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To Err is Human: Defining Engineering Judgment Through the Philosophy of Bernard Lonergan

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Abstract

Engineering judgment has long been recognized as a crucial professional skill. Recent efforts have focused on defining judgment and assessing student achievement on judgment-eliciting tasks; however, much more work is needed to thoroughly understand this complex capability. This paper will advance understanding of engineering judgment in two ways. First, Bernard Lonergan's philosophy from his book *Insight* will be used to articulate a clarified account of engineering judgment that deepens and philosophically grounds existing definitions. For Lonergan, judgment is a personal commitment, reached through reflection, which affirms or denies a truth claim. Second, Lonergan's framework is applied to interpret student data from a series of judgment-eliciting laboratories. This analysis applies his account of cognitive bias to diagnose systematic limitations in students' engagement with judgment-based tasks.

Introduction

Engineering failures are often attributed to limited information, unanticipated factors, or even negligence, but Henry Petroski argues that this view of failure is incomplete. He holds that "possibly the greatest tragedy underlying design errors and the resultant failures is that many of them do indeed seem to be avoidable." [1, p. ix] He gives prominent historical examples which show that failures are often better understood as failures of judgment—failures where engineers had access to the resources they needed but still did not reach sound conclusions. For this reason, judgment is not a peripheral skill in engineering practice, but if Petroski is correct, it is "the first and most indispensable design tool." [1, p. 121]

If, as has been argued [2], judgment is essential to engineering practice, it follows that it should also be a central aim of engineering education. In recent years, this view has gained traction. Judgment appears as a goal in higher-education assessment more broadly [3] and in the current ABET accreditation criteria [4]. Engineering educators increasingly incorporate open-ended problems to elicit student judgment, yet several studies have reported low levels of student engagement [4] and student resistance [5].

Current efforts to emphasize judgment coincide with a broader shift in student abilities as perceived by some faculty. A concern has been raised about students' ability to perform basic judgments on well-structured tasks as seen by increasing incidences of questions like "What does this word mean?" and "What is this sentence saying?" [6] If students have difficulty meeting well-structured expectations, it is reasonable to ask whether focusing on higher-level abilities like judgment is premature. Even if this perceived shift in student ability is not ultimately accurate, the question remains whether engineering judgment is an appropriate expectation at the undergraduate level.

It is sometimes suggested that judgment develops primarily through professional experience, and that undergraduate education should focus on foundational knowledge and procedures. This view is seen in the seminal Grinter Report which argues that "the ability to deal effectively with such broad issues comes only with experience and maturity in the years after college" [7, p. 5]. There is truth in this view. Certain forms of engineering judgment, such as anticipating failure modes or balancing competing design constraints, do depend on extended experience. However, this perspective risks overlooking a more basic point which is tacit in current concerns about student engagement with their coursework.

Even closed-ended problems involve basic judgments. They require students to conclude that they understand what they are being asked to do, that they have selected an appropriate procedure, and that their answer makes sense. These are not advanced professional judgments, but elementary acts of evaluation. Increased instances of students asking, "what is this asking me to do?" and "did I do this right?" indicates a deeper truth: all knowing requires some form of judgment. This claim was essential to the philosopher Bernard Lonergan, whose thought will guide this analysis of engineering judgment.

This paper proceeds from the assumption that greater clarity about the nature of judgment is helpful even if engineering educators do not intend to explicitly require judgment in open-ended problems. Judgment will be presented as a fundamental aspect of human cognition—one that is already present in students' engagement with well-structured tasks but often remains implicit. Judgment will be defined philosophically through the work of Bernard Lonergan, whose analysis of human understanding defines judgment as a reflective act in which a person takes responsibility for affirming or denying a claim. Drawing on Lonergan's work, this paper seeks to clarify the role of judgment in engineering, distinguish it from related concepts such as knowledge and decision making, and indicate factors which complicate student engagement with judgment.

Definitions From Engineering Education Literature

Consensus on a basic definition of engineering judgment remains elusive in the literature on engineering education. Clark et al. state that their "literature search uncovered many ideas about or notions of engineering judgment but no one concrete definition that integrated them." [8] As part of an NSF-funded project, the authors used an expert panel to work towards consensus on a definition of engineering judgment. They advance this preliminary definition based on their findings:

> Engineering judgment is the application of an engineer's knowledge, experience, and metacognitive thinking as well as their consideration of the situational context to perform critical thinking, including decision making and evaluation, in support of the design or problem-solving process, ultimately formatively impacting the engineer for life-long learning. [8]

This definition is helpful as an indicator of expert perceptions; however, it is also quite broad. It will be suggested below that this definition combines causes of judgment, like knowledge and experience, and effects of judgment, like decision making, along with the unique content of judgment itself. Further, the breadth of this definition poses challenges for identifying judgment in practice. This is particularly problematic when communicating judgment to students and assessing judgment in student work.

