Introductory physics for the life sciences: Vision and change in introductory physics

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Outline

• VCUBE
• Vision and change in introductory physics for the life sciences (IPLS)
• Audience and context
• Mathematics
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• Examples
• Challenges
"Physics for (molecular) biologists”, Michael Klymkowsky (a molecular biologist) from U Colorado in the APS Forum on Education F14 Newsletter

“…what seems to have been, rather surprisingly, neglected are the intra- and inter-disciplinary discussions needed to define what a coherent curricula look like. What can, realistically, be conveyed to students in the time (credit hours) available?”

“…. this essay (is) a call … to define the physics content that is needed by, or better put, would justify a molecular biology department requiring its students to take an introductory physics course or two.”

More often than not physics faculty are called on to imagine what makes physics relevant to biology students, without a clear appreciation of core biological concepts. Attempts to make physics “relevant” can lead to the inclusion of cartoonish biological examples (blood flow in giraffes or spherical cows).

“I would reject the premise that physics per se is generically useful to understanding molecular biology. A poorly designed course, perceived as irrelevant to the disciplinary interests or needs of students could be viewed as an inappropriate imposition.”
Vision and Change

Some in the physics education community have identified a difference in culture between physics and biology, namely that the biological sciences eschew mathematical approaches in contrast to the physical sciences, and have tailored their versions of IPLS correspondingly.

However, Vision and Change in Undergraduate Biology Education (VCUBE) advocates an approach that emphasizes mathematical and quantitative analyses.

Table 2.1: Core Competencies and Core of Ability in Practice

<table>
<thead>
<tr>
<th>Ability to apply the process of science</th>
<th>Ability to use quantitative reasoning</th>
<th>Ability to use modeling and simulation</th>
<th>Ability to tap into the interdisciplinary nature of science</th>
<th>Ability to communicate and collaborate with other disciplines</th>
<th>Ability to understand the relationship between science and society</th>
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</thead>
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<tr>
<td>Biology is an evidence-based discipline</td>
<td>Biology relies on applications of quantitative analysis and mathematical reasoning</td>
<td>Biology focuses on the study of complex systems</td>
<td>Biology is an interdisciplinary science</td>
<td>Biology is a collaborative scientific discipline</td>
<td>Biology is conducted in a societal context</td>
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Examples of Core Competencies Applied to Biology Practice

- Observational strategies: Hypothesis testing, Experimental design
- Developing strategies: Evaluation of experimental evidence, Developing problem-solving strategies
- Mathematical modeling: Applying statistical methods to diverse data, Mathematical modeling
- Computational modeling: Developing and interpreting graphs, Applying informatics tools
- Applying physical laws to biological dynamics, Applying imaging technologies
- Chemistry of molecules and biological systems, Scientific writing
- Team participation, Cross-cultural awareness
- Evaluating the relevance of social contexts to biological problems
- Developing biological applications to solve societal problems
- Evaluating ethical implications of biological research

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Vision and Change

VCUBE specifies many of the competencies that physicists seek for students to acquire in physics classes.

Where better than IPLS to first develop problem-solving strategies?

Where better than IPLS to first develop the ability to use quantitative reasoning?

Where better than IPLS to start developing the ability to use modeling and simulation?

Where better than IPLS to start developing the ability to apply physical laws to biological dynamics?

Where better than IPLS to start developing the ability to incorporate stochasticity into biological models?

VCUBE can be read as a call to transform IPLS into an engaging and exciting subject that is appreciated as essential to every biologist's undergraduate education.
Vision and Change

*IPLS/1 University physics for the life sciences* is a imagined IPLS sequence offered at Yale since 2010

My overall goals for *IPLS* are as follows:

- Introduce biological science majors and future clinicians to physical and mathematical principles and tools, that will enable a deeper scientific understanding of biological systems, including the human body, and how they may be studied and diagnosed.

- Demonstrate the application of physics and mathematics to the life sciences and medicine, via a host of authentic examples.

- Transform IPLS into an engaging and exciting subject, that is understood to be essential to every biologist’s undergraduate education by biology students and biology faculty alike.

