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Every Equation Tells a Story: Using Equation Dictionaries in Introductory Geophysics

Jacqueline Caplan-Auerbach[1]

ABSTRACT

Many students view equations as a series of variables and operators into which numbers should be plugged rather than as representative of a physical process. To solve a problem they may simply look for an equation with the correct variables and assume it meets their needs, rather than selecting an equation that represents the appropriate physical process. These issues can be addressed by encouraging students to think of equations as stories, and to describe them in prose. This is the goal of the Equation Dictionary project, used in Western Washington University's introductory geophysics course. Throughout the course, students create personal dictionaries consisting of (a) the equation itself, (b) a brief description of variables, (c) a prose description of the physical process described by the equation, and (d) additional notes that help them understand the equation. In writing these definitions students learn that equations are simplified descriptions of physical processes, and that understanding the process is more useful than memorizing a sequence of variables. Dictionaries also serve as formula sheets for exams, a task that encourages students to write meaningful, organized definitions. Furthermore, instructor review of the dictionaries is an excellent way to identify student misconceptions and learn how well they understand derivations and lectures.

INTRODUCTION

"What does the variable "t" mean in this equation?" the student asked. "Is it period or travel time?"

It was a simple question, and a reasonable question for an introductory seismology class. But it made obvious the fact that this student did not understand the equation we were discussing, since in this particular problem, wave period was irrelevant. Clearly if he knew what the variable meant, he could "plug and play" and get the right answer. But this question suggested a greater problem: he did not understand the physical process described by this equation, or at least did not know how to read an equation to decipher the physics presented within it. Questions like this are common and indicate that students often approach equations as sequences of variables and operators rather than as a concise way of describing relationships between physical parameters, controlled by physical processes.

To students who have a fear of math or believe themselves to be poor students of math, equations can be intimidating and overwhelming. This fear may be enhanced by the fact that qualitative and quantitative topics are often taught very differently: we describe qualitative concepts in prose, and we provide analogies and examples. In contrast quantitative material is often presented through derivation, or as a statement of fact ("this is the equation that describes the force of gravity.") For simple quantitative problems, this type of learning may be sufficient, but as the work becomes more challenging and students are asked to do more complex analysis with multiple calculations, students often have difficulty (Kenyon, 2000). Students who are uncomfortable with math may not know how to think about quantitative processes, and may shut down during the presentation of new material, waiting for the moment when the professor draws a box around the final equation and looks up from the board with a pleased smile. This fear can be somewhat alleviated by introducing equations in a manner that is similar to how we present other coursework; that is to say, present quantitative materials in a qualitative manner as well as with traditional techniques.

The use of qualitative descriptions of equations has been suggested by other researchers. Bailey (2000) describes a "question-based approach" in which students are asked to think about quantitative processes as a class and in small groups. By questioning students about a particular topic, an instructor can coach the students to describe the process via mathematical relationship (e.g. "if this parameter increases, this parameter decreases, and thus they must be inversely related"; Dupré and Evans, 2000). Verbalization of quantitative processes is also invoked by Manduca et al. (2008) as a benefit of small group work. An additional approach is to integrate quantitative analysis into a research problem. Observing and measuring physical processes makes it easier for students to see these relationships in equations or graphs (Keller et al., 2000).

Among the natural sciences, geology is often perceived as a relatively qualitative discipline, where field and lab skills are more important than quantitative abilities (Bailey, 2000; Manduca et al., 2008). People may choose to study geology because they enjoy science but dislike math. Consequently, math fear is common among geology majors. However, quantitative analysis is a critical part of scientific study and cannot be avoided if we are to provide students with a skill set appropriate to the study of geoscience.

At Western Washington University, all geology majors are required to take Geology 352, Introduction to Geophysics. This course is a quarter-long overview of geophysical topics including seismology, magnetism, heat flow, gravity and plate tectonics. Although calculus is a prerequisite for the class, most of the material is presented using techniques of algebra, geometry and trigonometry. Other prerequisites include Physical Geology, Historical Geology and Structural Geology, as well as a quarter of calculus-based physics. While most students in Geology 352 are geology majors, the course attracts a handful of

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math or physics majors. The background of students in Geology 352 makes it an excellent environment in which to study ways of presenting equations in a manner that is palatable to students who are uncomfortable with math.

