Preparing for the Experimental Exam

This problem set gives tips for preparing for the experimental exam at international-level Olympiads. For some other discussions, see chapter 7 of *Physics Olympiad: Basic to Advanced Exercises*. For more ideas for at-home experiments, see *Waves* by Crawford.

0 Introduction

Students often feel lost when facing the experimental exam. While there are abundant free resources for learning theory, it seems impossible to prepare for the experiment without access to lots of limited or expensive equipment. However, while doing real experiments certainly is the best way to prepare, many of the relevant skills can be trained without any equipment whatsoever.

Even for the parts that require equipment, students tend to vastly overestimate the time and expense required. For reference, the United States physics team receives no monetary support from the government, and so has a vastly lower budget than most other teams imagine. In a typical year like 2024, the American traveling team only receives 2 days of dedicated experimental training. And in 2021, the American team had no in-person experimental training at all, due to the pandemic; students came up with their own experiments at home with simple equipment like stopwatches, laser pointers, and kitchen tools. But in both years, the team won 5 gold medals.

The key skills required for the experimental exam come in several groups:

1. Fine motor skills.
2. Understanding the equipment and the underlying theory.
3. Designing an experimental procedure which can yield good results.
4. Analyzing the data and extracting good results, possibly with uncertainty analysis.

We'll consider each of these in turn, and present some simulation labs to practice on.

1 Fine Motor Skills

This category includes any sort of controlled, precise motion. These skills are often required to assemble the experiment, accurately tune the equipment, and accurately extract measurements.

Unfortunately, it seems these skills can't be substantially improved in a short time, even with the best equipment to practice on, and they can't be improved at all with theoretical exercises. However, in some years the equipment is almost entirely "digital" and requires no motor skills beyond pushing buttons. As for other years, you can usually still achieve a decent result even with poor motor skills, and a great result with only good motor skills.

In my experience, students with good motor skills have spent years developing them, in contexts unrelated to physics. For example, they might play a musical instrument, or videogames which require precise timing and quick reflexes. They often have practiced precisely making small objects, such as by writing compactly and neatly, or assembling puzzles or circuits. Motor skills generalize well between tasks, so if any of this describes you, you don't need to worry. If you don't have these skills at all, you still don't need to worry, as there's little you can do about it!

[1] **Problem 1.** To gauge your timing skills, get a stopwatch and try to stop it at 5.00 seconds a few times, as accurately as possible. Reliably staying within 100 ms is decent, and 50 ms is great.

Idea 1

For manual instruments like rulers, the expected accuracy of your measurement is half of the minimum division of the scale. A typical ruler has centimeter marks with millimeter divisions, so you're expected in Olympiads to measure lengths with an error of at most 0.5 mm. But you aren't expected to do better than this, because a more precise measurement would just get thrown off by imperfections in the instrument. In general, you should take data as fast as possible while maintaining this benchmark accuracy.

[1] **Problem 2.** Use a ruler to measure the dimensions of a piece of letter or A4 paper, reasonably quickly and accurately. Then look up the true answer and compare. If desired, you can repeat this exercise with other objects whose exact dimensions can be looked up, such as your phone.

2 Understanding the Setup

Before you begin an experiment, you have to understand the relevant theory. The selection of topics is strongly biased because a good Olympiad experiment has to be reasonably precise and reproducible, nontrivial to solve, compact, and relatively cheap. As such, almost all IPhO experiments fall into one of the following categories:

1. Optics: reflection, refraction, lenses, interference and diffraction, and polarization. The theory covered in **W2** and **W3** is sufficient.
2. Circuits. Usually nonlinear circuit elements, covered in **E6**, are involved.
3. Mechanical oscillations. The theory covered in **M4** is sufficient. Also, these systems often use magnets to exert nontrivial forces, so a bit of **E4** and **E8** is helpful. Statics and fluids sometimes come up, but less often because it's harder to make precise experiments with them.

Most of the few remaining experiments are about:

4. Solid state measurements, such as thermal conductivity.
5. Thermal radiation: the spectrum, angular distribution, and temperature dependence of light produced by hot objects, and its absorption by other objects.

Both of these topics are covered in **T2**. Most of the time, the experimental equipment doesn't require any particular knowledge to use, but for circuits and optics, some experience is helpful.

[3] **Problem 3.** A multimeter is the most complicated piece of equipment that ever shows up on Olympiad labs. Get a cheap multimeter – something like this will do. By reading the manual and experimenting, teach yourself what every setting on the multimeter does, and how to read the display. Test your knowledge by performing a variety of measurements on cheap circuit components, such as batteries, resistors, capacitors, and diodes. Be careful not to burn out the ammeter.

