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Using benchtop experiments to teach dimensional analysis and analogue modelling to graduate geoscience students.

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Abstract. The need for geoscience students to develop a quantitative skillset is ever increasing. However, this can be difficult to implement in university-style lecture courses in a way that is both manageable for the instructor and does not involve lengthy, potentially repetitive, question sheets for the students. Here, a method for teaching dimensional analysis, basic fluid dynamics, and the interpretation and scaling of experimental data is presented for a graduate student audience. The proposed method utilises simple fluid dynamic benchtop experiments that require a small amount of teaching space and use readily available, low cost materials. Our analysis of student performance through pre- and post-tests demonstrates that students have a better knowledge of dimensional analysis, data interpretation and experimental design after the series of practical sessions compared to instruction through a single, passive lecture. We therefore show that simple benchtop experiments can be an effective way to improve and integrate quantitative learning into a graduate geoscience class.

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INTRODUCTION

Geosciences as a discipline are becoming more quantitative – early works have provided rigorous qualitative descriptions, observations and classifications of the phenomenon and geological deposits studied (e.g., Folk, 1980; Le Maitre et al., 2005; Pettijohn, 1954; Walker, 1973). Despite this previous work, quantitative descriptions of geoscience processes are still required to accurately describe and forward model underlying physical and chemical processes. Examples of topic areas include, but are not limited to, (paleo)climate reconstructions, volcanic ash dispersion modelling, analysis of ice shelf stability and the deep imaging of planetary interiors. It therefore stands that the upcoming generation of geoscientists should be trained with a strong quantitative skillset. However, the integration of quantitative exercises that both extend beyond the simple use of formulae and are well matched to the curriculum is often challenging (Singha and Loheide II, 2011; Yuretich, 2003). Furthermore, in some cases these passive exercises can lead to discouragement of students from quantitative approaches in science (Seymour et al., 1997). In this study we focus on one aspect of quantitative skills development, in the form of dimensions, dimensional analysis and scaling. These skills, as further detailed herein, are fundamental to graduate and high-level, research undergraduate students who wish to design, conduct and interpret data arising from numerical and physical experiments (e.g., Brown, 2009; Hulin, 1980; Lira, 2013). The main focus here is on graduate (MSc) student learning.

Geological processes are often difficult to measure directly in the field due to the diverse range of timescales and episodic nature of events we seek to understand. Direct observations are limited to subaerial processes; subsurface processes can only be inferred indirectly. Each event is different such that repeat observations are not usually possible, and variables cannot be controlled in a systematic way. Natural events are also extremely complex, and their behaviour is a manifestation of many interacting processes. Given this, it is often challenging for the observer to isolate and characterize the fundamental constituent processes, yet this is essential for development of a physical or numerical model of the system. Additionally, if the phenomenon of interest is particularly dangerous (e.g. hurricane, landslides) the risks associated with working in these areas may limit observations. All of these compounding factors make (both physical and numerical) experimental studies a key source of information within the geosciences, although, geoscientists commonly face challenges in linking experimental datasets and physical models back to natural systems.

The challenges in improving our understanding of natural processes have a direct bearing on our ability to teach geoscience concepts to students who are still developing their intuition for physical processes and how to mathematically express them. Physical models have been previously deployed to support the introduction of new geoscience topics, commonly through analogical learning (Baker et al., 2004; Bolacha et al., 2011; Brady, 2009; Jee et al., 2010; Kastens and Rivet, 2008; King, 2016; Rust et al., 2008; Tolley and Richmond, 2003; Wadsworth et al., 2018). These physical models aid student comprehension and allow for broad, idealized relationships to be drawn between competing variables (Jee et al., 2010). Furthermore, physical models, especially those that are rigorously scaled to a natural system of interest, underpin a whole subset of geoscience research, and the experimental results are often used to constrain numerical model parameters and extract further quantitative information from field observations (e.g., Burgess et al., 2012; Kavanagh et al., 2018; Muto et al., 2016; Paola, 2000; Sasse et al., 2020). Thus, the ability to effectively design, scale and interpret analogue experiments is a useful skillset for graduate and research active undergraduate students.

In this paper we use the simple, and geologically common, problem of a particle settling in an ambient fluid as a platform to show (a) how to investigate the governing processes through dimensional analysis, (b) how to prepare simple bench top, classroom, experiments that develop student's intuition for the governing processes, and (c) how to quantify these processes through controlled, scaled, experiments. Using an assessment of student learning, we show how the use of simple analogue benchtop experiments can be an effective way to enhance quantitative skills amongst graduate (MSc) students and a methodology for teaching experimental scaling and data interpretation is outlined.

