The Biophysicist

Physics at the Molecular and Cellular Level (P@MCL): A New Curriculum for Introductory Physics

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ABSTRACT In this article, I describe a new curriculum for introductory physics for the life sciences, a 2-semester sequence usually required of all biology majors. Because biology-related applications on the macroscale are complex and require mathematics beyond introductory calculus, the focus is entirely on applications from molecular and cellular biology. Topics that are more relevant for engineering have been removed, and topics relevant to biology have been added. The curriculum is designed around 2 main themes: diffusion and electric dipoles. Diffusion illustrates the concepts of conservation of momentum and energy and provides the framework for introducing entropy from the perspective of statistical mechanics. Electric dipoles illustrate the basic concepts of electromagnetic theory and provide the framework for understanding light waves and light interactions with biomolecules. These themes are supported by small computational activities to help students understand the physics without advanced mathematics. This curriculum has been piloted over the past 4 years at Michigan State University and should be applicable to many colleges and universities.

KEY WORDS introductory physics; curriculum; biomolecules; computation

I. INTRODUCTION

The introductory physics curriculum has undergone a revolution in pedagogy over the past 2 decades, but the topics covered are the same as what was taught 50 years ago (1). The content covered is even older, essentially 17th-century ballistics and 19th-century electrostatics. This curriculum represents an impressive consensus among physicists of fundamental concepts and perhaps a belief that the most important physics to teach is what we learned ourselves. However, the topics and applications covered are most relevant for engineering students and use almost exclusively macroscopic examples, such as the rotation of a flywheel or the tension in a suspension bridge. Attempts to substitute macroscopic biological examples, such as animal locomotion and turbulence in the circulatory system, are hindered by the advanced mathematics required to understand topics and require such dramatic simplification as to render all biological content meaningless.

In contrast, the undergraduate biology curriculum has undergone a revolution in the past 50 years that reflects the advances in the larger field. Molecular and cellular biology (MCB) are now the core of the introductory biology sequence, starting with the central dogma of biology and discussing molecular details of fundamental processes, such as replication, translation, and photosynthesis. All life science

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majors, regardless of concentration, are expected to understand molecular biology; indeed, it is one of the 4 fundamental concepts in Next Generation Science Standards for high school life sciences (https://www.nextgenscience.org/overview-dci). Fortunately, it is relatively straightforward to make the connection between cellular and molecular biology and physics by using relatively simple mathematics, but requiring computation, which is discussed in detail in the following.

This effort is certainly not the first of its kind. A number of physics curricula or textbooks have been developed (2) or published geared directly at life science students, but they tend to stick very closely to the traditional curriculum, adding the biological content at the end of chapters (3, 4). Extra content is often medically oriented (5, 6). There are also several good biophysics textbooks, but they are aimed at upper-level and early graduate students and are missing much of the basic physics curriculum, such as kinematics and electrostatics (7–10). The National Experiment in Undergraduate Science Education/Physics consortium was created to reform the introductory physics for life sciences curriculum with the goal of eliminating topics irrelevant to biologists and shift the focus to molecular and statistical physics (11). Many of the materials on these topics provided inspiration for or were adapted for the curriculum presented here. Similar curricula have been developed at Yale and the University of North Carolina (12, 13). However, these curricula rely on more traditional physics and macroscopic biology examples than this new work, which integrates biology more tightly into the overall curriculum. Finally, over the past 10 years, several groups have developed very good individual modules to add molecular biology examples to the standard physics curriculum, as highlighted in the recently launched Living Physics Portal (https://www.livingphysicsportal.org/). It is my premise that to incorporate modern biology into the introductory physics for life sciences (IPLS) curriculum, it cannot be reformed gradually but requires a complete redesign.

In designing the new curriculum presented in this article, I started with the basic question: What physical phenomena are life science students likely to encounter in their advanced coursework? Certainly the concepts of momentum, energy, and electrostatics underlie all biology, but the connection may not be easily made by the student using the typical examples from physics courses. For example, although basic kinematics (motion with constant acceleration) can explain motion at all scales, 2-dimensional motion in which only one dimension undergoes acceleration due to gravity (i.e., ballistic trajectories) is not applicable. In fact, gravity is generally never relevant on the microscale in water because molecules and cells have close to neutral buoyancy. As many traditional physics problems "ignore friction," for many biology applications, it is reasonable to "ignore gravity." Similarly, although magnetism is an important concept to introduce because light is an electromagnetic wave (as well as the underlying unity of Maxwell equations), electromagnetic induction is only useful if one is building a macroscopic motor.