Gerhardt et al. [9] take a different approach to defining engineering judgment by applying results from the field of epistemic cognition. These authors describe engineering judgment through epistemic cognition in a way that is substantially aligned with the expert definition above:

> We argue that epistemic cognition directed toward specific epistemic tasks provides the conditions for engineers to integrate their technical knowledge, practical experiences, and professional identity to reach decisions in specific contexts. This is a tremendous responsibility and, applied to the classroom, means that students should encounter tasks that provoke their epistemic cognition in such ways as to recognize that responsibility [9].

Judgment here is an integration of knowledge, experience, and personal factors (identity) oriented towards decision making. One difference with the expert definition is the explicit acknowledgement of responsibility for judgment and the extension of this responsibility to engineering education.

This article will expand Clark's work defining judgment through consensus building and Gerhardt's work defining judgment through epistemic cognition by defining judgment philosophically. Philosophical methods are particularly helpful for defining and distinguishing concepts with greater precision; therefore, the philosophy of Bernard Lonergan in his book *Insight: A Study of Human Understanding* [10] is applied to define judgment generally and engineering judgment in particular.

Lonergan's epistemology applied to engineering judgment

Lonergan's epistemology in *Insight* is very rich. Given the constraints of the present article, only a general summary of his arguments can be provided, leading to his definition of judgment. Readers interested in a more thorough account of Lonergan's epistemology applied to engineering are directed to an article by Frezza and Nordquest [11].

Lonergan summarizes the general aim of *Insight* as "to convey an insight into insight… our concern is to reach the act of organizing intelligence that brings within a single perspective the insights of mathematicians, scientists, and men of common sense." [10, p. 4] His aim of unifying math, science, and common sense is particularly suited to engineering, which inherently integrates these three categories. While the goal is ambitious, many believe that Lonergan, broadly speaking, succeeds.

Lonergan summarizes what we learn about understanding by proceeding from mathematics to science, and finally to common sense as follows:

> While all acts of understanding have a certain family likeness, a full and balanced view is to be reached only by combining in a single account the evidence obtained from different fields of intelligent activity. Thus, the precise nature of the act of understanding is to be seen most clearly in mathematical examples; the dynamic context in which understanding occurs can be studied to best advantage in an investigation of scientific methods; the disturbance of that dynamic context by alien concerns is thrust upon one's attention by the manner in which various measures of common nonsense blend with common sense. [10, p. 4]

This quote is provided at length because it summarizes the relationship between fields of knowledge. Math gives precision, and science expands math to include a concrete context. Common sense, on the other hand, includes such a wide range of contextual factors that reasoning is often obscured and confused. As Lonergan says, "To err is human, and common sense is very human." [10, p. 250] As such, *Insight* seeks not only to investigate right reasoning, but also errors in understanding which occur especially in the field of common sense.

A general schematic of *Insight* will help the unfamiliar reader understand the emphasis Lonergan attaches to various subjects and will motivate his development of judgment. Chapter 1 deals primarily with mathematics. Chapter 2 pivots towards science. Chapters 3 through 5 deal with empirical methods and science generally. Chapters 6 and 7 mark a shift towards common sense. These latter chapters place substantial emphasis on errors in common sense which Lonergan calls cognitive biases. These biases will be considered in greater depth in the third section below; however, the attention Lonergan gives to bias motivates the shift to consideration of judgment. He defines judgment in Chapter 9 (after considering "things" generally in Chapter 8) and considers reflective understanding more broadly in Chapter 10. Together, these chapters form part one of the book, which concerns insight as a human activity.

Chapter 9 deals with the notion of judgment. This is the shortest chapter in *Insight*, and there is some evidence that this chapter was written before the sections on math, science and common sense [10, p. xxi]. If so, this would not be surprising given Lonergan's purpose to address bias and the "flight from understanding" which "engaged him far back in his student days." [10, p. xxii]. Two distinctions are needed to understand Lonergan's definition of judgment.

First, Lonergan distinguishes three levels of cognitional process: presentation, intelligence, and reflection. Presentation includes all the processes through which we receive information from the world. Intelligence includes all the processes by which we make sense of information, reason about relationships, and develop understanding. Reflection includes all the processes through which we evaluate our understanding. The term "levels" can be misleading because inquiry may not start at the first level of presentations; however, the distinction between these levels is helpful for defining judgment.

