Skill Development in Graduate Education

Roy Parker[1,*]
[1]Department of Molecular and Cellular Biology, University of Arizona, Tucson, AZ 85721, USA
*Correspondence: rrparker@email.arizona.edu
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The process of training new PhDs is complex and has significant dropout rates associated with loss of financial and time investments by the student, mentor, and program. One approach to improve graduate education is to make explicit the skills students need to develop and to put in place mechanisms to develop those skills.

Graduate training is a complex process for both faculty and students. Students are expected to learn an interconnected set of skills, although those skills are often not articulated and taught in an explicit manner. Moreover, faculty members who mentor students frequently do not have strong experience in training students until later in their careers. Students can also be burdened since we, as a community, often convey implicitly or explicitly that the major goal of the PhD program is to publish an important paper in a high-profile journal. Since such an outcome is beyond the absolute control of the student and can involve luck in the experimental and publishing process, many students feel discouraged when their research does not lead to such an outcome. This is analogous to athletics, where an emphasis on "winning" can lead to individuals being discouraged and abandoning sports, whereas an emphasis on skill development helps athletes improve their abilities and then win more often (see Thompson, 2003, for a more detailed discussion of these issues).

A Possible Solution: Equal Emphasis on Skill Development and Scientific Discovery

By analogy to athletic training, one way to improve PhD training is to identify skills that students need to master in their PhD training, to make those skills explicit to the students, and to put in place programs that develop those skills. Moreover, such skill development must be done in the context of research to make significant and important contributions, but the emphasis is balanced between developing scientific skills and making important discoveries. Herein, I attempt to articulate what such a program might entail.

Critical Scientific Skills

One can identify eight interconnected skills that need to be developed to become a scientist (Figure 1). These skills have substantial overlap and can be delineated differently. Such skills include obtaining and maintaining background knowledge, executing and communicating new research, and creativity to recognize new problems and have new insights. These skills can be made explicit to students, and a variety of different methods can be implemented to develop those skills (see below and Table 1), although every student/mentor/program should find what works best for them. For students, note that developing as a scientist requires effort beyond just working in the lab, and you can undertake this process with or without involvement of your mentor/program; it is your education. Robust training of students also requires effort from mentors.

The Basic Skills

Broad General Knowledge

Being a scientist requires the skills to acquire a broad base of knowledge. A reasonable starting point is a working knowledge of one's discipline at the level of an advanced undergraduate text, which allows enough information to be conversant in the field and to know where to look deeper when relevant. Such broad working knowledge can be developed by reading textbooks, self-motivated studies, or teaching.

A broad knowledge base needs to be maintained and expanded as knowledge increases and often refocused as one's career progresses. Thus, students need to become familiar with the process of generating a broad knowledge base in a new discipline/area. Maintenance of a broad knowledge base occurs by staying abreast of major developments in the literature, as well as attending seminars and journal clubs.

Broad Awareness of Experimental Approaches

A broad awareness of experimental approaches is important for several reasons. First, knowledge of different approaches allows one to recognize new ways to solve current problems. Indeed, one key to being interdisciplinary is an awareness of approaches in different disciplines and how they can be used individually or in conjunction. Second, an awareness of different methods allows for the development of novel approaches, since many new technologies are based on new combinations of existing technologies. Third, an awareness of experimental approaches is required for interpretation of the literature. Such a broad knowledge of approaches can be shallow, but provides the awareness of a method that can be researched in depth when relevant.

Several approaches can be used to develop an awareness of different methods. The primary point is made by emphasizing that an awareness of a broad range of approaches is important and must be developed and maintained. One method is for students to create an electronic file of different types of approaches and their strengths and weaknesses and to add to this file as they are exposed to new methods in classes, the lab, seminars, and journal clubs. Similar to a general knowledge base, an awareness of different methods and technologies needs to be maintained and expanded as science progresses.

