The role of introductory physics for life sciences in supporting students to use physical models flexibly

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Abstract

An important goal of introductory physics for the life sciences (IPLS) is for those students to be prepared to use physics to model and analyze biological situations in their future studies and careers. Here we report our findings on life science students’ ability to carry out a sophisticated biological modeling task at the end of first-semester introductory physics, some in a standard course \(N = 34\), and some in an IPLS course \(N = 61\), both taught with active learning and covering the same core physics concepts. We found that the IPLS students were dramatically more successful at building a model combining multiple ideas they had not previously seen combined, and at making complex decisions about how to apply an equation to a particular physical situation, although both groups displayed similar success at solving simpler problems. Both groups identified and applied simple models that they had previously used in very similar contexts, and executed calculations, at statistically indistinguishable rates. Further study is needed to determine whether IPLS students are more expert problem-solvers in general or solely in biological settings.

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I. INTRODUCTION: THE NEED FOR LONG-TERM OUTCOMES FROM INTRODUCTORY PHYSICS FOR LIFE SCIENCE STUDENTS

Recently, several investigators have developed and begun assessing introductory physics courses specifically aimed at supporting undergraduate life science and pre-medical students to gain a deeper understanding of the physical sciences, and to apply this understanding to the life and medical sciences [1–6]. These introductory physics for the life sciences (IPLS) courses were developed in response to calls from national professional societies in the life sciences and medicine, and seek to support students in developing problem solving and mathematical skills as well as topical understanding [7–10]. A common feature of such courses is an emphasis on modeling complex biological situations with physical principles; such courses make this a central repeated practice.

Arguably, to demonstrate the success of such courses, it should be shown that students continue using the concepts and methods learned in IPLS, in settings other than physics courses, long after the courses are over. Due to the significant challenges of longitudinal assessment, we are unaware of any long-term assessment to date of the durability of IPLS student learning or the ability of IPLS students to apply what they have learned outside of physics settings, other than the study we report separately of seniors in a biology capstone course [11]. (In that study, we find that former IPLS students performed more strongly than those who had not taken IPLS on a task that required them to quantitatively and mechanistically analyzing diffusion in a biological problem.)

In the work reported here, we seek to gain a preliminary measure of students’ ability to use physics to model and analyze biological settings at the end of introductory physics. Specifically, we analyze student work on a task given at the end of the mechanics semester of both introductory physics for life sciences (IPLS) and standard introductory physics, in which students analyzed an
unfamiliar biological situation using fluid dynamics, and in which model elements had to be combined in a manner not previously demonstrated in either course.

We find that IPLS students displayed a significantly greater ability to develop a complex model combining two different physical concepts, although both IPLS and non-IPLS students displayed similar ability to apply familiar models, both in that same task and in a companion problem that did not require the same amount of modeling. This suggests that IPLS students may be better prepared to independently and spontaneously recognize and apply physics to biological situations in which it is needed, consistent with preliminary evidence from embedded tasks in intermediate biology courses [12].

In this article we report both our findings and the rationale behind the development of the task, in the hopes that others may find this task either a valuable tool or a starting point to develop their own. Section II describes the two physics courses from which the study subjects were drawn; Section III describes the design of the task and Section IV its administration and analysis; Section V presents the results and our interpretation; and Section VI offers open questions and next steps.

II. STUDENT GROUPS AND COURSE DETAILS

In this study, we compare the modeling skills of life science students with and without IPLS by analyzing written work from a total of 95 life science students enrolled in either IPLS ($N = 61$) or standard ($N = 34$) introductory mechanics.

A. Subjects.

Although life science students at Swarthmore typically take the IPLS course, during Year 1 of this study, due to staffing limitations, only the standard mechanics course was offered. For this reason, most of the students in our study without IPLS ($N = 29$) took the standard course during this first
year; a small number ($N = 5$) took the standard course in Year 2, despite IPLS being offered, most likely due to a schedule conflict. All subjects with IPLS took the IPLS course in Year 2.

We expected that other than taking different introductory physics courses, the students with and without IPLS came from equivalent populations, as they represented all of the life science students enrolled in first semester introductory physics in a given year. We found that the distribution of the students in the two groups was indistinguishable across class years (first-years, sophomores, juniors, seniors; Fisher’s exact test, $p = 0.436$) and majors (biology/neuroscience, chemistry/biochemistry, or more quantitative majors such as engineering or mathematics; Fisher’s exact test, $p = 0.942$).

**B. Courses**

The same instructor taught the standard course both years; during Year 2, BDG taught the IPLS course. During Year 1, the standard course, as the only first semester mechanics course for non-physics majors offered, enrolled 81 students, meeting in two sections. (The standard course included engineering students as well as life science students; although we collected responses from the engineering students, we do not analyze them here.) During Year 2, the IPLS course enrolled 66 students and the non-IPLS course enrolled 47 students (nearly all engineering students), each taught in a single section. Both courses used active learning strategies in class, assigned students to read before class and complete pre-class questionnaires (modeled on Just-in-time Teaching PreFlights [13]), and used the same textbook (Knight, Physics for Scientists and Engineers, 3rd edition). Prior to the study, both BDG and the standard course instructor had several years of experience with active learning methods, although the standard course instructor was new to Swarthmore during Year 1 while BDG had taught at Swarthmore for 3 years.
Both courses covered the same topics in fluid statics and dynamics, including both the Bernoulli equation and the Hagen-Poiseuille relationship for viscous flow. Both courses also required a mix of conceptual reasoning and quantitative problem solving, although the IPLS course required somewhat less mathematically involved problems.

