Explaining Education to Engineers: Feedback Control Theory as a Metaphor

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Abstract - **One of the barriers for engaging engineering faculty in the scholarship of learning and teaching is the challenge of learning a new vocabulary. Becoming fluent in engineering education requires the acquisition of new concepts and ideas that are often expressed in unfamiliar terms. Feedback control is a technical field common to a range of engineering disciplines that can be used as a model to help bridge the conceptual gap between traditional engineering and engineering education. Many of the key elements of engineering education can be represented by the elements of a feedback control system, with their behaviour in a learning environment paralleling their behaviour in a process control context. The feedback control model can be used to explain: the importance of timely feedback to students, the significance of assessment and evaluation in the learning process, the impact of learning styles upon learning outcomes, and the need for student-centered teaching approaches. While both fields have complexities that cannot be captured by simple models, the basic ideas can be explained simply. Feedback control metaphors make the basics accessible to a wider audience of engineering faculty.**

Index Terms – Feedback Control, Formative Assessment, Summative Assessment, Program Evaluation

INTRODUCTION

Despite the fact that almost all engineering faculty teach, the vast majority have formal training in an engineering discipline rather than engineering education. These faculty members often lack a fundamental conception of the assumptions, beliefs, and foundational concepts of engineering education. In the engineering education literature concepts such as assessment and evaluation are key to understanding the field, forming the language and structure of the discipline of engineering education. Communication with colleagues focused on technical engineering disciplines can be hampered when education-specific terminology is used. Such breakdown in communications can lead not only to a lack of understanding of how students learn, but an active disdain of engineering education as “fuzzy studies”.

Could communication be improved if technically trained engineers had a better understanding of how engineering educators viewed and approached their discipline? It is possible that such understanding can be built by finding a common language that engineers, whether technically or education focused, can share? Due to the overlap between engineering education and education, sociology, and psychology, engineering education will, for the foreseeable future, need to keep a specialized jargon that describes concepts unequivocally. However by making analogies with concepts well understood by engineers across multiple disciplines, the communication barrier can be lowered.

This paper presents a set of analogies between ideas common to engineering education and ideas of control theory. Control theory is common to most engineering disciplines, and chemical, electrical, and mechanical engineers are particularly well versed in these ideas. Control theory additionally has developed a set of schematic diagrams where different parts of a system are broken down into functional units, and the behavior can be understood, at least in a global sense, by a relatively simple diagram. The remainder of this paper examines specific, and basic, concepts of control theory, and in each case makes an analogy with assessing and improving student learning. In each case well-known, textbook behaviors of systems are explored and similarities between the predictions of control theory and assessment of learning objectives are made.

This paper does not claim to make an exact match between engineering systems and students nor claim that all results of control theory have a matching analog in engineering education. Rather by offering analogies, or perhaps “technical parables”, it is hoped that the communication toolbox of the engineering educator can be improved. The remainder of the paper explores both open and closed loop control analogies. A set of short vignettes is presented covering examples of increasing sophistication in control and education. The vignettes are sequential in that each adds an additional element to improve the process outcome, at the cost of complexity. The goal of a series of vignettes is to assist faculty whose background is primarily engineering take the “next step” in improving course outcomes.

THE OPEN LOOP MODEL

Perhaps the most fundamental control system is the “open-loop” model. In control theory open loop systems are used when the system to be controlled is well defined. Examples of open-loop control systems are toasters or washing machines. Although the process can be adjusted (toast darkness or type and duration of wash cycle), there is no way, once the process is started, to change the outcomes without operator intervention.

The open-loop model is also one traditional model of education, shown (from the teacher perspective) in figure 1(a). In this model information is the input to the system, the instructor serves as the system which acts on the knowledge, and a lesson is the output from the system. Once the lecture reaches the student it is assumed that they will learn the material.

