go out into nature and find/invent ways to bring representatives of nature back to the centers. However, a major challenge facing scientists is that nearly all the delegates of the natural world offer various forms of resistance to being mobilized and transported. Most mountains are heavy, some gases can explode, plants die and decay, bacteria can kill their capturers, animals can be aggressive, stars are hot and far away. Because of this active resistance, scientists must find/invent ways to transform the delegates into more mobile, stable, and eventually combinable forms (they are “delegates” because they are almost always representatives of larger populations of rocks, plants, stars, etc.). Scientists must transform the delegates while simultaneously protecting them from too much deformation or degradation. In other words, scientists must try to ensure that the delegates remain the same despite the fact that they must be changed. Latour calls the products of such transformations of natural objects “immutable mobiles.”<sup>114</sup> However, Daston & Galison offer another helpful term for such products, “working objects.”<sup>115</sup> For the scientist, natural objects prove too plentiful and too various to deal with efficiently and constructively. Thus, natural objects must be selected and constituted. In order for science to work smoothly and efficiently, the representatives of the ‘sectors’ or ‘slices’ of nature under investigation must be made manageable. “No science can be

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112. See Latour 1987, Chapter 6, Part B.

113. See Latour 1987, Chapter 6, Part A.

114. Latour, “Visualization and Cognition,” 7.

115. Daston and Galison, *Objectivity*, 19.

without such standardized working objects,” as Daston & Galison explain, “for unrefined natural objects are too quirkily particular to cooperate in generalizations and comparisons.”<sup>116</sup>

Latour characterizes the practice of transforming more raw-form natural objects into more refined- or final-form working objects as scientific “acts of reference.”<sup>117</sup> Acts of reference, which I explain in detail in Section B of this document, can also be loosely defined as the ways in which scientists make the world more mobile, stable, immutable, combinable, and superimposable. In other words, acts of reference can be loosely defined as the ways in which scientists make the world more *abstract*. For Latour, scientific knowledge gain hinges upon scientists ability to successfully couple or chain multiple acts of reference together to form visible, material “circuits.”<sup>118</sup> I provide an example of a scientific circuit of reference in Section B. Such circuits of reference usually result in the production of numerous two-dimensional working objects that are written on paper. He calls these working objects “inscriptions.”<sup>119</sup> And so, in a Latourian scenography, we might say that scientific knowledge gain can be conceptualized as scientists engaging in cycles of accumulation in which the scientists select representatives of a natural world and help them take steps—by transforming them through acts of reference and then chaining these individual acts into coherent circuits—to becoming full-fledged members of a paper world, a world of inscriptions.

However, scientific knowledge gain does not stop with the production of paper-based inscriptions. According to Latour, inscriptions are then gathered *en masse* in centers of science

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116. Ibid., 19, 22.

117. See Latour 1999 (esp. Chapter 2), but also Latour 1995.

118. See Latour 1999 (esp. Chapter 2), but also Latour 1995.

119. See Latour and Woolgar 1986. See also Latour 1986; 1987; and 1999.

and subjected to additional work. In centers, inscriptions are resources that allow other scientists to see distant things and become familiar with distant events without ever having traveled far away from the center. And because scientists create elaborate accounting systems within their circuits of scientific reference, these same untraveled scientists can then venture out/back to the source of the inscriptions so that they may bring back even more working objects. Thus, in a Latourian scenography we can imagine that centers of science might also be called ‘centers of accumulation,’ for they are a central gathering point for the refined products numerous of scientific circuits of reference. As we will see later, it is these highly refined characteristics—*mobility, stability, immutability, superimposability, and combinability*—that eventually allow scientists to apply or extend scientific knowledge to the world outside of centers or, as Latour writes, to act on the natural world “from a distance.”<sup>120</sup>

Scientific centers of accumulation face a significant challenge, however; the more cycles of accumulation that are successfully completed, the more working objects delivered to the centers. Left untended and unprocessed, scientists within centers of accumulation would likely suffocate beneath the sheer volume of working objects, for these incoming objects would quickly clog and/or fill up the hallways, basements, offices, desks, cabinets, bookshelves, network servers, and computer hard drives. So, how do scientists inside of centers effectively manage the constant stream of scientific colleagues returning from cycles of accumulation with working objects in their hands, bags, boxes, crates, bottles, and briefcases? For Latour, the answer to this question is through performing yet additional acts of transformation. In other words, through the production of yet more working objects, which effectively consumes the

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120. See Latour 1987, Chapter 6, Part A. See also Latour 1986.

existing ones. In the hands of scientists (and often now in the circuitry of computers), each working object produced must be more condensed, more summarized, more reduced, and more abstracted than its predecessor. How else would the steady incoming tide of working objects be overcome? The scenario is comparable to a temperate forest ecosystem: in the absence of the various decomposing insects, fungi, molds, and bacteria present in the ecosystem, the forest would fill up with leaves. In scientific centers of accumulation, as in temperate forests, the active transformation of more raw-form entities into more refined forms is vital.

In a sense, each newly constituted working object (the *n*th form inscription) is a summary or collection of the working objects it replaces (the *n*th-1, *n*th-2, *n*th-3...*n*th-*n* forms). Through such “cascades of inscriptions,” inflated, three-dimensional natural objects are effectively transformed into deflated, flattened, two-dimensional forms that can then be combined in ways that they never could in their more worldly or earthly forms.<sup>121</sup> At this stage of science, centers of accumulation behave more like “centers of calculation.”<sup>122</sup> The forms produced by the cascades of inscriptions are increasingly abstract but yet still visible and still material. Even a single letter “E,” a standard letter used for “energy” in science and a highly abstracted form, still retains some visibility and materiality. For instance, it is often made of ink and printed on a matrix of wood-fibered, chemically treated paper. These visible, material characteristics allow it to be combined with other letters—for example, with letters such as “M” and “C” in equations—and brought into relationships with other inscriptions. In other words,

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121. See Latour 1999, Chapter 2. See also Latour 1986; 1995.

122. See Latour 1987, Chapter 6, Part B.

the working objects produced at this stage allow for something quite extraordinary and powerful to occur: finally, after many acts of reference have been coherently coupled or chained together, equations can be constructed and calculations can be made.

An important point to emphasize at this juncture is that mental or psychological “cognition” never appears in a Latourian account of scientific knowledge gain. At no point in a Latourian scenography are scientific objects and practices associated with knowledge gain located in the minds/brains of scientists. Instead, scientific objects and practices are externalized and located among a heterogeneous network that includes but is not limited to people, instruments, institutions, furniture, working objects, paper, technology, and money. Because Latour does not conceptualize knowledge gain as mental/cognitive or psychological, he creates that possibility of following and studying it without needing to know what scientists are thinking. Latour is not interested in what’s happening inside of scientists’ minds/brains when they are engaged in cycles of accumulation, working in centers of accumulation, or involved in making calculations. Instead, he is keenly interested in what’s happening outside of scientists’ minds/brains when they are engaged in these scientific activities. This dramatic shift opens up the possibility for analysts of science to conceptualize practices like abstraction and scientific reasoning as external processes—by which is meant objects and processes that are visible, material, accessible, and observable—that one can study empirically. As we will see, this also opens up similar possibilities in science education. That is, we can study abstraction and reasoning in classrooms as external processes. We can study them empirically.



## Knowledge Application

Knowledge gain is not enough. As we will see in Section B, scientists gain many advantages from cycles of accumulation, as well as from the additional transformational work accomplished inside of the centers of calculation. However, in science these advantages must be translated back to the periphery or else they will disappear. In order to translate these advantages back to the natural world, that is, in order to apply them to the world outside of scientific centers, there is still much work to be done. Abstract theories and concepts cannot be applied everywhere and at every time unless the world outside of centers of science is made to resemble the network in which the cascades of inscriptions were articulated. For Latour, this is partly accomplished through the work of “metrology.” As Latour explains,

Metrology is the name of this gigantic enterprise to make of the outside a work inside which facts and machines can survive. Termites build their obscure galleries with a mixture of mud and their own droppings; scientists build enlightened networks by giving the outside the same paper form as that of their instruments inside. In both cases the result is the same; they can travel very far without ever leaving home.<sup>123</sup>

I will have more to say about metrology later, but for now we can think about metrology as the scientific organization of stable measurement and standards such as those physical constants used to measure time, space, weight, wavelength, etc.<sup>124</sup> At least for now, however, we can say that scientific knowledge application involves the active and deliberate transformation of the world outside of scientific centers into spaces that resemble the world inside of scientific centers. For example, Latour ascertained through an historical study that Louis Pasteur had transformed provincial French farms into visible, material extensions of his

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123. Latour, *Science In Action*, 251.

124. Latour, “Visualization and Cognition,” 30. See also Latour 1987, Chapter 6, Part C.

Parisian-based laboratory. Similarly, Latour observed one of his own colleagues, a botanist, attach hundreds of little tin tags to branches of trees in a section of a Brazilian forest, and on which she wrote numbers such as “234.” The tags were used to help her—but also other scientists who had yet to visit this section of the Brazilian forest—find their way to particular spot at some point in the future. One of the things these transformations of the world enable is the execution of “rehearsals.”<sup>125</sup> For example, Latour notes that simulators allowed astronauts to land on the Moon thousands of times before they actually ever did so, and that scientists at the Delft Hydraulics Laboratory in Holland constructed a scaled down model of the Rotterdam harbor to rehearse various natural phenomena (e.g., flooding, silting, dredging scenarios) before they actually happened to the scaled up or actual/real harbor.

In sum, knowledge application in science involves anything and everything used to help abstract (yet still visible, material) forms—e.g., scientific inscriptions—travel and survive outside of centers of accumulation/calculation. Metrological work, transformations of the world to resemble laboratories, and rehearsals are just a few of the ways in which abstract scientific products such as laws, theories, and concepts earn the reputation of being ‘universal.’ It is how they appear to analysts of science as having their own internal momentum or inertia. However, in Latour this reputation and appearance are the result of the careful preparation of visible, material “landing strips”; they are the result of the transformation of as many points of the world outside of scientific centers into actively functioning instruments.<sup>126</sup>

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125. See Latour 1987, Chapter 6, Part C.

126. Latour, *Science In Action*, 253.

And so, in a Latourian scenography knowledge application is not the application of mental concepts and cognitive processes from a psychological domain to a natural/material one—from an internalized domain to an externalized one. If we want to talk about “cognition,” Latour is willing to talk about it but only if, once again, cognition is granted permission to be externalized. Thus, a Latourian scenography does not attend to the logics of science; by deliberate choice, it tends to the logistics of science. For Latour, the abstract products of science—e.g., facts, theories, and concepts—are like “trains, electricity, packages of computer bytes or frozen vegetables: they can go everywhere as long as the track along which they travel is not interrupted in the slightest”; they have no inertia of their own, like “kings or armies they cannot travel without their retinues or impedimenta.”<sup>127</sup>

A key question to pose at this juncture is this: How and where does a Latourian account of scientific knowledge gain and knowledge application intersect and/or overlap with approaches to knowledge gain and knowledge application found in college science education? This is an important question and it frames the main purpose of Section B. That is, in the next section I aim to connect—both conceptually and empirically—knowledge gain and knowledge application as practiced in science with knowledge gain and knowledge application as practiced in schools. I find the most visible and material intersection to be in the appearance of “figures” in both science classrooms and scientific publications. And so, Section B begins the task of forging a connection between these figures or *inscriptions*.

#### Section B: How to Speak Latourian about Scientific Figures

Figures 4.1 and 4.2 juxtapose two figures, a *scientific* and a *classroom* figure.

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127. Latour, *Science In Action*, 250.

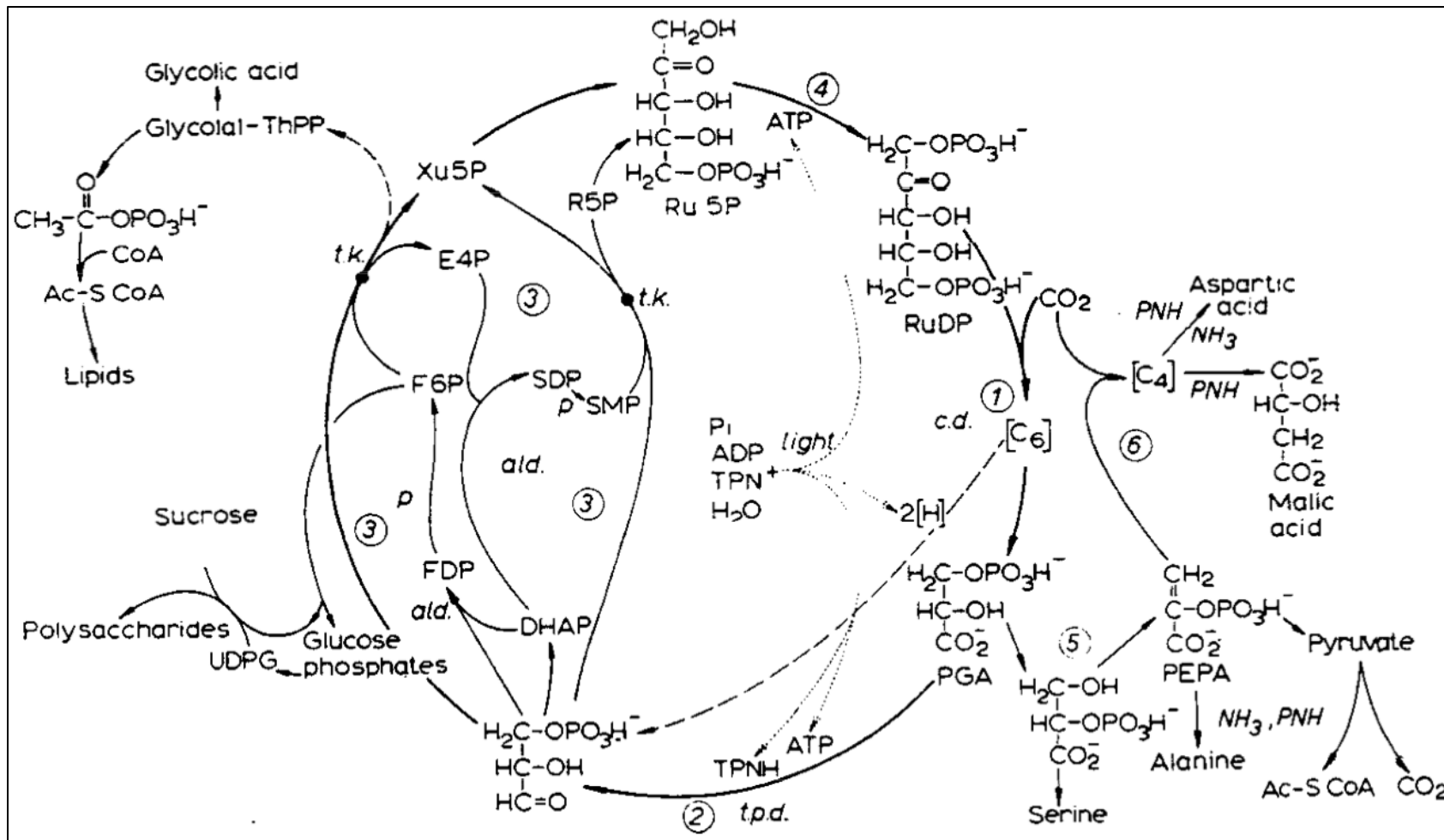


Figure 4.1. The photosynthetic carbon cycle. A figure used in a manuscript that Melvin Calvin submitted when accepting the 1961 Nobel Prize for chemistry. Figure 20 (Calvin 1961).

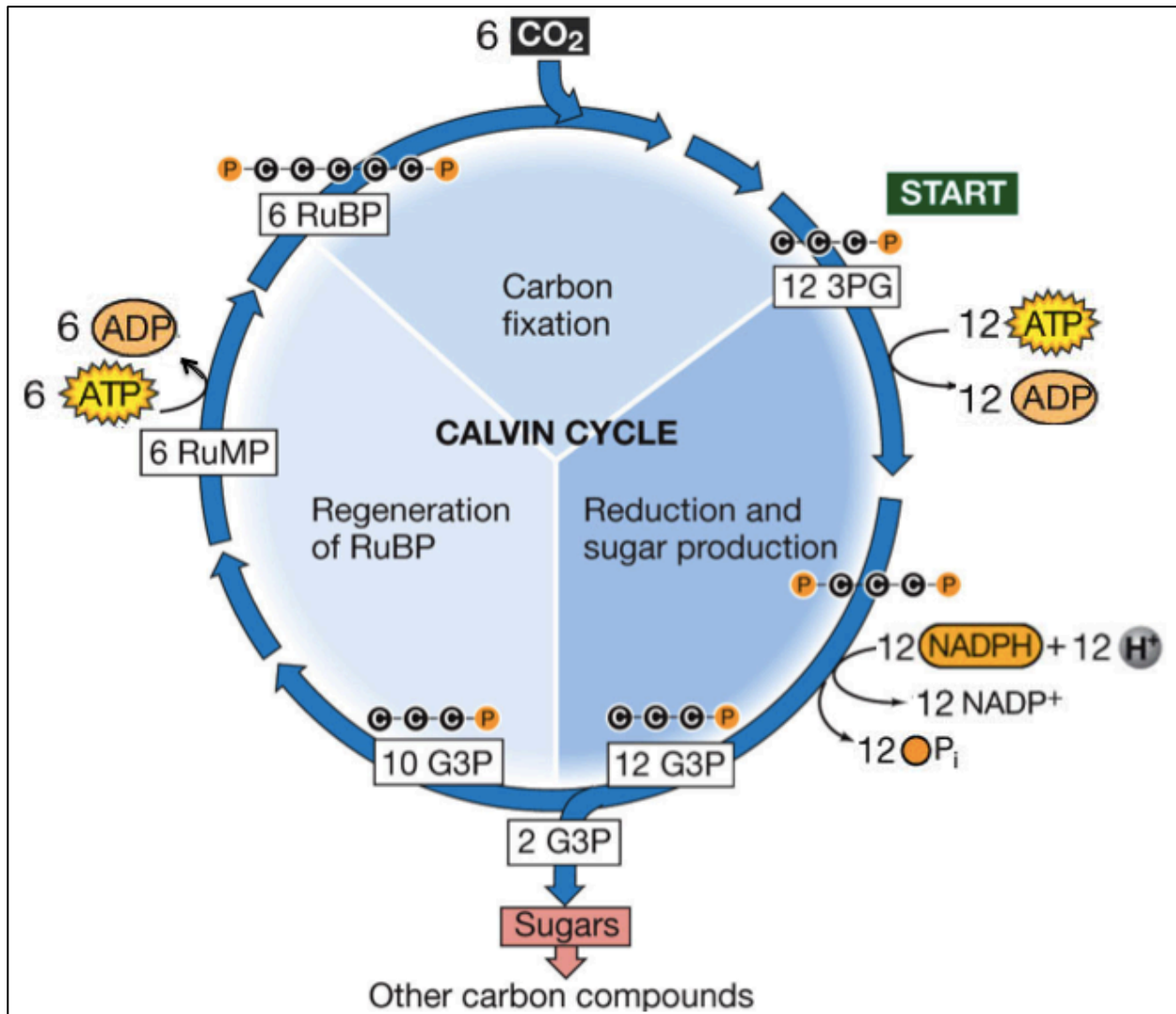


Figure 4.2. The Calvin Cycle. A figure shown to students during a photosynthesis unit in an undergraduate biology course. Figure 8.13 (Part 2) (Sadava et al. 2007). (Reprinted with permission by the copyright holder)

Figure 4.1 (“Fig. 20”) shows an example of a scientific figure. It was published in 1961 and is attributed to Melvin Calvin, a research scientist. Fig. 20 is one of nearly two-dozen figures included by Calvin in a manuscript submitted to the Nobel Foundation as part of his acceptance of the 1961 Nobel Prize for chemistry.<sup>128</sup> It never appeared in the Bio101 course I studied, either in lecture or in the course textbook. In other words, Fig. 20 was never made visible to Bio101 students.

Figure 4.2 (“Fig. 8.13 (Part 2)”) shows an example of a classroom figure. It was published in 2007 and is attributed to Sadava, Heller, Orians, Purves, and Hillis. All five of these individuals are research scientists. Fig. 8.13 (Part 2) is one of hundreds of figures included by Sadava et al. in a manuscript submitted to and developed with W.H. Freeman publishers. It appeared in the 8th edition of an introductory-level college textbook titled, *Life: The Science of Biology*.<sup>129</sup> Fig. 8.13 (Part 2) also appeared multiple times in the Bio101 classroom. It was included in the course textbook and it was also displayed on a large, white, theater-sized projection screen to and for the Bio101 students.

For Latour, Fig. 20 is a particular kind of scientific figure to which his attention was inescapably drawn while studying how research scientists gain scientific knowledge. What he once referred to as scientific literature’s most “powerful tool,” he less dramatically labeled “the visual display.”<sup>130</sup> With almost every group of scientists he ever followed—whether into laboratories or out on field excursions—Latour found that visual displays similar to Fig. 20 were distinctively involved in scientific communication and in the very production of scientific

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128. See Calvin 1961.

129. See Sadava et al. 2007.

130. Latour, *Science In Action*, 67.

knowledge.<sup>131</sup> It is one of Latour's colleagues, however, Michael Lynch, who offers us a more instructive conceptual and empirical orientation to scientific visual displays—including what they are, where they're found, and what they do in science.

For Lynch, as well as for Latour, visual displays such as Fig. 20 are “a characteristic feature of scientific activity.”<sup>132</sup> Furthermore, they are “the products of scientific work.”<sup>133</sup> Visual displays include, but are not limited to, “illustrative photographs, diagrams, graphs and other data displays.”<sup>134</sup> However, for Lynch visual displays are much more than “pictorial illustrations for scientific texts” and he makes the case that we are deficient in our understanding of scientific visual displays if we simply pay attention to what they are—we must also pay close attention to what they do.<sup>135</sup>

In a Lynchian scenography, which is complimentary to a Latourian one, visual displays have multiple functions. For example, they:

- 1) Enable greater public access to “new structures wrestled out of obscurity or chaos.”<sup>136</sup>
- 2) Display “objects, processes, relationships and theoretical constructs” of interest to scientists.<sup>137</sup>

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131. See Latour & Woolgar 1986; Latour 1987; 1999.

132. Lynch, “Discipline and Material Form,” 37.

133. Lynch, “The Externalized Retina,” 204.

134. Lynch, “Discipline and Material Form,” 37.

135. See Lynch 1988.

136. Lynch, “The Externalized Retina,” 204.

137. Lynch, “Discipline and Material Form,” 37.

3) Are “essential to how scientific objects and orderly relationships are revealed and made analyzable.”<sup>138</sup>

4) Are “irreplaceable as documents which enable objects of study to be initially perceived and analyzed.”<sup>139</sup>

5) “Systematically transform specimen materials into observable and mathematically analyzable data.”<sup>140</sup>

A common thread running through the collective functions listed above is an explicit emphasis on the external, the visual, and the publicly accessible. In a Lynchian vocabulary, as well as in a Latourian one, the scientific visual display is not a term reserved for internal viewership (e.g., visualization occurring within the ‘mind’s eye’), psychological imagery (e.g., mental models and/or representations), or private cognitive processes (e.g., thinking or reasoning abstractly). On the contrary, for both Lynch and Latour scientific visual displays always possess some sort of visible, material form that allows them to be studied empirically.

What scientific visual displays are and what they do let us quickly anticipate where they are found, which is primarily in “scientific publications and texts.”<sup>141</sup> However, as Lynch adds, we must be aware that visual documents can be found during “all stages of scientific research.”<sup>142</sup> In other words, even though highly cleansed, ultra-refined visual displays typically appear in scientific publications and texts, Lynch suggests that analysts of science should always

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138. Lynch, “The Externalized Retina,” 201-202.

139. Lynch, “Discipline and Material Form,” 37.

140. *Ibid.*, 37.

141. *Ibid.*, 37.

142. Lynch, “The Externalized Retina,” 202.



expect to see many other kinds of visual documents throughout scientific research. These other visual documents may be less cleansed and less refined than final-form visual displays appearing in scientific publications, but these documents will be no less visible and no less material. In describing the research process itself, Lynch writes that in much scientific research, “A series of [external] representations or renderings is produced, transferred, and modified as research proceeds from initial observation to final publication. At any stage in such a production, such representations constitute the physiognomy [i.e., *face, features, expression, look*] of the object of the research.”<sup>143</sup>

In classifying visual displays as one form—albeit one of the more polished forms—in a series of visual documents, and in describing scientific research as a set of practices involving the production, transfer, and modification of a series of external representations or renderings, Lynch opens up an interesting possibility: it would seem that final-form scientific visual displays such as Fig. 20 and others found in scientific publications could be understood as the later stages of a long(er) series of externally visible, material, and publicly accessible visual documents. In other words, in a Lynch scenography, highly polished scientific visual displays can be understood as the products of historical practices whose histories are closely linked to the production and transformation of other types of visual documents in science.

If Melvin Calvin’s Fig. 20 is the product of a set of historical practices, how might a history of this figure be written? To what other kinds or types scientific visual documents is Fig. 20 connected and related? From what other visual document or documents was it transformed or modified? From what other visual documents did it descend? Out of what types of scientific

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143. Ibid., 202 (emphasis in the original).

practices did it originate? If we can answer these questions about Fig. 20, we might find ourselves in a better position to see a connection between Fig. 20, a figure used in science, and Fig. 8.13 (Part 2), a figure used in science education.

For possible answers to these questions it's best to return to the vocabulary and empirical studies of Latour.

### **Shifting Terms: From Visual Displays to Inscriptions**

One good reason to come back to Latour at this point is economy: Latour simplifies Lynch's vocabulary. Instead of speaking of visual displays as one type of visual document appearing near the end of scientific research processes—which also suggests that there are other types of not-so-highly-polished visual displays produced within scientific research—Latour introduces the term “inscription” to subsume all of the different types of visual objects discussed and suggested by Lynch. For now, it's best to define inscriptions as some kind of written output regarded as having a direct relationship to some original entity or substance.<sup>144</sup> Melvin Calvin's Fig. 20 is a classic example of an inscription: it is written on paper and is said to have a direct relationship with processes said to occur in the chloroplasts of green plants. Similarly, Sadava et al.'s Fig. 8.13 (Part 2)) is also an inscription. It too is written on paper and it too is said to have a direct relationship with processes said to occur in the chloroplasts of green plants. Still, this similarity between Fig. 20 and Fig. 8.13 (Part 2) is not enough to render both inscriptions as scientific. While it is true that the authors of both figures—Calvin and Sadava, Heller, Orians, Purves, and Hillis 2007—are all research scientists, this professional status is not

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144. See Latour and Woolgar 1986, Chapter 2.

enough to render both inscriptions as scientific.<sup>145</sup> Similarly, while it is also true that both figures are visible and material, these two qualities of the two figures is still not enough to render both inscriptions as scientific. The simple fact remains that Fig. 20 and Fig. 8.13 (Part 2) are visibly different.

In the remaining parts of Section B, I draw heavily from Latour to help us understand how—despite their obvious visible differences—both Fig. 20 and Fig. 8.13 (Part 2) can be understood as two distinct stages (and, as it turns out, closely related stages) in a longer chain of scientific reference or, as Latour refers to it, “circulating reference.”

### **Circulating Reference: A Way of Understanding the Relationship between Fig. 20 and Fig. 8.13 (Part 2)**

To best understand Latour’s notion of circulating reference, it is best to walk step-by-step through a straightforward example of it. Before beginning, however, I must endeavor to make a straightforward substitution, which is best captured by the two scientific inscriptions juxtaposed in Figures 4.3 and 4.4.

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145. The textbook’s website discusses the *scientific* research interests of all four authors. W.H. Freeman, “Author Bios,” *Life: The Science of Biology*, accessed on August 10, 2013, <http://www.whfreeman.com/Catalog/authorseditorscontributors/discipline/Biology>.