Learning Objectives

The combined lecture and practical exercises outlined in this study were designed to meet a number of learning objectives (LO) that increase a geoscience student's ability to investigate physical science problems and rigorously design and interpret experimental data. Specifically, upon completion of the learning activities, a student should be able to:

- LO1: identify the fundamental base dimensions (e.g. length, mass, time, temperature);
- LO2: derive the fundamental base dimensions of key physical parameters (e.g. pressure, energy, force);
- LO3: combine a series of parameters into a dimensionless group by the Buckingham Pi theorem;
- LO4: evaluate the meaning of a dimensionless group;
- LO5: select appropriate variables to change, keep constant and measure when performing a set of analogue experiments;
- LO6: critically evaluate experiments to determine whether experiments are correctly scaled;
- LO7: scale experimental data generated using analogue materials to a natural geoscience problem.

These objectives also reflect learning objectives tested by the quantitative literacy or quantitative reasoning VALUE rubric set out by the Association of American Colleges and Universities (Rhodes, 2010). By the completion of LO's 1 through 7, and our practical sessions detailed herein students will also develop skills identified on the quantitative literacy rubric. Specifically, these include:

a) The ability to explain information present in mathematical form (e.g. equations, graphs);
b) The ability to convert relevant information into mathematical form (e.g. the formation of dimensionless groups from variables, graphing experimental data);
c) The ability to perform calculations (e.g. calculation of dimensionless numbers);
d) The ability to make judgements and draw conclusions from quantitative data and assess the limitations (e.g. identifying the correct scaling and relevance to a geoscience problem).

Study context

Dimensions, units and dimensional analysis are fundamental components of any quantitative education within the geosciences and are arguably the building blocks of physical science (Brown, 2009; Churchill, 1997; Fay and Joubert, 2002; Hulin, 1980; Lira, 2013; Phares and Durnin, 2016; Wagner, 2001). These topics are commonly taught through a traditional lecture style format during science and mathematics courses and sometimes further supplemented by written homework assignments (Lira, 2013). This is problematic since passive lectures have been shown to have limited effectiveness in a variety of science, technology, engineering, mathematics (STEM) disciplines (Eberlein et al., 2008; Freeman et al., 2014; Froyd, 2007; Hake, 1998; Knight and Wood, 2005). The passive approach has an inadequate amount of active engagement required for students to truly understand new concepts (Froyd, 2007). This effect can be further compounded if the learning objectives are quantitative and highly analytical in nature (Crouch and Mazur, 2001; Davies et al., 2013; Soule et al., 2018). In addition to the understanding of dimensions and units, geoscience studies rely heavily on experimental data. It is therefore important that graduate geoscience students (potential end users of experimental data from the literature or experimentalists themselves) are able to identify the important variables to a problem, design appropriate experiments to test them, and perhaps most importantly, relate experimental findings back to the natural system of interest. Despite such a reliance, the topics of experiment design and scaling are often completely absent from the geoscience curriculum, or limited to individual student research/ dissertation projects. These topics lend themselves to "hands-on" practical exercises, i.e. situations where students are able to physically interact with material/apparatus in the classroom, such as benchtop experiments, which is a singular approach in larger group of broader defined active learning strategies (Froyd, 2007). The addition of such "hands-on" exercises could prove particularly beneficial because it has been suggested that when widely introduced into university courses they increase student interest and understanding (Andersen, 2002; Baldock and Chanson, 2006; Stefani and Tariq, 1996).

This study, in line with the learning objectives previously outlined, presents a method, utilising classroom analogue experiments, to teach these quantitative and experimental skills to graduate geoscience students. The subject material could be any physical science problem that can be investigated by analogue experiments; however, here we focus on the settling of a solid particle within a viscous liquid. This problem was selected for multiple reasons: (a) the physics has many applications ranging from crystal settling and flow within volcanic plumbing systems (Glazner, 2014; Jones et al., 2019a) to the sedimentation of particles (e.g. ash, dust) from the atmosphere (Bonadonna et al., 1998) or in surface water; (b) it is feasible to implement as the apparatus required is inexpensive and can be contained to a single benchtop; and (c) falling sphere experiments are already used in many demonstrations and/or practical classes (Concari et al., 2006; Cross and Lindsey, 2014; Kinnas, n.d.; Nachtigall, 1990; Owen and Ryu, 2005) and provide a basis for the approach highlighted here. Our study goes beyond these previous works by evaluating and quantifying the benefits of active learning provided by bench-top experiments, with particular reference to experimental scaling, data interpretation and dimensional analysis.

