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# Open-inquiry in the laboratory: a case study of a scenario-based pipe flow activity

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**Abstract**

Laboratory activities are an essential part of an undergraduate engineering education. One of the challenges in effective use of the laboratory is to provide an engaging experience. This paper contributes a much needed case study of an ‘open-inquiry’ activity. The activity focussed on pipe flow, and used a scenario-based design to foster deeper inquiry and greater engagement.

We evaluated the activity after seven years of implementation in cohorts of 165-200 students. Qualitative evaluation of student outputs showed a significant improvement. Quantitative analysis of the student experience, via a survey covering nine dimensions of the experience and five different laboratory activities, showed that the activity in question was successful. Qualitative comments from students and teachers give further insight into how the activity succeeded.

By presenting a best-practice case study, accompanied by full teaching materials in an open repository, we show that concrete changes in the student experience and their outputs are possible by changing the following: the way teaching assistants work, expectations for behavior in the laboratory, and written materials.

## 1 Introduction

Laboratory activities are an essential part of an undergraduate engineering education. One of the challenges in effective use of the laboratory is to provide an engaging experience. There is often a stark contrast between the ‘inquiry’ with which a practising engineer uses a laboratory, and the ‘procedural’ approach of students that is manifest in formal education. This paper contributes a much needed case study of an ‘open-inquiry’ laboratory activity.

In the case study presented here the key constraints of a laboratory activity remain unchanged, namely the learning objectives, scheduling, group sizes, and equipment. We show that concrete changes in the student experience and outputs are possible by only changing the following: the way teaching assistants work, expectations for behavior in the laboratory, and supporting written materials.

The case study presented here is of an activity centred around pipe-flow, which applies in many branches of engineering including Mechanical, Civil, and Chemical. We begin with the educational context, the learning objectives, and a brief review of literature inquiry-based learning in laboratories. In the method section we describe the key features of the activity being reviewed, and separately share full written materials for the activity so that readers may consider adapting it to their own context.

The results center around three sources of evidence: student written reports, including before and after the changes to the activity; student experience from a survey including quantitative and qualitative responses; and teacher comments.

We discuss the key results, implications, and limitations, before summarising and concluding.

## 2 Background and literature review

### 2.1 Context of the activity

The context in which we describe the activity is a UK-based, STEM-focussed, research-intensive university. This paper focuses on the first undergraduate year of a four-year integrated Master's degree. Students are highly diverse in cultural, national, and socio-economic backgrounds, but first-year students are $> 99\%$ in the age-range 18-20.

### 2.2 Learning objectives

The activity presented here is part of a module (course) called 'Professional Engineering Skills' which combines practical application of theory learned in other modules; learning laboratory-related skills; and developing professional skills including team work and technical communication.

The learning objectives within that module that are addressed in this paper are listed below, with the relevant classification of objective from Feisel and Rosa [1] listed in italics:

- Keep careful, complete and systematic records of laboratory work (*experiment*)
- Understand the importance of, and appropriate methods for, the calculation of errors and uncertainties. (*experiment, data analysis*)
- Carry out experiments, using key equipment to make appropriate calculations and solve realistic, open engineering problems. (*experiment*)
- Analyse data collected, apply theory to one's own experimental measurements, evaluate results and draw conclusions. (*data analysis*)
- Write technical reports to justify experimental study, record procedures in the laboratory, communicate results and make concise robust conclusions. (*communication,ethics*)

The activity also supports subject-specific, academic learning objectives in fluid mechanics and pipeflow:

- Understand the pipe-flow energy equation
- Demonstrate a basic physical and qualitative understanding of turbulent flow
- Solve problems involving manometry

- Solve pipe flow problems by energy analysis

The learning objectives listed above are taken as the 'problem statement' of this paper, i.e. the problem is how best to achieve those objectives.

## 2.3 Appraisal of existing activity

The existing activity was reviewed to identify any areas for improvement. The appraisal identified aspects of the activity that should be maintained:

- Hands-on experience with lab equipment and with fluid flow
- Measurement of actual pressures and actual flow rates
- Application of theory to one's own measured data
- Report writing experience
- Group work
- Interaction with GTA (graduate teaching assistant)
- Excellent laboratory and technical support (for example, good data was possible to collect)
- Recent introduction of use of manometry (not electronic pressure gauges)
- Prompt feedback

The following problems needed addressing:

- Misalignment between high workload and low weighting of assessment
- Poorly timed activity (occuring before the relevant lectures were given)
- Unclear expectations and inconsistent grading
- Students could follow instructions but did not necessarily understand what they were doing
- Lecture material covered the Moody diagram but not empirical fits (suchas the Haaland equation) or discussion of dimensionless quantities
- The motivation to investigate pressure drops in pipes was not given
- The purpose of the activity was not clear
- Assumed that no preparation was required but the data obtained was poor, for example too many points in the transition zone.
- Step-by-step procedure for students to follow takes agency away from the students.
- Even the highest graded lab reports showed a poor level of understanding. For example no error bars, no expression of confidence in the results, no key conclusions.