- Seed an enduring appreciation by biologists and clinicians of the power of physical and mathematical approaches in biology and medicine, and in science more broadly.
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Audience and context

- About 590 students in total from Fall 2010 thru Fall 2014. Initially ~90/yr. Now ~130/yr.
- 66% female. Mainly sophomores and juniors. Some seniors. 2 or 3 freshers.
- Ethnically diverse: 39% self identify as white, 61% do not, including significant numbers from groups underrepresented in STEM (10% African American, 10% Hispanic).
when it enters the freight car. Your goal in this problem is to find the speed of the freight car plus its grain when a total mass arrives at the same time, grain begins to flow from a grain hopper into the freight car at a rate of .

**Problem 3: On the railroad**

3.7. **PROBLEMS**

- **What is the mass of the freight car plus the grain carried by the freight car at time** $t=0$? 
  \[ m = m_b + m_{grain} \]

- **Determine the momentum of the freight car plus the grain at time** $t=0$.
  \[ p = \frac{m}{t} \]

- **What is the net horizontal force on the system consisting of the freight car plus all the grain?**

\[ F_{net} = \frac{dp}{dt} \]

\[ \alpha \]

\[ dp = dt \]

\[ \frac{m}{t} \]

\[ \frac{m}{t} \]

\[ \frac{m}{t} \]

Figure 3.7: Audience and context

- **IPLS is 3 hrs of lectures/wk. Two 1 hr sections/wk. One evening study hall/wk. One weekly in-class quiz. Two midterms. Final exam. Weekly problem sets. Many in class clicker questions for participation. A few in-class activities. Pre-announced grade lines. Piazza.**

- **There's a separate lab. class with some overlap. (More overlap is being worked on.)**

- **IPLS/1 is one of 4 introductory physics sequences offered at Yale. The other courses consist of a traditional course at a similar math level (PHYS 180/1), and two higher math-level courses aimed at physics majors-to-be (PHYS 200/1 and PHYS 260/1).**

![Superman deflects bullets](http://1.bp.blogspot.com/-QjrFgBfd0qo/T1uScz2tj0I/AAAAAAAABO0/zfWj8trtsCs/s1600/superman1986.jpg)

- **Ethnicities of students, specified as a fraction of the total number of respondents:**

  - African American or African
  - East Asian
  - Hispanic
  - Middle Eastern or North African
  - Multi-racial
  - Native American
  - South Asian
  - White

![What is your ethnicity?](http://1.bp.blogspot.com/-QjrFgBfd0qo/T1uScz2tj0I/AAAAAAAABO0/zfWj8trtsCs/s1600/superman1986.jpg)

**Introductory physics for the life sciences:**

**Vision and change in introductory physics**

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There’s an oxygen concentration \( n_1 \) far from a cell. Do you expect the steady-state diffusion current (number of molecules per unit time) of oxygen into the cell to be proportional to:

(A) The volume \( (V = 4\pi R^3/3) \) of the cell?
(B) Independent of cell size?
(C) The radius \( (R) \) of the cell?
(D) The area \( (A = 4\pi R^2) \) of the cell?
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Example in-class activity, this one in Becton Plaza, seeking to aid student understanding of random walks*

* developed by Claudia de Grandi et al.
Audience and context

• 64% are biological science majors. 81% are pre-medical students.
• They possess considerable biological and chemical sophistication as a result of prior science courses.
• Most are involved in biomedical research and/or medical volunteer work.
• Ambitious and high achieving
• Very concerned about grades
Mathematics

“I have deeply regretted that I did not proceed far enough at least to understand something of the great leading principles of mathematics, for men thus endowed seem to have an extra sense.” Charles Darwin.

- A key issue is the level of mathematics of the class, because it profoundly affects what topics can be discussed and what students will be able to learn.

- Calculus is a prerequisite. (99% of IPLS/1 students have previously taken a first course in calculus.)

- IPLS/1 seeks to develop students’ mathematical skills. (Yields major improvements in math skills over the year, anecdotally.)

- Students encounter basic probability, simple differential equations, simple linear algebra, and complex numbers, each introduced and exploited as necessary, because these topics earn their place in the curriculum.

- Multi-dimensional integrals are largely avoided, because students find them challenging and the pay-off seems not worth it.
Mathematics

We use Wolfram Alpha (http://www.wolframalpha.com) to facilitate mathematical manipulations, including the solution of algebraic equations, the evaluation of derivatives and integrals, and the solution of simple differential equations.

WA empowers students to carry out more sophisticated mathematics than otherwise.

I’d like to give students the capability to use WA on exams.
Mathematics

We use Wolfram Demonstrations to carry out simulations and solve differential equations numerically.