METHODS

Study population and setting

The teaching approach presented here was conducted as part of a Master's of Science (MSc) elective course in the Department of Geosciences at the Eberhard Karls University of Tübingen, Germany. In total 24 students attended the course to its completion. The student cohort was of mixed gender with 10 female and 14 male students. No age and ethnicity data are available for this study, and the course was taught in English to an international group of students.

Materials and implementation

Initially a single, 1-hour lecture was given on dimensions, the SI unit system, dimensional analysis and the Buckingham Pi Theorem toward the beginning of the course in week three. This lecture was conducted by passive learning strategies wherein a small number of slides were projected overhead (e.g. SI unit system, table of fundamental base units), and examples (e.g. dimensional analysis of velocity, dimensional analysis of force, Buckingham Pi Theorem) were handwritten on a blackboard and the students were instructed to take their own notes. Following this, later in the teaching programme a series of weekly experimental sessions (3 in total) were delivered for a total duration of 4 hours each. Note that due to student class scheduling restrictions these 4-hour sessions were delivered in two, 2-hour sessions on consecutive days. At the beginning of the practical session the students were split into groups of 3 or 4 people due to the limited number of experimental apparatuses available. Students were encouraged to work collaboratively for all three practical sessions. Table 1 outlines the components of the course and those most relevant to this study. Next, we outline what was covered during these three practical sessions. For detailed background material and teaching resources readers are referred to the accompanying online supplementary materials.

Practical session 1: The physics of particle settling

In this first week the students were presented with the physics problem of a particle falling in a viscous liquid. A diagram (Figure 1) was drawn to illustrate the problem set-up wherein a spherical particle with diameter, D and density ρ_p is falling at a constant (i.e. terminal) velocity, V through a Newtonian liquid with viscosity, μ and density, ρ_f. Then the whole class was given ca. 10 mins to identify the important variables unique to this problem. During this time the instructor walked around the classroom offering support, and students were also encouraged to discuss amongst themselves. The important variables were identified as: the drag force (F_{drag}); the particle's settling velocity (V); the fluid viscosity (μ); the fluid density (ρ_f); and the particle size (D). These five important variables were subsequently written on the chalkboard at the front of the class to ensure that all student members were able to continue with the exercise. For the remainder of the session students were instructed to find the dimensionless groups relevant to this physics problem via the Buckingham Pi Theorem (referring back to the lecture previously given in week 3 as necessary). For the problem presented in this study, the two relevant dimensionless groups are the Reynolds number (Re) which is a ratio of inertial to viscous forces and the drag coefficient (C_d) which is a dimensionless quantity describing the amount of resistance on a specific sized particle as it moves through a fluid. To facilitate the use of our approach by others and as a teaching resource, a full dimensional analysis following the Buckingham Pi Theorem for this problem can be found in the online supplementary materials.

Towards the end of this first session it is recommended that students check their work with an instructor – errors and misunderstanding at this stage will make the data analysis challenging in the third week. A common mistake is writing the dimensions of velocity (m s^{-1}) as [M T^{-1}] instead of [L T^{-1}], where M, L and T are the primary dimensions of mass, length and time. It is also common for the students to have difficulty relating the Pi groups to well-known, frequently used, dimensionless groups. The instructor may need to emphasise the fact that the Pi groups are non-unique and can be manipulated (e.g. by multiplication by a factor, by the inversion of a fraction, by the combination with other Pi groups).

Practical session 2: Bench-top experiments

In the second week four hours were set aside to perform the well-known falling sphere experiments that are used in many courses and experimental studies to demine a liquid's viscosity (Dobson et al., 1996; Kushiro, 1976; Kushiro et al., 1976). However, here, a different approach is taken – the viscosity is already known and provided upfront to the students. This approach was taken to align with the learning objectives, allowing students to focus on investigating the role of dimensionless groups rather than determination of a physical property (viscosity). At the start of the session a short (ca. 10-15 min) presentation was given about the equipment available, safety and the viscosity information provided in the data sheet. The equipment available included: a thermometer; a mass balance; stopwatches; white card; digital callipers; numerous measuring cylinders with different internal diameters; a range of steel and glass spherical particles; water; rapeseed oil (canola oil); glycerol; golden (glucose) syrup; a data sheet (see online supplementary materials) and cleaning products. The students were also encouraged to use their mobile phones as video recording devices as necessary.