In this paper I present a method that seeks to improve student comfort with equations while also providing a study tool for exams and homework. I first discuss different methods of using equations on tests, and then describe the Equation Dictionary project. I discuss how student dictionaries provide a window into their thought processes and their understanding of course material. Although small class sizes preclude a complete statistical analysis of the dictionary's utility, student comments reveal enthusiasm for the project and suggest that it has been largely successful in alleviating math fear and helping them understand equations in geophysics.

HOW SHOULD EQUATIONS BE APPROACHED ON TESTS?

A quandary with which I have struggled in over a decade of teaching high school physics and undergraduate geophysics is what to require with respect to equations on quantitative exams. In some classes, notably high school Advanced Placement physics, I required students to memorize formulas, since they would be required to know them for the AP exam. In other situations, I allowed students to take open book exams, so that they would have access to whatever equations they needed. In yet other circumstances, I have allowed students use of a "cheat sheet" or "formula sheet" of their own making; in this paper I use these terms interchangeably. An additional option is employed by a colleague who provides her students with a handout that includes all of the equations they have used in the course thus far.

Although numerous studies have addressed the benefits of these different test-taking techniques, results are inconclusive. Dickson and Miller (2005) found that formula sheets did not result in significant improvement on upper division psychology tests, while Wachsman (2002) found a small increase in performance with their use. Hamed (2008) found that relative to open book tests, students did better on exams in which they brought in cheat sheets. Studies have also investigated the role of cheat sheets as a study tool. Trigwell (1987) found that encouraging creativity in the development of cheat sheets helped students study course material and reduced test anxiety, a conclusion supported by Wachsman (2002) and Erbe (2007). Interestingly, Dickson and Miller (2006) found that while creation of a crib sheet was not beneficial, use of a crib sheet created by a classmate resulted in improved performance on exams.

By far the most damning examination of cheat sheets is that of Rehfuss (2003). In this study, Rehfuss suggests that use of cheat sheets ignores the benefits associated with memorizing equations. He notes that formula sheets may actual discourage studying, as students believe that simply having the equations written down will be sufficient. Perhaps most importantly, Rehfuss (2003) suggests that the use of formula sheets discourages students from taking a conceptual approach to the topic. He contends that by simply writing down the equation they do not take the time to understand the physical meaning of complex mathematical symbols. In short, the jury appears to be out on the utility and benefit of cheat sheets.

To summarize, while many studies indicate that they are beneficial, the primary complaints regarding the use of formula sheets are (a) they discourage internalization of physical concepts, (b) they focus on mathematical relationships rather than conceptual processes, and (c) they may reduce the time students spend studying concepts. Thus, to be effective, a cheat sheet should encourage a conceptual approach to equations and should promote understanding of the physical processes and mathematical relationships.

THE EQUATION DICTIONARY

I propose that many of these issues can be addressed through the use of an expanded version of a formula sheet, which I call the Equation Dictionary. The Equation Dictionary not only serves as an equation cheat sheet, but it includes a prose "definition" of the equation that serves as a summary of the physical processes contained within the math. The goals of the dictionary are twofold: to provide help on exams and to guide the students in their understanding of quantitative processes. Creation of the Equation Dictionary is assigned as homework, and students are graded in part on their ability to describe, in words, the processes that underlie the math.

The Equation Dictionary is best written in table form, although some students prefer to develop their own styles. A typical entry in the Equation Dictionary contains four columns (Table 1). The first column contains the

TABLE 1. A SAMPLE DICTIONARY ENTRY FOR P-WAVE VELOCITY

Equation	Variables	Definition	Comments
$\alpha = \sqrt{\dfrac{K + \dfrac{4\mu}{3}}{\rho}}$	α = P-wave velocity (m/s) μ = shear modulus (N/m^2) K= bulk modulus (N/m^2) ρ = density (kg/m^3)	Body wave velocity is controlled by the material properties of the medium. The harder the medium is to deform, the faster the wave moves.	Note that velocity does not depend on frequency or amplitude! As density increases in Earth, so do the elastic moduli, so velocity increases.

