Physics 95 (F16) - Topics in Current Research

Running compilation of course notes for the Fall 2016 Harvard Physics 95 course.

1 Wednesday, August 31

- The objectives of Physics 95 are three fold:
  - Expose students to research areas in modern physics through talks by Department professors
  - Alert students to research opportunities within the Department
  - Allow students to practice various forms of technical communication
- A more general goal is to provide students with a feel for the culture, work, and community of physics research.
- Physics is a field of science within which there are many sub-fields, and it is important to distinguish sub-fields from the foundational subjects which are the grounding for these fields.
- **Sub-fields** are areas of current work or research in physics, while **foundational subjects** are formalisms (containing techniques and concepts) which are applied to study sub-fields.
  - Examples of **Foundational subjects**
    - o **Classical Mechanics** (*Phys 15A; Phys 16; Phys 151*): is concerned with properties of motion and causes of motion. Serves as the foundation for mechanics of materials or mechanical engineering subjects. Key concepts: equation of motion, Hamilton/Lagrangian Mechanics, Conservation Laws.
    - o **Electrodynamics** (*Phys 15B; Phys 232*): studies the creation and properties of electric and magnetic fields from various matter sources. Serves as theoretical foundation for electronics and electrical engineering subjects. Key concepts/results: Maxwell's Equations, Lorentz Force Law, Electromagnetic Radiation.
    - o **Quantum Mechanics** (*Phys 143A/B; Phys 251A/B*): the physical properties of systems on the scale of molecules, atoms, or sub-atomic particles. Key concepts/results: Schrödinger Equation, Measurement Problem, Entanglement, QFT[1].
    - o **Relativity** (*Phys 15A/16 (latter parts); Phys 210*) includes special relativity and general relativity. Special relativity concerns the implications of the constancy of the speed of light and the imposition that physical laws are the same in all inertial coordinate systems. General Relativity concerns how energy and momentum densities/fluxes curve space time. Key concepts/results: Principles of relativity, Einstein Field Equations, gravitational waves.
    - o **Statistical Mechanics** (*Phys 181; Phys 262*): studies the properties of systems with many (i.e., $N \sim 10^{20}$) degrees of freedom. Key concepts/results: Ensemble, Ergodicity, Master Equation. Serves as the microscopic foundation to thermodynamics and includes statistical field theory.

    Throughout most of your undergraduate education you have been learning the foundations which will allow you to begin studying sub-fields.
  - Examples of **Sub-Fields**

[1] Quantum Field Theory (QFT) is the result of combining quantum mechanics with special relativity

- **Biophysics:** using physical principles or experimental techniques, studies biological systems ranging in scale from organismal populations to cells and sub-cellular units.

  Reference: "Physics at Low Reynolds Number" by Purcell [1], *Biological Physics* by Nelson [2]

- **Astrophysics:** applies physics to systems with length scales on the order of planetary radii or larger. Includes cosmology and astronomy. The experimental work is different from much other work in experimental work in physics in that it is observational.

  Reference: *Chandra: a biography of S. Chandrasekhar* by Wali [3]

- **High Energy Physics (HEP)/Particle Physics:** study of physics on the smallest length scales and often at the highest energy scales. Experimental work is done at large colliders/accelerators around the world. Not all experimental particle physics is studied at high-energy.

  Reference: *Warped Passages* by Randall [4], *QFT in a Nutshell* by Zee [5]

- **Nuclear Physics:** studies states of matter and processes defined by the strong nuclear force. Has considerable cross-over with HEP. The experimental part of the field is developing into the "big science" which typifies high energy experiments.

  Reference: *Introduction to Elementary Particles* by Griffiths [6], *Introduction to Nuclear Physics* by Krane [7]

- **Public Policy:** governmental work which determines how science is funded and more generally regulated within the country. This work may not concern physics proper, but the government often employs physicists to do it.

  Reference: Suggestions welcome

- **Computational Physics:** applies numerical, programming, and algorithmic methods to solve physics problems, or develops new methods grounded in existing computing infrastructure.

  Reference: *Computational Physics: Problem Solving with Python* by R. Landau, Páez, Bordeianu [8]

- **Atomic, Molecular, Optical (AMO) Physics:** applies quantum mechanics to study atoms and molecules in isolation or how each interact with light in various systems. Work with Bose-Einstein condensation falls into this area.

