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Tools for Comprehensive Assessment of the 7 ABET Student Outcomes in Mechanical Engineering, with Application to Capstone Design

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Abstract

The seven ABET Student Outcomes are guidance from industry on the abilities that engineering graduates should have and are central to accreditation of engineering programs in the United States. To address the breadth of engineering abilities, some capstone design courses assess all of these outcomes. The recent revision of the 11 “a–k” outcomes into the current seven makes this approach more tractable; however, the change in scope for some of these outcomes requires a corresponding revision to assessment instruments. This paper reviews assessment tools for each of these outcomes. It also shares a comprehensive set of tools for assessing these outcomes, especially for use in capstone design. These tools are described in the context of the known benefits and limitations of assessment. In particular, they are designed to give students experience with the breadth of engineering competency in authentic settings, and to clearly demonstrate compliance with requirements of ABET and other accrediting bodies. Some notable features include a phase-gate product development process, a project management system inspired by agile scrum, and several assignments that call for individual students to make signature contributions to their project. Taken together, these tools are a model assessment system that can be adopted and modified by other programs. In the long run, we envision the engineering education community developing a shared set of assessment tools that are psychometrically sound and that clearly meet accreditor requirements.

Introduction

Although a culminating design experience can be implemented in numerous ways, here we describe a capstone design course in which teams of seniors spend most of their effort on developing and realizing a product that meets the needs of a real client. Capstone design is a challenging course to teach for a number of reasons such as:

- Defining expectations.
- Promoting fair workloads within teams.
- Promoting fair workloads between teams.
- Promoting good design process.
- Rewarding failure due to taking sensible risks while not allowing failure due to lack of conscientiousness.

- Ensuring compliance with ABET requirements (for ABET-accredited programs).
- Assessing student performance on a variety of outcomes, at the program level.

That final point, on assessment in capstone, is especially significant. Because the capstone experience is the part of the curriculum that best approximates professional practice, student outcome (SO) attainment in that course is particularly relevant to assessing the quality of the overall degree program. Moreover, a team design project is a natural opportunity for assessing numerous engineering skills, especially in design and teamwork.

In the Mechanical Engineering (ME) program at King's College (Wilkes-Barre, Pennsylvania), all seven ABET Student Outcomes are assessed in capstone design because our capstone course is intended to give students experience synthesizing the major engineering abilities for in an authentic context. This level of assessment is manageable because the course spans two semesters and has four credits per semester; also, this amount of time enables ambitious projects that industry is willing to sponsor. We also assess each outcome in at least one other course, typically in a way that is analogous to a corresponding activity in capstone. Thus, our capstone sequence and our assessment system are woven together. This paper describes our assessment tools, focusing on their use in capstone; many of the tools are used together to overcome the challenges noted above.

In describing a comprehensive assessment system for the current ABET student outcomes, this paper is similar in approach to some previous ones. Battistini and Kitch [1] describe a comprehensive assessment system for a new civil engineering program that recently earned ABET accreditation; they offer helpful details on implementation of an assessment plan, from file management to faculty consensus building. Notably, they include their rubrics. Rubrics are guides for scoring student work and ABET recommends their use in assessment [2]. Rubrics decompose student outcomes into performance indicators (PIs), increase inter-rater reliability, and define performance levels. Assessment of outcomes 3–7 in capstone has been described [3], as has a multidisciplinary capstone project in which all seven SOs are assessed [4]; however, those papers do not include the related rubrics. This paper builds on previous efforts by describing and promoting a pragmatic approach to assessment, stating the rationale for how each outcome is assessed, and showing the rubrics that are used in this system.

This assessment system is designed to be pragmatic, as opposed to ideal. One could envision a system that collects more data or only uses instruments that are validated. However, for reasons described in the following section, such apparent improvements would require more effort while yielding little additional benefit. Instead, this system prioritizes student learning as well as demonstrating compliance with accreditor requirements. For these reasons, we do not report data on the performance of this system, other than to say that once the data is scored as part of the grading process it does not require much work to process the data, that under this system our program earned ABET accreditation, and that existing validated instruments are used where feasible. This system was developed in a new program so it is not possible to compare with a previous assessment system. With that said, we could see a more ideal approach being worthwhile—but only with tools that are developed by an interdisciplinary team of researchers and educators.

Perhaps the most robust project for developing and sharing assessment tools for engineering education has been the Transferable Integrated Design Engineering Education (TIDEE) project; an early paper from that project reports rubrics for SOs 2, 3, and 5 [5]. The TIDEE project developed the IDEALS system, a collection of modules, assessment instruments, and online tools [6]. People associated with that project described a snapshot poster session to promote formative feedback from peers and project advisors [7]. The consortium is unfortunately no longer active. The Comprehensive Assessment of Team Member Effectiveness (CATME) project develops high-quality assessment tools for teamwork, and eases data collection and analysis through a web-based interface [8]. It would be beneficial if a consortium similar to TIDEE could be formed to develop ways to assess each ABET student outcome; by involving experts in educational measurement, and by automating the data collection process, such a consortium could make assessment more valid and less arduous.

In this paper, we refer to the Engineering Accreditation Commission of ABET simply as ABET. We work from the premise that the seven ABET outcomes are meaningful educational goals, due in part to industry's support of the prior a–k outcomes, which the current 1–7 outcomes resemble [9]. Here, assessment for the ABET is the focus, because that is the primary body that accredits engineering programs in the United States; some guidance is relevant to satisfying the expectations of regional accreditors in the United States and perhaps other accrediting bodies.

The following sections advocate for a pragmatic approach to assessment and explain how to use that approach. Subsequent sections show how each SO is addressed in our ME capstone course.

Assessment Should be Pragmatic

In student outcomes assessment, targets for student performance are defined, and performance against those targets is measured. If the target is not met, a corrective action is implemented. Cycles of measurement and action are repeated until the target is met. This discussion focuses on quantitative direct assessment of student work on program-level outcomes; other assessments may be worthwhile but are rarely necessary or sufficient to satisfy requirements of ABET and regional accreditors in the United States. Also, although educational research yields useful insights and some assessment systems use sound methodology, the focus here is on the many systems that have methodological weaknesses such as not having valid instruments, controls, and sufficient sample sizes.