Second, Lonergan identifies two processes at work in all three levels described above: the direct and introspective processes. The direct process concerns our relation to the things around us. This process is always happening. Our senses bring us information. Our minds develop understandings. We reflect to form conclusions. All this happens whether we are aware of it or not. In addition to this direct process, there is also an introspective process. The introspective process deals not with the things around us that make up our knowledge, but with our own relationship to our knowledge. Through this process we recognize that knowledge is not strictly a matter of things themselves, but rather is something that *we are doing*. While the direct process of knowing is always taking place, it is only with time that we recognize, acknowledge, and cultivate the introspective process.

Becoming self-aware as a knower can be uncomfortable. It confronts us with the recognition that we are responsible for our knowledge. This responsibility leads to three imperatives for Lonergan as we mature in our identity as knowers: we must be attentive in our experiences of the world; we must be intelligent in developing insights; we must be reasonable in evaluating our insights.

Having distinguished the three cognitive levels of presentation, intelligence, and reflection and the direct and introspective processes, we have reached Lonergan's definition of judgment: judgment is the introspective process at the level of reflection. Put more simply, we practice judgment when we recognize that we are reflecting on an understanding to affirm or deny a truth claim. If an engineer realizes that they are reflecting on a truth claim, and that their answer represents a personal commitment, only then are they making a judgment according to Lonergan's definition.

Lonergan's definition of judgment provides clarity for defining engineering judgment. While engineers must use knowledge, experience, and consideration of context, these factors are not judgment itself, but rather provide the engineer with something to reflect on and judge. It is also true that sound judgment is required for practical decision making, but Lonergan would advise that judgments must be recognized before responsible decisions can be made. To distinguish judgment from its causes and effects, and to highlight the role of responsibility, the following definition is suggested:

Engineering judgment is a reflective process through which an engineer takes responsibility to either affirm or deny a knowledge claim. Such judgment draws on mathematics, scientific theory, and practical experience and is performed in support of decision making.

Lonergan and student definitions of judgment

The previous section presented Lonergan's understanding of judgment as a distinct cognitive operation of reflection about a truth claim which leads to personal affirmation or denial. This section will apply Lonergan's framework to analyze student definitions of judgment; however, this analysis will be motivated by first analyzing thematic alignment with expert definitions.

Student definitions come from semi-structured interviews conducted at the beginning and end of a junior-level circuit analysis and design course with a significant emphasis on developing engineering judgment. The full interview protocol can be found in the appendix. These interviews are part of a larger study investigating student engagement with judgment through the AIR model of epistemic cognition. Further details on this project can be found elsewhere [12].

Table 1: Codes and percent prevalence of codes in expert definitions of engineering judgment from [8] along with percent prevalence of codes in student definitions at the beginning and end of the semester.

Code	**Experts (%)**	**Student Pre (%)**	**Student Post (%)**
1. Application of one's knowledge or experience	71	71	100
2. Approximation that achieves reasonableness	<12	14	29
3. Assessment of the reasonableness of a solution, assumption, etc.	29	71	57
4. Consideration of societal, ethical, cultural, global, or aesthetic contexts or issues	24	29	0
5. Creativity (within constraints)	<12	14	0
6. Critical thinking (i.e., disciplined gathering and use of information to guide action)	24	0	14
7. Decision making (including weighing of issues) amidst complexity and competing demands, objectives, or constraints	76	57	71
8. Identification of important vs. non-important details, including definition of the right problem	18	0	29
9. Foreseeing, anticipating, or predicting potential problems or outcomes with a solution, design, etc.	<12	14	14
10. Making assumptions (for simplification, solvability, etc.)	<12	0	29
11. Recognition of mistakes or errant conclusions, including via testing	<12	29	14
12. Use of feedback for refinement or adjustment	<12	0	0
13. Use of tools or standards/codes of practice	18	0	0
14. Effective communication with clarity, accuracy, and justification	<12	0	0

This course is part of a general engineering program at a small liberal-arts college. Eight participants were recruited at the beginning of the semester and seven completed both interviews. Although this sample size is too small to draw definitive conclusions, investigating complex cognitive abilities like judgment requires fine-grained data and therefore smaller samples are a practical necessity. While the conclusions below may be qualified by future research, they contribute to the growing body of work on engineering judgment which is recognized by many to be in its early stages.