Specifically, the students initially measured the particle mass and calculated the particle volume (by measuring the particle diameter). They then filled a graduated measuring cylinder (Figure 2) with a Newtonian fluid provided and recorded its temperature. The students then used the recorded temperature to calculate the fluid density and viscosity from the equations provided in the data sheet. A distance, h was marked on the measuring cylinder to identify the length over which the fall time was measured. Note that h should not be too close to the top of the fluid as the terminal, stead-state velocity needs to be calculated (Figure 2). A particle was then dropped centrally within the cylinder and its travel time recorded over the distance interval, h. Lastly, the fall velocity was calculated using the relationship velocity = h/time. This methodology was repeated numerous times by the students during the practical session using different particles and different fluids to cover as much of the parameter space as possible.

The exact level of instruction given to the students during the practical tasks will depend on their ability and previous experience performing experiments. Common problems included the introduction of bubbles in the viscous fluid and the inability to see the particle through the liquid. These can be avoided by tilting the measuring cylinder upon pouring and using the white card (or piece of paper) as a background.

Practical session 3: Data interpretation and analysis

In the previous session all of the raw measurements (particle fall velocity, liquid properties, particle size) were made and now the students were in a position to nondimensionalize and interpret their datasets. Firstly, in this session (4-hour total) students were instructed to calculate the dimensionless Reynolds number and dimensionless drag coefficient (Re and C_d, respectively) identified in practical session 1 for every experiment conducted and plot their results. An example of some data collected by MSc students at the University of Tübingen are shown in Figure 3. After the students plotted their data and formed some preliminary interpretations (e.g. Is C_d linearly dependant on Re? etc.) a literature search was undertaken with two purposes. First, to assess how their data align with previously published studies (e.g. Flemmer and Banks, 1986; Haider and Levenspiel, 1989; Morrison, 2013). A convenient way to do this is to plot other literature data on the same graph (e.g. the purple model fit from Morrison (2013) in Fig. 3). If the instructor is concerned about the ability of some students to do this independently, literature data could be provided directly to the students. Second, to *critically* relate relationships observed in the students' experiments to a well-known natural geoscience process, if possible. To do this, the range of Re space covered by the experiments must be the same as the range of Re expected in geologic settings. Therefore, the students calculated Re values for well-known geoscience processes and compared them to their experimental Re conditions. For students that found this challenging the instructor hinted at situations where particle settling was important (e.g., clay particles settling in a lake) and using approximate values they could roughly calculate Re values. Once comfortable, the students were left to independently search the literature for accurate values and/or other natural scenarios.

Finally, in this session, it is important for the students to note that there are many simplifications that have been made when relating these experiments to a natural scenario such as irregular particle shape, hindered settling and lateral motion (e.g., wind or water currents). Therefore, simple analogue experiments will always fail to explain a complex natural process in its entirety but can nevertheless provide insight into one of the fundamental physical processes operating (e.g. particle drag and viscous vs. inertial components in this analysis).

Data collection and analysis

The effectiveness of our teaching method in enabling students to meet the learning objectives was quantified by a pre-test given to 24 students at the very start of the MSc course followed by a post-test given to 12 randomly selected students one week after the lecture on dimensional analysis and to a further 12 students one week after the experiment sessions (Table 1). The methodology of pre- and post-tests has been challenged as a way to effectively measure student learning, problems include, but are not limited to, learner maturation with time, recollection of repeat questions and statistical validity (Cook and Campbell, 1979; Marsden and Torgerson, 2012; Shadish et al., 2002). To eliminate any bias with our pre- and post-test design the following steps were undertaken. First, the pre- and post-tests contained questions that evaluated the same knowledge but were not identical, therefore simple test repetition cannot explain a score increase. Secondly, the class was split into two groups (experiments and lecture vs. lecture only) to provide a reference/control result. Thirdly, both tests were taken exactly one week after the relevant instruction session, thus assessing long-term (week long) understanding rather than short-term memorization (i.e. immediately after instruction). The one-week time period was kept constant for both the pre- and post-test to eliminate changes due to differing knowledge retention over time (Dugard and Todman, 1995; Marsden and Torgerson, 2012; Teed and Franco, 2014). One limitation of this approach is that the students taking the post-test after the experiment sessions had also attended other lectures during the course (Table 1). However, the material covered in these classes did not address the learning objectives outlined in this study, and thus, we expect any additional knowledge gain pertinent to the post-test to be minimal.

