Syllabus

1 Course Structure

This course is structured around weekly problem sets. Each will have about 30 problems, ranging in difficulty from $F = ma$ to IPhO and beyond. Fundamentally, your learning will come from working on this diverse set of problems.

At the end of the week, we'll have an online meeting to discuss the problems and evaluate your solutions. Throughout the week, you can contact me at any time by chat or email to ask for clarifications or hints on the problem. Don't hesitate to do this, because this is the essential ingredient that makes tutoring better than learning from a book! You can also ask your fellow students, or the TA, in the course group chat.

Usually the entirety of the class will be devoted to discussing problems; I won't spend much time introducing the basic material. You should already know calculus-based physics at the level of Halliday and Resnick. Each problem set will also come with an assigned reading from some of the textbooks listed below. I expect you to do any necessary reading on your own, doing extra problems from the textbooks if necessary.

Your problem sets will be stored in a personal Dropbox folder. Official solutions to the problems will be added to the folder before each class. The solutions were written by me and the past course TAs, Gopal Goel and Sean Chen, both of whom were USAPhO campers and IPhO gold medalists.

2 Problem Sets

The problems are chosen so that all of them demonstrate different ideas, so you'll get more out of the course the more you do. That said, it certainly isn't necessary to do every problem. Every problem will have a point value from **1** to **5**, and each problem set comes with a cutoff which is roughly 60% of the point total. If you reach this cutoff, you'll have a good understanding of the material. Participants aiming at IPhO gold medals should try essentially everything.

Problems marked with **[A]** are "advanced". This doesn't mean that they're trickier, but rather that they require more sophisticated mathematical techniques. These problems are less relevant to Olympiad physics but are chosen to demonstrate interesting things.

If you're interested in USAPhO prep you should attempt all of the USAPhO problems, while if you're interested in IPhO prep you should attempt the international-level (IPhO, APhO, WoPhO, GPhO, EuPhO) problems. However, these latter problems are also valuable for USAPhO contestants. Don't be intimidated by them; they are usually worth **4** or **5** points, but that's just because of their length. The difficulty per time for older IPhOs is on par with current USAPhOs, and I don't use problems that are unreasonably hard. Often these longer problems have a lot to teach, since they have the time to do a more complete analysis of a physical system.

Some problems will be marked with a clock. They should be done under realistic conditions, which means you should use only pencil, paper and a scientific calculator. During this time you should write a solution by hand, with the same level of detail you would for a real Olympiad. If you run out of time but you're still making progress, feel free to continue, but draw a line on your solution indicating when time ran out. Common time limits will be

 – 22.5 minutes,  – 45 minutes,  – 100 minutes

for a USAPhO A, B, and full modern IPhO problem respectively. (Older IPhO questions are much shorter, and may have correspondingly shorter times.) After finishing, immediately check your answers and, if your solution was not complete, reflect on what you could have done differently.

3 Writing Solutions

You should submit your solutions within a day before class. For ease of reference, organize all your solutions for one problem set in a single PDF, and all PDFs in your Dropbox folder.

As stated above, for timed problems your solutions must be in handwritten Olympiad solution format, and scanned. For all other problems, handwritten solutions are also preferred, but you can also use LaTeX, either locally or online at Overleaf. These solutions don't have to be extremely detailed: you don't have to show all your algebra explicitly, and you don't have to restate anything written in the question. In general, I'm more concerned with the structure of the solution than the algebraic steps. That is, emphasize the ideas you used to write down the equations, as much as how you solved them.

4 Textbooks and Resources

We'll be using a wide variety of textbooks and resources. I recommend immediately getting a copy of the ones marked with stars. In most cases, I recommend getting the most recent edition.

- ⋆ Halliday, Resnick, and Krane, *Physics*. This book contains the foundational material required; you should know it forwards and backwards. Even today, a solid understanding of it is enough to get a gold medal at the IPhO, though of course more knowledge always helps. The 5th edition is more expensive, but worth it for the extra challenging problems included.

- Mahajan, *Order of Magnitude Physics*. A nice, short book about dimensional analysis and estimation. Also see *The Art of Insight*, a longer work by the same author on the same themes.

- ⋆ Kleppner and Kolenkow, *An Introduction to Mechanics*. Used at MIT, written more like a physics book. Has good problems with a practical emphasis. I recommend getting the 1st edition, not the 2nd, because the 1st edition has harder problems.

- ⋆ Morin, *Mechanics*. Used at Harvard, written more like a math book. Has a large stock of elegant and tricky, if sometimes contrived mechanics problems. Also contains an excellent, careful introduction to special relativity.