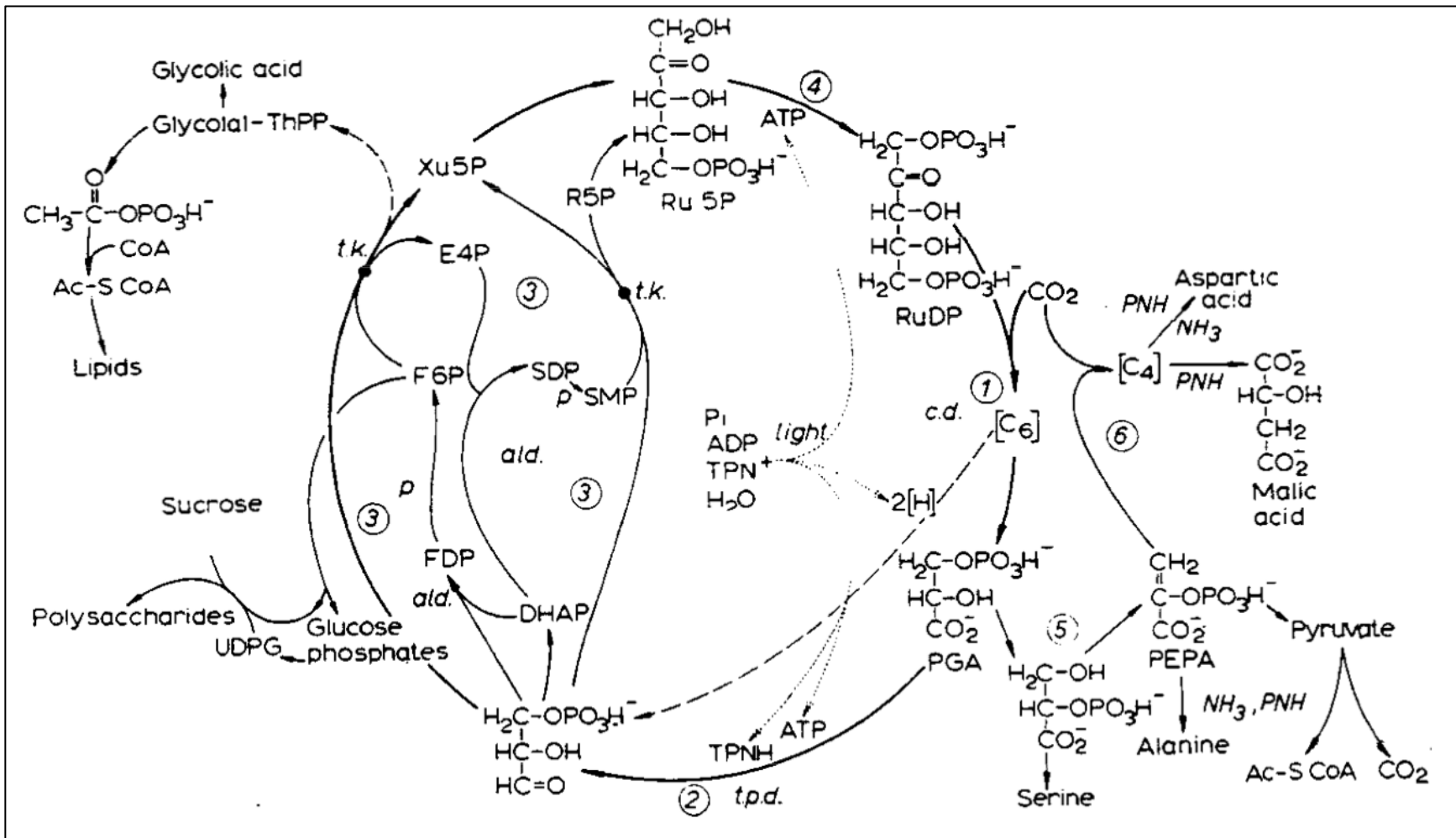


Figure 4.3. The photosynthetic carbon cycle. A figure used in a manuscript that Melvin Calvin submitted when accepting the 1961 Nobel Prize for chemistry. Figure 20 (Calvin 1961).

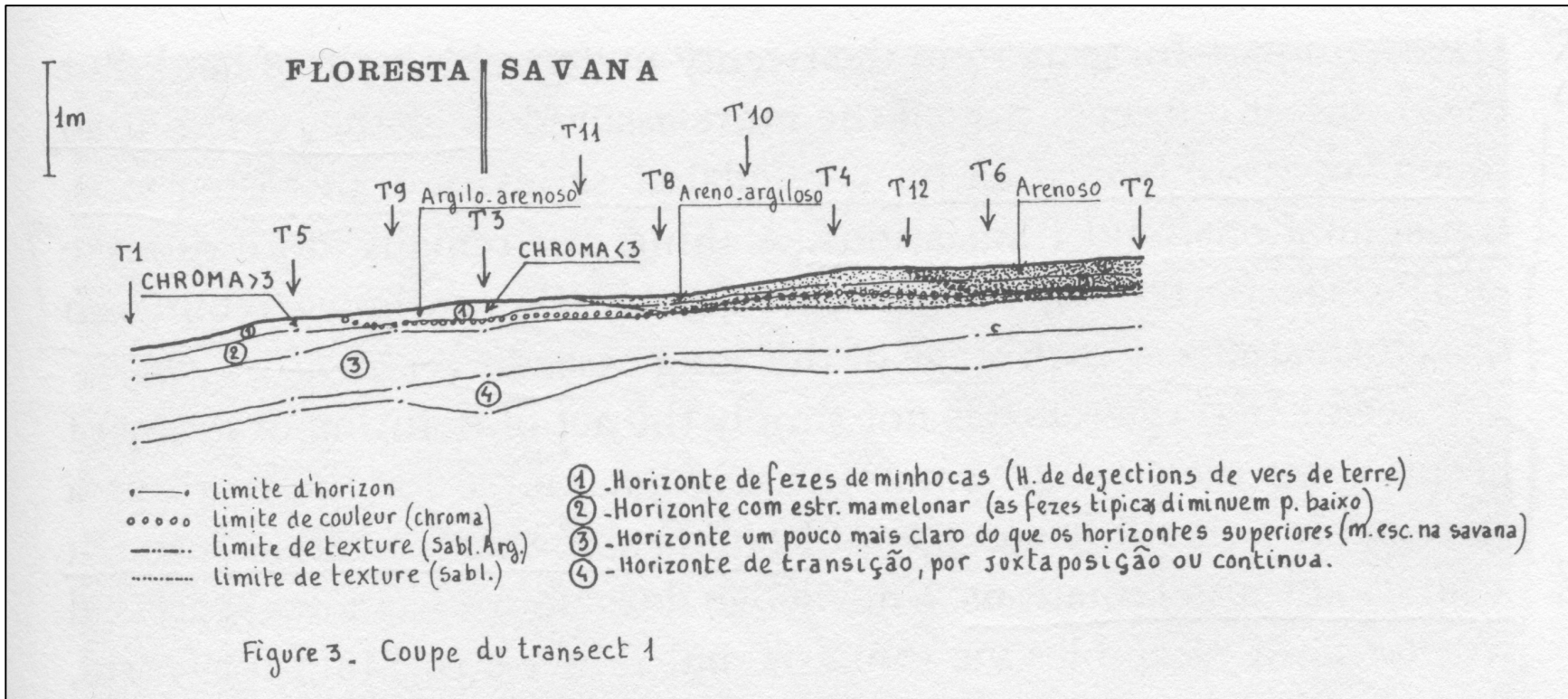


Figure 4.4. Figure 3. Coupe du transect 1 (Silva et al. 1991). A figure displayed in a scientific manuscript reporting on the findings of an expedition to region of Boa Vista, Roraima, Amazonia (Brazil). Figure 2.15 (Latour 1999). (Reprinted with permission by the copyright holder.)

In Figure 4.3 is the now familiar Figure 20 (“Fig. 20”). It is a description. It is Calvin’s map of certain processes said to occur in green plants throughout the world. In Figure 4.4 is Figure 3 (“Figure 3. Coupe de transect 1”).<sup>146</sup> It too is a description. It too is a map, but of certain soil characteristics in the Boa Vista region of Brazil. Both are scientific visual displays. Both are diagrams. Both are inscriptions. And by the end of this section we will understand why they should both be considered scientific.

I need to ask my readers to shift their collective attention—at least for a while—from Fig. 20 to Fig. 3 and to treat them as conceptual equals (near the end of Section B, however, I will ask readers to undo the current substitution and shift back to Calvin’s Fig. 20). The reason for this shift is because Latour did not articulate circulating reference by studying how Melvin Calvin and his many colleagues produced Fig. 20 over a period of twelve years. Instead, he articulated it by studying how a team of five scientists—Silva, Boulet, Filizola, Morais, Chauvel, and Latour—produced Fig. 3 over a period of approximately twelve days.<sup>147</sup> Even for someone as patient as Latour, the study of a research expedition lasting twelve days is preferable to one lasting more than twelve years.

Silva et al.’s Figure 3 will be prove an invaluable companion as we engage Latour’s account of how and why a group of French and Brazilian scientists created Figure 3, which was inserted into a scientific report at the conclusion of a scientific expedition.

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146. Figure 3 also appeared in *Pandora’s Hope* as “Figure 11.15” (see Latour 1999, p. 57).

147. Interestingly, Latour is included as one of the authors of a scientific report in which Figure 3 appeared. The report was titled, “Relations between Vegetation Dynamics and the Differentiation of Soils in the Forest-Savanna Transition Zone in the Region of Boa Vista, Roraima, Amazonia (Brazil). Report on Expedition in Roraima Province, October 2-14, 1991.”

## Scientific Knowledge Gain in Laboratories, Forests, and Fields

How does a handful of soil become an explanatory diagram published in a scientific report? By what means does a graspable piece of earth become a detailed illustration on a graspable piece of paper? In other words, how do *things* become *words*?<sup>148</sup> The relationship between things and words is Latour's primary concern in Chapter Two of *Pandora's Hope*. To explore how scientists load or "pack" the world into words Latour follows a team of scientists into a Brazilian forest intent on describing those scientific practices that "produce information about a state of affairs."<sup>149</sup> Following the completion of their twelve-day scientific expedition, Latour offers a fresh description of a highly specialized disciplinary practice that he calls "circulating reference." In order to better understand what Latour means by circulating reference, I will now summarize Latour's description of the practices of a group of soil scientists (pedologists).

### I. Acts of reference as crossing (small) gaps

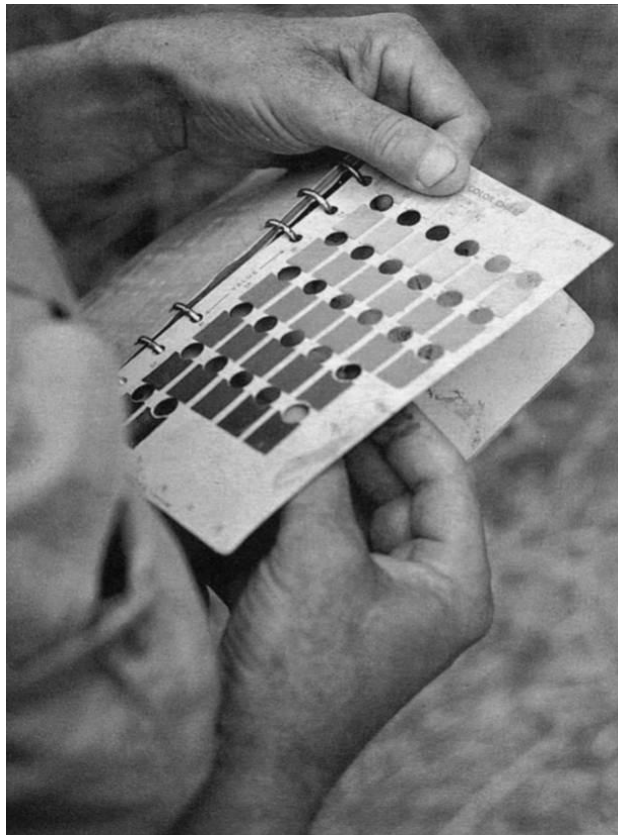
According to Latour, many scientists spend large portions of their professional careers performing routine "acts of reference." Acts of reference are instances of highly regulated, disciplinary-specific, and audience-specific transformations of things into words. We can think of transformations as the scientific practice of moving from more concrete things to more abstract words or, in the reverse direction, from more abstract words to more concrete things.

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148. Throughout *Pandora's Hope*, Latour uses a number of different dichotomies interchangeably: *world/word*, *thing/sign*, *matter/form*, *more abstract/less abstract*, and *state of affairs/statement*. In this paper, I too will use a number of terms in these dichotomies interchangeably.

149. Latour, *Pandora's Hope*, 24.

Such actions, Latour writes, could alternatively be considered "mediations" or "substitutions" in which things are changed in form or appearance. Take an earthly thing, say, a handful of soil. In the hands of a skilled pedologist, this soil will often undergo a series of carefully linked transformations. An example of a single transformation of a handful of soil is one that is facilitated by the pedologist's use of a slick tool inscribed with something called the "Munsell color system" or, for short, the "Munsell code." A picture of this tool appears in Figure 4.5.



*Figure 4.5.* Latour's photograph of a pedologist using a handheld, paginated text containing a wide range of color samples that have been aligned with alphanumeric Munsell codes. Figure 2.16 (Latour 1999). (Reprinted with permission by the copyright holder.)

Not unlike a collection of paper-based color swatches commonly found in paint supply or home improvement stores, this common pedological tool consists of samples of a



conventionally accepted palette of colors organized by three color-derived dimensions: hue, value (lightness) and chroma (color purity). Each Munsell color is aligned with a specific alphanumeric code: a somewhat saturated purple of medium lightness, for example, corresponds to the code “5P 5/10.”

Practicing pedologists regularly hold handfuls of soil next to the Munsell color samples to determine precisely which Munsell color, and thus which alphanumeric code, their soil samples most closely match. This basic matching exercise is a straightforward example of an act of reference: the alphanumeric code refers to a particular soil trait, i.e., color, of which there are three existing dimensions of interest to soil scientists. This matching exercise is also an example of a highly regulated transformation: the handful of soil (a thing) is transformed into an alphanumeric code (a sign) through the use of a standard disciplinary tool. Alternatively, Latour calls such a transformation the “loading” or “disciplining” of things into words. It is often said that there is a large gap between the world and the word, writes Latour, but in the hands of a skilled pedologist the gap between the two is incredibly small, not so imposing, entirely navigable, and completely understandable.

What is important to note in this single act of reference is that it creates a certain type of movement. In the example above, a thing (a handful of soil) has been transformed into a word (an alphanumeric code), and in this transformation the soil has taken one small step closer to becoming a more widely recognized sign among the world’s practicing pedologists. The movement illustrated here is not necessarily directional, that is, it is not a forward movement, as in ‘progress.’ It is simply a movement from a position of less abstraction to a position of more abstraction. Latour calls this movement from world to words or from things to

signs, "upstream" movement. In this upstream movement, much as in the translation of a foreign-language film for an English-speaking audience, something is lost. Or, as Latour writes, the resulting abstraction is "an economy, an induction, a shortcut, a funnel."<sup>150</sup> The newly produced Munsell code doesn't represent *all* of the many possible qualities of soil (e.g., color, mass, density, texture, etc.); it simply represents *one* of them (i.e., color). In other words, the transformation from thing to word decreases the soil's complexity. However, what the soil loses in terms of its worldly qualities, it gains in terms of its wordly ones. To put this differently, while the soil loses some of its *thing-ness*, at the same time it gains in terms of its *sign-ness*. For instance, in its rather unremarkable transformation from thing to word the soil is now more mobile, more compatible, more calculable, and more universal than before. In other words, the transformation of soil from a handful (not an inscription) to an alphanumeric code (an inscription) has increased the soil's *manageability*.

There is yet another movement made possible in the routine scientific transformations of things to inscriptions. Weeks after the pedologists leave the Brazilian forest, when they are in their university offices or laboratory and revisiting their field notes, the presence of a single Munsell code in one of their field notebooks is both a record and a reminder that they once kneeled and held a very specific handful Brazilian forest soil in their hands. A single Munsell code, as Latour writes, is itself "a guarantor, a record, a preservation, a footnote."<sup>151</sup> The collection of alphanumeric Munsell codes in their notebooks act as markers or signposts that allow them to travel from words back to things. Once again the gap between the world and the

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150. Latour, *Pandora's Hope*, 34.

151. *Ibid.*, 34.

word, but this time in the reverse direction, is not so imposingly large. In the hands of a meticulously organized pedologist, the field notebook is a tool to help scientists retrace their steps back to Brazil, and likely to the very spot where they extracted code “5P 5/10.”

The direction of movement described here is not a backwards movement, as in ‘regress.’ It is simply a movement from a position of more abstraction to a position of less abstraction. Latour calls this movement from words to world or from signs to things, “downstream” movement. This downstream movement from word to thing decreases the soil’s manageability: compared to the coded soil the handful of soil is much more difficult to discipline—it (quite literally) slips through one’s fingers. In other words, in moving from its coded form to its decoded form, the soil has lost some of its previous mobility, compatibility, standardizability, and universality. However, what the decoded soil loses in terms of its wordly qualities, it gains in terms of its worldly ones. This movement from word to thing increases the decoded soil’s *complexity*. When compared to the coded soil, the handful of soil has traits like color, mass, density, shape, and texture. Thus, in its downstream movement from code (an inscription) to handful (not an inscription), the soil has recaptured some of its earthly qualities.

To summarize one of the key characteristics of transformative acts of reference, we can say that a single act of reference *flows* both upstream and downstream to create a “double direction of the movement of reference.”<sup>152</sup> Often, these acts involve ingenious tools—like the Munsell code booklet—which mediates the transformation of more matter-like substances into more sign-like forms. In more practical terms, such tools mediate the transformation of handfuls of soil into alphanumeric codes. Such tools help scientists perform acts in which

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152. Ibid., 74.

something more concrete becomes something more abstract. However, with every transformation of matter in form there is a “dialectic between gain and loss.”<sup>153</sup> On the one hand, making something more abstract decreases its complexity. On the other hand, making something more abstract increases its manageability. For Latour, this double direction of the movement of reference and its accompanying dialectic of loss-gain is an important insight in trying to understand how it is that scientists gain scientific knowledge in places such as forests, fields, and laboratories.

Part of what makes an act of reference *scientific* is the careful mapping of the act itself, for both the upstream and downstream movement must be accounted for by the active scientist, as well as traceable by other scientists. That is, some sort of accounting system must be created and maintained in which it is possible to follow an upstream transformation back downstream. Whereas psychological studies of science offer us a picture of knowledge gain in which the manipulation of ideas and concepts in the mind/brain are the driving force of science, Latour’s empirical studies offer us one in which the transformation and accounting of earthly things into visible, material signs matters most. Already in this dissertation, I have referred to the former sensibility as “logics” and the later sensibility as “logistics.” In field and laboratory sciences, notebooks or logs are one of the central gathering points in which these accounting systems can be seen in a visible, material form. However, the system itself is distributed across other types of visible, material forms. For example, numbered cabinets in university hallways contain hundreds of individual field samples and each field sample has alphanumeric writing on

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153. Ibid., 74.

it that records such information as the sample date, sample location, sampling conditions, sample number, name of the sampling scientist/technician, etc.

II. Circulating reference: The coupling of multiple acts of reference into coherent circuits

Before we go further there is at least one pressing problem in need of attention. The Munsell code “5P 5/10” is clearly not the final-form inscription published by Silva et al. in their scientific report and shown in Figure 4.6 (Part C). To help emphasize this discontinuity, Figure 4.6 allows readers to visually compare (A) a handful of soil, (B) the Munsell code “5P 5/10,” and (C) Silva et al.’s Figure 3.



A. A handful of soil.

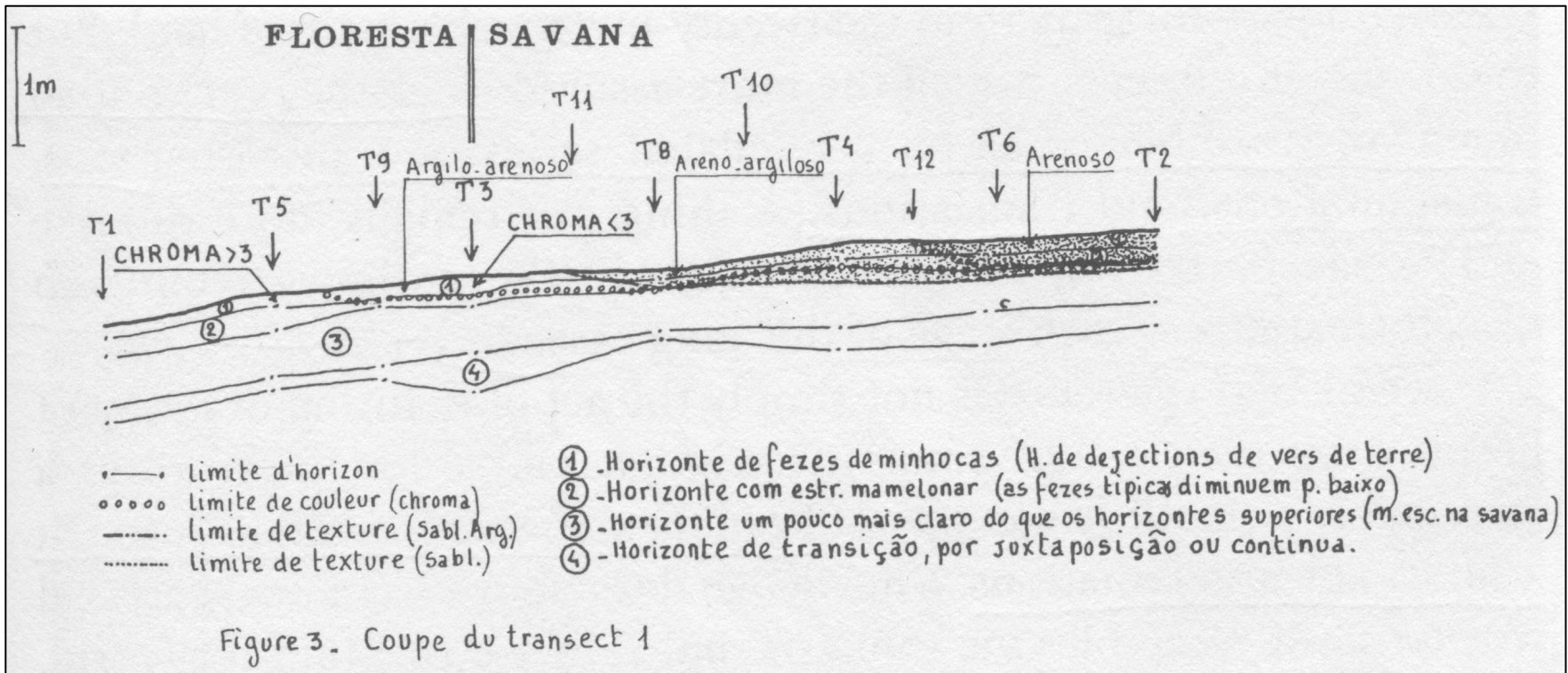
*Figure 4.6.* Three images—a photograph, a phrase, and a diagram—illustrating three stages of a coherent circuit of reference. A handful of soil (A); an example of a Munsell code (B); and Figure 3. Coupe du transect 1 (Silva et al. 1991). A figure displayed in a scientific manuscript reporting on the findings of an expedition to region of Boa Vista, Roraima, Amazonia (Brazil) (C).

*Figure 4.6. (cont'd)*

**“5P 5/10”**

B. An example of a Munsell code.

Figure 4.6. (cont'd)



C. A figure displayed in a scientific manuscript reporting on the findings of an expedition to region of Boa Vista, Roraima, Amazonia (Brazil). Figure 11.15 (Latour 1999). (Reprinted with permission by the copyright holder.)



When compared to Figure 3, the simplistic alphanumeric code “5P 5/10” (Figure 4.6, part B)—which resulted from a single act of reference performed on the more earthly soil (Figure 4.6, part A)—does indeed look like it still remains a great distance from the diagram that Silva et al. called “Figure 3. Coupe du transect 1” (Figure 4.6, part C). Indeed, it still looks to be on the far side of a yawning ontological gap that requires a giant leap-like movement to cross.

While it is true that one way to traverse sizable gaps is via giant leaps and bounds, as daredevils know all too well, giant leaps over large gaps leave much room for error and canyon walls can be unforgiving. Another way to traverse a large gap is to take it slow, one small step at a time, by descending down the steep canyon walls and traveling along the valley floor. Here, the gaps are much smaller and easier to navigate without superhuman powers or experimental rockets. Here, there is more room for error. In this next section, we will see how scientists cross large gaps between things and signs by nesting multiple acts of reference together into longer chains or “circuits.”

According to Latour, much of the beauty, elegance, efficiency, certainty, and truth-perpetuating value of scientific knowledge gain rests not on solitary acts of reference, but instead on the careful coupling of multiple acts of reference into coherent circuits. This coupling is easy to see by returning to the activities of our pedologists. In their laboratory, we can easily imagine our pedologists taking the Munsell codes assigned to each of their individual soil samples and subjecting them to yet another transformative act of reference. For example, we can image them physically transferring each of the alphanumeric codes from their field notebooks onto sticky notes, and then arranging these individual notes on a large piece of paper meant to represent a birds-eye view of the original study site. With the aid of other signs

and tools, such as GPS coordinates, topographic maps, and rulers, they might begin arranging the soil codes on a large, desk-sized piece of paper in their conference room. As they (quite literally) trace the similarities or tendencies amongst the alphanumeric codes with pens and pencils, we can imagine something resembling a contour map of the forest floor taking shape on their table.

This is a different kind of map of the forest floor, one that they cannot likely create with a camera or satellite imaging. This hand drawn map is the equivalent of a pedological strip mine: in the pedologists actions every animal, rock, and kilogram of vegetation is hypothetically scoured from the study site to reveal a view of the forest soil that our pedologists will likely never actually witness first hand. By making the Munsell codes more mobile via transferring them onto sticky notes, by placing and arranging the coded sticky notes on a large piece of paper, by connecting tendencies in codes with contour lines, and then by removing the codes to leave only the contour lines themselves, our pedologists have created a coherent circuit of scientific reference. This careful and deliberate coupling of at least two acts of reference into a chain or *circuit*—thus, *circulating* reference—allows for the flow of certain continuities or qualities in both the upstream and downstream directions. In the upstream direction—from the handfuls of soil towards the contour map—the pedologists can move from less abstract things to increasingly more abstract signs. This is how, as Latour writes, "a text truly speaks of the world."<sup>154</sup> In the downstream direction—from the contour map towards the handfuls of soil—the pedologists can also move, if they so desire, from the more abstract word to the less abstract world. This is how, as Latour writes, the pedologist establishes a "reversible route" that

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154. Ibid, 61.

makes it possible to retrace her own footsteps when needed: "Across the variations of matters/forms," Latour continues, "scientists forge a pathway."<sup>155</sup> Here, we no longer need speak about large gaps separating the world and the word. Instead, we can speak about the ever-present world and the ever-present word in a series of linked acts of reference.

One important feature of circulating reference to take special note of is the strange twist of fate of both world and word, of both things and signs. In the first act of reference above, a less abstract handful of soil (a *concrete* thing) was transformed into a more abstract Munsell code "5P 5/10" (an *abstract sign*). In a later act of reference within the same circuit, however, this same Munsell code shifted its own function from sign to thing. That is, the less abstract Munsell code "5P 5/10" (a *concrete* thing) was transformed into a more abstract contour line (an abstract sign). Thus, in a coherent circuit of reference the Munsell code "5P 5/10" has *both* worldly *and* wordly attributes depending on whether it is the abstract product of one transformation or the concrete material for a subsequent one. In other words, as soon as the alphanumeric code "5P 5/10" becomes integrated into a coherent scientific circuit of reference, it simultaneously acts as both thing and sign. By assigning both matter and form to the Munsell code "5P 5/10"—as well as to all of the other intermediate transformations found throughout a circuit of scientific reference for we must say *exactly the same thing* about the contour line for it too is both matter and sign—Latour offers a spirited challenge to canonical ways of conceptualizing the relationship between worldly things and wordly signs. In a Latourian scenography, something abstract will always have a visible, material form regardless of how far upstream it is located within a circuit. In other words, abstraction—whether as products or

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155. Ibid, 61.

processes—never fully disappears. An abstraction never becomes invisible or immaterial. If it does, it ceases to exist.

### Section C: How to Speak Latourian about Classroom Figures

Now is the moment when we need to reverse the previous substitution. Because the plant processes presented in Figure 20 are much closer to biological topics taught in Bio101, we must let a good deal of our attention slip away from soil, pedologists, Munsell codes, and contour lines. Figure 4.7 is meant to help readers accomplish this necessary shift as we now come to the third reading of Melvin Calvin's diagram of the "photosynthetic carbon cycle.

