Advice For Introductory Physics

In this file I answer some frequently asked questions about learning physics and entering physics competitions. For general logistical questions, see the USAPhO FAQ on the official AAPT website. For advice for how to continue after finishing introductory physics, see this file.

What should I know before I start learning physics?

In the American system, people typically learn physics in two stages. First, they take a year-long algebra-based introductory course, which covers all subjects (mechanics, electromagnetism, thermodynamics, a hint of modern physics), typically given in 10^{th} or 11^{th} grade. Those that are interested in learning more typically take a second, calculus-based introductory course, which covers only mechanics and electromagnetism.

To succeed in an algebra-based physics course, you need to have your mathematical basics down. You should have a good grasp of algebra and trigonometry, have good "number sense" for arithmetic, and know how to read a graph. This background is typically provided by Algebra II or Pre-Calculus high school courses. If you don't have this stuff down cold (e.g. if you take more than one second to recall the value of $\sin 30°$), then everything will be much harder, because a two-step problem will *feel* like it's twenty steps, as you scramble to remember math you've half-forgotten. It's like trying to play soccer while hopping on one leg.

What should I know before I start entering physics competitions?

For people coming from a math background, the most important thing to remember is that physics competitions aren't like math competitions. The reason is that the typical American 10^{th} grader has taken ten years of math in school and *zero* years of physics. If you're a bright student that likes math, math competitions are a fun way of extending the knowledge you've spend a decade building – you already have the foundations set.

If you've done well on math competitions, it's tempting to jump directly into physics competitions with the same attitude. After all, physics is just made of equations, which are math, right? If you haven't taken a solid year-long introductory physics course already, this attitude will make you crash and burn. It typically results in people memorizing big lists of equations, without being able to answer the most basic conceptual questions, and making ridiculous mistakes like confusing tension T for time T because they're the same letter. Without introductory physics under your belt, you're in the same position as a 1^{st} grader is in math, trying to do a math competition without even knowing how to add.

Another important difference is the role of more advanced classes. Richard Rusczyk famously wrote in *The Calculus Trap* about how the standard math curriculum (calculus, multivariable calculus, linear algebra) often just teaches a few calculational skills, without emphasizing the problem solving skills needed in math competitions.

This is true, but physics is different. Math competitions teach you a way of thinking, so their subject matter is somewhat arbitrary: for example, they typically contain lots of Euclidean geometry but no calculus, when it easily could have been the other way around. But both physics competitions and physics classes teach you a way of thinking *about the physical world*. Both competitions and advanced classes are getting at the same thing. There is no special "competition track". You just learn more about the world either way.

So if you've genuinely learned topics like relativity and quantum mechanics on your own time, don't hesitate to jump into competitions. And if you're debating whether or not it'd be useful to take that second, calculus-based physics class, just do it. It's all good stuff, because it's physics, and physics is fun.

How do I start learning physics?

The most common and best way to start learning physics is from your high school physics teacher!

What if I don't have a physics teacher, or want to start earlier?

You're in luck, because there are more resources for learning physics independently now than ever before. You can consider massive open online courses, offered by either EdX or Coursera. There are also many companies offering AP Physics 1/2 courses online, which also does the job. One option favored by many homeschoolers is Stanford's Open High School. If you're self-motivated, the most comprehensive option is to study from a good book, listed below.

If you're just starting out, I would advise against using any resource that isn't designed as a cohesive whole. For example, the popular websites Brilliant and Expii have lots of neat problems collected largely by volunteers. But at this point, their physics material isn't developed in a complete and logical manner. The problems have wildly different notation and conventions, and units tend not to be self-contained, often requiring knowledge from *later* units. It's akin to learning physics from Wikipedia, which often just magnifies confusion. I spent a lot of time on sources like this at a young age, wondering why somebody didn't just unify the material into a cohesive, linearly organized whole. Only later did I realize that this is literally what books and courses *are*.

