ŌTAUTAHI CHRISTCHURCH AOTEAROA NEW ZEALAND
35TH AUSTRALASIAN ASSOCIATION FOR ENGINEERING EDUCATION ANNUAL CONFERENCE
8-11 DEC 2024
THE ENGINEER AND THE WORLD

A typology for and review of educator and student perspectives of hands-on practical experiences in engineering education

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ABSTRACT

CONTEXT

In engineering education, there is a tension between the delivery of foundational engineering science and preparation for practice though engineering design. This tension has given rise to significant research on delivery and assessment approaches, but the role of practicals in bridging the gap between engineering science and engineering design has lacked attention. This is surprising given that accrediting bodies place substantial value on practical activities requiring that universities maintain the quality and staffing of their laboratories.

PURPOSE OR GOAL

Although the engineering practical appears to be an ideal platform for authentic, high-value learning experiences, the challenge of developing authentic practicals is at least a century old problem (Mann, 1918). Our goal is to investigate this challenge by evaluating practicals in an engineering curriculum.

APPROACH OR METHODOLOGY/METHODS

A typology is proposed that combines elements of the 5-D framework for authentic assessment of Gulikers et al. (2004) and the authentic assessment blueprint of Villarroel et al. (2018). The typology is presented alongside examples, highlighting the need for clarity of purpose and a programmatic view in the design of practicals to scaffold the underpinning competencies and fully realise their educational potential.

ACTUAL OR ANTICIPATED OUTCOMES

A new typology is presented and discussed using examples to demonstrates its value for critically evaluating and designing (or improving existing) engineering practicals.

CONCLUSIONS/RECOMMENDATIONS/SUMMARY

The typology will assist educators in the design engineering practicals including their programmatic role in the context of an engineering degree.

KEYWORDS

Engineering practicals, laboratories, assessment design

Introduction

Within engineering education, a tension exists between the delivery of foundational engineering science and the preparation for practice that comes from an increased focus on engineering design. This tension has given rise to significant research on delivery approaches and assessment techniques (e.g. Johri & Olds, 2014), but one area that has consistently lacked attention is the role of hands-on practical teaching in bridging the gap between engineering science and engineering design and the opportunity to overlay practice of global skills. This is surprising given that accrediting bodies appear to place substantial value on practical activities requiring that universities maintain the quality of their laboratories and ensure appropriate technical staff are available, (Engineers Australia, 2017), or to specify the requirement for either general or specific laboratory activities (ABET, 2024).

Examination of the history of engineering education shows that the tension between engineering science and practical engineering design has been ongoing for well over 100-years. For example, the well-established review by Mann (1918) was borne out of a suggestion that students were failing to both gain a satisfactory grounding in engineering science and adequate preparation for practical engineering design. In addition to these technical skills, Mann's research found that non-technical skills were the most significant indicator of future success as an engineer, and this finding is well aligned with work of current engineering technical societies who continue to identify global skills as critical to success (Engineers Australia, 2019).

Over the past two decades there has been a significant uptick in research devoted to assessment types, with a general agreement that there must be a rebalancing away from traditional forms such as the test or exam which might focus on algorithmic problems or recall of facts and toward 'authentic assessment' which has increased constructive alignment between instruction and assessment (Villarroel et al., 2017). While the exact definition of authentic assessment is itself a matter of research, in general the approach seeks to focus assessment on the demonstration of competencies that align with completing tasks associated with practice of a particular discipline. Well-designed authentic assessment also seeks to incorporate and build the resilience and flexibility needed to deal with real-world uncertainty and the communication skills required to work with people from different backgrounds, all of which are repeatedly raised as critical for the success of graduates (Gulikers et al, 2004).

Of significant note, even in a period where individual practical classes could run over a full day, there existed a challenge in devising authentic or open-ended practical experiences. For example while Mann (1918) points to industrial chemistry laboratory classes in which students were asked to develop a new product that is cheaper and better than any available for purchase but with no methodology provided, Benedict suggests that the 'the chief problem for students is likely to be that of following directions intelligently rather than that for finding answers to questions' and laboratory classes were found to mostly test the ability for a student to follow directions and verify principles rather than finding new answers to questions (Benedict, 1915). The focus on following a specific set of directions would appear to be further reinforced by off-the-shelf experiments that are currently widely available as they typically focus on the observation and measurement of a specific principal using a highly controlled, purpose-built apparatus which limits the ability to explore different methodologies.

