Physical Sciences 2 and 3: Physics for the Life Sciences

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What **physics** will be useful for the next generation of life scientists?

**Physics**

**RECOMMENDATION #1.3**

The principles of physics are central to the understanding of biological processes, and are increasingly important in sophisticated measurements in biology. The committee recommends that life science majors master the key physics concepts listed below. Experience with these principles provides a simple context in which to learn the relationship between observations and mathematical description and modeling.
## Physical Concepts for Life Scientists

### Motion, Dynamics, and Force Laws
- Measurement: physical quantities, units, time/length/mass, precision
- Equations of motion: position, velocity, acceleration, motion under gravity
- Newton's laws: force, mass, acceleration, springs and related material: stiffness, damping, exponential decay, harmonic motion
- Gravitational and spring potential energy, kinetic energy, power, heat from dissipation, work

### Thermal Processes at the Molecular Level
- Thermal motions: Brownian motion, thermal force (collisions), temperature, equilibrium
- Boltzmann's law, kT, examples
- Ideal gas statistical concepts using Boltzmann's law, pressure
- Diffusion limited dynamics, population dynamics

### Waves, Light, Optics, and Imaging
- Oscillators and waves
- Geometrical optics: rays, lenses, mirrors
- Optical instruments: microscopes and microscopy
- Physical optics: interference and diffraction
- X-ray scattering and structure determination
- Particle in a box; energy levels; spectroscopy from a quantum viewpoint
- Other microscopies: electron, scanning tunneling, atomic force

### Conservation Laws and Global Constraints
- Conservation of energy and momentum
  - Conservation of charge
    - First and Second Laws of thermodynamics

### Collective Behaviors and Systems far from Equilibrium
- Liquids, laminar flow, viscosity, turbulence
- Phase transitions, pattern formation, and symmetry breaking
- Dynamical networks: electrical, neural, chemical, genetic

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**Phys Sci 2**  
**Phys Sci 3**
Physical Sciences 2: Mechanics, Elasticity, Fluids, Diffusion

Goals:
- Show that physics is relevant to the life sciences
- Teach basic principles of physics (mechanics)
- Teach more topics in physics related to biology
- Show that learning physics can be enjoyable
Physics of the Cell

- Generate forces
- Change shape
- Swim and crawl

- Lots of physics here
- Cells aren’t just sacks of biochemicals
Physics of Materials

- How do material properties influence biological form and function?

- Elasticity
- Torsion
- Shear
- Viscosity
- Surface tension
Physical Sciences Laboratory

- Biologically-relevant physics

Periodic Motion: EKG Recording

Video Microscopy and Image Analysis: Measuring Brownian Motion

Forces and Motion: Jumping
Goal: Teach basic principles of physics

- Compare pre-test and post-test scores on Force Concept Inventory


No “gender gap” in student performance
Goal: Teach physics related to biology

- Spend **five weeks** on fluids and statistical physics

Flagellar motor in *E. coli*

Superhelical turns in DNA

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**Graph 1:**

**X-axis:** protonmotive force, mV  
**Y-axis:** speed, revolutions/s

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**Graph 2:**

**X-axis:** $\tau$  
**Y-axis:** Rel. Concentration $C/C_0$
Goal: Teach physics related to biology

- Interpret recent research:
  2008 final exam: Determine effective spring constant of cytoskeleton from the thermal motion of a nanoparticle

- Apply physics to biological problems:
  Find force on 5th lumbar vertebra

Discher, *Current Opinion in Hematology* 2000 7:117
Goal: Learning physics can be enjoyable

- Student evaluations have improved since the introduction of Physical Sciences 2
Goal: Show that physics is relevant

“What did you learn? How did this course change you?”

- Made me appreciate the integration of biology, medicine, and physics, and how physics operates in our everyday lives!
- Physics is not an intimidating cascade of equations, but rather a way of looking at and understanding the physical world.
- I apply physics to everything in the world. Every time I pour something or drop something, I'm thinking about physics.
- I saw why physics could be a medical school requirement.
- I actually approach the world differently now. For example, I hung something on a rack the other day and it started swinging, so I thought of torque and transfer of energy like a pendulum, etc. Then, when I came back a few minutes later, it was still swinging so I thought to myself: well, there must not be a lot of friction acting between those two surfaces. It was kind of cool actually.
Goals:

- Continuation of Physical Sciences 2
- Teach principles of E&M, waves, and optics
- Include relevant biological examples: microscopy, medical imaging (CT, MRI, etc.)
Electrical Potential in Cells

Resting potential

\[
\frac{c_2}{c_1} = e^{-\frac{q(V_2 - V_1)}{kT}}
\]
Digital logic: NAND gate

NAND (NOT AND)

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Networks of neurons for processing information
Two-photon Confocal Microscopy:

“Putting it all together” in PS3

• Light
• Ray optics (lenses)
• Wave optics (diffraction limit)
• Two-photon fluorescence

Photomultiplier tube measures light intensity not an image

Pinhole at image plane

Lens

Optical filter

488 nm

Ar ion LASER

Dichroic beam splitter

Collimated beam focuses at specimen

Objective lens

Microscope slide
How to incorporate broader learning goals into the curriculum?
Surveyed the physics faculty:

“Everyone who leaves Harvard with an undergraduate degree in physics should be able to . . .”

Received over 100 suggestions; grouped into six broad categories
Broad Goals for Physics Concentrators

- **Physical reasoning** (order of magnitude, dimensional analysis, scaling laws)
- **Quantitative analytical techniques** (computation, data analysis, statistics)
- **Scientific methodology** (modeling, connecting theory and experiment)
- **Communication** (writing and presentation skills)
- **Independent learning** (ultimately, ability to learn from the primary research literature)
- **Broader impact of physics** (applications, ethical considerations, current frontiers)
We expect our students, both majors and non-majors, to develop a number of **skills** while taking physics courses. Some of these are general skills: the ability to communicate clearly in **written work and oral presentation**; the ability to locate information through **library research** and other means; the ability to continue learning on a largely independent basis. Especially relevant to majors are skills in logical **problem-solving and mathematical analysis**, experimental design and the use of measurement **apparatus**, and the **use of computers in modeling physical phenomena** and for data acquisition and analysis.
How to teach these skills?

- Mechanics
- E&M
- Waves
- Quantum
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- Physical Reasoning
- Quantitative Analytical Skills
- Scientific Methodology
- Writing and Presentation
- Independent Learning
- Broader Impact of Physics
How to teach these skills?

The “Horizontal” Curriculum
How to teach these skills?

- “Horizontal” curriculum needs clear learning objectives and detailed syllabus
- Assign faculty to teach the horizontal curriculum, with regular teaching credit
- Ideally, use cohort model: instructor follows students through 4 semesters
Acknowledgments

- Physical Sciences 2 and 3: Melissa Franklin, Howard Stone, Vinothan Manoharan, John Huth, Masahiro Morii, Aravi Samuel, George Whitesides, Joon Pahk, Timothy French

- Broader learning goals: Christopher Stubbs, Amir Yacoby