A more accurate depiction of traditional lecture is shown in figure 1(b). Here the inputs to the system are the course content (information) and learning objectives. These inputs are first acted on by the instructor to produce a set of lessons which then serve as input to the student, resulting in learning. In this model the student is herself treated as a system which acts on the lessons to produce learning. The student system can often be imperfect and lossy, with students either not learning, or learning the wrong things. These losses can be exaggerated when students view the output of the process to be grades, rather than learning; this will be discussed subsequently.

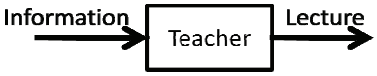

FIGURE 1(A): THE SIMPLEST CASE OPEN-LOOP CASE OF TEACHING WHERE AN INSTRUCTOR ACTS ON INFORMATION WHICH IS THEN TRANSMITTED TO STUDENTS.

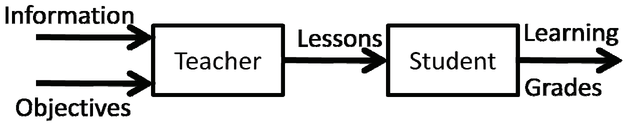

FIGURE 1(B): AN OPEN LOOP MODEL IN WHICH BOTH THE INSTRUCTOR AND STUDENTS AFFECT WHAT IS LEARNED.

This system is easily understood and is likely the mental model that many faculty members have of learning. Despite its simplicity, there are several valuable pedagogical lessons to be drawn from this system. Firstly, it is often assumed that there is little impedance mismatch between the output of the instructor and input of the student so the "knowledge transfer coefficient" is high. This is not always easy to achieve, as it takes an experienced instructor to craft lessons that can be efficiently accepted as input by the student. Secondly, this model treats the students generically. It is assumed that one "Student" block can be substituted for any other. Clearly this is not the case, and the conversion of lessons to learning is highly student dependent.

Although the assumptions inherent to the open loop model may potentially undermine its effectiveness, it is not without its advantages. Firstly, the open loop model is easy to implement, requiring a minimum of faculty time and/or overhead. Secondly, the open-loop model of teaching can be effective in practice-based activities such as learning multiplication tables. In these cases the process is of value to the students rather than just the outcome. As long as students perform the exercise correctly they learn.

FEEDBACK

In most education and process control systems some measure of quality control is implemented; most instructors need to both teach and assign grades. In the simplest case such quality control consists of examining the output of the process to ensure that what was created is what is desired. In the toaster example of an open loop control system, the hungry breakfaster changes the toaster setting depending on their desire for warm bread, crunchy golden-brown toast, or a charred smoking lump. The educational equivalent of checking the toast is summative assessment. Summative assessment is intended only to determine whether or not students have met the learning outcomes [1].

Summative assessment often takes the form of a final examination, which students complete, have marked, but just get back as a single number. Good examinations are difficult to write – it is a challenge to develop an assessment that accurately reflects what the students have learned, rather than being confounded by their ability to correctly interpret the question and cope with the stress of the examination context.

Assessment instruments play the part of the sensors in the learning control system, and they are subject to the same demands as sensors in a physical control system. In order to be effective, a sensor must be accurate – the measurement it reports must be close to the true value of the quantity being measured. A sensor must also be repeatable – separate measurements of unchanged conditions must return the same results. If a sensor cannot provide reliable information about the process, then the controller will make its decisions on wrong information, which will most likely lead to wrong decisions.

The difficulty comes from the impossibility of directly measuring student learning – instead learning has to be inferred from a proxy measure, such as answers to examination questions. The control theory analogy is estimator observer control [2]. In estimator observer control, a physical quantity is not measured, but rather inferred from observing some other quantity. The control system then uses those observations to estimate the variable in question. One example of such is the estimation of humidity through the observation of wet- and dry-bulb temperature measurements; another example is the estimation of the forces applied to a piezoelectric accelerometer by observing the electric current it generates. In both estimator observer control and writing exams, the goal is to make the relationship (transfer function) between the quantity observed and the quantity estimated to be as direct (close to unity) as possible. Since an estimator observer is itself a control system, it needs to meet certain characteristics to be effective—e.g. fast response time, sufficient dynamic range—and may itself impact the system response. In an education context a poorly designed exam provides little information on what students have learned and may introduce misconceptions.

