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Bringing three-dimensional learning to undergraduate physics: Insight from an introductory physics laboratory course

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Three-dimensional learning (3DL) is an approach to science instruction that was developed for K-12 science education and that can provide guidance for improving undergraduate physics laboratories. In this paper, we describe efforts to comprehensively integrate 3DL into a sequence of undergraduate introductory physics for life sciences (IPLS) laboratory courses. This paper is tailored for introductory physics faculty interested in advancing their course's learning goals by simultaneously engaging students in experimental practices, scientific reasoning, and conceptual knowledge. We first review how several well-known laboratory curricula are already implicitly aligned with 3DL. We then describe our IPLS course sequence and show how each 3DL dimension—science and engineering practices, disciplinary core ideas, and crosscutting concepts—is integrated throughout the curriculum. To support implementation, we provide samples of our course documentation, a detailed account of our 3DL integration efforts, a guide to training and supporting teaching and learning assistants in a 3DL course, and a sample set of activities to guide students in participating in 3DL instruction in the supplementary material.

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I. INTRODUCTION

Many undergraduate physics laboratory courses have undergone reforms to improve student engagement in scientific reasoning, critical thinking, and scientific practices.[1] These reforms have stemmed from ongoing calls to transition laboratory courses away from rote, confirmatory curricula focused on reinforcing lecture content and toward more authentic laboratory experiences that engage students in experimental practices and scientific reasoning (e.g., Ref. 2). While these efforts have produced valuable results for students and instructors, developing coherence and interconnectedness among the three dimensions of science learning—scientific concepts, experimental practices, and reasoning tools[3]—is a challenge. Students should have opportunities to consistently engage with these three dimensions of scientific learning in laboratory course settings, as they jointly prepare students to "think like a physicist" and develop authentic scientific expertise.[4] Laboratory courses remain a unique educational environment, where students can consistently interact with and learn about experimental practices, scientific concepts, and reasoning processes in ways not possible in other learning environments such as lecture halls or recitation sections. To provide these opportunities to students in ways that produce tangible change in student learning and engagement, it is important to implement explicit pedagogical scaffolds into physics laboratory curricula that build interconnectedness and coherence among experimental practices, conceptual material, and scientific reasoning.

We present an introductory physics for life sciences (IPLS) laboratory course sequence integrating the three-dimensional learning (3DL) framework into its existing laboratory curriculum. The 3DL framework is a conceptual framework from K-12 science education that is explicitly designed to coherently support students' scientific inquiry through integration of scientific practices, concepts, and modes of reasoning.[3] Composed of disciplinary core ideas (DCIs), science and engineering practices (SEPs), and crosscutting concepts (CCCs), 3DL is designed to promote students' active learning of overarching core scientific ideas (DCIs) by engaging students with scientific practices (SEPs) and reasoning tools (CCCs) within interesting or relevant scientific contexts (see Ref. 5 and our supplementary material[6] for additional references and resources that describe 3DL). A crucial feature of the 3DL framework is emphasis on student engagement with all 3DL dimensions coherently to build new knowledge and experience jointly, rather than focusing on each individually. Tables I and II show each component of the 3DL framework.

Table I. List of 3DL SEPs and CCCs.

Science and engineering practices (SEPs)	Crosscutting concepts (CCCs)
SEP 1: Asking questions and defining problems	CCC 1: Patterns
SEP 2: Developing and using models	CCC 2: Cause and effect
SEP 3: Planning and carrying out investigations	CCC 3: Scale, proportion, and quantity
SEP 4: Analyzing and interpreting data	CCC 4: Systems and system models
SEP 5: Using mathematics and computational thinking	CCC 5: Energy and matter
SEP 6: Constructing explanations and designing solutions	CCC 6: Structure and function
SEP 7: Engaging in argument from evidence	CCC 7: Stability and change
SEP 8: Obtaining, evaluating, and communicating information	…

Since its inception, 3DL has been widely adopted in United States K-12 education as a productive framework for science learning.[7] Recently, stakeholders have advocated that undergraduate curricula adopt aspects of 3DL since it can enhance students' deep investigation and use of complex knowledge in preparation for future academic and professional success.[8] In response, 3DL has slowly entered undergraduate STEM curricula in recent years, though its adoption rate in undergraduate physics settings is low (see Ref. 9 and our supplementary material[6] for references and additional information about 3DL in undergraduate STEM). However, many of the ongoing reform efforts in undergraduate physics instruction implicitly align with 3DL, as discussed in more detail in Sec. II. While a comprehensive review of the benefits of 3DL is beyond the scope of this paper, the following four benefits are ones that physics instructors are likely to see as highly aligned with their goals (see the supplementary material[6] for a full list of references detailing the benefits of 3DL described here). First, 3DL has been shown to develop coherence in multiple settings, which is important as university STEM instruction becomes more interdisciplinary (e.g., Ref. 10). Second, 3DL promotes students' abilities to develop scientific arguments while engaging in comprehensive scientific inquiry (e.g., Ref. 11). Third, 3DL emphasizes developing and using sophisticated scientific models to investigate complex scientific phenomena (e.g., Ref. 12); modeling has consistently been a primary goal for many undergraduate physics laboratory courses. Finally, research has shown that students in 3DL environments can construct explanations of scientific phenomena while accounting for results from inquiry or complex conceptual information (e.g., Ref. 13).

