Advice After Introductory Physics

I've met lots of people who have self-studied calculus-based physics, want to learn more, and are unsure what to do next. This document lists some resources for going further. If you want advice for how to start out learning physics or doing physics competitions, see my introductory advice file.

Deepening Core Knowledge

You're done with the introductory material after finishing a book like Halliday, Resnick, and Krane. If you enjoyed what you learned, there are many ways to deepen your knowledge.

- To get a deeper understanding of mechanics, try *An Introduction to Mechanics* by Kleppner and Kolenkow or *Introduction to Classical Mechanics* by Morin. These are used for honors introductory physics at MIT and Harvard, respectively. There's substantial overlap between the two, so just look at both and see which you like better. Morin has more sophisticated but less realistic problems. Morin's problems are about frictionless planes and massless strings, while Kleppner's problems are about cars and rockets.
- Halliday, Resnick, and Krane's brief coverage of relativity probably isn't enough to confidently handle Olympiad problems on the subject. You can learn more about the subject in the last few chapters of either Kleppner and Kolenkow or Morin. I think Morin's discussion of relativistic kinematics is excellent, carefully resolving many of the confusions a beginner might have.
- To get a deeper understanding of electromagnetism, try *Electricity and Magnetism* (3^{rd} edition) by Purcell and Morin, which is so exceptional that it's used for honors introductory physics at almost all top colleges. It has many insightful discussions and problems, but it's best known for a beautiful chapter that uses relativity to introduce magnetism. For a short and sweet introduction to vector calculus that complements the book, try Schey's *Div, Grad, Curl, and All That*, which has good pictures; for a more thorough introduction, see MIT OCW's 18.02.
- The waves and thermodynamics chapters in Halliday, Resnick, and Krane are enough to get started on competitions, but other books can help deepen your understanding. For a clear introduction intended explicitly for Olympiad preparation, try the first and second volumes of *Competitive Physics*, by Wang and Ricardo, respectively.
- It's also very rewarding to get a broad overview of physics as an intellectual tradition. I strongly recommend the *Feynman Lectures on Physics* for fascinating discussion from a master of the subject. If you're interested in the history behind the material in an introductory physics course, try *Understanding Physics* by Cassidy, Holton, and Rutherford.
- I generally recommend against reading any book with a title like "Modern Physics." These books have the same problem as algebra-based physics textbooks: they try to explain too much with too little. Equations that should be derived with two lines of math end up "motivated" with hundreds of words of vague argumentation. Since modern physics courses need to have a large bank of problems to test students with, but they don't teach the students to derive anything, the textbooks end up packed with thousands of joyless, cookie-cutter questions where you simply look up numbers in a table and plug them into a given formula. In my opinion, a standard introductory book such as Halliday, Resnick, and Krane already gives enough background on modern physics for the Olympiad. But if you really want to jump into these topics early, Krane's *Modern Physics* is well-written and comprehensible.

There are many resources out there, but don't get too worried about choosing one. All good books contain the same essential core. As long as you understand the resource you're using, and you're learning new things, you're on the right track. If you're not sure whether you can or should start a book, just read the first chapter and see how it feels!

Competition Practice

There are many good sources of practice problems for competitions.

- Your primary source should be past USAPhO exams. I've rewritten the solutions to these exams for clarity, but make sure to give each problem your best try before peeking; it's easy to waste one that way.
- If you run out of practice USAPhOs and really want more, AAPT sells a CD-ROM of USAPhO exams going back to 1997. You can ask your physics teacher to purchase this, though they're substantially easier than current USAPhOs.
- Many problem sources are listed in the Syllabus for my handouts, but my favorite are:
  - Jaan Kalda's study guides. These are exceptional because they pair problems with the specific ideas needed to do them, allowing for rapid progress. They leave a lot to the reader; you won't get far if you don't already know calculus-based physics well. Student-written solutions are available here.
  - 200 Puzzling Physics Problems. This is a set of entertaining and devilishly tricky problems, mostly compiled from Eastern European physics competitions. There are many great ideas in this book, but I don't recommend using it as your main source of practice, as a good number of problems are vaguely formulated or rely on obscure tricks.

More Advanced Physics

There's a lot you can do if you want to move beyond competitions, towards more advanced physics.

- First, a warning. At this level, you'll see a lot of "study guide" books marketed as "student friendly", "for students", or even "for dummies". They all have glowing reviews[1], but I strongly recommend against using them. They don't explain how the physics works; they just tell you the mechanical steps you need to remember to solve the simplest exam problems.

