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Things you should learn in graduate school

Ramanujan S. Hegde [1,*]

Becoming an academic scientist is neither linear nor formulaic. Rather, graduate education is mostly an apprenticeship without a discrete curriculum, clear sign posts of progress, or specific training metrics. In this science and society article I offer a few thoughts from my own experience for what a student beginning this journey might want to learn.

My friend Jim once compared medical school to being dropped in the dark choppy waters of a freezing cold sea at night, pointed toward the shore a mile away, and asked to swim back – a daunting and grueling endeavor for anyone. Graduate school, he quipped, was similar, except it's foggy (we were in San Francisco) and you're not even told where the shore is! What to do? Tread water and wait for help? Hope the weather clears? Just start swimming? And when do you change direction or strategy? Such uncertainties, disorientation, and self-doubt faced me as I started graduate school, fears that I thought were largely mine alone.

Far from being rare, the uncertainties about what is expected and how to go about it are near universal, and perhaps more surprisingly to a starting graduate student, persist throughout the entirety of an academic research career. It seems so obvious now: every explorer faces constant uncertainty, and research at its core is exploration. But to my naïve student eyes, it seemed as though scientists knew what to do and how to do it. But it isn't really true; we are each navigating the uncertainties of exploration, just as any graduate student.

The difference is a veneer of confidence propped up by our own past successes and a better capacity to draw on a larger foundation of lessons gleaned from others' successes and failures. If the goal of graduate school is to learn how to explore, what then should one actually learn? Surely experimental design, analytical skills, technical skills, speaking, writing, and interpersonal skills. But ultimately, I believe the critical skill to learn is how to make good decisions based on imperfect and incomplete information; decisions that help one choose what problems to investigate and guide progress as one explores the dark foggy sea of uncertainty toward some semblance of solid ground representing new knowledge.

In this article, I describe a few important skills one should learn during graduate school. Even if space were not limiting, I cannot offer step-by-step instructions for each (if only it were so simple!). But I suggest some key issues to consider as you begin developing these skills through mentored hands-on experiences (Box 1). An accompanying article covers a few practical approaches to acquiring some of these skills while enjoying a rewarding and successful experience.

Choosing research problems

Learn how new ideas emerge and how scientists choose their fields, topics, and projects. These choices are not static, so the critical skill of choosing research problems is applied dynamically and repeatedly throughout one's career. Successful scientists take into account a combination of biological importance, timeliness, feasibility, available resources, scientific environment, competition, plausibility, and fit to a trainee's skills, capabilities, and ambitions. The choices are necessarily multilayered: a challenging long-term problem can be approached only by breaking it into specific sub-problems, which are further divided into tractable projects and sub-projects whose timelines ideally fit into 3–5-year segments (the typical training period for students and postdocs). Scientists in different fields and disciplines often approach problems in very different ways, so getting some sense of the different strategies people use is illuminating.

You will likely begin graduate studies on a project framed primarily by your advisor. You should aim to end your PhD with the skills to conceive and articulate new (important and tractable) problems in that field. The easiest to identify will emerge directly from what you have discovered. But you should have developed the creativity and broader scientific vision to also find problems worthy of pursuit in other areas of the field or even other related fields. Getting to this point generally occurs in stages.

Start by learning how your project (and those of others in the lab) were chosen. Trace the history deeply – it's fun and a good way to start learning about your field, the past literature, and history of your chosen lab! As you progress, you'll hopefully question whether this is actually the best project and will have ideas for alternatives. Test them out with your lab mates, advisor, and other colleagues. They might initially turn out to be impractical, unimportant, or uninteresting, but you can learn a lot from the feedback if you're willing to take it seriously (but not personally). These interactions will help train your ability to conceive new ideas, critically assess their relative merits, and choose what is truly worth an investment of time and resources.

Conceiving and designing experiments

The skill of experimental design, a bedrock of most scientific research, seems fairly simple at first: decide what to test, choose a few controls, easy! But becoming a superb

Box 1. The role of mentoring in science

Improving as a scientist is aided by learning from others. This is a lifelong process, so it is crucial that you learn early how to find sources of guidance and mentorship for skills needed to progress in your career. Conversely, you have a responsibility to provide the same to your colleagues, and becoming a good mentor begins in graduate school (if not before). Your advisor is one source of mentorship, but should not be the only one for several reasons: not everyone is good at everything, there are multiple successful approaches for most things, and mentors with different backgrounds often provide valuable alternative viewpoints.

Thus, different people can and should provide guidance on different needs: scientific strategy, technical skills, career progression, resilience, interpersonal relationships, leadership, and others. Learn how to approach colleagues for guidance, think carefully ahead of time about what exactly you want from them (people are busy, so being prepared is really appreciated!), and learn how to take feedback (and sometimes pointed criticism). Mentorship need not be formalized. Over the years, individuals who have provided me with mentorship, often unknowingly, are consistently those in whom I see one or another admirable quality that I seek to develop in myself.

experimentalist takes considerable talent, knowledge, training, and experience. The goal is to obtain the most useful and decisive information relating to a research problem in the most efficient manner. There is no single strategy or solution for all situations. Sometimes, the right approach is a technically complex and challenging experiment designed to give a definitive result, but requires enormous preparation, resources, specialized equipment, and so forth. Other times, the best strategy is a series of carefully considered incremental small experiments, learning enough from each to design the next, culminating in a cohesive insight into the chosen problem.