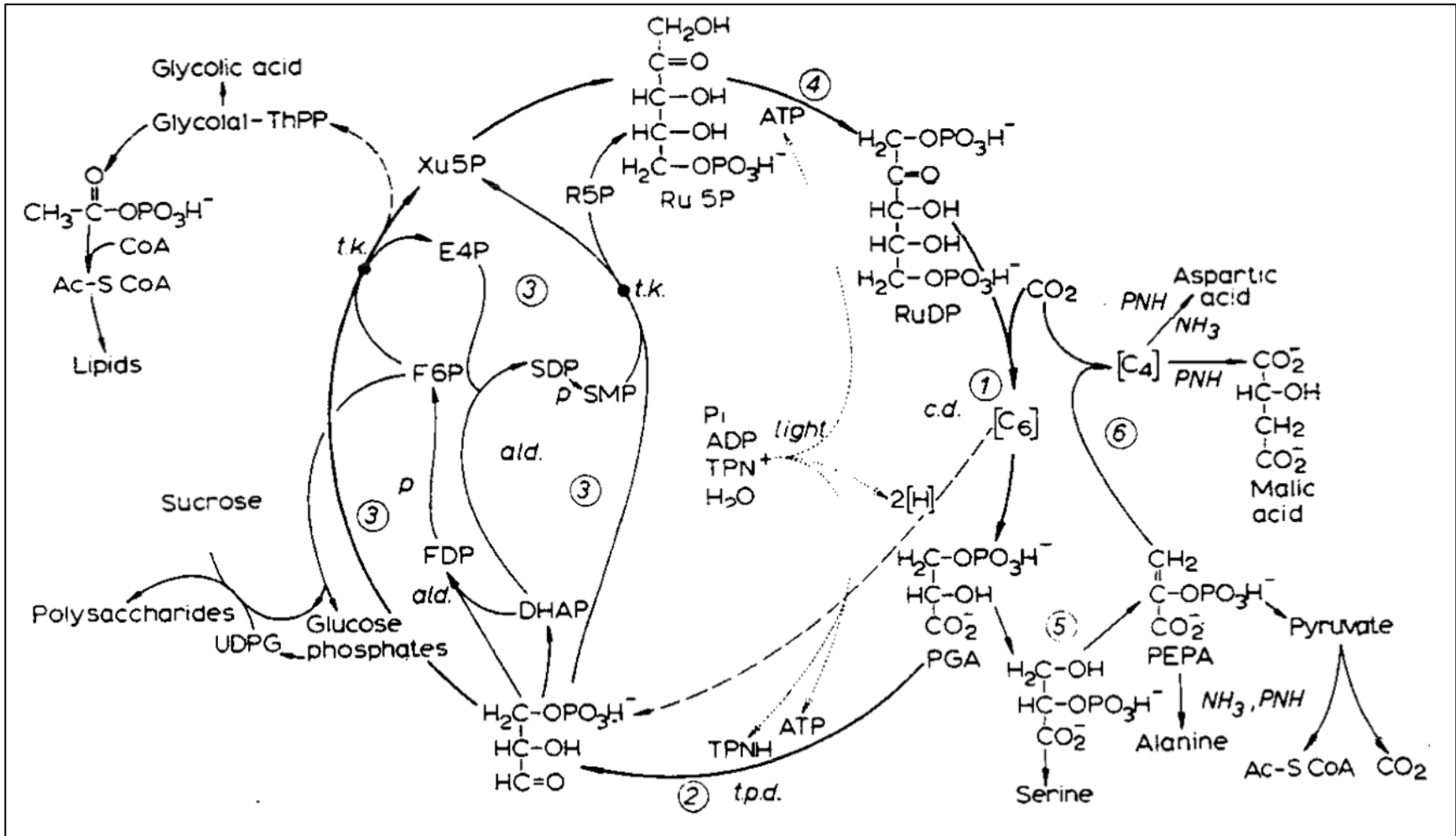


Figure 4.7. The photosynthetic carbon cycle. A figure used in a manuscript that Melvin Calvin submitted when accepting the 1961 Nobel Prize for chemistry. Figure 20 (Calvin 1961).

With the help of two Latourian concepts presented in Section B—*acts of reference* and *circuits of reference*—we can now see Calvin’s Figure 20 as part of an active scientific circuit of reference. Figure 20 is a *working object*; it is a *visual display* published in a scientific manuscript; it is an *inscription*. Figure 20 is also one of the refined products of multiple cycles of accumulation in a center of accumulation/calculation. Calvin and his colleagues at the University of California, Berkeley’s E.O. Lawrence Radiation Laboratory worked on its production mainly between the years 1949-1961. Figure 20 is also a visible, material form that is located a fair distance upstream of other inscriptions produced by Calvin and his many scientific collaborators.<sup>156</sup> Figure 20 is one of the more abstract products of many intersecting circuits of reference.

If we’ve learned anything about centers of calculation and scientific circuits of reference, however, it is that the abstract products of these centers and circuits can always be made even more abstract. There are always additional acts of reference that can be performed. There are always additional transformations that can be enacted. In other words, scientific circuits of reference are not closed loops; they are open-ended. To move farther upstream in circulating reference, a visible, material form simply needs to be made more mobile, more stable, more immutable, more combinable, and more superimposable. In other words, it simply needs to be made more abstract.

Finally, then, we are in position to connect—both conceptually and empirically—scientific figures and classroom figures. At last, we are in position to connect Calvin’s Fig. 20

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156. I’ve obtained and examined copies of most of the (declassified) scientific manuscripts produced by Calvin and his colleagues while at UC-Berkeley and I have examples of other working objects that are located farther downstream than Figure 20.

with Sadava et al.'s Fig. 8.13 (Part 2). Now deep within a Latourian scenography, we should be able to easily see Figure 8.13 as yet one more transformation, as yet one more act of reference. Figures 4.8 and 4.9 juxtapose Calvin's Fig. 20 with Sadava et al.'s Fig. 8.13 so as to help aid in this connective work.

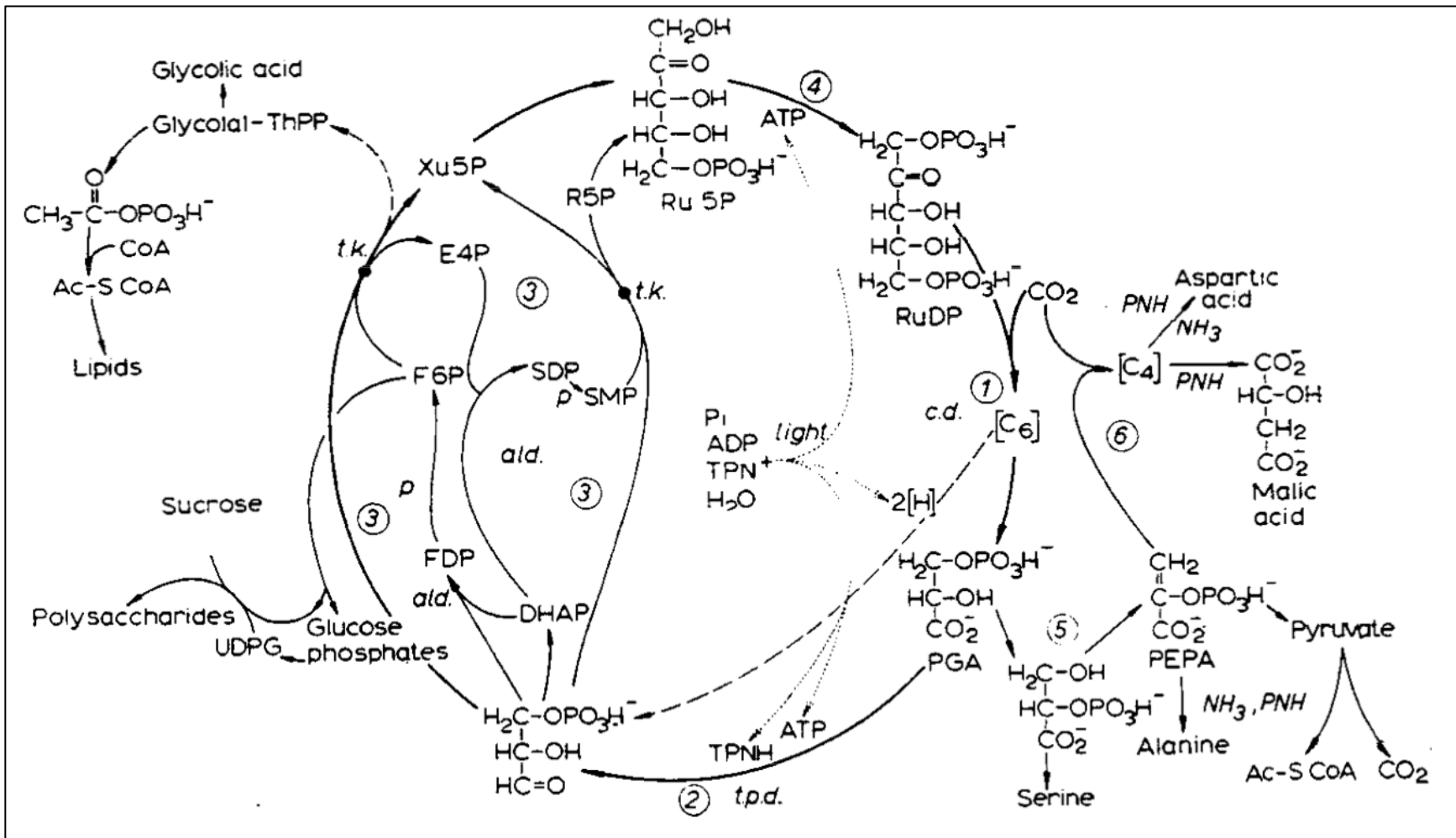


Figure 4.8. The photosynthetic carbon cycle. A figure used in a manuscript that Melvin Calvin submitted when accepting the 1961 Nobel Prize for chemistry. Figure 20 (Calvin 1961).



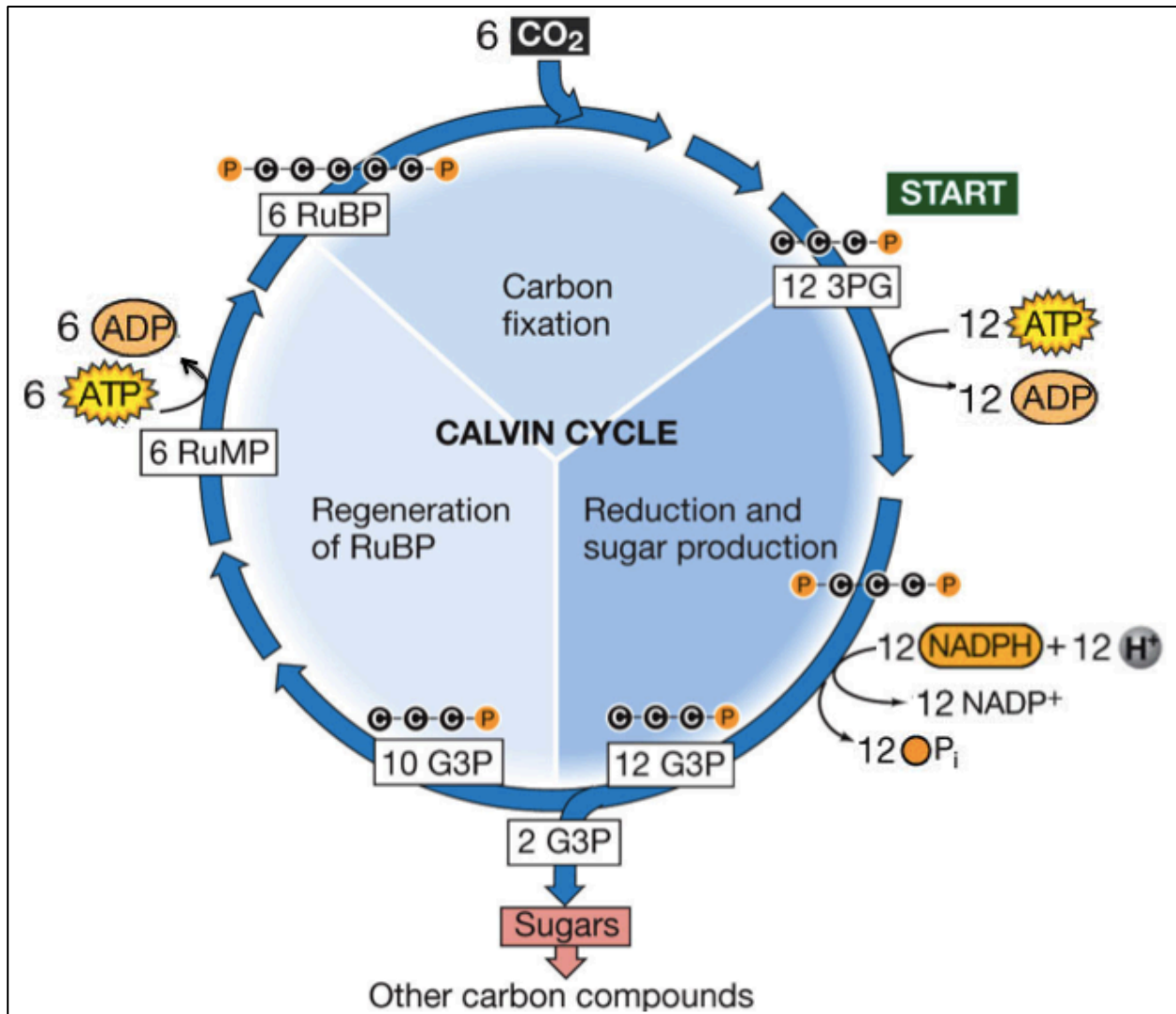


Figure 4.9. The Calvin Cycle. A figure shown to students during a photosynthesis unit in an undergraduate biology course. Figure 8.13 (Part 2) (Sadava et al. 2007). (Reprinted with permission by the copyright holder.)

Notice that the ‘distance’ between Fig. 20 to Fig. 8.13 is not simply an act of transformation (acts of transformation are not enough to be considered scientific); it is a *referenced* act of transformation. Through a combination of the phrase located in the middle of Fig. 8.13 (“CALVIN CYCLE”), the alphanumeric phrase that at one time appeared in the lower left hand portion of the figure (“Life 8e, Figure 8.13 (Part 2)”), and the index of “Figures” included in Sadava et al.’s textbook, we can, if we are both persistent and resourceful, eventually connect Fig. 8.13 with Fig. 20.

Admittedly, these two figures are sure to be separated by a number of other intermediary working objects created and published at various times between 1961-2007. However, just as we saw in the previous section, at every point along this circuit of reference we should expect to see working objects that simultaneously act as matter and form, thing and sign, world and word. And so, we must ask ourselves: At any point in the existing circuit of reference—which is organized in the downstream direction by Calvin’s Fig. 20 and in the upstream direction by Sadava et al.’s Fig. 8.13—do the intermediary figures in between these working objects ever lose their visibility or materiality? Here, we must recall the dialectic of loss and gain always present in circulating reference. We must remember that while every transformation upstream leads to a loss of locality, particularity, materiality, multiplicity, and continuity, at the same time this movement results in gains in compatibility, standardizability, textuality, calculability, circulability, and universality.<sup>157</sup>

When compared to Calvin’s Fig. 20, Sadava et al.’s Fig. 8.13 appears more highly cleansed. In other words, through observable—and possibly even quantifiable—differences in

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157. See Latour 1999, Chapter 2.

its use of color, symbols, formatting, and design, Sadava et al.'s inscription is more refined and more orderly. One of the gains afforded by this increased order is that Figure 8.13 is able to separate the cyclical process occurring in green plant cells into three equally weighted divisions or stages and label them as follows: "Carbon fixation," "Reduction and sugar production," and "Regeneration of RuBP." This same sort of tripartite division is not as clearly visible (if visible at all) in Figure 20. Indeed, with as many curved arrows and chemical substances that crisscross the middle of Calvin's inscription, it is visually difficult to cleanly divide the overarching cyclical process into the three stages so cogently presented in Figure 8.13.

However, in the dialectic of gain and loss such orderly gains always come at a price: when compared to Sadava et al.'s working object, Calvin's provides its readers with more detailed molecular drawings for a number of carbon-based compounds found within the Calvin Cycle. Whereas Sadava et al.'s working object displays the sequence and arrangement of mainly carbon ("C") and phosphorous ("P") atoms of the carbon-based compounds found within the cycle, Calvin's includes not only the sequence and arrangement "C" and "P" atoms, but also of oxygen ("O") and hydrogen ("H") atoms. Thus, while Fig. 8.13's more abstract form makes for some important affordances, at the same time this new form results in equally important losses.

Despite its greater degree of abstraction, however, Sadava et al.'s Figure 8.13 (Part 2) remains both visible and material for both inscriptions are paper-based. Both are two-dimensional traces of three-dimensional processes or entities said to exist in the chloroplasts of most green plants. Are they representations of one another? Yes and no. It's true, Sadava et al.'s inscription re-presents some of the information found in Calvin's inscription, but it does not re-present all of it. As mentioned above, there is a measurable loss of information that

occurs when Calvin's figure is transformed into Sadava et al.'s figure. Figure 8.13 (Part 2) is not an exact replica of Figure 20; they are by no means one hundred percent *mimetic*. There may be some resemblance between the two inscriptions, but there is no complete and faithful one-to-one correspondence.

#### Section D: Tracking Scientific Reference in Bio101

Here, we come to a key set of questions in this dissertation.

If Fig. 8.13 is already considered to be a part of an active circuit of scientific reference—in other words, if it is already an inscription in a circuit located slightly upstream of Calvin's Fig. 20—what happens to Sadava et al.'s Fig. 8.13 within the Bio101 classroom in the hands of the instructors? Is Fig. 8.13 part of any new acts of reference? In other words, similar to the work accomplished by scientists working in centers of accumulation/calculation, do the instructors engage in efforts to make Fig. 8.13 even more mobile, more stable, more immutable, more combinable, and more superimposable. Do they endeavor for or with their students to make Fig. 8.13 even more *abstract*?

The quick answer to this question is: *Yes, they do*. The Bio101 instructors do in fact transform Fig. 8.13 into other visible, material forms. In Figure 4.10 we can see what may be the furthest upstream visible, material form used by the Bio101 instructors.

# “Calvin Cycle”

*Figure 4.10.* “Calvin Cycle”. A frequently used term in the Bio101 classroom—both in spoken and written forms—and also on the exams.

Once again, we are confronted by something resembling a circuit of reference—which in this instance is bounded in the downstream direction by Sadava et al.’s Fig. 8.13 and in the upstream direction by a written phrase commonly used by the Bio101 instructors both in class and on exams (“Calvin Cycle”). I encourage readers to take a moment and briefly revisit Calvin’s Fig. 20 for the explicit purpose of reminding themselves that this circuit continues well into the downstream direction. I draw reader’s attention to Fig. 20 for the explicit purpose of pointing out that in the circuit of reference we have constructed, Sadava et al.’s inscription simultaneously acts as matter and form, thing and sign, world and word. When a product of the transformation of Calvin’s Fig. 20, Sadava et al.’s inscription is more abstract, more wordy than Fig. 20. However, when used itself as the raw material for a transformation into the phrase “Calvin Cycle,” Fig. 8.13 is suddenly more concrete and worldlier than the newly produced, more abstract(ed) sign.

The remaining two chapters in my dissertation are primarily concerned with how the Bio101 instructors transform more concrete figures such as Fig. 8.13 into more abstract phrases such as “Calvin Cycle.” In particular, I’m interested in all of the visible/material intermediary

forms that the instructors deploy as they move between thing-y signs and sign-y things. Since a critical feature of scientific circuits is the notion of reference, I'm also deeply interested in the system of accounting used during these various transformations: do the instructors create accounting systems that allow their students to move fluidly and confidently in both the upstream and downstream directions? Finally, I'm interested in describing—in strict empirical terms—the ways in which various circuits of reference created in the class overlap and intersect to create abstract concepts within the classroom. Among other affordances, this interest in abstraction (but also concretion) will allow me to revisit abstract conceptual learning theory with the hope of rearticulating it in accordance with a non-mental, non-psychological horizon of expectations.

## CHAPTER 5 HORIZONS IN ACTION

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Unfortunately, it is just this little word, this slogan of the enlightened—understand—that causes all the trouble. It is this word that brings a halt to the movement of reason, that destroys its confidence in itself, that distracts it by breaking the world of intelligence in two, by installing the division between the groping animal and the learned little man, between common sense and science. From the moment this slogan of duality is pronounced, all the perfecting of the ways of *making understood*, that great preoccupation of men of methods and progressives, is progress toward stultification.

—Jacques Rancière, *The Ignorant Schoolmaster*

### Looking Back

In the first half of Chapter 2, I documented how understanding is all the rage in the Age of Reform in Science Education. And how, during this educational era which began in the late 1980s and continues at present, many individuals, groups, and organizations within science education have increasingly promoted a particular construction of understanding known as “learning with understanding.” Learning with understanding is generally defined in terms of students or learners. Those who learn with understanding are said to be able to apply, extend or transfer a knowledge base that is deep in content and rich in connections to situations beyond the original context of learning. In this construction, the deep, rich knowledge base and the act of application/extension/transfer are both routinely characterized as mental or cognitive. That is, both knowing and doing are widely reported to occur in the minds/brains of

learners. When executed appropriately, such understanding is often said to be “conceptual,” “meaningful,” and “enduring.” This particular construction of learning with understanding is now widely acknowledged by many groups and organizations as a major goal of science teaching. In the second half of Chapter 2, I suggested that this particular mental/cognitive construction of learning with understanding has strong discursive and conceptual continuities with what Lemke has called “conceptual learning theory.” However, I added a minor amendment to Lemke’s work and used the term *abstract conceptual learning theory* (or ACLT) to reflect and emphasize the fact that educators seem to value abstract concepts above and beyond all other types of concepts.

The work undertaken in Chapters 1 and 2 helped make at least three statements possible about the construction of learning with and teaching for understanding in the Reform Age: First, this particular construction assumes a fundamentally psychological approach to teaching and learning. Second, it belongs to the tradition of mentalism. And third, it is part of a cognitive model of science education. I’ve suggested that this particular way of constructing learning with and teaching for understanding aligns it more closely with the governing principles and concepts of the psychological sciences than with those of the natural sciences. Popkewitz, who documents a similar trajectory in other educational settings—for example, in music and mathematics education, as well as in the writing of educational standards—uses the provocative concept of “the alchemy” to characterize the actions and events by which the academic disciplines are transformed, transmuted, and/or transmogrified into school subjects. By extending and relating the ideas of Popkewitz and Lemke to the discourse of learning with and teaching for understanding, I tried to draw critical attention to what I feel is one of the



most salient outcomes of an active psychological alchemy in Reform Age science education: To take a mentalist approach to entities such as knowledge, thinking, reasoning, and understanding is to make a choice that privileges individuality, secrecy, clandestinity, undocumentability, and universality over other qualities. In other words, to take a mentalist approach to these entities is to be selective and exclusive. It limits our conceptions of what these entities can be to a culturally and historically specific set of values, ethics, assumptions, and beliefs. More often than not in the Reform Age, students from backgrounds outside of the upper-middle class are more likely to struggle in educational moments in which knowledge and understanding are defined exclusively as mental and cognitive. These students tend not participate regularly enough in networks of cultural practices that promote, develop, and value psychologically conceived approaches to learning.

In an attempt to re-define entities such as knowledge and understanding as something other than mental or cognitive, I tried to disrupt the tenets of abstract conceptual learning theory in Chapters 3 and 4 by familiarizing readers with the anthropological and philosophical work of Latour, who offers us vital empirical insight into how scientists confront unfamiliar phenomena. This disruption was meant to prepare the ground, so to speak, not only for a radical revision of the psychological notions such as *concepts* and *abstraction*, but also for the specific purpose of trying to make ACLT more inclusive and less constraining for teachers and students. From the beginning, my contention has been that abstract conceptual learning theory doesn't have to be so individualized, secretive, clandestine, rationalistic, and universalized. This historically and culturally specific formulation is not inevitable. It can be different. It can be otherwise. More specifically, it can be more inclusive, more empirical, and more scientific.

In summary, a problem simultaneously faced by students, teachers, professors, and researchers can be distilled as follows: in the context of the Reform Age, understanding has become a form of learning and a style of pedagogy that is more psychological and less empirical. Because empirical chains of reference play such a central role in the modern natural sciences, we might also say that understanding has become a form of learning and a style of pedagogy that is more psychological and less *scientific*. From certain perspectives, this psychological alliance could be viewed as an odd choice for science education and science teacher education. Three examples might help illustrate the oddity or strangeness of this choice.

### *Authenticity*

For a good part of the past 30 years, science educators have heard steady calls for increased authenticity in K-16 science education. Although this term has at least three meanings within science education discourse, one of its principle meanings communicates the desire for school science to be more like scientists' science.<sup>158</sup>

However, if authentic disciplinary science undergoes a psychological alchemy on its way into the spaces of schooling, then school science won't necessarily be more like scientists science. Thus, it's possible that authenticity boosters could view the activity of the mental/cognitive alchemy as problematic to/for their aim and goals of making school science more like scientists' science.

### *Discipline-Based Educational Research*

Tertiary science educators have heard recent calls in their domain for "Discipline-Based Educational Research" or "DBER." One of DBER's principle tenets is that science

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158. See Buxton 2006.

education reform should be driven by educational research which is deeply grounded in the “priorities, worldview, knowledge, and practices” found in disciplinary science and engineering.<sup>159</sup> However, if scientific and engineering research undergoes a psychological alchemy on their way into the spaces of schooling, then discipline-based education research won’t necessarily be more like research in science and engineering. Thus, it’s possible that DBER boosters could view of the activity of the mental/cognitive alchemy as problematic to/for their aims and goals of making educational research more like research in disciplinary science and engineering.

### *Scientific Teaching*

Tertiary science educators have heard recent calls in their domain for “scientific teaching.” One of the principle tenets of scientific teaching is that science education reform should be approached “with the same rigor as science at its best.”<sup>160</sup> However, if scientific rigor undergoes a psychological alchemy on its way into the spaces of schooling, then rigor in the classroom teaching won’t necessarily be more like rigor in science. Thus, it’s possible that scientific teaching boosters could view the activity of the mental/cognitive alchemy as problematic to/for their aims and goals of making educational rigor more like scientific rigor.

It follows that any individuals, groups, or organizations working within or outside of science education that aspire to make any part of science education *more like* science face a significant challenge: to alchemize something authentic, scientific, or disciplinary in accordance

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159. NRC, *Discipline-Based Education Research*, p. 9.

160. Handelsman et al., “Scientific Teaching,” 521.

with the governing principles and concepts of the psychological rather than the natural sciences is not to create something which is more authentic, more scientific, or more disciplinary. On the contrary, it is to create something that is decidedly less so. Fortunately, those who face this challenge have a choice. There are other resources on which to base the alchemy of science education that are as authentic, as disciplinary, and as rigorous as science.

This is why I have proposed an alternative alchemy for learning with and teaching for understanding. This new alchemy aligns student learning and teacher pedagogy with governing principles and key concepts from the natural rather than the psychological sciences. I gathered the raw materials for this new alchemy—that is, the governing principles and concepts—from the domain of Science Studies. Since the 1970s, a diverse and loosely organized group of scholars and researchers including anthropologists, sociologists, historians, economists, philosophers, and political scientists (among others), have turned science and scientists into legitimate objects of interest.<sup>161</sup> In others words, they have studied working scientists in much the same way as scientists study working atoms, circuits, bacteria, ecosystems, and galaxies. Their research—and in particular the work of Bruno Latour—has rendered a number of the active governing principles and concepts of scientific work both visible, discussable, and available for use. Some of these principles and concepts have already found their way into science education research.<sup>162</sup>

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161. These scholars have also turned engineers and engineering into legitimate objects of interest.

162. The greatest density of work in science education has been brought forth by Wolff-Michael Roth and his extended research group. The work with the most relevance to my research includes work on *abstraction* (e.g., see Pozzer and Roth 2003; Roth and Hwang 2006); on *inscriptions* (e.g., see Roth and McGinn 1998; Roth and Tobin 1997); on *science education and*

For the better part of the past six years I've been working arduously to try and align something that people within my field care deeply about—that is, improving learning with and teaching for understanding—with relevant principles, concepts, ideas, sensibilities, and methods found in and promoted by those working within the domain of Science Studies. Yes, this too is an alchemical act. Yes, this too will lead to a magical transformation. Yes, this too will lead to transmutation and transmogrification. Yes, this too will lead to something other than 'real,' authentic, rigorous, disciplinary science. After all, science students are not scientists. However, I now find myself in the exciting and challenging position to hypothesize that by restructuring pedagogical practices in accordance with an *empirical* rather than a mental horizon of expectations, my sense is that such a shift—albeit a dramatic and difficult one—will likely result in substantial improvements in students' abilities to learn with—as well as teachers' abilities to teach for—deep, rich, conceptual, meaningful, and enduring understanding.

My hope is that others will see this alternative alchemy, as I do, as a positive contribution to the field. I say this because rather than subtract the mental/cognitive horizon of expectations from science education discourse, it is my intent to add an empirical one. My explication and communication of an empirical horizon is in no way meant to deny the psychological sciences a role in construction of learning with and teaching for understanding. In fact, once again I remind readers that I do not care whether or not learning with understanding actually is psychological, mental, and/or cognitive. Instead, I care only about two things: First, the fact that I am an active member of and participant in a field in which many of my colleagues and peers act *as if* learning with understanding is psychological. Second, the fact that I am

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*Science Technology and Society (STS) studies* (e.g., see Roth and McGinn 1998); and on alternative approaches to *cognition* (e.g., see Roth and McGinn 1997).

persuaded by the argument that empirical traits such as visibility, materiality, tangibility, publicity, specificity contextuality, locality, and historicity can play important and productive roles in the goal of improving students' abilities to learn with and teachers' abilities to teach for understanding.