  Reference: Suggestions welcome

- **Condensed Matter (CM) Physics** (Squishy (i.e., soft CM) and $\hbar$ (i.e., hard CM)): the study of any type of matter which is not in a gaseous phase. Includes, typical states like liquids as solids, but also nuclear matter like the quark gluon plasma and superconducting matter.

  Reference: "More is Different" by Anderson [9], *QFT in a Nutshell* by Zee [5], *Soft Condensed Matter* by Jones [10], *Condensed Matter Field Theory* by Atland and Simons [11].

- **Quantum Computing:** the implications and the construction possibilities of computation in the quantum regime. Extends from and can overlap with AMO physics.

Reference: "Quantum information and computation", by Bennet and DiVicenzo [12], "Undergraduate computational physics projects on quantum computing" by D. Candela [13]

- **Fluid Dynamics:** studies the physical properties which govern the evolution of systems which can be characterized as fluids. Typically not taught in the undergraduate physics curriculum.

  Reference: *Fluid Mechanics* by Landau [14]

- **Geophysics:** Study of the physical properties and processes of the earth. A field as multifarious as biophysics.

  Reference: Suggestions welcome

- $ **Physics/Quantitative Finance:** develops stochastic models of the stock market to predict/study the value of stocks and various other financial instruments. Arguably an area of applied mathematics, but firms where work was done previously employed physicists because of their quantitative modeling skills.

  Reference: *My Life as a Quant* by Derman [15], *The Physics of Wall Street* by Weatherall [16]

- **Sub-fields not mentioned:** History of Physics/Philosophy of Physics (e.g., *The Structure of Scientific Revolutions* [17]), Plasma Physics, Photonics.

- **Theorists and Experimentalists:** Ever since the middle of the 20th century, the knowledge and skills necessary to do physics research have become so specialized that the physics community has effectively divided into two cultures: theorists and experimentalists.
  - In general, theorists develop theoretical models of nature, and experimentalists test these models. Physics needs both to progress.
    - **Theorist examples:** Hideki Yukawa, Steven Weinberg, Subrahmanyan Chandrasekhar
    - **Experimentalist example:** I.I. Rabi, Chien-Shiung Wu, Edwin Hubble
  - Even if scientists sometimes change sub-fields, they often continue to work as experimentalists or theorists in their new discipline. The most historically famous counter example is Enrico Fermi.
  - **Educational Bias:** Your education up to this point has been largely biased toward training you to become and evaluating you according to the standards of theorists. Even experimental physics courses don't teach the spectrum of skills needed to become an able experimentalist. To obtain exposure to experimental physics, it's best to work under an experimentalist in a summer or semester research project.

- **Technical Communication:** Crucial to being a good scientist is not only doing good work but communicating that work to others. The course will provide practice in this direction in various ways.
  - **Elevator Pitch:** You're stuck in an elevator with someone you're trying to impress, or at least someone to whom you want to convey your work. You have 30 seconds to present the basics of your project, its purpose, and its goals. How do you do it?
    - **Another Educational Bias:** Students practice formal Powerpoint/Keynote talks often in their undergraduate education, but they often don't practice distilling and conveying the basics of their research. This course will practice elevator pitches among other aspects of oral communication.

- **Reading (and Writing) a Paper:** With the glut of scientific literature these days, physics papers are rarely read all the way through. Readers often look at
  1. Title (Is it interesting?)
  2. Authors (Are they credible?)
  3. Abstract/Figures (What is the general point?)

  (in that order) before deciding to make a full read through. You should keep this in mind as you write your own papers.
- **Evaluating a Talk:** When listening to a talk during the department colloquium, or at any other time during your undergraduate career. Ask:
  1. Can I talk to this person about their work?
  2. Are the tools and methods they're discussing interesting?
  3. Is this an effective talk?

  These questions can help you determine good people to contact for future research queries.

- **Homework (Details on Course Website):** Is the physicist's approach to solving problems useful in the life sciences?