- Schey, *Div, Grad, Curl, and All That*. A well-written, intuitive vector calculus book, with lots of good pictures. Also see the excellent MIT OCW 18.02 lectures.

- ⋆ Purcell and Morin, *Electricity and Magnetism*. Does electromagnetism with vector calculus and relativity baked in. Most famous for using relativity to derive magnetism, rather than just postulating it. Has well-written problems that provide insight. The 3rd edition is a substantial improvement on the 2nd, with SI units adopted throughout and more challenging problems.

- French, *Vibrations and Waves*. A very nice and accessible exposition of mechanics waves once used at MIT. Covers the wave equation, resonance, and normal modes; doesn't spend much time on specific waves. Also see Morin's *Waves* book draft, which is somewhat more sophisticated.

- Crawford, *Waves*. An excellent book on all aspects of waves and oscillations, with hundreds of real-world examples and home experiments; slightly more sophisticated than French.
- Schroeder, *An Introduction to Thermal Physics*. A nice, slim first thermodynamics book, which explains the core ideas with the simplest math possible.
- Blundell and Blundell, *Concepts in Thermal Physics*. A second thermodynamics book, covering important applications, using multivariable calculus and statistical mechanics. Much of it will be very useful, though at times it's too technical for Olympiads.
- Krane, *Modern Physics*. Modern physics just means everything that was done in the past hundred years, so this is an extremely broad area. Krane covers it in about the right level of detail for the Olympiad, refraining from using higher math.
- Some students have handwriting that's hard to read; if that's you, see this advice.
- If you prefer lectures to books, there's an exceptional amount of good content on MIT OCW. The classic references are the 8.01 (mechanics) and 8.02 (electromagnetism) lectures by Walter Lewin, which are mathematically elementary, but which have many interesting physical examples. Also see the 8.03 (waves) lectures, and the accompanying problem solving recitations.
- Khan and Anderson, *Conquering the Physics GRE*. This book is a light review of the undergraduate physics curriculum. You may also find it useful to try problems from the Physics GRE, which is like the $F = ma$ exam, but with less time pressure and covering more content.
- ⋆ *The Feynman Lectures on Physics*. A wonderful source of physical insight. Most problem sets will have some chapters assigned for entertainment and enrichment.

Besides past Olympiads and textbooks, problems are also sourced from the following books.

- ⋆ *200 Puzzling Physics Problems* and *200 More Puzzling Physics Problems*. Tricky questions written in Eastern European style. The first book is highly recommended; the second book is at times too mathematically contrived to be too relevant to Olympiads, but still lots of fun.
- ⋆ Handouts by Jaan Kalda. These handouts and formula sheets provide excellent training for Eastern European style Olympiads. Very different in style from the USAPhO (e.g. more circuits, less relativity/modern physics), but highly recommended. Good solutions written by students are available here. If you like the style of the EFPhO/NBPhO, you can find many more questions in the Estonian style here.
- Krotov, *Problems in Physics*. A collection of Russian Olympiad problems in typical style. It's like a shorter, refined version of Irodov's classic *Problems in General Physics*. (I don't recommend Irodov itself; it was one of the best books a few generations ago, but compared to books available today, it has too many tedious filler problems and not enough really deep ones.)
- Levi, *The Mathematical Mechanic*. A fun book which gives slick solutions for many mechanics and calculus problems.
- Povey, *Professor Povey's Perplexing Problems*. A collection of simple but tricky undergraduate admissions interview questions with neat historical anecdotes.

- Nahin's *In Praise of Simple Physics* and *Mrs. Perkins's Electric Quilt* provide a variety of simple but entertaining examples, accompanied with historical anecdotes. Students of this course will also probably enjoy his math-themed books *How to Fall Slower Than Gravity* and *Inside Interesting Integrals*.
- Thomas and Raine, *Physics to a Degree*. A collection of well-motivated questions used for undergraduate physics training, with many real-world applications.
- Cahn and Nadgorny, *A Guide to Physics Problems*. A collection of graduate school qualification exam problems. Some great classic problems are here, though most are too technical to be useful for Olympiad preparation.
- *Cavendish Problems in Classical Physics*. Another collection of classic problems, used for second year exams in Cambridge back when things were more hardcore. Also see *Thinking Like a Physicist* by Thompson, for more qualitative questions used in final year exams at Bristol.
- *Pathfinder for Olympiad & JEE*. This book is commonly recommended, but I advise *against* reading it if you're preparing for the USAPhO. The style is very different, and definitions and notation differ in confusing ways. Similarly, I advise against anything used to cram for the IIT JEE. These resources are designed to make you memorize things unthinkingly (and sometimes incorrectly) to maximize your score, rather than question if they actually make sense. (However, *Concepts of Physics* by H.C. Verma is good; it compactly covers all the relevant topics with many worked examples.)
- You can also consult resources used by other countries' physics teams. From easiest to hardest:
  - *Script Physics Olympiad*, used by the Swiss physics team.
  - *Upgrade Your Physics*, used by the British physics team.
  - *Physics Olympiad – Basic to Advanced Exercises*, used by the Japanese physics team.
  - ⋆ Wang and Ricardo, *Competitive Physics*, used by the Singapore physics team. This book contains clear, detailed explanations of the theory needed to bridge the gap from an introductory textbook to the IPhO. The main drawback is that many of its problems are physically straightforward but mathematically complicated, and thus not representative or particularly fun to do. Especially useful to get started in thermodynamics and waves.