Assessment would seem to be a reasonable way to improve program quality. However, assessment professionals concede that assessment has led to little demonstrable success [10, 11, 12]. Now, there are numerous accounts in which a target was not met, a change was made, and the target was then met. However, it is worth asking whether the change could have been proposed based on common sense rather than assessment data (and with much less effort), whether the measurements were sound, or whether the improved performance may be due to some confounding factor. Accrediting bodies do not require this scrutiny but do require accounts of data-driven improvements; thus, programs are incentivized to make it seem as if improvements are due to assessment when the truth is more murky. Therefore, although there are apparently many assessment success stories, there are few that demonstrate that assessment works and is worth the effort that is spent on it.

This lack of success is probably due to multiple issues, including the following.

- Few faculty have the expertise in psychological measurement to develop valid instruments [13, 14].
- Many programs have sample sizes that are too small for most effects to be measurable [15, 16].
- Efficacy of improvement is shown longitudinally, rather than through comparison with a control group.
- Faculty might not cooperate in collecting data.
- Based on whether faculty want to promote or prevent change, they are incentivized to assign low or high scores to student work.
- "Common sense" interpretations of data can lead to counterproductive interventions being proposed [14].
- Faculty might not make actions that are called for by the assessment process.
- Issues with workload, morale, and academic freedom can give faculty negative feelings about assessment [17]; those feelings can lead to disengagement or even reaction against the assessment system.

Overcoming these issues would be a major achievement that is beyond the scope of the paper. Until that happens, it is not worthwhile for most programs to put more effort into assessment than the minimum that is required to satisfy accreditors; for example, although measurement quality might be improved by having multiple raters apply a rubric to student work, that increase in effort is wasteful if the rubric itself is not valid.

Of course, there are laudable examples in the literature of excellent measurement and innovative practices leading to improvements in learning, especially with results that generalize. However, research in the science of learning requires proficiency with psychology, measurement, and statistics. In contrast, accrediting bodies do not hold programs accountable for using good methodology, perhaps because that expectation would be onerous for most programs. Some suggest that assessments that fall short of what is needed for research still produce data that can be of practical use. Now, assessment findings do not need to generalize to other settings; other than that, the reasons why such methodology is used in research are just as applicable to measurements for assessment. For example, with sample sizes that are too small, it is easy to generate false positives, and that problem is just as likely for assessment systems as it is for research projects. Low-quality measurements are likely to lead to counterproductive actions [14]. Ironically, programs are required to collect and act on (low-quality) data from their own students, but are not obligated to use published research findings [16]; this phenomenon has been compared to every town having to perform its own drug trials [14].

Despite these issues, some elements of assessment are clearly beneficial. The assessment process described in this paper promotes giving students structured experiences across the breadth of engineering competency as represented by the ABET student outcomes. Where possible, validated measurements are used. Overall, this system minimizes the effort spent on assessment, enabling faculty to focus on other activities that promote student learning, such as implementing evidence-based practices.

How to do Assessment Pragmatically for ABET Accreditation

Programs can struggle to determine what the rules are for assessment. Ideally, assessment would simply consist of making educational measurements and acting on them, and thus the rules for measurement would be based on sound research methodology. However, owing to its role in accreditation, the rules of assessment arise from a complex combination of educational measurement, what accreditors can reasonably expect programs to do, and how programs can demonstrate compliance with accreditor expectations. The tensions between these factors make it impossible for programs to intuit how much assessment is enough and what methodologies are required.

Fortunately, guidance on assessment for ABET is available. Based on the text of Criterion 4, materials from ABET regarding assessment and evaluation (such as the Fundamentals of Program Assessment Workshop [2]), and discussions with ABET officials and faculty who lead ABET accreditation efforts, we believe that the following unwritten rules should be observed to demonstrate compliance with Criterion 4.

- Student performance on each outcome must be assessed directly.
- Each outcome must be operationalized as several performance indicators.
- Data for each performance indicator must be scored based on student performance.
- Extent of performance indicator attainment must be defined, typically via a rubric.
- Each outcome must be assessed at least once.
- Each outcome must be assessed in the senior year.
- Attainment of an outcome must be defined; that is, there must be a formula that can be applied to the performance indicator scores to say whether or not the students collectively met the target.
- Program faculty must collectively review the assessment data.
- If an outcome is not attained, some corrective action must be taken.
- Corrective actions must be tracked over time until non-attainment of an outcome is resolved.

Some of these points are straightforward interpretations of the text of ABET definitions of assessment and evaluation, as well as Criterion 4, while other points require inferring what a program evaluator (PEV) would reasonably find problematic. Sufficient ambiguity is present in the ABET Criteria that, although these unwritten rules are not requirements from ABET, following them would reduce the likelihood of a PEV issuing a shortcoming. In particular, rubrics are not explicitly required but the ABET Fundamentals of Program Assessment Workshop [2] places major emphasis on them, probably because they help demonstrate compliance.

In addition to the preceding points, our program adheres to the following additional guidelines.

- All outcomes are assessed at two points in the curriculum.
- All outcomes are assessed in Capstone Design.
- All outcomes are assessed every year for every student in courses on the assessment map.
- For a given outcome, the same rubric is used for each assessment of that outcome.
- Where possible, performance indicators are derived from ABET language in outcomes (SOs 1, 4, 5, 6) or definitions (namely "engineering design" for SO 2).
- Outcome attainment is defined as 70% of students earning a median score of 3 or higher on the relevant rubric.
- Only quantitative direct assessments are used.
- All assessments are embedded in course assignments.
- Faculty discuss assessment results and commit to improvements after each semester.
- Assessment activities are documented in meeting minutes, annual program reports, and reports tracking improvement efforts over the years.

Not all of these rules are appropriate for all programs. However, these rules make it easy to demonstrate compliance to our administration and to ABET PEVs. For example, our definition of outcomes attainment has several arbitrary features; however, this definition is acceptable to ABET and by having a single definition, it is simple for everyone involved to document and confirm compliance.

