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, which roughly corresponds to the MIT courses 8.01 and 8.02. See the final exams for these courses if you want to check. If you enjoyed what you learned, there are many ways to deepen your knowledge.

- To get a deeper understanding of mechanics, try the books by Kleppner and Kolenkow (1st edition) or 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* (3rd edition) by Purcell and Morin, used for honors introductory physics at Princeton. It has many insightful problems, but it's best known for using relativity to introduce magnetism, in the brilliant chapter 5. 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.
- 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.
- If you prefer video lectures to books, there's an exceptional amount of good content on MIT OCW. The classic lectures by Walter Lewin for 8.01 (mechanics) and 8.02 (electromagnetism) are mathematically elementary, but have many interesting physical examples. Multivariable and vector calculus is covered very clearly in 18.02. For waves, see either Lewin's 8.03 lectures or the newer OCW version.
- 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 find any errors, email me!
- If you run out of practice USAPhOs, AAPT sells a CD-ROM of USAPhO exams going back to 1997. You can ask your physics teacher to purchase this.
- Many problem sources are listed in the Syllabus for my tutoring program, 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. (However, I don't recommend using this as your main source of practice. A number of problems rely on obscure tricks. It's best when used as food for thought.)

More Advanced Physics

There's also a lot you can do if you want to move 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.

[1] These reviews are especially dangerous because they make it hard to differentiate quality. For example, A Student's Guide to Maxwell's Equations is decent, but A Student's Guide to Lagrangians and Hamiltonians is atrocious: its notation goes undefined and its derivations are just wrong. Every month I see a nonsensical StackExchange question from a poor student who's been terribly misled by the latter book. But both have a hundred five-star ratings online.

- 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 course 8.03, with further background given in the course 18.03 on Differential Equations. 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 complement, see David Tong's notes on Dynamics.

- The standard undergraduate textbooks are clear, but they focus on explaining theory, at the expense of truly tricky problems. They can give you the mistaken impression that more advanced physics just consists of grinding out calculations using established procedures. 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$^{\text{th}}$ century loved tricky problems, and they invented these theoretical tools precisely to solve them. To see a bit of this side of physics, try flipping through *Exploring Classical Mechanics* by Kotkin and Serbo, and *Static and Dynamic Electricity* by Smythe. The latter is a real classic; it's the harder version of Jackson.

- 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 very clear and crisp.

- After learning about waves and differential equations, you could start introductory quantum mechanics, from the wave mechanics perspective. The most common book with the lowest prerequisites is *Introduction to Quantum Mechanics* by Griffiths, which comes with clear explanations and great problems. However, many complain the book uses too little math, hiding the essential structure of quantum mechanics behind elementary but messy derivations. For video lectures at a similar level, try the 8.04 lectures by Barton Zwiebach (more clear) and Allan Adams (more energetic).

[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.

- To get a deeper understanding of quantum mechanics, you're going to need to learn linear algebra. The book *Introduction to Linear Algebra* by Strang, used for 18.06 at MIT, is excellent for this. You might not see why linear algebra would be useful, given how it's glossed over in high school, but you'll probably use linear algebra constantly throughout your life, possibly even more than calculus, even if you don't go into physics!

- If you want a deeper introduction to quantum mechanics, that uses linear algebra freely, try *Principles of Quantum Mechanics* by Shankar, or the 8.05 lectures. Alternatively, if you have less physics background, consider Umesh Vazirani's Quantum Computation course. Quantum computation is a great place to start because it uses all the weirdest features of quantum mechanics, without the distraction of solving complicated differential equations.

- 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.

- 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.
  - 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.

[3] And it's easy to go astray even if you have excellent reading comprehension, because English is ambiguous. For example, if nothing is better than ice cream, and licorice is better than nothing, is licorice better than ice cream? There's a whole field of philosophy devoted to paradoxes like these, though to people who know math, it tends to look like trying to bang rocks together to make fire.

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 two main reasons advice can be bad. The first is that many study guides are written by people who have never actually learned the basics. 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. The second is that most of the remaining study 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. 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.

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 20 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 rough drafts of lecture notes that are honestly subpar, even compared to other free resources. It's constantly recommended because its length and author are impressive, but as far as I know, nobody has ever actually used it.

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

- A Physics Booklist. Once upon a time, the internet was arranged around discussion forums, the greatest of which was sci.physics. It died a slow, but natural death 20 years ago as crackpots came in and people who actually knew things quit in exasperation. 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.

Finding Friends

Learning alone is hard, and it's natural to search for likeminded people. Unfortunately, this is an almost impossible task, because physics is unpopular and deep knowledge is rare. As they say, everybody wants to be a physicist, but nobody wants to read these long-ass books.

Here's a simple illustration of this. What's the average distance, in 3D space, between two randomly chosen points in a unit ball? It's a simple question. Consulting the internet, we find that:

- On Math StackExchange, there are 4 answers, and 3 are detailed and correct.
- On Yahoo Answers, there are 9 answers. The top two are correct, and the rest are spam.
- On Reddit, there are 5 top-level comments, all of which say they can't solve it.
- On Quora, there are 11 answers, almost all of which are confidently wrong, or spam. The single correct answer is buried down the list.

