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Desktop Flow Visualisation Experiments for Guided Discovery of Boundary Layers

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Abstract

The theory of boundary layers, which is well established and taught in all undergraduate fluid mechanics courses, can be challenging for first-time learners to comprehend. Three challenges are identified in this paper, namely to visualise the existence, thinness, and attachment/separation of boundary layers. We frame these challenges as threshold concepts that may benefit from discovery-based learning. We present a new desktop experiment, where water flow is visualised in a transparent flow loop, that supports a 'guided discovery' approach.

Student lab books and reports from the activity provide evidence that the first two challenges were broadly solved, while the nuance of separation requiring strong positive gradients was recorded by approximately half of the students.

A survey on the student experience over four years (717 students, 331 replies — 46%) considered seven dimensions of the student experience. Overall results showed that students found the experiment engaging, and helpful in gaining a conceptual understanding of the boundary layer.

Overall, on the three challenges we identified, the equipment and the 'guided discovery' activity were judged to be successful. We also show prototype improvements for future, to aid with the third challenge, including equipment upgrades and the introduction of computational fluid dynamics (CFD).

1 Introduction

Boundary layer theory has its origins in the early 20th century with Prandtl's seminal work [1]. The theory then developed to become an essential part of fluid mechanics theory across disciplines in engineering sciences [2]. The theory is described in many textbooks, for example [3, 4], and is briefly summarised in the Appendix A.

Learning about boundary layers is challenging. We decompose the problem here into three sequential challenges which provide a kind of 'problem definition', to which this paper proposes and evaluates a solution.

1.1 Three challenges in learning boundary layer theory

The first challenge stems from the fact that boundary layers cannot be seen in everyday life. Despite technical information such measured data and theoretical results, the existence of the layers is often not intuitively clear to students.

> **Education challenge §1: evidence that boundary layers exist**
>
> Create a physical demonstration to be conducted by the student themselves to see first-hand the existence of boundary layers.

When the existence of boundary layers is clear, they can be analysed, which requires approximation of the equations of motion. It is convention to write the equations of motion and state the order of magnitude of each term to highlight which can be neglected. A summary of the analysis is in Appendix B.

The 'order of magnitude' analysis lacks *meaning* to the uninitiated learner. Further, the common assumption $\delta/L \ll 1$, where δ is the boundary layer thickness and L is its characteristic length, is not always true and it is not clear to the student that this assumption is based on physical observations. Student comments indicate the confusion:

> "I find it extremely difficult"
> "seem like jumps in reasoning"
> "Theres too much reading in between the lines to understand the theory"
> "order of magnitude analysis and general approximations content ... it's hard to see 'how' to do stuff, I just watch the lecturers 'do' stuff."

> **Education challenge §2: physical observations that boundary layers are thin**
>
> Visually illustrate by experiment that boundary layers are thin, relative to the length over which they develop ($\delta \ll L$), for high Reynolds numbers.

Approximation, based on the assumption of a thin boundary layer, leads to a solution given qualitatively by Prandtl [1] and then quantitatively by Blasius [5]: boundary layers remain attached in negative, zero, and light positive pressure gradients; but flow reverses in the presence of strong positive ('adverse') pressure gradients. When a boundary layer reverses, the thin shear layer 'separates' from the boundary and proceeds into the main flow. Separation has profound effects but the mechanism of separation is not obvious to students.

> **Education challenge §3: boundary layers attach or separate depending on pressure gradients**
>
> Students need to observe boundary layers in different pressure gradients:
> - Attached: in negative, zero, and light positive pressure gradients.
> - Separated: in strong positive ('adverse') pressure gradients.

In summary, all three challenges relate to concepts that are not clear or obvious to students. In this paper we present new experimental equipment, and appropriate classroom processes, to help students discover the key physical phenomena — existence, thinness, and separation of boundary layers — for themselves, hence to solve the three challenges.

1.2 Overview

The paper is structured as follows. We review educational frameworks in the next Section. In Section 3 we present a new desktop experiment, how it is deployed in the curriculum, and how we evaluated it. In Section 4 we present student outputs and survey results. In Section 5 we discuss the extent to which the new equipment and activities solve the three challenges. We outline future work in Section 6 and conclude in Section 7.

2 Literature review

In this Section we review two educational frameworks that can be applied to teaching boundary layers, namely threshold concepts and discovery learning. We then review practical teaching interventions that are relevant to boundary layers.

2.1 Threshold concepts

The *troublesome* nature of learning and teaching boundary layers relates to the framework of *threshold concepts* [6, 7]. In Table 1 we list the definitive characteristics of a threshold concept and in the second column justify applying threshold concepts to boundary layers.

The rigorous identification of threshold concepts is not well established [10, 11]. However, on the basis of Table 1 it is a relevant framework if used critically. In Table 2 we list the recommendations of threshold concepts for course design and evaluation, as given by Land et al. [12] and applied to boundary layers. Table 2 provides practical guidelines for working with boundary layers as a threshold concept, pointing towards 'discovery learning'.

2.2 Discovery learning

Discovery learning was introduced by Armstrong, in 1898, as "methods of teaching which involve our placing students as far as possible in the attitude of the discoverer — methods which involve their finding out instead of being merely told about things." [13, p.236]. Bruner built on these ideas, arguing for the "powerful effects that come from permitting the student to put things together for himself, to be his own discoverer" [14, p.21].

'Discovery' applies beyond scientific progress for mankind as a whole, to one discovering for oneself, even if already known by others. In the context of education, Armstrong referred to 'old results for new men' [13, p.236], and Bruner to 'obtaining knowledge for oneself' [14, p.21]. Bruner defines discovery as 'rearranging or transforming evidence in such a way ... to go beyond

Table 1: Mapping characteristics of Threshold Concepts to the case of boundary layer theory.