In practice, we go beyond these rules to improve our program: most outcomes are assessed more than twice, performance is observed beyond what rubrics document, we track performance at the performance indicator level, we implement improvements even when an outcome is met, we use qualitative and indirect information, and we frequently discuss how to improve student performance on the various outcomes. Such practices are not necessary or sufficient for accreditation. We are careful to not include these ad hoc efforts in our documented continuous improvement system for ABET accreditation, because doing so would obligate us to perform them with an onerous degree of regularity.

It took much effort to find and develop the assessment tools described here. Although that effort could have been spent more efficiently if these tools had been publicly available, the result is a system that offers structured learning experiences for each ABET student outcome. Because these activities are embedded within our courses and because almost all work is scored for assessment as part of the regular grading process, the ongoing additional work needed for data tabulation and analysis is minimal: transferring all capstone data from gradebooks to assessment forms takes less than one hour per year.

Our program recently earned accreditation from ABET. We cannot share any specific comments from ABET regarding our program. We can say that based on our experience, we recommend using the principles described here. Another program used a similar "straightforward" approach to assessment and recently earned initial ABET accreditation [1].

Overview of Tools

Many of our assessment tools were developed to be suitable for capstone design and then adapted for assignments earlier in the curriculum. Because SO 2 on design and SO 5 on teamwork and project management are central to capstone design, we discuss assessment tools for these outcomes first. Each section that follows addresses a separate student outcome, explaining our approach and discussing existing tools in the literature.

These tools were implemented to address some of the challenges described in the Introduction. The phase-gate process used for SO 2 is general enough to be applicable to many projects while specific enough to offer clear guidance. It also promotes good design process, and, related, lets teams demonstrate their conscientiousness even for projects that had limited success due to factors beyond their control.

The system used for SO 5—inspired by agile-scrum—promotes fair workload among and between teams, and increases the chances of project success. Because this project-management system has students take turns managing the team, assessment data is obtained for each student.

SOs 1, 4, 6, and 7 are assessed by individual assignments; for each outcome, each team member shows how they made a signature contribution to their project. One of their related reports is also assessed for SO 3 on communication. This strategy yields comprehensive assessment data for these outcomes. It also promotes fairness, because each student is rewarded for doing some modeling, some professional decision-making, some testing, and some self-directed learning. If the projects were graded entirely based on the quality of the resulting product, some teams would have unfair advantages due to the intrinsic difficulty of their project. Instead, this use of individual assignments can compensate for differences between projects by partially defining project completion in terms of how engaged each team member was; this system also rewards students for exercising the breadth of their engineering abilities.

Our main assessment tools are rubrics and assignment statements. Our rubrics are presented in Appendix A and our other tools are available by contacting the author.

SO 2: Design

ABET Student Outcome 2: *an ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors*

New products are often developed using a phase-gate (or Stage-Gate [18]) process. In such a process, designs have to clear "gates" of set criteria as evaluated by management; to do so, design teams work in "phases" that have corresponding activities. Such processes reduce project risk by tying increased investment to evidence that the investment is likely to be worthwhile. For example, in Cooper's Stage-Gate system, clearing the "Go to Development" gate requires a team to do the "Build a Business Case" stage; this gate is often called the "money gate" because it is at that point that substantial funding is then made available for prototyping and testing.

ABET's definition of Engineering Design says in part, that it "involves identifying opportunities, developing requirements, performing analysis and synthesis, generating multiple solutions, evaluating solutions against requirements, considering risks, and making trade-offs;" most of these items are a sequence of reasonable steps in a design process, with the final two being issues that a team should address throughout the process. Our rubric dimensions mostly correspond to the steps listed here, with one added for "select single concept." All but the last rubric dimension correspond to a gate in the phase-gate process that is used in our capstone design course. Teams can give evidence for most of these steps by presenting and discussing corresponding exhibits such as a table of specifications or a glass box diagram; many useful exhibits are described in [19]. At each gate, each team also submits a "design checklist" which describes how they are considering risks as well as the numerous "considerations" listed in the outcome. In the design checklist, teams also report use of codes and standards, multiple constraints, and knowledge gained in prior coursework, all of which help demonstrate compliance with ABET Criterion 5. In capstone design, phase-gate deliverables must be approved by clients, which ensures that the project is developing in a way that the client will ultimately approve of. At the end of the year, the set of gate reports is assessed using the rubric.

Due in part to the unique and open-ended nature of capstone design projects, assigning scores to project work can be challenging and it is not clear how best to do it (see, for example, [20] pp. 119–126). Davis describes design reviews that are essentially a 3-step phase-gate process [21]. Davis's rubrics are worth considering as course materials because they are detailed, thoughtful, and emphasize documentation. With that said, these rubrics involve collecting much more detail than is required by ABET; furthermore, the rubrics may be unduly cumbersome for design experiences that precede capstone design. Baine et al. [22] share an SO 2 rubric in two parts, with the first tied to ABET language (but in a different way from our rubric) and the second addressing things such as troubleshooting, use of engineering science, creativity, and holistic thought.

SO 5: Teamwork and Project Management
ABET Student Outcome 5: *an ability to function effectively on a team whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks, and meet objectives*

The project management system in our capstone course is based on agile scrum. Agile practices involve the client in the development process [23]. Scrum is a related project management methodology [24]. In scrum, work takes place in sprints of 1–4 weeks. At the end of the sprint, a sprint review meeting is held focusing on progress made on developing the product; also, in a sprint retrospective meeting, team function is inspected and improvements are proposed. Agile and scrum were created for software development and have been adapted for hardware design [25]; notably, the latest edition of Winning at New Products now describes how to integrate agile and Stage-Gate [18]. It can be challenging to apply agile scrum to hardware due to the costs of prototyping, testing, and release to manufacturing. These challenges are lessened for capstone projects if they can be implemented with rapid prototyping tools, and if documentation and analysis are seen as evidence of progress. Agile scrum deals well with scope change, uncertainty, and iterative development and is thus a good fit for many client-based capstone projects.