Recognition that MCB occurs in water led to 2 major organizing themes of the curriculum: diffusion and electric dipoles. Diffusion is covered in the first semester and is presented as an emergent phenomenon from many elastic collisions. It is then used as the introduction to entropy by defining snapshots of diffusing molecules as individual microstates, and this picture of entropy is used to understand the construction of Gibbs free-energy diagrams essential to MCB. In the second semester, electric force, field, and potential are covered in a more or less traditional way, but the primary example is the electric dipole, which is just a superposition of a positive and negative charge. Oscillating dipoles are then used to understand light as an electromagnetic wave, which can be either emitted or absorbed by biological molecules. In addition to these main themes, examples of biological molecules and cells are used throughout the course.

Table 1. Typical 2-semester curriculum for life science students. Topics in lightface italics were removed, and topics in boldface italics were significantly changed in physics at the molecular and cellular level (P@MCL).

First semester: mechanics
- Motion in 1 *and 2 dimensions*
- Force and Newton laws
- Work, energy, and momentum
- ***Oscillations*** and *rotation*
- *Static equilibrium*
- *Universal gravity*
- ***Thermodynamics***

Second semester: electricity and magnetism
- Electric force, field, and potential
- Capacitance and current
- *DC circuits*
- Magnetism
- *Electromagnetic induction*
- *AC circuits*
- ***Optics*** and waves
- *Special relativity*
- *Atomic, nuclear, and particle physics*

II. CURRICULUM OVERVIEW

A. Eliminated topics from the standard curriculum

The new curriculum (named Physics and the Molecular and Cellular Level, or P@MCL) is still organized with the same overall structure as the standard curriculum. In the first semester, students still study many of the canonical mechanics topics, such as kinematics, conservation of energy and momentum, and Newton laws. However, the topics in Table 1 marked in lightface italics are irrelevant to biology at the molecular level, as specified in Table 2. Generally, these topics are important for engineering in which rigid objects interact in air, which is usually ignored to simplify the example. They are also useful for illustrating the primary learning goals of mechanics, such as superposition of forces and conservation of energy and momentum. However, these concepts can also be demonstrated on the molecular level by using water as the medium, which cannot be ignored.

In the second semester, the canonical concepts are Maxwell laws of electromagnetism, although they are usually not presented explicitly in an introductory course. Traditionally, electric force, field, potential, and potential energy are presented with a series of useful static geometries as examples, such as lines and spheres of charge. In MCB, charge is usually not static but moves within water as salt ions or within protein and RNA structures, so these geometries are not relevant. The one simple case in which charges may be static is within a molecular dipole, which is the central theme of this semester. When the traditional course covers moving charge, it is within the context of circuits and electromagnetic induction (i.e., an electric motor), macroscopic examples that have little molecular relevance. The second semester often includes a survey of "modern physics" topics, such as atomic or nuclear physics. These topics include the important canonical concepts of quantum mechanics but use examples of simple atoms interacting in a gas or vacuum. There are many applications of quantum mechanics within MCB, but they must be considered within the context of macromolecules.

Table 2. Traditional topics that have been eliminated from physics at the molecular and cellular level (P@MCL).

Eliminated topic	Rationale
2-dimensional projectile motion	Gravity can be ignored for cells and molecules in water
Rotation	Large macromolecules, such as flagella, are not rigid, and angular momentum is not conserved in water due to drag
Static equilibrium	Molecules and cells are never in static equilibrium (i.e., a balance of all forces and torques)
Universal gravity ($F = GMm/r^2$)	All biology occurs in near-Earth gravity ($F = mg$)
DC circuits (i.e., Kirchoff laws)	Although current is important to some biological processes, construction of circuits from batteries, resistors, and capacitors only occurs on the macroscale
Electromagnetic induction	There is no biological equivalent of current-carrying wires in a magnetic field
AC circuits	There is no biological equivalent of sinusoidal current and voltage
Special relativity	All biology occurs at low velocities
Atomic, nuclear, and particle physics	Primary examples are atoms and subatomic particles instead of macromolecules

Table 3. Order of topics in the revised curriculum.