If you're looking for a calculus-based introductory course, instead of an algebra-based one, some of the very best options are free online courses. Two great options are Yale's Fundamentals of Physics courses and MIT's 8.01 and 8.02.

How do I know if I understand algebra-based introductory physics?

I'll let you in on a secret: there's a standard benchmark exam used in physics education research called the Force Concept Inventory, which is designed to expose all the common misconceptions students can have in introductory mechanics. Performance on this exam is used to evaluate new teaching methods. (Of course, it only works if people don't know about it beforehand – but I think there are few enough people reading this that it won't matter.)

Find a copy of this exam online. There are 29 questions in the original version. If you understand basic, algebra-based mechanics, you should get at least 90% (i.e. a perfect score up to silly mistakes) in less than 30 minutes. If you can't do this, you likely have deep misconceptions about mechanics that you should resolve before doing anything else.

The newly redesigned AP Physics 1 and 2 exams are also a good benchmark; these cover mechanics and everything else, respectively. If you can't comfortably score a 5 on AP Physics 1, your mechanics isn't in good shape. (AP Physics 2 is a bit different, because it covers a hodgepodge of topics rather superficially; I don't think you miss out on anything if you just save topics like thermodynamics and modern physics for later.)

What are some good introductory books at each level?

There's a standard set of book recommendations, which almost everybody, from USAPhO organizers to Art of Problem Solving instructors will tell you, and I agree with it.

- For basic algebra-based physics, I recommend *Conceptual Physics* by **Hewitt**. A great source of accompanying conceptual questions is *Thinking Physics* by Epstein. (If you're taking a school course, you could also use the book they give you, but generic high school books aren't very good. At the least, you want to make sure you get a book aimed at college students.)
- For basic calculus-based physics, there are many good and nearly identical books on the market. Good examples include *Physics for Scientists and Engineers* by Knight, and *Fundamentals of Physics* by Halliday, Resnick, and Walker.
- For more advanced calculus-based physics, I recommend *Physics* (5^{th} edition) by **Halliday, Resnick, and Krane**. This book was designed for college honors courses, and has significantly more challenging problems, which were edited by a past director of the USAPhO.

Make sure not to confuse the two books by Halliday and Resnick. If you want to get an idea of the difference, compare the tables of contents for both books. Generally, *Fundamentals of Physics* has roughly the most advanced one-third of each chapter of *Physics* removed, and simpler examples.

How much time will it take to qualify for USAPhO/qualify for USAPhO camp/win an IPhO gold medal?

This varies a lot depending on the person and their motivation, but here's my timeline.

- 9^{th} grade: I took a standard pre-calculus course in school and didn't know or learn any physics.
- 9^{th} grade summer: I don't recall learning anything during this time. I think a lot of videogames were involved, with occasional breaks to practice for math competitions.
- 10^{th} grade: I took a standard calculus course in school, concurrently with a standard algebra-based introductory physics course, with great teachers in both. I didn't do any prep for competitions, but I asked a lot of questions in class, thought carefully about the intuition behind the equations, and read the generic high school textbook given. This background was enough to qualify for the USAPhO, but not enough to do any of the questions on it.
- 10^{th} grade spring/summer: I self-studied calculus-based physics, at the level of AP Physics C. This took roughly 150 hours of work. Some of this was done while avoiding MOP homework.
- 11^{th} grade: I self-studied from Halliday, Resnick, and Krane and did practice tests. I worked roughly 10 hours a week on this, for about 250 hours in total. That year I qualified for camp and got an IPhO gold medal.

The main point here is that you don't have to jump the gun. You don't need multiple years of study to learn everything you need for physics competitions, you just need to get the basics down and spend maybe one year learning on top of that. As you can probably tell from the rest of this document, I think a lot of people are rushing, thinking that they need half a decade of exposure to competitions and expensive prep programs to succeed, when the real route involves building a solid foundation using what you learn in school. And this isn't just my experience. When we ask students who qualify for camp to describe their journey, they usually say something very similar.

