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How to enjoy and thrive in graduate school

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Scientific research is an exploration of the unknown. The process is full of uncertainty, missteps, delightful surprises, painful lessons, and ultimately a measure of insight into nature. In this Science and Society article I suggest a few practical strategies that helped me navigate these challenges at the earliest stages of becoming a cell biologist.

A few years after I finished graduate school, I jotted down a few contributing factors to the enjoyment and success of my PhD years. I added to and adjusted this list over time based on seeing student experiences, good and bad, viewed from the decidedly different perspective of an advisor. Some (perhaps most) of these might well be obvious, in which case take them as potentially useful reminders. My own work uses a mostly biochemical approach to explore cellular function, so the commentary is framed from the viewpoint of research in molecular cell biology. What follows are brief thoughts on a few topics that I feel are important. It is not a comprehensive guide (I doubt some universal recipe for success is realistic anyway), and different parts may resonate to different degrees with any given reader.

Choose a scientific home based on fit rather than topic

The biggest challenge in graduate training, which arguably matters most in the long run, is learning how to think scientifically. This ill-defined skill comes in many guises, but generally combines critical analysis, creativity, and judgement. Good scientists dynamically adjust how they combine analysis and creativity to make decisions, whether it is choosing what to study, what to do next, when to abandon a project, and which odd results to ignore or track down. Developing this skill comes from engaging in the process with those who consistently make good decisions under widely different circumstances to navigate scientific uncertainties.

Choose a laboratory where you have an easy rapport with your group leader, are comfortable with your colleagues, are free to ask critical or naïve questions (and get critical feedback), are challenged in a rigorous but nurturing manner, and can gain independence progressively. The thought process and decision-making should be transparent, not just in your own project but also in that of others, allowing you to learn directly and indirectly how advances emerge in science. There is no perfect lab, just ones that do or don't fit your primary training needs and personality.

Ignoring fit in lieu of a specific topic or project is a common, and sometimes painful, mistake. Future opportunities allow one to shift topics with relative ease, but learning how to think scientifically is best done early because it pays more dividends later than anything else. Learn how other labs and group leaders manage projects to see how different fields or disciplines approach research differently. Seeing multiple styles of scientific thinking is crucial to ultimately developing your own scientific personality, of which there are many successful variants.

Conceptualize your project as a story

Every project is a story, and each story should have beginning, middle, and end. I formulate every research project as a complete (hypothetical) narrative right from the start, then continually adjust the narrative as the project evolves with more information. What story are you trying to tell? What is the general issue, and what is the specific question? Why is this important? What is the strategy you are taking to address this question? What have you found (or if you are just starting a project, what do you expect)? What do you think might be going on (i.e., what is your best guess or working hypothesis)?

Compelling stories are ordered, organized, and logical in both structure and content, typically making them easy to communicate. They articulate the broader applicability of the findings, highlight general principles, and provide some degree of explanation for a previously unexplained biological phenomenon. A strong narrative brings out the excitement in any project, and you should look for this in what you read and practice articulating your work lucidly (Box 1). If you cannot describe your project as a good story to colleagues within and outside your field, I would critically assess whether it is in fact well thought out.

Create mini-figures from each experiment

Students often hear (and say), with alarming certainty I might add, that the vast majority of experiments fail. Completely absurd! If you learn something, anything, from an experiment, it is useful even if you did not get what you had expected or wanted. Because you are in control over how an experiment is planned, most of your experiments should have at least some information value and therefore are not failures. I tend to include at least a little part of each experiment, often seemingly trivial, from which I am sure to learn something even if the main experiment is less than fully interpretable. It is useful for maintaining motivation and forward progress, especially if you can learn (like me) to derive satisfaction and joy from even the smallest successes.

When you complete an experiment, generate a self-contained figure panel. In the case of my typical biochemical experiments, this exercise immediately reveals whether I organized the samples in a logical

Box 1. Consuming and conveying information

Reading papers actively: read the title and abstract, pause, then mentally construct the ideal version of that paper with the key experiments and results that would justify the main conclusions to your satisfaction. Then scan the figures to see if the authors' work matches your expectations, and if not, whether the authors' strategy was better or worse than yours. Consuming papers in this active manner can quickly identify deficiencies. Papers that meet or exceed your 'pre-read' expectations are typically well constructed, serve as models for honing your own skills in project planning and writing, and worth actually reading.