Characteristic	**Representation in boundary layer theory**
Conditional	Mastery of underlying concepts in fluid mechanics, in particular those of velocity fields, and force-momentum balances. The latter is the basis on which the relative importance of viscous effects can be discussed. The relative importance of viscous effects is a key concept to appreciate when employing boundary layer theory.
Discursive	Learners need to internalise the inter-related concepts in order to use them in their internal language of thought [8] and when expressing themselves. This includes the conditional (foundational) knowledge, and the concept of different regions of the flow; the dominant role of Reynolds number; the interaction of pressure gradients and velocity profiles.
Integrative	Only by combining the key discursive concepts can the boundary layer be appreciated.
Liminal	The inter-related nature of the relevant concepts leads to a liminal space where the learner builds blocks of partial understanding, which may lead to temporary set-backs, before emerging as full understanding.
Bounded	Boundary layer theory is bounded to thermofluid sciences. Basic boundary layer theory has further limitations such as not accounting for instabilities, transition, turbulence, three-dimensional and compressibility effects.
Transformative	A 'new way' of seeing high-Reynolds-number fluid flows, with thin but influential regions of viscous boundary layers adjoining larger, inertially dominated flows.
Irreversible	The transformed way of seeing is so simple and powerful that it becomes hard to 'unsee'.
Reconstitutive	According to Meyer and Land, learning threshold concepts can lead to a change in identity of the learner as they become members of a discipline (see [9] and legitimate peripheral participation). Evidence for this concept is beyond the scope of the present paper.

Table 2: Nine considerations when teaching a threshold concept, abbreviated from [12].

Consideration	**Application in boundary layer theory**
Jewels in the curriculum	Not relevant at the detailed level of focus in this paper.
Importance of engagement [12, p.57]	A key concept, highly applicable: • Develop a genuine understanding; use questions • Active engagement (not simply recall) • Ways of thinking and practicing (see Wenger (1998) [9]; 'thinking like an [engineer]') • Provocations: 'something else happening — other than the return of the same'
Listen for what is known	Give time for students to express themselves and identify their (lack of) understanding
'Supportive liminal environment'	Facilitate discomfort, give space for experimentation, making mistakes, exploring
Uncertainty	Use questions and a supportive culture; encourage uncertainty
Excursive journey	Facilitate discovery. Introduce recursiveness, e.g. multiple exposures to ideas, from different perspectives.
Pre-liminal variation	Account for the different states of knowledge with which students enter the process
Don't simplify	Break it down, but not beyond what is functional. Avoid 'false proxies'.
The underlying game	Beyond the scope of this paper

the evidence so reassmebled to additional new insights'. Bruner's definition is applicable for threshold concepts, especially physical concepts where concrete evidence plays a key role.

Bruner made a further point that "it may well be that an additional fact ... makes ... transformation ... possible. But it is often not even dependent on new information", emphasising the *process* of discovery, not just which facts are presented.

Discovery based learning, which departed from behaviourist theories, inspired many educationalists and led to many educational experiments [15]. Disagreements over definitions and appropriate experimental paradigms followed [16, 17]. For example, the difference between learning for discovery (learning how to discover — how to learn), and learning by discovery (learning specific knowledge by a different process). Also the distinction between completely free discovery; guided discovery; and didactic teaching. One comprehensive meta-review claims that free discovery has a limited benefit, while guided discovery is superior to either free discovery or didactic teaching [18]. Another systematic review claims a complete "failure of Constructivist, Discovery, Problem-Based, Experiential, and Inquiry-Based Teaching" [19].

The lack of consensus comes from different definitions, and different contexts. However, if didactic teaching has been troublesome, then introducing a component of discovery, with some guidance, is worth trying and evaluating.

2.3 Practical approaches in the literature

Lock et al. [20] worked specifically on boundary layers, using oil flow visualisation on wings and reporting positive results from student surveys. Pour et al. [21] used visualisation of thermal boundary layers to motivate students to study heat transfer, with surveys showing that students found the demonstrations to be helpful, interesting, well-explained and informative. One student commented "it is really hard to picture the boundary layer, so seeing it was great" [21, p.523], suggesting that visualisation may be useful.

Brown et al. [22] studied the effect of using a desktop demonstration module for open channel flow; with controlled tests they showed a large effect size (0.98) [23]. Richards et al. [24] reviewed simple hands-on fluid mechanics experiments and presented new desktop equipment. Controlled tests failed to distinguish an effect due to the equipment. The work of [22, 23, 24] all uses fluid mechanics experiments, but with less emphasis on visualisation.

A meta-study by Lis [25] showed that 'visualisation' can enhance engineering education, but focussing on the use of images in learning materials. Savander and Kolari [26] argue that visualisation helps with engineering problem solving, basing their claims on an informal explanation of how visualisation helps.

Feisel and Rosa defined 13 objectives for using the laboratory [27], however, improving conceptual understanding was not one of those objectives. In the present case, however, it is the key objective.

2.4 Summary of literature

The key points from the brief review are:

- Threshold concepts are relevant to boundary layers.
- Guidance (Table 2) suggests a discovery-based approach.
- Bruner emphasised the *process*, not just the intended outcome.
- ‘Guided discovery’ is intermediate between didactic or free discovery.
- Practical efforts gave mixed evidence, but suggest hands-on and visualisation are helpful.
- The laboratory as a place to visualise troublesome concepts is not a common approach.

The question of course design is *where on the spectrum*, between didactic and free discovery, we should position ourselves; and *how* to do this. To address this question, we need to try a new approach with an increased element of discovery, and to critically evaluate the results.

3 Method

In this Method section describes the implementation of new equipment and an associated activity. We summarise the educational context, describe the new apparatus, outline the scaffolding provided to aid students during the activity, define the assessments that can be used for analysis, and summarise a survey deployed to students to evaluate their experience.

3.1 Educational context

The context of this paper is a dedicated mechanical engineering degree programme which includes Fluid Mechanics modules in the first and second years that are both compulsory. The first module covers hydrostatics, kinematics, the Bernoulli equation, and control volume analyses. The second module derives and applies the differential equations of motion and is the focus of this paper. Students spend 125 hours on the module over one academic year. The module comprises weekly lectures, weekly self-study exercises, bi-weekly group tutorials, and a 3-hour experimental activity. Within the module, approximately 20-25 hours of study is focused on Boundary Layer theory; the experimental activity is also dedicated to boundary layers.

The original activity was instructional. Students would visit the wind tunnel and follow instructions to take velocity profiles near the wall. The other seven activities for the same cohort also followed an instructional approach. The implementation of discovery-based learning described in this paper is therefore unique for the students who experience it.