First semester: mechanics
Motion in one dimension
Conservation of momentum and energy
Diffusion
Force and Newton laws
Work, potential energy, and bound states
Entropy
Free energy of biomolecules
Second semester: electricity and magnetism
Electric force, field, and potential
Capacitance and current
Magnetism
Harmonic oscillations
Electromagnetic waves and light
Optics
Interactions of light with biomolecules

B. Revised topics from the standard curriculum

Table 1 shows 3 topics (in boldface italics) that were changed to accommodate the general themes of the new curriculum: (a) In the traditional curriculum, oscillations are usually discussed in the context of pendulums and springs. Pendulums require gravity, so are not relevant to MCB, but springs are an essential model of covalent bonds within macromolecules. Additionally, an oscillating dipole emits an oscillating electric and magnetic field that is the basis of light. Therefore, oscillations are discussed in the second semester to help explain molecular vibrations, fluorescence, and optical absorption. (b) Classical ray optics traditionally covers lenses, and mirrors and applications are drawn from telescopes. In the new curriculum, the application is the microscope, and curved mirrors are dropped, as they are rarely used in microscopy. (c) Thermodynamics is an essential aspect of MCB but is usually covered only briefly in an introductory physics curriculum. Traditional applications are drawn from engines that control volume, pressure, and temperature to do work. In biology, pressure is generally a constant, which is why Gibbs free energy is most relevant. Furthermore, on the molecular level, the best description of a collection of molecules uses a statistical mechanics framework instead of thermodynamics. Therefore, the new curriculum introduces microstates and macrostates and defines entropy first as $S = k \ln \Omega$, where Ω is the number of microstates. Once the statistical framework is established, the thermodynamic laws are presented as an extension to the macroscale.

C. New topics in the revised curriculum

Table 3 shows the order in which the material is presented in the revised curriculum. This order was chosen to ensure the students spend most of the semester understanding the 1 of 2 major themes, diffusion and dipoles, and to build to the advanced topics at the end of each semester, free energy of biomolecules and the interaction of light with biomolecules. These topics are discussed in detail in the following.

1. Diffusion

Students come into this class with a wide range of conceptions about diffusion. In my personal interactions with students, I find they tend to use the following phrases: (a) high to low, (b) energy plays a role, and (c) balance or equilibrium. These phrases are primarily phenomenological and do not describe anything about the physical basis of the process: diffusive motion is the result of multiple elastic collisions of a collection of molecules. Therefore, the semester has been organized to set out the physical principles of elastic collisions early in the semester. These requirements include kinematics, conservation of momentum, and conservation of energy. Because diffusion necessarily involves multiple objects, the presentation uses computation to observe the collisions of many balls within a box (see section II.C.6). Students can easily see apparently random motion by tracing one particular ball over time. Once diffusion has been observed by treating it as a series of elastic collisions, the same code is revisited from the perspective of the momentum principle ($F = dp/dt$) by using a force derived from the Lennard–Jones potential, thus cementing the relationship between change in momentum and force. Later in the semester, the same code is used to create “snapshots” of positions and velocities of all the balls to define a microstate and use the average kinetic energy of many snapshots to define a macrostate. Coin flips are used to derive a random walk and the diffusion coefficient in one dimension, thereby linking back to the simulation. Thus, the concept of diffusion supports the concept of entropy from a statistical perspective.

2. Enthalpy and free energy

Enthalpy, or chemical energy, is presented as one of several forms of energy, including kinetic, internal (i.e., heat due to friction), and conservative potential energies from near-Earth gravity and springs. Typically, the students are familiar with a van der Waal potential from previous courses, so the empirical Lennard–Jones potential is used during a discussion of potential energy to understand a bound state and oscillations within the well. The students attempt to observe such bound states computationally by using the diffusion code described previously. Finally, enthalpy and entropy are combined to define the Gibbs free energy, and the students create free energy profiles of simple protein structures.