equation itself with, where appropriate or useful, a name for the equation. Column 2 includes definitions of each of the variables. Many students chose to include units in this column as well. The third column is the meat of the dictionary. In this space students provide a prose description of the physical process represented by the equation. It is critical that students do not simply translate the variables into words (e.g. "distance equals rate times time"), but that they provide a description of process ("how far an object travels depends on how fast it is moving, and how long it is in motion"). Additional comments and hints about the equation may be included in a fourth column. This column may include reminders about when the equation is used, which variables exert the greatest influence, or in the case of a geophysics class, notes on how the equation is affected by Earth structure.

Each student creates his or her own Equation Dictionary, supplements it with new equations throughout the course, and uses it for homework and exams. At the beginning of the course, students are provided with a description of the project that includes two example entries. Throughout the course, I try to present new equations in a manner consistent with how I would like them to be presented their dictionaries so that they have a model for how to think about the physical processes. Thus when a new equation is presented or derived, I try to describe it in prose as well as mathematically. For example, in presenting the heat flux

$$Q = -k\frac{dT}{dZ}$$

equation, I might tell the class "When two places are at different temperatures, heat will flux from the warmer to the cooler region. The amount of heat depends on how steep the gradient is and how well the material conducts heat." This models the type of description that I hope they will develop in their dictionaries.

I begin with an example for the equation describing the velocity of a seismic P-wave. There a traditional formula sheet would simply write down the equation, a possible entry into an Equation Dictionary is shown in Table 1. From this entry a student can easily identify the equation for use on tests and in problem sets. The variables are defined with appropriate units, also useful for tests and homework problem sets. For students who are unsure of what elastic moduli are, a brief summary is included in the sentence describing their effect on velocity ("the harder the medium is to deform, the faster the wave moves"). In this case, the "definition" simply notes that a seismic wave moves at a speed that is solely determined by the medium. Since students often think that larger waves should travel faster, a comment correcting this misunderstanding is included as well. Finally, a comment is included that explains why both density and seismic velocity generally increase in the Earth.

In a testing situation it is likely that the student would only refer to the equation. However, should he or she need a reminder about the conditions under which the equation is used (e.g. for body waves, not surface waves), the information is available. Furthermore students have repeatedly stated that preparation of the dictionary helps solidify this material in their minds.

Two examples of student dictionary entries for the same P-wave velocity equation are shown in Table 2. The upper entry is substantially more succinct but lacks units. This student included a brief but useful description of how changes in elastic moduli in Earth affect seismic wave

TABLE 2. EXAMPLES OF STUDENT ENTRIES FOR P-WAVE VELOCITY

Equation	Variables	Definition	Comments
$\alpha = \sqrt{\frac{K + \frac{4}{3}\mu}{\rho}}$	α → P-wave velocity K → bulk modulus (resistance to squeezing) μ → shear modulus (resistance to shear deformation) ρ → density of material	P-wave velocity depends on material properties	Moves through liquid. α mostly increases until the outer core where it drops because liquid has no μ.
Body wave velocity (P) $\alpha = \sqrt{\frac{K + \frac{4}{3}\mu}{\rho}}$	$\alpha \rightarrow$ P-wave velocity (in m/s) $K \rightarrow$ bulk modulus $\mu \rightarrow$ shear modulus (both in N/m^2) $\rho \rightarrow$ density of the medium (in kg/m^3)	The velocity of P-waves depends of physical properties of the material it is going through (elastic moduli and density). Bulk modulus → if you press on it, how much will it deform. Shear modulus → if you push on it horizontally, how much will it deform.	P-waves travel slower in denser material, all other things being equal. (All other things are never equal → moduli are also higher for denser material). The velocity mostly depends on μ and K

velocity. The lower entry contains a significant amount of additional information regarding the meaning of the variables and the conditions under which P-wave velocity α changes. Although it may be too verbose for easy access on exams, it shows a detailed understanding of the physics behind the equation and the effects of different variables on seismic velocity.