Thus, you need to become adept at not only crafting any individual experiment, but also how to strategically string experiments together to work out the basis of a complex phenomenon. After an experiment, you'll sometimes realize it was foreseeably unhelpful. A thorough 'post-mortem' of each experiment is crucial to extract maximal information from its results and learn lessons for how you could (or should) have designed it better. Asking yourself why you didn't see the optimal design in the first place will help avoid analogous mistakes in the future. Over time, you should strive to develop the correct thought-to-work ratio for any given experiment to minimize foreseeable failures and maximize information content. Learning experimental design is far more enduring and valuable than any particular technique (Box 2).

Synthesizing imperfect information into decisions

Have you noticed how some scientists have exceptional instincts for what to do next, what is likely to be productive, and when to persist with versus abandon a line of inquiry? What exactly is scientific instinct? It is the ability to take many disparate pieces of information, weight them according to likely validity, place this all in the context of other knowledge and principles, and ultimately synthesize it all into a working model that might explain the observations. With a model in mind, one can then more sensibly make decisions about what to do next.

Because some people are remarkably fast at synthesis without articulating all the intermediate steps, the thoughts and decisions that emerge can seem instinctual when it is actually logical and reasoned. You need to learn how good scientists, ideally across different fields, make decisions. This is best done if you can see their thought process at work, either because they 'think aloud' or because you insist on the reasons for key decisions. In my experience, the hardest parts of this process are the weighting of information and making inferences from analogous problems in other fields. The latter benefits from reading widely and understanding in some depth topics beyond your own area. The former comes with experience as one learns enough methodological details and sees enough artefacts to better judge the reliability of different types of information.

Decisions have to be made almost daily about what to do next, how to do it, when to stop a project, whether or how to pursue unexpected anomalies, how to organize a body of work into papers, and many others. Assessing and reviewing experiments regularly as your frame of mind and working model evolve will improve these decisions. Although each decision can often seem rather modest and unimportant, their sum makes the difference between consistent progress versus persistent dejection. As already discussed, the biggest scientific decisions concern the choice of projects and overall research direction. Thus, synthesis and logical

Box 2. What about techniques?

Some readers might be surprised that 'learn a useful technique' is not among my top suggestions. Techniques are important, but their utility changes over time, and remarkably quickly these days. It is therefore more important to learn how to learn a new method; you will gain the mindset and confidence to do so repeatedly as science and your interests evolve.

With any unfamiliar technique, learn it well enough that you understand enough of the underlying principles to customize the method for your specific needs. Simply following protocols is very limiting, except for the most routine and highly standardized methods. Even something seemingly simple like immunoprecipitation has a very large number of variables, and one's precise choices among them can mean the difference between useful and useless results.

Learning the 'guts' of any method will allow you to use it as a highly versatile tool rather than as a rote protocol with only narrow applicability. By repeatedly learning methods in greater depth, you will appreciate how this process substantially improves experimental success and reduces the risk of foreseeable artefacts. The habit, ability, and fearlessness of incorporating new methods as warranted by your project will help minimize stagnation in your research.

decision-making are central to sustained success.

Writing compelling prose

Describing one's experimental results is a consistently overemphasized but ultimately trivial aspect of scientific writing. Far more crucial is a clear logical progression geared to the knowledge and mindset of the intended reader. Decide exactly what you want to convey, why you are convinced of this point, and the step-by-step path to lead someone from their current state of knowledge to the new viewpoint. The prose itself should be simple, devoid of unnecessary flourishes, and organized in coherent, short paragraphs that each make a single point. Each point should follow from the one before, with no appreciable breaks in logic.

The biggest challenge is to place yourself in the mind of a reader naïve to your work (but otherwise knowledgeable). Doing so is critical for constructing the appropriate logical narrative. Although many will disagree, I find it is best to write the paper in order from title through to the discussion (to me, starting with the results makes no sense). Have all the data you think is relevant for your paper on hand and place them into figures as you articulate your narrative; if your narrative shifts, adjust your draft figures accordingly. By developing the text and figures together, they will be more cohesive. Making all the figures first risks getting locked into one way of thinking, then writing to match the preassembled figures; instead, develop your arguments in the most logical and compelling way first, then organize your data panels into figures that linearly support your growing narrative.

Regardless of the exact approach you take (and there are many opinions and guides on the topic), the goal is to complete graduate school knowing how to compose logical, concise, and compelling prose to argue for your favored hypothesis supported by your data. This skill is invaluable, and you should begin developing it well before writing your first paper (or thesis) by explicitly recognizing what makes some papers compelling and others a bore.

Final thoughts

The skills highlighted in this article are crucial for, but not unique to, a career in academic research. Rather, the training is remarkably versatile. Numerous careers benefit from the capacity to strategically divide long-term problems into shorter-term projects, to think critically, to communicate effectively, to evaluate complex data, and to make difficult decisions from incomplete multidimensional information. Learning from the wisdom of others, especially from those with different viewpoints, and providing mentorship are skills that translate well beyond science and academia. Thus, devoting your graduate education to developing all of these traits, and not simply some techniques, will prepare you for many potential careers beyond academic research.

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[1]MRC Laboratory of Molecular Biology, Cambridge, UK

*Correspondence:
rhegde@mrc-lmb.cam.ac.uk (R.S. Hegde).

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