  In a course, they can be a life saver if you're pressed for time and mostly interested in grades, but the superficial understanding you'll get from them will collapse by the first lecture of the next course. It's like building the facade of a house without the foundation. If you're self-studying, there's no reason to ever use these books, because you have the time to do it right.
- If you're following a standard college curriculum, the next thing to do is to get an understanding of waves and oscillations. This corresponds to the MIT OCW's 8.03, with further background on differential equations given in 18.03. For entertaining demonstrations, see Walter Lewin's

[1] These reviews are annoying because they make it hard to differentiate quality. For example, A Student's Guide to Maxwell's Equations is good, but A Student's Guide to Lagrangians and Hamiltonians is atrocious: its derivations are vague or wrong, and half the problems aren't properly formulated. Every month I see a sad StackExchange question from a student who's been terribly misled by the latter book. But both have a hundred five-star ratings online.

old 8.03 lectures. For a textbook reference, *Vibrations and Waves* by French is short and clear, covering the essentials of the subject, while *Waves* by Crawford is more thorough, with many interesting real-world applications and home experiments. If you enjoyed Morin's style, you can also try his *Waves* book draft.

- For intermediate electromagnetism, the best book is *Introduction to Electrodynamics* by Griffiths, by a big margin. The book is very clear, and its problems get surprisingly deep, due to Griffiths' experience writing many papers on the subtleties of classical electromagnetism. This level of electromagnetism requires deeper familiarity with vector calculus, which you can pick up from the first few chapters. For a dedicated introduction to the math, see David Tong's notes on Vector Calculus for a clean approach that gets to tensors[2] and introduces index notation, a powerful tool for deriving more complicated vector calculus identities.

- After learning mechanics at the level of Morin or Kleppler and Kolenkow, you can start learning Lagrangian and Hamiltonian mechanics, which are typically not useful for the Olympiad, but extremely important for physics in general. For a clear and gentle introduction, see *Classical Mechanics* by Taylor. For a nice supplement, see David Tong's notes on Dynamics.

- The standard undergraduate textbooks are clear, but they focus on explaining theory, at the expense of truly difficult problems. They can give you the mistaken impression that more advanced physics just consists of routinely applying an ever-longer list of standard formulas. The worst example of this is how most undergraduate mechanics books cover the formalism of Hamiltonian mechanics for 100 pages, but then never use it to solve anything less trivial than the harmonic oscillator. Of course, the giants of the 19^{th} century loved tough problems, and they invented these theoretical tools precisely to solve them. To see a bit of this side of physics, try flipping through *Analytical Dynamics of Particles and Rigid Bodies* by Whittaker, and *Static and Dynamic Electricity* by Smythe. The former includes plenty of problems from the legendary Cambridge Tripos exam, which was an order of magnitude harder than any graduate exam today. The latter was designed, according to Smythe, to "weed out weaklings" in the Caltech graduate program. Unfortunately, these problems are very difficult today because they tend to assume familiarity with elementary yet exotic topics, like elliptic functions and parabolic coordinates. If you find Smythe too difficult, Jackson's relatively easy in comparison.

- For intermediate thermodynamics, I recommend either *Concepts in Thermal Physics* by Blundell and Blundell, or *Thermal Physics* by Schroeder. Blundell and Blundell is more comprehensive, with many interesting sidenotes and applications; Schroeder is short, clear, and crisp.

- All of the above is just an appetizer for what is arguably the main course of a physics major: quantum mechanics. There are two ways to enter the subject. The traditional way is to start with using Schrodinger's equations to solve for wavefunctions; this lets you seamlessly transition into it after finishing a course on waves, and supplies a lot of visual intuition. A newer approach

[2]By the way, tensors are another one of those topics where you need an "official" source, like a book chapter or a polished set of lecture notes. When I google "introduction to tensors", most of the first ten results are terrible for beginners. I recognize a few that once got me confused for days, because they were full of typos, and cross-checking them made things worse because they used incompatible conventions. Others are correct, but way too sophisticated to serve as a real introduction. It doesn't help that mathematicians, computer scientists, engineers, and physicists all mean different things when they say "tensor"! Don't try to brute force learning this kind of thing by opening twenty tabs. Just use one good source and stick with it. Exploring will deepen your knowledge only once you have the foundation set.

is to start by applying the fundamental postulates to low-dimensional systems, like the qubits of quantum computing; this makes the subject accessible to people with no physics background at all, but it is somewhat abstract and requires familiarity with linear algebra. Of course, if you want to really know quantum mechanics, you're have to understand both perspectives.