2 Monday, September 12

- Physics is characterized by a certain unity of approach:
  - **Reducing (Reductionism):** Studying physical systems by studying the fundamental interactions of the system; Leads to an "inward bound" [18] perspective on physics where the community seeks to develop physics on smaller and smaller distance scales.
    - **More is Different:** [9] One of the insights of post 1950s physics, is that the reductionist approach does not always provide the most important details of a system. Understanding the fundamental properties of a single particle does not allow you to predict what happens when there are $N \gg 1$ particles. In other words

$$\text{Whole} > \sum (\text{Parts}) \tag{1}$$

  - **Abstracting:** Taking a physical system and removing all details which are not seemingly relevant to the focal question. This is what is typically characterized as "Thinking Like a Physicist"
  - **Assumption Clarifying :** Being specific about what you're neglecting and including in your abstracted system.
  - **Quantitative and Mathematical:** Using formalisms and techniques in mathematics to answer questions about the physical world.
    - **Mathematical Modeling in and out of Physics:** Physics is not the only field of knowledge that uses mathematics, but mathematical modeling in physics is distinguished from modeling in other fields in that physics models are
      - Grounded in physical principles
      - Represent the constitutive reality of modeled system.

      As an example of the latter point, in general relativity $g_{\mu\nu}(x)$ does not merely *model* spacetime; it *is our most precise definition* of spacetime. But in economics, while a function $p(t)$ can model the price of a product, it does not define the product.

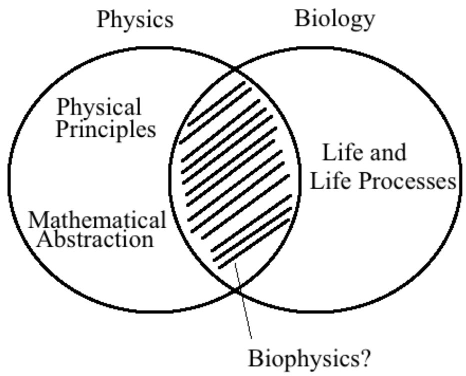

Figure 1: What characterizes Biophysics?

- **Falsifiable:** Developing predictions which can be compared with observations and are thus falsifiable. This is how Karl Popper [19] defined a valid scientific theory; Popper also claimed that the theories most consistent with predictions are the ones eventually accepted.
  - **Physicists against String Theory:** About a decade ago (and even still today), the common criticism levied against string theory was that it was not falsifiable and hence was more mathematics than science [20] [21]. Some string theorists rebutted that it takes time develop the apparatus to test novel theories.
  - **Kuhn against Popper:** Thomas Kuhn [17] (who studied physics and later the history of science here at Harvard) disagreed with Popper saying that theories are not accepted according to an objective accounting of number of falsifications, but subjective value systems defined by communities of scientists.
- **Empirical:** Studying the physical world through senses or experimental observations.

- **Physics Envy:** The "Physics Approach" is not all powerful. Often scientists run into problems when they try to apply this approach to non-physical systems, such as economies. (See Physics Envy)

- Biology is not necessarily amenable to the physics approach because biology concerns complicated, messy systems whose properties cannot always be reduced to a few universal (mathematically expressible) principles.

  - William Bialek [22] : "While physics is defined by a unity of approach, biology is defined by a unity of subject matter." All areas of physics make use of the following above listed approaches, but all areas of biology are concerned with the study of life or life-related processes. Biophysics attempts to find the cross over.
  - **Theory isn't everything:** There have been many scientists who started in experimental physics and moved on to molecular biology
    - Maurice Wilkins and Francis Crick who assisted in the discovery of DNA
    - Xiaowei Zhuang a Professor of Physics, Chemistry and Chemical Biology here at Harvard

- Does physics add value to biology?

  - **Pro:**
    - **Reductionism:** A reductionist model of science is useful when you have a lot of data
    - **Physical Principles:** Using physical principles allows you to access bigger picture results

  - o **Modeling:** Models give insights and allow you to search a smaller solution space; allows for computational techniques
- (Note:) All these explanations are consistent with the physicist's rather than the biologist's values.
- We're all physicists, so we might implicitly believe physics can contribute to biology, but to refine our own position/argument it's useful to take the contrarian one. What are the major criticisms levied against the use of physics in biology?
- **Con:**
  - o **Education:** Difficult to communicate work to other biologists. Biologists are trained through experiments not model building.
  - o **Spherical Cow Problem:** Oversimplification through modeling makes models irrelevant.
  - o **Tyranny of Equations:** Not every important result or idea in science can be reduced to an equal sign. For example, the central dogma of molecular biology (DNA$\rightarrow$ RNA $\rightarrow$ Protein) has no equal sign.
  - o **Statistics is Not Enough:** Models can be developed but attempts to fit to data can lead to fine-tuning and over fitting.