The problems that needed addressing were partly directly solvable with practical changes, but the bigger challenge was to re-imagine the activity in a way that would engage the students rather than have them effectively passively following instructions.

### 2.4 Inquiry based learning

This paper focuses on the use of inquiry as a teaching method to foster engagement and learning. In this section we review the literature on inquiry-based learning, which is a broad term with a long history in technical education [2, 3]. Inquiry-based learning is defined as students taking a more active role in choosing a line of inquiry, implementing, analysing, concluding, and communicating. It is distinct from following prescribed instructions.

Often interpreted as meaning scientific inquiry [4] as opposed to engineering inquiry, and used across schools [5, 6, 7] and higher education [8], inquiry-based learning covers many types of activity.

As with similarly titled ‘discovery-based’ learning ([9, 10, 11, 12, 13, 14]), inquiry-based learning varies greatly by context but has been shown on a large scale to be most effective when student inquiry is guided by some kind of scaffolding [8].

In engineering education, inquiry-based learning has been applied to core teaching of engineering concepts, such as in [15, 16], and laboratory activities, such as in [17, 18, 19]. Focussing specifically on undergraduate engineering laboratories and the use of inquiry-based learning, while there are a variety of small case studies, there is not a well established and coherent body of literature for this area — unlike, for example, science education in schools [6, 7]. This paper therefore makes an important contribution to establishing practices in inquiry-based, undergraduate engineering laboratories.

As a framework for characterizing levels of inquiry in undergraduate laboratories, Buck et al. [20] consider which aspects of a problem are provided by teachers[1], and which must be derived by students — see Table 1. The level of ‘inquiry’ corresponds to how much of the process is ‘provided’, and how much the students must discover for themselves.

Table 1: Levels of Inquiry Characteristics, from [20].

| **Characteristic** | **Level 0: Confirmation** | **Level 1/2 Structured Inquiry** | **Level 1 Guided Inquiry** | **Level 2 Open Inquiry** | **Level 3 Authentic Inquiry** |
|---|---|---|---|---|---|
| Problem/Question | Provided | Provided | Provided | Provided | Not provided |
| Theory/Background | Provided | Provided | Provided | Provided | Not provided |
| Procedures/Design | Provided | Provided | Provided | Not provided | Not provided |
| Results Analysis | Provided | Provided | Not provided | Not provided | Not provided |
| Communication | Provided | Not provided | Not provided | Not provided | Not provided |
| Conclusions | Provided | Not provided | Not provided | Not provided | Not provided |
| Notes | Applied pre-2019 | - | - | Applied from 2019 | - |

The approach described in this paper was to increase the level of inquiry. As indicated in Table 1 the change was from Level 0 (confirmation) to Level 2 (open inquiry). The reason for not moving

[1] Similar levels of inquiry are reviewed in [21]. We follow Buck et al. [20] here for its focus on higher education.

to level 3 was partly based on literature showing that scaffolding is important, especially for first-year students; but also because the activity was time-constrained and had specific learning objectives (unlike, for example, an open research project that may last weeks or months). The challenge in providing open inquiry is to meet the learning objectives while not explicitly instructing students on what to do.

## 3 Method

This section describes the activity that was newly implemented in 2019, and delivered over seven years, to introduce more inquiry into the activity and increase student engagement and learning. The constraints imposed were to keep the following constant:

- Learning objectives
- Timetable (3 hours per group, repeated 40 times over 10 weeks)
- Total student hours
- Lab equipment (Armfield C6)
- Cohort size (up to 200) and student group size (up to 5)

The method therefore focuses solely on the learning materials provided, the management of activities ('teaching'), and the assessment.

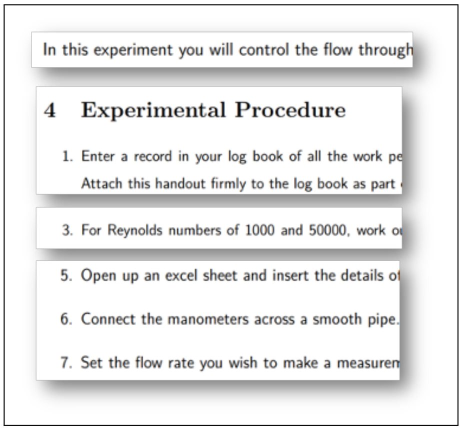
### 3.1 Providing a realistic scenario

The key design change in the new activity was to introduce a role for the student to play as an engineer in a company. Creating a realistic context helps justify the lack of step-by-step instructions, and also provides context that students can draw upon to make their own decisions.