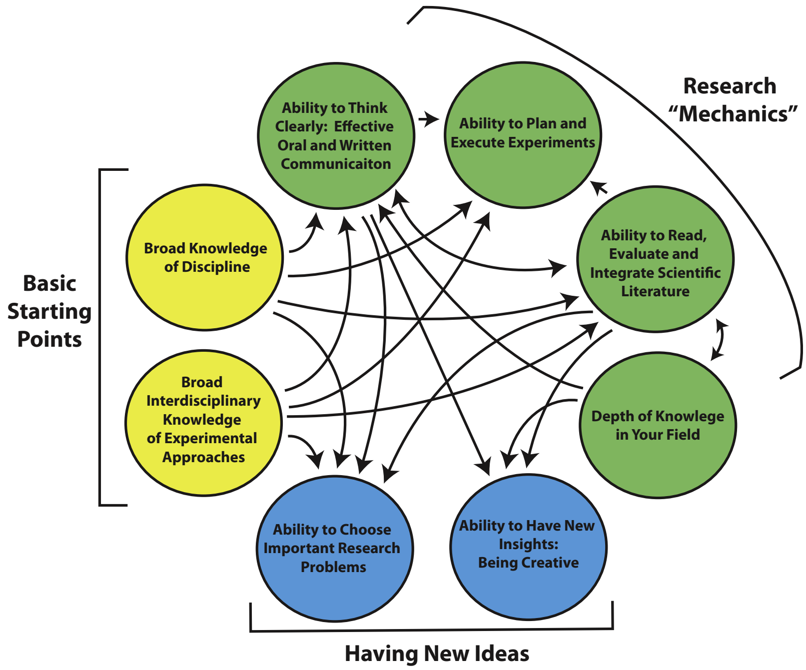

Figure 1. Interconnected Skills to Develop during Graduate Education
The figure shows one manner to break down specific skills to develop during graduate education and how they are interconnected.

Think and Communicate Clearly

It is important to be able to communicate effectively for two reasons. First, this is how you communicate your contributions, which is an essential part of the scientific process. Second, and of vital importance, is that clear communication requires clarity of thought. Therefore, the development of strong communication skills occurs in conjunction with the development of critical thinking abilities, which should occur in distinct phases during a graduate career.

In the first phase, and as a prerequisite to developing good communication skills and clarity of thought, one needs good mechanics of writing and organization of talks. For writing, it is worthwhile reviewing basic principles such as topic sentence, paragraph, and composition organization principles. For oral speaking, it is worthwhile identifying and discussing the principles of a good scientific talk in order to allow a presentation to be structured clearly enough for the logic to be illuminated (Alon, 2009a). Good fundamentals of writing and speaking are essential, since if these fundamentals are poorly executed, it is difficult to assess the critical thinking in any written document or oral presentation. Helpful feedback at this initial stage can be obtained by (1) identifying the key point of each paragraph/slide, (2) making sure that key point is expressed in the topic sentence or title of slide, (3) making sure relevant issues are within the body of paragraph or slide, and (4) assessing if key points are in the correct overall order.

In a second phase, reiterative writing and/or speaking about results or an area of science allows for one to push the intellectual understanding of that issue. Feedback here can be sequential (because this is how ideas develop!) and can be focused on the logical and intellectual aspects of the presentation.

Overall, the crux of developing good communication and thinking skills is (1) to emphasize that this is a critical part of being a scientist, (2) that ineffective communication reveals ineffective thinking, (3) learn the mechanics of writing and speaking so that the thought process becomes clear and can be evaluated, (4) having the student write and speak frequently in their development as a scientist (see below), and (5) holding the student accountable for poor communication and poor thinking. When a high bar is set for communication skills, it forces the development of critical thinking.

Read, Evaluate, and Integrate the Scientific Literature

Another important skill is to be able to read, evaluate, and integrate the scientific literature. This is another skill that needs to be taught at different levels. At the beginning level, it is critical to teach students how to read and critically evaluate a single scientific paper. It is absolutely essential to get this right, or numerous aspects of developing as a scientist will be flawed due to errors in interpreting the current literature. There are numerous ways to teach how to read a scientific paper (e.g., http://www.biochem.arizona.edu/classes/bioc568/papers.htm). One method includes students summarizing each paper by writing a brief description of the goal of the work, the approach (identifying any new methods), the experimental observations, the conclusions and whether they are well supported by the evidence, and the general strengths and weaknesses of the work. Writing such summaries is extremely useful, since this is a simple opportunity for students to develop their writing skills, reveal their critical thinking process, and allow the mentor to provide feedback. I find it helpful for students to also explicitly recognize what is good about a paper to balance the tendency to focus on a paper's problems.