- Why Do We Model? [23]: In determining the relevance of physics (specifically the development of models) to biology, we need to understand why we model. The purpose for modeling extends beyond just developing predictions. We make models to
  - Explain (distinct from predict)
  - Develop new questions
  - Challenge and refine intuition
  - Explore analogies
- **When Giving a Presentation:** Pay Attention to
  - Message: What is the single-sentence point you're trying to get across?
  - Audience: What are the audiences' values? What language are they likely most comfortable with?
  - Structure: How to organize the presentation?
    - o There is no single right answer, and you should cultivate your own style for presenting.
    - o But be mindful that people have short attention spans. For example, people rarely finish reading online articles ("Why You Won't Finish This Article" *Slate*).
    - o Main points of talk should be presented at least at the beginning (if not repeated and elaborated upon later)
- **Importance of Outlines:** For technical papers which concern complex material which needs to be conveyed with optimal clarity, thinking about how you want to represent your work (and not merely how to do the work) is essential.
  - Figures are useful: A good heuristic is to create figures and use these figures as the scaffold of your presentation/paper.
- **Homework (Details on Course Website):** Watch presentation on creating effective slides, and create a single slide explaining whether a reporter should worry about a spy satellite.

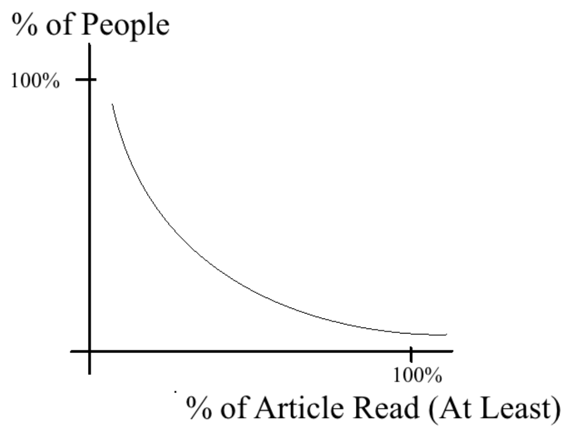

Figure 2: It's unlikely an online article will be read completely

3 Monday, September 19

The class was concerned with reviewing ways to create a single-slide presentation consistent with the assignment prompt. The prompt (paraphrased) was

> You've been contacted by a reporter who is concerned that U.S. satellites can read his text documents. Prepare one slide and an an accompanying talk explaining why this is not possible given current technology.

- **Importance of Title:** Titles convey the main message for your talk.
  - **Face of Talk:** The title also acts as the "face" of your talk when its presented in speaker lists or conference proceedings. Be true to your topic, but also try to capture your audience's interests. Title can be framed as a question as well.
- **Nature of Audience:** When presenting a topic, be cognizant of the values, education, and thinking frameworks of the audience.
  - **Americans, Math, and The Metric:** Americans are generally afraid of math (perhaps because they're bad at it?[2]) and do not think in metric units[3], so including many equations with discussions of kilograms and centimeters may confuse and annoy your audience (assuming you aren't speaking to people in a quantitative field of work).
  - **Equations for Non-Scientists:** In general, equations are only manifestly meaningful to people who constantly think through equations. Non-scientist audiences should not only be given equations and numbers, but should also be given a context to make the equations/numbers meaningful.
  - **Style of Explanation:** Both of the above points are pushing against our propensity to explain things the way we understand them. The speaker should always think about the explanation his audience will likely understand/accept.
- **Slides often Stand Alone:** Your slides are generally not only experienced with your voice over. If you give a good talk, you should expect that people will request your slides.

[2] "Americans are spectacularly bad at answering even the most basic math questions", *Quartz*

[3] These two tendencies which are perhaps related. (The United States and the Metric System, NIST)

- **Balancing Act:** Put too much text on your slides, and you're committing one of the common mistakes of slide presentations. Not enough text, and your slides are not understandable without your commentary. Finding the best way to present information so that it is meaningful in the moment and still useful afterwards involvess a delicate balance between clarity and aesthetics.