The scenario is provided by an *email*[2] from the company director to the engineer, reproduced in Figure 1. Realistically in life, but also conveniently for this activity, the director has gone away on holiday for a week so is not available to answer any questions; however a 'colleague' in the lab (played by a Graduate Teaching Assistant, GTA) is available for support. Again this context helps break from the teacher-leading-student paradigm, and empowers GTAs to put the onus on the students to solve their own problem but ask for help from a colleague when needed. These are also good principles for the students to take with them into the workplace — own your problems, but do ask colleagues for help.

The full scenario is provided separately in the repository accompanying this paper [22], and is summarised here. The company manufactures pipes, and a customer has recently purchased, and now complained about, some piping for a chemical plant. The customer refers to the 'friction factor', but the director appears ignorant of this technical concept. Here again the onus is put on the engineer (student) to take the technical lead, a challenge they may also face in industry when managed by someone with a broader remit in the organisation but lacking subject-specific expertise.

[2] In practice this comes in a PDF, looking like an email.




**Email from your director**

```
Date: 10 Jan 11:40:36 -0400
From: Taylor Evans <tevans3@pipeline.com>
To: Stu Dent <sdent19@pipeline.com >
Subject: They're at it again

Stu, I need a report that I can throw at the customer to prove
that our pipes are OK. I'm away this week so please can you do
this? The customer keeps rejecting my requests for more
information and they keep going on about friction factors but
I don't see what that's got to do with it? Can we even measure
that? Anyway look my bonus is on the line here so we need to
get this one right.

Use the labs as necessary and test some of the pipes. I had a
word with Keith and he is available to help - I've asked him
to install some steel pipes on the test rig for you. Gee will
also be using the lab but you should have time to share. I
think there's 4.5,8,11,15,17 ID pipes available to test. I
think the 15 ID pipe is our new line of insulated pipe which
we provided as a freebie to try and sweeten the deal.

Send me a response within a week.

T.
```

Figure 1: Materials provided to students. Left: the previous activity provided explicit instructions. Right: the new activity provides an an email from the director.

Some of the key details in the scenario are not necessarily emphasised by the layout of the text. The purpose of not emphasising key details is to encourage student inquiry. As an example, the director lists the diameters of pipe that were provided to the customer, and says that the list includes some new ‘insulated pipe’ that was included as a free sample. While the last point does not seem important, it explains why some pipes have a larger ratio of outer- to inner-diameter. Such a difference permits the educational laboratory to use artificial roughness inserts inside one or more pipes, seeding a ‘problem’ that students need to discover through measurement. Another key piece of information in the scenario is that the pipe roughness should be below 0.1 mm, which is sufficient for the students to infer what an ‘acceptable’ relative roughness would be and make conclusions, such as that a pipe is or is not acceptable.

The following information was not provided:

- Which measurements are needed
- How to process the measurements
- What the meaning of the processed measurements is
- What conclusion to tell the director

It is important to emphasise that the pipes on the kit being used can be swapped. Therefore it is not known to students, *a priori*, which pipes are rough and which are smooth. There is genuine uncertainty in the exercise until measurements have been made. Students cannot, for example, learn from other students what the ‘answer’ is — as it may change for different groups.

Table 2: A structured process for the activity.

| Activity | Type | Summary | Summative Assessment | Notes |
|---|---|---|---|---|
| Preparation | Reading | Background theory and scenario provided | - | |
| Pre-lab test | Online test | Basic questions check understanding of theory and the equipment | 5/80 | Deadline before the pre-lab |
| Pre-lab | Lab activity, 1 hr | Meet the 'colleague' (GTA) in the lab for one hour to discuss the problem and make a plan. | 10/80 | Assessed for Technical inquiry (5/80) and Professionalism (5/80) |
| Action plan | Online submission | One page outline of plan when visiting the lab | 10/80 | |
| Lab session | Lab activity, 3 hrs | Make all measurements | - | Mandatory but not directly assessed. |
| Report | Online submission | Detailed rubric provided | 55/80 | |
| Feedback | Online data | Grade comprising sub-grades; written feedback on the report. | - | |
| Feedback | In-person meeting, 10 mins | Discussion with GTA after receiving the feedback. | - | One-on-one |

### 3.2 Activity Design

In general the key to successful inquiry is structured thinking and measuring with purpose. The challenge in designing the activity was to ensure students did use structured thinking and define clear purpose to their measurements, but that they did it through their own agency. The solution was to add structure to the activities, while not prescribing the details of the activity. The structure is codified in Table 2.

