Advice After Introductory Physics

Over the years I've met a lot of high schoolers 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 (1^{st} 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* (3^{rd} 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 mid-undergraduate 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, 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. (The better ones have some derivations, but often the derivations are wrong!)

  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 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 Tong's lecture notes for a clean approach that gets to tensors 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.

- 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. On the other hand, some argue that 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).

- 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 a strong math background but 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 during high school. 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 that's all they are. On the internet you'll find many lost souls who have taken the analogies too literally, arriving at homemade theories that have little to do with anything in physics.[1]

  Anyway, if you're a bright high schooler 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.

  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.

Many more resources are listed in the Book Recommendations thread on Physics StackExchange. Also see Susan Fowler's book list, which documents her journey learning physics from scratch.

[1] 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?