[3] **Problem 4.** Using a stopwatch, mass, and light string, carry out the classic experiment to measure g with a pendulum, mentioned in the preliminary problem set. (Some common sources of error are discussed in **M4**, and some additional advice is given in the following section.) The bare minimum is 10% precision. If you do it well, you should be able to identify effects due to the finite size of the mass, and the correction to the period due to finite amplitude, discussed in **P1**.

[5] **Problem 5.** Get a laser pointer, a double slit, a diffraction grating, some polarizers, and a small block of clear plastic or glass. With this simple equipment, you can do a basic version of almost every kind of measurement that appears in optics labs. (You'll need a ruler and protractor, and you'll have to be creative about mounting the components, e.g. using household objects and tape.) Here's a series of increasingly difficult exercises you can try.

(a) Using the double slit, confirm that the laser light has its advertised wavelength.

(b) Measure the slit spacing of the diffraction grating.

(c) Measure the width of one of your hairs.

(d) Using a polarizer with known axis of polarization, check if your laser pointer produces polarized light. If it does, find its axis of polarization. If it doesn't, use the laser and polarizer together to measure the axis of polarization of a different polarizer.

(e) Measure the index of refraction of the block.

(f) $\star$ Using the block, find the axis of polarization of an unknown polarizer. (Hint: this requires knowing something about how polarized light reflects at interfaces.)

(g) $\star$ Get a block of calcite, which is by far the cheapest strongly birefringent material. (You need "optical" calcite, not the big, cloudy colored samples people like to use for "crystal healing". It should only cost a few dollars.) Birefringent materials have a higher and a lower index of refraction, depending on the polarization of the light. Measure both of them.

See the next section for some tips on carrying these measurements out accurately.

3 Designing the Experiment

The next step is to actually perform the experiment well. This presents two layers of subtlety. First, even when it's obvious what you have to do, there are a lot of small factors that impact how good your result will be. Second, sometimes the experiment presents theoretical subtleties, and you'll need a clever measurement strategy to get an answer at all. Let's consider these two issues in turn.

Example 1

How can we accurately measure the period of a pendulum with a stopwatch?

Solution

We've already discussed this in **P2** and **M4**, but now let's revisit it with a practical focus.

- Of course, you want to measure N consecutive periods and divide the total by N, because that reduces the error by a factor of N. To maximize N, you should wait until the pendulum's motion starts to die down, but stop before it becomes hard to see.
- To make sure N can be sufficiently high, you should release the pendulum with a significant amplitude, but not so high that corrections to the small angle approximation will matter, at the accuracy to which you're working.

- To accurately time periods, you should start your stopwatch only once the pendulum is stably swinging, not at the moment you release it.
- You should start and stop the stopwatch at the moment the pendulum passes by a fixed point near the bottom, because it moves the fastest at the bottom, so a fixed position accuracy yields a better timing accuracy. This is significantly more accurate than trying to see when the pendulum is momentarily at rest.

Example 2

Using a laser pointer and a ruler, how can we accurately measure the spacing of a diffraction grating or a double slit? How about the width of a single slit?

Solution

Again, the theory is straightforward, but the way the measurement is done matters.

- A diffraction grating and double slit produce bright, separated maxima, so you should measure the locations of the maxima. But a single slit produces broad bands of light separated by minima. It's difficult to tell exactly which point in a band has the maximum intensity, so you should instead measure the locations of the minima.
- The screen and the optical element have to be parallel, to avoid distorting the pattern. (At the level of Olympiad experiments, this usually won't be too hard, but for the extremely precise optics experiments done in research labs, alignment can take hours or even days.)
- The laser pointer should be relatively close to the optical element. Placing it further away doesn't help, and actually slightly hurts because the laser's beam will spread out more, making the final measurement less precise.
- The screen should be relatively far from the optical element, so that the things you're measuring get further apart. The limiting factor is either the length of your desk/room, or when the laser beam gets too dim to easily see.
- Of course, the room's light should be off, and your eyes adjusted to dim light.
- If the spacing is such that you can see many maxima, you should precisely measure the distance between two maxima at the edges of your screen, and divide by the number in between. This reduces the error by a factor of N, like timing multiple periods of a pendulum. (There is little benefit in measuring the maxima in between and plotting a line, because this relation will be precisely linear with no intercept.)

[2] **Problem 6.** You are given a small light bulb, a filter which lets only red light pass through, and a light meter which measures the total light intensity on it. How can you accurately measure the intensity of the red light given off by the bulb in a given direction, at a given distance?

[2] **Problem 7.** AuPhO 2012, problem 14. Another question about practical measurements.

Now for some brief advice for more subtle experiments.