Both the pre- and post-tests contained 10 similar questions to assess a number of learning objectives. These included the identification of the basic units of measurement (LO 1), dimensional analysis of common quantities such as energy, pressure and work (LO 2), the formation of dimensionless groups (LO 3), the identification of the groups meaning (LO 4) and the evaluation of experimental scaling (LO6). The other learning objectives are difficult to assess in written form so were not included in the pre- and post-tests. Both tests contained the same number of questions with very similar phrasing, yet different content, this was done to prevent test scores changing based on question clarity or answer exchange between students. All tests were carried out under closed book examination conditions (i.e. no peer discussion, no consulting other sources) and returned to the instructor for marking. The full pre and post tests can be found in the online supplementary materials.

RESULTS

The test scores show that 19 out of the 24 students improved their knowledge after completing the experimental sessions and/or attending the lecture (Figure 4). Knowledge gain is greatest for the students that completed the experiment sessions in addition to the lecture with an average post-text score of 6.6 out of 10, compared to 4.4 for the lecture only. Furthermore, the pre- and post-test results were separated based on the learning objective that they test (Table 2). We found that the number of correct responses increased for all learning objectives after the benchtop experiments and, with the exception of learning objective 4, for all after the lecture. However, the magnitude of the increase differs between these two test groups. The students who were tested after the benchtop experiments showed a 45% increase in the number of correct responses, whereas students tested after the lecture alone online showed an 18% increase (Table 2). To statistically test that the three result groups (Pre, Post-lecture, Post-experiments) can be separated based upon the % frequency of correct responses an analysis of variance (ANOVA) test was performed. The P-value of the ANOVA test was 0.0169 meaning that the Pre, Post-lecture, Post-experiments groups are different and not equal; however, it does not inform on which groups are different from the others. To determine this, a Tukey post hoc test was performed and the results are shown in Table 3. The null hypothesis (the two result groups are drawn from the same distribution) can be rejected at the 0.05% level (P-values < 0.05) for the pre-test and post-experiment comparison, but not for the pre-test and post-lecture comparison. This means that the post-experiment test results are statistically different from the pre-test whereas results from the post-lecture test are not. Furthermore, the increase in correct responses is not uniform and varies depending on the learning objective tested (Table 2). Questions that tested learning objectives which demand deeper understanding (e.g. learning objectives 4 and 6), rather than simple mathematics manipulation show poorer responses after instruction by lecture alone relative to after the benchtop experiments (Table 2).

DISCUSSION

Assessment of learning

Now that the 3-session practical teaching method utilizing benchtop experiments has been outlined, we discuss its effectiveness in terms of student learning based upon the pre- and post-test results. Our results show that students are able to meet all learning objectives with greater success after completing the series of practical sessions relative to lecture attendance alone (Figure 4). This improvement is likely to have resulted from a combination of two factors: (1) increased instruction time in the practical sessions vs. passive lecture alone and (2) active learning approaches during practical sessions. This suggests the superiority of active student learning (e.g. Freeman et al., 2014; Froyd, 2007) even when the learning objectives are a test of memory or simple numeric manipulation (learning objectives 1 to 3; VALUE rubric points a to c). Furthermore, although our teaching via practical exercises improved student understanding in all of the learning objectives tested, the improvement was largest in those that required a deeper understanding at higher cognitive levels (e.g., VALUE rubric point d). We suggest that this deeper understanding was largely achieved by working through the problem in its entirety – from experiment set-up and variable section to interpretation of results. We therefore contend that for students to truly understand dimensional analysis and experiment scaling, practical exercises must be undertaken (Table 2).

Lessons learned

Here we provide a list of key "lessons learned" from our teaching experiences with the purpose of helping readers successfully integrate benchtop experiments into their existing curriculum. These descriptions focus on the delivery of benchtop experiments in the classroom, learner experiences and the delivery of the learning objectives. Readers are directed to the "Materials and implementation" section for a description of common student mistakes and misconceptions.