We begin by briefly reviewing several well-known laboratory curricula and their implicit alignment with the 3DL framework, showing that faculty can integrate 3DL into their courses without a complete overhaul. Next, we describe our instructional setting, a recently reformed introductory physics for life sciences (IPLS) laboratory course sequence. We then detail how we integrated each dimension of the 3DL framework into our existing curriculum. We also provide in the supplementary material[6] additional information for interested faculty, including an in-depth guide detailing the progression of our integration efforts, a description of how we train and support our teaching and learning assistants (TAs and LAs, respectively) in 3DL instruction, various supplemental activities students complete to become familiar with 3DL in the course, and other relevant resources.

II. REVIEW OF REFORMED LABORATORY COURSES' ALIGNMENT WITH 3DL

At first glance, integrating the 3DL framework into an existing physics lab course may seem challenging. However, we find that many introductory physics lab curricula already contain aspects of 3DL's foundational characteristics, even though they were created before 3DL's development in 2012. We examined the following laboratory curricula to assess their alignment with 3DL: Investigative Science Learning Environment (ISLE),[14] Scientific Community Labs (SCL),[15] Modeling Framework for Experimental Physics,[16] Projects and Practices in Physics (P^3),[17] NEXUS/Physics,[18] and RealTime Physics.[19] For additional details about the reviewed curricula, please refer to the supplementary material.[6] We also include AAPT's 2014 laboratory recommendations, which has served as a guiding framework for many recent physics lab curriculum reforms.[4] These recommendations provide learning goals that faculty should implement into their courses, focusing primarily on practices and skills rather than content.

To compare these curricula with the 3DL framework, we first reviewed their curriculum (accessed via publicly available resources such as Physport and Living Physics Portal) and associated journal articles to determine which practices or skills (SEPs) they incorporated. Because many of these curricula were developed before 3DL's inception, direct alignment was infeasible. Rather, we searched for key terms and phrases commonly associated with each SEP to identify comparable practices or skills.

Some curricula explicitly prioritize a single SEP and use this as the central scaffold for their laboratory instruction. For example, a primary instructional goal for the ISLE curriculum is to engage students in experimental design (SEP 3). Similarly, the P^3 curriculum prioritizes student engagement in data analysis and visualization (SEP 4). Outside of the presented list, various PICUP community curricula are additional examples of having a singular emphasis on a defined practice, namely, computation. Table III shows how each of these lab curricula implicitly engages students in

Table II. Disciplinary core ideas (DCIs).[a]

Physics core ideas (PCIs)	Biology core ideas (BCIs)	Chemistry core ideas (CCIs)
PCI 1: Interactions can cause changes in motion	BCI 1: Cells—biological building blocks	CCI 1: Atomic/molecular interactions
PCI 2: Conservation of physical quantities	BCI 2: Biological systems	CCI 2: Atomic/molecular structure and properties
PCI 3: Interactions are mediated by fields	BCI 3: Biological structure and function	CCI 3: Energy

[a] DCIs listed in this table are specific to the IPLS courses presented in this paper.

3DL's SEPs. Though many of the curricula prioritize a single SEP, they overall prompt students to engage in many SEPs; this is unsurprising given that many lab courses have recently shifted to more intentionally prioritize students' engagement with scientific practices and technical skills.[1] However, while these curricula align with many SEPs, we did notice that many curricula did not explicitly engage students in ***Asking Questions and Defining Problems*** and ***Engaging in Argument from Evidence***, two SEPs that remain foundational in professional physics experimentation. Finally, we see that the AAPT recommendations align with the 3DL goal of integrating all eight SEPs into their curriculum.

We also reviewed each curriculum to identify if or how the courses organize their scientific concepts and topics into overarching DCIs. We determined that this generally did not occur. Rather, concepts and topics were often fragmented into individual lab experiments with few explicit curricular scaffolds devoted to building connections between them. For example, the ISLE lab curriculum engages students with forces and motion, 1D kinematics, Newton's laws, and circular motion, statics, gases, and thermodynamics, all of which reside within their own respective experiments. Similarly, RealTime Physics engages students with 1 D motion (labs 1 and 2), forces, gravity, and Newton's laws (labs 3–7), collisions and momentum (labs 8 and 9), projectile motion (lab 10), and energy (labs 11 and 12) with each topic residing within its own subset of lab experiments and no scaffolds between experiments to support students in building connections between the concepts. While there are undoubtedly connections between these conceptual topics, this unintentional confinement of physics concepts into individual lab experiments may implicitly prompt students to view the concepts as distinct and fragmented. Conversely, the P^3 curriculum is an example curriculum that was explicitly developed to align with course-defined DCIs and SEPs. For example, P^3 defines four physics DCIs and two computation DCIs that guide students' conceptual progression throughout the course by longitudinally connecting each investigation's learning goals and concepts. This is a promising example of a laboratory curriculum that explicitly uses DCIs to help students build connections between conceptual topics across lab investigations. We note again that the AAPT recommendations do not provide recommendations regarding laboratory content, in order to maintain generalizability across academic levels, student populations, and departmental needs.