In our capstone course, teams work in sprints of one to two weeks. Each sprint, a different team member takes on the role of sprint manager. At the end of the sprint, the sprint manager writes a sprint review report and sprint retrospective report. Project goals, which are big picture, are tracked on a goal list. Also, at four points during the project, students fill out the CATME survey [8] with additional questions on psychological safety [26].

Data for performance indicator (PI) 1 on "Provide leadership" is used to score the sprint retrospective report. This dimension is derived from the Member Strengths and Member Coaching scales in IDEALS [27]. That instrument is reliable and probably valid but the validity depends on implementation details. Our rubric collapses these scales into one dimension and uses a four- rather than five-point scale; these modifications streamline reporting to the program but may reduce reliability and validity. This choice is an example of our pragmatic approach. Within capstone, students do receive feedback for each of these separate scales.

The CATME additional questions on psychological safety are used to evaluate PI 2 "Create a collaborative and inclusive environment" because the scores are direct evidence of how the team environment is for each student. The main CATME dimensions have limited alignment with the wording of the outcome and the scores are not tied to samples of student work; an ABET program evaluator may thus give a shortcoming to programs that rely exclusively on CATME for assessment of this outcome. Although we do not use the main CATME items in program assessment, we do use the data for coaching teams.

Following the language of the outcome, project work is tracked at three levels of hierarchy: goals, objectives, and tasks. Goals are big-picture, such as clearing a phase-gate, or completing a major subsystem. Objectives are completable within a sprint. Tasks are completable within minutes or hours by a single person. The goal list is scored for PI 3 and one score is given for the whole team. The sprint review report is the main source of evidence for PIs 4 and 5, and is scored separately for each team member.

SO 1: Problem-Solving

ABET Student Outcome 1: *an ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics*

This outcome must be read in light of ABET's definition of a "complex engineering problem," which is broad and conveys that the focus is what a working engineer would see as a problem (see Ref. [28]), as opposed to a textbook problem. Although a complex engineering problem might not involve a mathematical model or even be quantitative, because the outcome mentions mathematics and because of the importance of models in mechanical engineering, our rubric is written with the assumption that a model would be the main tool in solving the complex engineering problem. A problem meets the definition of "complex" if it "includ[es] many component parts or sub-problems;" this characteristic is perhaps the most common and the simplest to demonstrate so we give it special focus.

Our SO 1 rubric uses performance indicators for "identify," "formulate," and "solve" steps of a problem-solving process. "Identify" is interpreted as stating the problem and "formulate" is taken to mean translating that problem into a set of related models.

To write the final "solve" dimension of this rubric, the program identified four criteria that are important for any model. This performance indicator is then scored based on how many of those criteria are met. Although rubric dimensions are typically constructed to describe a range of performance, it is occasionally reasonable to instead use a checklist. First, it can be hard for a team of faculty to reach consensus on typical rubric descriptors; in contrast, checklists can be readily developed through brainstorming. Second, the specificity of a checklist promotes reliability.

SO 3: Communication

ABET Student Outcome 3: *an ability to communicate effectively with a range of audiences*

Communication is assessed through presentations and reports at the end of each semester. These deliverables aggregate the work needed to pass through the gates. Students share their work in various forms with their client, other teams, and department faculty, which enables measurement of the "range of audiences" component of this outcome.

Our SO 3 rubric is based primarily on the AAC&U VALUE rubric on Oral Communication [29] and is applied to both presentations and reports. Now, the VALUE project also produced a Written Communication rubric. However, our program and institution prefer using a single rubric to evaluate a given outcome. In this case, the Oral Communication rubric was an adequate starting point for evaluating both presentations and reports. In contrast, some items on the Written Communication rubric are more appropriate for scholarly writing than for design projects; for example, the descriptors for the "Sources and Evidence" dimension are more suited for scoring use of citations than for presentation of data collected by the design teams. In contrast, the Oral Communication rubric has an item on "Supporting Material;" we reworded the examples of supporting material to refer to typical sources of evidence used by our teams, namely, "illustrations, charts, graphs, tables;" upon making that adjustment, the descriptors were clearly applicable to design project work. The Oral Communication rubric has items on having a "Central Message" and "Organization," both of which are critical facets of technical communication. For presentations only, we score the "Delivery" item drawn from the Oral Communication rubric. Presentations typically use slides with text; such writing, as well as writing in reports, is reasonably scored with our "Style" dimension, the descriptors of which are taken from the "Control of Syntax and Mechanics" Written Communication dimension.

SO 4: Professional Decision-Making

ABET Student Outcome 4: *an ability to recognize ethical and professional responsibilities in engineering situations and make informed judgments, which must consider the impact of engineering solutions in global, economic, environmental, and societal contexts*

One part of IDEALS assessed professional responsibility and is reliable and probably valid for the relevant outcome at the time [30]. In keeping with the text of SO 4, the rubric reported here places more emphasis on judgment and considering broad factors; it also has a performance indicator on identifying norms.

Many previous efforts at assessing this or related outcomes focus on application of codes of engineering ethics (e.g., [30]) and moral reasoning (e.g., [1], which makes use of an AAC&U rubric on ethics [29]). However, the rubric shown here promotes use of a broader set of relevant norms because such norms are likely to enable judgments. For example, when designing a machine, an engineer should guard rotating parts, perform calculations using standards, and ensure that a typical factor of safety is met; such judgments are made based on norms ranging from law to standards to informal best practices. Following norms prevents harm, and documentation of use of norms prevents liability.

Using a broad definition of norms also promotes consideration of broad factors and makes it straightforward for students to show that they are doing so. For example, students can review a hazards checklist (e.g., Ref. [31] Appendix A) or a list of design for environment guidelines (e.g., [32]), apply those guidelines to their projects, and explain how they did so.

The final dimension of this rubric, like the final dimension of the SO 1 rubric, is scored based on adherence to a checklist; again, doing so made it easy to construct and to apply.