If you want to learn more advanced physics, beyond the scope of the Olympiad syllabus, see my second advice file, my notes on Undergraduate Physics, and the following books.

- Agarwal and Lang, *Foundations of Analog and Digital Electronic Circuits*. An accessible book if you want to dig deeper into electrical engineering.
- Hecht, *Optics*. A well-written, though occasionally long-winded reference for interference, diffraction, and geometrical optics.
- Carroll and Ostlie, *An Introduction to Modern Astrophysics*. A massive, comprehensive book for undergraduate astrophysics.
- Griffiths, *Introduction to Electrodynamics*. A standard, and very clear book for advanced electromagnetism in college, with useful references to the modern literature. Requires comfort with vector calculus.

- Zee, *Fly By Night Physics.* An entertaining and irreverent journey through undergraduate physics, with an emphasis on blatantly unrigorous, seat of the pants reasoning. Comes with many neat historical asides. It's a fun book to read, but "don't try it at home", since Zee often leans heavily on his prior knowledge of the answer. As a typical example, he "derives" the Planck distribution by noting that it is proportional to $f(\hbar\omega/k_BT)$ where we know that $f(x) \to 1/x$ as $x \to 0$, and $f(x)$ rapidly decreases as $x \to \infty$, and therefore concludes $f(x) = 1/(e^x - 1)$.

- Lautrup, *Physics of Continuous Matter.* An excellent book on fluid and solid dynamics with many interesting real-world examples. Uses vector and tensor calculus heavily.

- Griffiths, *Introduction to Quantum Mechanics.* This is the most accessible first quantum mechanics book, requiring only single-variable calculus in the first few chapters, and barely using linear algebra at all. It thus leaves many topics out, but it'll get you doing nontrivial calculations as quickly as possible. If you prefer lectures, consider the MIT OCW 8.04 lectures by Barton Zwiebach (more clear) and Allan Adams (more energetic).

- Schutz, *A First Course in General Relativity.* The first few chapters gently introduce four-vectors and tensors, making it a valuable bridge between special relativity books like Morin and more serious general relativity books like Carroll.

- Griffiths, *Introduction to Elementary Particles.* If you want to learn quantum field theory in high school, my advice is to just *not*. The subject has extremely heavy prerequisites, even compared to general relativity, and if you don't have them you might be able to slog through calculations, but it'll be hard to appreciate how it all works. You can do it if you're really far ahead, but at a bare minimum, you should confidently know everything in both Griffiths books above, plus Schutz, and exposure to graduate-level quantum mechanics at the level of Sakurai would be a huge help. That said, if you want exposure to the *ideas* of quantum field theory, this third book by Griffiths is excellent. The first few chapters introduce the history, with minimal prerequisites. The rest can be followed with only undergraduate quantum mechanics.

You can also meet other students to discuss problems on the Physics Olympiad Discord server.

5 Olympiad Problems

You can access most of the Olympiad problems we'll do using the following links.

- Recent $F = ma$ and USAPhO exams can be accessed here.

- As part of this training, you'll also have access to older $F = ma$ exams, quarterfinals, semifinals, and their solutions.

- You can access past IPhO exams here and past APhO exams here.

- We'll also draw problems from the EuPhO, GPhO, EFPhO/NBPhO, BAUPC, BPhO, JPhO, AuPhO, CPhO, IZhO, INPhO, and PPRDPhO. (For some other Olympiads, see here.)

EFPhO/NBPhO problems will not be timed, but if you'd like to compare yourself against the competitors, this competition allows about 8 minutes per point (in contrast to the 10 minutes per point in international-level competitions). If you run into issues with math rendering in any of the documents, try downloading a local copy and opening it with a dedicated PDF viewer.