Open-loop control with a summative observer is fine for a toaster – the cost of a poorly-cooked slice of toast is very small. However in education "poorly-cooked" students have not mastered material, and this has lasting effects. While a good final examination gives an accurate measure of what students have or haven't learned, it will not change the fact that they have or haven't learned – and by then it may be too late to redress the situation.

CLOSED LOOP MODELS

A more effective strategy in both process control and education is to take measurements as the process takes place, and to interactively adapt the process. This is the closed loop approach to control, as shown in figure 2. In the educational context, these measurements are formative assessment – assessment that is intended to assist students to learn by identifying what they do and do not understand.

This section explores analogies between control closed system control engineering and effective teaching, with a focus on creating analogies rather than making direct one-to-one comparisons to help engineering education faculty explain good assessment practices to colleagues.

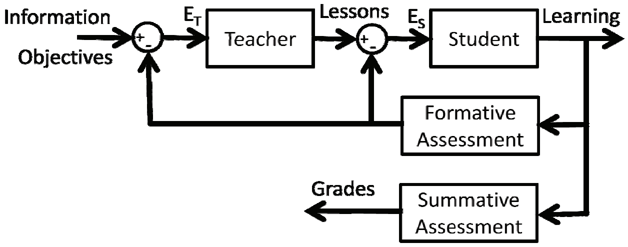

FIGURE 2: CONTROL SYSTEM DIAGRAM OF A COURSE THAT INCLUDES BOTH FORMATIVE AND SUMMATIVE ASSESSMENT.

As shown in Figure 2, formative assessment provides feedback both to the student and teacher. What form is this feedback and how does it affect the operation of the system? To understand this system it is necessary to look at the "signals" that control the process. The most important of these is the output. Unlike industrial processes where outputs are objectively measurable, in education the output is more subjective. Different students or instructors may use different criteria to judge the output of the learning process; i.e. students may focus on grades rather than learning while instructors are generally more interested in how much students learn. It is also important to note that motivation [3], or the importance an instructor or student places on the output, determines how much energy can be expended to correct the process; i.e. the gain available.

To judge the state of the output, both students and teachers use information generated by the process (course). For many instructors and students this information is in the form of grades; these can be letter grades, but are more commonly points which are used to determine an overall grade at the end of the course. However other types of information can also serve as process feedback signals including student metacognition [4], verbal or written feedback on assignments, or discussions with peers.

Based on the difference between the feedback signal and the desired outcome, both instructors and students expend effort to get the outcome to match the goals. For the instructor the goal is for students to master content and meet objectives, for the students the goal is generally to make their learning match the lesson. Usually neither is completely successful; in control terminology there is an error signal for both the teacher, E_T, and student, E_S, which influences system response as shown in Figure 2. This error signal depends on both formative and summative assessment. The instructor uses E_T to modify lessons to better match content and objectives while the students use E_S to influence how they approach the lessons in order to maximize learning and/or grades.

There are strong similarities between effective control systems and effective teaching which offer lessons to technically-oriented colleagues. Both the education and the control literature agree that to be effective, feedback needs to be provided as quickly as possible [2]. Control systems with faster feedback loops are more stable; students who receive feedback sooner learn better. If a physical system has moved since the measurements were taken, then the response is being calculated for a previous position, not the current position. Feedback becomes useless if there is too much lag and may even drive a system into instability; the lag must be short compared to the response time of the closed loop system. Such fast response time is nearly impossible to achieve in traditional assignments, but is possible through active learning or computer-based learning. Similar lessons can be drawn from the required frequency of sampling – fast sampling is required for stable control.

Another lesson from control theory is that the effectiveness of the control depends on the available gain; effective control requires high gain. The gain depends both on the motivation of students as discussed previously, and how the usefully the feedback is presented. Thus formative assessment may not have much impact for unmotivated students or when the feedback is simply a score rather than advice on how to improve performance [5].