The primary difference between the courses relevant to this study was that the IPLS course explicitly emphasized that building and choosing simple physical models for complex biological situations is an essential skill when using physics to analyze biomedical phenomena. The standard class offered a few biologically relevant problems as applications at the end of a unit, but did not explicitly focus on or teach the modeling process. The IPLS course framed each core physical idea as being useful for answering authentic biological questions (cite Watkins).

Prior to introducing fluid dynamics, the IPLS course provided students with repeated opportunities to choose a simple model, and to identify the physical parameters that make a particular model appropriate for a particular situation:

- While studying resistance to motion through fluids, students were introduced to multiple models, and assigned problems in which they had to choose an appropriate model based on information given in the problem. For example, students were provided with scenarios in which objects of different sizes move through different fluids, and had to identify which model for resistive force was most appropriate in each case. The Reynolds number was introduced as a way of assessing whether viscous or non-viscous drag was dominant.

- When learning about the elastic stretching of bones and ligaments, students were asked to carefully consider the limitations of Hooke’s law; Hooke’s law was framed as a model that must be applied flexibly, through careful consideration of the particular biophysical situation. Students were assigned to determine from force-vs-extension data whether the
stretching was or was not well modeled by Hooke’s Law, and were presented with multiple situations in which Hooke’s law failed.

- When studying different types of biological motion, IPLS students were asked to determine whether directed or diffusive (random) motion was faster. Depending on the length and time scales involved, organisms rely on directed or diffusive motion (or a combination of both) to accomplish physiological functions; students were given opportunities to rationalize why different models of motion were best suited for these various functions.

In the fluid dynamics unit, students worked through a series of problems and questions related to cardiology (Appendix A). As in previous units, they were explicitly asked to select the most appropriate fluid dynamics model. Students learned that when blood flows through a relatively wide and short opening like the aortic valve between the left ventricle and the left atrium, it is appropriate to model the motion using the Bernoulli equation; when blood flows through vessels that are relatively long and narrow, they must use the H-P model to account for viscous resistance.

III. TASK DESIGN

The goal of this task was to learn whether the IPLS course enhanced students’ ability (i) to model unfamiliar biological situations using physics, and (ii) to combine physics concepts in novel ways to do so. We therefore sought a biologically relevant situation which could be analyzed with introductory physics, but for which a correct analysis required combining the physical concepts taught in both courses in a new manner. We also sought a task which had not previously been used in our IPLS curriculum, so that students who received course materials from previous students would not have seen solutions to a related problem.

We designed a task analyzing the pressure difference between the roots and leaves of trees, an example which was not covered in either course, and which also was not discussed in
Swarthmore’s introductory biology course. The task was designed to require students to develop a model they had not been taught. Specifically, students had to combine the viscous flow model (the Hagen-Poiseuille equation), which applies only to horizontal pipes, with a term that modeled the effect of gravity on pressure. Previously, the effect of gravity on pressure had been introduced only in the context of fluid statics and nonviscous flow, so students had no experience modeling the effects of gravity in the context of a problem involving viscous flow. Furthermore, the problem statement did not explicitly invoke the ideas of either viscous or nonviscous flow, and did not explicitly mention any of the relevant equations or relationships.

Equations and constants related to fluids and thermodynamics were provided on a reference sheet at the end of the task, so that students did not have to spend time trying to recall them. (Both courses provided such reference sheets on all tests, so using them was familiar to all students.) Finally, we included a textbook thermodynamics problem, similar to those assigned in both courses, to allow controlling for students’ physics problem solving skills.

The fluids problem appears part-by-part in Figures 1-3; the full task, with initial instructions, equations, and the thermodynamics problem, is provided in Appendix B. The remainder of this section presents the detailed design logic of the task.

A. First part: Reminder of static pressure dependence on height, and measure of students’ ability to apply a simple model

Part (a) of the task, in which they analyzed the height dependence of the blood pressure of a giraffe, served two purposes: (i) to remind students about role of gravity in fluid pressure, and (ii) to determine their ability to apply a simple model learned in class to a new situation.
a) Adult male giraffes can reach a height of roughly 6 m. The minimum pressure of the blood leaving the giraffe’s heart is 1.24 atmospheres (124 kPa). (Although blood is a mixture of water and various types of blood cells, the density of blood is very close to the density of water because the cells also consist mostly of water.) Find an approximate value for the minimum blood pressure in the giraffe’s brain when its neck is extended to its full height. You may infer information from the picture of a giraffe provided.

Please briefly explain the reasoning you used to find your answer, including how you decided which equations to use, as well as any approximations you made. Also please show your work.

FIGURE 1. Part (a) of the fluids problem. The full task (with additional instructions before the problem, the thermodynamics problem, and the list of equations) is provided in Appendix B.

Detailed analysis (beyond the scope of the course) of the situation reveals that the dynamic corrections are small compared to the fluid static effects, so we felt it was reasonable to design this part so that students had enough information to analyze the fluid statics effects, and none of the information they would need to incorporate the dynamics. Some students did attempt to account for flow speed as well as gravity by using the Bernoulli equation, but all of them found ways (of variable correctness) to eliminate dependence on the (unspecified) flow speed, rather than estimating flow speeds. (The Bernoulli equation in the form presented in introductory physics does not account for the effects of branching, which is significant in the mammalian circulatory system, so using the Bernoulli equation with physiologically accurate flow speeds actually would give a very misleading result.)

As students in both courses had done problems calculating the effect of fluid pressure on height, this part of the task also allowed us to evaluate students’ level of problem solving skill. The second problem on thermodynamics (section D) also served the same purpose.