What makes a competition prep program effective?

The only thing that makes a prep program effective is the student. The simple fact is that if a student isn't engaged, then prep programs are useless at best. This is obvious if you just look at the numbers. Suppose an unmotivated student is dragged to a 1.5 hour class every week for eight weeks, then grudgingly spends an hour a week on the homework. That only adds up to 20 hours of experience, and not very high-quality ones at that. If practice stops entirely once the class ends, most of that knowledge will be quickly forgotten.

Compare this to what I listed above: 400 hours accumulated over a year. Objectively, that isn't a lot of time; people could easily spend longer than that on a single high-school course if it's loaded with busywork. But these hours were focused ones, and they were spaced out regularly. I didn't need to cram, because I'd been immersed in physics the whole time.

You might think that prep programs can cut down the hours needed because they "teach to the test". However, this is a myth. Even the $F = ma$ exam requires a broad understanding of mechanics, precisely the same understanding that a college student would learn in an honors introductory mechanics class. It's certainly possible to characterize the solutions to individual $F = ma$ problems as "tricks", but if you don't have the full background, there will be an overwhelmingly large number of tricks for you to memorize, and they'll be ten times as hard to remember because you won't know where they come from.

If that doesn't convince you, think about learning an instrument, playing a sport, or learning a language. Do football players cram in eight hours of practice the day before a big match? Have you ever seen a pianist who got anywhere on an hour a week of practice? Of course not, and learning physics (yet another language) is no different. There is no secret. You just have to engage.

In the tutoring program I offer, class is held for one hour a week, but I expect all students to work, at the very least, an hour a day outside of class. My students credit me for helping them develop their intuition and finding interesting problems for them to do, but they don't credit me for teaching them physics in general, and rightfully so. That learning has to happen outside of class.

Is prep program X, book Y, or course Z enough for USAPhO?

This isn't a meaningful question. It's not about how much money you spend, it's about how much time and meaningful effort you spend on physics in general. Almost any full calculus-based physics course, book, or prep program is "enough", in the sense that they'll all cover everything you need. It's up to you to turn that coverage into understanding. A common trap seems to be collecting a huge pile of resources, then only using them superficially or not at all. In fact, two prep programs that you spend 2.5 hours a week each on are probably less effective than one book that you spend 5 hours a week on, just because your attention won't be divided.

Do I really have to learn X if I want to win competitions?

For almost any value of X, the answer is "probably not", but if you ask this kind of question constantly, you won't do well anyway. Stop and find a different extracurricular, one where you're excited to do more rather than bargaining to do less.

Okay, but can I qualify for USAPhO without knowing calculus?

Every problem on the $F = ma$ exam can be solved without calculus. However, most students who pass the exam know calculus-based physics. The reason is that it's hard to derive most equations in physics without using calculus. And if you don't know how the equations are derived, you might end up seeing them as a disconnected pile of results instead of an interconnected web of ideas. This penalizes you on the $F = ma$, where many questions require the test taker to think carefully about which equations apply and why. It's certainly not impossible to pass without calculus, but you're going to have to put in the time to build a solid conceptual understanding either way. In fact, this might end up taking *longer* if you try to do it without calculus.

How should I prepare for the $F = ma$?

The $F = ma$ is a bit strange because it throws a lot of multiple choice questions at you, under extreme time pressure. You only have three minutes per problem, but some problems could take over an hour if you approach them the wrong way.

If you have trouble with these kinds of fast-paced exams, the best thing to do is to train on similar problems and under timed conditions. I recommend past $F = ma$ competitions and the multiple choice problems in Halliday, Resnick, and Krane. After completing the $F = ma$ exams, you can check against the official solutions manual, which is available for free on the AAPT website. Another excellent resource is Morin's *Problems and Solutions in Introductory Mechanics*, which contains a lot of multiple choice questions, with explanations, at about the right level.