Milestones for the process are integrated into the structure including deadlines for summative assessments. For example reading before the first lab visit, and planning before the second lab visit. The timing between stages is flexible depending on local requirements. In the case described here, the timetable constraints meant that the pre-lab visit was one week before the main activity; however in future implementations this could be as little as a few hours, which is enough time to prepare a spreadsheet to process measurements.

Table 3: Examples of good, poor, and disallowed questions, for GTA training.

| Quality | Question | Notes |
|---|---|---|
| Good | "How is the plan going" | Open, non-judgemental, not giving direction |
| Poor | "Have you written that correctly?" | A leading question that implies the GTA has a point to make. This type of question is reserved for concerning cases where the group are off-track and short of time. |
| Not allowed | "Write down the friction factor formula" | This instruction takes agency away from the students. It encourages dependence on the teacher and discourages inquiry. |

### 3.3 Practical Considerations

The most challenging part of the process was managing the pre-lab activity. Students worked in groups and were hosted by a GTA who may have no teaching experience. Key advice for the GTAs was:

- Ask don't tell
- Only students touch the equipment
- Only students write on the whiteboard

While these rules can be broken for the purposes of safety or if equipment needs troubleshooting, they are a good rule of thumb to give students agency and emphasise the need for students to lead the enquiry.

Figure 2 shows a pre-lab activity. The GTA is aside from the group, who are leading the development of their plan. They write explicitly on the whiteboard, and the GTA checks that the students are making adequate progress. If the GTA sees an issue, then they intervene with a question. A guide to intervening is given in Table 3, and a focus group with GTAs was used to gauge their experience.

### 3.4 Feedback from students

Student feedback was gathered by a survey which is dedicated to undergraduate engineering laboratories. The survey is described in detail in [23] and summarised here. Quantitative questions ask for a response to a 5-point Likert agreement scale on nine different questions, where each question addresses a 'dimension' of the experience: purpose, conceptual learning, positive challenge, technical communication skills, documentation, engagement, support, feedback, collaboration. Full questions are given in the appendix.

The survey also asked for qualitative comments. Further, in the first year of the new activity an additional two questions were added to ask students about their experience in this particular activity.

The survey was used uniformly for all five activities that the cohort experienced, and was run for


Figure 2: A pre-lab activity. The GTA stands aside from the group of students, who are leading the activity themselves.

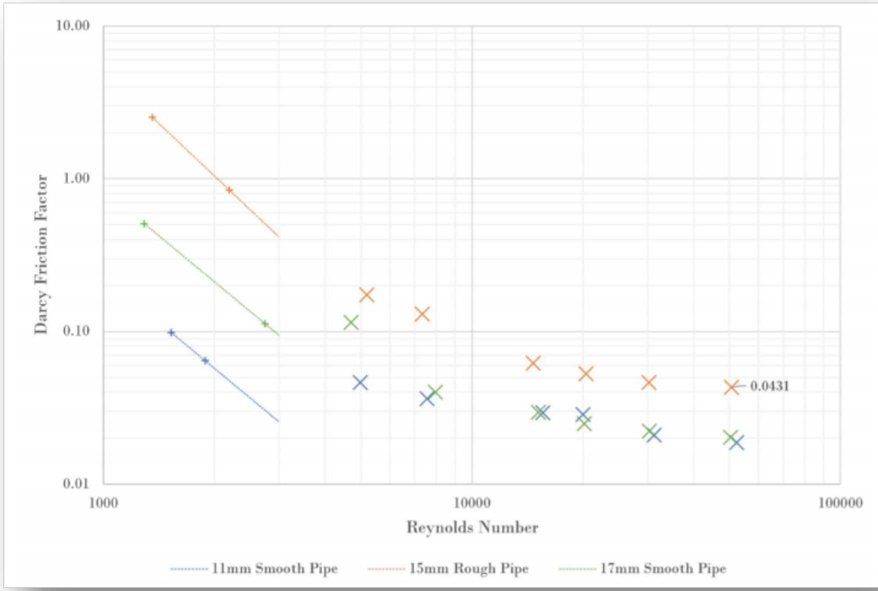
seven consecutive years. The survey was anonymous and not compulsory, and approved by the IRB with number EERP2425-118.