- **Flip-side to Math Phobia:** The flip-side to math-phobia is that audiences are often willing to grant intellectual credibility to those who justify their work through equations. Without agreeing with the legitimacy of such granting, we can say that placing mathematics in a presentation (if only for "shock and awe" purposes) can sometimes contribute to your ethos as a speaker/presenter.

- **Future Presentations:** Moving toward this class's goal of cultivating communication skills, in the future each person will prepare two kinds of talks
  - A technical talk pitched at your peers in class (i.e., an undergrad in the middle of completing a physics major)
  - A lay talk pitched at people without any extensive science education

- **Homework (Details on Course Website):** Create an elevator pitch on a topic from the provided list or an approved topic of your choice.

4 Monday, September 26

- Points to remember for Elevator Pitches (or for general informal but purposeful introductions)
  - **Hello:** State who you are according to your sense of what qualities are important to your message. Are you a denizen of San-Francisco who is interested in the problem of gentrification? A undergraduate researcher interested in improving computing resources for the college population?
  - **Content:** State what you want to communicate. Try to present a narrative focused around one or two main points, rather than a list of statements. You can begin generally and abstractly, but your content should eventually evolve toward something that is concrete and is actionable for your audience.
  - **Follow-Up:** State how you will follow up with the person. Did this first conversation go so well, that you can meet them for lunch? Or is it more appropriate to ask for an email address and continue the conversation online?

- **Best Laid Plans:** It is important to plan what you will say, but remember you are having a conversation not giving a monologue. You will likely be interrupted and derailed by questions, so don't allow your delivery to be so practiced as to be inflexible.

- **Future Weeks Schedule**
  - Oct 3: Lab Tours
  - Oct 10: Columbus Day Holiday
  - Oct 17: Presentations begin

- After October 17, you will be giving two kinds of presentations: Technical and Non-Technical

- For your future presentations, worry more about the delivery rather than the content.

5 Monday, October 3

- John Doyle and Erel Levine Lab Tours

6 Monday, October 10

- Columbus Day Holiday

7 Monday, October 17

Group A: Technical Presentations

- **Single Top Control Region** (by Katie Fraser): Outlines research work investigating top quark production and attempts to better estimate the associated background
- **Investigating H_2O Continuum effects on Runaway Greenhouse scenarios using 1D Radiative Transfer Models** (by Constantin Arnscheidt): Describes the potential uncontrollable increase in planetary temperature (i.e., the runaway greenhouse effect) as studied through the H_2O absorption spectrum
- **Global Warming and Cooling (and Warming)** (by Josh Coven): Outlines how earth was formed with a focus on the formation of the iron core
- **LIGO detects gravitational waves using an interferometer** (by Hayley Wyeth): Describes the physics behind LIGO's two gravitational interferometer detectors
- **The Acousto-Optic Effect and Applications** (by Charlotte Cole): Describes how sound wave propagation through a medium can effect the medium's index of refraction and hence the properties of light propagation. Discusses applications as well.
- **Michelson-Morley Experiment** (by Anna Peterman): Describes student work completed in the Physics 15c lab where the Michelson-Morley experiment was replicated
- **Aurora Borealis** (by Kirstin Anderson): Describes how the aurora borealis forms from charged particles traveling through the magnetic field of the north pole

8 Monday, October 17

Group B: Technical Presentations

- **Searching for Higgs Pair Production at the LHC** (by Gray Putnam): Describes studies involving the main decay channel ($h \to b\bar{b}$) for studying the production of two Higgs bosons at the LHC
- **Imaging of Electron Flow through Quantum-Point Contacts in High Mobility Graphene** (by Andrew Lin): Outlines attempts to obtain images of the flow of electrons in graphene using narrow waveguide-like spacers for electrons
- **The MicroMegas Trigger Processor Hardware** (by Noah Wuerfel): Describes student work in building new trigger hardware for muon detection in the CMS experiment
- **A theoretical Treatment of the Effect of Translation Dynamics on the Membrane Localization of mRNA in Bacteria** (Elgin Gulpinar): Reviews the central dogma of biology before continuing on to describe the importance of mRNA's location within a bacterial cell and how location can be tuned
- **A study of variability in a nearby supermassive Black Hole** (by Francesca Childs): Describes student work studying the electromagnetic spectrum of a quasar (PDS 456) in our universe
- **An Experimental Study of the Compton Effect** (by Shadi Fadaee): Describes student work completed in the Physics 191r lab. Work models the angular distribution of photon scattering from a target in order to test the Compton formula