#### Addressing a Few Unresolved Issues

At this point I would like to point out and address at least two unresolved issues in my current work. The first issue is the lack of a more descriptive account of the psychological alchemy in action within the context of Bio101, and especially within the context of the classes leading up to the exam upon which the Mutant Spinach Question appeared. The second issue is the lack of a more descriptive account of the empirical alchemy in action within the context of Bio101, and again, especially within the context of the classes leading up to the exam upon which the Mutant Spinach Question appeared. Without these two descriptive accounts, readers might make choices that they might not otherwise make. For example, a teacher or professor might have difficulty imagining what sorts of pedagogies an empirical alchemy might lead to (and I wouldn't blame them, the mind is not to entrusted with such an important task!). Without this image, they might chose the sorts of pedagogies that psychological alchemies leads to, not because they find them more agreeable, but because they find them more familiar. There is, however, one significant obstacle standing in the way of the production of these two descriptive accounts. I maintain that the pedagogy I witnessed in Bio101 in fall 2006 was, at least for the most part, in large part formed by a psychological alchemy. In other words, I maintain the claim that the Bio101 professors approached teaching and learning science as if they were primarily mental/cognitive tasks. My obstacle arises from the fact that I have no

example of the Bio101 professors approaching teaching and learning science as if they were primarily empirical tasks. And so, how can I create a descriptive account of an empirical alchemy in action that others would find persuasive and useful within the scope and sequence of this dissertation? How can I bring the 2006 versions of the Bio101 professors, the application moment, and the Mutant Spinach Question into a productive relationship with my alternative (2013) notion of *empirical teaching* and *empirical learning*? In other words, how can I create a description of a collection of actors and events that never occupied the same time and space?

There's only one way I can think of to accomplish such a feat.

I need to treat the 2006 versions of the Bio101 professors, the application moment, and the Mutant Spinach Question *as if* they were an example of an empirical alchemy in action. To do this, I'll need to employ a tool or device which is capable of reanimating the teaching and learning that actually occurred in fall 2006 in accordance with governing principles and concepts that are more scientific and less psychological. Fortunately, I have just such a device in mind. It's a simulator (or emulator) and it recruits and enlists the empirical principles and concepts I developed in close partnership with Latour in the previous chapter. I call this device the *EmSIM 3000*.

With the help of Latour and the *EmSIM 3000* I intend to resolve the two previously unresolved issues stated above. I will generate descriptive accounts. I will bring the 2006 versions of the Bio101 professors, the application moment, and the Mutant Spinach Question into a productive relationship with my alternative notion of empirical teaching and empirical learning. I will manage to create a description of a cadre of actors and events that never occupied the same time and space. Using the data I collected in fall 2006 as the basis for both

accounts, I will not only create an empirical description of the psychologically-informed practices leading up to question “52,” but I will also—with the help of the *EmSIM 3000*—create an empirical description of the empirically-informed practices leading up to question “52.” To better facilitate the reader’s ability to compare and contrast these two accounts, I will present the two accounts as a single narrative in which both the psychological (or actual) and empirical (or hypothetical) narratives of the alchemies unfold side-by-side. One of my purposes in juxtaposing these two narratives in this way is so that they may be of greater assistance to those enthusiastic readers (should there be any still left at this point!) who may already be tempted to tinker and experiment with the existing mental/cognitive alchemy of learning with and teaching for understanding.

I would like readers to consider these two descriptive accounts as an attempt to establish empirical profiles or baselines for two pedagogical substances, or rather, pedagogical *practices*. The first practice, a much more widely known and familiar practice shaped by a psychological alchemy, I will hereafter refer to as *Pedagogia psychologicus* (*P. psychologicus*). The second practice, a much less widely known and familiar practice shaped by an empirical alchemy, I will hereafter refer to as *Pedagogia empiricus* (*P. empiricus*). If this particular framing of what is about to come sounds rather scientific, that’s because it is meant to sound this way. I see the next section of this dissertation as a genuine experiment. We are about to put two actors—one more known and one less unknown—through a series of trials so as to assess characteristic such as their purity, potency, composition, activity, and/or strength relative to one another. In science, such experiments and trials constitute something called an *assay*. In biology, such events are called *bioassays*. Since my much work unfolds within the context of



biology education, I will call this particular genre of experimentation, the *bioeducational assay*.

By the end of this particular assay, I hope to be able to generate preliminary answers to important pedagogical questions such as:

- What new types of pedagogical practices are made possible by an empirical alchemy?
- What can teaching for understanding look like when constructed in accordance with an empirical horizon?
- What can teachers actually do in classrooms in which empirical practices are enacted?

As well as to important questions about learners and learning such as:

- What new types of learning practices are made possible by an empirical alchemy?
- What can learning with understanding look like when constructed in accordance with an empirical horizon?
- What can students actually do in classrooms in which empirical practices are enacted?

Furthermore, the use of the *EmSIM 3000* should allow us to generate a speculative reality in which we can see a (virtual) Mutant Spinach Question posed to an (imaginary) group of students within a (simulated) classroom experiencing an (ostensibly) empirically-infused pedagogy. We can then use this simulation to generate a preliminary answer to yet another important question:

- What is the likelihood that an empirical alchemy of pedagogy could have led to a higher percentage of Bio101 students in fall 2006 able to successfully demonstrate the ability to learn with understanding on question “52”?<sup>163</sup>

Since this is an essay meant to be a type of experiment, I will follow some of the protocols of scientific research. Thus, before presenting the two descriptive accounts of *P. psychologicus* and *P. empiricus*, I will first tend to a number of the other important conventions characteristic of scientific writing. For example, after stating research questions I will include a “Methods” section, which will be immediately followed by a “Results” section. I’ve moved part of the “Discussion” section to Chapter 6 and it serves not only as the concluding section to the bioeducational essay, but also as the concluding section to the dissertation.

#### Research Question

We are simultaneously pursuing three research questions in this inquiry:

(A) What are the empirical characteristics of the psychologically-informed pedagogical practices that led up to the exam on which students were asked the Mutant Spinach Question? In other words, what is the empirical profile of a pedagogical practice that we are calling *Pedagogia psychologicus*?

(B) What are the empirical characteristics of the empirically-informed pedagogical practices that led up to the exam on which students were asked the Mutant Spinach Question? In other words, what is the empirical profile of a pedagogical practice that we are calling *Pedagogia empiricus*?

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163. As we will see later, however, we never needed to go so far into a virtual, hypothetical reality. We only needed to travel to the Bio101 classroom a mere two days after the midterm exam.

(C) What is the relative 'purity,' 'composition,' 'activity,' and/or 'potency' of a lesser known pedagogical practice (*P. empiricus*) relative to better known pedagogical practice (*P. psychologicus*)?

Because this inquiry is a descriptive project, is it not hypothesis-driven. However, I intend to use the answers to all three questions, and especially research question (C), to generate hypotheses regarding past, present, and future uses of pedagogies informed by the psychological and natural sciences. This speculation and hypothesis generation is included in Chapter 6.

## Methods

### **Practices of study**

This study assumes the existence of two practices, *Pedagogia psychologicus* and *Pedagogia empiricus*. Since it is an empirical study, this means that I am interested in everything that can be seen, heard, touched, tasted and/or smelled. This also means that I am interested in both subjects and objects, or rather, humans and non-humans. In other words, I am as interested in those things contained within the hands, backpacks, flash drives, and notebooks of professors and students as I am in the professors and students themselves. I am not, however, interested in those things contained within the minds, heads, hearts, and/or guts of professors and students because I do not have adequate empirical access to the contents of these places/spaces.

### **Equipment**

The data used in this bioeducational assay takes the form of 1) digital video tapes containing recordings of every fall 2006 class meeting, 2) digital audio files containing a number

of interviews with the course instructors, 3) a collection of notebooks filled with field notes, 4) a copy of the course textbook, and 5) three-ring binders containing paper artifacts collected from the course (e.g., exams, handouts, course syllabi, lesson plans, homework assignments etc.). To collect this data, I used a digital video camera, a camera tripod, a handheld digital voice recording, blank field notebooks, a computer flash drive (or memory stick), a laptop computer, and a number of empty three-ring binders.

To perform the bioeducational assay required the use of both hardware and software. In terms of hardware, I used a digital video camera and a laptop computer. I used the digital video camera to upload the digital videotapes onto the drive of my laptop computer for viewing and analysis. I used Apple's *Quicktime Pro* (which includes viewing, editing, and file converting capabilities) for this portion of the data processing/analysis.<sup>164</sup> A second use of the laptop computer was to facilitate the transcription of the digital video of classroom instruction into two types of transcripts. I generated one set of transcripts of the auditory classroom discourse. To do this, I used Apple's *Quicktime Pro* and Microsoft's *Word 2010*.<sup>165</sup> I generated another set of transcripts of the visual classroom discourse. To do this, I used Apple's *Quicktime Pro*, Microsoft's *Word 2010*, and Chimoosoft's *Capture Me*.<sup>166</sup> The *Capture Me* software is a screen-capture software that allowed me to create still images of various moments during the playback of the digital video files. To archive all of this digital content I relied upon CD-R/W and

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164. Quicktime v.7 (<http://www.apple.com/quicktime/>).

165. Microsoft Office (including Microsoft Word) (<http://office.microsoft.com/en-001/>).

166. Capture Me v1.3 (<http://www.chimoosoft.com/products/captureme/>).

DVD-R/W disks, internal and external hard drives, and cloud computing storage services such as Google Drive.<sup>167</sup>

In addition to some of the equipment mentioned above (e.g., the laptop computer, *Capture Me*, *Word 2010*), part of my construction of the *EmSIM 3000* required the use of Google's *Picasa 3* software.<sup>168</sup> In addition to image organizing, viewing, and editing capabilities, *Picasa 3* also has image sorting, tagging, and tracking capabilities. For example, in addition to unique filenames, *Picasa 3* users can also assign unique or overlapping keywords, captions, tags, folder names, and other metadata (including facial and color recognition). Users can use a built-in search bar feature to track photos according to any/all of this metadata. The *EmSIM 3000* makes use of *Picasa 3*'s powerful "tags" feature, which I discuss in greater detail in my Procedures (below).

## **Procedures**

### *(A) Pedagogia psychologicus*

The purpose of Trial (A) in the bioeducational assay is to generate an empirical profile of *Pedagogia psychologicus* in classes that I determined to have direct relevance to students' ability to answer the Mutant Spinach Question (question "52") correctly. I determined the relevance of the classes with the help of interviews with the professors. When talking about the Mutant Spinach Question in the interviews, the professors named key topics and concepts such as "photosynthesis," "Z-scheme," "thylakoid membranes," "cyclic photophosphorylation," "non-cyclic photophosphorylation," the "light reactions," and the "light-dependent reactions."

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167. Google Drive (<https://drive.google.com/>).

168. Google Picasa v3.9 (<http://picasa.google.com/>).

This discursive constellation of topics/concepts allowed me to narrow the forty-five 50-minute classes down to four “lectures”: Lectures 11 (09-25-2006), 12 (09-27-2006), 13 (09-29-2006), and 14 (10-02-2006).

I recorded all the Bio101 lectures by placing a single digital video camera in the same general area in which the Bio101 students sat during lecture. I did nearly all of my filming from the first row of student seating and to the (left) side of a large auditorium. Although at times I directed the camera toward the instructors and students, most of the time I trained my camera on what the professors were displaying to/for students on a large, theater-sized projection screen located at the front of the lecture hall. I made consistent use of the camera’s zoom feature to capture any and all empirical activities related to the many images and writing that appeared on the projection screen. These were the videos of these lectures that I watched repeatedly, eventually deciding to transform them into the two kinds of transcripts. One set of transcripts contained a written record of the auditory (or verbal) features of classroom discourse and the other set of transcripts contained a graphical record of the visual (or pictorial) features of classroom discourse. This second set of transcripts also contained a graphical record of the material (or tangible) features of classroom discourse, and this record was supplemented by entries contained within my field notebooks. Here, I use the term “classroom discourse” to refer to and include all observable classroom agents—human and non-human—which appear as though they have an active role in the goal of making biology understandable.<sup>169</sup> When required, I consulted my field notebooks, the written transcripts of interviews with the

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169. This definition of the term *discourse* is inspired by Fendler’s description of Foucault’s use of it (see Fendler 2010, 16).

professors, the course textbook, copies of the exams given to me by the instructors, and other available empirical artifacts for the purpose of clarification and/or attempting to improve our accuracy/precision.

The two kinds of transcripts were then used to construct the narrative account (or “profile”) of the psychologically-informed pedagogical practice, *Pedagogia psychologicus*, in the days leading up to the Mutant Spinach Question.

(B) *Pedagogia empiricus*

The purpose of Trial (B) in the bioeducational assay is to create an empirical profile of *Pedagogia empiricus* in classes that I determined to have direct relevance to students’ ability to answer question “52” (the Mutant Spinach Question) correctly. The procedures for Trial (B) were exactly the same as those used in Trial (A), but included the construction and use of an empirical simulator, the *EmSim3000*. Recall that there is no existing data set in which the same Bio101 professors engaged the same four hundred students in pedagogical practices that were a) aimed at preparing students to answer question “52,” and b) structured in accordance with an empirical horizon of expectations. Because of this unfortunate fact, I determined that an empirical simulator is needed to generate a hypothetical, parallel, or virtual reality in which we can see the Mutant Spinach Question posed to students within the (simulated) context of an empirically-infused pedagogy.

I undertook the construction of the empirical simulator in accordance with governing principles and concepts taken from the research, scholarship, and empirical philosophy of Bruno Latour. Although the official name of this simulator is the *Latour EmSIM 3000*, for convenience I will use a shortened version, the *EmSIM 3000*.

## How to construct the *EmSIM 3000*

### PHASE 1

Every time something visibly new appeared on the projection screen at the front of the lecture hall (as seen in the videotapes), I used the *Capture Me* screen-capture software to record a still image of it. On those occasions in which the professors displayed a single image for a substantial period of time (for example, a “figure”), I made multiple screenshots of what appeared on the projection screen for the purpose of documenting what the instructors had done to the image—e.g., added written annotation—for and with their students. On those occasions in which the professors projected animations onto the screen, again I took multiple screenshots of what appeared on the projection screen for the purpose of documenting the different stages of the animation that were visible to students. At the end of this phase, I printed reproductions of each of the still images onto individual ‘cards’ measuring approximately 3”x5”. Each card contained a color reproduction of the image, metadata (e.g., Lecture no., date, Figure no., etc.), and blank space for additional inscribing/writing.

### PHASE 2

With the entire collection of imaged cards, I then used a combination of the original digital video tapes and the two types of transcripts to “tag” the still images with single words and/or short phrases reflecting certain auditory (or verbal) features of classroom discourse. For the most part, these tags consisted of scientific (or ‘technical’) tags. That is, the tags were meant to reflect the linguistic and/or semiotic content of biology. The



tags themselves were generated by the words, phrases, and/or sentences spoken and/or written mostly by the professors, but occasionally by the students (e.g., when asking one of the professors a question in class). Some examples of the content tags generated by the classroom discourse include (but are by no means limited to): *photosynthesis, thylakoid(s), permeability, permeable, membrane(s), light reactions, light-dependent reactions, proton(s), plant(s), electron donor, ATP, NADPH, H<sup>+</sup>, sugar(s), sunlight, oxygen, O<sub>2</sub>, carbon dioxide, CO<sub>2</sub>, and spinach*. By the end of this phase, every still image displayed to/for students on the projection screen during the four photosynthesis lectures had been assigned (often multiple) tags. Each still image—but still in card or paper form—was assigned tags that were determined to be reflective of the classroom discourse in circulation while the image was on display (but also sometime soon before and/or soon after an image was removed from actual view).

### PHASE 3

Each of the original still images was then imported into Google's *Picasa 3* program. The image cards were then used to guide the digital tagging of each still image in *Picasa 3* using the software's built-in tagging feature. The last still image I imported into the software was the image of question "52," the Mutant Spinach Question. Just as I did with the other images, I also tagged this image with various content tags (e.g., "spinach," "mutant," "thylakoid membrane," etc.). At the end of this phase, I had constructed a searchable database that I treated as if it were a visible, material *knowledge base*. I saw this knowledge base as not only deep (in terms of the number of tagged images present),

but also rich (in terms of searchable connections). In other words, I considered this new visible, material (and digital) knowledge base to constitute understanding that could be considered conceptual, meaningful, and enduring, as well as applicable, extendable, and/or transferable to new, unfamiliar, unscripted contexts.<sup>170</sup>

In conjunction with the two kinds of transcripts already produced for use in Trial (A), I then used the *EmSIM 3000* to help construct the narrative account (or “profile”) of the empirically-informed pedagogical practice, *Pedagogia empiricus*, in the days leading up to the Mutant Spinach Question.

### Data Analysis

Once the profiles of *P. psychologicus* and *P. empiricus* were constructed, I subjected them both to a mode of analysis derived from and heavily informed by the work of Latour. *P. psychologicus* and *P. empiricus* were compared and contrasted in regards to their ability to create (or not) coherent, visible, material “circuits of reference,” a concept that features prominently in a number of Latour’s empirical studies of science in action.<sup>171</sup> This concept depends on other Latourian concepts, such as “acts of reference,” “chains of reference,” “translation,” “inscription,” and “amplification/reduction.”<sup>172</sup> All of the concepts play an active role in my statements about the educational or pedagogical ‘purity,’ ‘potency,’ ‘composition,’

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170. Functional caveat: this knowledge base will be considered ‘enduring’ for as long as my laptop and external hard drives remain in working order, as well as for as long as Google’s Picasa remains a well-supported, functioning, multi-platform, bug-free software program.

171. For example, see Latour 1986; 1987; 1999.

172. These are discussed at length in Chapter 4.

'activity,' and/or 'strength' of the lesser known *P. empiricus* relative to the better known *P. psychologicus*.

## Results

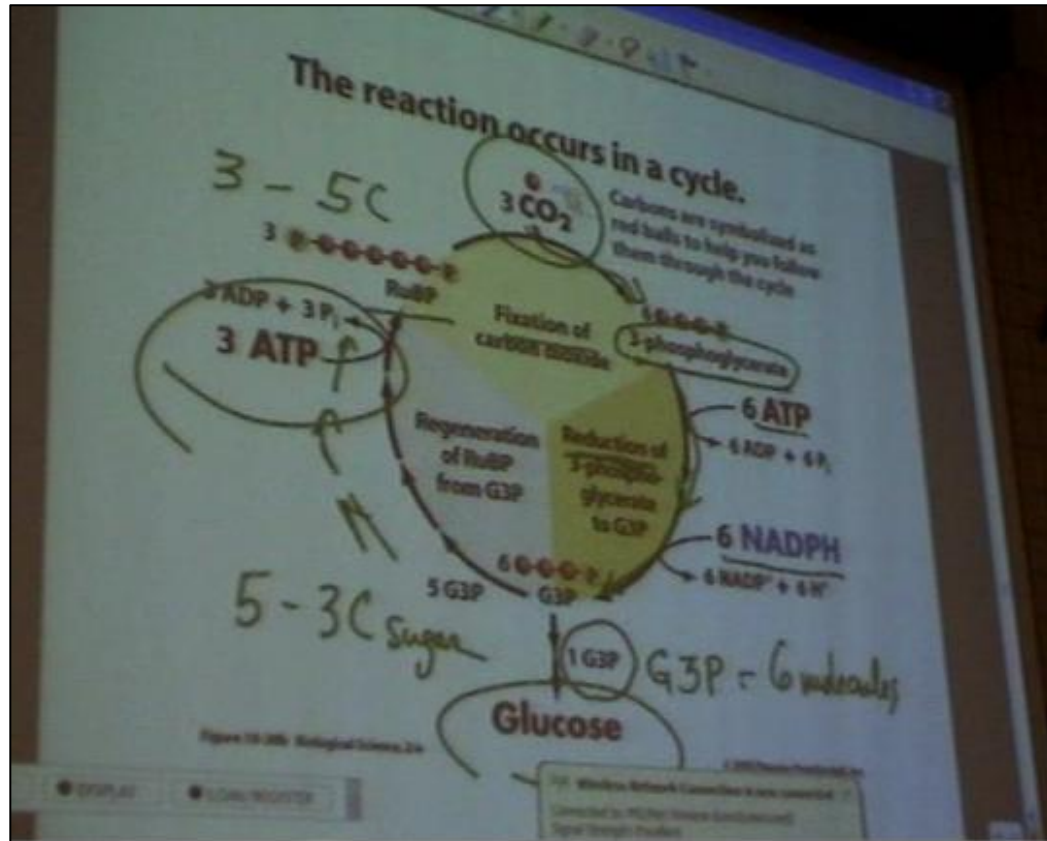
The results or findings of this bioeducational assay are divided into three major sections that reflect the three main pedagogical practices enacted in Bio101. These three major practices are each named after the most visible, material element present in the practice. For example, the first practice, "Figures," is so named because of the significant presence of the figures displayed by the two professors to/for their students during this practice. Each of these three practices is then divided into three main sections. The first main section contains a detailed empirical description of the pedagogical practice. The second and third main sections consist of two perspectives. The first perspective develops an empirical profile of *P. psychologicus* for that practice. That is, it describes the pedagogical practice when it is constructed and executed in accordance with a mental horizon of expectations. The second perspective develops an empirical profile of *P. empiricus* for that same practice. That is, it describes the pedagogical practice when it is constructed and executed in accordance with an empirical horizon of expectations. The juxtaposition of these two perspectives within each of the three major pedagogical practices should help facilitate a comparison of their characteristics and qualities relative to one another.

## Practice 1: Figures

During the four-day photosynthesis unit, Bio101 professors and students spent the majority of their class time together looking at and talking about “figures.”<sup>173</sup> On the first day of the unit, the professors displayed ten figures. On the second, they displayed twenty-one figures. On the third, they displayed twenty-two figures. On the fourth day, a day in which only half the period was devoted to the topic of photosynthesis, they displayed seven figures. In total, the Bio101 professors displayed no less than *sixty* visible, material figures to/for students during the four-day unit. Two of these sixty figures are shown in Figure 5.1.

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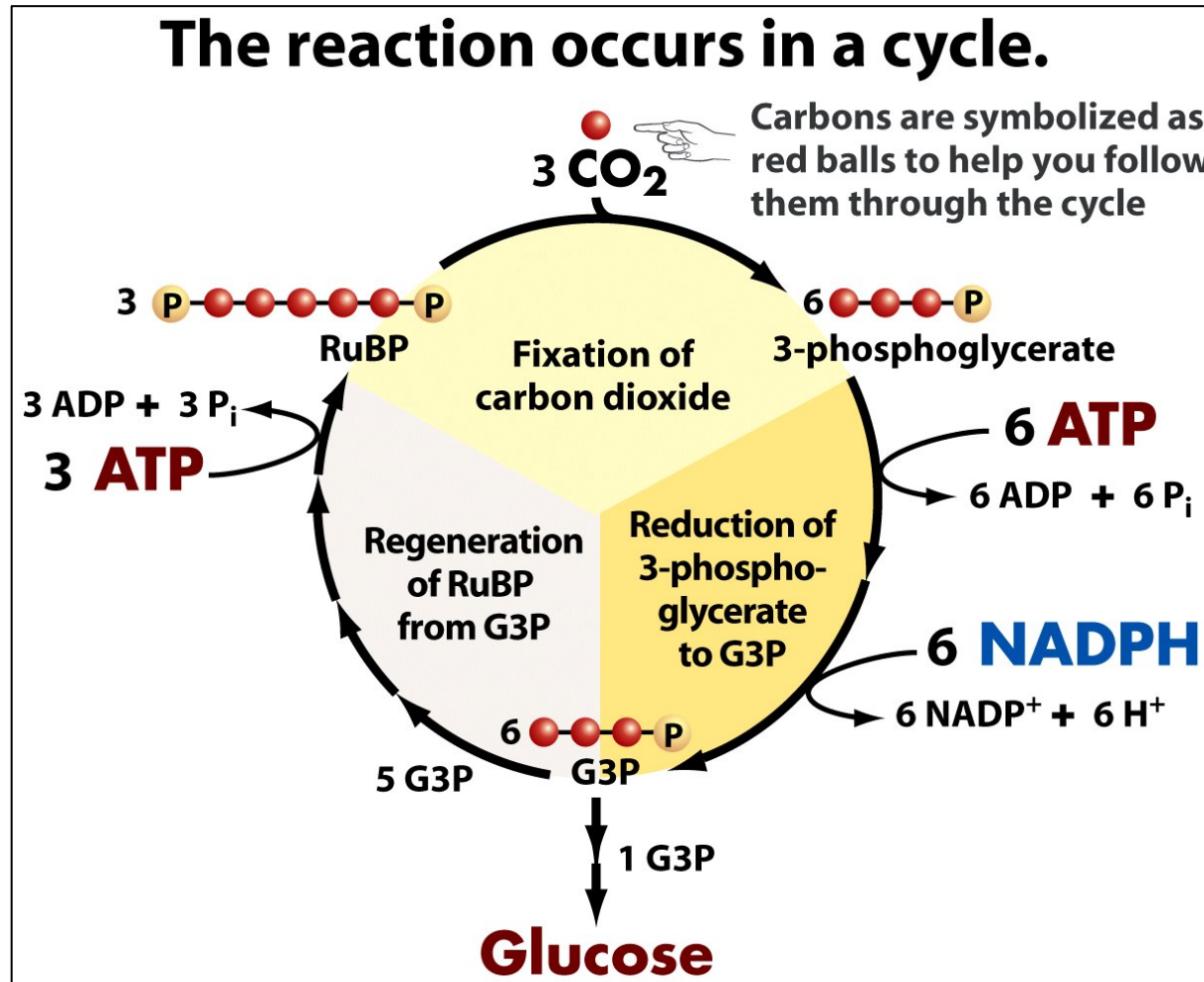
173. “Figures” are discussed briefly in Chapter 3, and at length in Chapter 4.



A. A figure of the “Calvin Cycle” shown to students on Day 3 (Lecture 13, 09-29-2006).

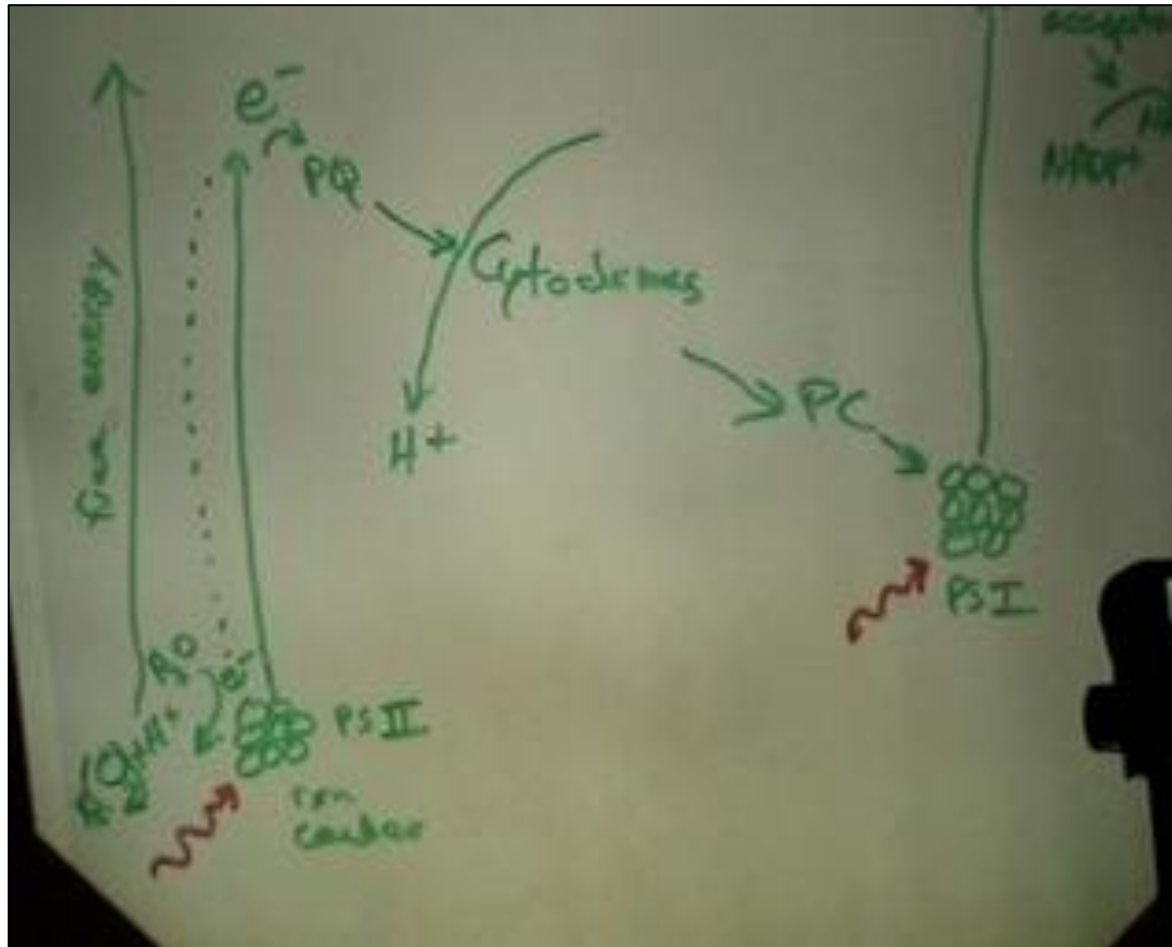
Figure 5.1. Photographs of two figures (A and C) shown to undergraduate students by the course instructors during the photosynthesis lectures. Because the images and text shown in photographs A and C may be difficult to see/read, the original images (B and D) are presented with the ones used in the photosynthesis lectures. A figure of the “Calvin Cycle” shown to students on Day 3 (Lecture 13, 09-29-2006) (A); the figure of the “Calvin Cycle” as it appears in the instructional materials (B); a figure of the “Z-scheme” shown to students on Day 2 (Lecture 12, 09-27-2006) (C); and the figure of the “Z-scheme” as it appears in the instructional materials (D). (Reprinted with permission by the copyright holder.)