## 4 Results

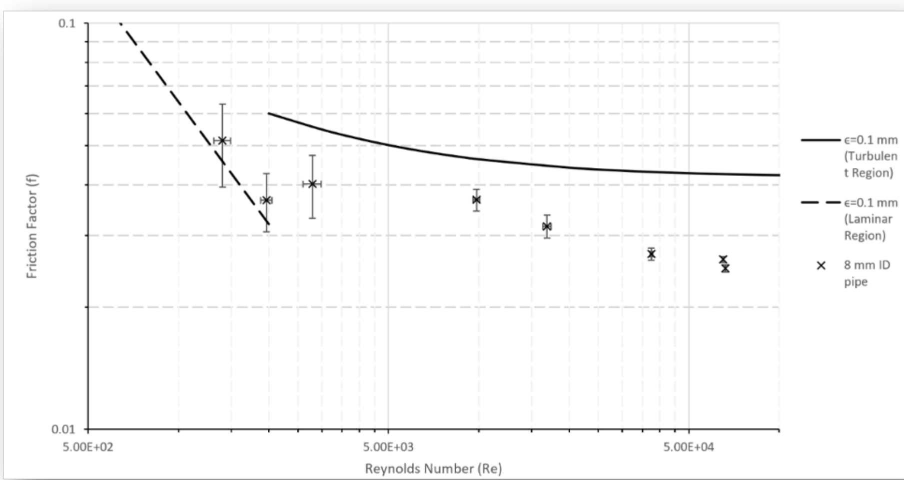
### 4.1 Written Reports

Example results plots from students' written reports are shared in Figure 3. There is a big contrast between the two plots, as described in the caption, and this is representative of the cohort in general. We attribute the changes firstly to an emphasis on error analysis in the pre-lab activity, and secondly on the clear purpose of the activity so that results are presented in a way that supports an argument and a conclusion.

Example conclusions from written reports are shared in Figure 4. There is a clear contrast in the conclusions, with the new conclusion reflecting a stronger purpose. The change is because there is a person to write the report for, and a reason why they need the results. These improvements stem from the scenario.




(a) The highest marked report from the previous activity. Laminar flow results do not coincide and are clearly too high in some cases. There are no error bars. Results from the literature (i.e. the Moody diagram) are not used for comparison. The 15 mm pipe was labelled to the students as 'rough', so there was no inquiry necesary to find the results. No conclusion is possible.




(b) A student report from the new activity includes reference empirical data and error bars. A conclusion is obvious: the results match the literature in laminar flow, and show that the pipe roughness in the turbulent region is below the reference of 0.1 mm. The better graded reports showed the results from all pipes in one plot; this one is more common, showing one plot per pipe.

Figure 3: A comparison of work produced by students before and after the activity changes.

## 3 Conclusion

The pressure drop across three pipes and three fittings was measured. The relationships between pressure drop and Reynolds number, inlet velocity, pipe diameter and internal surface finish were found. Darcy friction factors were calculated at each Reynolds number and the graph plotted compared to the Moody Diagram allowing the roughness of the rough pipe to be found. Finally, loss coefficients were calculated for each fitting at each Reynolds number to compare the energy loss from the flow caused by each fitting.

It was found that the pressure drop increased with Bulk Average Velocity and Reynolds number. For the tested pipes, at constant Reynolds number, the smaller the diameter of the pipe, the greater the pressure and energy loss. The graph plotted for Darcy Friction Factor against Reynolds number was similar to the Moody diagram and the relative roughness of the rough pipe was estimated to be 0.015. The sharp bend fitting had greater loss coefficients at all Reynolds numbers meaning it caused the greatest energy loss from the fluid flow. It was suggested that the loss coefficient of 200 at a Reynolds number of 1400 was due to the stagnation of the flow at the fitting. All three fittings had a characteristic loss coefficient at turbulent flow which was estimated to be 1.9 for the sharp bend, 0.5 for the short bend and 0.25 for the venturi.

(a) The conclusion from the highest marked report from the previous activity. The writing quality is high, but the conclusion is long and lacks clarity.

## 5. Conclusion

The 15mm pipe that we gave to the company is faulty due to the roughness on the inside of the pipe exceeding 0.1mm by a significant margin. The manufacturing of these pipes should be checked for flaws. The other pipes have been proven within the uncertainty of the results to be functioning normally and with a roughness of below 0.1mm, hence if the customer reports errors with the pressure drop in these pipes as well then that is most likely due to corrosion of the pipes due to the chemicals in use or due to an installation error on their side.

(b) A conclusion from a student report from the new activity. It is concise and clear, solving the problem.

Figure 4: A comparison of work produced by students in the previous and new activities.

### 4.2 Student Evaluations

The student survey was run for seven years with response rates of 73%, 53%, 55%, 41%, 66%, 44%, 42% from 2019 to 2025 respectively. Cohort sizes ranged from 165 to 200.

