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, and corresponding to AP Physics 1 and 2. Those that are interested in learning more typically take a second, calculus-based introductory course, which covers only mechanics and electromagnetism, corresponding to AP Physics C.

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 $\sin 30^\circ$), 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 can I tell if I understand algebra-based introductory physics?

I'll let you in on a secret: there are standard benchmark exams used in physics education research which have been designed over years to measure exactly this, for the purpose of evaluating new teaching methods. Examples include the Force Concept Inventory and the Conceptual Survey of Electricity and Magnetism. (Of course, they only work for research if people haven't seen them beforehand, but I think there are few enough people reading this that it won't matter.)

Find these exams online. If you understand basic mechanics and electromagnetism, you should be able to get above 90% on the FCI within 30 minutes, and above 80% on the CSEM within 45 minutes. If you can't do this, you likely have misconceptions 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 robust ecosystem of physics textbooks, with many good options. The recommendations I give below are pretty standard; for more data, you can consult AIP's survey of physics teachers.

- For basic algebra-based physics, the most commonly used books are *Holt Physics*, *Physics Principles and Problems*, *Conceptual Physics* by Hewitt, and *Physics: Principles with Applications* by Giancoli. I recommend the last two. Hewitt is a good option for a typical high school course, while Giancoli is good for an honors high school course, such as for AP Physics 2. Neither are enough for physics competitions, but they'll set a good foundation. If you're comfortable with calculus, you might be able to skip this level entirely.
- For basic calculus-based physics, there are many books, such as the ones by Giancoli, Knight, Serway and Jewett, Tipler and Mosca, Sears and Zemansky, and Halliday, Resnick, and Walker. They all cover the same material, with nearly identical tables of contents. They are also all about equally good, though I would recommend Serway and Jewett if you had to choose one.
- For more advanced calculus-based physics, I recommend *Physics* (5^{th} edition) by Halliday, Resnick, and Krane. This book is used in college honors courses, and has significantly more challenging problems, which were edited by a past director of the USAPhO. The explanations are very clear, and I know many people who have succeeded using it.

For historical context, the modern era of introductory calculus-based physics textbooks in the United States was started by Halliday and Resnick in 1960. It became so popular that all the other calculus-based textbooks listed above are just watered down descendants of it (i.e. taking topics out, but never adding any new topics in), which explains why they're so similar. Even Halliday and Resnick itself has been watered down: *Fundamentals of Physics* by Halliday, Resnick, and Walker is essentially *Physics* with the most advanced third of each chapter removed.

When shopping for these books, you might notice that they come in many editions, sometimes more than 10, and that the latest edition costs much more than the rest. In general, there is very little difference between the most recent edition and the previous three. The purpose of making so many editions is to keep the used book market down and hence the money coming in, since courses generally require students to buy the latest edition. If you're self-studying, there's no need to buy the latest edition. An exception is Halliday, Resnick, and Krane, since many new questions were added in the 5^{th} edition, including all of the very useful multiple choice questions.

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, and 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 occasionally skimmed the mediocre *Holt Physics* book 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 by reading the even more mediocre Barron's AP Physics C prep book and randomly googling whenever I got confused. This took roughly 150 hours of work. Some of this was done while avoiding MOP homework.
- 11^{th} grade: I read the awesome Halliday, Resnick, and Krane book 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 need multiple years of study or a ton of prep programs to succeed. You just need to get the basics down, and spend about one year learning on top of that. 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?

Almost any full calculus-based physics course, book, or prep program is "enough", in the sense that they'll all cover everything you need. But it's up to you to turn that coverage into understanding!

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 technically 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 only see 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. In general, if you're the kind of student interested in physics competitions, you would almost certainly enjoy learning calculus, so you should go ahead and do so!

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

The $F = ma$ is a bit strange because it throws a lot of tricky 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 past solutions, available for free on the AAPT website, or the more refined official solutions manual. 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 problems, you can also try past PhysicsBowl questions, the CAP prize exam, the first round of the British Physics Olympiad, or the Hong Kong 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 some 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 spaced repetition: immediately apply the idea once you learn it, then reencounter and reuse it regularly. Good physics books and courses will automatically make you do this, 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, then IPhO/APhO problems if relevant.

What's the most important trap to avoid?

If you're at a "great" high school, the biggest trap is signing up for as many AP classes as your school can possibly provide, and spending all your nights and weekends grinding out busywork that you don't really care about. Or jockeying for "leadership" positions in a huge array of artificial clubs that go on to do nothing. People do this out of some perceived obligation to be "well-rounded", but that's really not how it works. (And even if it *were* how it worked, it wouldn't be worth doing!)

Provided you escaped this rat race, the second 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 just *do* physics.

Do I have enough talent to succeed?