We learned form early attempts to introduce ‘discovery’ that any experiments conducted before the related theory is taught, should be in close temporal proximity to the relevant lesson. The pandemic then catalysed wider change as we needed to replace the wind tunnel with something that could be shipped to students around the world in lockdown and used without technical assistance. To meet this need we developed a water visualisation kit. The success of the kit led us

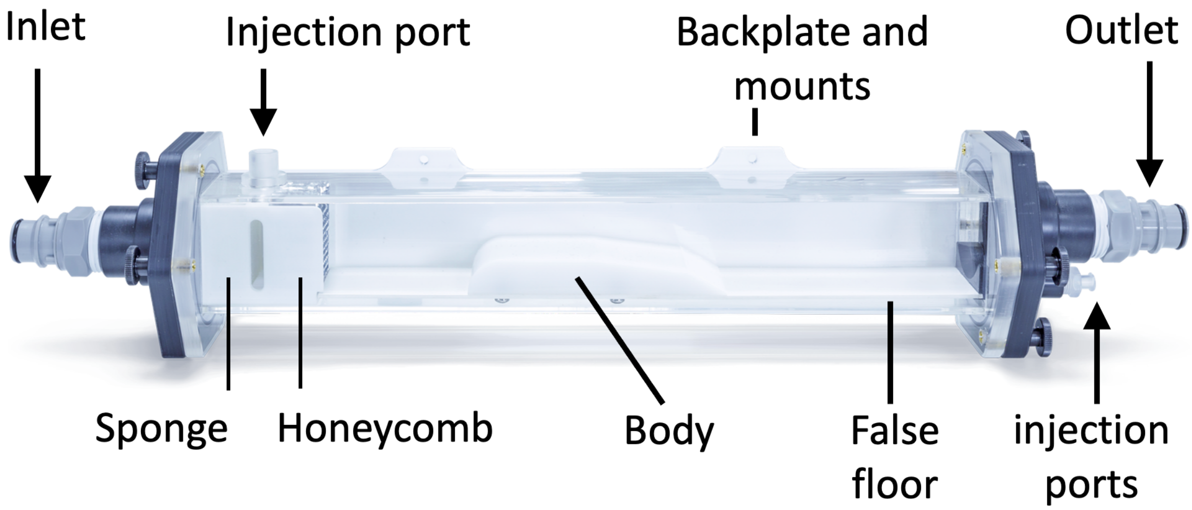


Figure 1: The desktop flow loop showing key features. Tracer fluid is introduced through injection ports: one upstream for a needle to inject into the main flow from an adjustable height; and two downstream that dock with the false floor and are routed to the body to eject from the surface.

to continue using it after lockdown (2022, 2023, 2024, and in future) but in a classroom environment.

3.2 Description of the apparatus

The apparatus is a transparent water flow loop, with flow visualisation features, illustrated in Figure 1. It is small enough that it can be used on a table top in a classroom, with students working in pairs or alone. The ability to schedule large numbers of students together — while still working in pairs on their own equipment — makes scheduling in-sync with whole-class lectures possible.

The working section of the flow loop is a transparent square tube with internal sides of $h = 44\,\mathrm{mm}$ and a length of at least 300 mm depending on the model. Water is pumped from a source by an electric submersible pump, for example an aquarium pump, providing flow rates on the order of up to 300 litres per hour ($Q = 83 \times 10^{-6}\,\mathrm{m}^3/\mathrm{s}$), leading to channel Reynolds numbers up to $Re_h \equiv Q/(h\nu) \approx 1900$ where ν is the kinematic viscosity. At these flow rates the flow is laminar, but the channel boundary layers are thin.

Flow conditioning using a sponge and honeycomb was effective to achieve a uniform flow at the entrance — if bubbles are absent. Tracer fluid with neutral buoyancy can be sourced from commercial suppliers (CAS 3536-49-0) or as a reasonable alternative pen ink can be mixed with water at a ratio of approximately 1:40.

A body shape was engineered to be placed inside the working section and provide flows of interest. The body is a simplified version of the 'Ahmed body', with a circular nose, a flat top, and angled downstream sides at 7° and 30° — see Figure 2.

Tracer fluid can be injected upstream from an adjustable height; and additionally from within the

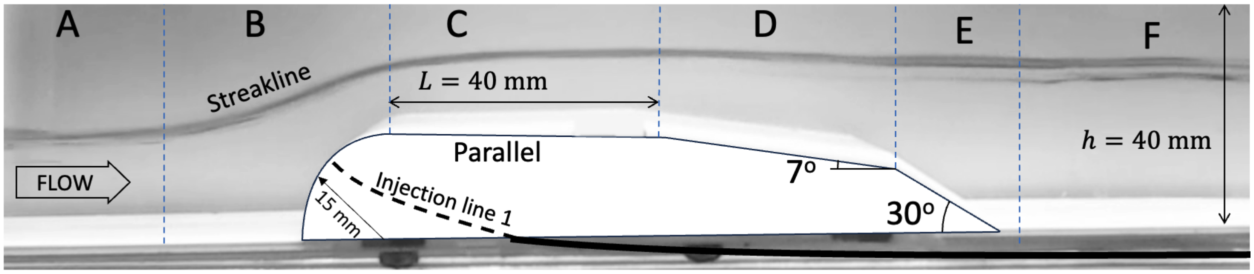


Figure 2: The working section with water flowing and a streakline from upstream. Geometry is annotated, and zones labelled A-F identify the different pressure gradients. The length scale L and height h are indicated. The injection line, which runs under a false floor and inside the body, is sketched.

body. The latter is important to ensure the boundary layer can be visualised with relative ease. Flow visualisation should represent the same flow that would be present in the absence of the visualisation. Therefore it is recommended that injections are at 90 degrees to the flow at a gentle pace, or counter to the flow at a gentle pace, in both cases this is to avoid creating an artificial jet when injecting.

Measurements that are possible from the basic experiment include measuring volume flow rate, inferring Reynolds number and pressure gradients (using the Bernoulli equation). Visualisation can capture streaklines of flow over the body; the existence of uniform flow in the main flow; slower flow on the boundaries; velocity profiles at the boundaries; attachment and separation of the boundary layer; re-circulation regions; and more exotic flows when employed by a curious user, such as turbulent jets, free surface flows, and wake patterns. The working section can handle alternative bodies for example cylinders, wings, or other shapes. The primary means of capturing flow visualisations is by photos and videos, typically by students using their own smartphones.

3.3 Activity management

The kits have been used annually for four years (2021–2024). In the first deployment (2021), students were at home due to lockdown and were sent their own kits and worked physically alone, with peers on a video call. In later years (2022–2024) students were accommodated on campus and worked in pairs.

Students are managed in groups of up to 50 at a time, working in pairs on their own equipment and at their own pace. Cohorts of up to 200 were managed, and scheduled to be in-sync with lectures. First observations by students were immediately *before* the first related lecture. The same equipment is also used during lectures for demonstration purposes throughout the module.