Idea 2

In trickier experiments, it might not be obvious how to perform a measurement. Sometimes, it's because the experiment contains strong noise sources, so that an accurate result can only be extracted by a clever choice of procedure. Other times, it's because the experimental apparatus itself might behave in an unpredictable way; for instance, it might contain a nonlinear circuit element whose general behavior you won't be told. (As an extreme case, some experiments are "black boxes" where you have to figure out what's inside.) Finally, in some cases there are several adjustable input variables which are related to the output variables in a complicated way, so that you won't be able to solve for the parameter if you just take arbitrary data points.

Doing these experiments requires two stages. The first is exploration. Before settling on a strategy, you should figure out everything the experiment can do. Figure out all the ways that the pieces of the experimental apparatus can be combined. For every adjustable parameter, quickly sweep over its full range, and observe what happens to the outputs. (For example, the output might just change linearly, or it might not change at all, or peak, or qualitatively change at some point.) Figure out why each part of the experiment kit is included.

Second, you have to settle on a strategy. Usually, this involves setting up the experiment in a particular configuration, varying one parameter over a well-chosen range, and fixing all other parameters to appropriate values (e.g. minimum, maximum, or intermediate ones, depending on what works best). It's hard to say more about this process without getting into specific examples, but doing simulation labs is a fantastic way to practice it, since it's essentially those labs' only source of difficulty. A variety of good simulation labs are listed at the end of this problem set.

4 Analyzing Data

Idea 3

The zeroth step of data analysis is to neatly organize your work.

- Always make an organized data table, with a row for each data point. For each column, specify the physical quantity calculated, and give its units. If your data points have uncertainties, indicate them on the table.
- Draw neat graphs using a ruler and graph paper. Always label the axes with the corresponding quantities, and their units.
- Set the axis scale so that the graphed data points cover almost the entire page. To achieve this, it can help to start the x and/or y axes at a nonzero value, though you should let the x-axis include $x = 0$ if you need to find a y-intercept.
- It's usually not allowed to use a calculator to find best-fit slopes and intercepts. Instead, you should eyeball the best-fit line, draw it with a ruler, compute the slope using two

distant points on it, and show this computation explicitly. If theory implies that $y = 0$ when $x = 0$, you should force the best fit line to pass through the origin.

- Often, you'll have to transform your data points before plotting, e.g. by raising them to a power, or applying a trigonometric function. You should learn how to do this as quickly and efficiently as possible with your calculator. It also helps to avoid keeping too many insignificant figures; your data points should never have more than 2 uncertain digits.

These are all small things, but they really do help get reliable results, and many rubrics include explicit penalties if they aren't done.

Idea 4

How much data is required for full credit on a given task? It's tempting to give a rule of thumb, like "always take X data points for a line", but the real answer is that it depends on the context. Generally, rubrics expect the student to spend the entire 5 hours making their results as accurate as possible. This means that you should stop taking data once the result won't get much better, or when it's not reasonable in the time given.

To gauge how much time is reasonable, note that a 5 hour experimental exam contains 20 points, so 1 point should take 15 minutes. Usually, you'll spend a bit less than half your time collecting data. (But in some experiments, you'll have to collect data "passively", waiting several minutes for each data point. In these cases, you should collect data for most of the time, doing your thinking and data analysis while waiting.)

To plot a completely generic line, it's reasonable to take 6 to 8 data points. But there are plenty of exceptions, depending on the context.

- Sometimes, it takes an extremely long time to get each data point, or the equipment might only support a limited number of types of measurement. In these cases, fewer than 6 data points might be acceptable.
- Sometimes, the data has a lot of noise, and/or is very fast to collect. (For example, you might be trying to measure a very small displacement or voltage, or the lab might be a simulation that instantly gives results.) In this case, you should take more measurements, to reduce the uncertainty. This can be done by repeating the same measurement several times and averaging the results, which helps save time making adjustments.
- Sometimes, the trend isn't a single line, but has features like peaks or transitions between different regimes. In these cases, you should take enough data to cleanly identify each feature, e.g. at least a few around each peak or transition region. In fact, this is the fundamental reason that an *ordinary* linear relation usually needs 5 to 7 data points: that's how you show it's linear in the first place.

Idea 5

If you're plotting a line to extract a slope and intercept, there are a few important rules of thumb for collecting the data.

- Ensure your data encompasses the widest possible valid range of parameters. The wider the range, the longer your "lever" is for getting an accurate result.
- If you're plotting a transformed quantity (such as T^2, where you measure T), then you should arrange your measurements so that the plotted data points are relatively evenly spaced. Otherwise, they may pile up in one end of the graph, making them less useful.
- If the measurements in the experiment are tricky to make, then it's quite likely that you'll make a few mistakes, leading to data points that are far, far off the best fit line. So, when you see such an outlier, you should measure it again to see if it's a real feature, or if you simply made a mistake.