Research question

At face value, the engineering practical appears to be an ideal vessel for authentic assessment bridging the gap between engineering science and engineering design with an additional overlay of global skills associated with uncertainty and communication. One might expect students to be exposed to the collection and processing of real (i.e. messy and/or uncertain) data by applying engineering science principles, and then use this data to carry out engineering design through to completion and communication. However, despite the obvious potential, and the expectation from accrediting bodies that practicals are high value learning experiences, the challenge of developing authentic hands-on practical experiences appears to be a century old problem.

We seek to investigate this issue by developing a typology of engineering practical experiences. It is expected that the typology will assist educators in the design and redesign of engineering practicals such that they are able to better understand the educational dimensions of the practical activity, their costs and benefits as well as their role in the broader context of an engineering qualification.

Typology

In this paper a 5-D typology for application to engineering practical experiences is presented (Figure 1). The typology draws on attributes of the authentic assessment framework by Gulikers et al. (2004) and the authentic assessment blueprint of Villarroel et al. (2017). These were selected as starting points, in the absence of existing typologies specific to practicals, as their focus on authenticity aligns well with the common attributes of practicals. Dimensions from the original typologies were combined into five that seek a balance between ease of use and discrimination. The 5 dimensions are:

(i) **Realism of task**: examining to degree to which tasks are authentic to engineering practice or, if not authentic to practice, the degree to which they provide a frame of reference used in practice.

(ii) **Cognitive challenge:** the degree to which the activity allows students to move beyond the lower levels of Bloom's Taxonomy (Krathwohl, 2002), enabling connections to be developed between multiple ideas or for new ideas to be developed.

(iii) **Evaluative Judgement:** the ability for the activity to either foster the development of engineering judgement or apply engineering judgement in the completion of the task.

(iv) **Social context:** the degree and nature of engagement with peers or instructors while completing tasks or in later professional practice.

(v) **Educational intent:** defines the underlying skills and/or broader competencies that are intended to be developed via the completion and assessment of the activity.

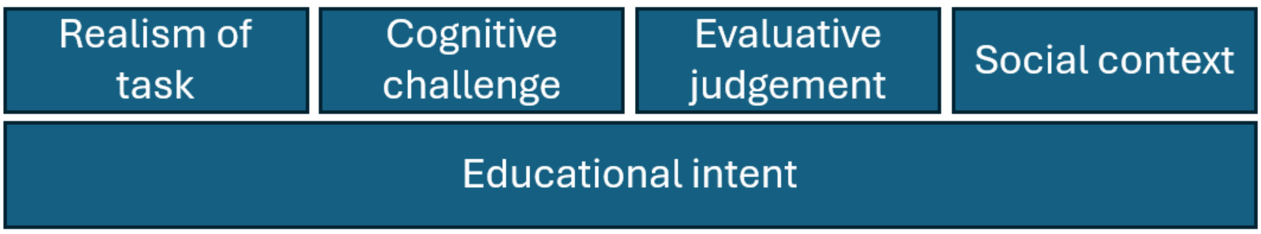

Figure 1: overview of the 5-D typology for assessing engineering practicals

Table 1 provides a non-exhaustive list of key questions to stimulate reflection and discussion when evaluating or designing practical experiences in line with the typology's dimensions. Importantly, it must be emphasised that it is not the intention of the typology to imply that practicals are either 'good' or 'bad' based on the number of questions answered in the affirmative (or negative). Rather, the typology provides a tool intended to help those that are looking after individual courses, suites of courses, or a program to identify and map if there is a sufficient range and sufficient scaffolding of activities to effectively support student learning.

Following Table 1 a more detailed description of the dimensions is provided alongside a discussion of how an activity may be mapped as part of a broader suite of activities using examples. For example, even tasks which might not be authentic to practice or might not provide a high degree of cognitive challenge at face value, may be an important scaffolding step in the education of an engineer (whereas, a highly open-ended, socially complex task that requires the application of significant engineering judgement may be less appropriate, or indeed overwhelming for students, in early introductions to this aspect of practice).