Student definitions of engineering judgment were analyzed using the 14 codes applied to expert definitions in [8]. These codes can be seen in Table 1 along with code prevalence in expert definitions. For the present study, student definitions before and after the semester were coded independently by two reviewers: one from the engineering department and one from the education department. After all responses were coded independently, codes were reviewed and a consensus for final coding was reached. Final percentages are reported in Table 1. A similar procedure was used in [8].

Table 1 shows significant thematic alignment between student and expert definitions of engineering judgment. Both groups emphasized application of knowledge and experience, and decision making. Students were somewhat more likely to discuss verification of knowledge than experts. This is particularly seen in codes 2, 3, and 11 where students were slightly more likely to discuss assessment of reasonableness and recognition of mistakes. These results present some evidence that students are more aligned with Lonergan's definition of judgment as evaluation of a knowledge claim than experts.

The alignment between student and expert themes in defining engineering judgment is a potentially unexpected result especially since this alignment can be observed even before judgment was formally discussed in class. It is suggested here that these codes are not fine-grained enough to capture nuances in definitions of judgment. This is particularly true for students who may have unsuitable notions of judgment which cannot be seen by looking at codes alone. As such, several participants' definitions of judgment are presented below and analyzed using Lonergan's framework. Each pair of responses below comes from a single participant.

> (Beginning of semester) It's an interesting term because you have to understand the context. If you're designing this bridge and all the numbers are checking out, everything is looking good. Normal engineering judgment would be: that bridge is good, that bridge is fine to go up. But then an engineering ethics question would be: Is there some kind of impact socially that this bridge location would have?
>
> (End of semester) Probably the best definition I could give for engineering judgment based on my experiences is that it's being able to make certain judgment calls, because in engineering we can do all the math, we can do all the work and sit down and we'll say: we've got these three or four options here as to how we're going to solve this problem. The engineering judgment comes in place where you have to sit there and go of these four options, which one's the best one?

This participant demonstrates a significant increase in his understanding of the role of engineering judgment. At the beginning of the semester, he seems to claim that engineering analysis aligns perfectly with reality. His initial definition limits judgment to ethics and defines engineering work strictly in terms of mathematics and science. By the end of the semester, his awareness has shifted to recognize what Lonergan would call common-sense judgments in design work. This is seen in his emphasis on selecting the best option, which is always subject to judgment.

Another participant gave the following definitions:

> (Beginning of semester) I feel like it's using your experience from different engineering classes to impact what you actually think about a certain situation. Like I feel like if you are chemistry based you might have a different thought than someone that's mathematical

> based. Just in a certain situation, you'll have different views from your experience in school.
>
> (End of semester) I think that would just be the assumptions we make within a situation, but we would have to use what we learn to actually make those assumptions and judge them correctly.

In one sense, this participant's answer before the semester is closer to Lonergan's definition of judgment, particularly her statement that judgment is "what you actually think about a certain situation." She even addresses math and science as distinct ways of knowing much in line with Lonergan. On the other hand, after the semester she has a concrete example of when engineers need to apply judgment; namely in service of making assumptions and evaluating their suitability.

Another participant gave the following definitions:

> (Beginning of semester) Well, I'd say engineering judgment is like once it's all said and done, how you evaluate your solution, or how you decipher what way to go cause sometimes there's multiple solutions and you have to decide what's the best solution. And so I guess just using your, I don't want to say like common sense but kind of. It's not really common sense. Let's say using your background in engineering to decipher what's the best way to go about a certain task or project.
>
> (End of semester) I would say engineering judgment is using your calculations and your background in like these classes, but those aren't enough. Like anybody can do a math equation or plug numbers into a thing. But then it's using those equations to decide on what is the best route to go when selecting types of material or types of motors or pumps or kind of the stuff that we did in the labs. You use all these equations, but then you find out that some of the values that you're getting in the specifications aren't going to be correct and you have to use your judgment to say what is more important, like power or efficiency. Like you have to look at the big picture. I feel like for engineering judgment the equations and simulations aren't always going to be correct and you have to use like your common sense I guess. Yeah, backed up with the equations too.

This participant's initial definition of engineering judgment focused on evaluation, particularly in terms of common sense; however, he initially felt uncomfortable using that term. After the semester, he demonstrated a clearer understanding of how math, science, and common sense combine to evaluate solutions, and to correct for errors.