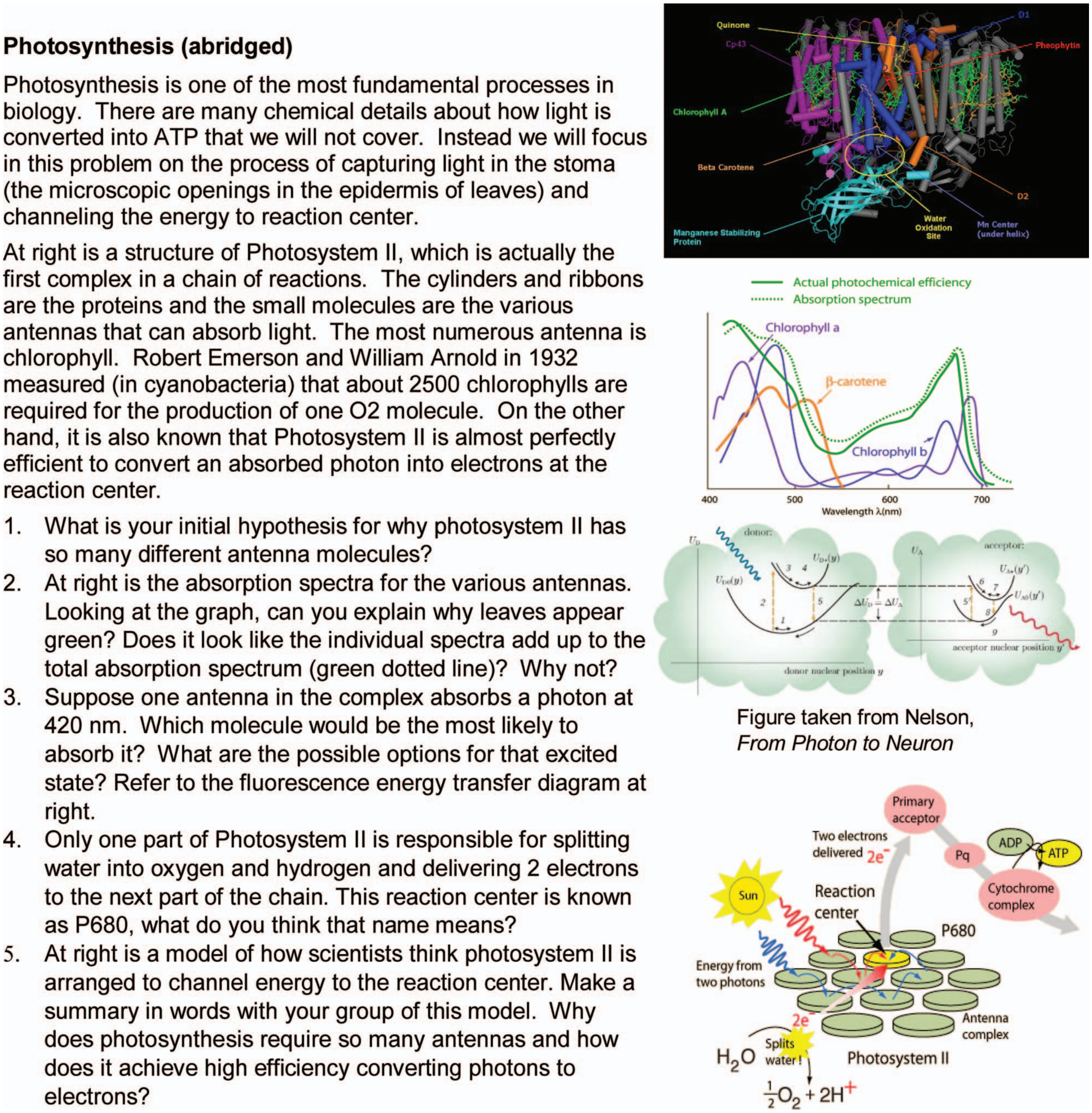
A major learning goal of the course is that energy is conserved. Like most traditional curricula, this concept is reinforced by pushing the students to define the system such that the energy "budget" remains constant. In macroscopic examples, this is often difficult to do quantitatively because energy dissipation due to friction, air resistance, or drag is hard for the students to account for. Even in many molecular-level examples, scientists often ignore the effect of the solvent and talk about increases and decreases in the free energy of the macromolecules only. When possible, we try to explicitly account for solvent energies as well. For example, in discussing the hydrophobic effect, the students develop the idea that water molecules surrounding a hydrophobic molecule have a lower entropy than bulk water due to the reduced number of arrangements.