If you run out of other resources, you can also try past PhysicsBowl questions, the CAP prize exam, or the first round of the British Physics Olympiad. There are also old $F = ma$ exams going back to 1997 available for purchase on the AAPT website. However, all these competitions are somewhat more straightforward, and also contain non-mechanics questions.

What's the best way to spend my time learning?

There are a million books and blogs and papers out there about how to "optimize" learning, but ultimately everybody agrees on a few basic principles.

- When you read about a new physical idea, turn it over in your head. Ask yourself where you've seen the idea at work in the real world. Look at the logical development of the idea – what assumptions do you need to get from one equation to another? Take limiting cases of the equations, and try to relate them to ones you already know.

- Make sure you can reconstruct the idea, or at least the intuition for it, from scratch. One of the best ways to do this is to try to explain it to somebody else. You can also just imagine doing this, by talking to a rubber duck or writing your own notes.

- The best way to remember something is by spaced repetition: immediately apply the idea once you learn it, then reencounter and using the idea regularly. Physics books and classes will automatically do this for you, as long as you work steadily and linearly through them.

- Do practice problems that are at or just above your current level. They should be hard enough to require your full attention, but not so hard that you spend long stretches of time making no progress. Don't peek at solutions until you give each problem a good try. If you need to peek at the solutions for more than half of the problems you're attempting, they're too hard.

- When you finish doing a practice problem, reflect on what went well or poorly. If you weren't able to do it, figure out the crucial steps you were missing. (If these "missing steps" were more than half of the entire solution, you may have to go back and do more reading.)

- Make sure your studying is healthy. Long cram sessions aren't effective. Take regular breaks and use them to stretch your legs. Sleep at least eight hours a day, drink water, eat food, and generally obey common sense. Studying when your brain or body is tired is only useful for mindless tasks like cramming things into short-term memory, the opposite of what you need.

At the introductory level, your practice problems will be from whatever book you're reading. Gradually you'll be able to mix in $F = ma$ problems, then USAPhO Quarterfinal problems, then full USAPhO problems.

What's the most important trap to avoid?

The biggest trap is overplanning. A lot of people get caught up on finding the *optimal* books and the *optimal* practice problems, and never actually starting to do either. Some people even make a detailed, multi-year study plan for getting an IPhO gold medal set before they learn Newton's laws, which is both a waste of time, and seriously demotivating once they realize that making a plan is much easier than doing it.

Again, sports are a good analogy. Consider somebody who made their country's youth soccer team. They probably started by playing casual games with their friends, perhaps on their school's soccer team, gradually building up their skills while having fun. As they got better, the stakes were gradually raised, until they ended up doing daily, carefully designed practice with a coach. But it wouldn't have made sense to go looking for that coach before even learning the rules of soccer!

Long-term motivation comes from small, consistent wins, not distant goals. After an hour of learning, it is much more motivating to think "now I know why sunsets are red" or "now I know why violins have those f-shaped holes" than "now I am 0.1% closer to an IPhO gold medal". Excessive planning gives you a false sense of a distant goal moving closer, which can be exciting, but ultimately isn't good for anything. The trap is to get addicted to that *feeling* of progress, to the point that you want it more than *actual* progress.

If you want to learn physics, the most important thing is to do physics. Even reading the worst possible book is better than doing nothing. (When I decided to start learning physics, I chose a book almost at random, buying a cheap used copy of HRK with the spine falling off, and started reading it the day it arrived.) If you can't bring yourself to even open a physics book, after months of deliberation, then you should do something else, something that you're actually interested in.

What physics should I learn after finishing introductory calculus-based physics?

First, congratulate yourself on learning a tremendous amount about the world! You now understand the world around you better than 99% of humans who have ever lived. You've assimilated a body of knowledge built by thousands of physicists throughout history.

Then clean up the confetti and see my second advice file for lots of options for further reading. Now that you're done with the basics, your options open dramatically, and you've earned that freedom.