An intermediate level of this skill is to read and integrate a small group of papers. This can be done in classes, journal clubs, and writing minireviews. Finally, by completion of their PhD, every student should develop the skill set to be able to read and integrate a large portion of a field. Methods to read and integrate a set of papers can be developed and taught to students (see Figure 2 for one example).

Doing New Research

Specific Knowledge in Your Area

In order to be successful, one needs to know the literature in the current area of research as well as a clear and deep understanding of the methods, and their weaknesses, being utilized. This takes effort, but how can one expect to be an independent scientist making important

Table 1. Skill Development Integrated into a PhD Program

Skill	How to Develop	How Mapped to Curriculum	How to Assess
Broad knowledge of discipline	Read and summarize undergraduate text Maintain from literature, seminars, journal clubs	First year course; self-motivated learning	Written and oral exams
Broad interdisciplinary knowledge of experimental approaches	Write file of method summaries Maintain from literature, seminars, journal clubs	First year course; self-motivated learning	Written and oral exams
Clarity of thought: effective writing and speaking	Learn mechanics of writing Learn mechanics of speaking Speak, speak, speak Write, write, write	First year course; first year course classes; research presentations; journal clubs; paper and method summaries; written experimental analyses	Written and oral exams; research presentations; journal clubs; committee meetings
Read, evaluate, and integrate scientific literature	Learn how to read scientific papers Read and integrate group of papers Read and integrate larger set of papers	First year course; journal clubs; write minireview (second year); introduction to manuscript (second/third year); introduction to oral proposal (second/third year); substantial reviews of field (third/fourth year)	First year exam performance in research; dissertation committee meetings; orals
Deep knowledge of your field of research	Gather, read, and write summaries of relevant literature Maintain by following new literature, conferences, journal clubs, seminars	Second year with mentor; self-motivated learning	Oral exam; committee meetings
Plan and execute experiments	Integrate knowledge, technology, experimental design Pay attention to detail Write summaries of observations and interpretation of experiments See what is there, not what you expect to see	Rotations; dissertation research	Successful completion of experiments
Have new insights	Learn method(s) to have new insights Develop/practice method throughout graduate school	First year course; explanations of results, seminars, literature (self-motivated)	First year exam on hypothesis development
Identifying important issues for research	Be aware of different approaches to defining important issue Develop and write *your* approach to choosing research problem Stay aware of evolving state of science and societal issues	First year course; self-motivated learning	First year exam; oral exam

contributions without knowing the current status of a field? (Students: are you willing to trust your overly busy mentor with your career fate?) One method to develop this depth of understanding is as follows. First, identify the key issue one is interested in and consider the a priori range of possibilities and their experimental predictions. This prepares the mind for interpreting previously done experiments from an unbiased perspective and avoids being tethered intellectually to current dogma. Second, gather and read the relevant literature. One approach is to begin with the oldest relevant papers and work forward, since alternatives in interpretation are best identified when they first occur and then carried forward in considering more recent experimental work. Third, for each paper, write a short summary of the piece of work (as discussed above) that includes the main point of the manuscript, the critical evidence for this conclusion, any other interesting or inconsistent observations in the work, and the strengths and weaknesses of the work. This process helps to develop a knowledge base of the specific field of research, identifies additional experimental methods to be aware of, and provides practice in critical thinking and writing. It also provides the student with a database of easily accessed summaries of relevant work.