- To start the first way, read *Introduction to Quantum Mechanics* by Griffiths, which comes with clear explanations and great problems. For video lectures at a similar level, try the MIT OCW 8.04 lectures by Barton Zwiebach (more clear) and Allan Adams (more energetic).
- To start the second way, read *Introduction to Linear Algebra* by Strang, used for MIT OCW's 18.06. (This is an excellent thing to do in general, even if you don't stay in physics, because linear algebra is arguably even more useful than calculus. You'll probably still need to use it if you go into computer science, finance, data science, or even, god forbid, management consulting.) Then read the first half of *Quantum Computation and Quantum Information* by Nielsen and Chuang.
- More advanced quantum mechanics courses will freely use both perspectives. For material at this level, see *Principles of Quantum Mechanics* by Shankar, or the MIT OCW 8.05 lectures.
- If you want to start heading towards general relativity, the two gentlest books are *Gravity* by Hartle and *A First Course in General Relativity* by Schutz. While both cover similar ground, Schutz puts all the mathematical background up front (including a great introduction to four-vectors and tensors), while Hartle starts with physical results, having you take some of the math on faith until it's filled in later. Both are good, so just pick whichever style you prefer.
- If you're interested in fancy stuff like quantum field theory or string theory, I generally *don't* recommend reading anything about it at this stage. String theory in particular has an enormous amount of prerequisites, which means that books which try to popularize it skew towards "mindblowing" metaphysics. These books are built on layers of analogies, and you'll naturally want to probe deeper. But the second you try, the analogies will fall apart, because they are merely shadows on the wall. You'll find many lost souls online who have taken the analogies too literally, arriving at homemade theories that have little to do with anything in physics.[3]

  Anyway, if you're determined to get a taste of these subjects, I recommend resources with at least a few equations in them. For example, in ascending order of difficulty:

  - Cumrun Vafa's *Puzzles to Unravel the Universe* is like a popular string theory book, but with points explained with neat mathematical puzzles. It's meant for freshmen at Harvard, which means you only need high school algebra to understand it.
  - David Tong's Particle Physics lecture notes cover the basics of the Standard Model and beyond, with many references to the history and deeper theory, and only high school math.

[3] And it's easy to go astray even if you have excellent reading comprehension skills, because English is ambiguous. For example, mathematicians say that if $x > y$ and $y > z$, then $z < x$. But for dessert, nothing is better than ice cream, and ice cream is better than licorice, but licorice is better than nothing! So have we just overturned the foundations of mathematics? There's a whole field of philosophy devoted to questions like these, though to people who know math, it tends to look like trying to bang rocks together to make fire. Unfortunately, if you base your understanding on pop science alone, the questions and ideas you'll come up with might sound insightful to nonphysicists, but they'll all be senseless in exactly this way.

- Leonard Susskind's Theoretical Minimum lectures cover graduate-level topics using just calculus. They're not nearly detailed enough to serve as a foundation, but they do a great job of giving the flavor of the logic.
- Griffiths' *Introduction to Elementary Particles* clearly explains the basics of particle physics and the structure of the Standard Model, along with how to do some toy calculations in quantum field theory. It requires a good understanding of undergraduate quantum mechanics and special relativity.
- Barton Zwiebach's *A First Course in String Theory* is the string theory textbook with the least prerequisites, and it actually derives many of the results it uses. It also requires undergraduate quantum mechanics and special relativity.

Don't get too confident if you use these – they only cover a small fraction of what typical introductory books in these subjects do. To really get started in these fields, you should at minimum learn graduate-level quantum mechanics first, at the level of Sakurai. For more advanced resources for each subfield of physics, see the introductory pages of my lecture notes.

Second Opinions

The internet has some great sources for physics learning advice, and unfortunately many not-so-great sources. There are several reasons advice can be bad. First, much of it is given by people who don't actually know the basics themselves. They write guides because it takes less effort to compile a big list of books and *imagine* knowing what's in them than to open a single book and *actually* learn something. Second, many other guides are written by eminent professors who haven't read an undergraduate-level book in decades. They're not going to start doing that again, so they tend to recommend outdated books that worked for them forty years ago. Or, worse, they simply skim through a newer book's table of contents and recommend it if the chapter titles and the author's name sound familiar; this way of doing things keeps a lot of subpar books on the market. Finally, most of the remaining guides are written by senior students or bright autodidacts who are more interested in showing off than imparting useful information. They often insist you start with the hardest book they've ever heard of – even if they themselves read plenty of easier books first, or don't even know what's in the harder book. They include only books with "hardcore" reputations, regardless of whether those books are actually comprehensive, modern, or readable.

While I would rather not dive into too many specifics, here are some red flags for bad advice.