Finally, our review showed that these curricula sometimes used CCC-related language implicitly in instruction. We suspect faculty may not explicitly focus on integrating CCC-based language into their curriculum to engage students in scientific reasoning and sensemaking during experimentation and instead expect this to occur organically during instruction. Thus, we searched for general prompts in the curricula that may help guide students to engage in reasoning or sensemaking during experimentation. Some common trends emerged across the curricula, including that identifying ***Patterns*** was a common instructional focus. For example, the ISLE curriculum frequently prompts faculty to guide students as they "identify patterns in… observations and… develop a qualitative explanation for the patterns that have been identified." Also, the NEXUS/Physics curriculum frequently emphasizes that students utilize their knowledge of a biological specimens' structure to empirically investigate its properties and functions (***Structure and Function***). Finally, consistent throughout many curricula was an expectation that students investigate and provide explanations for causal relationships (***Cause and Effect***). For example, all four of P^3's physics DCIs incorporate language that implies a focus on causal relationships within physical systems (e.g., "F4: torques external to a system **can change** the system's angular momentum"). The AAPT Recommendations did not include specific recommendations on student reasoning or sensemaking in laboratory courses.

Overall, these curricula contain foundational aspects of 3DL but do not intentionally utilize a coherent instructional

Table III. Physics lab curriculum SEP alignment.

Lab Curricula	SEP 1: Asking questions and defining problems	SEP 2: Developing and using models	SEP 3: Planning and carrying out investigations	SEP 4: Analyzing and interpreting data	SEP 5: Using mathematics and computational thinking	SEP 6: Constructing explanations and designing solutions	SEP 7: Engaging in argument from evidence	SEP 8: Obtaining, evaluating, and communicating information
Investigative Science Learning Environment (ISLE)	⋯	⋯	[a]	√	√	√	⋯	√
Scientific Community Labs (SCL)	⋯	⋯	√	√	⋯	√	⋯	√
Modeling Framework for Experimental Physics	⋯	[a]	√[b]	√	√	√	⋯	√
Projects and Practices in Physics (P^3)	⋯	√	√	[a]	√	√	√	⋯
NEXUS/Physics	⋯	√	√[b]	√	√	√	⋯	⋯
RealTime Physics	⋯	√	√[b]	√	√	⋯	⋯	⋯
AAPT Lab Recommendations	√	√	√	√	√	√	√	√

[a] Primary SEP focus.

[b] Carrying Out Investigations only, no explicit focus on planning.

framework to simultaneously use each dimension of 3DL to engage students in coherent scientific instruction. Their relative alignment with many of 3DL's key principles is unsurprising, given that many of these curricula were developed shortly before or after 3DL. We believe that many other current physics lab curricula include similar types of implicit alignment with 3DL that can be built upon and brought together to engage students in utilizing scientific practices (SEPs) during experimentation to generate a coherent understanding of scientific concepts (DCIs) while using multiple modes of scientific reasoning (CCCs).

III. IPLS COURSE DESCRIPTION

In this section, we provide a brief description of our two-semester introductory physics for life sciences (IPLS) laboratory course sequence. These courses were previously reformed to transition from an algebra-based physics curriculum loosely based on RealTime Physics[19] to an adapted NEXUS/Physics[18] IPLS curriculum. The primary learning goals include: (1) engaging students in complex scientific practices within realistic research-like experimental environments, (2) engaging students with interdisciplinary topics through relevant biological phenomena, and (3) providing students opportunities to collaboratively sense-make about mechanisms and causal relationships in biological systems through experimentation. Since piloting the courses during Spring 2018, they have enrolled roughly 2000 undergraduate students. Together, both courses enroll roughly 400 students each semester. Students are mostly pre-medical (roughly 70%) students in their final two years (roughly 88%) of undergraduate studies. (At our institution, it is customary for pre-medical students to defer enrollment in introductory physics courses until after they complete their upper-division medical school course requirements in biology and chemistry.) Students are expected to concurrently enroll in the corresponding introductory physics lecture courses. However, there is limited connection between the lecture and lab courses, and the lab course curriculum and apparatus are tailored for the enrolled population; most of whom have significant academic experience in cellular biology, organic chemistry, and human anatomy.