- **Non-Coalescent Milimetric Droplets as Macroscopic Quantum Analogues** (by Tommy Peeples): Describes a system where liquid spheres (maintained through their own surface tension) of a viscous fluid can bounce on a bath of that fluid and produce effects analogous to those found in a quantum system

9 Monday, October 31

Group A: Public Presentations

- **Dark Matter** (by Katie Fraser): Describes how dark matter fits into the matter and energy content of the universe and how scientists are currently searching for it
- **Neutrino Oscillations - a summary** (by Constantin Arnscheidt): Provides an informal description of the history and mechanism of neutrino oscillations
- **The Ideal Gas Law and Football Air Pressure** (by Josh Coven): Summarizes the physics of gases (mostly the Ideal Gas Law) and applies it to understanding the controversy known as deflategate
- **Hydrogen Fueling in Massachusetts** (by Hayley Wyeth): Describes a new type of electrochemical battery which is coming to Massachusetts
- **Preservation, Conservation, and Switching to Sustainable Energy** (by Charlotte Cole): Describes how an oil baron became interested in wind turbines as an energy source and what his story means for the future of sustainable energy
- **Making Humans a Multiplanetary Species** (by Anna Peterman): Describes SpaceX's rationale and plan for getting humans to Mars within the decade
- **The Physics of Sailing** (by Kirstin Anderson): Describes the vector physics which allows sail boats to move and travel faster even than the wind that is propelling them

10 Monday, November 7

Group B: Public Presentations

- **The Higgs** (by Gray Putnam): Describes what the Higgs particle is and motivates why mass is important in physics
- **Graphene and the 2D Revolution: New Opportunities in Materials Science** (by Andrew Lin): Summarizes the history of the discovery of 2D graphene and what the discovery means for condensed matter theory and materials science
- **2000 Nobel Prize in Physics** (by Noah Wuerfel): Describes the history and concepts which led to integrated circuits and semiconductor heterostructures
- **Introduction to Quantum Physics** (Elgin Gulpinar): Using *Mathematica* simulations provides an interesting overview of fundamental effects in quantum physics
- **Understanding Comets: The Rosetta Mission** (by Francesca Childs): Provides an overview of the goals and problems of the Rosetta mission and what new information it found about the comet 67P
- **DWave 2X Quantum Computer** (by Shadi Fadaee): Describes what a qubit is and provides some conceptual motivation for the quantum annealing algorithm at the heart of the DWave quantum computing system
- **ExoMars and the Schiaparelli Lander** (by Tommy Peeples): Describes what caused the Schiaparelli Lander to crash land on mars and why the mission was not a complete failure

11 Monday, November 14

Advice on Building and Presenting Posters

- **Structure of Poster:** Design your poster as a single document; do not print out slides and post them to a single board.
  - **Vertical or Horizontal:** A horizontally aligned poster is typically better than a vertically aligned poster because audience members won't need to crane their necks for the former.
  - **Background:** white or grey background is best choice. Black background with white text is usually a poor aesthetic choice.
  - **Arrows:** If you need arrows to indicate the flow of information on your poster, you're probably using a too non-traditional poster design.
- **Are visuals Important?** Visuals help attract your people to your poster. Uninterrupted blocks of text are off-putting, and people typically judge whether to give a poster a closer look when they're a meter or more away from it.
- **Titles are important**
  - **Face of the Work:** Your title is the first textual introduction of your work.
  - **Result or Motivation:** Should the title be a final statement of your work (i.e., a result) or a larger question you were trying to answer (i.e., original motivation)? Depends on context. In general pay attention to your audience and consider which title format is most appropriate for your venue.
- **Spiel:** Prepared remarks associated with your poster discussion.
  - **Wait to be Spoken To:** It is typically a bad idea to give spiels which have not been requested. Wait until passerbys engage you with a question, and then directly answer that question without falling into a long summary of your entire work.
  - **Come prepared:** Still it is a good idea to have a spiel prepared in case some one wants to hear it.

12 Monday, November 21

Peer Reviews of Student Press Releases

13 Monday, November 28

Poster Presentations @ the Physics Colloquium!

References

[1] E. M. Purcell, "Life at low reynolds number," *Am. J. Phys*, vol. 45, no. 1, pp. 3–11, 1977.

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