- When introducing the series of practical sessions, it is useful to list and detail the apparatus that will be made available (e.g. stopwatch, thermometer, cylinder(s), particles) early in the instruction. This prohibits students from planning unrealistic experiments (e.g. requesting the same size particles with differing density) and allows the students to better manage their time – by knowing the apparatus available, they can predict the number of experiments that could be performed.
- A group size of 3-4 students per set of apparatus allows for all group members to have a meaningful task and be time effective.
- It is highly recommended that food products are used as experimental fluids. This reduces any safety issues and does not require special laboratory facilities (e.g. fume hood). Furthermore, the physical properties of food products can be easily found in the literature (e.g. Jones et al., 2019b; Jones and Llewellin, 2020; Kavanagh et al., 2018; Schellart, 2011) and thus, easily included in a datasheet provided to the students.
- We recommend using only one fluid type in a given cylinder – do not empty and refill. This reduces the risk of spillages and the post-experiment cleaning time. Depending on the facilities available, the instructor may consider filling the cylinders with the fluids for the students ahead of the scheduled practical session.

- Although time consuming the practical sessions outlined here were valued highly by the students. Several students commented on how much they enjoyed and benefitted from the active learning strategies deployed.
- Practical based learning objectives (e.g. LO 5 & 7) are difficult to assess directly, it is therefore recommended that the students combine their work from practical sessions 1 through 3 into a report. This would detail their experiment methodology, results and interpretations and could be assessed by the instructor to give an indication of the number of students meeting such learning objectives.

Adaptations for different contact times

The concept of particle settling (i.e. the motivation behind the experiments) is a widespread process making it amenable to several geoscience courses, examples include: sediment transport in sedimentology, geomorphology, and oceanography; force balances and buoyancy in entry level physics or geodynamics, and ash fallout or crystal settling in volcanology. However, the teaching strategy outlined in this study requires 12 hours of contact time – this may not be feasible in many existing teaching programs; thus, modifications and simplifications would be needed. To reduce the contact time required we propose that modifications could be made in at least two ways that retain active learning strategies and still address the learning objectives. First, 'practical session one' could be reduced to a 1-hour interactive lecture format, wherein the learners are given a worked, step-by-step solution to the Buckingham Pi Theorem as a hard copy handout. The instructor could use a combination of overhead visuals and handwritten calculations on a board to deliver the material in segments after the students are given time to complete the step themselves on their handout. Example lecture slides are provided in the online supporting information. Although this reduction will still address LO's 1-4, less time will be spent on task and may result in a reduced understanding and/or retention. Second, 'practical session three' could be reduced to one hour by providing the students with comparative Re and C_d data upfront at the start of the session. These data could include the published C_d Re relationship for a smooth spherical particle as shown in Figure 3 and the Re ranges for some key geoscience scenarios (Table 4). Practical session three could then be devoted to comparing their experimental datasets to the published data as in Figure 3 & Table 4. Students will still be able to critically evaluate their experimental data and determine the most appropriate geoscience scenario (if any) that their experiments are scaled for (cf. LO's 5 & 6). The modifications discussed above were not conducted as part of this study and should be tested as part of future research. Furthermore, it is left to the reader to decide if these time saving modifications also make the material more suitable for less advanced audiences, such as undergraduates.

In the rare case of more contact time being available, a second set of more complex experiments could be conducted. These extensions could include: the use of fluids with a non-Newtonian (shear-rate dependant) rheology; irregular shaped particles and variable particle/container diameters (Chhabra et al., 2003; Dioguardi and Mele, 2015; Hölzer and Sommerfeld, 2008; Jones et al., 2020; Uhlherr and Chhabra, 1995). These adaptations are explained fully in the online supplementary text and Figure S1.

Limitations

Before translating the results of this study to other courses within the geo- and other physical sciences there are a number of limitations that must be considered. First, the course "Natural Hazards and their Physics" in which this study was conducted was an elective, therefore the students may have been more motivated during instruction relative to a compulsory university course. Second, the sample size is small with only 24 students. Third, the student cohort was comprised of postgraduate master's level students. Fourth, despite eliminating as much bias as possible our pre- and post-test results have limitations. For example, the students have additional time on task during the experiments vs. lecture alone so the benefits of active learning vs. additional teaching time cannot be exclusively separated. Finally, we are unable to evaluate if our benchtop teaching approach contributed to enhanced learning by the students in their subsequent university courses. Further work should test the effectiveness of benchtop experiments to teach experimental design, scaling and analysis in undergraduate courses with larger enrolment, and perhaps evaluate if they were able to apply to material learned here to subsequent courses.