As previously noted, the Equation Dictionary serves two major purposes. Its role as a formula sheet for students to use on exams and for homework has been summarized above. But a second, equally important use is as a window into student understanding of the concepts presented in class. By reviewing students' dictionaries, I can (a) check their understanding of the physical concepts, (b) identify common misconceptions resulting from my lectures or derivations, and (c) gain insight into how well the students understand how to apply equations to different problems.

STYLISTIC DIFFERENCES IN DICTIONARIES: A WINDOW INTO STUDENT THOUGHT PROCESSES

When a number of equation dictionaries are viewed side by side it is easy to see that students have very different perspectives on which equations to include in their dictionaries (a similar problem occurs on cheat sheets). Some students include equations that are actually intermediate steps in a longer derivation. Dictionaries such as these indicate that the student did not understand the goal of the derivation, an important window into how well they were able to follow the lecture.

An additional observation is that some students include several versions of a single equation while others prefer a more succinct representation of the math. This dichotomy may be analogous to the "lumpers versus splitters" model observed in genetics and taxonomy (McKusick, 1969). Some students prefer to list each variant on a process while others are clearly more comfortable with a more broad-reaching equation. Identifying which equations students felt were important provides an intriguing insight into how they view the topic and can be useful to the instructor in identifying different learning styles.

An example in which several related equations are presented is shown in Table 3, an entry addressing heat flux in oceanic lithosphere. The first equation describes the heat flux at a given depth in a cooling halfspace. The middle equation is the simplified case where z = 0 (i.e. the seafloor), and the bottom equation is a further simplified version using "standard" values for the temperature and physical properties of oceanic lithosphere. The heat flux process could be equally well represented by the top equation only. However, this entry provides a quick means by which the student can evaluate special cases. Of note, however, is the fact that this student included the three equations in a single entry, indicating that he/she understood that they were representative of a common process. In contrast, students who separated the three equations below into different entries may not have understood the relationship between those equations: that they describe the same process under increasingly specific conditions.

The lumpers and splitters often take different approaches to the section of the course devoted to gravity. After introducing the concept of gravity and Newton's Law of Universal Gravitation, we spend a significant amount of time discussing how gravity is used in geophysical studies of the shallow subsurface. We first discuss the effects of Earth's shape and rotation on g, the acceleration due to gravity. Next, we discuss the Free Air and Bouguer corrections, and how these are used to determine the expected value of gravity in a given location. Thus students are exposed to a large number of equations: the acceleration due to gravity, the acceleration due to gravity on a rotating ellipsoid, the Free Air and Bouguer corrections and the Free Air and Bouguer anomalies. In their dictionaries, some students used up to 10 entries to describe the gravity relationships while others expressed them as a combined entry.

The student dictionaries presented in Tables 4 and 5 both show equations used to calculate the Free Air anomaly. The student who wrote the dictionary shown in Table 4 combined numerous equations into a succinct entry. Presumably this student understands that if there is no elevation correction, h, and hence the Free Air correction, is equal to zero. In contrast, the dictionary in Table 5 separates the Free Air equations into three entries and does not use consistent terminology between them (g and FA_{corr} are synonymous in this dictionary). In this case, the equations may be too completely split, as it is more difficult to see the linkage between correction and anomaly. Note too that the single row in Table 4 also

TABLE 3. A STUDENT ENTRY FOR LITHOSPHERIC HEAT FLUX

Equation	Variables	Definition	Comments
$Q = \frac{-kT_a}{\sqrt{\kappa \pi t}} e^{z^2/4\kappa t}$ $Q = \frac{-kT_a}{\sqrt{\kappa \pi}} \frac{1}{\sqrt{t}}$ $Q = -1.8x10^{-6} \frac{1}{\sqrt{t}}$	Q = heat flux (W/m^2) T_a = asthenosphere temperature (^{o}C) k = thermal conductivity (W/m^{o}C) κ = thermal diffusivity (m^2/s) t = time (s)	Heat fluxes upward (negative direction) from a cooling halfspace (oceanic lithosphere). At the seafloor (z=0), heat flux is a function of the square root of time.	For "standard" values of oceanic lithosphere, can use the bottom equation.