SO 6: Experimentation
ABET Student Outcome 6: *an ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions*

This rubric has dimensions that mostly follow the language of the outcome. It happens to have many similarities to that of [1] but differs in separating "analyze" from "interpret", with "analyze" corresponding to figures and tables and "interpret" corresponding to the results section of a report.

SO 7: Self-Directed Learning
ABET Student Outcome 7: *an ability to acquire and apply new knowledge as needed, using appropriate learning strategies.*

Although comparable in scope to the former ABET outcome on lifelong learning, the wording of this outcome differs enough that a new rubric is needed. Few appropriate rubrics are available in the literature. This outcome could reasonably be interpreted in various ways and assessed differently based on context; for example, this outcome has been assessed in a measurement systems course with rubric items developed specific to individual lab activities [33].

The language on "apply new knowledge as needed" reflects how engineers are expected to learn in response to a business outcome, with the learning ultimately being demonstrated through that outcome being met. Thus, this outcome goes beyond information literacy. Working engineers also engage in open-ended learning that is driven by curiosity rather than immediate need; the AAC&U rubric on Lifelong Learning [29] is appropriate for measuring such learning so others have assessed this outcome using a rubric based on that one [1]. Potential disadvantages to that approach are that it places less emphasis on learning to a specific end and it relies on student reflection on learning outside of a course context.

Our tools are based on those given by colleagues who had previously been involved in developing a tool for assessing professional development as part of IDEALS [34]; their change in approach may be tied to the change between the current outcome and the corresponding one from the previous set.

Acknowledgments
The assessment tools here are the product of collective effort. The SO 3 rubric is based on the AAC&U Oral Communication and Written Communication rubrics. The SO 5 and 7 rubrics, and

related assignment statements and templates, are based on those generously provided by Patricia Brackin and Jay McCormack. The SO 6 rubric is based on one generously provided by Craig Beal. The SO 1 rubric was originally developed by the Engineering Department at King's College. The SO 2 and 4 rubrics were developed by the Mechanical Engineering faculty at King's College, who also revised all of the rubrics described here. I am grateful for the generosity of those who shared rubrics and for the collaborative efforts of my colleagues.

References

[1] A. Battistini and W. A. Kitch, "Make assessment straightforward: A case study on the successful implementation of ABET student outcomes 1-7," in *2021 ASEE Virtual Annual Conference Content Access*, 2021.

[2] ABET, "Fundamentals of program assessment workshop," ABET, Tech. Rep., 2019.

[3] G. Watkins, "Incorporating new ABET outcomes into a two-semester capstone design course," in *Proceedings of the 2022 Capstone Design Conference, Dallas, Texas*, 2022.

[4] K. Meah, D. Hake, and S. D. Wilkerson, "A multidisciplinary capstone design project to satisfy ABET student outcomes," *Education Research International*, vol. 2020, 2020.

[5] D. C. Davis, K. L. Gentili, M. S. Trevisan, and D. E. Calkins, "Engineering design assessment processes and scoring scales for program improvement and accountability," *Journal of Engineering Education*, vol. 91, no. 2, pp. 211–221, 2002.

[6] J. Lebeau, M. Trevisan, J. McCormack, S. Beyerlein, D. Davis, P. Leiffer, P. Thompson, H. Davis, S. Howe, P. Brackin *et al.*, "Alumni perspective on professional skills gained through integrated assessment and learning," *International Journal of Engineering Education*, vol. 30, no. 1, pp. 48–59, 2014.

[7] J. McCormack, S. Beyerlein, P. Brackin, E. Odom, and D. Cordon, "Snapshot style poster sessions for formative inter-team design feedback in capstone courses," *International Journal of Engineering Education*, vol. 31, no. 6(B), pp. 1736–1747, 2015.

[8] M. W. Ohland, M. L. Loughry, D. J. Woehr, L. G. Bullard, R. M. Felder, C. J. Finelli, R. A. Layton, H. R. Pomeranz, and D. G. Schmucker, "The comprehensive assessment of team member effectiveness: Development of a behaviorally anchored rating scale for self-and peer evaluation," *Academy of Management Learning & Education*, vol. 11, no. 4, pp. 609–630, 2012.

[9] L. R. Lattuca, P. T. Terenzini, J. F. Volkwein, and G. D. Peterson, "Engineering change: A study of the impact of EC2000," *The Bridge*, pp. 5–13, 2006.

[10] T. W. Banta and C. Blaich, "Closing the assessment loop," *Change: The Magazine of Higher Learning*, vol. 43, no. 1, pp. 22–27, 2010.

[11] E. T. Metzler and L. Kurz, "Assessment 2.0: An organic supplement to standard assessment procedure." National Institute for Learning Outcomes Assessment, Tech. Rep., 2018.

[12] N. A. Jankowski, J. D. Timmer, J. Kinzie, and G. D. Kuh, "Assessment that matters: Trending toward practices that document authentic student learning." National Institute for Learning Outcomes Assessment, Tech. Rep., 2018.

[13] P. T. Terenzini, "Assessment with open eyes: Pitfalls in studying student outcomes," *The Journal of Higher Education*, vol. 60, no. 6, pp. 644–664, 1989.

[14] D. Eubanks, "A guide for the perplexed," *Intersection*, pp. 4–13, 2017.

[15] ——, "Addressing the assessment paradox," *Peer Review*, vol. 20, no. 4, pp. 30–32, 2018.

[16] D. R. Bacon and K. A. Stewart, "Why assessment will never work at many business schools: A call for better utilization of pedagogical research," *Journal of Management Education*, vol. 41, no. 2, pp. 181–200, 2017.

[17] C. M. Chewar, K. L. Huggins, and J. R. Blair, "Avoiding the pratfalls of program assessment," in *Working group reports on ITiCSE on Innovation and technology in computer science education*, 2006, pp. 29–33.

[18] R. G. Cooper, *Winning at new products: Creating value through innovation*, 5th ed. Basic Books, 2017.

[19] C. Dym, P. Little, and E. Orwin, *Engineering Design: A Project-Based Introduction*, 4th ed. Wiley, 2014.