To prepare for the activity, students were provided with six short videos, totalling 30 minutes. Videos were watched by about 55% of students (some of whom may have been in pairs or groups so total viewing may be higher), with a 90% completion rate for those who viewed them. Written slides were also available as an alternative. The briefing was to familiarise students with the equipment and how to use it; and to establish the goals of the session. The goal was to record evidence of the existence, thickness, and behaviour (attachment/separation) of boundary layers.

Guidance for students

An outline for the session provided 'guided discovery':

- Setup the equipment, and show a risk assessment before water is provided (15 mins)
- Activity 1: Measure the flow rate, calculate the channel Reynolds number, and observe streaklines in the main flow (30 mins)
- Activity 2: Establish the velocity and pressure fields (30 mins)
- Mid-session review (optional depending on tutor and class dynamic) (15 mins)
- Activity 3: Observe the boundary layer (20 mins)
- Activity 4: Custom experiment - optional (20 mins)
- Discussion, conclusions, clear up, and support (20 mins)

Activity 2 is a reminder of an earlier exercise which concludes that the pressure gradient is negative at B, zero at C, positive at D and E but stronger at E than D.

Activity 3 comprises the three Challenges in this paper, i.e. to observe the existence, thickness, and the attachment/separation of boundary layers related to pressure gradients.

A key part of cementing expectations is telling students that they will conduct their own experiments, and tutors welcoming students with "Welcome, you may start your experiments. I'm here to help so feel free to ask". The introduction makes it clear that students are the agents of the activity. Tutors check-in regularly to maintain a dialogue with the students, but without dictating their activities.

In addition to the 2.5 hours described above, students can optionally visit the Wind Tunnel in a different room for 30 minutes, which is outside the scope of this paper.

Tutors were trained with video footage from previous years and then met with the module leader for guidance. A summary of the training follows:

Guidance for tutors

- Reflect on the purpose of the activity and how students experience it
- Students have written guidance and can complete the activity independently
- Avoid telling students things directly or giving them instructions
- Listen to students, understand their point of view first and use that as a starting point
- Be positive and encouraging, give them positive feedback
- Share your passion for the subject
- Discuss their results with them
- Challenge high performing students and encourage them to be critical in their analysis

An example of a tutor with a pair of students is illustrated in Figure 3. At the time illustrated, the students have previously suggested how they will conduct an experiment to gather evidence. The

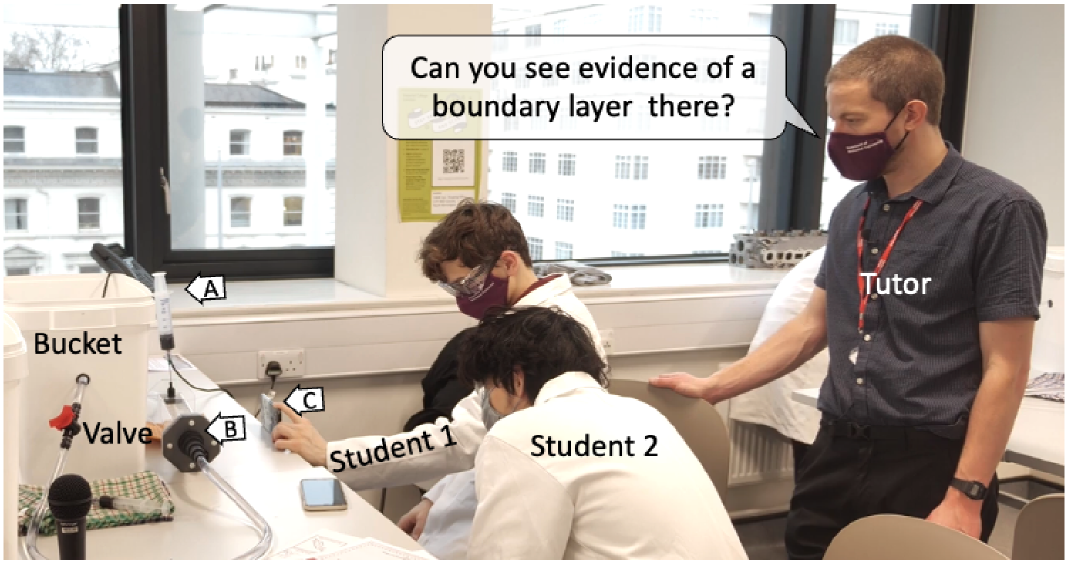


Figure 3: A tutor visits a pair of students. The students are actively using the kit to experiment, while the tutor prompts with questions. A: tracer fluid injection. B: working section. C: student smartphone to record evidence. The kit in use is a previous version to the one in Figure 1 but with the same working section. Masks were mandatory at the time the footage was taken. Permission to publish was given prior to filming.

students are the agents of the experiment, and the tutor is positioned separately so as not to take control or dictate activities. The tutor's question is open, but focusses the students' attention on the important aspect of the experiment.

3.4 Assessment of outputs

Two aspects of summative assessment relate directly to the laboratory session: the lab book, and a report. Students scan and submit their lab books at the end of the session, for low-stakes summative assessment (3.75% of 5 ECTS where one year is 60 ECTS). Assessment marks were broken down such that statistics were available on which conclusions were evidenced in the lab books.

Students also wrote a lab report. One quarter of students wrote a lab report on the activity described in this paper, with summative assessment weighted at 15% of 5 ECTS. The remaining students wrote a lab report on a different activity.

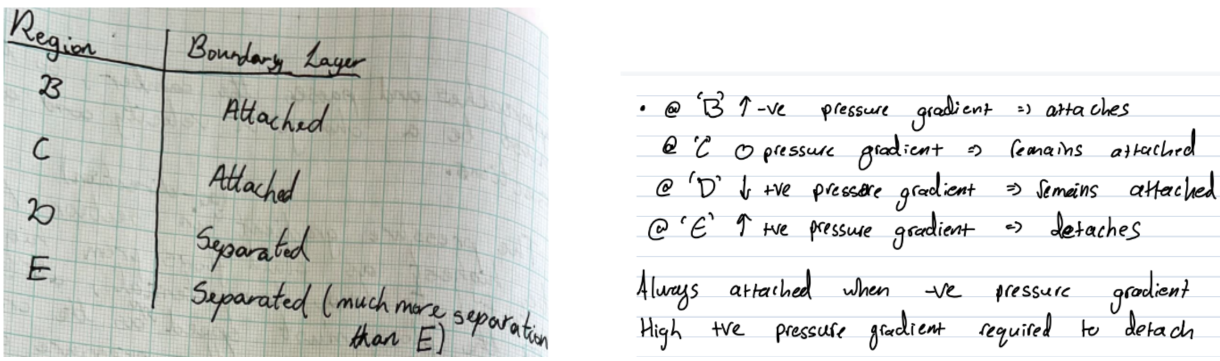
3.5 Survey of student experience

To evaluate the student experience we used a survey developed by [28] specifically for laboratory activities. The survey comprises quantitative (Likert) questions on nine dimensions of experience across all activities; free comments are also solicited for qualitative analysis. The survey is detailed in [28], showing good repeatability and sensitivity. The nine dimensions are purpose, conceptual learning, positive challenge, documentation and guidance, engagement, support, collaboration, feedback, and technical communication skills. The last two dimensions are omitted in this paper because of censoring effects related to lab report allocation.