Plan, Execute, and Analyze Experiments

Scientists must be able to plan, execute, and analyze experiments. This requires the integration of identifying an important

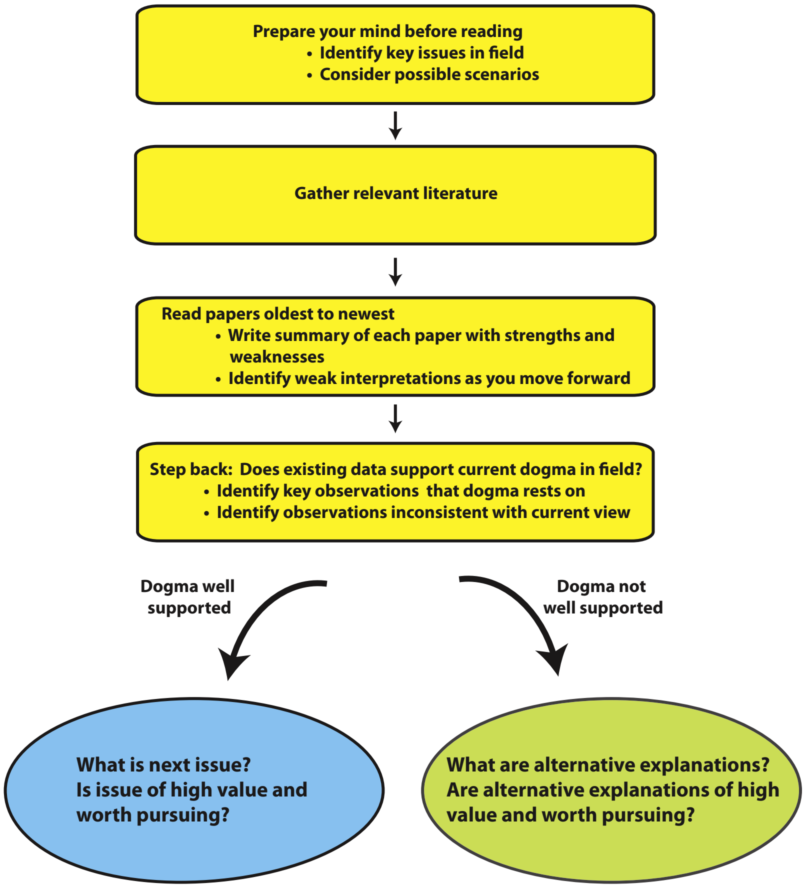

Figure 2. How to Read and Integrate Scientific Papers
The figure shows one methodology for how to read a group of papers and integrate their contents into a higher level of understanding.

issue, experimental methods, execution in the lab, and analysis of the resulting data. This skill can be developed by first emphasizing its key components: planning an experiment, executing the work, problem solving, and interpreting the results. Key aspects to be communicated include the importance of positive and negative controls, knowing the details of methods used to be able to properly execute them, being able to use clear thinking in refining experiments that failed, and developing skill in interpreting the outcome of an experiment. It is important to focus while executing experiments in the lab, since even a low error rate at any one step will doom the typical multi-step protocol to repeated failures. One method for developing these skills is to have students write a summary of each experiment that includes the goal, the general approach, the observations that come from the experiment, and the interpretation of the observations. A critical aspect is for students to develop the ability to see what the results really are and not what they expect to see.

New Ideas and New Problems

Having New Insights

All students need to develop the ability to have new insights. Although individuals differ in their innate creativity, it is important to train students in methods for having new insights and to emphasize that new insights often develop from attempts to form a mechanistic or causal understanding of the issue/process under research. One key to developing creativity is to emphasize that this skill can be developed and then expect students to demonstrate insights whenever they discuss their work. A second key is to teach students one or more ways to have new ideas. Algorithms for forming new insights or hypotheses can be made explicit (see Figure 3 for one example), and these approaches can be developed in classes or lab groups.

The ability to have new ideas and be creative requires a set of subskills that can be emphasized and/or identified to students. First, one must have an interest in understanding the underlying process that is at work, as well as a willingness to put intellectual energy into gaining such understanding. Second, it requires a working knowledge of the observations trying to be explained. Third, it requires the ability to imagine the range of possibilities, either by analogy (helped by broad general knowledge), by first principles (requires understanding the common principles of biological systems), or by mathematical modeling. Finally, it requires the ability to predict how a possible system would function and what experimental predictions it would make.