TABLE 4. EXAMPLE OF A "LUMPER": A STUDENT ENTRY FOR GRAVITY ANOMALIES

Equation	Variables	Definition	Comments
$g_{anomaly} = g_{obs} - g(\lambda) + FA_{corr} - B_{corr}$ $g(\lambda) = g_{eq}(1 + \alpha \sin^2 \lambda + \beta \sin^4 \lambda)$ $FA_{corr} = 0.3086h$ $B_{corr} = 2G\pi\rho h$	g_{anom} = gravity anomaly. g_{obs} = observed (measured) value of g $g(\lambda)$ = expected value of g at latitude λ h = elevation (m)	Correcting for the shape and rotation of Earth ($g(\lambda)$) and the effects of topography (FA and Bouguer corrections) yields an expected value for g. A difference between observed and expected g indicates a subsurface gravity (density) anomaly	Pay attention to units! FA_{corr} is in mgal/m, B_{corr} is in m/s^2!

includes the Bouguer correction, whereas the student who wrote Table 5 used two more entries (not shown) to incorporate that additional term. These examples suggest that while it can be beneficial to split an equation into its requisite parts, it is critical to identify linkages between processes. Following identification of these issues the instructor may then choose to stress with the student, or with the class as a whole, the connections between different equations.

Neither the lumping nor the splitting techniques is fundamentally advantageous or problematic. A student who writes too few equations may give him/herself more work than is necessary, particularly in an exam context when time is limited. In contrast a dictionary with too many equations (e.g. Table 5) may overwhelm the student as he/she tries to identify the appropriate one to use for problem solving. Students should therefore be encouraged to find a happy medium in which equations are clearly presented with a minimum of repetition.

IDENTIFYING STUDENT MISCONCEPTIONS

In virtually any class, one of the great challenges to the instructor is identifying what students do not understand. A student may do poorly on a question because he or she did not understand the question, did not understand how to solve it, or made a simple calculation error. If the student is to learn from his or her mistakes, the cause of the trouble needs to be clearly identified. This is particularly true for coursework that builds on earlier material, or if the same type of problem will be addressed again.

The Equation Dictionary is an excellent means by

TABLE 5. EXAMPLE OF EXCESSIVE "SPLITTING": A STUDENT ENTRY FOR GRAVITY ANOMALIES

Equation	Variables	Definition	Comments
$g(\lambda) = g_{eq}(1 + \alpha \sin^2 \lambda + \beta \sin^4 \lambda)$	g_{eq} = 978.03185 Gal (cm/s^2) α = 5.2789 x 10^{-3} β = 2.3462 x 10^{-5}	Gravity at latitude corrected for spin and latitude.	
$g = h(0.3086x10^{-3})gal/m$ Free air correction	h = elevation from sea level (2g/r) = 0.3086 x 10^{-3} gal/m	Correction for gravity at elevation a above or below sea level	
$g_{FA} = g(\lambda) \pm FA_{corr}$ Gravity corrected for elevation	g_{FA} = gravity at latitude corrected for elevation	Gravity at latitude is for mean sea level; this corrects for measurements closer or further from center of earth	- above sea level + below sea level (gravity is greater nearer center)
$g_{FAA} = g_{obs} - g(\lambda) + FA_{corr}$ Free air anomaly	$g_{observed}$-g_{FA}	The anomaly is the difference between expected elevation-corrected gravity and observed gravity	

TABLE 6. ENTRY WITH AN INCORRECT DEFINITION

Equation	Variables	Definition	Comments
$\sin\theta_c = \frac{v_1}{v_2}\sin(90^o)$	θ_c: critical angle v_1: velocity of wave in layer 1 v_2: velocity of wave in layer 2	Calculates critical angle, which is the angle at which a seismic wave refracts to bounce back up to the surface. This is the first wave that will hit a geophone	

which student misconceptions may be identified. An error in an individual's dictionary indicates a single person's misunderstanding of course material. An error or misinterpretation in multiple dictionaries may reflect the fact that a topic was not sufficiently explained by the instructor. Because students must describe their understanding of the utility of a given equation, these misconceptions may be easily identified before the student is asked to apply their knowledge on an exam and may explain errors on homework assignments.