Survey results use Likert scores of 5.0 correspond to ‘strongly agree’, 4.0 ‘agree’, 3.0 ‘neutral’, 2.0 ‘disagree’, and 1.0 ‘strongly disagree’. Average scores above 4.0 are considered good and not needing improvement, although aspirational teachers aim for 4.5. Changes of approximately 0.5 are considered significant. The benefits of the survey are to provide high level feedback on the quality of a laboratory experience and to highlight areas that may need further attention.

4 Results

In this Section, we begin by presenting results of student outputs and assessments. Then we review the results of evaluating the student experience.



(a) (b)

Figure 4: Examples of student lab books. (a) Observed separation but made incorrect conclusions. (b) Correctly distinguished between weak and strong positive gradients.

4.1 Student outputs

Examples of student lab books are presented in Figure 4 including a partially correct example (Figure 4a) and a more complete example (Figure 4b). In Figure 4a the student correctly identified the existence and thickness of the boundary layer, and recorded observations on separation. However, the observations on separation are incorrect, suggesting separation at D (incorrect) and ‘more separation’ at E[1] which is not a valid concept.

Figure 4b shows a more complete conclusion that a strong positive gradient is required in order to observe separation. In other examples, not included in Figure 4, students also recorded observations of flow reversal in section E.

The proportion of students who presented evidence in the lab book for each of the three challenges addressed in this paper is plotted in Figure 5. There is a trend over the four years where students became more successful at recording evidence for these key phenomena. For the

[1]Written as D in the logbook, presumably a basic error.

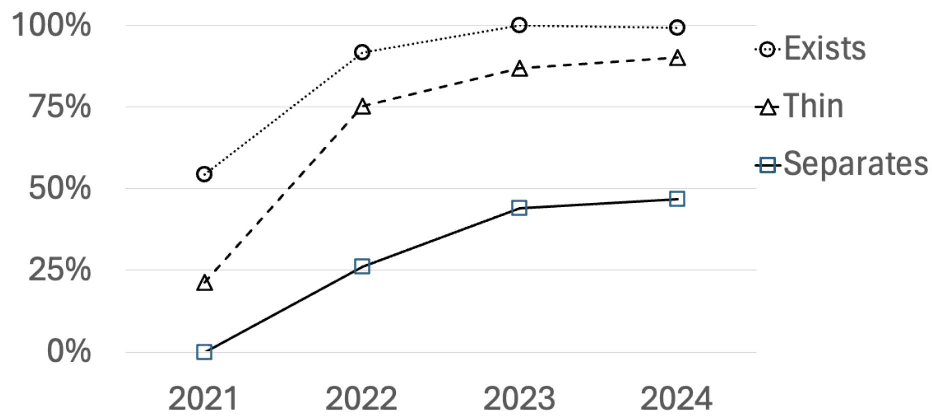


Figure 5: Proportion of the cohort who provided evidence in the lab book for the three key conclusions about boundary layers.

last two years, results were stable and the two students in Figure 4 each represent about half of the cohort (see data in Figure 5).

Reports written after the activity enabled students to provide more detailed evidence, and to incorporate theory that had been taught through lectures, self-study exercises, and group tutorials. Figure 6 shows evidence of students observing the key basic phenomena, namely the existence, thinness, and attachment/separation of the boundary layer. Further, in Figure 6a streamlines for the main flow are visible, which helps infer pressure gradients; and recirculation is visible in Figure 6c, which helps distinguish boundary layer growth from boundary layer separation.

All students informally observed the existence of a slow layer near the body during their session. There is a distinction, however, between ‘seeing’ by eye, which was very accessible, and recording convincing evidence, which was less common. Figure 7 shows advanced results from the report of an innovative student who did provide strong evidence.

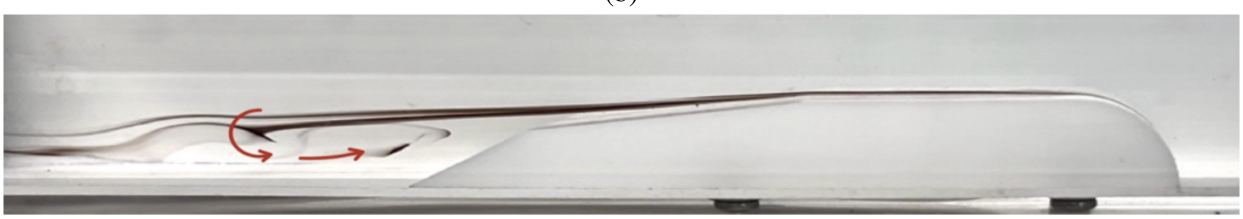
Converting key observations to compelling evidence in reports was not always successful. Consistent with the lab book results (Figure 5), and despite feedback about the strength of evidence in their lab books, some students still failed to grasp that separation is a distinct event associated with flow reversal.

For example, a minority of students insisted that the boundary layer separated in region D, despite this not being the case. This confusion arose from the view in Figure 6c, where the tracer fluid in the boundary layer ‘moves further from the body’ in region D where the boundary layer grows quickly in a light positive pressure gradient. This moving further away is the growth of the boundary layer, but not the ‘separation’.

Assessment scores for reports were relatively consistent over four years — in contrast to the lab book marks illustrated in Figure 5. On the measure of completeness of results in the reports, the proportion receiving a grade ‘A’ was 54%, 48%, 67%, 63% for years 2021 to 2024 respectively. The trend was similar for conclusions in the report (68%, 54%, 65%, 79%) with a possibly significant increase in 2024, which correlates with the purpose of the lab being clarified in the handout.

(a)

(b)



(c)

Figure 6: Results from student lab reports, taken during first-time use in a three hour session. Flow is right-to-left and annotations are original from student reports. This figure shows the key pheonemona that students observed: (a) streamlines in the main flow. (b) a slow moving layer on the body, which is initially attached but separates in region E. (c) recirculation in the wake region.