Figure 5.1. (cont'd)



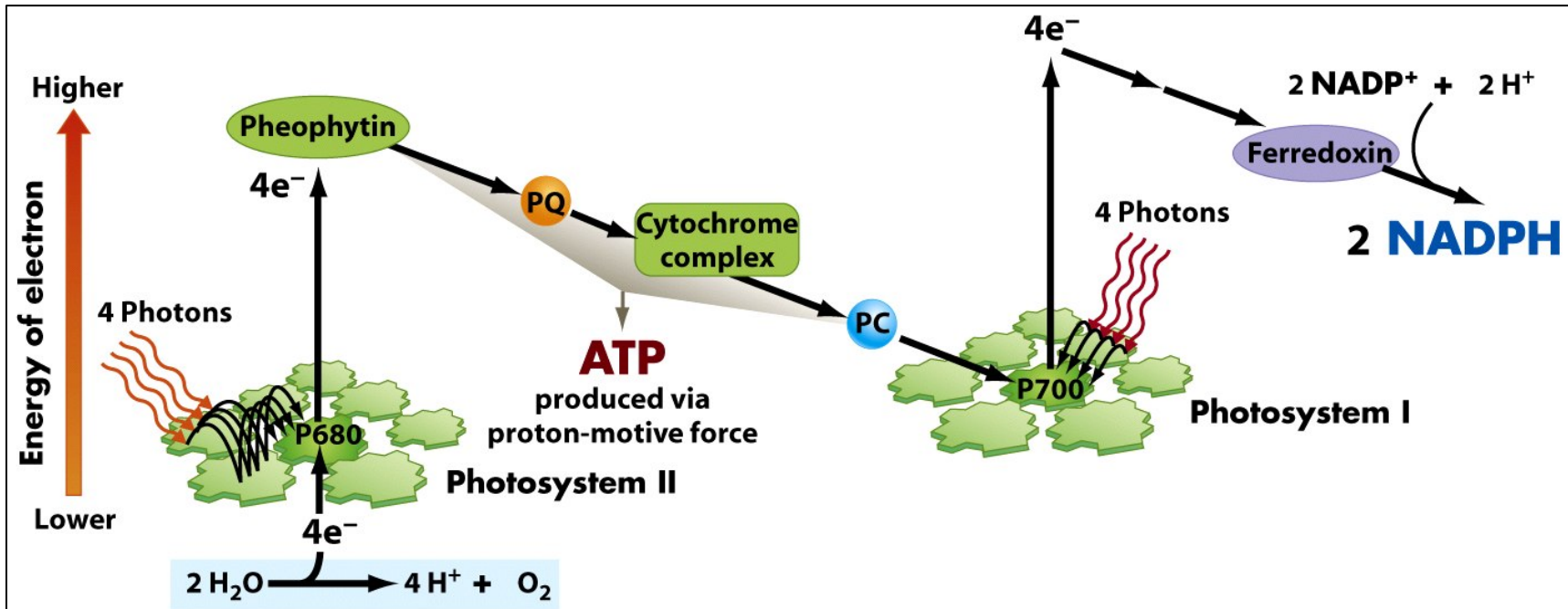
B. The figure of the “Calvin Cycle” as it appears in the instructional materials.

Figure 5.1. (cont'd)



C. A figure of the "Z-scheme" shown to students on Day 2 (Lecture 12, 09-27-2006).

Figure 5.1. (cont'd)



D. The figure of the “Z-scheme” as it appears in the instructional materials.



In Figure 5.1(A), we can see visible evidence of the manual addition of annotations to the published figure. For example, we can see where certain elements already inscribed into the figure are circled or underlined. These additional annotations are not the work of the company who created them; they are the work of the professors. This activity is representative of the type of visible, material work that the Bio101 professors do on a daily basis to many of the figures they project for students onto a large projection at the front of the classroom. In Figure 5.1(C), we can see that figures are not always pre-printed by companies. In other words, some figures are drawn in their entirety by the professors themselves from scratch. This is a nearly completed figure of the “Z-scheme” drawn for students on the second day of instruction during the photosynthesis unit.

While the professors display, annotate, and create figures, they are in almost constant verbal communication with the students. More often than not, they are speaking to the students at the same time as they are annotating and/or drawing the figures. The professor’s spoken discourse contains many scientific or technical terms. For example, while displaying Figure 5.1(A) for students, one of the Bio101 professors spoke no less than 57 content-related terms while annotating it. While displaying Figure 5.1(C), one of the Bio101 professors spoke no less than 88 content-related terms while drawing it. Table 5.1 (below) contains a complete manifest of the terms spoken by the professors while they were annotating and/or drawing them. The manifest in Table 5.1 is not meant to include the terms that are visible within the figures themselves in Figure 5.1. Nevertheless, readers will likely not be surprised to see that there is a significant degree of overlap between them.

In the table, I've adopted the use of the “#” symbol to help signal the beginning (and end) of each content-related term. However, while functional, this decision is also conceptual. In many digital social networking services (e.g., Twitter, Tumblr, Instagram, and Google+), when the “#” symbol is added to a word or phrase as its prefix, the term becomes a “hashtag” which can then be used as a form of metadata tag. Especially in digital environments, such tags can help facilitate analytical tasks such as grouping, searching, and identifying trends.

Table 5.1. A table showing the content related terms spoken by the instructors while two figures were visible to students.

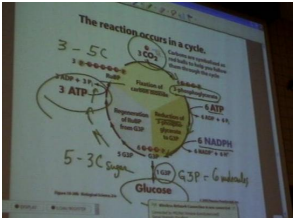
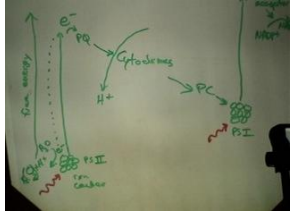
<p>FIGURE</p> <p>(Total number of content-related terms)</p>	<p>Content-related terms used by the instructors while the figure was visible to students</p>
<p>Figure 5.1(A): Calvin Cycle</p>  <p>(57)</p>	<p>#phosphoglycerate, #three phosphoglycerate, #reduction, #sugar production, #glyceraldehyde three phosphate, #energy, #reduction reactions, #endergonic, #ATP (molecules), #NADPH, #CO<sub>2</sub> (molecules), #three-carbon sugar(s), #carbon(s), #reaction(s), #step(s), #molecule(s), #glyceraldehyde three phosphate production, #reduction step, #acid, #sugar, #high-energy intermediates, #light-dependent reactions, #reduction phase, #glycolysis, #phosphoenolpyruvate, #conversion, #pyruvate, #polymerize(d), #reverse, #glycolysis steps, #glucose, #calvin cycle, #glucose (molecule), #ribulose bisphosphate, #five-carbon molecule, #three-carbon RuBP(s), #RuBP, #starting material, #rearrangement, #photosystem I, #cyclic (photosystem), #ATP surplus, #ATP use, #CO<sub>2</sub> fixation, #photosynthesis, #three-carbon photosynthesis, #atmosphere, #three-carbon acid, #carbon fixation, #carbon reduction, #cell, #chloroplast, #plant cell, #exit, #mechanism, #carbon-fixing reactions, #light-independent reactions</p>

Table 5.1 (cont'd)

<p>Figure 5.1(C): Z-Scheme</p>  <p>(88)</p>	<p>#photosynthesis, #light reactions, #Z-scheme, #(energy) scale, #free energy, #axis, #chlorophyll (molecules), #reaction center(s), #chlorophyll groups, #cooperation, #photon ‘trapping’, #photon, #photon absorption, #(light) energy absorption, #(large) molecules, #energy level, #electron shell(s), #excited chlorophyll, #electron ‘bumping’, #energy state, #electron, #energized chlorophyll, #excited electron(s), #electron transfer, #electron acceptor, #plastoquinone, #missing electron(s), #electron ‘getting’, #oxidized chlorophyll, #electron loss, #oxidizing agent, #water, #ground state, #water ‘taking’, #H<sub>2</sub>O, #electron stripping, #oxygen ions, #hydrogen ions, #(molecular) oxygen, #O<sub>2</sub>, #water ‘splitting,’ #breathing, #origin, #Earth, #atmosphere, #plants, #ancient Earth, #respiration, #high-energy electron(s), #NADH, #process, #electron transport chain, #energy ‘lowering’, #proton gradient, #proton ‘pumping,’ #membrane, #concentration (gradient), #battery, #ATP synthase, #ATP production, #electron passing, #cytochromes, #plastocyanin, #hydrogen ion ‘pumping’, #hydrogen ion ‘building’, #photosystem (I &amp; II), #photo excitement, #enzyme, #NADP reductase, #electron ‘adding’, #NADP+, #NADPH production, #phosphate group, #NAD, #NADP, #electron ‘trapping’, #hydrogen ion gradient, #ATP synthesis</p>
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At the end of each of the four photosynthesis lectures, both the professors and students place all of the figures they collected, annotated, and/or created in class into various folders, books, binders, shoulder bags, and backpacks. They do not leave them behind. These items are taken with them as they leave the lecture hall.

Perspective 1A - *P. psychologicus*

Recall that in *P. psychologicus*, learning with understanding is treated as if it were a mental activity. Students who learn with understanding are said to be able to *mentally* apply, extend or transfer their deep, rich knowledge base to situations beyond the original context of learning. What follows is an empirical profile of how professors teach photosynthesis for understanding when learning photosynthesis for understanding is construed as mental.

When teaching photosynthesis for understanding, the Bio101 professors use visible, material figures as one of the primary pedagogical devices to help students develop a mental knowledge base. Structurally, the figures displayed to/for students mainly consist of various visible, material symbolic (or semiotic) linguistic elements—for example, words, numbers, arrows, geometric figures, and other symbolic elements. During class, the professors often add additional visible, material linguistic elements to them—for example, circles, lines, arrows, and more words. The figures on display are constantly supplemented by *spoken* or *verbal* linguistic elements. Compared to the symbolic elements of the figures, these verbal elements are much less visible and much less material. Although the professors transform some of these verbal elements into a symbolic form as they annotate the figures, they do not transform all of them. Those students who decide to “take notes” also do this transformational work. However, the sheer number of verbal elements spoken during the display of a single figure ensures that very few of the Bio101 students could ever hope to copy all of these elements down onto paper.<sup>174</sup>

The coherency feature of the knowledge base is addressed in part by the presentation of the figures in a particular order or sequence, but it is also addressed by the presentation of the verbal element in a particular order or sequence (and also with changes in the use of the voice). One of the most common strategies used by the Bio101 professors to promote the coherency of the knowledge base is to proceed from the ‘whole’ of a concept to its constituent ‘parts.’ For example, the overarching concept of “photosynthesis” is broken up into two parts

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174. Occasionally, some students can be seen putting tape recording devices on their desks during class. Some students, then, have devised a way of capturing a greater percentage of the verbal elements. Exactly what they do with the digital forms of these elements once they leave the classroom I do not know.

or “reactions.” These two reactions are then broken up into yet other parts. For example, the “light independent reactions” are divided into “phases,” “stages” and/or “steps.”

In *P. psychologicus*, the figures on display are treated as if they were the visible shadows or projections of the Idea or Concept of Photosynthesis.<sup>175</sup> In *P. psychologicus*, The Concept of Photosynthesis (or Photosynthesis) is treated in class as if it was always already an abstract reality in the world and, the professors hope, soon to be an abstract reality within students’ minds/brains. The work done by professors and students in class with figures are pedagogical practices designed to help students develop the abstract Concept of Photosynthesis in their minds. To do this, the professors rely on their students’ ability to generalize from the different instances and aspects of photosynthesis shown in the figures. In these figures, students are supposed to ‘see’ the conceptual unity of the abstract Concepts of Photosynthesis across the use of the many figures presented during the four-day unit.<sup>176</sup> The professors’ spoken words are meant to help facilitate this particular way of ‘seeing’ (seeing-as-generalizing, seeing-as-abstracting). By the end of the photosynthesis unit, the professors expect their students to have assembled the abstract Concept of Photosynthesis in their minds. Furthermore, they expect their students to be able to ‘see’ and recognize those instances outside of their minds in which the corresponding abstract Concept of Photosynthesis is present. In *P. psychologicus*, the transfer of learning is seen as the ability of students to ‘leap’ to situations in which abstract Ideas or Concepts are always already present.

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175. This helps explain why professors often refer to figures as “visual representations.” The visual, material figures are meant to *re-present* what is seen as an original or authentic presentation of an abstract Idea or Concept.

176. This helps explain why professors often refer to figures as “visual aides.” The visual, material figures are meant to *help* students develop abstract Ideas or Concepts.

During the four days in which the Bio101 professors taught photosynthesis for understanding, they used figures so that their students might develop the mental forms of certain Concepts, which would allow them to 'see' the presence of these same abstract Concepts within or behind phenomena as strange and unfamiliar as a "mutant strain of spinach." The professors acknowledge that seeing, hearing about, and writing down (or on) the figures used in class will not be enough to develop the abstract Concepts they require for the exam. This is why the professors encourage—and sometimes require—students to engage in other Concept-developing activities. For example, among other actions, students are told to "read the textbook before class," "do the homework problems," "take notes during class," "take notes outside of class," "recopy notes outside of class," "reorganize notes outside of class," "make flash cards," "write down definitions," "form a study group," and "review the material presented in lecture. After a certain amount of practice and repetition, it's postulated that the students will 'get' the Concepts at abstract level that they need. All of these means are directed towards a particular end: the complete internalization of a coherent knowledge base which can be mentally extrapolated and applied to new, different contexts.

#### Perspective 1B - *P. empiricus*

Recall that in *P. empiricus*, learning with understanding is treated as if it were an empirical activity. Students who learn with understanding are said to be able to *empirically* apply, extend or transfer their deep, rich knowledge base to situations beyond the original context of learning. What follows is a virtual, simulated, and empirical profile of how professors teach photosynthesis for understanding when learning photosynthesis for understanding is construed as empirical.

When teaching photosynthesis for understanding, the Bio101 professors use visible, material figures as one of the primary pedagogical devices to help students develop an empirical knowledge base. In particular, they exploit some of the structural features contained within them. First, they ask their students to pay close attention to the visible, material symbolic (or semiotic) linguistic elements within the figures (words, numbers, arrows, geometric figures, etc.). The instructors tell the students to consider putting the words present in the figures into a basic table with empty rows and columns. They recommend that students think of these content-related terms as “hashtagged” terms (just like the ones used on Twitter). They tell students that these tagged terms might be useful when doing the homework assignments or answering clicker questions in class. By suggesting that students begin to find ways to ‘tag’ both the written and spoken content-related terms, the professors are helping students develop the notion of a *connected* and *coherent* knowledge base. During class, the professors often add additional visible, material linguistic elements to the figures—for example, circles, lines, arrows, and more words. The instructors tell the students to pay close attention to the content-related terms in the figures that they’ve underlined, circled, and/or otherwise emphasized during lecture. They encourage their students to then consider highlighting these same content-related terms to their tables to indicate a certain density of emphasis/use.

The Bio101 professors are constantly supplementing the displayed figures with *spoken* or *verbal* linguistic elements. The professors know that these verbal elements are much less visible and much less material when compared to the symbolic elements in the figures. They know that many of these verbal content-related terms will never make their way onto students’ papers in a written form unless they find a way to help facilitate this process. They do this in



two different ways: First, they record their lectures and make the recordings available to their students on a course website. Students can listen to the lecture for the purpose of going back to the figures and creating another set of content-related terms to add to their (now expanding) tables. Second, while the professors speak about a particular figure, one of the teaching assistants keeps a record of the content-related terms they've used. They then make these lists available through the course website. In this way, the Bio101 professors and their assistants help keep their students from becoming overwhelmed by the sheer volume of verbal elements spoken during the display of the figures. For their part, the students begin to see the knowledge base growing before their very eyes. They can touch it. They can grasp it. They begin to see patterns and trends. Some even find ways to begin transforming the table into something different. As the lectures begin to pile up, however, the organization and coherence of the knowledge base becomes more difficult. New strategies of organization must be adopted. New transformations of the knowledge base must be performed.

In *P. empiricus*, the figures on display are not treated as if they were the visible shadows or projections of the Idea or Concept of Photosynthesis. The Concept of Photosynthesis (or Photosynthesis) is not treated as if it were always already an abstract reality in the world or an abstract reality within students' minds/brains. The work done by professors and students in class with figures are pedagogical practices designed to help students develop a more *concrete* (i.e., visible, material) Concept of Photosynthesis outside of their minds. To do this, the professors encourage their students to 'tag' a number of linguistic features of the different instances and aspects of photosynthesis shown in the figures. From these figures, students are supposed to physically assemble and align conceptual unity by performing a variety of carefully

linked visible, material transformations. These actions render—in visible and material forms—a concrete Concept of Photosynthesis across the use of the many figures presented during the four-day unit. The professors’ insistence that students learn how to tag content-related terms is meant to help facilitate a particular way of ‘seeing’ (seeing-as-tagging, seeing-as-aligning, seeing-as-arranging). By the end of the photosynthesis unit, the professors expect their students to have assembled a concrete Concept of Photosynthesis outside of their minds. Furthermore, they don’t expect their students to be able to automatically ‘see’ and recognize those instances outside of their minds in which other say a corresponding abstract Concept of Photosynthesis is present. In *P. empiricus*, the transfer of learning is seen as the ability of students to construct or assemble visible, material bridges to situations those where others have said abstract Ideas or Concepts exist.

### **Practice 2: Clicker Questions**

Once or twice each class period, the professors display something other than a figure like the ones shown in Figure 5.1. On these occasions, the students are shown a multiple-choice question on the large projection screen at the front of the lecture hall. These questions almost never contain any of the figures that so often precede and follow them. Most of the time, the professors display the questions and choose to read the stem question and the 4-5 answer choices out loud. A wireless microphone worn by the professors helps them project their voice with ease throughout the large lecture hall. Typically, students are then encouraged to talk to one another (“discuss it with your neighbor”) for a minute or so. At the end of the discussion period, one of the professors or a teaching assistant activates a software program on a computer located at the front of the classroom. The computer is connected to a radio

frequency (Rf) receiver through one of its USB ports. This receiver allows the Bio101 students to send the professors their answers to the multiple-choice question displayed on the projection screen. They do this via the use of small, handheld Rf transmitting units which these professors and student call “clickers.” Students are given a predetermined amount of time in which to answer these questions (usually two minutes). According to its default setting, the clicker software program places a small timer in the lower right corner of the question on the screen. The instructors place few limitations on students’ actions during this brief window of time. They can speak to each other as much or as little as they choose (which many of them, especially those setting within the first ten or so rows, often do). They can also use any of the items typically found in front of them, e.g., their textbooks, handouts, notes, and figures. Examples of two of these clicker questions are shown in Figure 5.2.

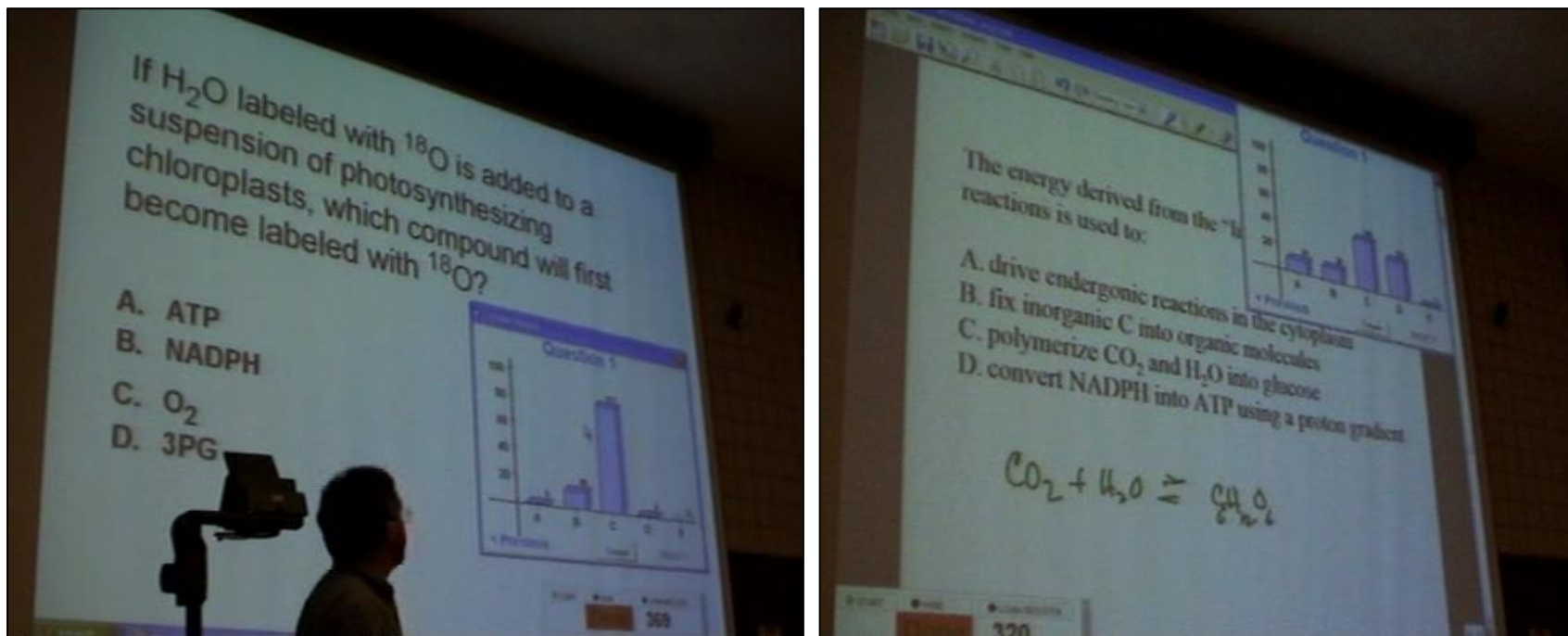
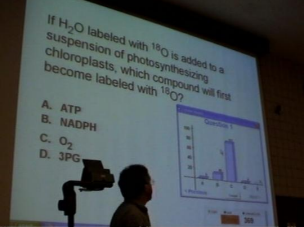
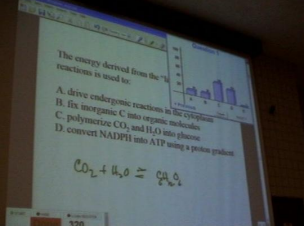


Figure 5.2. (At left): A clicker question shown to students on Day 2 of the photosynthesis unit (Lecture 12, 09-27-2006). (At right): A clicker question shown to students on Day 3 of the photosynthesis unit (Lecture 13, 09-29-2006). The full text of the clicker question at left reads as follows: "If H<sub>2</sub>O labeled with <sup>18</sup>O is added to a suspension of photosynthesizing chloroplasts, which compound will first become labeled with <sup>18</sup>O? A. ATP B. NADPH C. O<sub>2</sub> D. 3PG." The full text of the clicker question at right reads as follows: "The energy derived from the "light dependent" reactions is used to: A. drive endergonic reactions in the cytoplasm B. fix inorganic C into organic molecules C. polymerize CO<sub>2</sub> and H<sub>2</sub>O into glucose D. convert NADPH into ATP using a proton gradient." The bargraphs seen in the corners of the two figures contain information that is not relevant to my analysis.

In both of the images included in Figure 5.2, we can see one other important empirical feature of the clicker questions. We can see that there are a number of the content-related terms present within the stem portions of the (two) questions, as well as in their (eight) answer choices. In this way, we can see some visual, material continuity between the clicker questions and the figures: they both contain a number of content-related terms that take written forms (e.g., words, symbols, numbers, geometric figures).

Just as they did when speaking about the figures they were busy annotating and creating, the two professors also routinely spoke to students (as well as to each other) while displaying the clicker questions on the projection screen. Here, then, we see another continuity between the clicker questions and the figures: they both involve a number of content-related terms that take verbal or auditory forms. Table 5.2 (below) contains a complete manifest of the written *and* verbal content-related terms in circulation during the use of each of the two clicker questions. Once again, I've used the hashtag format so as to allow readers the opportunity—should they wish to do so—to take notice any similarities in the use content-related terms between the manifests seen in Tables 5.1 and 5.2.

Table 5.2. A table showing the content related terms spoken by the instructors while two clicker questions and their answers were visible to students.

<p>FIGURE</p> <p>(Total number of content-related terms)</p>	<p>Content-related terms used in the question and by the instructors while the clicker question was visible to students</p>
<p>Figure 5.2 (at left) Day 2 Clicker Question</p>  <p>(13)</p>	<p><i>Written terms: 9</i></p> <p>#H<sub>2</sub>O, #<sup>18</sup>O, #suspension, #photosynthesizing chloroplasts, #compound, #ATP, #NADPH, #O<sub>2</sub>, #3PG</p> <p><i>Spoken terms: 4</i></p> <p>#water, #heavy water, #isotope, and #sugar</p>
<p>Figure 5.1 (at right) Day 3 Clicker Question</p>  <p>(38)</p>	<p><i>Written terms: 13</i></p> <p>#energy, #light-dependent reactions, #endergonic reactions, #cytoplasm, #inorganic (carbon), #fix(ing), #organic molecules, #CO<sub>2</sub> polymerization, #H<sub>2</sub>O, #glucose, #NADPH conversion, #ATP, #proton gradient</p> <p><i>Spoken terms: 25</i></p> <p>#chloroplast(s), #organelle(s), #ATP production, #mitochondria, #ATP export, #cellular respiration, #cytoplasm, #transport system, #plant cell(s), #work, #photosynthesis, #formula, #CO<sub>2</sub>, #C<sub>6</sub>H<sub>12</sub>O<sub>6</sub>, #carbon dioxide, #water, #glucose, #carbon, #atmosphere, #inorganic, #organic, #energy, #second phase of photosynthesis, #sugar production, #reactions</p>

Unlike many of the figures, the course textbook does not contain any of the clicker questions used by the professors. This is because the professors either construct them themselves or else they get from other colleagues. This makes them different from the pre-produced figures, but similar to the figures the professors create from scratch. That is, if students want to take a visible, material copy of a clicker question with them away from class, they must either write it down in their notebooks by hand or take a photograph of it with a digital device (e.g., an iPad<sup>®</sup> or a smartphone). Many of the students I observed did exactly this and thus found a way to take visible, material copies of the clicker questions away from class with them.<sup>177</sup> At the end of each of the four photosynthesis lectures, both the professors and students place all of their materials—including those clicker questions they've acquired—into various folders, books, binders, shoulder bags, and backpacks. They do not leave them behind. These items are taken with them as they leave the lecture hall.

#### Perspective 2A - *P. psychologicus*

Recall that in *P. psychologicus*, learning with understanding is treated as if it were a mental activity. Students who learn with understanding are said to be able to mentally apply, extend or transfer their deep, rich knowledge base to situations beyond the original context of learning. What follows is an empirical profile of how professors teach photosynthesis for understanding when learning photosynthesis for understanding is construed as mental.

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177. In fall 2006, the Bio101 instructors also often made their Microsoft PowerPoint presentations available to students either before or soon after each class. The slides of these presentations almost always contained the clicker questions, and so this constituted yet another way for students to acquire visible, material copies of them.