3. Electric dipoles

The learning goals on electrostatics are essentially the same as for a traditional class, but the primary example is a permanent dipole, i.e., a positive and negative charge held at a fixed distance. The electric field from each charge can be calculated or illustrated, and the total field can be understood as a superposition of point charge fields. Although the students may be able to draw dipole field lines, calculating the field quantitatively is best accomplished computationally. This also allows the students to calculate the magnitude of the field as a function of distance, which yields the $1/r^3$ dependence that is difficult to derive analytically. Superposition can also be used to calculate the force between each charge in 2 water molecules to understand why hydrogen bonding is a net attractive force under certain orientations and distance ranges and how the entropy of such orientations results in the separation of oil and water and the formation of lipid bilayers. A similar computational activity calculating the magnetic field from a ring of charge yields the same dipole field lines observed for electric dipoles. Finally, oscillatory electric and magnetic fields can be computed as a function of time, as the distance between 2 charges is made to oscillate computationally. These oscillating fields are defined as light. The application of a light wave from an external source is also shown computationally to induce oscillation of a separate dipole.

4. Quantum physics

The primary way in which life science students encounter quantum phenomena is via light interactions with biomolecules. Under certain conditions, a molecule can be modeled as a classical harmonic oscillator and absorption of light induces oscillation within the potential well. However, for higher energy interactions, a quantum mechanical model is more appropriate. Students are introduced to fluorescence from atoms by using an online interactive simulation (PhET; https://phet.colorado.edu) that describes energy transitions as discrete and monoenergetic. Then, molecules are introduced by using a framework adapted from *From Photon to Neuron: Light, Imaging, Vision* by Nelson that combines the classical and quantum pictures, which leads to broadening of absorption and fluorescence spectra compared with atoms (9). This leads into a description of



Photosynthesis (abridged)

Photosynthesis is one of the most fundamental processes in biology. There are many chemical details about how light is converted into ATP that we will not cover. Instead we will focus in this problem on the process of capturing light in the stoma (the microscopic openings in the epidermis of leaves) and channeling the energy to reaction center.

At right is a structure of Photosystem II, which is actually the first complex in a chain of reactions. The cylinders and ribbons are the proteins and the small molecules are the various antennas that can absorb light. The most numerous antenna is chlorophyll. Robert Emerson and William Arnold in 1932 measured (in cyanobacteria) that about 2500 chlorophylls are required for the production of one O2 molecule. On the other hand, it is also known that Photosystem II is almost perfectly efficient to convert an absorbed photon into electrons at the reaction center.

1. What is your initial hypothesis for why photosystem II has so many different antenna molecules?
2. At right is the absorption spectra for the various antennas. Looking at the graph, can you explain why leaves appear green? Does it look like the individual spectra add up to the total absorption spectrum (green dotted line)? Why not?
3. Suppose one antenna in the complex absorbs a photon at 420 nm. Which molecule would be the most likely to absorb it? What are the possible options for that excited state? Refer to the fluorescence energy transfer diagram at right.
4. Only one part of Photosystem II is responsible for splitting water into oxygen and hydrogen and delivering 2 electrons to the next part of the chain. This reaction center is known as P680, what do you think that name means?
5. At right is a model of how scientists think photosystem II is arranged to channel energy to the reaction center. Make a summary in words with your group of this model. Why does photosynthesis require so many antennas and how does it achieve high efficiency converting photons to electrons?

Figure taken from Nelson, *From Photon to Neuron*

Fig 1. A sample activity from second semester E&M. The students have learned a semiclassical model of optical absorption and fluorescence for molecules and how energy is quantum mechanically transferred between molecules. Here, they apply that to understanding the arrangement of optical antennae in photosynthesis.

fluorescence resonance energy transfer that is used to explain the arrangement of antennae in photosynthesis (see Fig 1).