Each lab section consists of 24 students working in groups of four while supported by a physics teaching assistant (TA) and a STEM learning assistant (LA). TAs and LAs receive pre-course training and weekly instructional support to introduce them to the 3DL integration and guide them in 3DL-aligned instruction (see the supplementary material[6] for resources detailing TA/LA training for 3DL courses). Weekly lab sessions last three hours, and each investigation is two or three weeks in length, resulting in lab investigations of six to nine total lab hours. In each investigation, student groups are given guiding prompts related to complex scientific phenomena. They collaboratively develop experimental research questions, design and conduct their experiments, engage in argumentation sessions with their peers, and write lab reports that undergo a double-anonymous peer review, all with scaffolded support from TAs and LAs. The investigation descriptions and an overview of their guiding prompts are given in Table IV.

IV. BRINGING 3DL INTO PHYSICS LAB INSTRUCTION

In this section, we describe how each dimension of 3DL is integrated into our course curriculum. For interested faculty,

Table IV. Course overview.

First semester IPLS course	
Laboratory investigation	Students investigate…
Lab 1: Biological kinematics	… zebrafish kinematics (velocity, acceleration) and extrapolate findings to topics, including social behavior, metabolic processes, reproductive processes, etc.
Lab 2: Macroscopic fluid dynamics	… properties (kinematics, resistive forces, energy) of objects moving through fluids and develop models of extraneous biological phenomena, including blood flow, evolutionary structural biology, fluid resistance (drag) in intracellular transport, etc.
Lab 3: Investigating Brownian motion and diffusion	… Brownian motion of synthetic microspheres and extrapolate findings to other topics, including dynamic cellular environments and intracellular motility, active versus passive transport, energetics of living cells, etc.
Lab 4: Molecular motors	… kinematics or energetics of molecular motor proteins in onion cells to build an understanding of more complex phenomena or systems, including muscular contraction, meiosis and mitosis, cilia and flagella, neurophysiological diseases, etc.
Second semester IPLS course	
Lab 5: Hemodynamics	… properties of microscopic blood flow in capillaries and extrapolate findings to phenomena, including cardiac output, effects of blood-related diseases or disorders (e.g., sickle-cell anemia, thrombocytopenia), etc.
Lab 6: Electrophoresis up close	… electrophysiological properties of charged microscopic objects to generate a deeper understanding of topics, including electrophoresis as an experimental technique, screening (Debye) effects in electrophoresis, etc.
Lab 7: Spectroscopy and fluorescence	… spectroscopic, fluorescent, and quantum properties of physical and biological samples and develop mechanistic explanations for bioluminescence and ocular evolution.
Lab 8: Axon signal transmission	… neural axons by building and analyzing a simple circuit system as a model for passive axonal transmission and extrapolate results to study differences between passive and active axonal transport, electrophysiological aspects of living nervous systems, and axonal evolutionary characteristics.

we provide samples of our course documentation, a detailed account of our 3DL integration efforts, a guide to training and supporting TAs and LAs in a 3DL course, a sample set of activities to guide students in participating in 3DL instruction, and additional resources and references for all incorporated curricular strategies in the supplementary material.[6]

A. Science and engineering practices (SEPs): Authentic scientific experimentation

In the course sequence, engaging students in SEPs is the primary focus for instruction, as is common in many physics lab courses. Lab activities are modeled after the argument-driven inquiry (ADI) instructional model,[20] which has been shown to align with all eight SEPs.[21] ADI is a well-known instructional model that has been integrated into physics, chemistry, and biology curriculum at the K-12 and college levels. Table V presents the laboratory activities and their alignment with the SEPs. In addition to our goal of engaging students in all eight SEPs, we prioritize a subset of SEPs, ***SEP 1: Asking Questions and Defining Problems*** and ***SEP 7: Engaging in Argument from Evidence***. To emphasize SEP 1, we utilize a question-formulation-technique (QFT) activity prior to experimentation.[22] To emphasize SEP 7, we frame students' investigations around developing a scientific argument to answer their research question; the ADI model supports this framing.

To illustrate how the curriculum engages students with all eight SEPs, we provide a brief overview of students' activities in an example lab investigation: Lab 3: Investigating Brownian motion and diffusion. In Lab 3, students begin by completing a warm-up activity, which guides them through introductory steps of setting up, collecting, and analyzing translational motion data from a sample of synthetic microspheres suspended in a fluid. This warm-up activity prepares students to carry out their investigations using the lab apparatus (SEP 3) and analyze collected experimental data using relevant computer software (SEPs 4–5).

After completing the warm-up activity, students are provided a general overview of: (a) the scientific phenomena available for study, (b) the guiding prompts that help frame their research questions and design plans, and (c) the available experimental apparatus and analytical methods (see the supplementary material[6] for an example lab 3 introductory video provided to students to prepare them for their experiments). Students develop a research question and design plan (SEP 1 and 3) by completing a QFT activity. The QFT activity guides students to: (a) individually brainstorm multiple possible research questions, (b) classify questions as open or closed questions, (c) evaluate the questions' testability within the course's constraints (i.e., available apparatus, timing), (d) identify how various CCCs (e.g., cause and effect) might be used in their questions and investigations to generate deeper understandings of their phenomena (e.g., mechanisms underlying causal relationships), and (e) develop a research question and initial experimental plan as a group. While developing their research question and design plans, students are prompted by TAs, LAs, and lab documentation to consider how their laboratory investigation might serve as a model for relevant complex biophysical phenomena (SEP 2). In lab 3, students often use the Brownian motion of synthetic microspheres in a fluid as a model for intracellular passive diffusion to show that active transport within cells is necessary to sustain life.