CONCLUSIONS

It has been shown that simple benchtop experiments can be an effective way to improve and integrate quantitative learning into a geoscience class. In the approach shown here, a common geologic process was investigated, the governing physical principles explained, and the tool of dimensional analysis was introduced. The falling sphere experiments are simple to perform, cost effective and relate to many geoscience problems. A thorough scaling and analysis of these simple experiments proves to be an effective way to teach: (1) basic fluid dynamic principles; (2) the Buckingham Pi theorem of scaling; (3) data analysis and (4) the extrapolation of experimental data to real geoscience situations. We show that the introduction of a simple benchtop experiment into a university course increases student understanding relative to instruction by traditional lecture alone.

Competing Interests

The authors are not aware of any circumstances that might be seen as competing interests.

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DISPLAY ITEMS & CAPTIONS:

Week	Teaching content	Important events for this study
1	Studying natural hazards, risk and resilience	All 24 students take the pre-test
2	Magma and its properties	--
3	Dimensional analysis and scaling (1 hr)	All 24 students attend lecture
4	Magma plumbing systems and intrusions	12 random students take post-test
5	Fluid dynamics and permeability	--
6	Eruption plumes	--
7	Granular flows	--
8	Lava flows	--
9	Earthquakes	--
10	Rock falls and mechanics problems	--
11	Practical session 1	All 24 students attend practical
12	Practical session 2	All 24 students attend practical
13	Practical session 3	All 24 students attend practical
14	Models in natural hazards research, future directions	12 remaining students take post-test

Table 1: MSc Natural Hazards and their Physics course syllabus with key events pertinent to this study highlighted.

		% Frequency of correct responses				
Learning Objective	**Question(s) #**	**Pre**	**Post lecture**	**% Change**	**Post experiments**	**% Change**
1	1	50	75	25	92	42
2	4,5	17	54	37	63	46
3	2	0	33	33	50	50
4	3	13	8	-5	67	54
6	6,7,8,9,10	42	43	1	73	31

Table 2: Pre-post comparison of correct responses with reference to the related learning objective tested.

Groups compared	P-value
Pre-test & Post-lecture	0.3776
Pre-test & Post-experiment	0.0135

Table 3: Tukey test (post-hoc test) results based on the % frequency of correct responses.

Geologic scenario	Re range	Reference
Tephra settling in air	10^{-2} to 10^{5}	(Bonadonna et al., 1998)
Crystal settling in magma	$< 10^{-6}$	(Glazner, 2014)
Ripples, dunes and turbidity currents	10^{4} to 10^{9}	(Glazner, 2014; Sharp, 1963)
Sedimentation in the ocean	10^{-7} to 10^{0}	(McCave, 1975)

Table 4: Reynolds number (Re) ranges for common geoscience scenarios. This list is not exhaustive and only serves as

approximate values for the purpose of student comparison.

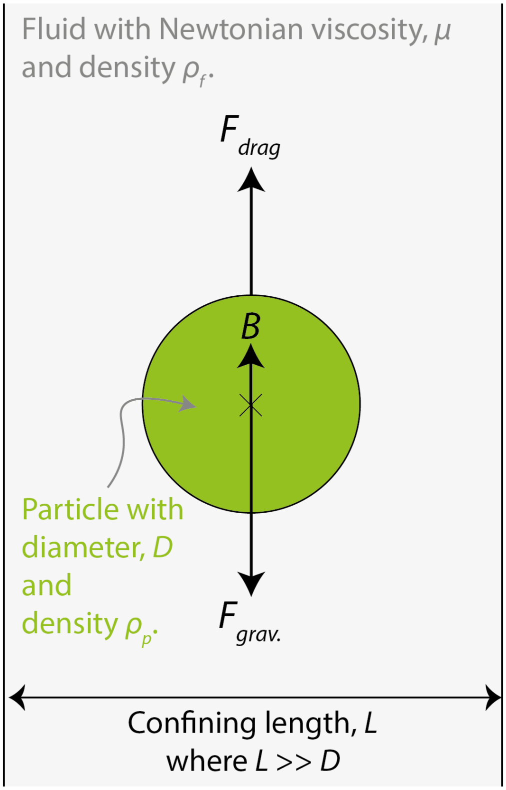

Figure 1: Free body diagram showing the forces, dimensions, and the fluid/particle properties relevant to the exercises described in the text. *B* represents the buoyancy force of the particle. See online supplementary materials for a detailed description of the underlying physics of this experiment.