B. Second part: identifying nature of flow and incorporating gravity

This part served as our measure of students’ ability to build new models using the physics they had learned. As previously described, for a fully correct answer, students needed to combine the Hagen-Poiseuille equation for viscous flow through horizontal cylindrical tubes with the effect of
b) In trees, water is carried from the roots to the leaves by the flow of sap (water with other kinds of molecules dissolved in it) through stiff tube-like structures, called xylem. Although sizes vary, a typical diameter would be 100 µm. In the main trunk of the tree, they extend close to the full height of the tree, which is commonly as great as 30 meters tall or taller (5 species of tree are known to reach 90 -110 m in height). These extremely narrow, long tubes, called xylem, contain a continuous column of water which can then flow into the leaves. The evaporation of water from the leaves (called transpiration) causes water to be steadily drawn into the leaves from the xylem. The structure of the leaves allows the pressure of water in the xylem to not necessarily be the same as the surrounding atmospheric pressure.

Consider a tree in which sap flows through each 100 µm-diameter xylem at a volume flow rate of \(1.1 \times 10^{-10} \text{ m}^3/\text{s}\) (equal to \(1.1 \times 10^{-4} \text{ mL/s}\) or \(0.40 \text{ mL/hr}\)), corresponding to an average flow speed of 0.014 m/s. (Given the huge number of xylem, the total flow for the entire tree is substantial!) If the pressure in the roots is equal to atmospheric pressure, what is the pressure at the top of a 30 m tall xylem in the trunk?

Please briefly explain the reasoning you used to find your answer, including how you decided which equations to use, as well any approximations you made. Also please show your work.

FIGURE 2. Part (b) of fluids problem.

Gravity. The viscous nature of the flow had to be inferred from the dimensions of the tubes (xylem), as no explicit mention of viscosity was made. So that students did not have to also account for surface tension of the water exiting the leaf pores, or worry about partial pressures and phases, students were told to find the pressure inside the trunk at the top, and that the pressure in the leaves did not have to match the surrounding atmospheric pressure.

Flow speeds and xylem sizes were taken from Niklas and Spatz, *Plant Physics* [14]. The tree height was chosen so that students would obtain a negative pressure at the top of the trunk if they correctly implemented any model involving gravity, whether using viscous or nonviscous flow.

C. Third part: considering the implications of negative pressure

The purpose of this part was twofold: to give students confidence that the negative values obtained in the previous part were appropriate, and to investigate (very minimally) whether students could learn from new ideas provided in the task. We based the design on the theoretical framework of “preparation for future learning” [15] [16] as a mode of transfer, although due to the limitations of the task, we could not incorporate the full design used in seminal studies of this model.
c) You should have found different signs for your answers to (a) and (b). In this course, we have not discussed the possibility of negative values of pressure. A more in-depth study of pressure reveals that negative pressures can exist in cohesive substances such as liquids. Just as for positive pressures, a pressure difference across a surface corresponds to a force.

A critical difference between the fluid transport systems of trees and animals like giraffes is that blood vessels through which blood flows are made of a stretchy material, while the xylem through which sap flows are made of a very rigid material.

How do your results for (a) and (b) illustrate part of the reason why trees can grow much taller than land animals? **Explain your answer using the ideas from this course and your physical intuition. Be as specific as you can be in your explanation.**

FIGURE 3. Part (c) of fluids problem.

We anticipated that upon obtaining a negative value for pressure, many students would assume they had made a mistake and modify their calculation so as to obtain a positive value. To avoid this, in the prompt for the third part (shown in Fig. 3), we told students that they should have obtained a negative value in the second part, which was possible for cohesive liquids although not for ideal gases, and that a pressure difference across a boundary still corresponded to a force even with negative values. We further explained that a critical difference between fluid transport systems in trees and in mammals is the use of rigid (xylem) vs elastic (blood vessels), and asked them to use ideas from the course to explain why trees can grow much taller than land animals.

Our intent was for them to consider the response of an elastic blood vessel (which requires excess pressure inside to remain open for flow) vs a stiff xylem (which can support a column of water in order to sustain a negative pressure). We expected this would be very challenging for students, but that their responses nonetheless would give us some insight into their ability to learn from and reason with new material.

**D. Thermodynamics problem**

We included a textbook problem on thermodynamics (Appendix B) to serve as a separate measure of student problem solving skill, as well as to allow the task to serve as a complete “practice test” for students (see discussion of task administration below), as fluids and thermodynamics had been
taught since the last exam. The third part of the problem also involved nontrivial modeling, namely, to recognize that the gas undergoes constant pressure expansion (rather than remaining at constant volume), but in a situation analyzed in the physics course rather than a novel biological situation.

IV. METHODS: TASK ADMINISTRATION AND ANALYSIS

We administered the task to all students in both courses as long-form problems, and analyzed those students’ written responses. Following our analysis of the written responses, we also conducted think-aloud interviews with five students in a subsequent offering of the IPLS mechanics course, and analyzed transcripts of those interviews.