In response to this difficult question, many well-intentioned adults assert that talent does not exist, or that anybody can do anything if they really try. These sentiments come from a good place, but they're rarely satisfying to their recipients because they're clearly not true. Talent does exist. It's the reason that wealthy families often need to spend tens of thousands of dollars propping up their children's SAT scores, to get outscored by less advantaged kids using only the $20 Blue Book. More dramatically, it's the reason that Ramanujan went from being the son of an Indian clerk, doing mathematics alone in near starvation, to the apex of mathematics in Cambridge.

The more nuanced story is this: in legitimate systems, success comes from ability, and ability comes from dedicated, effective practice. Dedicated practice comes from interest, and interest is mediated by a combination of talent and socioeconomic factors. To illustrate this point, consider the extreme case of child prodigies. Prodigies exist in chess, music, math, and programming, but not in law, medicine, history, or literature, because the former allow rapid learning and feedback, starting from minimal background knowledge. Children naturally learn quickly, and a child knows immediately whether they've won or lost at chess, and when they've made a clever move. Talent determines how often these exciting wins happen, and if there are enough, a child can take a liking to chess, and begin a phase of rapid improvement.

Of course, socioeconomic factors play a role. Chess prodigies need someone to introduce them to the game in the first place. They need stable homes and supportive parents, so that they have space to focus on learning. They benefit from chess-playing adults they can look up to, a community to help them learn faster, and a system of competitions to help them set goals and measure their progress. That's of course why chess prodigies appear in the West, Go prodigies appear in Asia, and neither appear in bad times.

What does this have to do with physics? When I was a kid, I had a naive view of physics based on talent. I thought every "level" of physics required some minimum bar of talent, and that people just kept climbing until they hit a wall, a level of abstraction they were simply unable to grasp. After all, that's how adults talked about it. They'd say things like, "math stopped making sense for me at trigonometry", or "I couldn't make it past differential equations." So when things got hard, such as when I started quantum field theory, I had a sinking feeling that I was "hitting the wall."

But in reality, the complexity of learning things stays relatively constant. With modern resources, the difficulty of learning quantum mechanics is about the same as learning introductory physics, *provided you have equal mastery of the prerequisites.* The reason people hit walls is largely not because the material gets inherently harder, but because they suddenly fall through the massive holes in their foundations. (These holes can be prevented or patched by a combination of talent, effort, or good teaching.) Algorithmically, differentiating functions is not more complex than doing long division: the number of things to keep track of, and new rules to apply, is comparable. But people get stuck at the former because it tends to expose all the misunderstandings they've ever had about basic things, like simplifying fractions. That's the problem; it's not the raw complexity of manipulating the symbols, because all of us can fluently follow a much larger set of rules for manipulating a much larger set of symbols, namely our own language.

Incidentally, while I brought up child prodigies to illustrate a point, they shouldn't worry you in physics, even though they certainly exist. Sometimes people give up because they know people younger than them who are "ahead". This makes as little sense as worrying about all the people older than them who know more. How are you ever going to catch up to the people who are already in graduate school? The question doesn't make sense, because success doesn't come from "catching up" to people. (In this respect, chess was a bad analogy, since your ability there is directly

measured against others.) There's no reason to dislike prodigies, as if they were doing something developmentally unnatural. There is nothing especially natural about learning algebra at age 14, introductory physics at age 16, quantum mechanics at age 20, and quantum field theory at age 23. It's only how the usual track through our system happens to be set up at this moment, as a product of history and circumstance. And there's no reason to get insecure over prodigies either. Success in physics comes from accumulating a body of knowledge, which takes on the order of one year for high school physics competitions, and ten years for physics research. People who get to that point earlier in life just get more time to use it; they don't stop you from doing the same.

So let's say that you're interested in learning more physics. In the ideal case, this interest came from talent mediated by socioeconomic factors. You already had strong foundations in math, and when you learned basic elements of physics, whether from a physics teacher, books, or Youtube videos, things clicked for you. You saw the world in a different way, and it felt good.[1] You have some idea of what knowing more physics is like, whether it's from older adults, famous physicists, or popular science books, and you want that. You know that while people tend to say learning physics is not too practical, it's not *impractical* either; the employment prospects for physics majors are great, even though faculty positions are scarce.

If this applies to you, then if you continue learning physics, it will keep paying off. You'll continue to get "aha!" moments. You'll continue to be able to piece together, with concentrated effort, new ways of looking at the world. Of course, the *rate* at which you do this is partially determined by talent. But if you've made physical insights before, you will continue to make them in the future, provided your foundations are good. There is no wall; how far you go is up to you.

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

First, congratulate yourself on learning a tremendous amount about the world! You've assimilated a body of knowledge built by thousands of physicists over centuries. You've been inducted into a deep new way of looking at the world, which has produced some of the most awe-inspiring intellectual achievements of humanity.

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.

[1] If you're reading this document, but this has never happened to you, that's a red flag. It could mean that you prefer the idea of doing physics, or the prospect of using it to get into college, to actually doing physics. You should stop and figure out whether you're actually interested in physics itself. If you're not, learning it will be very difficult.