Table 1: detailed description of typology criteria

Key questions	Description
Realism of tasks	
Demonstration versus hands-on?	Is the task undertaken by the students or demonstrated to the student?
Knowledge/skill building versus connection building?	Is the task is undertaken to acquire or demonstrate competency in a specific skill or undertaken to build connections/understand the consequences of an action?
Authentic to practice or authentic academic achievement?	Is the task authentic to what is undertaken while practicing or to develop a specific skill or judgement necessary for practice?
Scale, resourcing, time reflective of authenticity in practice verses simplified for exposition	Is the scale, resourcing and time devoted to the activity authentic or is it simplified for exposition.
Cognitive challenge	
Simplified/well-structured or complex/ill-structured?	Does the activity focus on following a prescribed set of instructions or does it require problem solving/decision making to enable completion? This question should be applied separately to the activity and the interpretation/presentation of results.
Tightly time boxed or flexible?	Do tasks need to be completed within a reasonable (typically scheduled) time or is there flexibility in time to explore solutions and build new connections.
Evaluative judgement	
Degree to which tasks require application of 'engineering judgement'.	Does the activity require students to exercise 'engineering judgment' including self-checking, critical reflection, observation or prediction to interpret the approach, collect information or interpret results.
Open-ended versus specified questions	Are students prompted to address specific questions or is the investigation task or reporting largely open-ended?
Social context	
Individual or group work?	Is the task completed in a group or individually?
Collaborative or competitive	Do the students genuinely need to work as a team to complete a task or are the students able to complete the task alone even if it is undertaken in a group setting?
Teacher driven or discovery driven?	Does the task or an aspect of the task allow for student led activity/interpretation or is it instructor led?
Face-to-face versus broadcast	Is the activity observed via simulation or broadcast, or is it observed in the real-world?
Educational intent	
What are the underlying technical or global skills that are developed through the activity?	For example, conceptual understanding, intrinsic engagement and motivation, inquiry and discovery, integration of knowledge, ethical and professional behaviour, development of communication skills, development of the scientific method.
Formative or summative skill development?	Is all or part of the task being undertaken for learning or is it part of assessment of learning?

Realism of task considers the degree to which tasks are authentic to engineering practice or if not authentic to practice the degree to which they provide a frame of reference used in practice. To assess where a task sits within this theme in Table 1, questions related to authenticity, scale and resourcing, knowledge building versus skills building and the delivery mode of the activity (demonstration versus hands-on) are asked. When considering this theme, the following are important to remember:

- Not all tasks need to be authentic to practice or hands-on. For example, consider the case of a materials practical that may be delivered to civil or mechanical engineering students, in which a piece of steel is tested to failure to determine its material characteristics. The physical act of testing the material is not authentic to practice for a civil or mechanical engineer, and given the high cost of the test equipment, the activity is most often delivered as a demonstration, but this does not make the activity unworthy of resourcing. That is, by observing this demonstration and interpreting test results students gain an understanding material behaviour which otherwise might only be developed through the presentation of a standard mathematical material model.
- A further important factor to consider under the theme or realism is the relationship between the physical scale of the activity and resourcing. For example, real world scale for some electronic engineering applications may be possible to recreate in a teaching laboratory using relatively simple equipment and low-cost consumables. Whereas, in the discipline of civil engineering it is unlikely that many student practicals can be delivered at the scale of engineering practice. This does not mean that practicals are less important in civil engineering than in electronic engineering, but rather that the impact of scale must be considered as it relates to both the educational intent of the activity and how the activity is resourced.

Cognitive challenge considers the degree to which the activity allows students to move beyond the lower levels of Bloom's Taxonomy (Krathwohl, 2002; Bloom, 1956), enabling connections to be developed between multiple ideas or for new ideas to be developed. When considering cognitive challenge, it is important to remember that not all activities must be highly complex or ill-structured in order to be valuable and indeed not all authentic engineering practice is complex or ill-structured. For example, consider a practical to tune the parameters for a feedback controller. Authentic practice can be to use a standard control strategy and to choose parameters following a well-established procedure. In this case there is value in learning the procedure and observing outcomes. An alternative approach, which would exercise higher levels of cognitive challenge, might leave students to design a control strategy and to derive aspects of their solution from theory.

Evaluative judgement considers the ability for an activity to allow students to demonstrate the application of 'engineering judgement' in the completion of the task. This may be in defining the process required to achieve a specific end point, the application of judgement to connect underlying theory to messy real-world observations, or the separation of key concerns from those which are trivial.