After the QFT activity, students begin their investigation by preparing samples of synthetic microspheres for video collection. Students use microscopes and mounted microscope cameras to collect videos of microspheres moving within fluids (SEP 3), which they then analyze to determine their velocities, rates of Brownian motion (diffusion coefficient), or other characteristics. Throughout their investigation, students are prompted to search for and utilize conceptual information from relevant external literature (i.e., peer-reviewed journal articles) to assess the viability of their experiment and conceptually make sense of their ongoing results (SEP 8). Using a spreadsheet program, students analyze their data by engaging in several analytical and computational processes such as tabulating and reducing data sets, defining variables, creating equations to perform calculations, and assessing computational results. In this, students use equations and computational skills to efficiently perform thousands of calculations on large data sets and generate graphical representations of their work (SEP 4 and 5).

After analyzing data, students generate explanations and scientific arguments to present to their peers (SEP 6 and 7). Often, students continue reviewing external resources to identify relevant information to support their explanations and arguments (SEP 8). Using the claim-evidence-reasoning (CER) argumentation framework,[23] students posit their claim (answer to their experimental research question in the form of a scientific explanation), support their claim with evidence (analyzed and interpreted experimental data), and describe their scientific reasoning of why the evidence supports the claim. To prepare for argumentation sessions, students are prompted to consider not only their CER components but also what critiques they may receive from their peers and how they will respond to them. They then present their CER arguments to their peers for critical feedback, which they integrate into their final results and subsequent lab reports (SEP 8).

B. Disciplinary core ideas (DCIs): Building coherence in scientific concepts

This IPLS course sequence, by using a 3DL framework approach, builds connections between target physics, biology, and chemistry concepts by categorizing them into larger sets of course-specific DCIs (see Table VI). Our course-specific DCIs are based on documented DCIs in other undergraduate STEM course environments (refer to our 3DL integration guide in the supplementary material[6] for more information on how we developed our course-specific DCIs).[24] These DCIs guide the progression of lab investigations throughout the course sequence, as the concepts and systems under investigation in each laboratory experiment are designed to specifically build on each other such that students revisit scientific concepts across investigations within different experimental contexts. As shown in Table VII, each lab investigation involves multiple DCIs from different disciplines, offering an interdisciplinary focus on each experimental system. Each DCI is also revisited multiple times each semester with students engaging with new scientific concepts that relate and add to their understanding of a larger DCI. Below, we highlight respective examples of the interdisciplinary DCI engagement and the longitudinal revisitation of DCIs.

Lab 4 is a notable example of students' interdisciplinary DCI engagement. In lab 4, students utilize their prior

Table V. IPLS lab activities.

Lab sequence activities	Description	SEP 1: Asking questions and defining problems	SEP 2: Developing and using models	SEP 3: Planning and carrying out investigations	SEP 4: Analyzing and interpreting data	SEP 5: Using mathematics and computational thinking	SEP 6: Constructing explanations and designing solutions	SEP 7: Engaging in argument from evidence	SEP 8: Obtaining, evaluating, and communicating information
Warm-up activity	Students engage in introductory experimental tasks to become familiar with the apparatus and background conceptual information related to pertinent DCIs.	⋯	⋯	√	√	√	√	⋯	⋯
Lab introduction	Teaching assistants (TAs) give a brief overview of the experiment and supplementary information.	⋯	⋯	⋯	⋯	⋯	⋯	⋯	⋯
Development of research question and design plan	Student groups develop a research question based on an open-ended guiding prompt and relevant background information and plan their experiment in line with available apparatus, materials, and course expectations.	√	√	√	⋯	⋯	⋯	⋯	⋯
Investigation	Groups carry out their experimental plans by collecting and analyzing data in order to generate explanations and develop scientific arguments.	⋯	√	√	√	√	√	√	√
Argumentation session	Groups develop and present their scientific argument and results to members of other groups, receiving initial feedback from their peers and TAs/LAs.	√	⋯	⋯	⋯	⋯	√	√	√
Lab reports and double-anonymous peer review	Students individually draft lab reports based on their experiment's scientific argument and participate in a peer-to-peer double-anonymous peer review process, providing (receiving) constructive feedback to (from) peers.	⋯	⋯	⋯	⋯	⋯	√	√	√

Table VI. IPLS course disciplinary core ideas.