One further set of definitions is provided for breadth:

> (Beginning of semester) I'd say there's always some kind of answer that you can use. And you know, like a mathematician looks for a mathematical answer, a scientist looks for a scientific answer, but an engineer looks for more for a practical, real world answer. Why does this make sense here? Why doesn't it line up with the formulas? And I think it just takes a little bit more imagination to make that kind of judgment. It's tough to say though, because I don't think we've, I don't think I've really made many engineering judgments yet. I probably will have to coming up, but it's just kind of hard to think about, you know, an engineering judgment when you really haven't done much so.
>
> (End of semester) Judgment is, you know, using data and assumptions and inferences that you have to make a decision and see if something correlates or if a final hypothesis is

> proven or disproven. I kind of thought judgment would be something that you do at the end of the experiment, but you have to do a judgment throughout all parts of the experiment and even before the experiment. You know, why does that make sense? Why do we do this? And that's like, how would that affect our final judgment going in the future?

This participant exactly mirrors Lonergan's division of knowledge into mathematics, science, and common sense even at the beginning of the semester. His definitions incorporate several questions like "why does this make sense?" Lonergan would distinguish that these are questions for intelligence and not reflection since they cannot be answered by a yes or no. By the end of the semester, this participant has come to recognize judgment in terms of questions like "if something correlates or if a final hypothesis is proven or disproven." These are more clearly questions for reflection and if an engineer recognizes that they are personally affirming or denying these claims, then this definition aligns with Lonergan.

The interview responses above suggest that Lonergan's framework may be naturally aligned with the way students already think about judgment. Many participants defined engineering judgment in terms of the relationship between math, science, and common sense. This is not necessarily surprising given that the engineering curriculum is arranged around these fields, but these data indicate that students already associate judgment with the relationship between these areas. Student responses at the beginning of the semester indicate only vague awareness of judgment. By the end of the semester, students recognize more concrete questions for engineering judgment including: is this the best design? Is this assumption reasonable? Is this hypothesis proven or disproven?

These results indicate that even before judgment is discussed in class, students have picked up a working definition of engineering judgment which is substantially aligned with expert definitions. Other studies have likewise found that students are able to give competent definitions of engineering judgment, but this ability does not always translate into apt performance on judgment tasks. In fact, many studies have reported significant student resistance to judgment tasks. Lonergan's theory of cognitive bias will be presented below to explain this observation.

Cognitive bias and engineering judgment

Several studies have observed student resistance to judgment tasks. For example, [4] developed an open-ended problem to promote judgment as part of a sophomore-level laboratory, but found that "none of the students attempted the open-ended design problem." Likewise, [5] noted a tension between students' preference for application-based assignments and their desire for a high level of guidance on such tasks. The authors concluded that:

> Given the recurring theme that engineering students (and students in general) want more guidance for (open-ended project learning), the question must be asked: how much guidance is the proper amount? Perhaps the ideal amount has already been found and students just do not like it. This could mean that we as educators need to do a better job communicating to students what is important within their education. [5]

The implication here seems to be that developing understanding and judgment is more important than following procedures. If this is the authors' intent, then their recommendation is well aligned with research in epistemic cognition; particularly, the AIR framework from Chinn et al [13].

The AIR framework represents knowledge through three dimensions of Aims and value, Ideals, and Reliable processes. Aims and value are the reasons why a person seeks knowledge. Ideals are the criteria used to verify knowledge. Reliable processes are the ways a person works to attain knowledge. A unique feature of this theoretical framework is the inclusion of aims and value as a part of knowledge itself. The AIR framework claims that aims directly affect what a person can know. Like the authors in [5], Chinn et al. argue that instruction needs to explicitly work to promote epistemic aims and value:

> Our discussion of aims and value points to what seems to us to be a seriously neglected instructional issue – promoting a broad disposition to adopt epistemic aims. Instruction designed to promote better reasoning should, for example, encourage students to care about and seek the truth – even if the truth should prove inconvenient. We are not aware of major educational initiatives that have explicitly made this a central instructional focus. [13, p. 446]

The authors claim that better student reasoning would result from a greater desire to pursue truth. This claim is largely self-evident, but it is not clear that instruction can effectively change this disposition. Lonergan's theory of cognitive bias is presented here to suggest that fundamental changes to epistemic aims and value may be harder to achieve than the authors seem to acknowledge. If Lonergan is correct about the role of cognitive bias, instructional approaches which focus on developing the aim of seeking the truth may be very likely to fail.

Cognitive biases are systematic distortions which occur in the process of seeking the truth. Lonergan gives significant attention to several forms of bias, three of which are grouped together in Chapter 7 of *Insight*. Individual bias arises from egocentric preference, where personal advantage or comfort restricts the range of questions one is willing to entertain. Group bias occurs when the shared interests or assumptions of a social group suppress insights that threaten their self-understanding or power. General bias reflects an overreliance on common sense, privileging what works practically in the short term while dismissing theoretical considerations or long-term consequences. This last bias is called "general" because everyone is affected by it to a greater or lesser extent. Together, these biases do not merely produce occasional errors; they systematically interfere with the human pursuit of the truth. While all these biases may play a role in student resistance to judgment tasks, a fourth bias from Lonergan appears to play the greatest role.