A quantitative analysis of the 9 dimensions of the lab experience from the survey is plotted in Figure 5(a). A score of 5.0 implies all respondents strongly agreed, while 3.0 implies on average agreement cancels out with disagreement. A score of 1.0 implies all students strongly disagreed. We consider a score of 4.0 to be a successful outcome, hence highlighting the region above 4.0 in green in Figure 5. Variations of $> 0.5$ between years are considered significant [23].

Figure 5(a) shows that for the inquiry-based pipe-flow activity, all except one of the dimensions ('feedback') scored above 4.0 every year. The spread between each of those dimensions, in each year, was small. An overall trend can be seen with the highest results in 2021, where the activity was particularly well adapted to lockdown measures relative to other activities; and a drop in 2022 during the pandemic when students often needed to isolate and sharing enclosed spaces was stressful for many. Nevertheless, the variations over the seven years are relatively small ($< 0.5$).

The 'feedback' dimension is an exception and requires explanation. Initially, in 2019, feedback only comprised written comments on reports and a numerical grade. The score of 3.5 in 2019 is significantly lower than the other dimensions and prompted a change.

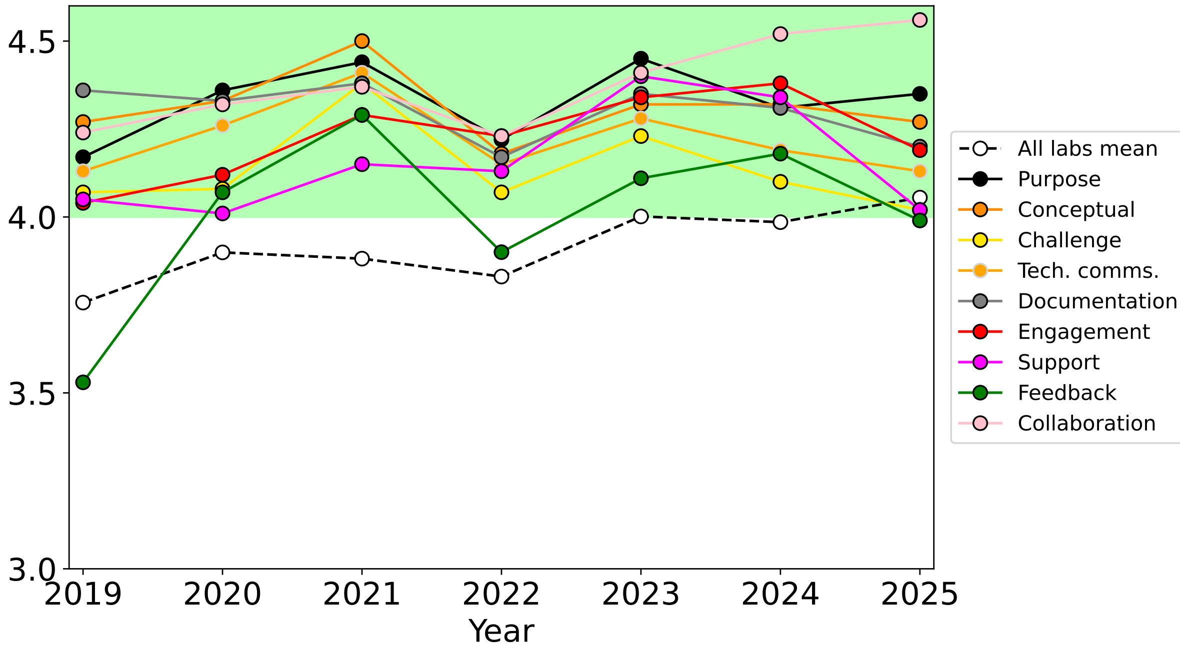
To improve the feedback, in 2020 a system of oral feedback sessions after written feedback had been provided was implemented. The sessions were in groups in 2020, and following qualitative comments were changed from 2021 onwards to one-to-one sessions. The staff time was unchanged, so while group sessions were allocated 50 minutes, one-to-one sessions were 10 minutes each. Results show that these changes increased the feedback score above 4.0; one exception was 2022 where feedback sessions, which were in-person, were attended less due to concerns in the pandemic, and were therefore less effective.

Figure 5(b) compares the overall average for the activity studied here, to the same metric for four other activities experienced by the same students. The results show that the activity studied here scored highest. The second highest scoring session ('Fairground') was also scenario-based, although with a lower level of inquiry.