5. MCB applications

In addition to the topics outlined previously, each traditional topic incorporates biological content on the molecular and cellular level. Table 4 lists some of these examples and which physical concept it is illustrating. More traditional macroscopic examples are also included in the curriculum for the purposes of expediency in developing tractable homework and test questions. However, it is also important that the students understand that physical principles work on any length scale.

6. Mathematics and computation

The typical IPLS curriculum is algebra, rather than calculus based, which is an anachronism

Table 4. Biological examples used in physics at the molecular and cellular level (P@MCL) to illustrate physical concepts.

Biological example	Physical concept
Motion of kinesin on actin	Newton's third law
Muscular structure and the motion of myosin	Spring forces
Lattice models of protein folding	Entropy and Gibbs free energy
DNA packing in vitro and in vivo	Entropy and entropic springs
Lipid bilayer structure	Dipole–dipole interactions and entropy
Adenosine triphosphate synthase function	Electrostatic potential energy
Electron transport in bacterial pili	Ohm's law
Iridescence in biological structures	Wave interference
Rod cells in the retina	Fluorescence resonance energy transfer and bound states

from when biology students were not required to take calculus. However, at least one semester of calculus is now required for life science students in an increasing number of programs. Therefore, we have incorporated calculus into this curriculum, although mostly conceptually. Students are expected to understand what a derivative and integral are and be able to go between discrete and continuous representations, for example, $\Delta x/\Delta t = \bar{v}$ and $dx/dt = v$. Because many life science students are less comfortable with calculus than a typical engineering student, we do not ask them to perform many integrals, but we have endeavored to make the class as quantitatively rigorous as an engineering curriculum.

Some of the new topics described previously require advanced mathematics that is not known by life science students, such as multivariate calculus and differential equations. However, these analytic treatments often reflect emergent phenomena that have a simple physical and mathematic basis that can be calculated numerically. For example, the diffusion equation requires an understanding of differential equations, and a full treatment uses partial differentials. However, diffusion just results from a collection of collisions between balls. In the numeric simulation, the position and velocity of each ball is calculated by the Euler method

$$x_{i+1} = x_i + v_i \Delta t$$

$$v_{i+1} = v_i + \Delta p_i / m,$$

where x is the position and v is the velocity of a ball at any particular time step i. The change in momentum Δp is given by