Physics core ideas (PCIs)	Description
PCI 1: Interactions can cause changes in motion	Changes in an object's motion are the result of interactions between it and its external environment. Multiple interactions between an object and its surroundings can result in a predictable change in motion.
PCI 2: Conservation of physical quantities	Various physical quantities (energy, mass, charge, etc.) come in many forms and can be transformed from one form to another within a given system or transferred between systems within conservatory constraints.
PCI 3: Interactions are mediated by fields	Fields are generated by charges/masses. Fields affect charges/masses. In circuits, fields induce currents.
Biology core ideas (BCIs)	**Description**
BCI 1: Cells—Biological building blocks	Cells are the fundamental building blocks of all living organisms, the structure upon which all more complex biological systems are built.
BCI 2: Biological systems	Ecosystems, organisms, tissues, and cells act as systems.
BCI 3: Biological structure and function	The functions and properties of ecosystems, organisms, tissues, cells, and biological molecules are determined by their structures.
Chemistry core ideas (CCIs)	**Description**
CCI 1: Atomic/molecular interactions	Attractive and repulsive electrostatic forces govern noncovalent and bonding (covalent and ionic) interactions between atoms and molecules. The strength of these forces depends on the magnitude of the charges involved and the distances between them.
CCI 2: Atomic/molecular structure and properties	The macroscopic physical and chemical properties of a substance are determined by the three-dimensional structure, the distribution of electron density, and the nature and extent of the noncovalent interactions between particles.
CCI 3: Energy	Energy changes are either the cause or the consequence of change in chemical systems, which can be considered on different scales and can be accounted for by conserving the total energy of the system of interest and the surroundings.

biological knowledge of cellular systems, composed of cellular organelles, membranes, and cytoskeleton (BCI 2), to investigate the physical properties of molecular motor proteins. In their experiments, students investigate how molecular motors utilize ATP as energy sources (CCI 3) to move (PCI 1) through viscous cell cytoplasm (BCI 1 and 3). They study how energy expenditure maintains energy conservation within the system (PCI 2) and results in the continuous motion of a cargo vesicle through a resistive fluid (PCI 1). During the investigation, students are guided as they move fluidly between disciplinary concepts to explain their biological system's mechanisms and experimental results, contributing to their interdisciplinary scientific knowledge.

PCI 1 is a notable example of longitudinal revisitation of a DCI. Here, we focus on how PCI 1 is integrated throughout the first-semester course. Students begin in lab 1 by studying basic kinematics of zebrafish, collecting and analyzing data of the fish's speed and acceleration. Here, students are introduced to physical concepts and properties within a relatively simple biological system such as speed, acceleration, inertia, momentum, and resistance. In lab 2, students use simple fluids and macroscopic objects to build a model of a biological system that involves objects moving through viscous fluids (e.g., capillary flow, intracellular diffusion). Students more explicitly study how resistive forces impact motion and begin theorizing how various biological systems account for and act against resistive forces to promote constant motion. In lab 3, students study how properties of an object's external environment (e.g., temperature, viscosity) affect Brownian motion and diffusion. Here, students use their experiments as models to quantify how temperature, viscosity, or other physical properties cause changes in stochastic

Table VII. Course overview.

First semester IPLS course									
Laboratory investigation	PCI 1	PCI 2	PCI 3	BCI 1	BCI 2	BCI 3	CCI 1	CCI 2	CCI 3
Lab 1: Biological kinematics	√	···	···	···	√	···	···	···	···
Lab 2: Macroscopic fluid dynamics	√	√	···	···	···	√	···	···	···
Lab 3: Investigating Brownian motion and diffusion	√	···	···	√	···	√	√	···	√
Lab 4: Molecular motors	√	√	···	√	√	√	···	···	√
Second semester IPLS course									
Lab 5: Hemodynamics	√	√	···	√	√	√	···	···	···
Lab 6: Electrophoresis up close	···	···	√	√	···	···	√	√	√
Lab 7: Spectroscopy and fluorescence	···	√	√	···	···	···	√	√	√
Lab 8: Axon signal transmission	···	···	√	√	√	√	···	···	√

motion in cellular living systems. Students also begin considering how interactions between objects of similar size (sphere–sphere interactions) may result in changes in momentum and energy, relating this to their Brownian motion. In lab 4, students conclude by investigating how fluid system properties, thermodynamic principles, and cellular structures impact the energetic properties of molecular motors in living cells. Here, students often focus on biological motor proteins' energy and power outputs as they move vesicle cargo through intracellular fluids, building interdisciplinary connections between DCIs. By the end of the semester, students experience multiple opportunities to engage with related physical concepts (speed, acceleration, momentum, forces, and energy) as part of a larger physics DCI, rather than through fragmented concepts as are often common in traditional physics curriculum.