For example, in a case where data is being collected students may be developing self-checking skills to determine whether the data collection approach appears to be working (or has failed). In the simplest of cases this may entail checking whether the recorded data is in the order of magnitude expected or that data is being logged at all.

Likewise, civil engineering students may apply their evaluative judgement in their execution of a specified task to collect observations of head-loss in a pipe spanning laminar and turbulent flow regimes for a range of pipe sizes on a given apparatus without further guidance. Throughout the practical students should be considering the available data and their choice of flowrate to ensure they have correctly sampled from the specified flow regimes. Whereas, if they blindly sample this will not necessarily be achieved.

Design-oriented tasks often require judgement to establish an initial design or heuristic that will then be refined through evaluation and iteration. For example, in many electronic circuits, an initial choice of component values can be made based on experience. A careful practical design might expose students to this challenge while being cognisant that without the benefit of experience, the choice of sensible initial values can seem mysteriously arbitrary.

It should be noted that the role of evaluative judgement should be considered even for demonstrated activities because although students may not be making choices related to the design of a process or the collection of data, the observations they make help build engineering judgement. For example, in structural engineering practicals where students may observe a reinforced concrete element loaded to failure, a critical takeaway is the speed and catastrophic nature of failure which helps develop the context for the rules that are applied in design.

Social context considers the nature of engagement with peers or instructors and the following may be important to consider:

- If a task is being completed as part of a group is there a genuine need to collaborate such that is not possible for a student to have 'their part'. That is, do students need to work together completing activities in parallel to achieve an overarching goal. While it would be ideal for all group tasks to be completed in a group because they require genuine collaboration, in practice resourcing often necessitates activities be completed in groups that are larger than ideal. The activity designer should therefore consider how the complexity of the activity can match the group size.
- While on face value it may appear that all activities should be student centred, a significant amount of engineering practice involves the application of standard approaches to solving standard well-defined problems where reinvention of the wheel is undesirable. It is therefore appropriate that some activities are focused on the completion of tasks following a specified process and can therefore be considered teacher centric.

Educational intent is an underpinning/interfacing consideration of all dimensions and is a further lens through which to evaluate the engineering practical activity as a whole with the goal of achieving clarity of purpose. It considers the approach taken to developing/assessing activities and the suite of global and technical skills that are delivered within the context of an activity as well as whether the task being undertaken is primarily for learning (e.g. formative) or part of assessment of learning (e.g. summative). The educational intent of a practical may span development of conceptual understanding, intrinsic engagement and motivation, inquiry and discovery, integration of knowledge, ethical and professional behaviour, development of communication skills, or development of the scientific method as appropriate for the course learning outcomes.

While an engineering practical will often have a primary stated (or more prominent) goal of assessing the hands-on application of a skill, concept or method often broader skills and competencies may be integrated as part of the assessment. For example, while a practical engineering task may focus on measuring a particular physical phenomena the assessment may be designed to also require application of the scientific method or communication skills.

Furthermore, while it may be possible to consider a many-layered engineering practical assessment task covering a variety of educational intents, appropriate scaffolding and consideration of student cognitive load is required. For example, in the later year levels engineering practicals may represent a vehicle for programmatic assessment integrating many technical and global skills in one larger practical experience. However, this may not be possible at lower year levels where practicals may need to focus on skill building using well-structured problems.

Desktop Review

As an initial test of the taxonomy, the authors have applied it to a sample of practicals in their own disciplines. The following observations are based on the authors' own reflections, while data collection proceeds from engineering academics and students at The University of Adelaide as part of a broader study.

Early years electronic engineering: hands-on use of test equipment and prototyping techniques set a *realistic* context, but technical considerations are abstracted. Simplified, well-structured problems and instructions limit the *cognitive challenge*. There is some development of *evaluative judgement* through self-checking in analysis. The *social context* is in groups, with a collaborative mindset encouraged. Development of practical skills in constructing and testing electronic circuits is a primary *educational intent* along with building motivation by demonstrating useful applications of theory.

Later years electronic engineering: mid-scale apparatus combined with commercial industrial control elements provide a degree of *realism* despite a laboratory environment. Students undertake measurement tasks that develop engineering judgement required for practice, although field measurement may not be authentic to engineering practice. Prescribed instructions for experimental procedures, presentation and analysis of results limit the *cognitive challenge*. Some *evaluative judgement* is required in analysis but not design. The *social context* is in groups, with a collaborative mindset encouraged. The *educational intent* is development of understanding through the observation of real systems.