It should be noted that not *all* data analysis requires drawing lines. Sometimes it suffices to take the same data point several times and average the results. In addition, sometimes you may have to sketch more general curves through data points, such as resonance curves, and eyeball minima, maxima, or transition points.

Remark

If you're unusually scrupulous, you might object to the point about outliers above: isn't throwing out data a kind of scientific fraud? Well, in *social science* it's a huge problem, because it's one of the methods used for "p-hacking", endlessly tweaking the data analysis to argue that a nonexistent effect is "significant". That's why there's a movement in social science to preregister data analyses, fixing all the procedures in advance.

By contrast, physics is inherently reproducible. In an Olympiad experiment, a measurement will give the same result (within uncertainty) every time you perform it correctly. And the relevant physical laws are quantitatively true, making reliable and concrete predictions. As a result, there's just no way you can fake a result by retaking and replacing mistaken data points. Doing this will get you closer to the truth, rather than further away.

Now, if you're unusually unscrupulous, you might be wondering if you can just *make up* a bunch of data points. Students try this occasionally, but it's an awful idea for many reasons. First, this actually *is* scientific fraud, because it can be used to justify false results as well as true ones. Second, it's against the rules, often easily detectable, and grounds for immediate disqualification. Third, it doesn't actually help you get good results. As mentioned above, rubrics generally demand you take the number of data points that gets you the most accurate result in the time available. Real data points make your answer more accurate, while fake data points don't. So if the rubric wants at least 7, and you take 2 and fake 10 more, then the most likely result is that your final answer will be outside the window that gets credit.

[2] **Problem 8.** AuPhO 2016, problem 14. A simple question about plotting data. You'll need to print out pages 8-9 of the answer sheets.

Remark

Two problems above are from the Australian Physics Olympiad, which has a strong emphasis on real-world physics. However, partly because of its innovative nature, some of its questions can be a bit confusing. If you'd like to try more of it, refer to this list of corrections.

Idea 6

Generally, students do too much formal error analysis, and not enough informal error analysis. Formal error analysis refers to applying the formulas in **P2** for error propagation. If you're spending a lot of time on it, then you're probably doing something wrong, because:

- About half of IPhO experiments don't ask for any error analysis at all!
- Even when you have to do error analysis, one source of error will often dominate, so that you can neglect the rest. If you're unlucky and two are comparable in importance, you should add them in quadrature, but adding them "directly" is also acceptable. I've never seen a case where three sources of error are simultaneously significant.
- Error bars are rarely expected when graphing lines. To perform error analysis for best fit lines, you should just plot the points directly, then draw the steepest and shallowest allowed lines by eyeballing the data points. (For example, the steepest line should pass above most of the points on the right, and below most of the points on the left.) The resulting range of slopes and intercepts gives the uncertainty on those parameters.
- Most errors can be assigned by rules of thumb. As discussed above, for a ruler you should take $\Delta x = 0.5\,\mathrm{mm}$. If a voltmeter stably shows $16.2\,\mathrm{V}$, you should take $\Delta V = 0.05\,\mathrm{V}$. If a voltmeter is fluctuating between $0.73\,\mathrm{V}$ and $0.77\,\mathrm{V}$, you should take $\Delta V = 0.02\,\mathrm{V}$.

The reason the requirements are so loose is that there's not a widespread agreement on what an error bar even means, at the high school level. To a statistician, it should mean a standard deviation. But at the introductory level, it often is construed to mean "the range which almost certainly encompasses the true value", which is more like two standard deviations, and motivates "direct" addition of uncertainty. Because of this mismatch, error analysis at Olympiads is always ambiguous by roughly a factor of 2, and the exact result you arrive at doesn't matter too much, as long as it's reasonable.

What *is* important is that you figure out how to get accurate experimental results, and that requires constantly performing informal error analysis, whether the question asked for it or not. If your experimental method depends on extracting a parameter by finding a small difference between two large measurements, your result probably isn't going to be very accurate. If you think you need to do extremely precise measurements, of lengths smaller than 0.5 mm or of voltages on the mV scale, or it's hard to see the physical effect because of an enormous spread in your data points, then there's probably a better way.

5 Simulation Labs

[5] **Problem 9.** US Experimental Team Selection Test, 2022. This was designed to be a warmup

for the other simulation labs, and should be done first. It's very clean and simple, illustrates many of the principles discussed above, and comes with detailed solutions worth reading.

[5] **Problem 10.** EuPhO 2020. (If you're using a Mac, you'll have to run "chmod +x" in the terminal to get these files to work.)

[5] **Problem 11.** EuPhO 2021.

[5] **Problem 12.** IPhO 2022.