A. Written task administration

We wanted students to give the task their best effort, but felt it would be unfair to the non-IPLS students to put the fluids problem on a test, given that their course had not prepared them well to solve it; we also anticipated both IPLS and non-IPLS students would find the fluids problem difficult and thus potentially very stressful. We therefore gave the task (both problems) to the students as a “practice test” to complete during reading period, between the end of classes and the final exam, and offered the incentive of getting detailed feedback on their solutions to help them prepare for the final exam. We stated they should complete the task under test-like conditions (no use of any resources other than the provided equations and the permitted single sheet of notes) but offered full credit for “completeness and demonstrated effort”. Indeed, all solutions that we submitted displayed significant thought and effort. In both courses, all exams involved long-form problems for which students were required to show work that demonstrated the logic of their solution to obtain full credit, so our “practice test” followed exactly those expectations.
In the IPLS course, 63 of 66 students submitted the problem; in the standard course, 69 of 128 students (over two years, including engineering as well as life science students) submitted the problem. Although the thoroughness of their solutions indicated that all students who completed the task took it seriously, the IPLS students may have been more invested in the task, as the IPLS instructor told the students that he would give feedback, while the standard course instructor told the students that they would get feedback from his physics colleagues. (The study authors provided the feedback for all courses.)

B. Analysis of written work

We developed an emergent coding scheme for student work on the task, based on the types of modeling and problem-solving competencies that were the goals of the IPLS course. Two team members read through the de-identified, anonymized student work and iteratively developed a code for parts (a) and (b) which documented whether the student's work demonstrated these competencies. Part (c), which in the spirit of preparation for future learning [15], gave students new ideas to use, was coded more globally for correctness and coherence.

Initially, BDG and MT independently developed codes. Next, they compared their codes, developed a combined code, independently applied it to a subset of the student responses, and compared results, iterating this process until both coders reached agreement. CHC then applied the code to confirm its reliability (Cohen’s kappa was at least 0.85 for all coding elements). Any remaining disagreements were resolved on a case-by-case basis to generate a final code for analysis, which was applied to all responses by MT.

The fluids task code is presented in Table 1; the thermodynamics problem code is presented in Appendix C.
TABLE 1. Fluids task code

Part (a) (up to 6 points)

| Competency                                      | Scoring Criteria                                                                                                                                                                                                 |
|-------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| **Model justification** (0-1 pt)                | +1 for showing that $p_2 = p_1 + \rho g \Delta d$ is a special case of the Bernoulli equation OR +1 if the student uses the viscous model (Hagen-Poiseuille) and explains why viscosity is relevant                      |
| **Reasonableness** (0-1 pt)                     | +1 for choosing a heart to brain distance less than 6m                                                                                                                                                                  |
| **Coordinating equation with physical situation** (0-2 pt) | +2 for finding that the pressure at the brain is less than the pressure at the heart NOTE: Points awarded regardless of whether student uses the fluid statics equation “correctly” (e.g. points awarded even if student assigns a negative value to $g$ or reverses the sign of $\Delta d$ in order to obtain $p_{\text{brain}} < p_{\text{heart}}$) |
| **Coordinating diagram with equation** (0-1 pt)  | +1 for including a diagram that defines $p_1$ and $p_2$ correctly OR +1 for a diagram that labels the heart and brain and clearly demonstrates coordination between the diagram and pressure values in the equation (e.g. labeling the heart and brain in diagram and rewriting hydrostatic equation as $p_{\text{heart}} = p_{\text{brain}} + \rho g (d_{\text{brain}} - d_{\text{heart}})$ OR +0.5 for a diagram that labels the distance between the heart and the brain, regardless of distance chosen (e.g. 6m) |
| **Calculation and numerical skill** (0-1 pt)     | +1 for correct numerical answer, given the model and height approximation used. NOTE: Point awarded for students who find the pressure at the brain is greater than the pressure at the heart, as long as their numerical calculation is otherwise correct. |

Part (b) (up to 6 points)

| Competency                                      | Scoring Criteria                                                                                                                                                                                                 |
|-------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| **Model justification** (0-2 pt)                | For students who use Hagen-Poiseuille (H-P), +2 for justifying use of H-P with xylem dimensions (long and skinny), OR +1 for justifying only by stating that the fluid is viscous. |
| For students who use Bernoulli,                  | +2 for attempt to justify using xylem dimensions (even though incorrect) OR +1 for stating that the fluid is non-viscous.                                                                                                    |
| **Flexible coordination of multiple models** (0-2 pt) | For H-P, +2 for including the gravity term by adding $\rho gh$ to $\Delta p$. OR +1 for considering the role of gravity but not by adding $\rho gh$ in the calculation.                                               |
| For Bernoulli, no points are awardable.         |                                                                                                                                                                                                                       |
| **Model implementation**                        | For H-P, +1 for correctly implementing $\Delta p = p_{\text{roots}} - p_{\text{leaves}} = \rho gh_{\text{leaves}}$                                                                                                    |
with physical situation

OR
+0.5 for recognizing \( \Delta p \) is a difference but not properly implementing it.

For Bernoulli,
+1 if it is used with justification for eliminating velocities (e.g. continuity),
OR
+0.5 if used correctly with partial justification

Calculation and numerical skill

For H-P,
+1 for correct numerical result, given model and value chosen for viscosity

For Bernoulli,
+1 for correct numerical result given model

Part (c): scored holistically for correctness and for coherence/completeness

Correctness of reasoning about negative pressure

| 2 pt | 1 pt | 0 pt |
|------|------|------|
| Identifies the pressure difference across xylem walls AND notes that the negative sign for xylem indicates a risk of collapsing inward. | Identifies pressure difference across xylem walls, but gets the direction wrong. | Does not identify pressure difference across xylem walls. |

Coherence and completeness:

| 2 pt | 1 pt | 0 pt |
|------|------|------|
| Highly coherent and complete: logically sound explanation for the conclusion. Clearly and carefully explains all physical mechanisms invoked. | Somewhat coherent and complete: logically sound and mostly internally consistent, addresses the question, but does not explain physical mechanism clearly/carefully | Not particularly coherent or complete, or doesn’t get at the question asked |

C. Statistical analysis

All statistical analyses were performed in the R software environment using appropriate packages. For comparisons between scores earned by IPLS and those earned by non-IPLS students, we compared the score distributions from the two student groups using a Mann-Whitney-Wilcoxon test (also known as a Wilcoxon two-sample test, hereafter referred to as a “Wilcoxon” test), the nonparametric equivalent of a two-sample t-test, [17] because Anderson-Darling normality tests indicated that the data were nonparametric. (Most of our coded scores had relatively few possible values, as can be seen in Figures 4-7, so this is not surprising.)