When teaching photosynthesis for understanding, the Bio101 professors use visible, material clicker questions as one of their pedagogical devices. They use them for at least two purposes. First, they use them to help students continue to develop a coherent mental knowledge base. In other words, the professors see the clicker questions as yet another useful way of helping students develop the abstract Concept of Photosynthesis. Second, they use them to determine for themselves the degree to which their students have—at that moment—developed some of the foundations of a coherent knowledge base. In the professors’ own words, they use the clicker questions as a way of “checking for understanding.” Many of the clicker questions check for understanding by posing questions that are similar to the context of instruction. That is, in these questions there tends to be much overlap in the content-related words used in the text of the clicker question and those used in the series of figures immediate preceding its appearance. This is not always the case, however, as sometimes the professors use clicker questions that are different from the context of instruction. These clicker questions usually have a different linguistic relationship with the figures that preceded them. That is, in these questions there tends to be less overlap in the content-related words used in the text of the clicker question and those used in the series of figures immediate preceding its appearance. Thus, while the professors use some clicker questions to determine the degree to which students have—at that moment—begun to develop coherent mental knowledge bases, they use others to determine the degree to which students’ with knowledge bases can—at that moment—mentally extrapolate them to contexts with differing degrees of contextual familiarity.<sup>178</sup>

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178. Because the students can see how they did on the clicker questions almost



Structurally, the clicker questions displayed to/for students are similar to figures in the sense that they consist of symbolic (or semiotic) linguistic elements. Unlike figures, however, which almost always contain a greater diversity of elements, the clicker questions mostly contain only words (and occasionally numbers). The clicker questions almost never contain figures in them. One of the reasons for this is because some of the clicker questions are used to see what—if any—conceptual features of the figures preceding the clicker questions students have successfully managed to *abstract* to their minds/brains. The professors teach as though certain key words and phrases within the text of the clicker questions can trigger or activate the use of the abstract Concept of Photosynthesis. When students do this successfully, some science educators say that the students have managed to structure their mental knowledge base in meaningful or useful ways.<sup>179</sup> This is one of the ways that the Bio101 professors and others speak to the coherence feature of the knowledge base.

As they did with figures, the professors also acknowledge that reading, answering, talking about, and writing down the clicker questions used in class is not sufficient practice for adequately internalizing the most important aspects of them. Again, this is why the professors encourage their students—but sometimes requires them—to engage in a number of different learning activities. All of them, however, are directed towards a particular end: the complete internalization of a coherent knowledge base which can be mentally extrapolated and applied to new, different contexts.

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instantaneously, I should add that these questions allow for students to determine for themselves the degree to which they have, at that moment, begun to develop a coherent mental knowledge base that can be mentally extrapolated to contexts with varying degrees of contextual familiarity.

179. This seems to me the main idea behind mental or cognitive “frameworks.”

## Perspective 2B - *P. empiricus*

Recall that in *P. empiricus*, learning with understanding is treated as if it were an empirical activity. Students who learn with understanding are said to be able to empirically apply, extend or transfer their deep, rich knowledge base to situations beyond the original context of learning. What follows is a virtual, simulated, and empirical profile of how professors teach photosynthesis for understanding when learning photosynthesis for understanding is construed as empirical.

When teaching photosynthesis for understanding, the Bio101 professors use visible, material clicker questions as one of their pedagogical devices. They use them for at least two purposes. First, to continue helping students develop a coherent empirical knowledge base. In other words, the professors see the clicker questions as yet another useful way of helping students develop the concrete Concept of Photosynthesis (or Photosynthesis). Second, to begin to determine the degree to which their students have—at that moment—developed the foundations of a coherent knowledge base. In the professors' own words, they use the clicker questions as a way of "checking for understanding." Just as they did with students when showing them figures, the Bio101 professors ask the students to tag the concept-related terms seen in the text of the clicker questions. Right there in the lecture hall, students put these terms into a table with empty rows and columns. Next to this new table, they have the one they've created for keeping track of the content-related terms used in the figures. Placed side-by-side on the tops of their desks, students begin noticing linguistic continuities between the figures and the clicker questions. By suggesting that students begin to find ways to tag and compare

the content-related terms in both the figures and the clicker questions, the professors are helping students develop the notion of a *connected* and *coherent* knowledge base.

Many of the clicker questions used in Bio101 check for understanding by posing conditions that are very similar to the context of instruction. The professors work hard to show their students how to see and measure this feature in terms of amount of overlap present in the use of content-related terms. They do the same for and with their students with clicker questions that are very different from the context of instruction. These clicker questions usually have a different type of linguistic relationship with the figures that preceded them. That is, there is less overlap present between the content-related words seen in the clicker question and those seen and/or spoken in the series of figures immediate preceding the it. In this way, students learn how to empirically extrapolate to contexts with differing degrees of contextual familiarity. Once at home, students begin to add layers to the tagging techniques. They begin to create families of related terms. To these families they add additional diagrams from their textbooks, definitions of unfamiliar terms, and simplified drawings of some of the figures presented in class. The students see their knowledge base growing now. They can touch it, but it no longer fits neatly in their folders. They can grasp it, but it takes two hands and even then part of the knowledge base falls to the floor. There is more work to be done. There is more organization to accomplish. There are more connections to be made. There are more patterns and trends to see. The concrete Concept of Photosynthesis is starting to take shape.

### **Practice 3: Exam Questions**

Approximately once every three to four weeks, students come to class to take an exam. The professors told the Bio101 students that the material covered during the four

photosynthesis lectures would be assessed on “Exam 2.” Just as they did during the lectures, many students bring book bags and backpacks into the classroom on examination days. However, one of the major differences between lectures and examination days is that much of what students have in their bags and backpacks is never removed from them. The only empirical allies students are allowed to remove from their bags and put to use during the exams include paper (in the form of an already inscribed paper exam given to them by the Bio101 professors or their teacher assistance), a pencil (only No.2 pencils, however), a wristwatch (but there is also a clock for use on the classroom wall), and a university-issued photographic ID, but that is all.

While the paper, pencils, and wristwatches are used during the examination, students typically use the photographic ID only after the completion of it. It turns out that the professors don’t trust their own mental faculties to remember the names and faces of their nearly four hundred undergraduate students—a number of whom only occasionally show up for classes. So, the professors ask each of their students to prove their identity by means of triangulation. Each student’s true identity is held between three visible, material objects: the photographic ID (which contains a photograph of the student, their legal name, and a one-of-a-kind 9-digit alphanumeric code or “student number”), a paper class roster provided by the university Registrar’s office (which contains each student's legal name and student number), and the actual (physical) face of the student. Besides these three allies, the enlistment of all other empirical allies—including other *students*—is strictly forbidden. In fact, right before distributing the paper exams to their students, the professors often remind those present to tuck all unapproved empirical allies safely away underneath their chairs and/or place them into folders,

purses, shoulder bags, backpacks, etc. As a final way of dissuading students from enlisting any other student's exam paper as an ally, the professors also usually tell students to, "Keep your eyes and hands on your own exam." Figure 5.3 (below) shows an example of an exam question from Exam 2. It is question "52," the Mutant Spinach Question.

52) Suppose you discovered a mutant strain of spinach in which the thylakoid membranes were slightly permeable to H<sup>+</sup> ions, thus allowing a slow leakage (remember that in normal membranes, H<sup>+</sup> is not permeable at all). What change in the reactions of photosynthesis might occur in compensation for this defect?

- F) cyclic photophosphorylation would increase
- G) non-cyclic photophosphorylation would increase
- H) O<sub>2</sub> production would decrease
- I) cyclic photophosphorylation would decrease
- J) non-cyclic photophosphorylation would decrease

Figure 5.3. Question "52," the Mutant Spinach Question, from Bio101 Exam 2 (fall 2006)

A quick glance at question "52" makes visible a common characteristic of most exam questions—with very few exceptions, the questions contain almost no visible, material figures within them. In this way they have much in common in terms of their visible and material features with the clicker questions. Both are laden with content related terms. The content-related terms in question "52" include: #mutant, #strain, #spinach, #thylakoid, #membrane(s), #permeable, #H<sup>+</sup>, #ions, #leakage, #normal membrane(s), #reactions, #photosynthesis, #compensation, #defect, #cyclic photophosphorylation, #non-cyclic photophosphorylation, #O<sub>2</sub> production. In total there are 17 content-related terms contained with the text of question "52." Unlike either of the two previous pedagogical practices, during exams questions like question

“52” almost never receive and verbal addressing by the professors. The only time any verbal addressing usually occurs is if there is something found to be wrong with the question (e.g., a misspelled or misplaced word). The professors and students are noticeably silent during exams, and this makes the practice rather unlike the figure- and clicker question-based practices.

When finished, the students turn in their exams and scoring sheets to the professors or teacher assistants. They do not take it home with them. They do, however, tend to take all of the other items they brought with them into the exam (e.g., folders, books, binders, shoulder bags, and backpacks), which the students never removed from them. In these un-accessed items were many of the figures and clicker questions the students had collected, created, and annotated—and on behalf of whom so much verbal activity had been espoused—during the four days of the photosynthesis unit.

A few days after the exam, the Bio101 professors receive the results of the exam from the university scoring office. The results for question “52” quickly grab their attention. According to the report, only twenty percent of the Bio 101 students answered the Mutant Spinach Question correctly. It was the most missed question on entire exam. Over three quarters of the Bio101 students failed to apply their existing knowledge to the novel phenomenon as the professors had hoped they would. In other words, more than three quarters of the students failed to demonstrate that they had learned the concept of the “light reactions of photosynthesis” in a way that could be considered deep, rich, conceptual, meaningful and/or enduring.

### Perspective 3A - *P. psychologicus*

Recall that in *P. psychologicus*, learning with understanding is treated as if it were a mental activity. Students who learn with understanding are said to be able to mentally apply, extend or transfer their deep, rich knowledge base to situations beyond the original context of learning. What follows is an empirical profile of how professors teach photosynthesis for understanding when learning photosynthesis for understanding is construed as mental.

When teaching photosynthesis for understanding, the Bio101 professors use visible, material exam questions to assess whether or not students have learned with photosynthesis with understanding. Structurally, the exam questions are almost identical to clicker questions. They too mostly contain only words (and occasionally numbers) and, like clicker questions, the exam questions almost never contain figures in them. The exam questions serve at least two purposes. First, they are used to determine the degree to which students have—at that moment—developed coherent mental knowledge bases. Second, they are used to determine the degree to which students' with knowledge bases can—at that moment—mentally extrapolate them to contexts with differing degrees of contextual familiarity. In both cases, students are not allowed to use any of the visible, material figures or clicker questions as allies. In other words, students are not allowed to use any of the shadows of the Idea or Concept of Photosynthesis. On the exams, all students have to rely on are mental allies such as the abstract Concept of Photosynthesis in their minds/brains.

Although no (visible, material) figures or clicker questions are permitted for use on the exam, the Bio101 professors allow students to bring with them a number of mental allies. In addition to abstract concepts, students can rely upon such mental allies as *logic, reason, facts,*

*induction, deduction, analytical skills, critical thinking skills, and abstract thinking skills.* In addition, the professors encourage students to perform all kinds of mental operations on factual knowledge. For example, students are encouraged to *integrate and assemble it; to put it together and pull it apart; to tie and fit it together; to organize and reorganize it; and to use it* (in the service of actions such as “making predictions,” “drawing explanations,” and “gaining insights”). On the Mutant Spinach Question, however, only twenty percent of the Bio101 students were able to demonstrate that they could trigger/activate the mental allies needed to demonstrate learning with understanding. Only one fifth of the students were able to mentally extrapolate abstract concepts such as the Concept of the Light Dependent Reactions and the Concepts of Cyclic and Non-Cyclic Photophosphorylation and apply them correctly to the unscripted context.

#### Perspective 3B - *P. empiricus*

Recall that in *P. empiricus*, learning with understanding is treated as if it were an empirical activity. Students who learn with understanding are said to be able to empirically apply, extend or transfer their deep, rich knowledge base to situations beyond the original context of learning. What follows is a virtual or simulated empirical profile of how professors teach photosynthesis for understanding when learning photosynthesis for understanding is construed as empirical.

When teaching photosynthesis for understanding, the Bio101 professors use visible, material exam questions to assess whether or not students have learned with photosynthesis with understanding. On exam day, the professors know that they can't ask their students to place the bulk of their trust in mental allies. Although the professors would like for students to



be able to rely purely on mental allies such as the abstract Concept of Photosynthesis, they know from their own work as biologists that learning with understanding in science often depends on the successful execution of a wide variety of well coordinate, empirical strategies. Therefore, they encourage their biology students to bring a collection of empirical allies with them for use during the exam including their empirical knowledge base.

Because the exam questions are structurally similar to clicker questions, the Bio101 students tend to take a similar (empirical) approach to them. The first thing they do is identify the key content-related terms and extract (rather than abstract) them away from the question. These terms don't travel far—only as far as a table of blank rows and columns placed next to the exam, where they remain both visible and material. Once isolated from the exam question, the students check these content-related terms against other completed tables in their empirical knowledge bases. Many of them begin to see overlap between the terms used in one exam question (question “52”), two clicker questions, and three figures used in class. Soon, students have used their empirical knowledge bases to identify two figures and a single clicker question. They then use these graspable items to help them select one of the five answer choices.

Because the Bio101 professors trust empirical allies more so than mental ones in much of their work as biologists, they allow students to bring with them into the exam a number of empirical allies. In addition to more concrete concepts, students call upon allies as *logic* and *reason*, but these ‘skills’ are done with things like hands and eyes. In addition, the professors encourage students to perform all kinds of empirical operations on factual knowledge. For example, students are encouraged to *integrate* and *assemble it*; to *put it together* and *pull it*

*apart; to tie and fit it together; to organize and reorganize it; and to use it* (in the service of actions such as “making predictions,” “drawing explanations,” and “gaining insights”). On the Mutant Spinach Question, the results are rather promising: sixty percent of the students are able to demonstrate that they could mobilize/recruit the empirical allies needed to demonstrate learning with understanding.

#### Discussion - Part A

The design of the bioeducational assay proposed three research questions. The first research question was: What is the empirical profile of a pedagogical practice that we are calling *Pedagogia psychologicus* (*P. psychologicus*)?

#### **Empirical profile (A) - *P. psychologicus***<sup>180</sup>

In this undergraduate biology course, *P. psychologicus* takes the empirical form of three main pedagogical practices so named for the empirical actors most commonly found within them: “figures,” “clicker questions,” and “exams.” In *P. psychologicus*, teaching for and learning with understanding can be described across these three pedagogical practices as a progression from the empirical to the mental. In the four days of instruction leading up to an exam, teachers directed much of their students’ visual and auditory attention toward an almost continuous presentation of visible, material “figures” and “clicker questions.” These two empirical actors were at the center of much of what goes on in the classroom on a daily basis. However, these two actors mainly played the part of “visual aids” and/or “visual representations.” That is, they were

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180. Readers may notice similarities between this empirical profile and the anthropologist’s report of the “pedagogical expedition” from Chapter 3.

enlisted by the professors in the service of the development of a more important set of student allies, a group of mental actors called abstract science concepts (or Concepts). In *P. psychologicus*, Concepts are treated as if they were always already abstract realities in the world. The work done by professors and students with figures and clicker questions in the classroom are practices designed to help students develop (abstract) Concepts in their minds—for example, the Photosynthesis. In *P. psychologicus*, the professors accomplish this by relying on their students' ability to generalize from the different instances and aspects of the Concept of Photosynthesis (re)presented in the figures and clicker questions. In these empirical objects, students are supposed to 'see' the conceptual unity of Photosynthesis across the use of the many figures and clicker questions presented and used during the four-day unit. The professors' speech is meant to help facilitate this particular way of 'seeing' (seeing-as-generalizing, seeing-as-abstracting). By the end of the four-day unit, the professors expected their students to have adequately assembled the abstract Concept of Photosynthesis in their minds. When examination day arrived, they expected their students to be able to see and recognize instances of it outside of their minds/brains, and in which the corresponding abstract Concept of Photosynthesis was simultaneously present—for example, in a "mutant strain of spinach." On exams questions, learning with understanding is demonstrated when students successfully extrapolate their mental understanding and use it to 'leap' to situations or phenomena in which the abstract Ideas or Concepts are always already present. To summarize, within the context of this undergraduate biology course, *P. psychologicus* can be described as a set of practices whose ultimate trajectory

is the successful transformation or transfiguration of vast numbers of empirical allies into mental ones. If there were one word that could characterize *P. psychologicus*, that word would be “INNERstanding.”

The second research question was: What is the empirical profile of a pedagogical practice that we are calling *Pedagogia empiricus* (*P. empiricus*)?

### **Empirical profile (B) - *P. empiricus***<sup>181</sup>

In this undergraduate biology course, *P. empiricus* takes the empirical form of three main pedagogical practices so named for the empirical actors most commonly found within them: “figures,” “clicker questions,” and “exams.” In *P. empiricus*, teaching for and learning with understanding can be described across these three practices as a four-day engagement with empirical allies. Although it would be silly to deny that the science students must engage in mental/cognitive practices such as thinking and reasoning, the professors do not feel that it is necessarily to consider these important actions as exclusively psychological practices. When confronted by a phenomena known as the Concept of Photosynthesis (or Photosynthesis)—an abstract concept which they could not understand at first glance or, for that matter, at second, third or fourth glance—the professors, who happened to be research scientists themselves, taught their undergraduate students how to make sense of a perplexing Concept by asking them to deliberately shifting the weight of responsibility from their internal, mental faculties to a network of empirically observable objects and practices. Rather than the students’

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181. Readers may notice similarities between this empirical profile and the anthropologist’s report of the “scientific expedition” from Chapter 3.

minds/brains, it appears as though the professors' primary expectation of their students is that they each find ways to efficiently and effectively externalize the confusing Concept of Photosynthesis. To summarize, within the context of this classroom, *P. empiricus* learning with understanding can be described as a set of practices whose ultimate success depends upon the students' abilities to learn how to coherently and carefully coordinate a vast army of empirical allies. In the heat of an epistemological engagement, the professors' pedagogical mantra is this: mental allies can't be trusted. If there were one word that could characterize *P. empiricus*, that word would be "OVERstanding."

The third research question was: What is the relative purity, composition, activity, and/or potency of a lesser known pedagogical practice (*P. empiricus*) relative to better known pedagogical practice (*P. psychologicus*)?

An answer to this final research question is given at the beginning of Chapter 6 (Discussion - Part B).

**CHAPTER 6**  
**NEW HORIZONS FOR SCIENTIST TEACHERS**

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I could not think without writing.

—Jean Piaget

“Thinking is hand-work,” as Heidegger said, but what is in the hands are inscriptions.

—Bruno Latour

Discussion - Part B

In scientific assays—for example, in bioassays—recording mechanisms such as myographs or gamma counters are connected to organisms, whether to cells, muscles, or whole animals, so as to produce easily readable traces.<sup>182</sup> In this next section, I use a device of my own making—the *bioeducational* assay—to produce readable traces of the two pedagogical practices named in Chapter 5, *P. psychologicus* and *P. empiricus*. The practices are evaluated according to traits or characteristics such as purity, composition, activity, and potency. However, I have taken these scientific characteristics and re-contextualized them for use in my study.

The research question I asked in Chapter 5 is: What is the educational or pedagogical purity, composition, activity, and potency of the lesser known *Pedagogia empiricus* relative to *Pedagogia psychologicus*? Sections 6.1-6.4 contain the discussion of and interpretations for these four pedagogically reformulated traits.

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182. Latour, *Laboratory Life*, 58.

## 6.1 Purity

The scientific concept of purity draws our attention to the degree of homogeneity and/or uniformity in character or constitution. In this bioeducational essay, I interpret “degree of homogeneity” and “degree of uniformity” as referring to the number and types of pedagogical modes of expression enacted in the classroom.

In terms of purity, *P. empiricus* should be considered as purer than *P. psychologicus*. *P. empiricus*'s greater purity is derived from the fact that its pedagogical expression remains entirely within an empirical mode during the four-day photosynthesis unit. For example, in *P. empiricus* the Bio101 professors constantly drew their students' attentions to visible, material figures and clicker questions and encouraged students to tag the figures and questions with yet other visible, material objects (for instance, with hashtagged terms such as “#light reactions” and “#cyclic photophosphorylation”). *P. psychologicus*'s lesser purity is due to the fact that it does not remain in a single pedagogical mode during the unit. Instead, *P. psychologicus* demands that students shift constantly from empirical to mental modes of expression. For example, the Bio101 instructors constantly drew their students' attention to visible, material figures and clicker questions while in *P. psychologicus*. Furthermore, they expected students to transform the figures and questions into mental or cognitive objects (for example, into the Concept of the Light Reactions and the Concept of Cyclic Photophosphorylation). The effects of these continuous modal shifts between psychological and empirical modes—which is one of the defining features of teaching for understanding in *P. psychologicus*—could have any number of significant consequences on students' ability to learn with understanding and deserves further investigation. If research scientists spend much of their time learning with understanding in a

single mode—an empirical one—then what does it mean for science teachers to ask their science students to be ‘bimodal?’ In term of modal practices, does this mean that science teachers demand more of novice science students than expert scientists demand of themselves? In other words, does this mean that science education demands more of undergraduate science students than science demands of its Nobel Prize-winning researchers?

## 6.2 Composition

The scientific concept of composition draws our attention to the type of matter that makes up an object, as well as the arrangement of the matter in the object. In this bioeducational essay, I interpret “type of matter” as referring to the number and types of human and non-humans involved in a pedagogical practice. I interpret “arrangement of the matter” as referring to how those human and non-humans are arranged in time and space.

### 6.2a Number and type of humans

The unconventional design of this bioeducational essay makes it difficult to detect compositional differences between *P. empiricus* and *P. psychologicus* in terms of the number of humans present. That is, the number of humans in both trials was exactly the same: two professors and four hundred or so students. However, the essay reveals a compositional difference in the types of humans present. In *P. empiricus*, the Bio101 professors’ commitment to teaching their students empirical practices similar to those commonly used in scientific research means that we must simultaneously acknowledge the professors as scientists. Rather than as science teachers, we might instead consider them as *scientist teachers*. This title draws attention to their firm commitment to empirical practices in both science and science education. In *P. psychologicus*, the Bio101 professors made a firm commitment to teaching their students



psychological practices, which in their work as research scientists outside of the classroom they typically eschew at the insistence of their colleagues. Thus, we can conclude that *P. empiricus* and *P. psychologicus* have different ways of constructing their professors: *P. empiricus* tends to construct its professors as scientists whereas *P. psychologicus* tends to construct its professors as something other than scientists. The irony in *P. psychologicus* should already be apparent. College professors of science are discouraged from acting like scientists while teaching science.

#### 6.2b Number and type of non-humans

It is relatively easy to detect a compositional difference between *P. empiricus* and *P. psychologicus* in terms of the number and type of non-humans present. In both *P. empiricus* and *P. psychologicus* we see equal numbers of figures and clicker questions used in class. We also see equal number of exam questions used on the exams. However, one significant difference is that in *P. empiricus* we see the birth of an entirely new type or genre of empirical objects in the “tables” used by students to track the presence of both the written and spoken content-related terms. In *P. empiricus*, students used these tables to add depth and coherence to their empirical knowledge bases. This depth and coherence took forms that were visible, material, tangible, public, and documentable. In *P. psychologicus* we never see the birth of an entirely new genre of empirical objects because students’ knowledge bases are treated as if they were entirely mental or cognitive. When treated psychologically, the depth and coherence of mental knowledge base take forms that are significantly less visible, less material, less tangible, less public, and less documentable. In other words, they take forms that are more secretive, more clandestine, and more universal. Thus, we can conclude that *P. empiricus* and *P. psychologicus* have different ways of constructing knowledge bases defined by qualities such as

depth and coherence: *P. empiricus* tends to construct knowledge bases empirically whereas *P. psychologicus* tends to construct knowledge bases as something other than empirical. Again, the irony in *P. psychologicus* should be apparent. College professors of science are discouraged from teaching their students how to assemble the same kinds of empirical knowledge bases that they find so useful in their work as research scientists.

#### 6.2c How humans and non-humans are arranged in time and space

The bioeducational essay also reveals a significant compositional difference in how humans and non-humans are arranged in time and space. In this example, I will focus on how a non-human—the concept of photosynthesis (or Concept of Photosynthesis)—is temporally and spatially arranged in Bio101.

In *P. psychologicus*, the Concept of Photosynthesis is treated as if it existed outside of all language including representational systems such as images, symbols, and actions in at least three places. First, the Concept of Photosynthesis is treated as if it existed in phenomena in nature (i.e., ‘out there’).<sup>183</sup> Second, the Concept of Photosynthesis is treated as if it existed in the mind of the scientist or professor (‘in there’).<sup>184</sup> It’s important to note, however, that the Concept of Photosynthesis out in nature is treated as if it were *exactly the same* as the Concept of Photosynthesis in the mind of the scientist/professor. In other words, these two concepts are treated as if they were one-and-the-same Concept, as if they shared a one-to-one correspondence, as if they were mimetic. Third, the Concept of Photosynthesis is treated as if it existed in the minds of students who have successfully learned with understanding. Here again,

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183. Lemke characterizes this view as philosophical *realism* (see Lemke 2002).

184. Lemke characterizes this view as an updated form of Plato’s *idealism* (see Lemke 2002).

it's important to note that the corresponding Concept of Photosynthesis out in nature and in the mind of the scientist/professor are treated as if they were *exactly the same* as the Concept of Photosynthesis in minds of accomplished students. In other words, these three concepts are all treated as if they were one-and-the-same Concept, as if they shared a one-to-one-to-one correspondence, as if they were mimetic.<sup>185</sup> Here, we can see that *P. psychologicus* constructs the Concept of Photosynthesis as if it had three distinct features. First, it constructs Photosynthesis as if it were invisible. In other words, *P. psychologicus* treats Photosynthesis as if it were simultaneously hiding just behind natural phenomena and also within mental phenomena. Second, it constructs Photosynthesis as if it were universal. In other words, *P. psychologicus* treats Photosynthesis as if it were exactly same both out in nature and in the mind. Third, it constructs Photosynthesis as if it were ahistoric (or timeless). In other words, *P. psychologicus* treats Photosynthesis as if it had always been out in nature awaiting discovery by scientists and students. This particular conceptual scenography is precisely what makes it possible for professors to expect their students to be able to a) *discover* the Concept of Photosynthesis for themselves, b) *generalize* from different figures and clicker questions and 'see' (internally) the conceptual unity of the various representations of the abstract Concept of Photosynthesis, and c) *leap* to the abstraction in situations beyond the context of instruction (in other words, cognitive transfer is possible because the abstract Concept of Photosynthesis is real and therefore always already naturally there as a target two which one can leap).

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185. Latour characterizes this view as a product of a "Kantian scenography," where phenomena are said to "reside at the meeting point between the inaccessible things in themselves and categorizing work made by the Active Ego" (see Latour 1999, 72).

In *P. empiricus*, the concept of photosynthesis is not treated as if it existed outside of all language. It is not treated as if it resided in the face-to-face confrontation of scientific minds with natural objects and phenomena. Instead, the concept of photosynthesis is treated as if it was what routinely circulates through cascades of visible, material transformations.<sup>186</sup>

Although in science these transformations often proceed from the more concrete to the more abstract—i.e., from *things* to *signs*, from *matter* to *form*, from the *worldly* to the more *wordly*—a critical feature of the transformations is that the upstream movement must be reversible and traceable in the downstream direction. In other words, scientists must be able to trace the concept of photosynthesis both upstream and downstream, but regardless of their location in stream (or circuit) the concept must always remain visible and material. Even when put into one of its more abstract forms in Bio101—for instance, as when one of the professors wrote the abbreviation “PS” during a lecture—this form remained both visible (students could see it on the projection screen) and material (students could touch it if they picked up the overhead transparency on which it was written in green ink). Where and when do these attitudes and assumptions locate the concept of photosynthesis? In *P. empiricus*, photosynthesis is still treated as if it were real, but in a different sense. *P. empiricus* doesn’t treat photosynthesis as if it re-presented a pre-existing reality. It also doesn’t treat photosynthesis as if it were some pre-destined mentality. Instead, *P. empiricus* treats photosynthesis as if it were that which is held constant through a series of visible, material, and empirically traceable transformations.<sup>187</sup> In other words, *P. empiricus* draws attention away from (on the one hand) that which is hidden

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186. See Latour 1999, 69.

187. See Latour 1999, 58.

'behind' trees growing on a sunny hillside and 'within' mind of students, and toward (on the other hand) all of the visible, material practices found in between these two extreme poles. The written abbreviation "PS" may be abstract in the sense that it has lost some of its visibility and materiality compared to when it is written as "photosynthesis," and even more of its visibility and materiality compared to when it is written as "light energy + CO<sub>2</sub> + H<sub>2</sub>O → C<sub>6</sub>H<sub>12</sub>O<sub>6</sub> + O<sub>2</sub> + H<sub>2</sub>O", but the photosynthesis cannot not afford to lose all visibility and materiality because to lose all of these two traits—at least in the natural sciences—is not to exist! In *P. empiricus*, abstraction is a *relative* quality, which means that even abstract concepts can still be considered concrete.

Here, I think Lemke's treatise on concepts is perhaps even more instructive than I can communicate, but I have taken the liberty of re-contextualizing his treatise on the concept of energy to fit with our current discussion of photosynthesis.