To be clear, students don’t see any code, but they can conveniently run the simulations/calculations in their web browsers and interact with the simulations/calculations via sliders.

Incorporating computation is reflective of an important mode of current scientific research, including biomedical research. Computational approaches will become even more important in the future.
Mathematics

At the end of the first semester, I carry out an anonymous survey to ascertain students’ opinions.

Conclusion: the level of mathematics and calculus is appropriate for the IPLS audience.
“Have nothing in your house that you do not know to be useful, or believe to be beautiful.”
William Morris (nineteenth century designer and philosopher) on interior design.

“Have nothing in your course that you do not know to be useful, or believe to be beautiful.”
William Morris on IPLS curriculum design.
Important design considerations included:

- Student preparation – they know a lot of chemistry and biology already.
- IPLS/1 will be the final physics course its students will ever take.
- There is no reason to prepare students for more advanced physics classes, or the physics major and no excuse to delay important/interesting/beautiful topics until later. There is no later.
- The content of recent, excellent advanced textbooks, Bio2010, SFFP, VCUBE, MCAT 2015 guidelines, etc.
- Consultations with colleagues in biological science departments at Yale and the YSM.
- It is a physics course. “To thine own self be true.” Polonius in Hamlet.
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Curriculum

Represented as a concept map.

Arrows indicate dependencies.

The IPLS learning goals and curriculum have been continuously refined from those of 2010 to reflect the course that I currently think I should teach.

Many modules are similar to traditional intro. Physics: 1, 2, 3, ....

Many modules correspond to IPLS re-imagined: 5, 6, 7, 8, 9, 10 ....

Some are in the middle: 4 ...
Reception

Buy-in from many IPLS students:

“I just want to thank you for making physics a lot of fun for me. It means a lot. I am from a traditional Indian education system, that emphasized on learning a science in order to get into a college, and not for the pure pleasure of it all. As a result, I developed a huge aversion to physics and really delayed the taking of this class. However, my views have changed a lot. I am fascinated by this subject and the amount of scope it has. Thank you for making that possible.”

“Thank you for an awesome semester! I can't believe I'd ever say this but I actually like physics now. Thank you for showing me how cool it can be.”

“I was skeptical about 170 at first and I mainly chose it over 180 because I didn't have the multivariable calculus background needed to take 181. You have really turned me around. The first third of this class was pretty standard physics (mechanics, momentum), but the latter part of the semester really tied in to biological phenomena. Obviously, the models were over-simplifications of biological systems but they added another layer of understanding to concepts that I previously took as a given. The idea of diffusion as explained using probability is not something I would have ever thought of on my own. I doubt I would find that in a biology or biochemistry textbook either. I took biochemistry (MBB300) at the same time as 170 this semester and I was pleasantly surprised to see the Michaelis-Menten equation derived via different methods in both classes. It is wonderful to see the same ideas presented on a biological, chemical, and physical level.”

“I took IPLS because I had no physics background coming in and because I generally find natural sciences courses tailored to premeds much more interesting. I am very satisfied with my choice as some of the things we learned were mind blowing and extremely interesting.”
Reception

Buy-in from many IPLS students:

“Thank you for class this semester. It has been really great to make links between all of my science courses at Yale, and in many ways (and I am shy to admit this, but against my expectations) IPLS provided the platform for just that.”

“This class is amazing if you genuinely like biology. If you're a biology major because you're premed or whatever you might not like it as much, but if you really care about biology this class is great. Physics is the future of biology, and this class gives you a taste of all the cool ways we can use quantitative techniques to describe living systems.”

“The biological aspects of this class really opened my eyes and changed my perspective of the world! You'll def learn some really fascinating and awesome stuff if you genuinely like biology or chemistry, and it was incredibly cool to approach chemical/biological processes from the different perspective of this class.”

“The applications to biology at first seem stretched, but then you realize that they are REAL, ESTABLISHED concepts in biology (statistical mechanics, Brownian walks, Michaelis-Menten enzyme kinetics) that will keep appearing in your other coursework - so really, you'll leave the course thankful that you had the exposure you did to these concepts, even if the math was a bit simplified.”

“I LOVE the topics presented in 170. It really ties in to what I've learned in my other science classes (biology, biochemistry, and to a lesser extent chemistry), and it's wonderful to gain a new perspective/insight into mechanisms that I've just taken for granted, like diffusion, actin filament polymerization, enzyme kinetics, etc. It's just a really cool class, and has made me realize how much I love science - to the extent that it has, in part, motivated me to double major in another science field.”
Reception

But not all students buy-in:

“I wish that I had taken traditional physics because I actually like the subject of classical physics and I feel like IPLS is a lot of strange applications, whereas I would rather learn the fundamentals.”