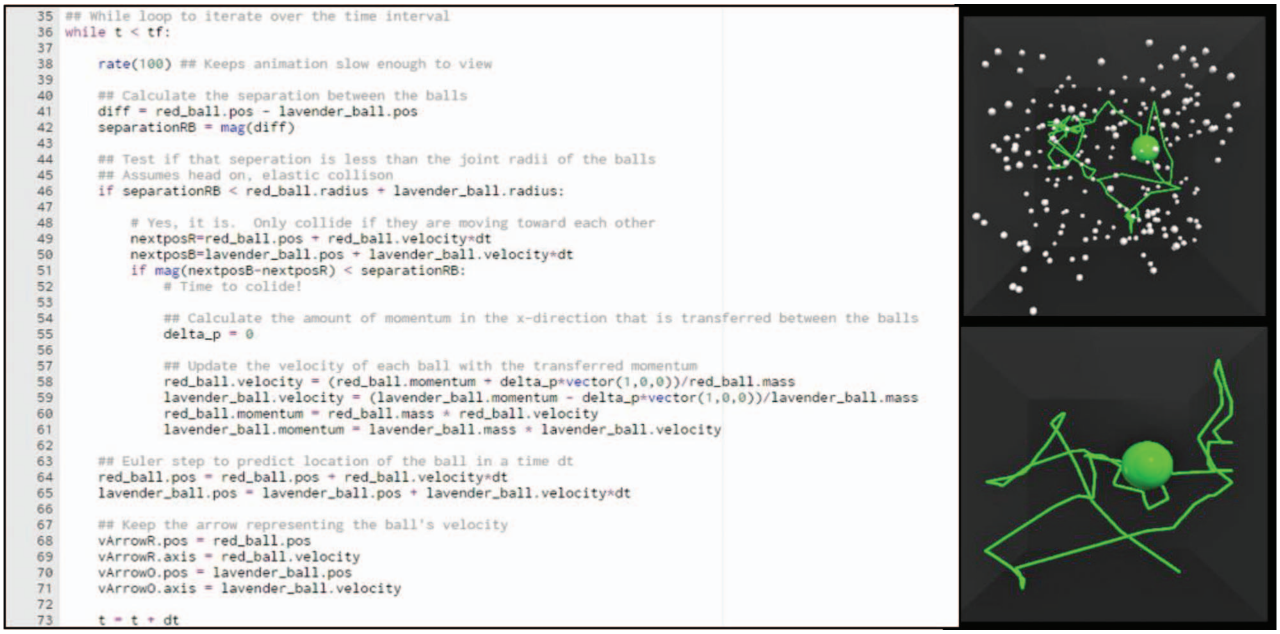
$$\Delta p = F \Delta t,$$

where the force F can be any conservative force, such as Coulomb or Lennard–Jones (these quantities are always treated as vectors). These kinematic and Newtonian equations are the main learning goals for the entire first semester. By using computation, the students can see the physical basis for complex phenomena (14). However, the only way students can really grasp these ideas is to do some coding themselves to see that it works. Another goal of these activities is to show the students that computation also removes the need to do as much analytic math, which they generally dislike.

The coding activities in this curriculum use "minimally operational programs" (see Fig 2) (14–16). These are codes that are almost complete and run without errors but lack 1 to 2 lines of code or have some incorrect physics (e.g., $\Delta p = 0$ during a collision). All coding is done in vPython (https://vpython.org/), a programming language that has simple commands for visual objects, making it easy to visualize simulated physics. No programming experience is assumed for the students. There are a small number of videos and homework problems that cover basic programming concepts, such as lists and loops, which force the students to engage with the codes outside of class.

D. Implementation and pedagogy

The curriculum has been offered at Michigan State University since 2016 in small trial sections and is expected to be offered to all life science majors (∼1,100 per semester) by



```
35 ## While loop to iterate over the time interval
36 while t < tf:
37
38     rate(100) ## Keeps animation slow enough to view
39
40     ## Calculate the separation between the balls
41     diff = red_ball.pos - lavender_ball.pos
42     separationRB = mag(diff)
43
44     ## Test if that seperation is less than the joint radii of the balls
45     ## Assumes head on, elastic collison
46     if separationRB < red_ball.radius + lavender_ball.radius:
47
48         # Yes, it is.  Only collide if they are moving toward each other
49         nextposR=red_ball.pos + red_ball.velocity*dt
50         nextposB=lavender_ball.pos + lavender_ball.velocity*dt
51         if mag(nextposB-nextposR) < separationRB:
52             # Time to colide!
53
54             ## Calculate the amount of momentum in the x-direction that is transferred between the balls
55             delta_p = 0
56
57             ## Update the velocity of each ball with the transferred momentum
58             red_ball.velocity = (red_ball.momentum + delta_p*vector(1,0,0))/red_ball.mass
59             lavender_ball.velocity = (lavender_ball.momentum - delta_p*vector(1,0,0))/lavender_ball.mass
60             red_ball.momentum = red_ball.mass * red_ball.velocity
61             lavender_ball.momentum = lavender_ball.mass * lavender_ball.velocity
62
63     ## Euler step to predict location of the ball in a time dt
64     red_ball.pos = red_ball.pos + red_ball.velocity*dt
65     lavender_ball.pos = lavender_ball.pos + lavender_ball.velocity*dt
66
67     ## Keep the arrow representing the ball's velocity
68     vArrowR.pos = red_ball.pos
69     vArrowR.axis = red_ball.velocity
70     vArrowO.pos = lavender_ball.pos
71     vArrowO.axis = lavender_ball.velocity
72
73     t = t + dt
```

Fig 2. Section of code that simulates an elastic collision in one dimension (left). The students must change line 55 to the correct formula for momentum transfer. Snapshots of a simulation of collisions of many balls in 3 dimensions (right). The simulation is intended to model one protein (green ball) and many water molecules (white balls). The green track shows the random walk of the protein. The bottom panel sets the water to be invisible, as would be observed in a typical microscopy measurement. Students would typically advance from the 1-dimensional code to the 3-dimensional code in 3 to 4 class hours.