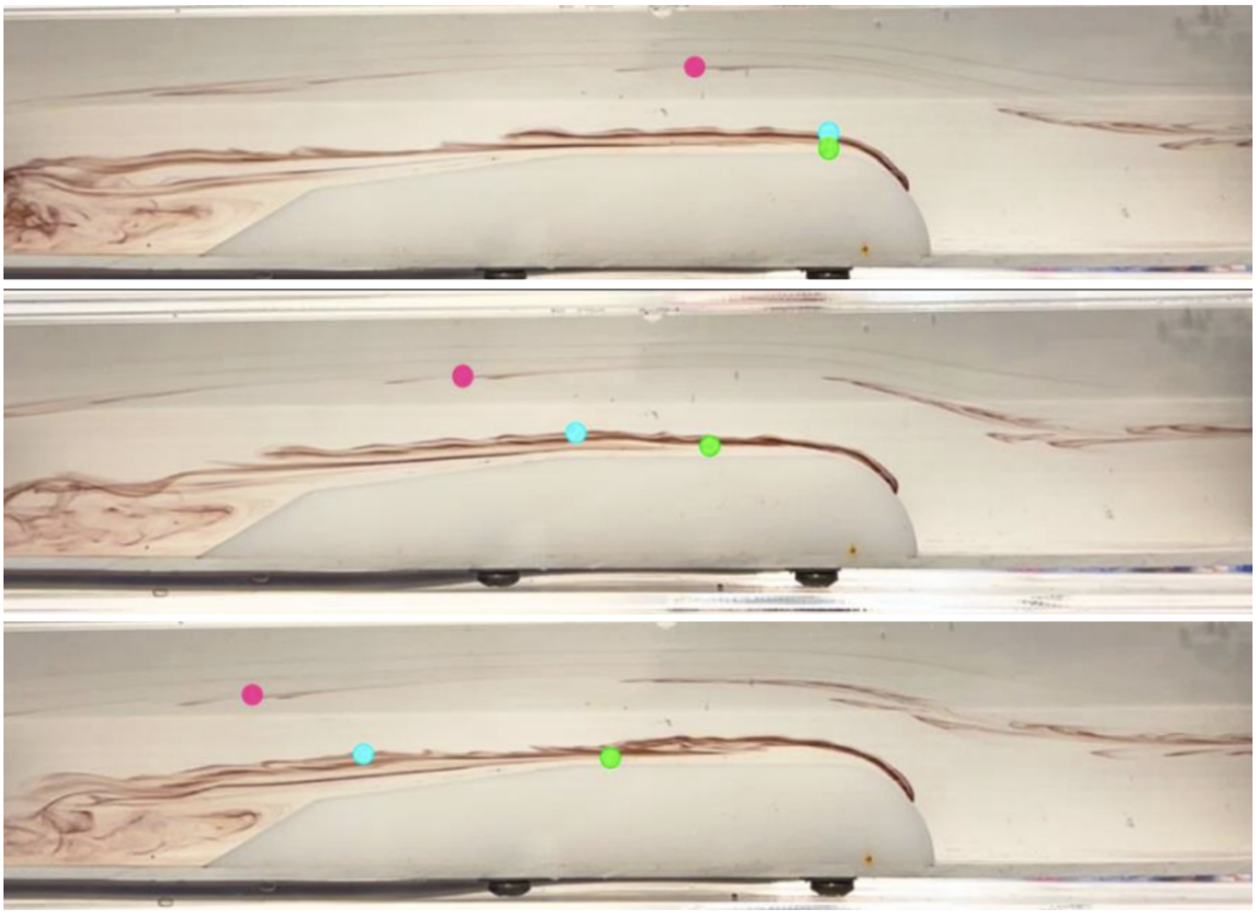


Figure 7: Advanced results from a student lab report showing innovation. Three frames from a video are shown, 0.5 seconds apart. Flow is right-to-left and annotations are original from the student report. The student has pulsed tracer fluid from within the body, so that initially it enters the boundary layer (green), but subsequent injections go outside the boundary layer (cyan). A central streamline (magenta), comes from upstream. The equal motion of the magenta and cyan, but slower motion of the green, are evidence of both the existence and the thickness of the boundary layer. Also evident is boundary layer separation, and flow reversal in the wake.

Table 3: Statistical information about the survey that was administered to students. The 'mean for 8 activities' is labelled 'Annual mean' in Figure 8.

	2021	2022	2023	2024
n	87/167 (52%)	81/172 (47%)	72/196(36%)	91/182 (50%)
Annual mean for fluid mechanics	4.27	4.16	3.93	4.25
Annual mean for 8 activities	3.89	4.01	4.00	4.05
Annual max for 8 activities	4.27	4.16	4.18	4.25

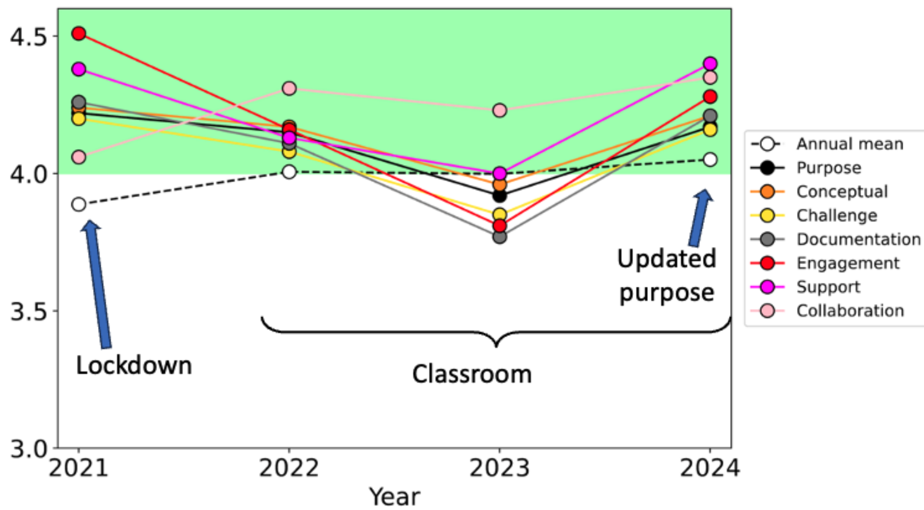


Figure 8: Average scores for seven dimensions of the lab activity over four years. Additionally, the 'annual mean' is the mean of means for all seven dimensions and all eight activities; this serves as a reference for inter-year trends.