“I believe IPLS would benefit significantly from removing half of the topics that we currently spend time on. The Newtonian mechanics and forces section are all completely relevant to introductory physics as well as acceleration and conservation of momentum and energy. I would also strongly suggest adding a lesson on centripetal acceleration and centripetal motion and ending with radiation. The topics that cover Gaussian probability distributions, probability, ligand vectors, fluid mechanics, and other concepts focusing on statistics and probability should be removed. The rates and membrane permeability information should also be removed.”

“I don't think I have gained a strong understanding of general physics concepts that I should know, especially since I plan on taking the MCAT in the future. I do not feel prepared at all.”

“I cannot stand the probability unit. I understand why and how it is applicable to physics and biology and pre-med, but this is not a statistics course. I did not intend or want to learn these topics, but rather wished to learn what would be tested on the MCAT - classical physics.”

“I would have preferred to maybe learn more fundamental physics problems, such as those concerning a ball rolling down a hill. Though objectively more boring, I feel that those types of problems would give me a more solid physics foundation.”
Reception 100% of students like grading transparency

“I really appreciated the efforts that you made to improve the transparency of grading, and I wish my other classes followed the same policy. This definitely helped alleviate some of my stress over the course.”

“Physics 170 grading (I think) is designed to help students. Having an absolute cutoff for a grade rather than a relative one means the students aren't competing against each other but rather should cooperate so everyone does better.”

“I like that I can see my grades, as my other classes do not give me access. I believe the grading is fair, as this is a challenging course.”

“It's absolutely wonderful. It's the only class where I'm a lot more relaxed about my grade, not because it's easier, but because I know exactly how I'm doing and where I need to improve in order to get a good grade. I wish all of my classes were this transparent about grades.”

“THANK YOU for being transparent about grades. This is absolutely something that you should continue to do in the future. It has relieved a lot of my stress, and prevented me from worrying as much about how I stand relative to my classmates (because grades aren't assigned by percentiles). I think that grading for the class overall is reasonable. It might help relieve some stress if we could drop 3 quizzes instead of 2.”

“Thank you thank you thank you thank you infinitely for this policy. It is not only empowering but it is incredibly gracious. In most classes, I'm super frustrated BECAUSE I don't know where I stand and no mater how hard I work, I get surprised by my grade. I appreciate this so much!!!”

“OMG THIS IS THE BEST POLICY. I LOVE THIS POLICY. I WOULD MARRY THIS POLICY. I WISH ALL CLASSES HAD THIS POLICY.”
Reception

Even more anonymous feedback from IPLS students:

- Has physics been a harder course, about the same, or easier than you imagined it would be?
- How would you assess the pace of physics?
- Physics improved your problem solving skills?
- What is your feeling regarding the amount of time you spend on physics?
- How many hours do you spend on physics outside of class?
Course goals* are well-aligned with measured outcomes

*Students should believe that physics is relevant to biology and medicine.
10. Statistical mechanics: Boltzmann factors, PCR, and Brownian ratchets

The Boltzmann factor, DNA melting, and Brownian ratchets: Topics in an introductory physics sequence for biology and premedical students
S. G. J. Mochrie

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View online: http://dx.doi.org/10.1119/1.3638908
10. Statistical mechanics: Boltzmann factors, PCR, and Brownian ratchets

Problem 6: Unzipping ratchet revisited (18 points)

Problem 6: Unzipping ratchet revisited (18 points)

In this problem, we will develop an alternative model for how helicase unzips DNA. As we discussed in Module 10, helicase is a motor protein that steps unimpeded, via a biased random walk, on ssDNA towards the ssDNA-dsDNA junction, until it encounters the junction, which then prevents its further progress. However, at the junction, according to the Boltzmann factor, there is a non-zero probability that the junction is unzipped one or more base pairs beyond the helicase. There is then a non-zero probability for the helicase to step into the just-unzipped region. If the helicase does this, it prevents the DNA from zipping back up again. In this way, the junction is moved one step in the unzipping direction. Repeating this process many times leads to the complete unzipping of the DNA.