6 Curriculum

An outline of the full curriculum is shown below. You can go through it in any order, though generally each problem set within a topic requires all of the previous ones. Units that are especially relevant to USAPhO preparation are underlined. In all cases, the prerequisites are a strong grasp of calculus, and the relevant material in Halliday, Resnick, and Krane. Prior exposure to vector/multivariable calculus is useful, especially for thermodynamics and electromagnetism, but not necessary.

- 2 weeks of problem solving.
  - **P1**: dimensional analysis, limiting cases, series expansions, differentials, iterative solutions.
  - **P2**: probability, error analysis, data analysis, estimation, experimental technique.
- 8 weeks of mechanics.
  - **M1**: kinematics. Solving $F = ma$, projectile motion, optimal launching. (**P1** helpful)
  - **M2**: statics. Force and torque balance, extended bodies, pressure and surface tension.
  - **M3**: dynamics. Momentum, energy and center-of-mass energy, collisions.
  - **M4**: oscillations. Damped/driven oscillators, normal modes, small oscillations, adiabaticity.
  - **M5**: rotation. Angular kinematics, angular impulse, physical pendulums. (**P2** helpful)
  - **M6**: gravity. Kepler's laws, rocket science, non-inertial frames, tides.
  - **M7**: fluids. Buoyancy, Bernoulli's principle, viscosity and surface tension. (**M2** helpful)
  - **M8**: synthesis. 3D rotation, precession, and tricky problems.
- 3 weeks of thermodynamics.
  - **T1**: ideal gases, statistical mechanics, kinetic theory, the atmosphere. (**M7** required)
  - **T2**: laws of thermodynamics, quantum statistical mechanics, radiation, conduction.
  - **T3**: surface tension, real fluids, phase transitions, compressible flow.
- 8 weeks of electromagnetism.
  - **E1**: electrostatics. Coulomb's law, Gauss's law, potentials, conductors.
  - **E2**: electricity. Images, capacitors, conduction, DC circuits.
  - **E3**: magnetostatics. More circuits, Biot–Savart law, Ampere's law, dipoles and solenoids.
  - **E4**: Lorentz force. Dynamic charges, permanent magnets, solid state physics. (**M4** helpful)
  - **E5**: induction. Faraday's law, inductors, dynamos, superconductors.
  - **E6**: circuits. RLC circuits, filters, normal modes, diodes. (**M4** required)
  - **E7**: electrodynamics. More circuits, displacement current, radiation, field energy-momentum.
  - **E8**: synthesis. Electromagnetic fields in matter, and tricky problems.
- 3 weeks of relativity.
  - **R1**: kinematics. Lorentz transformations, Doppler effect, acceleration, classic paradoxes.
  - **R2**: dynamics. Momentum, energy, four-vectors, forces, relativistic strings. (**E4** helpful)

  - **R3**: fields. Electromagnetic field transformations, the equivalence principle. (**E7** required)

- 3 weeks of waves.
  - <u>**W1**</u>: wave equation, standing waves, music, interferometry. (**M4** required)
  - <u>**W2**</u>: interference and diffraction, crystallography, real world examples. (**E7** required)
  - **W3**: sound waves, water waves, polarization, geometrical optics. (**M7** required)

- 3 weeks of modern physics.
  - <u>**X1**</u>: semiclassical quantum mechanics, bosons and fermions. (**M4**, **T2**, **W1** required)
  - **X2**: nuclear, particle, and atomic physics. (**R2** required)
  - **X3**: condensed matter, astrophysics, and cosmology. (**W3** helpful)

The core material relevant to the USAPhO consists of two weeks of problem solving, seven weeks of mechanics, seven weeks of electromagnetism, and eight weeks of special topics, for a total of 24. My recommended path through the curriculum is **P1**, **P2**, **M1–4**, **E1–4**, **M5–7**, **T1–3**, **E5–7**, **R1**, **R2**, **W1**, **W2**, **X1**. (This ordering reflects the technical sophistication of the problems, and also splits up the long topics so you don't work on one for too long at a time.) There are six further advanced units which are more relevant for IPhO preparation. Towards the end of the year, there will be three review problem sets and eleven graded practice USAPhOs.

The USAPhO/IPhO point distribution is very roughly as follows:

	USAPhO	IPhO (theory)
Mechanics/Fluids	30%	25%
Electromagnetism	25%	20%
Relativity	10%	15%
Thermodynamics	15%	15%
Waves	10%	10%
Modern	10%	15%