4.2 Survey results

Survey statistics are provided in Table 3 showing good response rates. Figure 8 shows average survey scores for the seven dimensions of the lab activity that were tested by Likert scales. The score for collaboration was understandably lower during lockdown (2021), and consistently higher in later years as students worked in pairs to complete the activity. The remaining six dimensions show a common pattern: they began in lockdown (2021) with very high values showing a strong success. In 2022, with activities back in-person, scores converged to averages of approximately 4.1. In 2023, scores reduced further, to below-average values, although the delivery was nominally identical. In 2024, with a renewed emphasis on gathering evidence, and improved staff training, scores all increased again to high levels.

Qualitative ('free') comments in the survey were limited. There were 17 comments that specifically mentioned the activity discussed in this paper. While some themes such as engagement (positive; four comments), and lack of clarity of purpose or other practical confusion (negative; four comments) were informally evident, the qualitative data was not sufficient to conduct a more rigorous thematic analysis.

5 Discussion

Based on the three Challenges defined in the Introduction we ask:

- Were students able to visualise boundary layers as intended?
- How did they experience the 'guided discovery'?

5.1 Technical success

The new equipment enabled all students to experiment personally, and in-sync with the theoretical instruction (lectures). Students worked at their own pace, which is key to facilitate discovery.

The results in Figure 5 from student lab books, and Figure 6 from student reports, show evidence that the three challenges have been met in principle. The vast majority of students succeeded in providing evidence for two out of the three conclusions. Half of the students in the cohort recorded evidence of the third conclusion during the three hour activity. Overall this outcome is a major improvement on previous activities, which didn't visualise the boundary layer at all, and did not address flow separation at all.

5.2 Quality of evidence

Evidence provided by students could be improved. Their instructional training had not prepared them to emphasise concrete, repeatable (i.e. scientific) evidence as a warrant for their conclusions. If a discovery approach were taken more often during their studies, then students would likely improve at this skill before attending the second-year activity described in this paper. The broader point is that 'discovery' approaches need to be consistent across multiple activities to gain the full benefits. Habit and routine are important parts of a successful educational approach.

5.3 Interpreting the survey

Quantitative scores in the survey we stable across eight activities, but varied for the Fluid Mechanics activity described in this paper. Receiving kits at home in lockdown (2021) was a welcome excitement. In the classroom in 2022 and 2023 scores reduced consistently until they were below average for the programme. The reductions do not correlate with any known changes in the delivery.

Following 2023 the survey highlighted an unclear purpose to the activity. An emphasis on 'gathering evidence', rather than simply 'exploring' may have caused the increase in scores in 2024, although confounding effects include the support in the room, which increased significantly from 4.00 to 4.40 and may have had wider impacts on student perception.

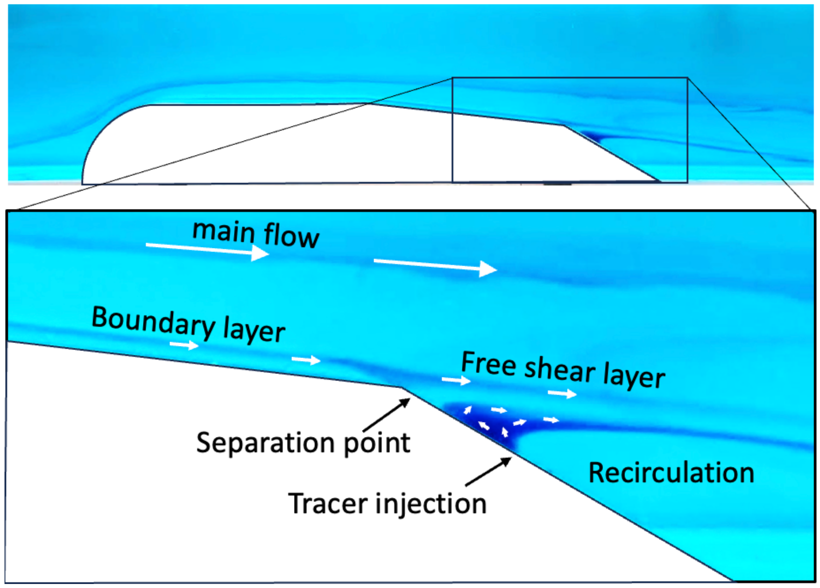


Figure 9: New experiments by the authors with an additional injection point in the recirculation zone, providing clearer evidence of flow reversal and boundary layer separation.

5.4 Limitations

A common struggle for students was the nuance that flow separation only occurs specifically in strong positive pressure gradients. Further, a significant minority of students struggled to identify separation as a distinct point, associated with stagnation and reversal; for example notes like ‘more separated at E [than D]’, which is a misconception.

To identify flow reversal, some playing is required before tracer fluid settles in the recirculating wake region. Without this innovation, which many students did not discover, it is not clear to students that the flow reverses in Region E but not in Region D.

Returning to the student experience, survey data are useful but limited. For deeper or more general insights into threshold concepts and guided discovery, focus groups are recommended.

6 Future work

6.1 Equipment improvements

The equipment can be improved to help discover flow reversal in the wake region. A third tracer injection point can be added to the downstream side of the object (in Region E). A prototype is illustrated in Figure 9. Tracer fluid injected at the centre-point of Section E travels upstream before turning to join the main flow. The flow is much slower in the wake, so the effect requires some nuance to identify, but the addition of the new port makes the situation much clearer and will be used in future.