Choosing Good Problems for Research

Finally, it is imperative for students to learn how to choose important problems for future research. There are a wide variety of different ways to approach this issue, and science as an ''ecosystem'' is well served by a diversity of approaches on how to define an important problem. Several commentaries have addressed this issue (e.g., McKnight, 2009; Koshland, 2007; Alon, 2009b). In brief, important areas for research can be chosen by those that address a critical societal or human issue, an unsolved fundamental issue, or an unexplained observation or unexplored area whose understanding will reveal a deeper insight. The key issue for training students is to emphasize that developing their skills at choosing a good research problem is critical to their long-term success. Moreover, students need to develop an approach to this problem that fits with their disposition, as different types of personalities fit better with different types of problems (see Shneider, 2009).

How Might a Skill-Focused PhD Program Look?

Given the above skills, or any other related set, a challenge is how to map the development of these skills into a PhD program and to assess whether any such method

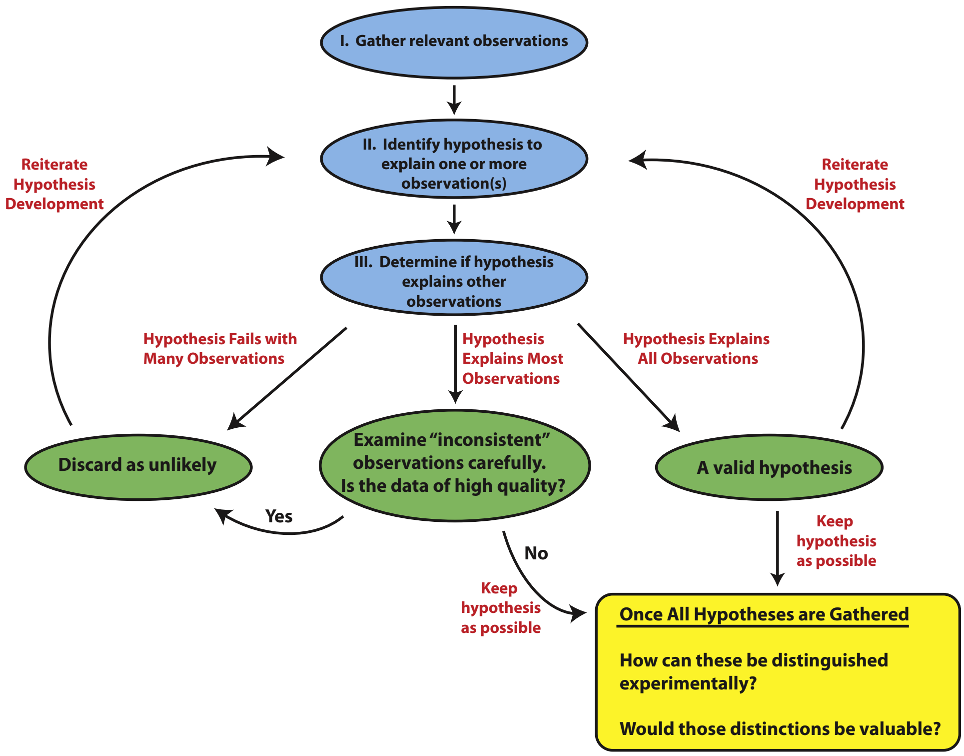

Figure 3. A Method for Developing New Hypotheses
The figure shows one flow chart that can be used to develop new hypotheses.

is successful at teaching those skills. One way to map these skills onto a PhD program is shown in Table 1. The crux of such a program is to use a course, not to cover a wide range of current knowledge, but to explicitly introduce students to the skills to learn basic material and methods, to think and communicate clearly, and to be creative and identify important problems for future research. The second key is to use lab rotations and independent research, under the guidance of mentors, to teach the skills for executing and interpreting experiments, as well as reinforcing and further developing the nascent skills learned in the first year of course work (see examples in Table 1). While assessment of these skills can be incorporated into many of the typical assessment tools used in graduate school (see Table 1), such assessments can be highly useful if targeted to the specific skills being developed.

A skill-focused PhD program must integrate the explicit development of scientific skills with the process of doing new independent research. Due to the overlapping nature of many of the skills outlined above and their intersection with research work, there are multiple manners to integrate these into a PhD program. Each PhD student, mentor, or program could consider the optimal method to improve their PhD training by being explicit about what skills need to be developed and putting in place methods to develop those skills.

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