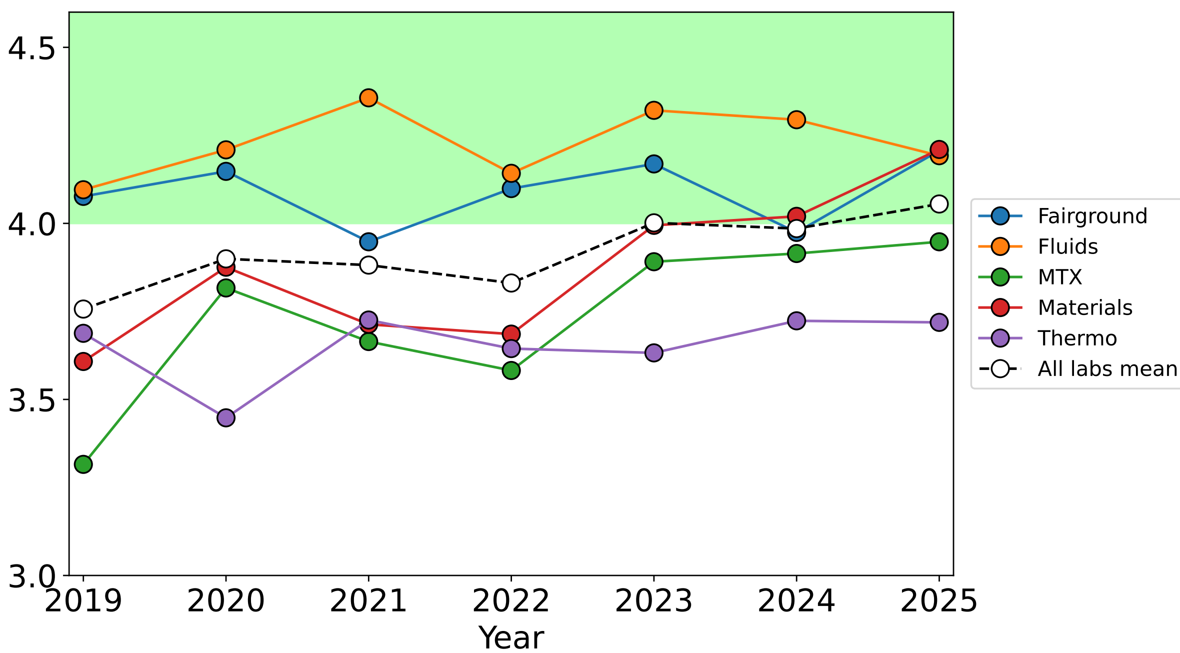
In the first year of deployment, we included two additional closed questions on the survey: dud respondents liked the pre-lab *session*, and did they find the pre-lab *test* useful. The response was that 89% and 81%, respectively, responded positively.

In free comments, the students were positive, for example:

- "pre-lab sessions were good, should be put in place for all labs"
- "I really enjoyed how fluids was self led"
- "Loved solving realistic problems. Challenged me in a different way and provided incentives to find the best solution, not just an answer. Fluids lab was superb!"
- "Fluids was exceptional having the 1-1 feedback session to discuss the report"
- "I liked that we weren't just given a set of instructions to blindly follow and that we got to do everything ourselves."




(a) 9 dimensions, for the new activity.




(b) Overall scores for the five activities in the cohort.

Figure 5: Quantitative results from the student survey.

- “The freedom of decision in the Fluids Lab was definitely a factor which stimulated my mind.”

No major issues were identified in the comments. Minor issues included background workload, sychronisation with the related lecture course, and the quality of GTA support.

### 4.3 Teacher Experience

GTAs are typically inexperienced PhD students and it can be intimidating to be given such a sensitive and complex role. However, it is also stimulating and rewarding work. Comments from the GTAs reflected these aspects, as well as observing concrete benefits to the inquiry-based approach:

- “All of them have looked at background notes and scenario (last year none had prepared). Preparation is effective . . . e.g. they know where the valve is.”
- “Some groups lead the discussion. Others require questioning. The [grading] rubric is adequate for this.”
- “Pre-lab is the most valuable part for the student.”
- “Introduction and conclusion are much better written”
- “Pre-lab is fun.”

## 5 Discussion

This paper presented a much needed case study of best practice for an inquiry-based laboratory activity for an undergraduate engineering laboratory in fluid mechanics. The aim to improve learning and engagement without needing to change learning objectives, timetabling, student groups, or equipment, was met. The approach was to remove instructions and provide a scenario-based problem that fosters inquiry.

The key evidence for success after 7 years of implementation are:

- Student reports improved dramatically: a typical report is now clearly superior to the highest rated report from the previous activity (Section 4.1).
- Students are highly satisfied with the experience across 9 dimensions of measurement, both in an absolute sense (scores above 4.0 on a 5-point Likert scale, in all categories across all years), and in a relative sense when comparing to other activities (Section 4.2).
- Teachers observe the difference in student behaviour and outputs, and also find the process more rewarding (Section 4.3).