The free energy of a single unzipped base pair is $\Delta G$. The free energy of a single zipped (paired) base pair is 0. The free energy of $m$ unzipped base pairs is $m \Delta G$.

(a) Throughout this problem, consider only the DNA in front of the helicase. In terms of the partition function $Z$, what is the probability $P_m$ that zero base pairs in front of the helicase are unzipped? (1 point)

(b) In terms of $\Delta G$ and $k_B T$ and the partition function $Z$, what is the probability $P_m$ that $m$ base pairs in front of the helicase are unzipped? $m = 0, 1, 2, \ldots$ (2 points)

(c) What is the partition function of the DNA in front of the helicase, in terms of $\Delta G$ and $k_B T$ only? Assume that the number of possible unzipped base pairs, $m$, ranges from $m = 0$ to $m = \infty$. (4 points)

To answer this part, you may find it useful to know that

$$\sum_{m=0}^{\infty} e^{-\alpha G(k_B T)} = \frac{1}{1 - e^{-\Delta G(k_B T)}}$$

or that

$$\sum_{m=0}^{\infty} e^{-n \Delta G(k_B T)} = \frac{e^{-n \Delta G(k_B T)}}{1 - e^{-\Delta G(k_B T)}}$$

or that

$$\sum_{m=1}^{\infty} e^{-\alpha G(k_B T)} = \frac{e^{-\Delta G(k_B T)}}{1 - e^{-\Delta G(k_B T)}}$$

where $\sum_{m=0}^{\infty} e^{-\alpha G(k_B T)}$ indicates the sum over all values of $m$ from 0 to $\infty$.

(d) What is the probability $Q_m$ that one or more base pairs are unzipped in terms of $\Delta G$ and $k_B T$ only? (3 points)

(e) As in the module, the probability that a helicase attempts a forward step in a time $\Delta t$ is $k_f \Delta t$. The helicase succeeds in taking a step forward, only if one or more base pairs in front of it are unzipped. What is the probability that the helicase succeeds in taking a step forward in a time $\Delta t$? (4 points)

(f) If the step size is $b$ and the probability that a helicase takes a backward step in a time $\Delta t$ is $k_r \Delta t$, what is the mean displacement of the helicase in $\Delta t$? Call this mean displacement $\langle w \rangle$. (2 points)

(g) What is the corresponding mean velocity of the helicase as it unzips dsDNA in terms of $b$, $\Delta G$, $k_f T$, $k_r$, and $k_f$? Call this mean velocity $v$. (2 points)

Answer:

$$\langle w \rangle = \frac{b k_f}{1 + \frac{k_f}{k_r} e^{\Delta G(k_B T) / k_r} - \frac{k_f}{k_r}}$$

which is the desired result. In comparison, the result in the module for the mean velocity of the helicase is

$$v = \frac{b k_r}{1 + \frac{k_r}{k_f} e^{\Delta G(k_B T) / k_f} - \frac{k_r}{k_f}}$$

Thus, we see that the two results agree for $m \gg k_r$, which is realistic.

#### the Second Law in action
Biologic: Gene circuits and feedback in an introductory physics sequence for biology and premedical students

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We describe an educational module on feedback and gene circuits that constitute the final topic in a new year-long introductory physics sequence aimed at biology and premedical students at Yale University. The overall goals of this sequence are threefold. First to demonstrate the application of physics and mathematics in the life sciences. Second to introduce biological science majors to mathematical and physical tools, principles, and experiences. Third to seed an enduring appreciation of quantitative approaches in biology and medicine. Here, we present a module on feedback and gene circuits that focuses on a genetic toggle switch and a repressilator. The genetic toggle switch consists of two genes, each of whose protein products repress the other’s expression, while the repressilator consists of three genes, each of whose protein products represses the next gene’s expression. Analytic, numerical, and electronic treatments of the genetic toggle switch show bistability. A similar treatment of the repressilator reveals sustained oscillations.

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I. BACKGROUND AND INTRODUCTION

Two recent reports, the NRC’s “BIO2010: Transforming Undergraduate Education for Future Research Biologists,” and the AAMC/HHMI’s “Scientific Foundations for Future Physicians,” have highlighted the increasing importance of quantitative skills for students who are planning biomedical careers. Since the 2010–2011 academic year, our physics department has offered a new introductory physics sequence aimed at biology and premedical students that seeks to implement a number of the recommendations from these...
9. Rates of change: Infections, epidemics and weapons of mass destruction

“HIV is certainly character-building. It’s made me see all of the shallow things we cling to, like ego and vanity. Of course, I’d rather have a few more T-cells and a little less character.” Randy Shilts

“I know not with what weapons World War III will be fought, but World War IV will be fought with sticks and stones.” Albert Einstein.
9. Rates of change: Infections, epidemics and weapons of mass destruction

Student learning goals:

Appreciate that it is possible to represent physical quantities, relationships and processes mathematically via "chemical rate equations".