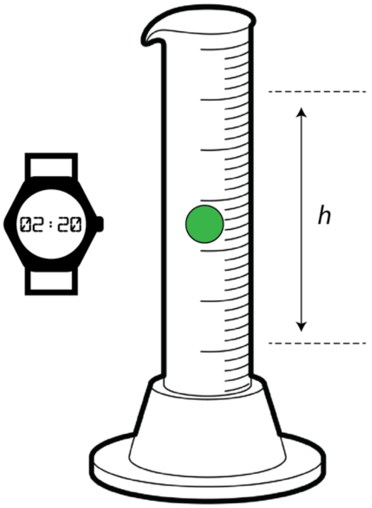

Figure 2: The experimental set-up. A graduated cylinder filled with a Newtonian liquid in which a spherical particle is dropped, and it's fall time is measured over some distance, *h*.

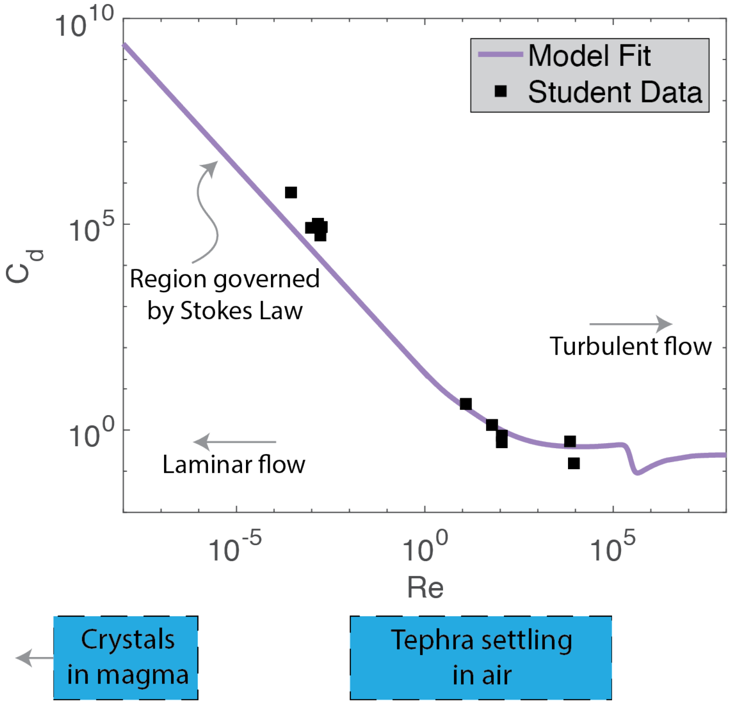

Figure 3: Non-dimensional plot of the Reynolds number (Re) against the dimensionless drag coefficient (C_d). The black squares are data collected in class by MSc students at the University of Tübingen. The solid purple line is from Morrison (2013) and is the C_d Re relationship for a smooth spherical particle. The blue boxes mark approximate Re space where crystal settling in magmas and tephra settling in the atmosphere occurs.

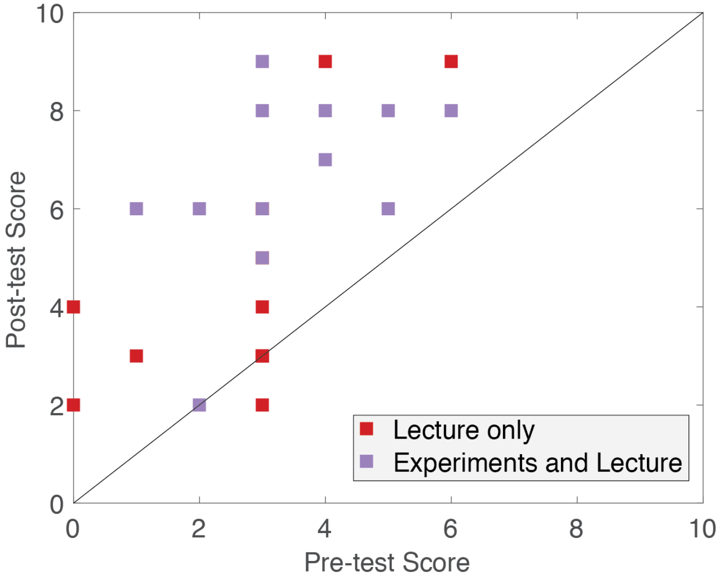

Figure 4: Pre- and post-test student scores (both out of 10). Each data point corresponds to a single student. The red data points represent students that completed the post-test one week after the lecture on dimensions and dimensional analysis and the purple data points represent students that completed the post-test one week after the experimental sessions were complete. The solid black line marks no change in pre- and post-test scores.