Another analogy between control systems and engineering education is the importance of error terms - the discrepancy between the actual output and the desired output. In control systems common types of errors are response time, settling time, overshoot, and steady state error. The first three are measures of the dynamic responses of a system to a step function input.

A step function manifests as a sudden change in the learning environment, such as a surprise announcement by the instructor that "students need to know chapter nine for the exam next week." The students' responses will be characterized by features such as late night cramming to learn as much material as quickly as possible (response time), the amount forgotten between putting down the books and taking the exam (settling time), and how much unnecessary effort is put into learning chapter nine based on it perceived importance on the test (overshoot). The time it takes students to respond is critically important, particularly when students have high workloads. If an instructor does not allow sufficient time for students to learn the material the dynamic errors can be large.

The steady state error on the other hand is the difference between the desired and actual steady state response of the system. In education this corresponds to the learning that is retained following completion of the class; i.e. knowledge that can be transferred to closely related problems [4]. Arguably this is one of the most important outcomes of a course, but the discrete course structure of university degree programs makes steady state error difficult to measure. Increasingly external assessment provides the mechanism to eliminate steady state error; an example is ABET's requirement to assess both short term learning outcomes and long term objectives to help programs measure steady state error.

In summary, for effective learning, instructors need to minimize the error term, E_T, in Figure 2. What this means from a practical standpoint is that the input to the process of creating classroom lessons is not "what should they learn", but rather "what do they not understand?" Good instructors measure both how fast students are learning to minimize dynamic errors, but also how well they retain what they learn over the long term. They motivate students to maximize the available gain of the feedback mechanism, strive to create assessment with unity transfer function to align goals and learning, and ensure students get feedback on a time scale that is much faster than the course introduces new concepts.

NESTED LOOPS AND PRIOR KNOWLEDGE

While the discussion above applies to individual instructors and courses, an educational system is in fact a network of nested layers. Each lecture fits within a week of semester, each week fits within the semester long unit, each semester long unit fits within a degree and so forth. The open-loop lecturer who uses only a final exam to assess learning will change their lesson plans for the following year to address areas that were not learned well; however they will not know if these have been successful until the next examination is completed. Similarly, if the department chooses to replace one faculty member with another, it may take multiple years to determine if the change has been truly effective, particularly if the change occurs early in the program.

Figure 3 expands figure 2 to show how prior knowledge impacts upon the current learning experience, affecting both the input and the error term of the model. The term prior knowledge includes both what has been previously taught in the instructor's course as well as what has, or has not, been taught in prerequisite courses.

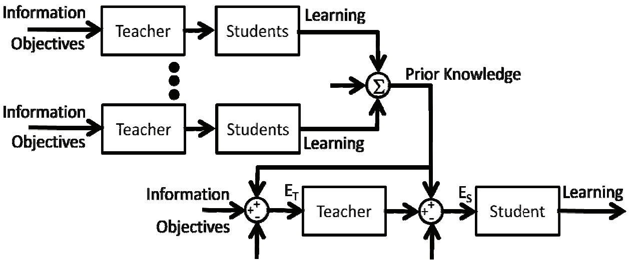

FIGURE 3: COURSES NEED TO CONSIDER THE PRIOR KNOWLEDGE POSSESSED BY STUDENTS AND IMPARTED BY THE PROGRAM AS CONTRIBUTING TO THE ERROR TERMS.

Not shown in the diagram is the fact that each of the inputs to the summation block for prior knowledge itself depends on what students already know. As mentioned in the previous section, it is difficult to measure steady state error, and thus difficult for most instructors to adequately compensate for prior knowledge. This situation can be compounded if program level assessment is not performed or not communicated to faculty. Good instructors thus often assess requisite knowledge at the start of their course.