2022. Up to 300 students per semester have used the curriculum for a total of ∼1,000 students from all life science majors since implementation. A standardized assessment (either Force and Motion Concept Inventory or Brief Electricity and Magnetism Assessment) of student learning has been given at the beginning and end of every semester. Learning gains have been modest, in part, due to much of the material on these assessments not being covered in this curriculum. Development of a new, more relevant assessment is being planned.

Michigan State has made a commitment to incorporating active learning into introductory physics courses, so this course has been offered in a "flipped" format. There are no lectures, but readings and homework are required before class. During class periods, the students work in groups of 3 to 5 to work through open-ended problems that guide the students to develop and understand the learning goals.

Some sections have also incorporated laboratory activities in a "studio" format in which lab equipment is used when appropriate to further the learning goals. Most of these activities use fairly standard physics kits, such as air tracks to measure collisions and circuit boards to examine the Ohm law. The one piece of uncommon lab equipment used is a microscope to image the motion of polystyrene microspheres to observe diffusion or fluid flow under pressure or in an electric field. Movies of these spheres can be imported into a program, such as Tracker, which produces position, velocity, and acceleration data of a particular bead for every frame. Tracker is also used for macroscale motion in other parts of the curriculum. A microscope of sufficient quality with an attached charge-coupled device camera can be purchased for several hundred dollars.

During the preparation and review of this manuscript, Michigan State, like most universities, switched to online learning in the face of coronavirus pandemic. For the most part, the active learning component was maintained through this transition by using breakout rooms within conference software (Zoom) to have the students work through the activities in groups as before. Attendance and engagement have remained high (>80%) throughout the transition. Thus, it appears that it is possible to deliver active learning content without having students be in the same room.

Nevertheless, this curriculum is agnostic on pedagogy. Although the active learning (or studio) format is appealing and has generally been demonstrated to achieve learning goals better than lectures (17, 18), it is not feasible for many universities because of either the space or staffing requirements. Therefore, I am currently developing lecture notes and audience response (i.e., clicker) questions that mirror active learning activities. These materials will be tested with partners at a variety of colleges and universities.

III. DISCUSSION AND CONCLUSION

IPLS is generally considered a service course, a requirement for students in other disciplines. This curriculum has been designed with the goal of teaching life science students what they need to be successful in their subsequent courses within their major. A recent report on reforming IPLS curricula argued that (a) the physics curriculum must be informed by the needs of life scientists and that (b) given the diversity of life science curricula, ranging from biochemistry to physical therapy, each physics course has to be designed for the specific needs of the particular population of life science students it serves (19). Although I strongly agree with the first point, I disagree with the second. Life science students' career goals are diverse, but their introductory biology training is more uniform, namely molecular and cell biology. This point is supported by Geller et al. (20) in a study that surveyed life science students in a reformed physics course about which topics seemed most relevant and interesting. Two of the top choices were membrane potential and nerve signaling, and more obviously medical topics, such as pacemaker safety and electrocardiography, were rated lower, despite most considering themselves to be prehealth students. The authors found this result very surprising, but I do not, for the simple fact that although these students may intend to go to medical school, they are currently in the middle of studying biochemistry and cell biology. Therefore, I believe common biological themes related to MCB are suitable for a wide range of life science student populations.

As biophysicists, we do research at the intersection of biology, chemistry, and physics, but we typically have to teach within only one of those departments. Most physicists have very little background in biology, and that background may be quite dated. Therefore, many recent advances in MCB may be unknown to the average physics instructor, and there may be significant resistance to introducing this curriculum as one of the service courses offered by a physics department in a large university. The physical concepts in this curriculum are well understood by all physicists and may even be valued as more relevant to students, but the average instructor may feel ill-equipped to teach it. In my experience, the largest barrier to physicists acquiring biological knowledge is the overwhelming amount of specialized terms found in an introductory textbook. Because the physics instructor only needs a limited amount of biological knowledge to teach the examples shown in Table 4, it is straightforward to offer short "explainers" on these topics.

This curriculum has evolved through discussions with many biophysicists, and this community has much more to contribute, such as development of new MCB applications to IPLS and explaining such applications to physicists from a physical perspective. Biophysicists are also essential for encouraging physics departments to take the large step of reforming their IPLS curricula to make it more relevant to life science students by focusing on the molecular and cellular level. This curriculum is offered as one option in such an effort.

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