This illustrates the difference between the main sites. StackExchange is quite reliable, but discourages socialization. Yahoo Answers was rough and occasionally brilliant, but it's shut down now. Reddit is lively but tends to be superficial, since comments are rarely seen again after a day. And Quora, well... when I started college, they were growing fast with an endless pile of cash, and seemingly everybody wanted to intern with them. Their press releases declared they were revolutionizing human knowledge. A Stanford particle physicist quit his professorship, declaring that our field was dead and Quora was the future. Brilliant minds devoted their energy to maximizing its growth, using every cheap trick in the book.

Unfortunately, along the way they forgot that engagement numbers and SEO are only worth something if your site actually has content worth reading. Now it's a sad pile of trash – though it's also a really *big* pile of trash, with a $2 billion valuation, which should allow them to continue playing this game for years. The lesson for you is that the sites holding the top Google search results are often there because they hire engineers to optimize their rankings, not because they're any good. That is why, despite all the promise of the internet, search results in physics are still not as reliable as the average library.

You can try to look for smaller pockets of enthusiasts, but here you need to be even more careful. You're definitely smart enough to not fall for Flat Earthers, but this can give you false confidence: it can make you think that you have the "critical thinking" skills to reliably tell truth from bullshit, even in unfamiliar domains. In reality, there is no such thing as critical thinking skills. There is only domain expertise, and if you don't have it, you're just another sucker.

Here's an example. Vector calculus notation looks neat, but as you use it more, you'll see its shortcomings. For example, parts of it collapse when you change the number of dimensions, and it has to resort to ugly hacks like "dyadics" to represent tensors. Therefore, more advanced physics textbooks teach you two more tools: index notation, which is a powerful general method for manipulating tensors, and differential forms, which are an extremely elegant way to deal with antisymmetric tensors.

Unfortunately, if you're at the first stage, but then fire up your web browser instead of opening a book, you'll probably get sucked into "geometric algebra", or "Clifford algebra", which has a thriving online community. This is a more powerful notation than vector calculus, but it's not used in physics because it's less powerful than index notation and less elegant than differential forms. Its enthusiastic proponents, however, rarely know this, and instead conclude that physicists are in a conspiracy to "suppress" geometric algebra! If you swallow this and join the community, you'll soon run into much crazier claims, such as homemade theories of everything that claim to resolve all problems by switching to geometric algebra notation, which is no more plausible than solving famous problems by switching your font size or page margins.

It would be easy to give ten more examples, or a hundred more, but then I would have a big target painted on my back, and this document would be too long to read. Let's just keep it simple.

- Read physics. Not too much. Mostly books.
- Consult books before Google. Consult Google for entertainment, or to find a book to read next.
- Trust only what you can personally verify. Simply ignore big or puzzling claims in fields where you can't verify anything; you'll get there in time.
- *Eloquence has no relation to truth.* If I put a physics prompt into GPT-3, it can instantly spit out pages of flowing prose. And if I squint, it'll look okay; the right keywords will be there, in roughly the right order. But on a second glance, it'll turn out to be completely wrong. That's because writing with flow is easy, and understanding physics is hard. Remarkably, many people have trained themselves to become knockoff versions of GPT-3. You can sometimes find them writing very long, popular answers on social media, which consist entirely of snippets from Wikipedia, with the sentence structure changed up, glued together with transition phrases. They're well-intentioned, and merely following how we were all taught to write papers in high school English class, but they're probably not worth reading because you can just go to Wikipedia yourself.
- Don't unconditionally trust any guru figures. Especially if they say a few things that make sense – many such figures hook you with correct explanations of classical physics, then gradually transition to spouting nonsense about more advanced physics.[4]
- Don't unconditionally trust articles. There is an endless supply of bottom-tier popular science sites that exclusively produce clickbait. Their "journalists" don't even understand introductory physics, and the only difference between them and a total rando is that they get paid five cents a word. If something sounds too mindblowing, it's probably fake, though sometimes it's real but just garbled. The only way you'll ever be able to tell is by working through textbooks.
- Don't unconditionally trust real newspapers either. Their journalists are still only human, and while they're better writers, they still usually don't understand introductory physics. They can be tricked by a charismatic figure just like you can. Of course, the same goes for TED talks, "ideas" festivals, and podcasts.
- Don't unconditionally trust university press releases or scientific articles. Sadly, there are many unreliable journals where peer review is perfunctory at best. And university press offices often

[4] Another hint is that often their understanding of physics is quite shallow, and after a short time they'll start repeating a couple phrases like a deranged Pokemon. I once met a guy who would not stop saying that an electron was "two photons going 'round and 'round". When I told him why this couldn't be, he tracked down where I lived to threaten me.

exaggerate their university's role in new research, or suggest it has more important implications than it does, sometimes through sneaky wordplay.

- Don't unconditionally trust documents with a lot of math. For example, if you ever see a paper that goes through 20 pages of abstract category theory, then triumphantly concludes that it has explained, say, the origin of life, you should be very suspicious. Math doesn't have magic powers; it is just a useful formal language for reasoning. If a mathematical argument doesn't start with concrete physical assumptions, it can't lead to nontrivial physical conclusions.
- Don't trust anything that could only be true if all physicists were evil or stupid. If somebody ever tells you the only reason their idea is rejected is that physicists are closed minded, what they're really saying is, "there are extremely strong arguments against my claims, but I'd rather you not know them." If there actually was a good reason to overturn conventional physics, we would not be suppressing it, we would all be racing to explore it and claim a Nobel Prize.

And if you want a real physics learning community, don't search online. Find a few likeminded friends, and meet in person. Large groups tend to devolve into complaining about physics, or trying to game tests. Keep it small, because only small groups can change the world.