Because several of these comparisons found no statistically significant difference between the two groups, we followed with Bayesian analysis to give another measure of the degree of confidence in the null hypothesis, i.e., the equivalence of the two groups. The Bayes factor is the
odds ratio of the posterior distributions from a model (the “alternative hypothesis” in statistics terminology) and the null model (or “null hypothesis”) [18]. In our study, this corresponds to the odds ratio for a model in which the two groups differ to the null model in which they are equivalent. The Bayes factor can be inverted to give the odds ratio of the null model to the non-null model, thereby giving another measure of confidence in the null model. For example, a Bayes factor of 1:3 comparing the model of differences between the populations to the null model means that the Bayes factor of the inverse comparison is 3:1, indicating three times the likelihood of the null model compared to the alternative. Conventionally, an odds ratio ranging from 1:1 to 1:3 (or the inverse) indicates weak evidence, 1:3 to 1:10 moderate evidence, and 1:10 to 1:30 strong evidence, with even larger odds ratios giving even stronger evidence.

For comparisons of frequencies within populations, such as the percentages of different majors or different class years, we used either chi-squared frequency tests, or Fisher’s exact test of independence if one or two frequency table entries were small [17].

V. RESULTS AND DISCUSSION

A. Both groups solve simple problems with comparable success

Figure 4(a) shows the results of both IPLS and non-IPLS students’ ability to solve a problem using a simple model that had been used previously in class, in part (a) of the fluids problem—calculating the giraffe’s blood pressure as a function of height. This problem was very similar to others both groups had encountered in their physics courses, although neither course had presented or assigned this problem. A Wilcoxon test (non-parametric test comparing two samples) indicated no significant difference ($p = 0.94$). Likewise, the first two parts of the thermodynamics problem required implementing a model studied in class; the total coded scores for both groups are shown in Fig. 4(b), and again we found no significant difference ($p = 0.13$).
FIGURE 4. Non-IPLS and IPLS students’ total problem solving score on problems requiring implementing a model that had been previously used in class: (a) part (a) of the fluids task (code provided in Table 1). (b) parts (a) and (b) of the thermodynamics task (code in Appendix C).

To determine the confidence with which we could confirm the null hypothesis in the data shown in Fig. 4, Bayesian analysis was carried out on the same data. For Fig. 4(a), an odds ratio of 2.8 in favor of the null hypothesis (equivalent scores) vs the alternative hypothesis (different) was obtained; for Fig. 4(b), the odds ratio was 2.3, both corresponding to a weak confirmation of the null hypothesis. It is likely that the discrete scores with only a small number of possible values limited the effectiveness of modeling the posterior distributions.

From this analysis, we conclude that both groups demonstrated comparable skill in solving physics problems that can be solved by application of a single unambiguous model.

FIGURE 5. IPLS and non-IPLS students’ scores on calculation, summed across all problems.
We also examined students’ basic problem-solving skills across all parts of both problems, and found that students from both IPLS and standard courses displayed equivalent levels of skill in carrying out calculations. Figure 5 displays the total score (up to 5 points) on all code elements labeled “calculation and numerical skill” from all parts of both problems (two elements on problem 1 and three on problem 2, each worth 1 point, see Table 1 and Appendix C). The distributions are statistically indistinguishable ($p = 0.93$, Wilcoxon test); Bayes analysis gave an odds ratio of 4.4, corresponding to moderate confirmation of the null hypothesis (equivalent skill). We also found that in both groups, students drew diagrams at indistinguishable rates (roughly half of each group drew them; $p = 0.625$ from a chi-squared test of frequency).

All of these analyses indicate that IPLS and non-IPLS students in our study achieved similar skill levels in routine physics problem solving. We see a difference, however, in solving problems that require more extensive and sophisticated modeling.

**B. IPLS students are significantly more successful with flexible modeling that requires combining concepts**

Part (b) of the fluids task requires students to recognize that the fluid flow is viscous based on the dimensions of the xylem, rather than to use the Bernoulli equation because of superficial matching equations to information provided in problem (height and velocity). 93% of IPLS students used a viscous flow model (the Hagen-Poiseuille equation), while only 69% of non-IPLS students did, a significant difference ($p = 0.004$, Fisher’s exact test). This difference may have arisen from the greater attention to model choice given in the IPLS course, or greater time being devoted to viscous flow in the IPLS course, or both. Nearly all students who used the viscous flow model justified it based on the dimensions of the xylem.
A fully correct solution requires not only recognizing that the flow is viscous, but also combining two different models in a way not specifically encountered in the course. While 46% of IPLS students combined two models together to solve problem 1(b), only a single one of the non-IPLS students did, a difference which is highly significant ($p = 5 \times 10^{-6}$, Fisher’s exact test). Overall, as shown in Figure 6(a), IPLS students had much greater success in solving problem 1(b), as indicated by higher overall coded scores ($\Delta$(median) = 2, $p < 0.001$). We also found that the IPLS students outperformed the non-IPLS students on the elements of the problem 1b code that are specific to modeling decisions, omitting the points awarded for model implementation, as shown in Figure 6(b). This difference corresponds to an effect size (Cohen’s $d$) of 1.44 for the total scores and 1.61 for the combination of justification and modeling scores.