An example of a student's dictionary entry in which a misconception is evident is shown in Table 6. In this example, from the seismic refraction portion of the course, the student presents Snell's law but misunderstands the meaning of the critical angle. Although the student is correct that the first arriving "refraction" reflects at the critical angle, he/she confuses that term with the critical distance (the minimum source-receiver distance required to record a refracted arrival). Review of the student's dictionary made it clear that the student was having difficulty visualizing the path that reflected and refracted waves take in a two-layer system. In this case a recommendation was made that the student add a sketch to the dictionary to better distinguish between reflected and refracted waves and their travel paths.

In a second example (Table 7), the student's definition indicates a misunderstanding of the relationship between elastic moduli and density (furthermore, the definition does not describe the physical process contained in the equation, so the text would have been more appropriate as a comment rather than a definition). Given class discussion about this equation, and by comparing this student's interpretations with those of other students in the class, it became evident that the student was confused by the effect of density on seismic velocity. It is likely that the student was trying to explain the fact that changes in density are also accompanied by changes in elastic moduli (hence, despite the inverse correlation, velocity usually increases as density increases). However, the written definition indicates that the student's understanding of this process was weak. Happily, it was possible to identify this misunderstanding in the dictionary so that the student could address it before being tested on the topic.

STUDENT RESPONSES

Students had two opportunities to discuss their experience with and thoughts about the Equation Dictionary. First, students were asked to specifically address the topic in their mandatory end of the quarter course evaluation forms. These anonymous forms include a numerical response sheet and a page for written comments. Secondly, students were asked via email to voluntarily provide additional thoughts about the dictionary. Because the email responses were not anonymous, they contained predominantly positive comments. Thus the course evaluations are likely a more accurate reflection of students' thoughts on the dictionary assignment.

Overall, student responses were quite positive. Of 52 students who returned the anonymous course evaluation forms, 31 had exclusively positive comments about the dictionary project. Nine students provided responses that were neutral; of these nine, seven included both positive and negative comments and two were neutral as to the benefits or disadvantages of the assignment. Only a single student stated a clear dislike of the project, calling it "busy work" and "pointless." The remaining 11 evaluation forms did not comment on the dictionary project. Because of the low number of students enrolled in my section of Introduction to Geophysics (~20 per year), no formal statistics were applied to these evaluations.

In their evaluations and emails, students indicated that they found the dictionary to be an excellent study aid and noted that putting together the dictionary was a critical part of their test preparation. "The equation dictionary worked perfectly. Usually just taking the time to write it was enough to know most of it" reported one student, while another stated "Just typing it out aids in the understanding of the equations and concepts, and it's really nice to not have to waste time memorizing

TABLE 7. INCORRECT DESCRIPTION OF THE EFFECTS OF DENSITY

Equation	Variables	Definition	Comments
$\alpha = \sqrt{\frac{K + \frac{4}{3}\mu}{\rho}}$	μ: shear modulus K: bulk modulus ρ: density	P-wave velocity equation, when the density changes the μ will also to maintain balance.	

equations." Many comments centered on how it helped them with organization of their notes and thoughts, both of which were critical in success on tests. According to one student, "The Equation Dictionary was essential to my success in your class. It was a perfect study aid; way better than any notes I would have made on my own. It provided an opportunity for the slightly scatter-brained student to organize equations, notes and little hints in a reliable and easy-to-read manner." Others focused their comments on the fact that the dictionary helped them understand the meaning behind the equations. "Making the dictionary forced me to really understand what each equation and each variable means", one student wrote. "Without it, I might have been a little lazier and simply memorize the equations, but since we could use it on tests, I had no need to memorize anything, just understand. That really worked for me." Also, as noted by Wachsman (2002) and Erbe (2007), many students commented that having the dictionary in hand dramatically reduced their test anxiety.