[20] S. D. Sheppard, K. Macatangay, A. Colby, and W. M. Sullivan, *Educating Engineers: Designing for the Future of the Field*. Jossey-Bass, 2008.

[21] D. Davis, *Project Design Reviews: A Mentor for Successful Design Reviews*. Verity Design Learning, 2018.

[22] N. Baine, K. Brakora, and C. Pung, "Evaluating ABET student outcome (2) in a multidisciplinary capstone project sequence," in *2022 ASEE Annual Conference & Exposition*, 2022.

[23] M. Fowler, J. Highsmith *et al.*, "The agile manifesto," *Software development*, vol. 9, no. 8, pp. 28–35, 2001.

[24] K. Schwaber and J. Sutherland, "The scrum guide. 2020," *Accessed April*, 2021.

[25] D. G. Ullman, *Scrum for Hardware Design: Supporting Material for The Mechanical Design Process*. David G. Ullman, 2019.

[26] A. Edmondson, "Psychological safety and learning behavior in work teams," *Administrative science quarterly*, vol. 44, no. 2, pp. 350–383, 1999.

[27] D. Davis, M. Trevisan, R. Gerlick, H. Davis, J. McCormack, S. Beyerlein, P. Thompson, S. Howe, P. Leiffer, and P. Brackin, "Assessing team member citizenship in capstone engineering design courses," *International Journal of Engineering Education*, vol. 26, no. 4, pp. 771–783, 2010.

[28] D. Jonassen, J. Strobel, and C. B. Lee, "Everyday problem solving in engineering: Lessons for engineering educators," *Journal of Engineering Education*, vol. 95, no. 2, pp. 139–151, 2006.

[29] Association of American Colleges & Universities, "VALUE rubric development project," Association of American Colleges & Universities, Tech. Rep., 2017.

[30] J. McCormack, S. Beyerlein, D. Davis, M. Trevisan, J. Lebeau, H. Davis, S. Howe, P. Brackin, P. Thompson, R. Gerlick *et al.*, "Contextualizing professionalism in capstone projects using the ideals professional responsibility assessment," *The International journal of engineering education*, vol. 28, no. 2, pp. 416–424, 2012.

[31] K. L. d'Entremont, *Engineering Ethics and Design for Product Safety*. McGraw Hill, 2020.

[32] C. Telenko, J. M. O'Rourke, C. Conner Seepersad, and M. E. Webber, "A compilation of design for environment guidelines," *Journal of Mechanical Design*, vol. 138, no. 3, 2016.

[33] J. Mynderse, "Assessing ABET student outcome 7 (new knowledge) with measurement systems," in *2022 ASEE Annual Conference & Exposition*, 2022.

[34] J. McCormack, S. Beyerlein, P. Brackin, D. Davis, M. Trevisan, H. Davis, J. Lebeau, R. Gerlick, P. Thompson, M. J. Khan *et al.*, "Assessing professional skill development in capstone design courses," *International Journal of Engineering Education*, vol. 27, no. 6, pp. 1308–1323, 2011.

Appendix A: Rubrics for ABET Outcomes

ABET Student Outcome 1: an ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics

	Exemplary (4)	Accomplished (3)	Developing (2)	Beginning (1)
Identify a complex engineering problem	A problem is described with sufficient detail and purpose that someone unfamiliar with the project can model it to achieve a stated end. Schematics and tables of given information are comprehensive.	A problem is described with almost all of the detail and purpose that someone unfamiliar with the project can model it to achieve a stated end. Schematics and tables of given information are missing some information.	The problem description is only comprehensible to someone already familiar with the problem. Schematics and tables of given information are missing critical information.	The problem is seriously misunderstood or expression of the problem is superficial.
Formulate a complex engineering problem	The problem is properly decomposed into multiple models that are united under an overall model.	The problem is decomposed into enough models that are united enough to enable a reasonable solution.	Major features of the problem are not modeled or model components are combined inappropriately.	The problem is only modeled superficially, neglecting or misapplying most major components.
Solve a complex engineering problem	•Problem solved accurately or with only minor errors •Intermediate results clearly indicated. •Results are checked for reasonableness. •A conclusion is drawn that follows the model results.	Meets 3 of the criteria for Exemplary performance.	Meets 2 of the criteria for Exemplary performance.	Meets 1 of the criteria for Exemplary performance.

ABET Student Outcome 2: an ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors

	Exemplary (4)	Accomplished (3)	Developing (2)	Beginning (1)
Identify opportunities	Goal stated from client point of view Goal posed as opportunity	Client view partially captured Opportunity unclear	Goal posed in technical rather than human terms	Need statement flawed, e.g., erroneous, biased, impaired by implied solutions, fake requirements taken literally
Develop requirements	Objectives are comprehensive but not redundant Objectives describe value (rather than functions or means) Objectives ranked based on priority Metrics are clear and appropriate	Meets 3 of the criteria for Exemplary performance.	Meets 2 of the criteria for Exemplary performance.	Meets 1 of the criteria for Exemplary performance.
Decompose a problem into functions and devise means to perform them	Functions decomposed comprehensively Multiple creative means are proposed for each function	Most functions and functional relationships indicated Multiple means proposed for most functions	Most functions listed but connections (power, material) not indicated Means for most functions are superficial	Token effort at function decomposition Means unrelated to functional decomposition
Generate multiple solutions	Means combined to develop multiple solutions	Means combined to develop multiple solutions but solutions focus on limited parts of the design space	Multiple solutions developed but only one developed in detail	One solution developed
Select single concept	Concept selected based on consideration of all criteria, emphasizing most important objectives	Concept selected based on consideration of most criteria, with some mistakes in emphasis and estimation of performance	Concept selected based on consideration of some criteria Important criteria neglected Criteria emphasized arbitrarily	Very few criteria used or very few options considered
Evaluate design against requirements	Performance for each requirement is quantified[1] and compared with targets Judgment about design well-reasoned and based on evidence	Performance quantification is sound but is somewhat incomplete or inaccurate Judgment is sound but there is some misapplication of reasoning or misuse of evidence	Performance quantification is unsound due to being incomplete or inaccurate Judgment is unsound or unclear	Performance quantification is unfounded No judgment stated

Consider broad factors[2], as relevant	All broad factors explicitly considered All relevant factors considered in detail	Some broad factors explicitly considered Some factors considered in detail	Few broad factors explicitly considered Few factors considered in detail	Broad factors mentioned but not considered in design

[1]Quantification should be reasonable given the circumstances. For many metrics, the ideal would be testing or results of user surveys. Estimates or models may be appropriate alternatives. Quantification should be documented.