![FIGURE 6. IPLS and non-IPLS students’ scores on part b of the fluids task: (a) total score over all elements, (b) score on just the justification and modeling parts of the task, (c) scores on part (c) of the thermodynamics task, which required some modeling.](image-url)
Interestingly, the third part of the thermodynamics problem also required making a modeling choice, but one that had been introduced in class (identifying whether to calculate heat capacity at constant volume or constant pressure). The IPLS students were more successful at modeling this problem, with a median score of 2 rather than 1.5, but not significantly ($p = 0.14$, Bayes factor for the odds ratio of the alternative hypothesis over the null hypothesis of 0.68), as shown in Figure 6(c).

Finally, on both parts (a) and (b) of the fluids task, careful thought had to be given to apply the equations for pressure correctly to the physical situation. Combining the scores for the “coordinating equation with physical situation” codes from 1(a) and 1(b) together, the IPLS students were significantly more successful than the non-IPLS students ($p = 1 \times 10^{-6}$, Wilcoxon two-sample), as shown in Fig. 7, suggesting that the IPLS course may have cultivated attention to the physical meaning of equations in a manner that the standard course did not.

![Figure 7](image)

Figure 7. Overall score for coordinating equations to physical situations from 1a and 1b.

**C. IPLS students provide more coherent discussions when using new knowledge**

Both IPLS and non-IPLS students struggled to articulate mechanistic and physically accurate explanations for why trees (but not animals) can withstand the negative pressure calculated in the previous part of the task. Many students from both groups brought in specific biological
knowledge about plant biology to try to account for the negative result, but few did so in a way that made clear that their thinking about the physical mechanism was complete and correct.

The large negative pressure obtained in the previous part of the problem is associated with a strong inward force, which only stiff xylem (but not flexible blood vessels) can withstand. Only about 40% of the students in the study even mentioned this idea of inward-outward (radial) force, with the remaining 60% providing explanations that involved only vertical differences in pressure (associated with height differences). This percentage was about the same for both groups. Furthermore, among the approximately 40% of students who did mention the inward-outward force, only about one of third of these students correctly identified the direction of the force as inward. Many students did not specify a direction, and some incorrectly thought the net force would be outward. Here, too, the results were similar across both groups.

While students from both the IPLS and standard courses found it similarly challenging to provide a fully correct physical mechanism underlying the negative pressure result (as measured by a “correctness” score in our code for (1c), Table I), the IPLS student responses to this part of the task were more coherent (as measured by a “coherence” score). A response received a higher coherence score if the conclusions followed logically from the specific physical principles stated, and if it did not include extraneous physical or biological principles that were unrelated to the conclusions drawn. Although they were no more frequently correct about physical mechanism than their non-IPLS peers, the IPLS student responses to 1(c) scored higher for coherence.

V. CONCLUSIONS AND OUTLOOK
This article presents our findings on IPLS vs non-IPLS students’ ability to carry out a sophisticated biological modeling task at the end of first-semester introductory physics. We found that the IPLS
students were dramatically more successful at building a model which combines multiple ideas they had not previously seen combined, and at making complex decisions about how to apply an equation to a particular physical situation. This seems unlikely to correspond to differences in basic problem solving ability or calculational skill; both groups of students carried out calculations, and identified and applied simple models that they were introduced to in class, at statistically indistinguishable rates. Rather, it seems likely that the difference is due to some aspect of the IPLS course. As our analysis is correlational rather than causal, we cannot rule out the possibility of another confounding factor.

Our study does not directly shed any light on how the IPLS course might have accomplished this difference, although as solving such problems are one of the key learning goals of the IPLS course, guesses can be made based on how the IPLS course is designed. The IPLS course explicitly emphasized modeling skills, and this is particularly central in the fluid dynamics unit. The Bernoulli equation and the Hagen-Poiseuille equation were introduced as nonviscous and viscous models of fluid flow, respectively, and students solved fluid dynamics problems both in class and on homework that required them to clearly choose between these two models. The IPLS course also strongly emphasized that many equations apply in only limited cases. (The textbook used for both courses also emphasizes this, so the non-IPLS students should have had the opportunity to learn this as well. It is possible that the in-class discussion of the Hagen-Poiseuille equation in the non-IPLS course made it less clear to the students that the equation in the form they learned applies only to horizontal pipes.)

In a companion study, our research team found that the IPLS course cultivated durable increases in students’ perception of the value and relevance of physics for biology [19]. This could have lead to the greater success of the IPLS students in a variety of ways. Although as equivalent
groups of life science majors, both groups would presumably have been equally likely to find the flow of sap through trees interesting (or not), the problem is fairly technical and the analysis required is quite challenging. Success required a combination of creativity and courage that may have been more likely in a group that had already come to see physics as relevant and valuable for understanding biological phenomena. Finally, IPLS students may have been more motivated in approaching physics course tasks than non-IPLS students, out of a sense that the course as a whole was a valuable and supportive experience for them, which could also have led to improved performance.

Further study is needed to identify which of these possible mechanisms are at work, and whether there are others. Further study is also needed to determine whether IPLS students are more successful at complex modeling in general or solely in biological settings.

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APPENDIX A. Problem sequence applying fluid dynamics to cardiology, used in IPLS course.