Middle years civil engineering: relies on the use of very small (i.e. table-top) up to small apparatus to conduct hands-on tasks in a knowledge building/confirming context. As such the tasks have some degree of *realism* but they have been extensively simplified for exposition. *Cognitive challenge* is capped by the well-structured problems, stepwise instructions and degree of change that can be accommodated by the apparatus. Some development of *evaluative judgement* is encouraged as the learners have a degree of freedom in choosing their approach to sampling (i.e. the measurements taken) and this leads to the need to self-check that samples taken meet the goals of the practical. While learners work together in a *social context* to take measurement in groups during the practical they work individually on presenting results and interpretation. The primary *educational intent* for these practicals relates to observing phenomena and verifying theoretical trends through the ability to interact with the materials under investigation.

Discussion

In establishing the typology and reviewing the practicals that the authors have both delivered and completed, a number of overarching themes emerged which are worthy of further discussion.

The need for domain knowledge: although there is a tendency towards centralisation of learning and teaching administration and support there is a need to consider the unique constraints and requirements of each engineering discipline rather than taking a one size fits all approach. In the examples presented above, it is clear that because of the differing scales at which electronic engineers and structural engineers work the nature of practicals is different. The small scale, low cost and reusability of electrical components means that it is more likely that hands-on, authentic to practice experiences can be run for individual or small groups of students, compared to structural engineering where an authentic scale is highly challenging and the destructive nature of testing means ongoing investment is required to construct new test components such that students are most likely observing demonstrations. In this comparison, to someone without discipline knowledge it would be easy to suggest one area approaches practicals better than the other, or that one area better utilises resources, but as the typology has highlighted both approaches have clear educational value.

Scalability and resourcing: beyond the financial cost highlighted in the above example, scalability is also important for student learning. For example, in the electronic engineering example the reusability of components is beneficial in that ongoing investment can lead to the completion of activities at scale such that there can be better alignment between the delivery of fundamental theory and the application in a practical. This is opposed to the structural engineering example where, as a result of the test being destructive, ongoing investment is required each year to run the same practical.

Assessment inertia: our desktop review of practicals highlighted that while courses have evolved over time practicals have remained relatively static. While one may argue that this is because the fundamentals of engineering have remained the same and therefore the practicals are still of high value, given the high cost of practicals and the increased demands on student time, there is a need to consider how each practical can best deliver its educational intent.

The need for a programmatic view (no 'one size fits all' and no 'holy grail'): our paper commenced with a vision of an engineering practical that reflects authentic engineering problem solving, requiring application of engineering science, engineering design and global skills. After reviewing existing practicals, it has become clear that this ambition, if it is to be approached at all, can only come after scaffolded development of the underpinning capabilities. Even then, to be authentic in scale, scope and cognitive challenge it would look more like a capstone project than a series of practical classes. Our review also uncovered risks associated with course-by-course design of practicals. Without a program-wide view, there is a temptation to address every possible educational outcome in a practical, and yet deliver it in a resource constrained environment. Incongruous designs and student experiences can be the result. Examples include practicals where the primary intent is to build intrinsic motivation through the demonstration of theory to popular applications, and yet the assessment carries high summative stakes; practicals with many pages of supporting background theory and yet where the practical task itself is trivial; or practicals requiring a formal report when it is not clear how this aligns with any of the course learning outcomes.

Conclusion and future research

In an initial review of engineering practicals, we have found the taxonomy usefully draws out key characteristics so that patterns and hypothesis have begun to emerge. Key among these is that maximising the benefit of practicals requires a program-wide approach that should be evident through changes in the types of practicals students encounter as their studies progress.

Surveys of academic staff and students, as well as a broader desktop review of practical experiences, are currently in progress as part of the study's next stage. This broader investigation will allow the taxonomy to be refined and the outcomes further generalised. The academic survey and desktop review will draw out the attributes of existing practicals and map these against the dimensions of the typology. The student survey will also map practicals against the topology, but this time based on student perceptions. This will allow a comparison of academics and student perceptions, as well as analysis of the distribution of practical experiences across a variety of undergraduate engineering programs.

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Acknowledgements

Approval for the study was received from the Human Research Ethics Committee of The University of Adelaide (H-2024-120).