The concept of [photosynthesis] is not a single anything; it is a whole system of disparate but linked practices, ways of talking, ways of measuring, ways of calculating, ways of seeing. To learn this concept is to learn how to apply it in ever-widening circles of practical contexts, to learn how exactly our culture, our historical scientific tradition, constructs connections between this situation and that, that and the next.

You cannot "grasp" a concept like [photosynthesis]; to teach that you can is to promote an intellectually and socially dangerous illusion. You can construct a higher-order pattern, a pattern in the strategies by which our culture connects situations of different types, but this will not enable you to anticipate how the concept of [photosynthesis] will apply to a totally new situation—or even whether or not it can usefully be made to. Historically, and in the intellectual recapitulation of culture that grounds the educational process, it has always taken new work, new insight, new ways of constructing new kinds of connections to apply the concept of [photosynthesis] to new domains. In each successful instance the concept of [photosynthesis] itself was changed, was extended.

The same is true for all abstractions, all concepts, all categories, but especially for the most abstract ones, those that apply to the most superficially dissimilar instances. They are not singular, not unitary. The "concept" is not the same in any real sense from one situation to another very different one: to use the concept we must do very different things, use different discourses and construct different semantic patterns in language, draw different diagrams, perform different manipulations of objects. That we have a "concept" merely means that we ALSO have ANOTHER set of procedures for connecting what we do in one case with what we did in the other.

This means that the similarities on which abstract concepts are based are not "there" for all to see. Either they are entirely cultural constructions, or even if not, the ones on which a particular concept is based are indistinguishable from the infinite other possible similarities that may be construed between any two objects, until we are taught how to attend to, pick out, and/or construe the ones our culture, our physics wants us to see. Consequently, there is no reason to expect "transfer of learning" from one situation type to another. We must be taught, separately in each case, how to apply "a concept" to that case. In fact, we must be taught two things: how to operate in the new context, and how to construct a conventional similarity between that operation-in-context and all the others to which our culture gives the same name.<sup>188</sup>

The conceptual scenography articulated by Lemke is precisely what makes it possible to expect professors to teach their students how to talk, how to measure, how to calculate, and how to see. These can be understood as empirical practices. It is also what makes it possible to expect professors to teach their students how to construct higher-order patterns and how scientists connect situations of different types. These too can be understood as empirical practices. It is also what makes it possible to expect professors to teach their students how to engage in the types of work that they do as scientists, including how they operate in new contexts and how they construct conventional similarities between situations to which the

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188. Lemke, "The Missing Context," para. 16-19.

scientific culture gives the same name (but only retroactively!). Again, these too can be understood—as they already have by Lemke, Latour, and others—as empirical practices.

### 6.3 Activity

Among other characteristics, the scientific concept of activity draws our attention to the types of action or movement enacted by substances.<sup>189</sup> In this bioeducational essay, I interpret “substances” as referring to the types of action or movement enacted by humans and non-humans involved in a pedagogical practice. Let us briefly consider the two types of actions or movements enacted by students: saltation and ambulation.<sup>190</sup>

*P. psychologicus* often draws attention to the need for students to enact conceptual “leaps” over yawning “gaps.” Such movement can be characterized as *saltatory* (from Latin *saltare*, ‘to hop’ or ‘to leap’). This was the case with the Mutant Spinach Question, when students had to leap from the context of classroom instruction to the strange, unfamiliar context of a test question about a “mutant strain of spinach” with leaky membranes. Of the Bio101 students who could not make this abstract leap successfully, it might be said of them that the reason they could not make this leap is because they were not thinking abstractly enough. In other words, it might be said of them that they were thinking too concretely.

*P. empiricus* often draws attention to an entirely different type of movement altogether. Instead of leaps and gaps, which are discursive artifacts of a commitment to a one-to-one theory of correspondence, *P. empiricus* draws attention to student and teacher movements that can be characterized as *ambulatory* (from Latin *ambulare*, ‘to walk’ or ‘to step’).

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189. For example, the scientific concept of *activity* also draws attention to the capacity of a substance to undergo change.

190. See Latour 1999, Chapter 2.

Ambulatory movement is action that is aligned with the principles of circulating reference.

While it may be true that the Mutant Spinach Question requires a large leap from the context of classroom instruction to the strange, unfamiliar context of a test question, it's not necessarily true that students must a) make use of only mental allies in this task, and b) do it all at once. Instead, students can cross the yawning chasm by means of circulating reference, which a) makes use of empirical allies, and b) requires students to take small, carefully articulated and well aligned steps. The former action is cognitive *transfer*; the later action is empirical *transformation*. The former action is a common characteristic of contemporary school science; the later action is a common characteristic of scientists' science.

#### **6.4 Potency**

The scientific concept of potency draws our attention to the capacity or potential of a substance to produce strong effects. In this bioeducational essay, I interpret "strong effects" as referring to the capacity of a pedagogical practice to enable Bio101 students to answer the Mutant Spinach Question correctly.

Exam 2, question "52" served as a way of testing the potency of *P. psychologicus*. In fall 2006, *P. psychologicus* was only able to produce a strong effect in twenty percent of the Bio101 students. In other words, eighty percent of the Bio101 students could not demonstrate that they had learned with understanding. In this non-simulated reality, students could first turn their attention to the visual, material text of question "52." Here, they could register the content-related terms within the stem and answer choice components of the question, but soon after that they quickly needed to switch to their mental/cognitive faculties. For reasons that surely vary, but that may have a good deal to do with a student's particular cultural



background, a majority of the Bio101 students were unable to perform the necessary abstract psychological operations. In this particular instance, the potency of *P. psychologicus* was weak.

To assess the potency of *P. empiricus*, I had to use the *EmSIM 3000*. Recall that the *EmSIM 3000* was used to tag all of the visible, material elements used by the Bio101 professors with students during class. The *EmSIM 3000* not only allows us to act as if the professors had done this type of empirical work with their students, but also to act as if the students had been allowed to keep the products of their empirical work in front of them when confronting question “52.” If this was the reality of Bio101, then one of the first tasks to which students would turn their immediate attention are the numerous content-related terms present in the text of the stem of the question. In *P. empiricus*, although these terms are some of the more abstract forms that students encountered during instruction, they are still visible and still material. Rather than have students shift their attention from an empirical to a mental mode (as is required in *P. psychologicus*), *P. empiricus* has its students shift their attention from one empirical element (e.g., a single content-related term such as “#mutant” or “#spinach”) to other empirical elements that have visible, material connections to the content-related terms in the stem of the question.

I’ve used the *EmSIM 3000* to model what this process might look like. Table 6.1 shows what happens when students begin looking within their visible, material knowledge bases for elements that overlap with the content-related terms found in the stem of question “52.”

Table 6.1: A table showing the number of content-related hits generated by the *EmSIM 3000*.

Content-related term (Q52)	Number of hits	Distribution of hits
#mutant	2	— — 2 on 09-29-06
#strain	0	—
#spinach	0	—
#thlakoid(s)	5	1 on 09-25-06 3 on 09-27-06 1 on 09-29-06
#membrane(s)	11	3 on 09-25-06 7 on 09-27-06 1 on 09-29-06
#thylakoid(s) membrane(s)	4	1 on 09-25-06 2 on 09-27-06 1 on 09-29-06
#permeable or #permeability	0	—
#ions	3	— 2 on 09-27-06 1 on 09-29-06
#H+ ion	4	— 3 on 09-27-06 1 on 09-29-06
#hydrogen	5	— 4 on 09-27-06 1 on 09-29-06
#reaction(s)	27	4 on 09-25-06 10 on 09-27-06 13 on 09-29-06

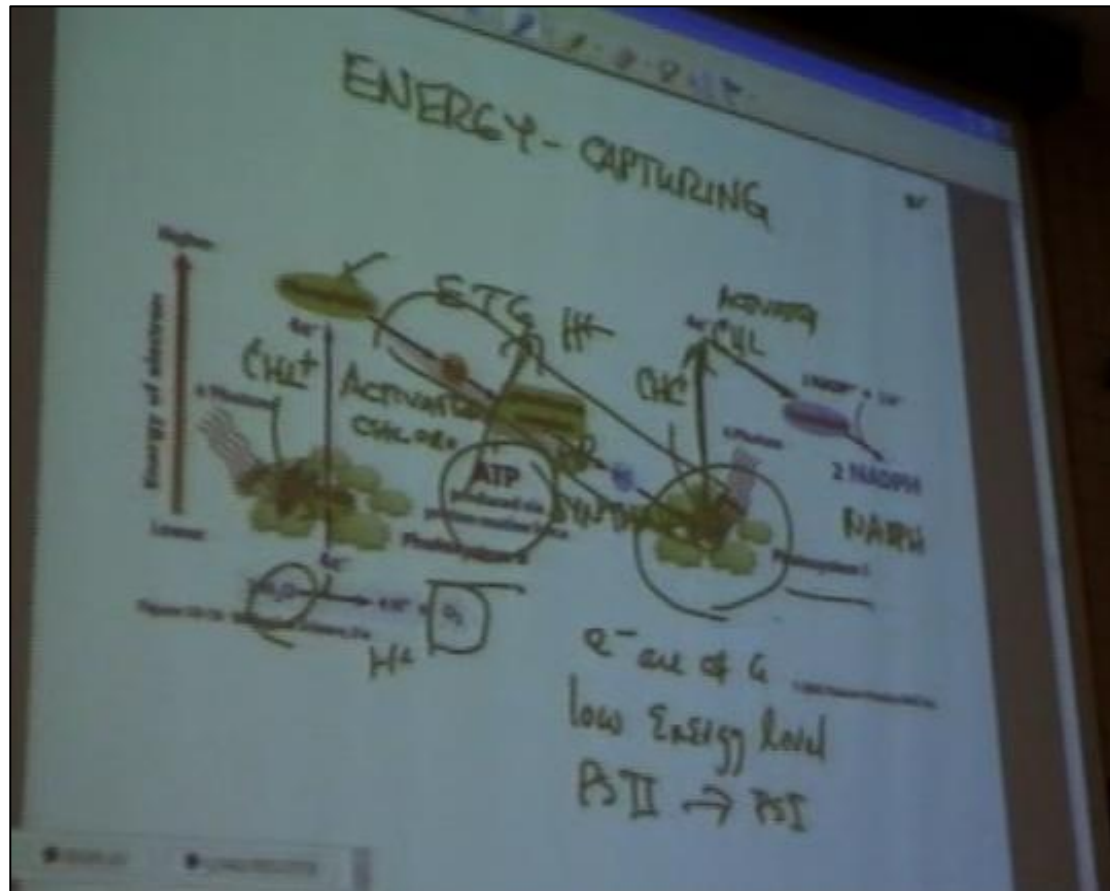
Table 6.1 (cont'd)

#photosynthesis	53	10 on 09-25-06 21 on 09-27-06 22 on 09-29-06
#photosynthesis reactions	28	4 on 09-25-06 10 on 09-27-06 14 on 09-29-06

As an example of how to interpret the table, students looking for figures and clicker questions in their knowledge bases having to do with “#photosynthesis” would have their attention drawn to at least fifty-three visible, material elements presented during the four-day photosynthesis unit. Ten of these elements were presented during Lecture 1 (09-25-06), twenty-one of these elements were presented during Lecture 2 (09-27-06), and twenty-two of these elements were presented during Lecture 3 (09-29-06). These same students might be overwhelmed by the results of the large number of ‘hits’ produced when searching their knowledge base for “#photosynthesis,” so they might instead try looking in the direction of other content-related terms that result in fewer hits.

If students were to then shift their attention to the collection of content-related terms that initially produced a more manageable number of hits, say, between three and eleven, then their attention would be drawn to terms such as “#thylakoid(s),” “#membrane(s),” “# thylakoid membrane(s),” “#ions,” “#H+ ion,” and “#hydrogen.” If they were to then pursue the identities of the figures and clicker questions associated with these particular hits within their knowledge bases, they will quickly find that their pool of potentially useful visible, material allies consisted of a total of fourteen numbered elements. Of these fourteen numbered elements, they would quickly see that there was a higher density of hits on just seven of these fourteen numbered

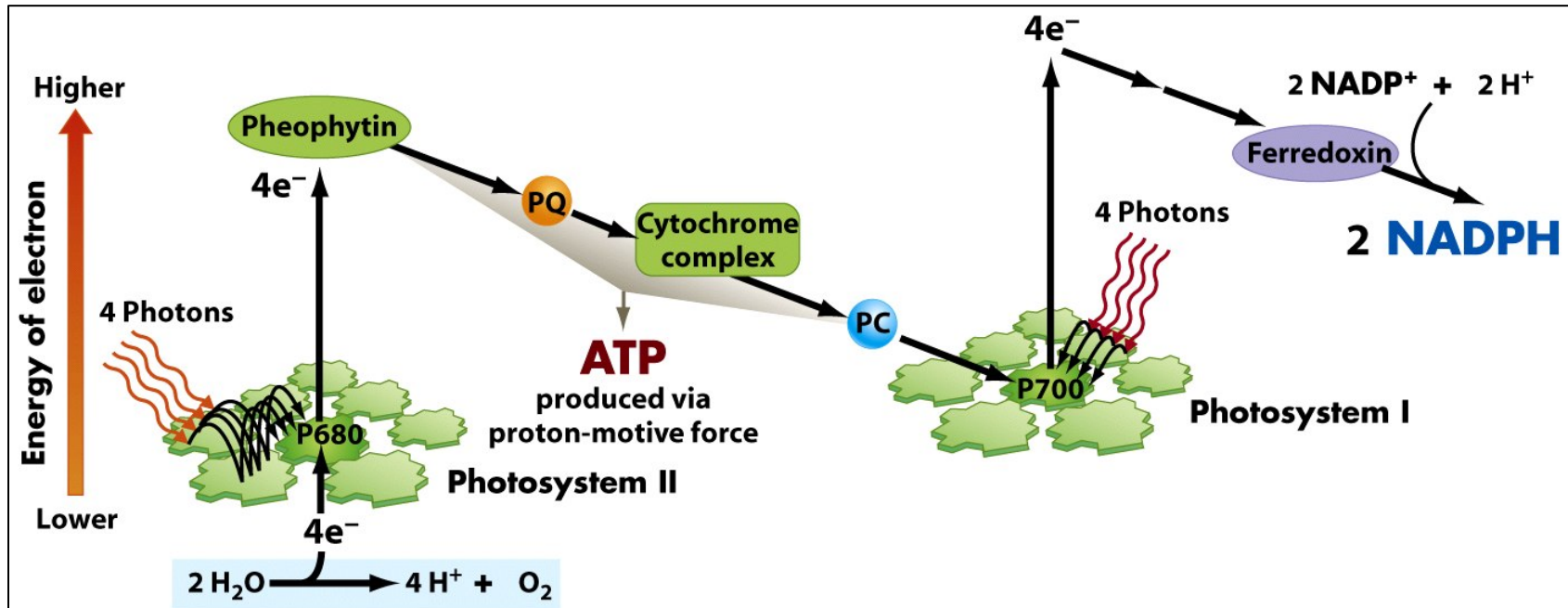
elements (specifically, Elements 23, 15e, 20, 12b, 9c, 17, and 6). Of these seven filtered elements, students would quickly see that Element 6, which is a copy of Figure 10.16 from Lecture 3 (09-29-06), had the greatest number of total hits (six), and that Element 17, which is a still image made from an animation shown to students in Lecture 2 (09-27-06), had the second greatest number of total hits (four). Elements 6 and 17 are shown in Figures 6.1 and 6.2.



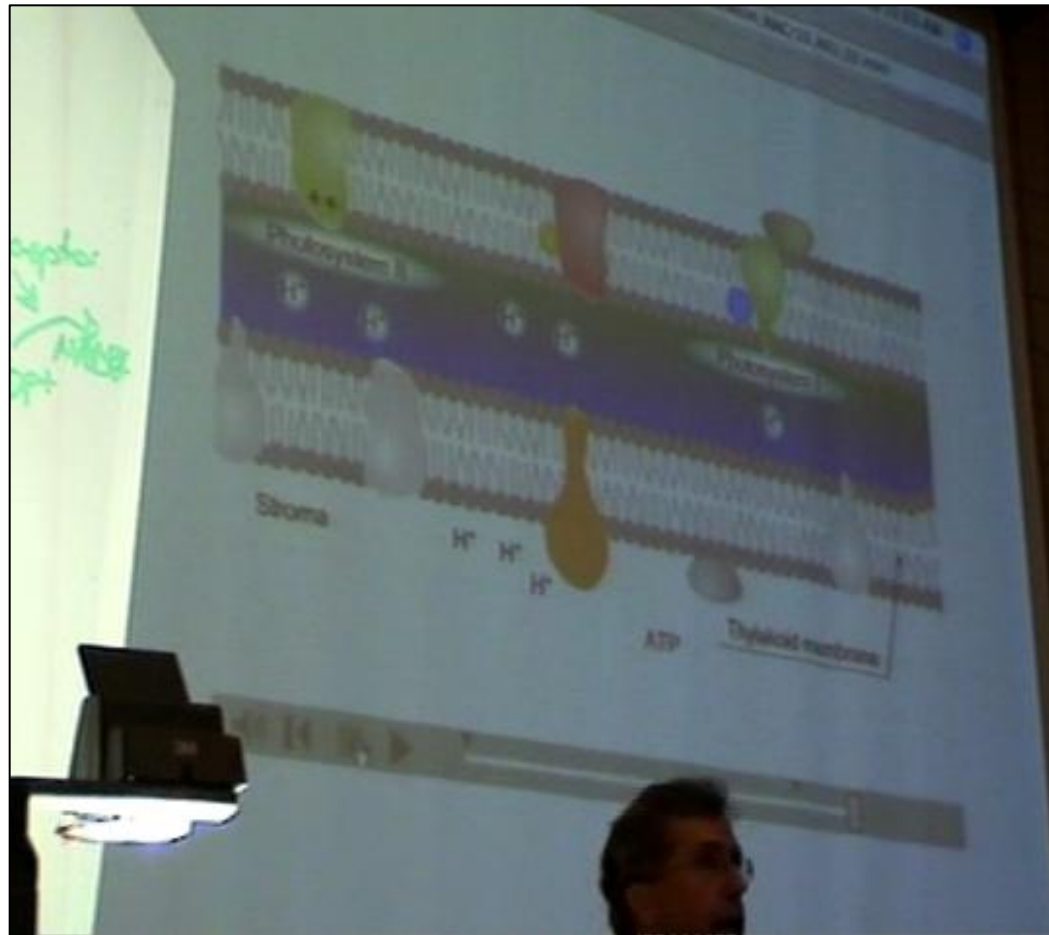
A. Figure 10.16 shown by the Bio101 professors during Lecture 3 (09-29-06).

Figure 6.1: Two versions of Element 6, which was identified by the *EmSIM 3000* as having the most relevance to question “52.” Two versions of Element 6 are included because the images and text in the photographed version may be difficult to read/see. Figure 10.16 shown by the Bio101 professors during Lecture 3 (09-29-06) (A); and a non-annotated version of Figure 10.16 as it appears in the instructional materials (B). (Reprinted with permission by the copyright holder.)

Figure 6.1. (cont'd)



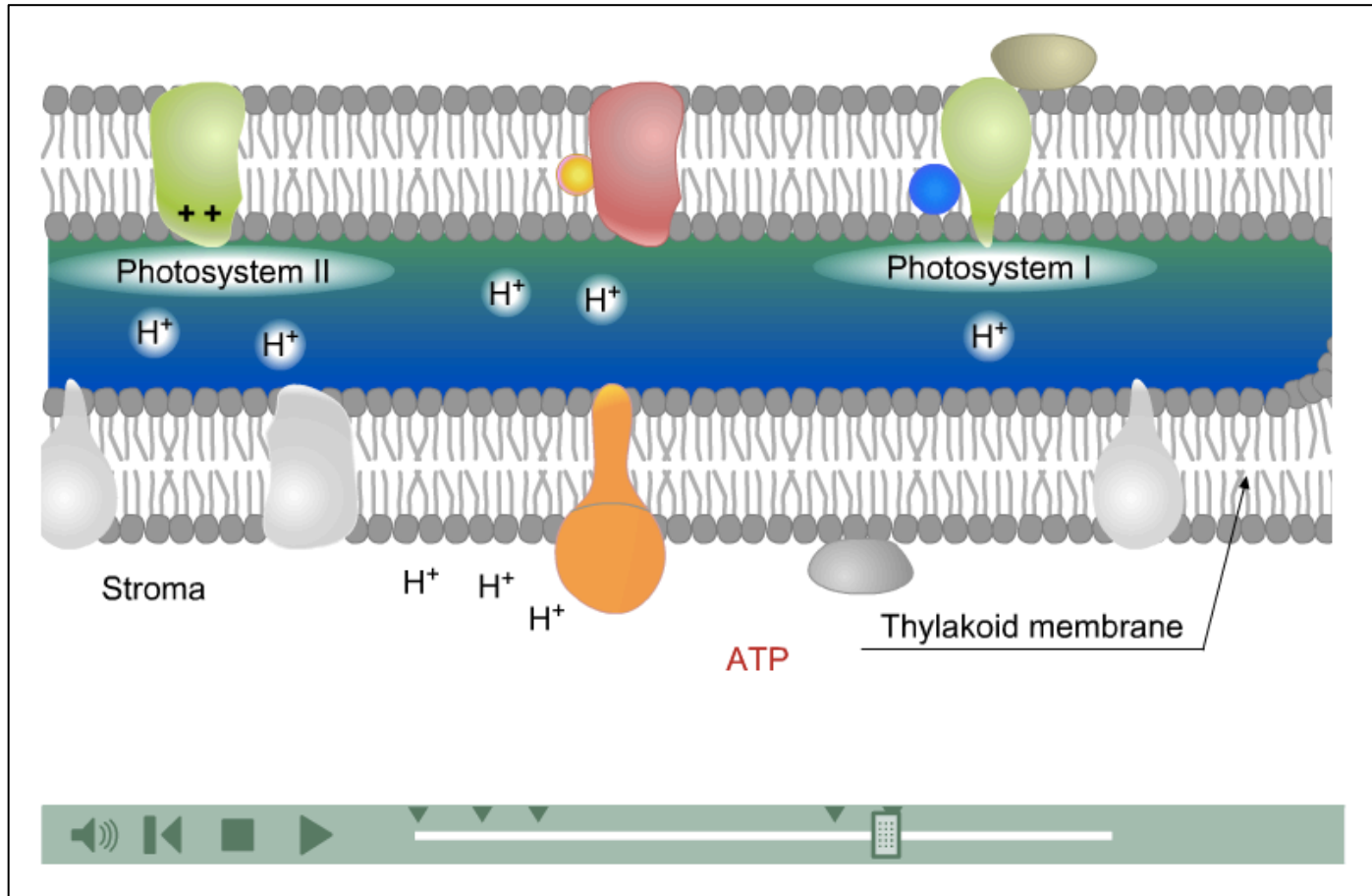
B. A non-annotated version of Figure 10.16 as it appears in the instructional materials.



A. A still image made from an animation shown by the Bio101 professors during Lecture 2 (09-27-06).

*Figure 6.2:* Two versions of Element 17, which was identified by the *EmSIM 3000* as having the second most relevance to question “52.” Two versions of Element 17 are included because the images and text in the photographed version may be difficult to read/see. A still image made from an animation shown by the Bio101 professors during Lecture 2 (09-27-06) (A); and a still image made from the animation as it appears in the instructional materials (B). (Reprinted with permission by the copyright holder.)

Figure 6.2. (cont'd)



B. A still image made from the animation as it appears in the instructional materials.



The *EmSIM 3000* identified Element 6 (Figure 6.1(A) and (B)) and Element 17 (Figure 6.2(A) and (B)) as the visible, material elements most likely to aid Bio101 students in their attempts to answer question “52” correctly.<sup>191</sup> However, in the unsimulated version of Bio101 the students were not allowed to have the visible, material form of either element with them when attempting to answer the exam question. In other words, we have no way of simulating whether the possession of visible, material copies of these two figures would have helped more than twenty percent of the Bio101 students demonstrate that they had learned with understanding. Thus, it appears as though we have no way of evaluating and/or validating the *EmSIM 3000*’s selection of these two figures. Fortunately for us, just two days after Exam 2 one of the Bio101 professors offered us a way of doing just this. They offered a real time example of the very scenario that the *EmSIM 3000* identified.

#### Exam 2 Review: Lecture 20

Two days after Exam 2, the Bio101 professors decided to re-visit the Mutant Spinach Question with the students during class. This was a relatively common practice in Bio 101. The instructors often identified one or two of the most missed questions on an exam and discussed them in some detail with students in class. Question “52” was the most missed question on Exam 2, and one of the professors took this opportunity to lead the students through an exercise that I had never seen him do before. As the professor framed the task,

**Professor 2:** There were a couple particularly difficult questions that I’d like to go over...this is one of them, number “52,” that asked you about a leaky thylakoid membrane. OK. And I want to take some time to show you the kind of logic that you

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191. Interestingly, when I searched all at once for a combination of all the content-related terms found within the stem of the Mutant Spinach Question, the *EmSIM 3000* spit out a single hit: Element 6, Figure 10.16, 09-29-06.

might use...I'm not...there might be other ways of solving the problem...I want to show you the way I might step through that problem to get to the correct answer, OK. And I'm going to do that by using the clicker. All right? So everybody get your clickers out and let's begin. All right?<sup>192</sup>

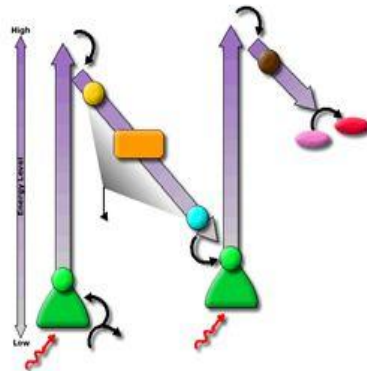
Making use of the same technology used to ask clicker questions of students prior to Exam 2, the professor broke question "52" down into six different clicker questions designed to help students see how they should have approached the Mutant Spinach Question. Unlike any of the clicker questions used in the four days leading up to Exam 2, four of these six clicker questions made use of written text combined with the use of one of two figures. The two figures used in the four sequential clicker questions are shown in Figure 6.3.

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192. Lecture Transcript (October 18, 2006): 00:01:26 - 00:01:56.

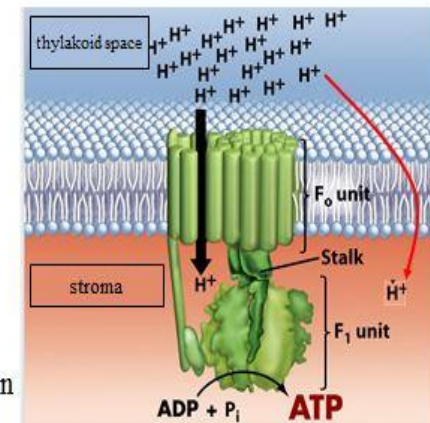
ATP and NADPH are the sources of energy used during the carbon fixing and reduction reactions (Calvin Cycle). They are needed in approximately 3:2 ratio (ATP:NADPH), however, non-cyclic photophosphorylation (the “Z-scheme”) yields a lower ratio (less than the needed amount of ATP). **How is this ratio “corrected”?**

- a) cyclic photophosphorylation
- b) slow Calvin Cycle
- c) decreased sugar yield
- d) decreased NADP production
- e) No change



What would be the effect of having a thylakoid membrane that was somewhat “leaky” to  $H^+$ ?

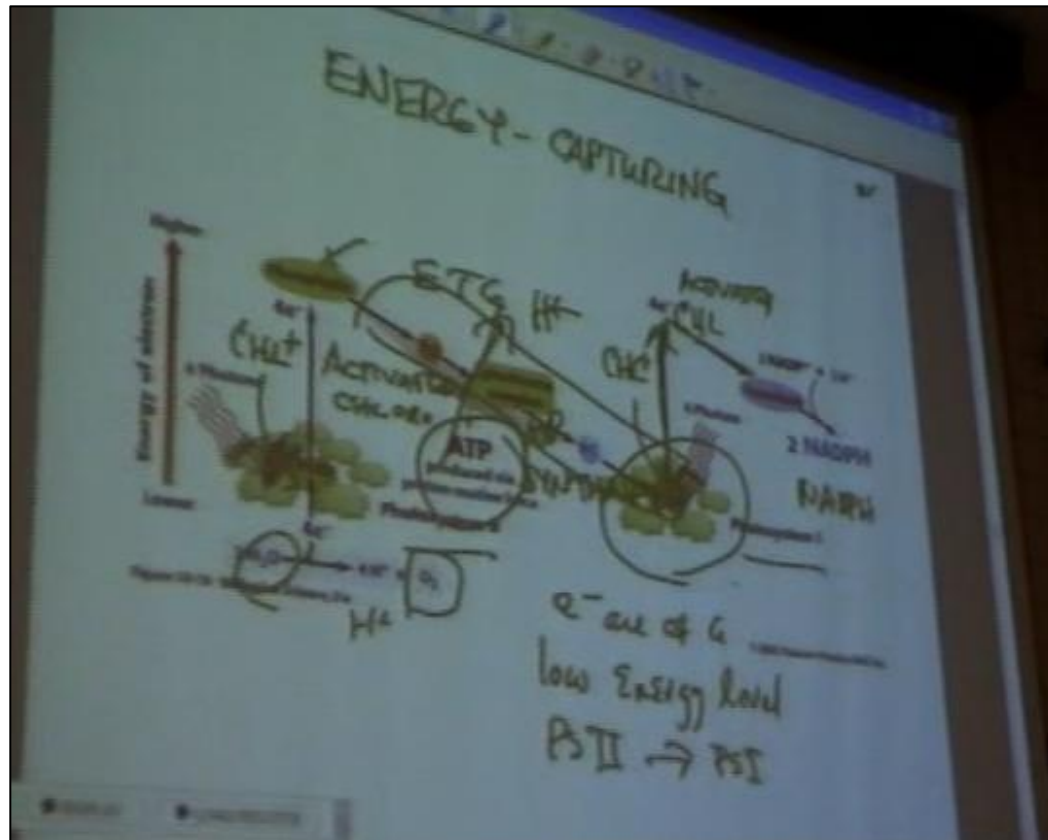
- a) NADPH yield decrease
- b) NADPH yield increase
- c) ATP yield decrease
- d) ATP yield increase
- e) No change



\*hint: “yield” is the amount of “product” per amount of input, in this case amount of product per  $H^+$ .