Both the curriculum and pedagogy support the integration of DCIs. First, instructional scaffolds within the laboratory documentation prompt students to reflect on the development of their conceptual knowledge between lab investigations. After each lab investigation, students complete a reflection assignment to self-assess their DCI-based conceptual knowledge from their completed investigations. Second, lab manuals consistently prompt students to consider how the concepts and outcomes of prior investigations are related to their current investigations. Third, TAs and LAs consistently engage with students to revisit conceptual discussions from prior lab investigations to build longitudinal connections among conceptual topics. TAs and LAs are also trained to guide students to consider their ongoing experimental outcomes and discussions from different disciplinary contexts. TAs/LAs guide students to shift between physical, biological, or chemical explanations for their studied phenomena. This longitudinal and interdisciplinary engagement with DCIs is a hallmark feature of 3DL and may help students develop scientific coherence within single disciplines and across multiple disciplines (e.g., Ref. 10).

C. Crosscutting concepts (CCCs): Generating scientific reasoning

When utilized in laboratory settings, CCCs can provide students opportunities to use experimentation as a means to engage in scientific reasoning about their studied phenomena and underlying concepts. CCCs are integrated into the course sequence in two ways. (Table VIII shows how each CCC is emphasized throughout the courses.) First, course documentation (warm-up activities, lab manuals, technical documents, introductory slides, etc.) includes CCC language aimed to prompt students towards enacting CCCs to engage in scientific reasoning and sensemaking during experimentation. Second, students are prompted by TAs and LAs throughout experimentation to incorporate CCC-aligned reasoning as they develop explanations and arguments of their experimental results. To illustrate, we provide a brief example of how ***CCC 2: Cause and Effect*** is interwoven through course documentation and TA and LA support. This CCC is prioritized throughout the curriculum to meet one of the courses' primary learning goals: to have students collaboratively reason about mechanisms and causal relationships in biological systems through experimentation.

CCC 2: Cause and Effect is directly integrated throughout the course documentation provided to students. Several labs' guiding prompts emphasize focus on ***CCC 2: Cause and Effect*** by including relevant terminology. For example, lab 3's guiding prompt states:

> "… you can create an investigation that studies Brownian motion that can provide evidence and/or insight into **how diffusion occurs**. Some possible research avenues are below: a) In terms of cellular motility, why would cells prefer different internal environments? **How does this affect diffusion inside the cell?**"

Also, the research question and design plan rubric includes a requirement that: "The group's Design Plan will shed light on the **mechanism (cause) underlying the behavior (effect)** of the system." As a result, students' research questions, developed during the QFT activity, often evoke study of causal relationships. For example, a student group engaging in lab 3 asked the following research question:

> "How does the internal environment of a human with a higher body temperature **change** cellular motility in comparison to a human with a lower body temperature? Why would a higher body temperature **cause more cellular motility** than a body with a lower temperature?"

Students' experimentation, thus, frequently continues integrating ***CCC 2: Cause and Effect*** to work towards answering their developed causally focused research questions.

Students are also prompted to utilize ***CCC 2: Cause and Effect*** as a reasoning tool through discussion with TAs and

Table VIII. CCC alignment with IPLS labs.

First semester IPLS course							
Laboratory investigation	CCC 1	CCC 2	CCC 3	CCC 4	CCC 5	CCC 6	CCC 7
Lab 1: Biological kinematics	√	√	⋯	⋯	⋯	⋯	⋯
Lab 2: Macroscopic fluid dynamics	⋯	√	⋯	√	⋯	⋯	⋯
Lab 3: Investigating Brownian motion and diffusion	⋯	⋯	√	⋯	⋯	⋯	√
Lab 4: Molecular motors	⋯	⋯	⋯	⋯	√	√	⋯
Second semester IPLS course							
Lab 5: Hemodynamics	⋯	⋯	√	⋯	⋯	√	⋯
Lab 6: Electrophoresis up close	⋯	√	⋯	⋯	⋯	⋯	√
Lab 7: Spectroscopy and fluorescence	⋯	⋯	⋯	⋯	√	⋯	⋯
Lab 8: Axon signal transmission	√	⋯	⋯	⋯	⋯	√	⋯

LAs. Throughout the course, students are prompted by TAs and LAs to consider cause and effect relationships in their studied biological phenomena. As students complete the QFT activity, they are prompted by TAs and LAs to consider how their investigations might generate new knowledge about the causal relationships between entities in their phenomena (e.g., a TA may ask a student group: "So how might changing X help you learn about how Y and Z are causally related?"). TAs and LAs often discuss with students how one of the central components of generating testable research questions is being able to determine how changes in one entity might impact another entity. TAs and LAs also consistently revisit these potential causal relationships throughout students' investigations, asking students to explain how their preliminary results might serve as evidence of causal relationships.

While Table VIII denotes how each CCC is emphasized throughout the course sequence, students are encouraged to shift between various CCCs to engage in different forms of reasoning as they complete their experiments.