Talking about your work: frequently discuss your project with colleagues (or anyone else who will listen). Develop the ability to communicate your work in a lucid and informative manner. If someone did not understand, figure out why, and next time adjust your description accordingly. It takes practice, but conveying your work to people with different views and scientific backgrounds is worthwhile. The better someone understands what you are doing, the more likely you will benefit from their unique perspective and expertise, especially scientists outside your field who could provide unexpected insights. No such insights can be expected if they get bored or confused.

order, the data are clean, the right type of gel was used to resolve the needed bands, the amounts loaded were sensible, and appropriate controls were present. All needed exposures should be obtained, and if loading controls are necessary, the appropriate gels should be scanned in and included as part of the figure. Write a series of bullet points under the figure with your main conclusions, ideas, and how you would have improved the experiment.

Doing this regularly will be of considerable help in reviewing your data later, in preparing a talk, or in preparing a paper at a later time. It is also very good practice in both figure assembly and writing. This habit will help you improve experimental design because you will quickly realize if your 'figures' are always missing key controls or if they are organized poorly, loaded inappropriately, or of inappropriate exposures. Eventually, you will just think in terms of figures in designing and performing experiments, and the results will more often than not become figures that allow you to assemble your thesis, papers, and talks more quickly; plus, the experiments themselves will be more informative and speed progress!

Game out experiments before doing them

I like to draw hypothetical figures of what the results of an experiment might look like in its various potential outcomes, then consider how each possibility would change my thinking about the project and its next steps. This helps to identify controls that might be missing, how to organize the samples (e.g., the order to load a gel), and the best- and worst-case scenarios. The strategy also helps to decide whether the experiment is even worth doing: if the results, regardless of what they are, don't really change your thinking much or what you would do next, then why bother? Sometimes, students will say 'well, I'm curious and it's easy to do', which is not a particularly compelling argument for spending time that could be invested elsewhere.

Clarity about what you might expect also helps you to quickly spot anomalies by recognizing the things you did not explicitly draw out or anticipate. Interpret everything you observe, not just the parts that formed the initial intention of the experiment, and especially that anomaly. Unexplained anomalies are sometimes the first clue that you've been thinking about a problem in completely the wrong way, which can be a bit scary, but also very exciting!

Review your data regularly

Nobody can remember every detail of all earlier experiments, but one should certainly recall what you have done and what the key results and conclusions were. Thus, it is invariably necessary on a regular basis to look back at earlier data, notes, notebooks, protocols, etc. The more organized these records are, the more productive you will be. This gives you mental space to critically think about your project: is it still going in the right direction? What is the next best thing to do? Is your working hypothesis still the best one? etc. There are many ways of organizing data (Box 2), but in all instances things should be easy to find and easy to re-interpret.

On a regular basis (typically weekly, but at least monthly), thumb through all of your earlier data on a particular project in chronological order (which goes quickly if you are organized). Such reviews are very helpful for reminding yourself about what kinds of things you have tried, and what you were thinking about in earlier stages of a project. It also is useful to refresh your memory about experiments that perhaps did not make sense at the time, but now can be re-interpreted in light of new data, a new model, or a new frame of reference. Regular data reviews help you assess whether your original goals and story have changed, or should be changed to tell a different story. I do this when assembling a paper, and students always find it surprising how many old experiments – which at the time seemed confusing or not helpful – wind up as panels in figures or supplementary figures.

Enjoy the process

The joy of revealing something new about nature is what makes science so stimulating, rewarding, and fun. The satisfaction I get from even tiny insights has long motivated me to design better experiments, think harder about what they mean, and conceive the most compelling ways to convey them. Now that my own experiments are a bit scarce (but I still have hope!), seeing that same 'light-bulb moment' in my students is just as satisfying (well, almost). It has become rather cliché

Box 2. Organizing your experiments for facile review

Avoid the embarrassment of your advisor knowing more than you about your own experiments. The best strategy is to organize your experiments clearly, review them regularly, and constantly re-evaluate their interpretations:

- A table of contents to find everything.
- Summarize each result clearly with essential information such as a brief outline of the experiment, loading amounts and sample order, exposure time(s), identities of key bands, any unexplained bands, antibodies (be specific!), etc.
- Bullet point your interpretations, errors, and what you would do next or do differently. Such summaries complement your detailed protocol, which can be cumbersome to review quickly.
- Quantification should be plotted and labeled clearly. Make a simple graph or table that summarizes the key data. Don't just dump the raw, yet-to-be organized data in your notebook. You might not return to it before forgetting, and it will take forever to review this data later.
- Key experiments that you return to often (to look up key conditions of an assay, etc.) should be highlighted, ideally with a separate list of such key experiments. Examples include key purifications, key assays, examples of certain cloning strategies, protein preps, etc.
- References to experiments with key frequently used reagents – such as the initial characterization of antibodies, constructs, proteins, etc. – are also worth tabulating.

for a reason, but the most reliable way to longevity in science is to thoroughly enjoy the journey. Because it is easier to enjoy something you are good at, it is well worth honing your craft to maximize your enjoyment!

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