Figure 6.3. (At left): The first of six clicker questions asked during the post-Exam 2 review session. The text contained within, on top, and underneath the vertical arrow to the far left of the figure appearing within the clicker question reads as follows: “Energy Level” (within), “High” (on top), and “Low” (underneath). (At right): The second of six clicker questions asked during the post-Exam 2 review session. The text in the upper (blue) portion of the figure contained within the clicker question reads as follows (starting in the top left of this upper portion and proceeding in a clockwise direction): “thylakoid space,” (multiple) “ $H^+$ ,” and “ $F_0$  unit.” The text in the lower (orange) portion of the figure reads as follows (starting in the top left of this lower portion and proceeding in a clockwise direction): “stroma,” “ $H^+$ ,” “Stalk,” “ $H^+$ ,” “ $F_1$  unit,” “ATP,” and “ADP +  $P_i$ .”

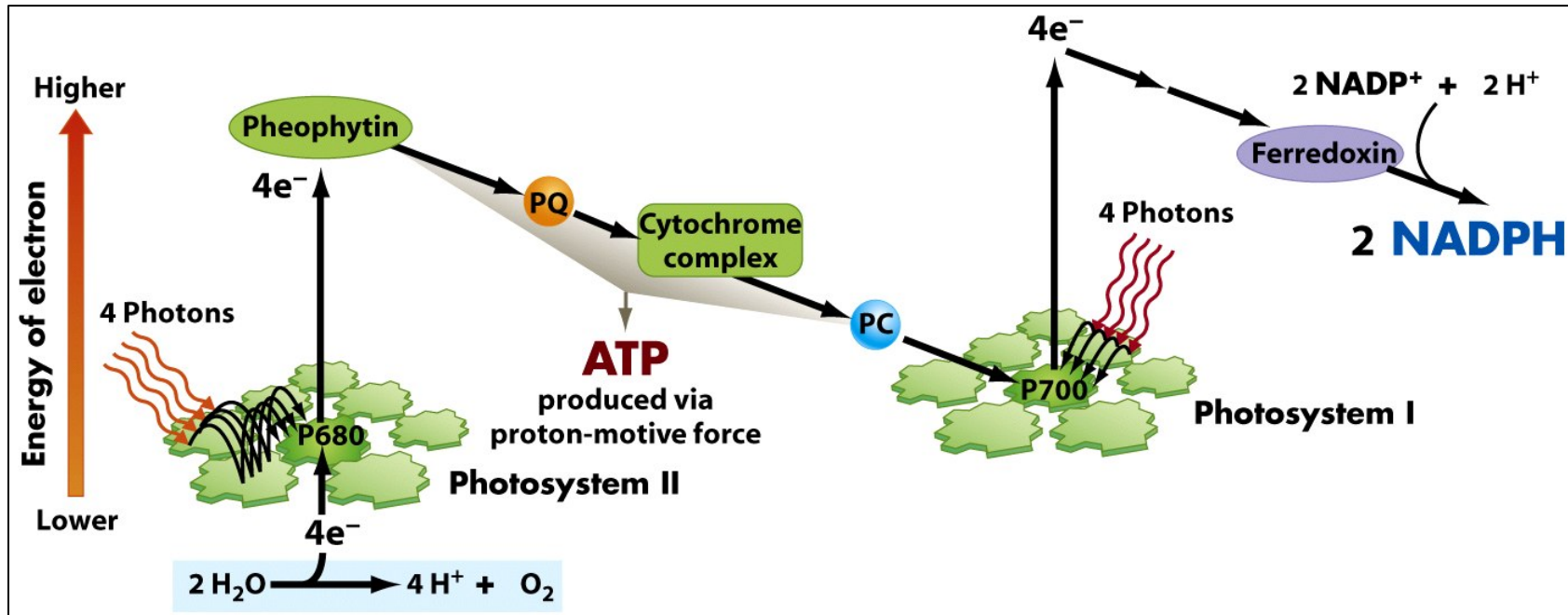
We first need to focus our attention on the figure embedded in the first of the six clicker questions used by the professor during the post-Exam 2 review session—in other words, the “N”-shaped figure at left of Figure 6.3. This is a figure that the professor spent a substantial portion of time discussing with students when showing them “the kind of logic” that they might use to solve question “52.” If we juxtapose this figure with Element 6 (Figure 6.1), which was one of the two images identified by the *EmSIM 3000*, then it appears we have taken a positive step in validating the empirical simulator’s performance. This juxtaposition is done for you in Figure 6.4.



A. Figure 10.16 shown by the Bio101 professors to students during Lecture 3 (09-29-06), but also the element (Element 6) identified by the *EmSIM 3000* as having the most relevance to question 52.

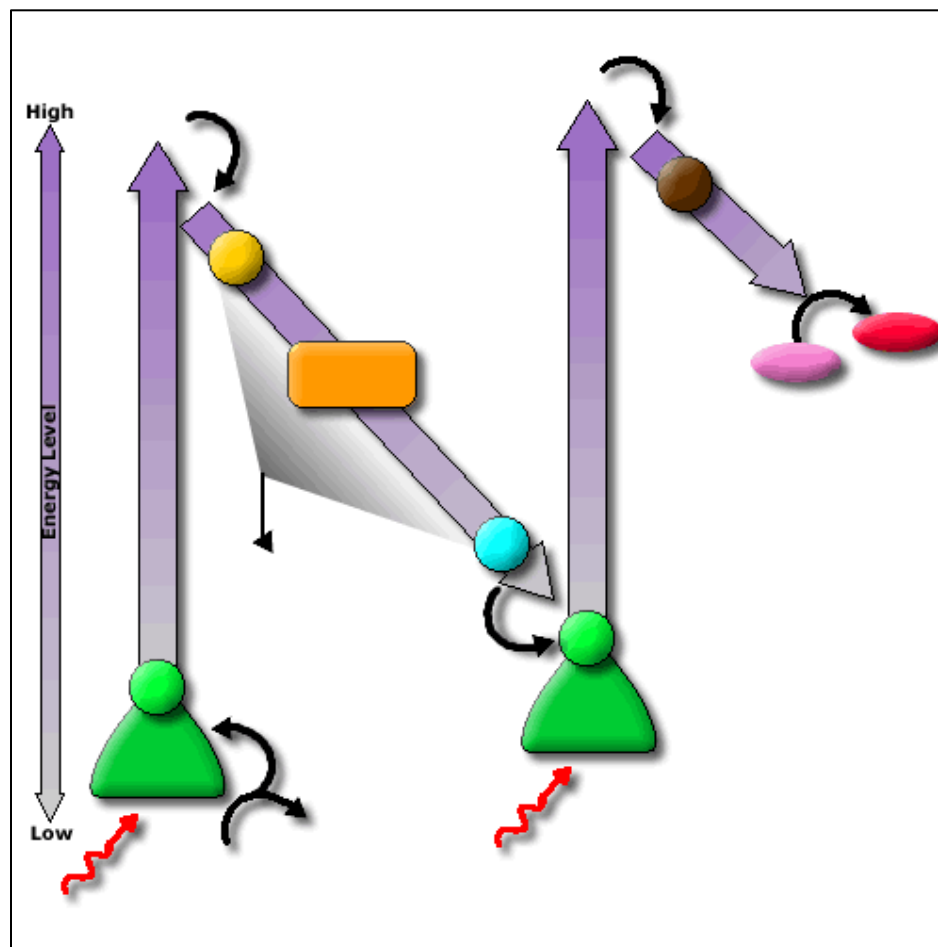
*Figure 6.4.* Juxtaposition of Element 6 and a figure used with Bio101 students during the post-Exam 2 review session. Figure 10.16 shown by the Bio101 professors to students during Lecture 3 (09-29-06), but also the element (Element 6) identified by the *EmSIM 3000* as having the most relevance to question 52 (A); A non-annotated version of Figure 10.16 as it appears in the instructional materials. Notice the Z- (or N-shaped) scheme visible in the image. (B); and a close-up of the image used in the first of six clicker questions asked during the post-Exam 2 review session. Notice the Z- (or N-shaped) scheme visible in the image. The text contained within, on top, and underneath the vertical arrow to the far left of the figure reads as follows: “Energy Level” (within), “High” (on top), and “Low” (underneath) (C). (Reprinted with permission by the copyright holder.)

Figure 6.4. (cont'd)



B. A non-annotated version of Figure 10.16 as it appears in the instructional materials. Notice the Z- (or N-shaped) scheme visible in the image.

Figure 6.4. (cont'd)



C. A close-up of the image used in the first of six clicker questions asked during the post-Exam 2 review session. Notice the Z- (or N-shaped) scheme visible in the image. The text contained within, on top, and underneath the vertical arrow to the far left of the figure reads as follows: “Energy Level” (within), “High” (on top), and “Low” (underneath).

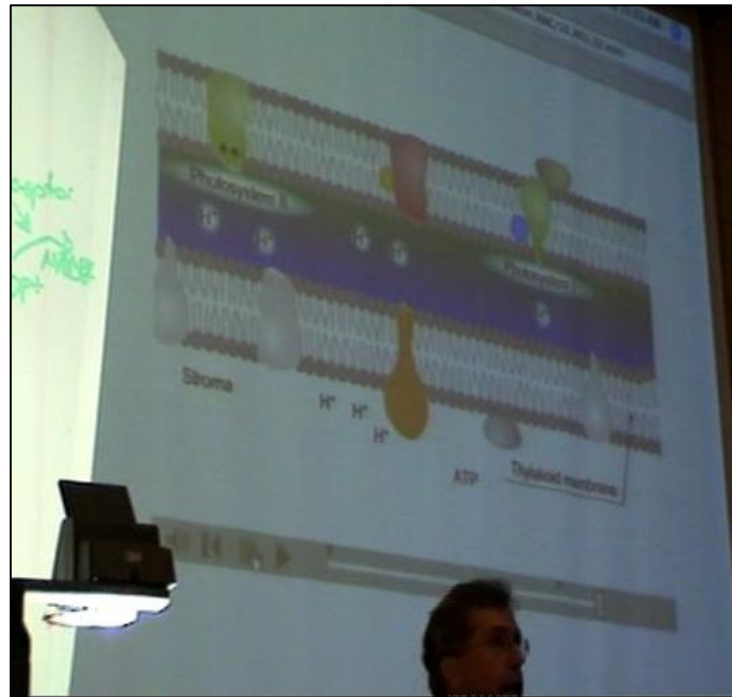
Despite the appearance of more information in the figure at left, the two figures are clearly related.<sup>193</sup> This means that the professor chose to show students a figure during his Exam 2 review that was similar to the first figure selected by the *EmSIM 3000*.

If we now to our attention instead to the figure embedded in the second of the six clicker questions used by the professor during the post-Exam 2 review session—in other words, the figure with the large, green apparatus at right of Figure 6.3—then we get a similar result. The juxtaposition of this figure with Element 17 shows that we have taken another positive step in validating the empirical simulator’s performance. This juxtaposition is done for you in Figure 6.5.

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193. The Bio101 professors might describe both figures as representations of the “Concept of the Light-Dependent Reactions of Photosynthesis.”

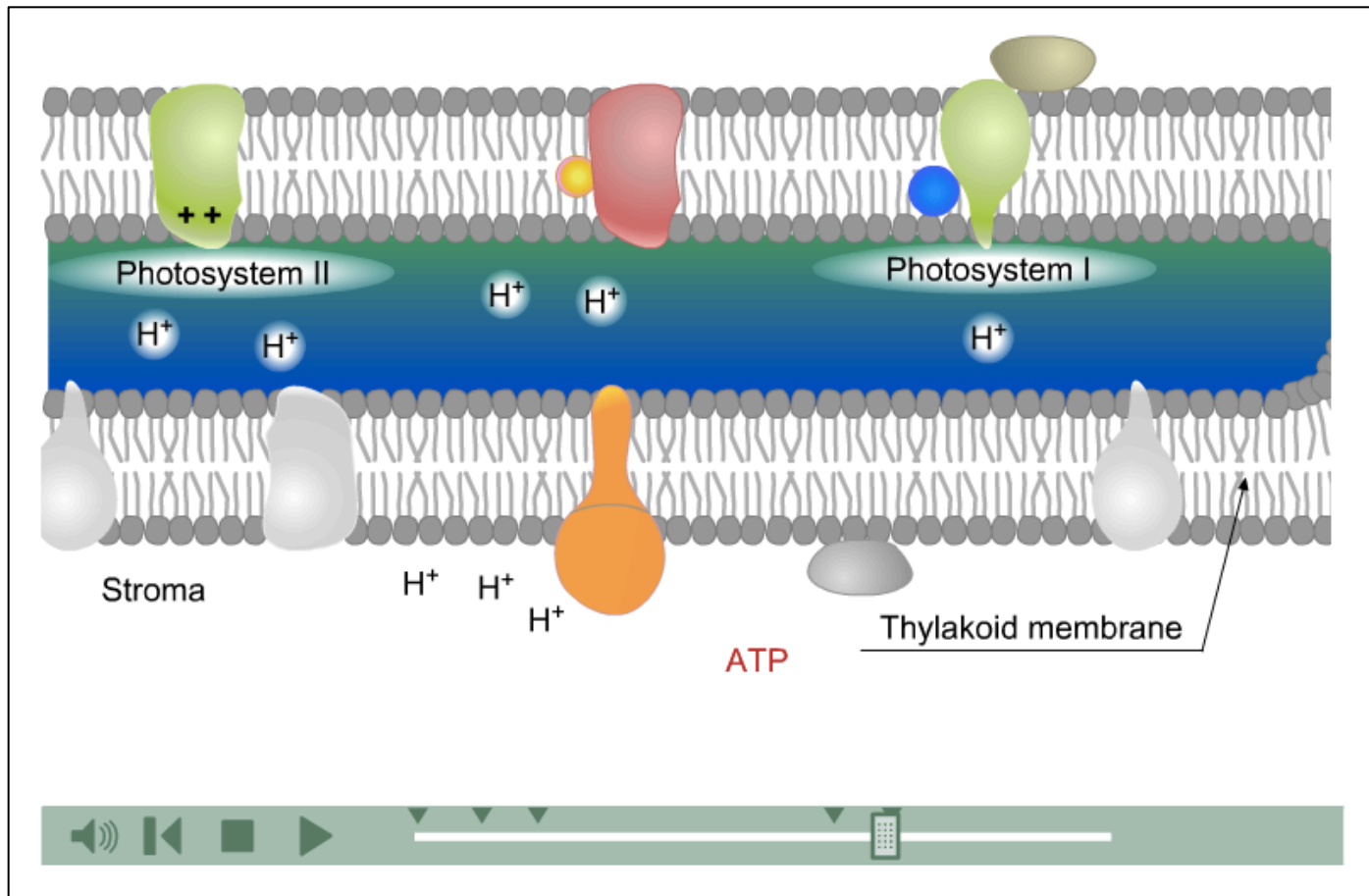




A. A still image made from an animation shown by the Bio101 professors during Lecture 2 (09-27-06), but also the element (Element 17) identified by the *EmSIM 3000* as having the second most relevance to question “52.”

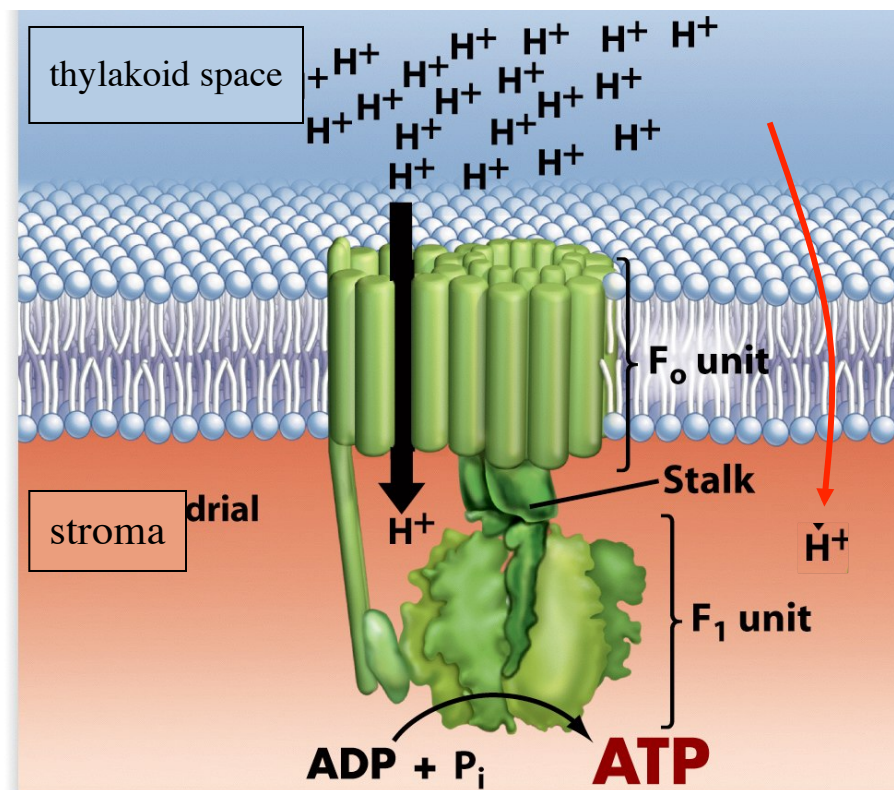
*Figure 6.5.* Juxtaposition of Element 17 and a figure used with Bio101 students during the post-Exam 2 review session. A still image made from an animation shown by the Bio101 professors during Lecture 2 (09-27-06), but also the element (Element 17) identified by the *EmSIM 3000* as having the second most relevance to question “52” (A); a still image made from the animation as it appears in the instructional materials (B). Notice the (orange) pear-shaped structure visible in the center of image; and a close-up of the image used in the second of six clicker questions asked during the post-Exam 2 review session (C). The text in the upper (blue) portion of the figure contained within the clicker question reads as follows (starting in the top left of this upper portion and proceeding in a clockwise direction): “thylakoid space,” (multiple) “H+,” and “F<sub>0</sub> unit.” The text in the lower (orange) portion of the figure reads as follows (starting in the top left of this lower portion and proceeding in a clockwise direction): “stroma,” “H+,” “Stalk,” “H+” “F<sub>1</sub> unit,” “ATP,” and “ADP + Pi.” Notice the similarities between the (green) structure in the center of the image and the (orange) pear-shaped in the previous image.

Figure 6.5. (cont'd)



B. A still image made from the animation as it appears in the instructional materials. Notice the (orange) pear-shaped structure visible in the center of image.

Figure 6.5. (cont'd)



C. A close-up of the image used in the second of six clicker questions asked during the post-Exam 2 review session. The text in the upper (blue) portion of the figure contained within the clicker question reads as follows (starting in the top left of this upper portion and proceeding in a clockwise direction): “thylakoid space,” (multiple) “H<sup>+</sup>,” and “F<sub>0</sub> unit.” The text in the lower (orange) portion of the figure reads as follows (starting in the top left of this lower portion and proceeding in a clockwise direction): “stroma,” “H<sup>+</sup>,” “Stalk,” “H<sup>+</sup>,” “F<sub>1</sub> unit,” “ATP,” and “ADP + P<sub>i</sub>.” Notice the similarities between the (green) structure in the center of the image and the (orange) pear-shaped in the previous image.

Despite differences in the two figures, they are clearly related.<sup>194</sup> This means that the professor chose to show students a figure during his Exam 2 review that was similar to the second figure selected by the *EmSIM 3000*.

To summarize, when showing students “the kind of logic” they might use to solve question 52, and when showing students the way he might “step through that problem to get the correct answer,” Professor 2 relied not on mental allies, but instead on two empirical allies—two visible, material figures—both of which had been identified by an empirical tagging (or circuit-building) exercise facilitated by the *EmSIM 3000*. Therefore, in this particular instance the potency of *P. empiricus* was particularly strong. The tagging techniques used by the *EmSIM 3000* helped us choose two visible, material elements from a pool of over from over fifty-three visible, material elements presented to students during a four-day photosynthesis unit. Most importantly, these happened to be the same two empirical elements selected by one of the Bio101 professors when showing his students how to apply their newfound scholarship to a problem students didn’t think they knew how to solve.

### Conclusions

I’ve used a device of my own making—the *bioeducational* assay—to produce readable traces of two pedagogical practices, *P. psychologicus* and *P. empiricus*. These practices were evaluated according to their relative purity, composition, activity, and potency. One of the main purposes of this experiment was to not only to further delineate the boundaries of a pedagogical practice constructed in accordance with a mental/cognitive horizon of expectations,

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194. The Bio101 professors might describe both figures as representations of the “Concept of the Proton Gradient” (or “Proton Transport”) and/or the “Concept of ATP Production.”

but also to begin sketching and elaborating an envelope of a pedagogical practice constructed in accordance with an empirical horizon.

*P. empiricus*, which I've tried to align with the governing principles and concepts of science rather than those of psychology, should be viewed as yet another way that professors can help their students find ways to learn with understanding. To be sure, I have enacted an alchemy that distorts and oversimplifies many of the complexities and purposes of scientific practices. To make matters worse, I have begun modifying the five defining features associated with learning with understanding. In the scenography that I have developed thus far, students who learn with understanding are still said to possess a coherent knowledge base, but this knowledge base can take more visible, material forms. Students who learn with understanding are still said to be able to apply, extend or extrapolate their deep, rich knowledge base to certain types of situations, but to do so they must rely on circulating reference instead of cognitive transfer. Furthermore, I've used the ideas of Popkewitz, Lemke, and Latour to help me re-imagine the ways that abstract conceptual learning theory can operate in university biology classrooms. One of my prime motivations is to try and find ways to exclude fewer students from meeting the goals of science education. A brief anecdote will help illustrate why I think this sort of action is needed.

### **A Student's Plea for Help**

In fall 2007, I interviewed a number of Bio101 students regarding their answers to three application questions related to the topic of photosynthesis. The students were each offered a decent sum of money for an hour's worth of their time. However, one student, whom I'll call "Louisa," wasn't interested in coming to the interview for the money. Louisa's interest

stemmed from the fact that she had seen me videotaping the lectures during parts of the semester from the rear of the lecture hall. She reasoned that I must be one of the instructors and she thought she might be able to use this interview to ask for advice. “You see,” she told me before the formal portion of the interview commenced, “I’ve done horrible on the first two Bio101 midterm exams and I’m worried that I might fail the course.” When I asked her about things like whether or not she attended class regularly, completed the homework assignments, did the course readings, etc. she quickly convinced me that this was not a case of personal irresponsibility, disinterest, or neglect. On the contrary, she had a perfect attendance record, sat near the front of the room, completed all the readings before class, and formed study groups with her peers. In other words, Louisa was doing many of the things her Bio101 professors hoped their students would do. It was soon after we established these facts that she then surprised me. She began to cry.

As tears ran down her cheeks Louisa apologized profusely, but what she did next caught me by complete surprise. She unzipped her backpack rather hurriedly and began stacking a series of colorful, spirally bound notebooks on the small interview table. As she began opening them, one by one, and flipping through them page by page, her sadness quickly became mixed with anger and frustration. “Do you see these?” She said while continuing to flip through the individual pages—and then through the larger tabbed sections—of her notebooks, “Nobody in this class works as hard as I do.” Indeed, Louisa’s notebooks were impressive. They were neat, thorough, extensive, organized, highlighted, and underlined. These were not the notebooks of a lazy or an unmotivated student. “I just don’t understand,” she added, “No matter what I do

outside of class...no matter how hard I work...I just can't seem to make it pay off on the exams. I don't know what else I can do. Can you help me?"

### **From Innerstanding to Overstanding**

There are many ways we could read Louisa's situation, but I want to move away from the psychological or cognitive readings of it and propose something entirely empirical. What if Louisa's main problem stems from the fact that she is routinely asked by her college science professors to place nearly all of her trust in her mind/brain? What if she were allowed to enlist more allies that were something *other than* mental? What if she could be taught how to re-organize the contents of her notebooks according to the principles of circulating reference instead of those such as 'chunking' information and improving short-term memory? What if she were expected to engage in chains of transformation instead of instances of transfer? In other words, what if she were allowed to be more like research scientists when it came to learning with understanding?

*P. empiricus* can get us closer to a point in science education where it becomes possible to 'think' and to 'reason' with both hands and eyes.<sup>195</sup> With a substantial amount of work and almost constant maintenance, it can get us closer to a point in science education where it becomes possible to shift the attention from the mind to the surface of visible, empirical resources that can be moved more freely—and with more integrity—through both space and time. It can get us closer to a point in science education where it becomes possible to treat logic as if it were about logistics.<sup>196</sup> And, it can get us closer to a point in science education where it

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195. See Latour 1986.

196. See Latour 1987, Chapter 6.

becomes possible to treat understanding less as *innerstanding*—where understanding tends to remain secretive and clandestine—and more as *overstanding*—where it can be rendered more public, more accessible, and more equitable. Latour, always skeptical of the special powers so often attributed to the human mind, reminds of us the power of empirical practices,

The role of the mind has been vastly exaggerated, as has been that of perception (Arnheim, 1969). An average mind or an average man, with the same perceptual abilities, within normal social conditions, will generate totally different output depending on whether his or her average skills apply to the confusing world or to inscriptions.<sup>197</sup>

Perhaps the presence of *P. empiricus* in this dissertation—despite its clear need of further trials, additional strengthening, and much more extensive elaboration—signals the beginning of an era in science education in which the psychological sciences can be made to loosen their historically tightened grip on the notions of teaching for and learning with understanding. To open up these notions to the reach and influence of the natural sciences would not only make room for more authenticity in science education, but also for more inclusion. It is possible that transforming science via a more scientific or empirical alchemy would result in a much greater percentage of college students demonstrating that are capable of learning with understanding. As I said before, to take a mentalist approach to classroom allies is to be selective and exclusive. It limits our conceptions of what these entities can be to a culturally and historically specific set of values, ethics, assumptions, and beliefs—mostly those of “upper-middle class” cultural backgrounds. By taking a mentalist approach, those students from backgrounds outside of the upper-middle class are more likely to struggle in educational

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197. Latour, “Visualization and Cognition,” 22.



moments in which knowledge and understanding are defined exclusively as mental and cognitive.

Shifting the alchemy from the psychological sciences to the natural or empirical sciences also means that science professors are reconnected to their 'other' lives as research scientists. Instead of living schizophrenic lives as empirical practitioners outside of the classroom and psychological practitioners inside of it, through the magic of a more scientifically informed alchemy the two split selves are reunited in the form of a single person—the *scientist teacher*. Rather than having to leave their most treasured research practices and sensibilities at the door to the classroom, like a checked overcoat or a bulky piece of luggage, these habits and sensibilities would be allowed to flood the space of the classroom each and every day.

This stance does not deny that there are such entities as “reasoning,” “thinking,” “minds-on” learning, “abstract concepts,” and “understanding by design.” Nor does it deny the existence of discursive features such as knowledge base, coherence, transfer, extrapolation, and cognition. On the contrary, it endorses all of these actors but with one vital caveat: none of these actors must be defined in accordance to a mental/cognitive horizon of expectations. There can be such things as reasoning, thinking, minds-on learning, abstract concepts, and understanding by design, and there can such entities as knowledge base, coherence, transfer, extrapolation, and cognition, but they can also be defined by logistical practices instead of (or in addition to) logical practices. It is a matter of choice. It is a matter of taste. It is a matter of preference. It is a matter of importance. It is a matter of alchemy.

But wouldn't it be an interesting new reality in contemporary science education if average students—in partnership with their scientist teachers—could routinely perform extraordinary deeds?

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