A. Your circulatory system includes many vessels and valves with different cross-sectional area. Blood has relatively low but not completely negligible viscosity.
   - In which vessels is the flow best described with viscous flow?
   - In which is non-viscous flow the best description?\(^1\)

B. In aortic stenosis, the open area of the aortic valve has changed from its normal value. The patient’s heart adjusts to maintain the same flow rate as in a healthy individual, until it can no longer change. Based on the flow velocity data shown, how does the valve area of the patient with aortic stenosis, \(A_{\text{stenotic}}\), compare to the valve area of the normal person \(A_{\text{normal}}\)?

C. Based on the figure to the right, which model is most appropriate for blood being pumped through the aortic valve, the nonviscous model or the viscous model?\(^2\)

After answering, discuss: Why does the model you chose make sense (i.e. if you chose the viscous model, why would you expect there to be a lot of viscous interactions? If you chose the nonviscous model, why would viscous interactions be minimal? Look at the equation for the pressure drop in the nonviscous model.)

D. Which branch gets the largest fraction of the total flow?

If you finish: The circulatory system can adjust the amount of flow that goes to each branch dynamically. How might it do that? What feature of the viscous flow equation makes that possible?

---

1 Hint: Think about where the frictional losses happen. Would these be greater for small or large diameter vessels?
2 Hint: Look at the axes of the graph and figure out what is shown. What kind of relationship between pressure difference and flow is predicted for viscous flow? For nonviscous flow? Which matches the graph?
APPENDIX B. Complete task, beginning with the instructions provided to students

Practice problems for feedback, due to homework box by Monday December 17 at 10 AM
*Turning in your solutions by Friday 6 PM will get you feedback by Saturday afternoon!*
Worth 1/2 homework assignment, full credit for completeness and demonstrated effort

These problems bring together multiple ideas from the course, particularly the material since the second midterm (fluids and thermodynamics). They are provided for you to practice solving problems in a test-like situation and receive feedback before the final exam. Please solve these problems by yourself (no books or talking to fellow students; feel free to use your page of notes if you have it prepared).

Take as much time as you like; the problems are designed so that you should be able to complete them in up to 45 minutes if you are well prepared. If you give these problems your best effort, it will give you the most useful feedback!

The last page gives equations and values of useful parameters such as the density and viscosity of water.

Problem 1.

(a) Adult male giraffes can reach a height of roughly 6 m. The minimum pressure of the blood$^3$ leaving the giraffe’s heart is 1.24 atmospheres (124 kPa). Find an approximate value for the minimum blood pressure in the giraffe’s brain when its neck is extended to its full height. You may infer information from the picture of a giraffe provided.

*Please briefly explain the reasoning you used to find your answer, including how you decided which equations to use, as well any approximations you made. Also please show your work.*

(b) In trees, water is carried from the roots to the leaves by the flow of sap (water with other kinds of molecules dissolved in it) through stiff tube-like structures, called xylem. Although sizes vary, a typical diameter would be 100 µm. In the main trunk of the tree, they extend close to the full height of the tree, which is commonly as great as 30 meters tall or taller (5 species of tree are known to reach 90 -110 m in height). These extremely narrow, long tubes, called xylem, contain a continuous column of water which can then flow into the leaves. The evaporation of water from the leaves (called transpiration) causes water to be steadily drawn into the leaves from the xylem. The structure of the leaves allows the pressure of water in the xylem to not necessarily be the same as the surrounding atmospheric pressure.

Consider a tree in which sap flows through each 100 µm-diameter xylem at a volume flow rate of 1.1x10$^{-10}$ m$^3$/s (equal to 1.1x10$^{-4}$ mL/s or 0.40 mL/hr), corresponding to an average flow speed of 0.014 m/s. (Given the huge number of xylem, the total flow for the entire tree is substantial!) If the pressure in the roots is equal to atmospheric pressure, what is the pressure at the top of a 30 m tall xylem in the trunk?

*Please briefly explain the reasoning you used to find your answer, including how you decided which equations to use, as well any approximations you made. Also please show your work.*

---

$^3$ Although blood is a mixture of water and various types of blood cells, the density of blood is very close to the density of water because the cells also consist mostly of water.
(c) You should have found different signs for your answers to (a) and (b). In this course, we have not discussed the possibility of negative values of pressure. A more in-depth study of pressure reveals that negative pressures can exist in cohesive substances such as liquids. Just as for positive pressures, a pressure difference across a surface corresponds to a force.

A critical difference between the fluid transport systems of trees and animals like giraffes is that blood vessels through which blood flows are made of a stretchy material, while the xylem through which sap flows are made of a very rigid material.

How do your results for (a) and (b) illustrate part of the reason why trees can grow much taller than land animals? *Explain your answer using the ideas from this course and your physical intuition. Be as specific as you can be in your explanation.*

**Problem 2.**
A 6.0-cm-diameter cylinder of helium (He) gas has a 1 kg movable copper piston. The cylinder is oriented vertically, as shown, and the air above the piston is evacuated. When the gas temperature is 20°C, the piston floats 20 cm above the bottom of the cylinder.

In answering the following questions, be sure to *explain your reasoning*, and *explain why you choose to use the equations that you use.*

a) What is the gas pressure?

b) How many moles of gas are in the cylinder?