Pressure gradients are key to the conclusions that students reach about boundary layers. With the

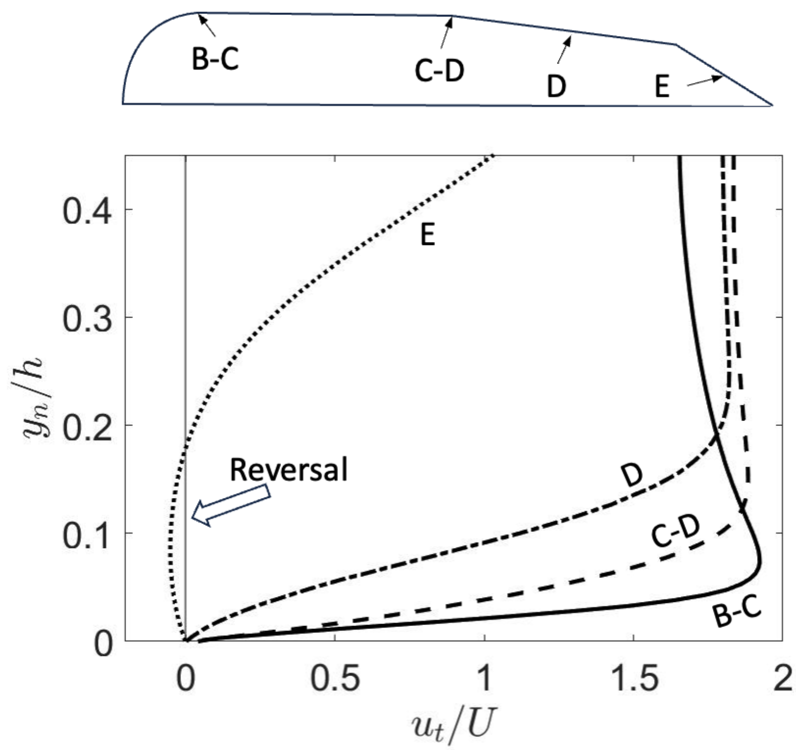


Figure 10: Combined velocity profiles from CFD, where u_t is the component of velocity tangential to the surface of the body; y_n is the distance normal to the surface of the body. Profiles are taken at locations B-C (—); the transition C-D (– –); the middle of section D (– ·); and the middle of section E (· ·) where the flow has reversed.

current equipment, pressure gradients are inferred from theoretical arguments. The equipment could be improved by including pressure taps that allow direct measurement.

6.2 Computational fluid dynamics (CFD)

Further insight can be gained by students by using results from computational fluid dynamics (CFD) [21]. Preliminary steady laminar flow simulations have been carried out in OpenFoam using simpleFoam, with details given in [29]. Profiles (normal to the body surface) of the tangential velocity at different locations along the channel are plotted in Figure 10.

The profiles show a characteristic bulge at B-C after developing in a negative pressure gradient, then a classic profile at C-D in a negigilbe pressure gradient. In the light positive ('adverse') pressure gradient at D, the profile begins to inflect and decelerate. No reversal is evident until point E, which indicates separation.

Velocity profiles combined with visualisation may help students clarify the relationship between flow reversal and boundary layer separation.

In future we will extend the comparison between the CFD and the experiments for validation. We also need to consider how students can obtain these results through guided discovery.

6.3 Educational practice

Two possible improvements to the activity are suggested here. Firstly, students can normalise beforehand to the basic 'discovery' approach and to flow visualisation. A staged approach would be consistent with cognitive load theory [30]. Each session could have smaller goals such as measuring flow rate, visualising streamlines, and identifying pressure gradients, prior to investigating boundary layers.

Secondly, students without complete conclusions can be invited back to the lab. A revisit may have benefits for equity and inclusion, and motivation, but also has economic implications.

The student experience also warrants further investigation. For deeper research beyond the student outputs and the survey, focus groups would provide more insight. The question of 'how guided' discovery should be would be a valuable focal point.

7 Conclusion

A discovery approach to boundary layers, where students visualise flow in their own experiments, can improve their conceptual understanding of boundary layers. We reached this conclusion by developing new equipment and a new activity for students.

We decomposed struggles learning about boundary layers into three challenges: students need to learn that boundary layers *exist*, are *thin* for high Reynolds numbers, and *attach or separate* depending on the pressure gradient. The new equipment for this purpose was a desktop flow loop with a simplified Ahmed body and tracer fluid injection for visualisation.

Using the equipment and our discovery-based activity, the first two challenges were met by most students. The third challenge was met by about half of students. The difficulties with the third challenge centered around the conceptual idea of separation and its link to flow reversal.

To address the third challenge more effectively, we showed results from a future variant of the equipment that allows tracer injection into the wake to see flow reversal directly. We also presented preliminary results from computational fluid dynamics (CFD) simulations that may help students clarify when flow reversal occurs.

Survey data showed a positive student experience, with improvements coming by clarifying the activity purpose of 'obtaining evidence', and improved tutor training.

Implementing a discovery approach in the context of a more instructional norm was challenging. A broader change toward guided discovery would likely produce greater gains toward a discovery mindset in students.

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Appendices

A: Summary of boundary layer theory

Boundary layers are a viscous phenomenon. The governing equations in the case of incompressible flow and Newtonian viscosity are the Navier–Stokes equations. The force per unit volume within the fluid due to viscous effects is represented by

$$\mu \overrightarrow{\text{Laplacian}}(\vec{u}), \tag{1}$$

where μ is dynamic viscosity, $\vec{u}$ is the velocity vector, and the Laplacian operator is the divergence of the gradient — sometimes written alternatively as ∇^2. The numerical value of viscosity, μ, is low for common fluids and flows which tempts analysts to consider the whole of (1) to be small enough to neglect, and to remove it from the governing equations. Prandtl's insight was that the smallness of the viscosity is not sufficient to conclude that the viscous forces (1) are small because the term (1) is the product of two terms: the viscosity *and* the Laplacian. Viscous effects are only small if the Laplacian of the velocity field, i.e. second gradients in velocity, is also small.

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For flows that are uniform or have high Reynolds numbers, the velocity gradients and second gradients may be small throughout most of the fluid, but they become very large at the boundary of an object. At the boundary the velocity rapidly decreases to zero relative to the object, known as the 'no-slip' condition. Due to the high gradients at the boundary, viscous effects not negligible in that region.

B: Analysis of boundary layers

In two-dimensional Cartesian coordinates (x,y), with x parallel to the flow, with velocity components $\vec{u} = [u \;\; v]^T$, the first component of the viscous force per unit volume (see (1) in the Appendix) can be written as:

$$\underbrace{\mu \frac{\partial^2 u}{\partial x^2}}_{\mathscr{O}(\mu U/L^2)} + \underbrace{\mu \frac{\partial^2 u}{\partial y^2}}_{\mathscr{O}(\mu U/\delta^2)} . \tag{2}$$

The 'order of magnitude' of the terms are obtained using U and V for the streamwise- and transverse- velocities; and L and δ for the streamise- and transverse length scales. The scale L is indicated in Figure 2 and U is the bulk velocity. V and δ are to be determined. Using the relation $U/V \sim L/\delta$ from mass conservation and grouping terms gives:

$$\frac{\mu U}{L^2}\left[\mathscr{O}(1) + \mathscr{O}\left(\frac{L}{\delta}\right)\right]. \tag{3}$$

In the case that $\delta/L \ll 1$, we can neglect the first term in (2).