The key challenge in implementing an inquiry-based activity was to ensure learning objectives were met while also ensuring that students worked under their own agency rather than following instructions. Success depended on providing adequate structure while not giving explicit instruction. The work required to train GTAs, prepare written materials, and manage the structured process required dedication and attention to detail. The results provided in this paper show that such an investment is justified.

Two key questions arise from the evidence presented here related to the generalisability of the approach presented here, and the prospects for realising the same benefits in other laboratory activities:

- Given the clear performance data over seven years, and similar performance by the ‘fairground’ activity which is also inquiry-based with a realistic scenario, why haven’t the other sessions in our degree programme been revised in the same vane?
- To what extent do the results presented here transcend subject matter and local context — for application in other contexts?

The answer to the first question is that, following successful outcomes in 2019 and 2020, two other laboratory activities were converted to use a realistic scenario and an inquiry-based approach. One of the sessions was the ‘thermodynamics’ activity included in Figure 5(b), and the other was a Heat Transfer activity in a different year group. In both cases, the changes were not immediately successful, and — evidently in Figure 5(b) — there are still challenges to overcome.

As any practising teacher knows, small things can make a big difference; and teaching comprises many small things. Formulating success, even within our own team serving the same students within the same programme, is challenging.

What this paper claims is to show an example of an engaging learning experience in the laboratory, with enough information in our open repository [22] that other teachers may, with this paper, have some tools to help them deliver with such success in their local context. It comes with a caution, however, that replication requires more than the artefacts provided.

We may also ask to what extent *inquiry* and a *realistic scenario* are important for success. We have presented previously [24] at ASEE a successful flow visualisation laboratory that emphasises discovery, but *without* a realistic scenario. We also have activities in mechatronics, in a different year group, that are more procedural (not inquiry-based, and without a scenario) but remain engaging.

Learning design is complex, especially in the laboratory, and a more comprehensive study of the fundamental ingredients of success would require further research.

## 6 Conclusions

A scenario-, and inquiry-based activity for undergraduate engineering students to learn about pipe flow has been presented. Analysis of student reports, student surveys, and teacher comments shows that the approach is very effective at engaging students and achieving the learning objectives. It remains to be seen to what extent these results are transferable between subjects and educational contexts.

The activities were described briefly here but are also shared openly in a Zenodo repository [22] so that teachers can adapt the materials to their own uses. The changes implemented are independent of typical constraints like schedule, curriculum, and equipment; we therefore hope that they can be used by other practitioners. If other teachers do implement a similar activity, we would be interested in collaborating to compare effects in different contexts.

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## Appendices

### Learning objectives by Feisel and Rosa

Learning objectives defined by Feisel and Rosa [1], reproduced here for the objectives relevant to the paper (all text is quoted):

- *Instrumentation*. Apply appropriate sensors, instrumentation, and/or software tools to make measurements of physical quantities.
- *Experiment*. Devise an experimental approach, specify appropriate equipment and procedures, implement these procedures, and interpret the resulting data to characterize an engineering material, component, or system.
- *Data Analysis*. Demonstrate the ability to collect, analyze, and interpret data, and to form and support conclusions. Make order of magnitude judgments and use measurement unit systems and conversions.
- *Communication*. Communicate effectively about laboratory work with a specific audience, both orally and in writing, at levels ranging from executive summaries to comprehensive technical reports.
- *Ethics in the Laboratory*. Behave with highest ethical standards, including reporting information objectively and interacting with integrity.

### Survey questions

Full questions for the student survey are in Table 4.

Table 4: Full survey questions from 2023 onwards. The questions evolved over initial years (2019-2023) and changes are indicated: * = different in previous years; + = clarified from previous years.

| **Short name** | **Full statement** |
|---|---|
| Purpose | The purpose of the lab was clear to me. |
| Conceptual | The lab session gave me a better understanding of the abstract concepts taught in the related module (e.g., energy, pressure, stress, entropy, current, resistance, etc.). |
| Challenge | The lab session challenged me in a positive way. |
| Tech. comm. skills+ | Preparing a report/presentation helped me develop technical communication skills. |
| Documentation and guidance* | The documentation and guidance for the lab session was clear, organised and well prepared. Consider:<br>- Handouts, videos, interactive content<br>- Guidance in the live sessions<br>- Using the practical equipment (where appropriate) |
| Engagement | I felt engaged in the experience and enjoyed the lab session. |
| Support* | I was well supported by GTAs or other staff during the lab session. |
| Feedback | I received good feedback [link to College page about feedback]. When answering this question consider feedback during lab sessions as well as the marks on your final report/presentation. |
| Collaboration* | I was able to collaborate with my colleagues (to the extent required). |