[2]Namely, public health, safety, and welfare, as well as global, cultural, economic, environmental, and societal factors

ABET Student Outcome 3: an ability to communicate effectively with a range of audiences

	Exemplary (4)	Accomplished (3)	Developing (2)	Beginning (1)
Central Message	Central message is compelling (precisely stated, appropriately repeated, memorable, and strongly supported.)	Central message is clear and consistent with the supporting material.	Central message is basically understandable but is not often repeated and is not memorable.	Central message can be deduced, but is not explicitly stated in the communication.
Organization	Organizational pattern (specific introduction and conclusion, sequenced material within the body, and transitions) is clearly and consistently observable and is skillful and makes the content of the communication cohesive.	Organizational pattern (specific introduction and conclusion, sequenced material within the body, and transitions) is clearly and consistently observable within the communication.	Organizational pattern (specific introduction and conclusion, sequenced material within the body, and transitions) is intermittently observable within the communication.	Organizational pattern (specific introduction and conclusion, sequenced material within the body, and transitions) is not observable within the communication.
Supporting Material	Supporting materials (illustrations, charts, graphs, tables) show information or analysis that significantly supports and compliments the communication	Supporting materials (illustrations, charts, graphs, tables) show information or analysis that generally supports the communication	Supporting materials (illustrations, charts, graphs, tables) show information or analysis that partially supports the communication	Insufficient supporting materials (illustrations, charts, graphs, tables) show information or analysis that minimally supports the communication.
Style	Uses language that skillfully communicates meaning with clarity and fluency, and is virtually error-free.	Uses straightforward language that generally conveys meaning and generally supports the effectiveness of the communication. The language has few errors.	Uses language that generally conveys meaning with clarity, although the language partially supports the effectiveness of the communication.	Uses language that sometimes impedes meaning because of errors in usage.
Oral Communication only: Delivery	Delivery techniques (posture, gesture, eye contact, and vocal expressiveness) make the presentation compelling, and speaker appears polished and confident.	Delivery techniques (posture, gesture, eye contact, and vocal expressiveness) make the presentation interesting, and speaker appears comfortable.	Delivery techniques (posture, gesture, eye contact, and vocal expressiveness) make the presentation understandable, and speaker appears tentative.	Delivery techniques (posture, gesture, eye contact, and vocal expressiveness) detract from the understandability of the presentation, and speaker appears uncomfortable.

ABET Student Outcome 4: an ability to recognize ethical and professional responsibilities in engineering situations and make informed judgments, which must consider the impact of engineering solutions in global, economic, environmental, and societal contexts

	Exemplary (4)	**Accomplished (3)**	**Developing (2)**	**Beginning (1)**
Identify and apply relevant ethical and professional norms[1]	All relevant norms identified specifically and applied appropriately	All essential norms identified specifically and most applied correctly	Essential norms not identified, or applied in a way that could lead to problems	Norms only identified in broad strokes, or not meaningfully applied
Consider broad factors[2], as relevant	All broad factors explicitly considered All relevant factors considered in detail	Some broad factors explicitly considered Some factors considered in detail	Few broad factors explicitly considered Few factors considered in detail	Broad factors mentioned but not related to engineering judgment
Make informed judgments	All affected parties understood Relevant facts gathered and given appropriate emphasis Judgment is sophisticated (e.g., addressing conflicting needs or considering multiple possible solutions). Judgment follows from evidence and principles	Meets 3 of the criteria for Exemplary performance.	Meets 2 of the criteria for Exemplary performance.	Meets 1 of the criteria for Exemplary performance.

[1]Such as ethical principles, legal responsibilities, codes, standards, regulations, norms protecting reputation

[2]Namely, public health, safety, and welfare, as well as global, cultural, economic, environmental, and societal factors

ABET Student Outcome 5: an ability to function effectively on a team whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks, and meet objectives

	Exemplary (4)	Accomplished (3)	Developing (2)	Beginning (1)
Provide leadership	Impressive grasp; insightful description of evidence Insightful description of benefits; inspires continued actions Superb explanation of desired state; insightful details Impressive plan; steps clearly likely to be implemented	Credible grasp of strengths; good list of evidence Clear mention of benefits; helpful connection to action Good explanation of desired state; many specific details Clear. Good plan; most steps feasible to implement	Moderate grasp of strengths; some relevant evidence Moderate mention of benefits; some relevance to actions Okay description of state; some correct details Reasonable steps; some possible to implement	Little understanding; little attempt to explain strengths Casual mention of benefits; little relevance to actions Weak description of desired state; few correct details Mostly vague steps; most are difficult to implement
Create a collaborative and inclusive environment	CATME items, see below			
Establish project goals	Value clear and compelling Scope is so clear that project risk is minimized Project success criteria are exemplary	Value articulated Scope anticipates the bulk of the work Project success defined	Value referenced Scope anticipates some major tasks Criteria for project success are given but judgment of success would be subjective	Value alluded to Scope sufficiently unclear that the project would be impossible or trivial in the time available Criteria for project success are unclear
Write objectives that enable progress on goals	Objectives decompose goals Objectives are SMART Objectives ordered to reflect project priorities, available work, and time Objectives are so well-written that project risk is minimized All objectives are completed with quality	Objectives decompose goals Objectives are SMART Objectives ordered to reflect project priorities, available work time, and project risk Most objectives are acceptably completed	Objectives decompose goals but some are missing Objectives are <75% SMART Objective ordering reflects some intention Lack of objective completion entails an increased workload in the future	Objectives are unrelated to goals Objectives are <50% SMART Objective ordering arbitrary Lack of objective completion entails decreased project scope