THE VECTOR PROBLEM

The use of formative assessment to provide feedback has been demonstrated improve both students' performance and their ability to achieve learning outcomes [4, 6]. The difficulty for the academic, however, is that usually they are responsible for teaching multiple students, rather than just one. This transforms the problem from a scalar problem to a vector problem, requiring more complex approaches.

Different physical plants respond differently to the same control signals; so too do different students respond differently to the same lesson, as illustrated in Figure 4. Unless the students are identical in their approaches to learning, the outcomes of the learning process will be different. To understand the dynamics of multiple students in this model, it is useful to adopt a signal processing perspective for the feedback control.

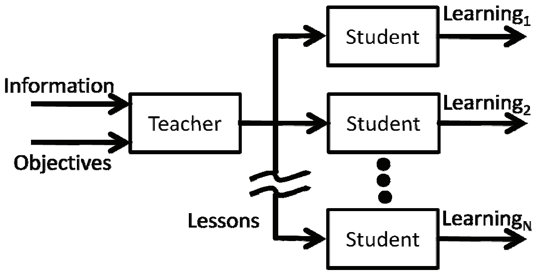

FIGURE 4: THE INSTRUCTOR NEEDS TO CONSIDER MULTIPLE STUDENTS IN A CLASS, EACH OF WHOM WILL CONVERT THE LESSON TO LEARNING IN THEIR OWN FASHION.

One possible model for representing students is to consider them as proportional integral derivative (PID) controllers. Different students exhibit different gain coefficients and thus different responses to feedback. Some students are predominately proportional controllers, the effort they expend depends on how closely the student's goals match what being learned at that moment in time. Proportional controllers can respond quickly but suffer from overshoot. Other students, often high performers, are driven by the derivative. Their efforts are proportional to how much they perceive their grade is going up or down. Derivative controllers are not as sensitive to overshoot, but take longer to respond and are sensitive to noise and rapid changes in state. Other students are integral controllers, their effort is related to how well learning is converging to their overall course goal. Integral controllers minimize steady state error but may take a long time to settle. Ideally students develop metacognition to choose a response strategy that is most effective. Similar analogies to PID controllers can be made for instructors and program assessment.

An alternative representation of students is to model them as filters. A filter takes a signal and may amplify some inputs, attenuate others, or let others signals pass through unchanged. In this regard students either extend their knowledge beyond the lesson by reading on their own, learning a fraction of what they need, or mastering the material presented by the instructor. If the instructor relies upon only one type of lesson then only the students with a particular filter transfer function will effectively convert these lessons into learning. Other students will instead attenuate these signals, and not learn the material.

In order to provide each student with the ideal learning environment, it would be necessary to tailor the lessons to exactly meet their learning style – to make the transfer function of the instruction to be the inverse of that of the student model. Each student will have a different ideal form of instruction, making it impossible to apply a single uniform solution that is ideal for all,. While ideal results for all are impossible, there are similarities in approach that can be exploited to optimize information transfer.

In the control system analogy, some form of addressing is often used to multiplex signals to a destination that can optimally receive them. In education, effective instructors use multiple pedagogies to multiplex the signal (Figure 5) and thus address individual learning styles. Multiple approaches such as lectures, active learning, labs, and on-line course material are superimposed so students can attenuate approaches that do not work for them, and amplify ones that do.

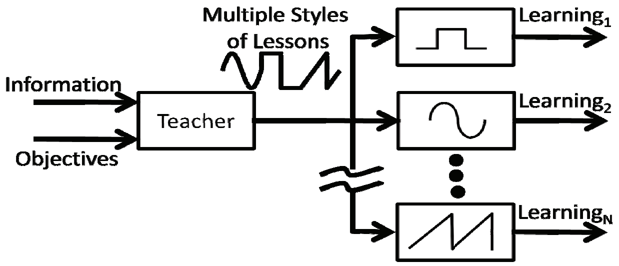

FIGURE 5: DIFFERENT TEACHING STYLES CORRESPOND TO MULTIPLEXING THE SIGNAL TO SYSTEMS THAT RESPOND DIFFERENTLY..