Recognize linear and non-linear equations.

Solve differential equations by direct substitution of a given trial solution to find a general solution, and by then imposing initial conditions to find the particular solution of interest.

Recognize that exponential growth or decay often follows when the rate equations are linear equations, or may be approximated as linear equations.

Understand that different physical processes (including biological and medically-relevant processes) can be described by similar equations and that similar equations have similar solutions.

Be able to explain and build simple mathematical models of physical processes, such as the initial progression of an infection, such as HIV, within an individual's body, the progression of a contagious disease, such as measles or the flu, through a susceptible population, and even the detonation of an atomic bomb.
Recognize that at long times, rate equations may realize a steady-state, in which the quantities of interest are constant in time.
9. Rates of change: Infections, epidemics and weapons of mass destruction

The equation of motion of a bead falling through a viscous fluid from Module 2:

\[
\frac{dv}{dt} = \left( \frac{m - m_B}{M} \right) g - \frac{\zeta}{M} v.
\]

For a drug in the bloodstream, intravenous infusion increases the number or concentration \( n \) at a rate \( \alpha \), while there’s a degradation probability per unit time \( \beta \), leading to

\[
\frac{dN}{dt} = \alpha - \beta N.
\]

The same equations have the same solutions, so exponential relaxation to the terminal velocity, that we know about from Module 2, corresponds to exponential relaxation to the final drug concentration.
9. Rates of change: Infections, epidemics and weapons of mass destruction

Not only drug molecules, but also HIV particles (V), uninfected T cells (U), and infected T cells (I) can be represented in this way. We argue from the cartoon that

\[
\frac{dU}{dt} = \alpha - \beta U - \gamma UV.
\]

\[
\frac{dI}{dt} = \gamma UV - \kappa I.
\]

\[
\frac{dV}{dt} = m\kappa I - \lambda V - \gamma VU.
\]

These (complicated) equations can be solved numerically using a Mathematica Demonstration. We notice an exponential growth of V and I and U constant at early times
9. Rates of change: Infections, epidemics and weapons of mass destruction

Not only drug molecules, but also HIV particles (V), uninfected T cells (U), and infected T cells (I) can be represented in this way. We argue from the cartoon that

\[
\frac{dU}{dt} = \alpha - \beta U - \gamma UV. \\
\frac{dI}{dt} = \gamma UV - \kappa I. \\
\frac{dV}{dt} = m\kappa I - \lambda V - \gamma VU.
\]

Remarkably, the model recapitulates experimental measurements of (a proxy for) the Simian Immunodeficiency Virus (SIV) load in deliberately infected macaques.
9. Rates of change: Infections, epidemics and weapons of mass destruction

“How can this possibly be physics?”
9. Rates of change: Infections, epidemics and weapons of mass destruction

The cartoons for HIV infection of T cells and for neutron-initiated fission of U\(^{235}\) are similar. The fission equations are a little simpler.

\[
\begin{align*}
\frac{dQ}{dt} &= -\gamma Qn, \\
\frac{dU}{dt} &= \gamma Qn - \kappa U, \\
\frac{dn}{dt} &= m\kappa U - \gamma nQ,
\end{align*}
\]

At early times, \(Q=U^{235}\) is constant, and \(U=U^{236}\) and \(n=\)neutrons grow exponentially, just like \(I\) and \(V\) in the HIV case.

What could be more “Physics” than an atomic bomb? But could anything be more relevant for future clinicians than HIV?

“In some sort of crude sense which no vulgarity, no humor, no overstatement can quite extinguish, the physicists have known sin; and this is a knowledge which they cannot lose.” J. Robert Oppenheimer
9. Rates of change: Infections, epidemics and weapons of mass destruction

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\[
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\]

\[
\frac{dn}{dt} = m\kappa U - \gamma nQ,
\]

At early times, \(Q=U^{235}\) is constant, and \(U=U^{236}\) and \(n=\)neutrons grow exponentially, just like HIV.