Chapter 6 introduces the discussion of bias through consideration of dramatic bias, which Lonergan names "dramatic" in reference to the roles characters play within a drama. This bias arises when an insight threatens a perceived role, leading to the largely unconscious rejection of that insight. While other forms of bias may rationalize inconvenient insights, this form operates at a deeper level: it prevents certain questions from being recognized at all. The result is not the rejection of a truth claim, but an intellectual blind spot in which the underlying question is never recognized. Like other biases, it should not be understood as abnormal; it is a common feature of human knowing.

The interruptions caused by dramatic bias in education are illustrated through analysis of a student interview. This analysis shows how bias interferes not only with the student's engagement in open-ended laboratories, but also with their willingness to consider the underlying purpose of such learning tasks. I do not suggest that this student is unusual; rather, as noted above, dramatic bias affects everyone to some extent. Although further research is needed to support this claim, if this student reflects the dispositions of many engineering students, then his responses point to a crucial challenge in implementing judgment tasks. Specifically, *students may never even consider the value of judgment in the first place*, much less cultivate the capacity itself.

The interview response below took place at the beginning of the semester. This student is responding to the question: "How would you describe yourself as a student—both in terms of interest, strengths and the kinds of learning tasks you find most challenging?" The responses below have been edited to remove false starts, digressions, and to promote coherence with an effort to preserve the original meaning. The participant's response began as follows:

> I like doing hands-on labs and stuff like that as long as it's like a good lab. You know, some labs are better than others quality wise. But I'd say that the Materials lab was really good. Just kind of walking you around, showing you how it works in real time, things like that.

A tension can be observed in this response which indicates that cognitive bias may be a factor. He says that he likes "hands-on labs" but describes a "really good" lab that is more like a demonstration. The interviewer followed up by asking the participant to further explain his ideal lab.

> I guess it's not that (other labs) were bad. It was more like I didn't—we didn't really understand why we were doing the lab. I think that was the most important part. It's not that the lab was bad or that we didn't understand the formulas that the lab is trying to talk about. A lot of Physics II lab is—you have a principle and a formula and you're trying to figure out: Does this hold up in the real world? Or are there discrepancies? Or is the error so big that this doesn't really apply? Or is this formula consistent? And usually, it works. There's a reason that it's there. But it's like - why would we do this? Where do we see this?
>
> And you know, I think that was the difference between a lot of the Physics II labs and what I just saw in Materials. It's like, well, now we understand if you dump hot steel and water, you get kind of like cracks and things and it's the way that it gets back to normal. And then you put it in air and you have all these crystals form and the different structures and so you understand what's going on and why it's happening and why that's important. And I think that's what separates the good labs from the not as good labs.

There is a telling false start above when the participant begins to say "I didn't understand why we were doing the lab," but quickly changes it to "we didn't understand." While he gives some indication of the kinds of tasks in a Physics lab (i.e. determining a mathematical relationship experimentally), he denies knowing why these tasks are valuable. The interviewer probed further by asking what he thinks is the purpose of physics labs, which led to the following response describing a particular lab:

> We had a lab like trying different resistor combinations and series parallel and so you could use like 14 combinations or something like that and you had to figure out OK will hold up? Then we have to graph it. But I don't know, I guess also like maybe trying to understand it in class to try to make that connection to the lab was a little bit difficult. Yeah, that that was definitely more challenging. That was probably one of the hardest classes I've ever taken as a student.

There is a noticeable change here in the way he talks about his quality of understanding. In the section above, he affirms his (or more accurately, his peer's) understanding of the theoretical content of the lab, saying "It's not that the lab was bad or that we didn't understand the formulas that the lab is trying to talk about." In this section, he reconsiders that judgment, saying "But I don't know, I guess also like maybe trying to understand it in class to try to make that connection to the lab was a little bit difficult." Part of the challenge of the physics labs is that they build on prerequisite knowledge and this student initially resisted admitting that they might not have understood the theoretical content of the lab. To probe further into this point, the interviewer asks the participant to summarize the difference between the physics labs and the materials lab which he stated as his ideal.