In the education literature this is often refered to as student-centered learning [4]. In the prevalent model of higher education it is not possible to design an optimal input for every individual student, thus the instructor essentially superimposes multiple signals to minimize the overall error function. Unfortunately, many academics continue to teach the way they themselves were taught (and learned) despite the fact that for many academics both the discipline and society have changed since they attended the university. This situation is exacerbated since the kinds of students that go on to become academics are usually not representative of the overall student cohort. They have different learning styles, learning skills and motivations. As such, what works for that part of the cohort will not necessarily work for the whole of the student body and vice versa. Instructors must actively work to tune their output to maximize transfer in the student system between lessons and learning.

NONLINEAR MODELS: ADAPTIVE CONTROL

In the process and system control field many types of systems have parameters that change slowly with time; for example a significant proportion of an aircraft's takeoff weight is fuel which is lost throughout the flight. These types of systems use adaptive control, where the control algorithms adapt over time. Many instructors, however, believe that once a course is developed they will get the same outcomes repeatedly despite the fact that the system input (goals and content), teaching models, and the students are in a state of constant change. To take an industrial process, change the type of desired outcomes, change the type of materials it operates upon, leave the control system unchanged and then expect the same outcome is unrealistic. For the same reasons, teaching methods must evolve over time.

There are several types of changes that instructors need to adapt to as each element of the student-instructor-program system evolves dynamically over time. First, and likely simplest for technical faculty, is adaptation to changes in the nature of the discipline and the needs of a 21st century workforce. Second, and more problematic for most faculty, is the fact that students are changing. As discussed previously, the teaching approaches that faculty remember working for them–and as such are intuitively most likely to want to replicate–will not necessarily work for their students. Third, and on a shorter time scale, are the changes that occur in students as they develop as engineers as the result of a successful course or program. Most instructors account for students' increased knowledge, but changes in students' motivation, affect, or technical abilities may not be as easy to quantify or adjust to.

In control theory much of the work in adaptive control theory attempts to make the response of the non-linear system linear within given constraints. Much the same is done in education through the process of accreditation and program review. Control theory clearly shows that a changed set-point and a changed plant require a changed controller; similarly new learning objectives and a new cohort will require new instructional methods. Year-by-year, each of these changes is likely to be relatively small. This year's cohort is much the same as last year's; the equipment has not become obsolete in twelve months. The system remains predominately linear. But over time these gradual changes will add up, and the set-points of the feedback system will need to change. Ultimately it is the process of self-reflection, such as occurs during external program accreditation, that serves to provide a mechanism of adaptive control to keep the program up-to-date with changes. One caveat is that is not only necessary to evaluate programs, but faculty need also to use the results of program evaluation in their teaching.

CONCLUSIONS

This paper presents feedback control as an analogy for the student learning process. This analogy allows for a number of key themes in engineering education to be presented in a format that a wide range of engineering faculty find familiar. Like any analogy, this model will break down if taken to extremes; it would be dangerous to try to quantify the response of the system given the current state of understanding of how students learn. However, the analogies between engineering education and control theory may be useful to make the following concepts clear to technical colleagues:

- The significance of assessment and evaluation in the learning process;
- The need for student-centered teaching approaches;
- The impact of learning styles upon learning outcomes;
- The importance of timely feedback to students.

The feedback control analogy presented in this paper has been built on simple, linear models. As with any system, this assumption allows for the simplicity necessary for understanding the results. Since the goal of a university program is technical and personal development, it is also necessary to consider students and the discipline as changing in time, or being fundamentally non-linear. These changes may occur rapidly and are forced, in part, by universities. Thus good teaching doesn't just adapt to the students, it changes the students. As the students acquire lifelong learning skills–gaining new filters with which to learn–the way in which they learn will evolve. Accounting for these changes requires a more sophisticated feedback control model. Such non-linear control models do exist, and it may be worth looking into lessons from control theory to expand the toolbox of program evaluators.

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