This corresponds to an atomic explosion, such as at Bikini atoll.

What really is Physics is the analogy that permits us to understand atomic explosions if we already understand HIV infection.
To investigate the early-time, exponential behavior relevant for atomic bombs, we may exploit the fact that the rate equations are approximately linear at early times.

Analogously to HIV infection, in the nuclear-chain-reaction case, at early times, we may expect an exponential growth in the number of neutrons and U\(^{235}\) nuclei. The parameter \(Q\), which contains the nuclear physics of neutron capture by a U\(^{235}\) nucleus, is effectively constant at early times, and we investigate the behavior assuming that \(Q\) is constant. Then, the above equations become:

\[
\frac{dU}{dt} = \gamma Q n - \kappa U,
\]

\[
\frac{dn}{dt} = m \kappa U - \gamma n Q,
\]

Since each fission event is accompanied by an energy release of about 180 MeV, which is equivalent to 70 TeraJoules/kg, we can see that the energy is released upon fission because the binding energy of the fission fragments is no longer involved in nuclear binding, that is transformed into kinetic energy and causes the ensuing atomic explosion.

Remarkably, another very significant application of equations similar to EQ. 8.5 through EQ. 8.7 is to an atomic bomb. You will explore the behavior of the atomic bomb and its implications in an in-class activity.
9. Rates of change: Infections, epidemics and weapons of mass destruction

Solution via direct substitution:

\[ n = n(t) = n_0 e^{\Lambda t} \quad \text{and} \quad U = U(t) = U_0 e^{\Lambda t} \]

To find:

\[ (\Lambda + \kappa)U = \gamma Qn \]

\[ (\Lambda + \gamma Q)n = m\kappa U, \]

and thence the eigenvalues, \( \Lambda \), and eigenvectors (1,n/U).
9. Rates of change: Infections, epidemics and weapons of mass destruction

Picking $m=3$ and $\gamma Q=2\kappa$ to simplify algebra, the eigenmodes are:

\[ (U, n) = A(1, 1)e^{\kappa t}, \]

\[ (U, n) = B(1, -\frac{3}{2})e^{-4\kappa t}, \]

Revealing one eigenmode that grows exponentially. Whew!

Introduce the concept of superposition

Apply superposition to satisfy initial conditions

Only ever two-dimensional examples.
9. Rates of change: Infections, epidemics and weapons of mass destruction

Other examples/applications

- SIR model of disease epidemics and exponential growth of flu infection UNLESS there are enough vaccinations.
- Zombie apocalypse.
- Two compartment (GI tract and circulatory system) model of drug concentration accurately recapitulates experimental measurements of serum blood concentration.
9. Rates of change: Infections, epidemics and weapons of mass destruction

The material of module 9 enables/facilitates:

- Coupled harmonic oscillators, eigenfrequencies, and eigenmodes*
- Standing waves
- Superposition of electric and magnetic fields
- Quantum mechanics, orbitals, and quantized energy levels
- Biologic, via the stability of steady-state solutions

*”Now let us summarize the ideas discussed above, which are all aspects of what is probably the most general and wonderful principle of mathematical physics. ... no matter how it does move, this motion can be represented as a superposition of pure sinusoidal motions.... Another way of saying this is that any linear vibrating system is equivalent to a set of independent harmonic oscillators, with the natural frequencies corresponding to the modes”. Richard P. Feynman in The Feynman Lectures on Physics.
Challenges going forward

- Sustainability. How can a re-imagined IPLS be sustained, when other physics faculty are reluctant to buy-in or take on the material?

- Everyone is an expert on ILPS content: “You can’t do intro. physics without covering rotational motion”; “You shouldn’t use Wolfram Alpha”; “Eigenvalues are too difficult”; “You can’t do Maxwell’s equations”; “You have to do Maxwell’s equations”; etc.

- Student preconceptions and prejudices concerning what is and what is not physics.

- Difficulties achieving student buy-in, including student social and other obstacles to active and collaborative learning approaches.
Challenges going forward

- Universities’ organizational structure into disciplinary departments discourages meaningful cross-departmental teaching collaboration.

- Physics and biology faculty have very different teaching loads, creating additional difficulties for collaboration on an equal footing.

- Additional teaching personnel demands of active learning approaches, especially when a reduction is overall graduate student teaching is being sought, while at the same time the number of undergraduates is set to increase.
The End.

Thank you!

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