- They recommend you read the oldest possible sources, such as Newton's *Principia Mathematica* or Einstein's papers in the original German. Often these recommendations come from young philosophy students, who think texts automatically get more true with age. The reality is that physics is a living science, and old sources are a bad place to start. They usually contain tons of discussion which is misguided or no longer relevant. The original papers are works of genius, with gems of insight throughout, but modern textbooks are the result of hundreds of geniuses refining those arguments over decades or centuries, and they're designed to be learned from.
- They recommend *The Road to Reality*, a wildly popular coffee-table book that promises to cover all of physics in a couple hundred pages. I suspect less than 10% of people who have bought it and recommend it have read past the first chapter, and less than 10% of those people were learning anything new. If you already know the material, it's a brilliant and masterful review, which explains the praise from professors. But if you don't, there's absolutely no way you can

climb from arithmetic to quantum gravity with it. It is not made to be learned from, and people who recommend it are usually doing so only on the basis of its long table of contents.

- They recommend *Gravitation* by Misner, Thorne, and Wheeler. This is an impressively *large* general relativity textbook. It weighs six pounds, runs to 1300 pages, and uses extra large paper with large font and large margins, so that you can't even open it without the spine falling apart. For this reason, many young students assume it must be the final word on the subject – but it's not. It is 50 years old, which puts it before the development of cosmology, precision solar system and terrestrial tests, and the discoveries of black holes and gravitational waves. It also doesn't cover that much material: if you convert it to normal font, and strip out the hundreds of pages of vague, equation-free speculations (which have not held up over time), it is no bigger than any modern textbook[4]. Older professors treat this book with great respect because it dates from the "golden age" of relativity, which led to the great advances of the past 50 years. But learning from it today is like learning electromagnetism from Maxwell's *Treatise*.

The basic rule is that you should only believe a book recommendation if it was written by somebody who actually read and understood the book, didn't already know the subject before reading the book, and knows how it compares to other books and the modern research literature, preferably because they actually use its content in practice. With that out of the way, here are links to some often-cited internet resources.

- Chicago Undergraduate Physics Bibliography. This is a list of books aimed towards learning theoretical particle physics. It has solid advice, but it's also 20 years out of date and missing many of the canonical books.
- How to Learn Math and Physics. This list, oriented towards mathematical physics, is also 20 years out of date. It has great books on the list, but it could be difficult to use for a self-learner because fluffy, equation-free popular books are placed right next to advanced graduate texts; undergraduate level books are almost absent.
- How to become a GOOD Theoretical Physicist. Gerard 't Hooft was one of the giants of particle physics. About 30 years ago, he compiled a massive list of resources available around the internet at the time. Unfortunately, the list was never finished or updated. Now, half the links are broken, and the rest point to abandoned, unfinished drafts of lecture notes from random universities that are honestly subpar, even compared to Wikipedia. It's constantly recommended because its length and author are impressive, but as far as I know, nobody has ever actually used it. If you ever run into anybody who claims this is the best overall resource for learning physics, you can be sure that they don't know anything about physics at all.
- So You Want to Learn Physics.... Susan Rigetti's book list is much more useful than the others here, because she understands how it felt to be a student. This short list covers a full undergraduate and graduate education, based on the canonical books.
- So You Want To Be A Physicist. This is a huge resource that covers everything about the process of becoming a physicist in the US, from high school to postdoc applications. There's

[4]Indeed, when it was published, the great physicist Chandrasekhar complained that "there is needless repetition (indeed, almost everything is stated at least three times) and the style fluctuates from precise mathematical rigor to evangelical rhetoric (which often obscures and confuses the issues)."

not much on the learning process itself, but it's helpful, especially if you're coming from outside physics or outside the US.[5]

- 4chan's Physics Textbook Recommendations. A surprisingly solid list, including references to much older books, along with rather brief but opinionated commentary.
- A Physics Booklist. Once upon a time, the internet was arranged around discussion forums, the greatest of which was sci.physics. As old-timers bitterly recount, it died a slow, agonizing death 20 years ago as crackpots came online and outnumbered the people who actually knew things. This unhelpfully long list is one of the relics of this lost civilization.
- Book Recommendations. I help curate this massive list of lists of book recommendations on Physics StackExchange, which is the closest thing to a successor of sci.physics. It's many times larger than all the other lists here combined, but that also means it has a lot of cruft.

[5]If you're an international student, you can also find information on Academia.SE. However, I don't recommend taking the site too seriously, because it has a strong bias. Any post that complains about international students quickly receives a hundred upvotes and thousands of views. But any post *from* an international student being mistreated is condescendingly mocked, downvoted, closed, and deleted. I've heard privately from several people demoralized by this process, and I'm sorry. The reason is structural: the people who spend all day on that site moralizing about the "inferior culture" of other countries are sad, jaded folks who have fallen victim to the adjunctification of higher education. Like the vast majority of "professors" in the US, they zip around several college campuses a day administering high-school level multiple choice exams to unmotivated students (who really *are* constantly cheating), for less than minimum wage, and no job security. This process turns them nasty, as it would to anyone.