There were a number of concerns brought up in these evaluations as well. A common complaint centered on how the dictionaries were graded. Students felt that since the purpose of the dictionary was to help them understand the equations, anything that worked for them should have been sufficient. As one student wrote, "I felt like the Equation Dictionary was for us and that we should write it in a way that we would understand. When you graded it, it seemed that it had to be a certain way. I would suggest that you…just give credit for doing it and getting it in." This complaint suggests that the second goal of the dictionary project, as a means by which students would demonstrate their understanding of concepts, was not always clear to the students. Instead they viewed the dictionary as an expanded personal formula sheet.

Other students were frustrated because I did not catch all of the errors in their dictionaries, and this caused some of them to make mistakes on the exam. Similarly, students sometimes neglected to include equations that were required in exam problems and were upset that my review of their dictionaries did not identify all missing equations. I first addressed this by reminding students that it is their responsibility to ensure that the equations are written correctly. However, this could also be addressed by assigning equations to be included in the dictionary or providing students with a list of recommended equations prior to exams. Assigning a few specific equations with each homework, rather than as a separate project, would also address the concerns of students who felt that the dictionary took too long to write (these students may have put the dictionary together immediately prior to its due date, rather than creating it gradually as equations were introduced).

Several of the students described the dictionary as "busy work" and indicated they would have been just as happy with a standard formula sheet. Interestingly, most of these students also described themselves as "math-oriented", suggesting that perhaps they already internalize the meaning of the equation and did not benefit from the exercise of writing it out. The comments of students who are comfortable with math are of particular interest because it is likely that professors teaching quantitative processes are themselves "math-oriented". Those of us who already translate equations into processes out of habit may not recognize that this trait is not common to all students, and that many students are just learning how to think about mathematical processes (Guertin, 2000). These student comments illuminate the need to define the project, and the criteria for grading, carefully and clearly. It is critical that students understand that their dictionary entries must demonstrate an understanding of the processes that underlie the equations. Instructors using a technique such as this should carefully explain their grading criteria and should consider what to do if a student neglects to include an important equation in their dictionary.

CHALLENGES FOR THE INSTRUCTOR

While I have been pleased with the students' responses to the dictionary, I have found that the project involves a host of challenges for the instructor as well. As reflected by student comments, a major challenge is how to grade the assignment. On the one hand, the dictionary is a means by which student understanding of physical processes may be evaluated. However, the dictionary is also a tool for students to use on homework and exams, and needs to be written in a way that is useful to them. In my geophysics course, criteria used to evaluate the dictionaries include completeness, organization and most importantly, how well students explain the process represented by the equation. However, I allow for a wide range of styles, and try not to deduct points for simple misunderstandings. The dictionary grade makes up only 5% of the student's term grade, so it is a minor contribution to their final percentage. Grading the dictionaries is a tedious and time-consuming process that may be mitigated by requiring students to turn in their dictionaries on a weekly basis when only a few new equations have been introduced.

An additional issue is that of students who fail to turn in their dictionaries. This means that some students' formula sheets are not reviewed prior to the exam. Because there are certain things that I do not allow to be included in formula sheets (e.g. example problems), students who did not turn in dictionaries were required to turn in their formula sheets with their exams. However, these sheets were not graded.

Finally, in one class I found that a number of students had simply copied equations from students who took the class the previous year. Not only is this an obvious violation of academic honesty, it means that the students did not earn the benefit of creating the dictionary themselves. Perhaps not surprisingly, of all of the classes in which I have required use of the dictionary, students in that class expressed the most dissatisfaction with the project. This type of cheating could be mitigated by requiring that students write their dictionaries by hand, but this is non-ideal, as digital dictionaries are easier to organize and grade. A possible solution is to have the students work on their dictionaries in small groups during class time. Small group work can both discourage cheating and encourage discussion of the physical processes.

CONCLUSIONS

While there has been no formal statistical study of the relative utility of the dictionary over standard formula sheets, student comments indicate that their experience of the Equation Dictionary has been overwhelmingly positive. Describing equations in prose helps students put equations in a physical context and helps them investigate the relationship between variables. The dictionary serves as a study guide, organizational tool, and exam formula sheet. It also provides a window into how students think about physical and mathematical concepts and can help illuminate student misunderstandings. Preliminary and informal evaluations of the project suggest it is successful, but more formal study is required to properly determine its effectiveness as a learning tool.

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