> I think it is just explanation wise. The materials lab professor was very thorough and he was like engaging. You know, talking about different properties and kind of getting us to do the lab with him in a way, in a sense. We weren't actually touching steel with the tongs and putting it in the in the bucket, but in a way we kind of were in that we were following along very easily with what he was saying. And I think the physics lab, it was kind of like, well, here's the formula. And then, you know, maybe there's like a like a different way you can write it and prove something else about the formula. And then it's like, OK, here's what's on your table. Go and do it and then graph it and then come back. And maybe there's Part 2, maybe there's not. And so I think it was like the kind of explanation or it's just on the board. You're like, OK, like, I see what you're saying, but you know. There's there was no real like there was no real engagement. There was no real answer. Why are we using like these kind of resistors? Why are we using resistors at all? Why are we using batteries at all? Why not like create the proper circuit or why are we not doing like this and that? So many unanswered things.

Given the importance of roles in dramatic bias, this interview section is crucial. The participant clearly defines the roles he attributes to professors and students. In his ideal situation the professor's role includes being thorough, engaging, and even doing the lab. The students' role is limited to following along. The Physics lab was considered lower quality because it did not align with these roles. Rather, in the Physics lab the professor's role included presenting theory, setting up the learning environment, and assigning tasks. The student role was more comprehensive and included development of experimentation, data analysis, and drawing conclusions for themselves.

The student ends his discussion of roles by stating that the physics lab had "so many unanswered things." In fact, one of the main purposes of a science experiment is to find answers from nature without having to rely on an authority, like the professor. This should be known by a STEM major in their junior year. It is possible that the issue here lies in uncertainty more broadly about the purposes of laboratories [14]. At minimum, the participant could give a more concrete definition of the purpose of a laboratory, such as developing experimental and data analytical skills.

To probe into whether this participant can at least articulate a perspective on the purpose of science experiments which is different than his own, the interviewer asked "Has your education up until now given you some answer to the 'why' for science? Do you think your education has given you any reason why experimental knowledge is valued in science?" The participant responded:

> I knew there was a purpose when I was rearranging the resistors. I just didn't know what purpose was.

This interaction demonstrates Lonergan's main point about dramatic bias. It is not just that people disagree about their roles. Lonergan's point is much deeper, and more subtle. The problem of dramatic bias is that the roles we ascribe to ourselves and others fundamentally and largely unconsciously limit the kinds of insights we allow. It is not simply that we reject alternative insights; we fail to see that these insights exist in the first place.

If Lonergan is right about the intellectual blind spots which result from dramatic bias, then addressing judgment with students becomes significantly more challenging. Fundamentally, judgment is about affirming or denying an answer. If a student believes verification of answers is the role of their teachers and professors, they may reject judgment tasks as flawed pedagogy. Crucially, this rejection is not entirely conscious. Attempts to, as Carkin says, “do a better job communicating to students what is important within their education” [5] are likely to face significant resistance, for such attempts try to get students to think about something which they would rather not consider.

Conclusions

This paper’s primary theoretical contribution is the application of Bernard Lonergan’s philosophy to recent definitions of engineering judgment. Judgment is distinct from its causes, like knowledge and experience, and its effects, like decision making. The specific content of judgment is defined here as reflection about a truth claim leading to affirmation or denial which involves personal responsibility. Student data illustrate this paper’s theoretical ideas. Student interviews show many similar themes observed in expert definitions of judgment. Student interviews also show evidence of cognitive bias, which is claimed here as a major limitation to student engagement with judgment. While the small sample size (N=7) of the present study does not offer definitive proof, it does provide evidence that engineering judgment is an important phenomenon which deserves further investigation.

While it is desirable to indicate solutions to the challenges which this work and other publications have identified in student engagement with judgment, any simple recommendations have a high risk of being naive. The challenges surrounding judgment should not be surprising. The Greek word for judgment, *krisis*, highlights that judgment always includes risk. For Lonergan, the crisis of knowing occurs when the human search for truth meets the equally human avoidance of truth through cognitive bias. He concludes that it is not realistic to expect a programmatic solution to these fundamental problems. The same cautious approach is recommended for engineering educators who value judgment; however, a few admittedly general conclusions are suggested.

First, educators should raise student awareness of the role of judgment in all knowing. Even doing a basic homework assignment involves judgments such as “the assigned question list on Canvas can be trusted” or “the procedures in my Physics book are valid.” Competent performance on well-structured tasks should be seen as preparation for higher judgments. These basic judgments should be verified before moving onto open-ended judgments.