V. CLOSING REMARKS

In recent years, many in the physics education community have advocated for shifting lab instruction away from rote procedural labs that verify known principles and towards inquiry-based labs that engage students in authentic scientific practices, critical thinking, and scientific reasoning. We have described a sequence of reformed undergraduate introductory physics for life sciences laboratory courses that utilizes a 3DL framework to engage students in authentic scientific practices (SEPs) while simultaneously using reasoning tools (CCCs) to make sense about complex interdisciplinary scientific phenomena related to larger core scientific ideas (DCIs). The supplementary material[6] for this paper provides additional details of our 3DL integration process, TA and LA training and support, laboratory documentation, and supporting student activities. Key elements for 3DL have been explicitly included in course materials, including those meant for the instructional team, making it relatively straightforward to continue high-fidelity implementation in the future. In addition, the department has allocated adequate instructional resources, including both graduate TAs and undergraduate LAs, to enable sufficient student support.

This paper provides a unique contribution to the existing physics laboratory literature by introducing the 3DL framework to the physics laboratory community-at-large and by providing detailed descriptions of the efforts (presented in the supplementary material[6]) and curricular results of fully integrating 3DL into an existing reform-based introductory physics laboratory course sequence. As described in Sec. II, many well-known introductory physics laboratory courses already possess implicit alignment with many aspects of 3DL, allowing for 3DL integration that does not necessarily require a complete curricular overhaul. We hope that the example curriculum and the supplementary material presented in this paper may inspire and guide future reforms aimed at bringing 3DL into introductory physics laboratory courses more widely.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts of interest to disclose.

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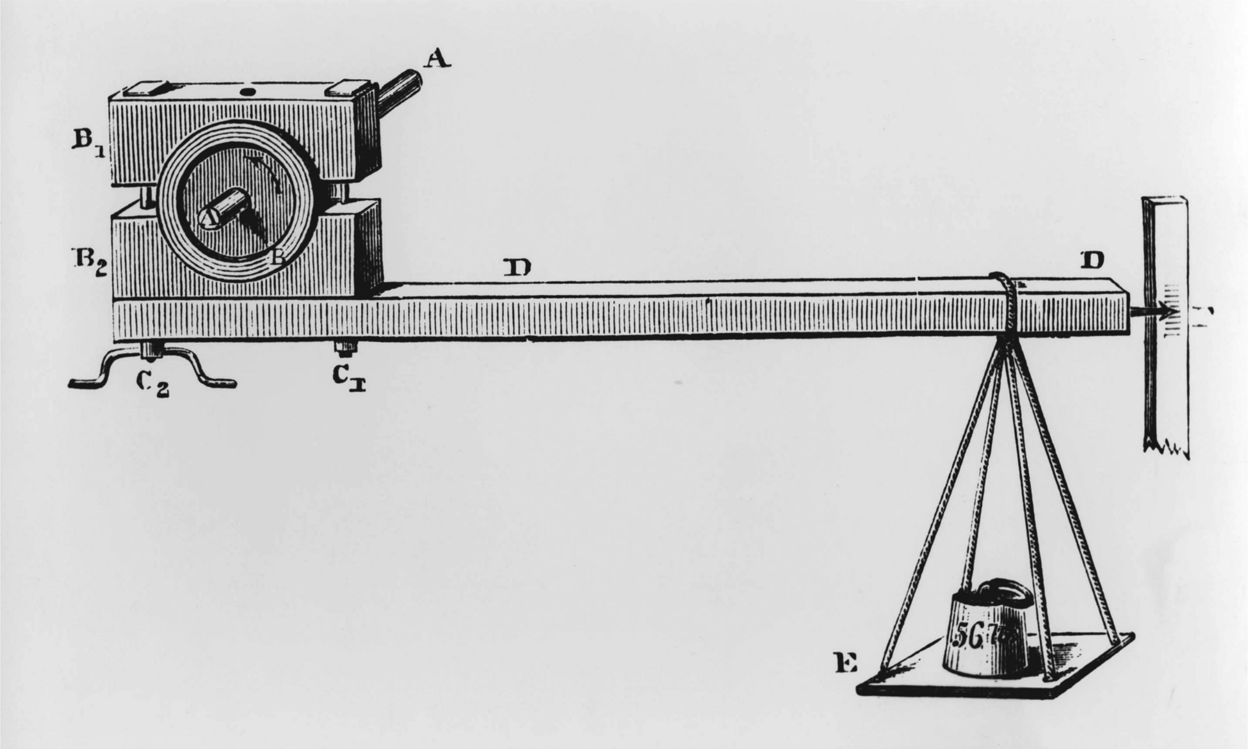

Prony Brake

This mechanical device was invented in 1821 by Gaspard de Prony (1755-1839) and is used to measure the power output of rotating machinery. A clamp around the stationary shaft is tightened until the weight at the end of the beam is just supported. The shaft is then set turning and the weight to keep the end of the beam is observed. From these two values, the rotation rate, the lever arm and the radius of the shaft, the work per unit time to overcome the frictional force can be calculated. To this day we still talk about "brake" horsepower. The figure is from J. Ganot, *Elementary Treatise on Physics* (William Wood and Co., New York, 1883) pg 422. (Text by Thomas B. Greenslade, Jr., Kenyon College)