Then 2.0 J of heat energy are transferred to the gas.

c) What is the new equilibrium temperature of the gas?
**Equations for Practice Problems**

Properties of water (at 20°C)

- **Density:** \( \rho_{\text{water}} = 997 \text{ kg/m}^3 \)
- **Viscosity:** \( \mu_{\text{water}} = 1.005 \times 10^{-3} \text{ Pa} \cdot \text{s} \)

Units and constants:

- \( g = 9.80 \text{ m/s}^2 \)
- \( 1 \text{ N} = 1 \text{ kg/m} \cdot \text{s}^2 \)
- \( 1 \text{ Pa} = 1 \text{ N/m}^2 \)
- \( 1 \text{ L} = 1 \times 10^{-3} \text{ m}^3 \)
- \( k_B = 1.38 \times 10^{-23} \text{ J/K} \)
- \( T_K = T_C + 273 \)
- \( N_A = 6.023 \times 10^{23} \text{ per mole} \)
- Atomic mass unit: \( 1 \text{ u} = 1.66 \times 10^{-27} \text{ kg} \)

**Force of gravity near Earth’s surface:** \( F = mg \)

**Density, pressure, and hydrostatics:**

\[
\rho = \frac{m}{V} \quad F = pA \quad p_2 = p_1 + \rho g \Delta d
\]

**Fluid dynamics:**

- **Continuity:** \( Q_{\text{volume}} = \frac{d(\text{volume})}{dt} = vA \)
- **Bernoulli:** \( p_1 + \rho g v_1^2 + \frac{1}{2} \rho v_1^2 = p_2 + \rho g v_2^2 + \frac{1}{2} \rho v_2^2 \)
- **Hagen-Poiseuille:** \( Q = \frac{\Delta p \pi R^4}{8\mu} \quad \nu_{\text{avg}} = \frac{\Delta p R^2}{\ell 8\mu} \)

**First law of thermodynamics:** \( \Delta E_{\text{th}} = W + Q \)

**Specific heat and calorimetry:** \( Q = Mc\Delta T = nC\Delta T \)

**Ideal gas properties:**

\[
pV = Nk_BT \quad \text{and} \quad pV = nRT
\]

\[
\nu_{\text{avg}} = \frac{1}{2} m_{\text{atom}} v_{\text{rms}}^2 = \frac{3}{2} k_BT
\]

\[
K_{\text{micro}} = \frac{3}{2} pV = \frac{3}{2} Nk_BT
\]

\[
C_p = C_v + R
\]

For a monatomic ideal gas, \( E_{\text{th}} = K_{\text{micro}} \) and \( C_v = \frac{3}{2} R \)

**Work done in ideal gas process**

\[
W = \int_{V_i}^{V_f} p \, dV
\]
APPENDIX C. Code for thermodynamics problem.

**Part A (up to 3 points)**

| Competency                                                                 | Scoring Criteria                                                                                                                                                                                                 |
|---------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Using an appropriate model (0-1 pt)                                       | +1 for using \( p = F/A = mg/A \) to find pressure. Award points if the student writes \( F = ma \) but substitutes gravity for acceleration.  
  OR  
  +0.5 for using \( p = F/A = mg/A \) but student equates area to surface area of cylinder or width*diameter of figure. |
| Coordinating a diagram with an equation (0-1 pt)                          | +1 for correct FBD of piston given model chosen,  
  OR  
  +0.5 for FBD with incorrect or incomplete labeling of the forces. |
| Numerical calculation and facility with units* (0-1 pt)                   | +1 for solving correctly for \( p \) (including units), given the equation used.                                                                                                                                   |

**Part b (up to 2 points)**

| Competency                                                                 | Scoring Criteria                                                                                                                                                                                                 |
|---------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Using an appropriate model (0-1 pt)                                       | +1 for using \( pV = nRT \).                                                                                                                                                                                  |
| Numerical calculation and facility with units (0-1 pt)                    | +1 for solving correctly for \( n \) (including units), given the equation used.                                                                                                                                  |

**Part c (up to 3 points)**

| Competency                                                                 | Scoring Criteria                                                                                                                                                                                                 |
|---------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Using an appropriate model (0-1 pt)                                       | +1 for using the appropriate model: \( Q = nC_p \Delta T \) or \( Q = (5/2)nR\Delta T \)  
  OR  
  +1 for deriving the appropriate model: \( Q = \Delta E - W \), with \( \Delta E = (3/2)nR\Delta T \) and \( W = -p\Delta V = -nR\Delta T \).  
  OR  
  +0.5 for a model involving \( Q = nC_\Delta T \) without recognizing constant pressure. This can include:  
  - \( Q = nC_v \Delta T \)  
  - \( Q = mc\Delta T \), where \( m=n \) molar mass  
  - \( \Delta E = (f/2)NR\Delta T \), with first law justification |
| Model justification (0-1 pt)                                              | +1 for a justification of choice between \( C_v \) and \( C_p \). Stating that \( C_v \) OR \( C_p \) applies (without further justification) is sufficient; students only need to recognize that different heat capacities apply under different conditions.  
  OR  
  +1 if an incorrect model is used but a rigorous justification for the model choice is provided. |
Implementation and numerical calculation and facility with units (0-1 pt) | +1 for solving correctly for $T$ (including units), given the equation used, including finding $C_v$ or $C_p$ correctly.

**Numerical calculation and facility with units competency clarification:**

| Award point | Do not award point for... |
|-------------|--------------------------|
| “Careless” or trivial substitution error | Clear algebraic error |
| • Ex. substitute $1.1 \times 10^{-2}$ instead of $1.1 \times 10^{-3}$ | • Ex. simplify $\pi R^4$ to $A^2$ |
| Award point regardless of the equation copied or utilized as long as the following computation follows | Meaningful substitution error |
| | • Ex. substitute diameter for $R$ |
| | Unit conversion and magnitude errors |