Second, instructors developing open-ended judgment tasks should anticipate student resistance. This paper links resistance to dramatic bias, and the fact that students may feel they are being asked to take on something outside their role. Scaffolding is key to negotiating this resistance. Early judgment tasks should be built from basic abilities, like checking work for factual errors, towards capabilities like estimation and sensitivity analysis. These tasks can be presented as skills which should improve their reception.

Third, close attention should be paid to the quality of student communication about judgment. Current strategies for assessing judgment equate it with giving reasons why a solution is adequate [4]. This aligns with the reflective nature of judgment advocated here. Complexity of reasoning should build over the course of an engineering program from simple explanations to complex argumentation. Eventually, the quality of student argumentation must be graded, but dramatic bias will likely make this a source of tension. Many students will want to know *how* their reasoning will be graded. In part, this question can be answered by pointing to processes described in the previous recommendation; however, at a deeper level, norms around sound judgment will likely be sources of tension which must be navigated.

Building evaluation skills and communication abilities are important parts of engineering education, however, they only address part of the definition of judgment advocated here. They get students to reflect on whether their answers are believable, but not whether the student *believes in* their answers. Ultimately, judgment for Lonergan is more than saying "I have reasons for my answer." It is the statement "I stand behind my answer." The difference between these responses is subtle, but crucial, because it bears on the personal responsibility one takes for their answers.

Educators should accept that students cannot be forced to make judgments in this highest sense because such judgments would lack authentic value unless they are free personal commitments. It is doubtful that authentic judgment at the level of personal responsibility can ever be graded. Yet, grading and assessment are not the same thing [15]. Although responsibility for judgment cannot be graded, it can likely be observed. Educators should develop methods for investigating student beliefs about their answers, but the current state of research only hints at how this may be done. Future research should help identify reliable evidence that students are taking ownership of their knowledge claims and making their own judgments.

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Appendix: interview protocol

Participants met with the PI at the beginning of the semester for 60 minutes and at the end of the semester for 30 minutes. The questions covered in each interview can be seen below:

First interview

1. How would you describe yourself as a student—both in terms of interest, strengths and the kinds of learning tasks you find most challenging?
2. What are your goals for your college education, especially in studying engineering?
3. Have your goals for education changed throughout your time in college? If so, please describe.
4. What are your goals for this course?
5. Imagine you're in a job interview and are asked: “What is the hardest engineering problem you’ve ever solved? Tell me what made it hard, and how you went about finding a solution.” How would you answer this question today?
6. Have you ever found open-ended problem solving frustrating? If so, can you describe what made it frustrating and how you responded?
7. Please take a look at the objectives for this course below. Which seems most valuable to you and why?

- Analyze circuit behavior using scientific and mathematic theories
- Construct circuits from schematics using prototype wiring and microcontrollers
- Assess circuit design choices showing a practical understanding of circuit elements
- Demonstrate experimental skills by performing measurements, analyzing data to determine relationships between variables, and applying engineering judgment to draw conclusions about results
- Show responsibility for project management in terms of planning, implementation, accountability, and evaluation

8. Which seems least valuable to you and why?
9. How would you define engineering judgment?
10. Please give me a few examples of engineering testing or experimentation
11. What are some important aims of engineers in performing tests or experiments?
12. What kinds of judgments do engineers need to make when testing components or performing experiments?

Second interview:

1. How would you now define engineering judgment based on your experience this semester?

The questions below are based on the tasks from labs 2 and 3 this semester:
Lab 2: choose a motor, test the solar panel, choose a mass, and predict the rate of potential energy storage

Lab 3: choose a pump, test the pump, test the battery, choose a reservoir height, predict the potential energy stored in five minutes, predict the productivity of your setup.

2. Think of a task above when you or your team practiced good judgment which helped you work towards a solution. Please describe what your group was trying to do, how you went about working toward your goal, and why you believe you made a good judgment.
3. Think of a task above when you or your team practiced inadequate judgment which did not help you work towards a solution. Please describe what your group was trying to do, how you went about working toward your goal, and why you believe you made an inadequate judgment.
4. Have you found any strategies that you feel will help you make better judgments in these types of tasks in the future?

The questions below are based on the case studied we discussed this semester:

5. We discussed a few case studies of engineering judgment this semester. Can you name any of the cases you remember?
6. Can you choose a particular case and explain how engineering judgment was involved?
7. Please list some specific examples of engineering testing or experimentation.
8. What are some important aims of engineers in performing tests or experiments?
9. What kinds of judgments do engineers need to make when testing components or performing experiments?

Optional final question if time permits: We will be doing more of these labs next semester. Do you have any thoughts on what would make that experience productive and enjoyable for you?