Define tasks to complete objectives	Tasks completely decompose objectives Task assignment is fair and realistic Tasks are SMART All tasks are completed with quality	Tasks decompose objectives Task assignment is fair and realistic Tasks are SMART The most important tasks are completed	Tasks decompose objectives but some are missing Task assignment is unfair or unrealistic Tasks are <75% SMART Lack of task completion entails an increased workload in the future	Tasks are unrelated to objectives Task assignment is unclear or so poor that it increases project risk Tasks are <50% SMART Lack of task completion entails decreased project scope

Notes on evidence:
PI 1 Status report: peer coaching
PI 2 Peer assessment using 7-point Likert scale, target score 5.5
PI 3 Student-written statement of project goals
PI 4 Status report
PI 5 Status report

PI 2 is measured by peer assessments using the following CATME Psychological Safety items on a 1–7 scale

- If you make a mistake on this team, it is often held against you. (scale reversed)
- Members of this team are able to bring up problems and tough issues.
- People on this team sometimes reject others for being different. (scale reversed)
- It is safe to take a risk on this team.
- It is difficult to ask other members of this team for help. (scale reversed)
- No one on this team would deliberately act in a way that undermines my efforts.
- Working with members of this team, my unique skills and talents are valued and utilized.
- PI 2 attainment is defined as having a mean score of 5.5 or higher (accounting for reversed scales, of course).

If a target is met, the PI score is recorded as a 3; otherwise, it is a 2.
Because SO attainment is defined by the median, a more precise mapping is not needed.

ABET Student Outcome 6: an ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions.

	Exemplary (4)	Accomplished (3)	Developing (2)	Beginning (1)
Design and conduct an experiment	The experiment has a clear and worthwhile purpose. A logical approach is used to address the problem statement. Procedure described to argue for confidence in results. Steps and the sequence are documented clearly. Multiple trials are used to reduce the influence of random variation.	The experiment has a clear purpose but a more valuable purpose could have been addressed. Approach to addressing problem statement is workable and produces reasonable data. Sequence of steps clear, but not documented. Limited number of experimental trials.	The experiment's purpose is unclear or contrived. Procedure reads like instructions to be followed. Weak motivation for specific approach. Some problems with the procedure are apparent. Experiments performed without any repetition.	The experiment has no stated purpose. Problem statement not addressed. Procedure unworkable or incomplete. Experimental trials missing.
Analyze data	The results of the procedure are described and presented via relevant data structures, such as figures and tables. Data structures are labeled clearly. Measures of the quality of or confidence in results are included with visual representations (error bars, etc.). Data appropriate for addressing problem statement.	Formatting of data in figures and tables could be improved by choosing better subsets of data, scales, formats, etc. Some ambiguous labeling.	Data is not reduced and may be given in lists or printouts instead of well-formatted figures or tables. Data structures poorly labeled. Data are given with little indication of uncertainty.	Formatting is weak. Data missing, erroneous, or unclear. Quality of results not indicated. Data inapplicable to problem statement.

Interpret data	Major trends in data are described. Outliers and/or erroneous data are discussed and handled appropriately. If applicable, student provides thoughtful analysis of the quality of the match of theory and experiment and gives rational explanation for observed differences. Sources of uncertainty are quantified and effects on resulting values are estimated.	Results are compared to expectations. If applicable, comparison to theory is included. Weak or missing analysis of mismatch. Data is discussed generally, without looking at the details. Uncertainty quantified, but not properly propagated or numbers are unsupported.	Comparison to expectations missing. Comparison to theory/models contains errors. Data analysis is very basic.	Expectations are not addressed. Comparison to theory/models missing, inaccurate. No quantification of the uncertainty. No analysis of sources of error.
Draw conclusions	Questions and issues in the problem statement are answered and supported by summarized data. Conclusion depends on presented data. Course concepts and terminology used in explanation.	Problem statement partially answered. Course concepts mentioned in general, but not strongly connected.	Problem statement mentioned but conclusions not offered. Conclusions unsupported by data. Weak use of concepts & terminology.	Problem statement ignored. Conclusions missing or completely incorrect. Course concepts and terminology not apparently employed in completion of lab.

ABET Student Outcome 7: an ability to acquire and apply new knowledge as needed, using appropriate learning strategies

	Exemplary (4)	Accomplished (3)	Developing (2)	Beginning (1)
Identify a knowledge need by writing a learning objective (LO)	The LO captures the future ability of the learner. It is clear how attainment of the LO will be measured. Achieving the LO will require effort commensurate with the assignment. Achieving the LO will have a positive long-term impact on the student.	The LO captures the future ability of the learner. The plan to measure the LO needs minor revision. Achieving the LO will require effort commensurate with the assignment. Achieving the LO will enhance the project.	The LO focuses on content rather than ability. There is ambiguity in how attainment of the LO will be measured or the measures are not comprehensive. It is unclear how much effort is needed to achieve the LO. The LO is related to the project and may enhance it.	The LO is unclear. There is minimal information on how attainment of the LO will be measured. Achieving the LO is impossible or requires a small time investment. Achieving the LO will not enhance the project.
Develop a learning plan	The LO is broken into an insightful list of topics that clearly required substantial learning to identify. The topics are all fundamental to achieving the LO. The resources are rich and varied. Excellent plan; highly likely to achieve LO.	The LO is broken into at least three topic areas. The topics are all relevant to the LO. The resources are varied, described with sufficient detail to see their relevance, and are likely to aid in learning. Acceptable plan; likely to achieve LO	The LO is insufficiently broken into topics or the topics are not all relevant to the LO. The resources are uninspired, incomplete, vague, or unlikely to aid in learning. Unrealistic plan; unlikely to achieve LO.	The LO is rephrased but not broken into topics. Resources are not clearly stated. Vague plan; unlikely to achieve LO.
Apply the knowledge to an engineering goal	The LO is achieved, enhancing the project. Achieving the LO will have a positive, long-term effect on the student.	The LO is achieved, enhancing the project.	LO is partially achieved.	Poor evidence or irrelevant evidence of LO achievement.