

Catalyzing the transition from student to scientist—a model for graduate research training

Whether students enter graduate school intent on becoming ecologists, molecular biologists, or limnologists, all have one thing in common: they will emerge as what society calls scientists. For this to be more than just a title, students must develop the disciplined, critically thinking, and creative minds that are the hallmarks of scientists. Although graduate school is a continuation of the education process, it differs markedly from previous education. Undergraduate students are rewarded for their ability to parrot back what they are required to study, with limited call placed on their ability to work independently or think creatively (Volpe 1984). Graduate school, by contrast, requires students to learn new thought processes because a premium is placed on the amount, originality, and depth of thoughts and on the ability to communicate these thoughts in a manner that other scientists can assimilate and evaluate. Given the radical change in scholastic environments, how do beginning graduate students take the first few steps toward becoming scientists?

We begin with a definition of science. Webster's Dictionary defines science as "knowledge...obtained and tested through scientific method." Therefore, a scientist must be a person capable of generating new knowledge through the application of the scientific method. To generate knowledge, a scientist must learn to achieve an interplay among four traits: curiosity, creativity, critical-thinking abilities, and knowledge of rigorous testing procedures. Curiosity supplies the scientist with knowledge about the system being studied (Figure 1). Knowledge serves as the

raw material from which creativity extracts and elaborates new ideas about how the study system might operate. Critical-thinking abilities are filters through which ideas are passed to assess their merit. The best ideas become subject to rigorous testing to determine their validity, and the resulting knowledge is integrated into the whole of scientific understanding. The entire process, from curiosity to the generation of new knowledge, is the scientific method.

For most graduate students, thesis (or dissertation) research is their first opportunity to apply the scientific method. Because new graduate students are inexperienced researchers, graduate committees often require that students prepare plans detailing the research they will conduct. Previous authors provide guidance about how to prepare graduate research plans (Stoek 1985, Stearns 1987), but the process warrants greater attention because the preparation of a solid research plan should serve as a microcosm of the scientific method. In this article, we outline a step-by-step model (Figure 2) for the development of graduate research plans that explicitly incorporates the scientific method and highlights the roles of curiosity, creativity, critical thinking, and rigorous testing in research design.

Step 1.—Thesis topic selection

Selecting a thesis topic is arguably the most important step in developing a thesis. Selection of a poor topic will preclude an outstanding thesis from the outset, whereas selection of a good topic increases the probability of a significant contribution to science and provides the student a springboard into career development. The student-advisor team begins the topic selection process with general discussions about potential thesis topics. During these discussions, the

advisor's task is to gauge the student's abilities and interests and to tailor advice relative to the amount of creative freedom that exists and is expected for the degree being sought. To the extent practical, the advisor guides the student constructively along channels that follow his or her natural curiosities. Pursuit of natural curiosities makes it more probable that the student will begin thinking and working somewhat independently and eventually find a fascinating thesis topic. The importance of learning to think and work independently is obvious, but finding a thesis topic that fascinates the student is equally important because natural curiosity is the engine driving the student through 2-4 years of work on the topic.

Students should undertake topic selection by heeding the spirit of the advice given by Stearns (1987) to "read and think widely and exhaustively for a year." The goal early in the selection of a thesis topic (or the scientific method) is to acquire as many relevant facts as possible (Figure 1). Students should start by acquainting themselves with current thought in their discipline. They should seek out faculty members or graduate students working in areas of interest and question them about what they feel is cutting-edge research and which peer-reviewed journals they read. The library should become a familiar setting as students explore the primary literature, especially journals that are central to a discipline. Reading works that played important roles in shaping a discipline can help students obtain a historical perspective and understand how current thought emerged. Important works can be identified either by asking the opinions of others or by noting references that are frequently cited in bibliographies. Classes or seminars focusing on the hot topics within a discipline can

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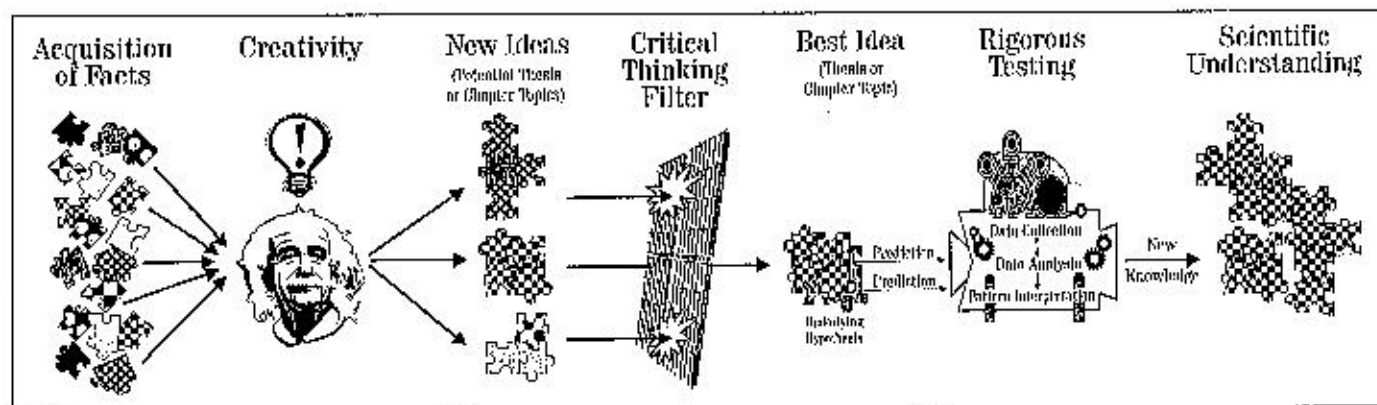


Figure 1. Schematic of the scientific method and graduate research plan development.

also be good sources of ideas for thesis topics if they cover areas of natural curiosity for the student.

Useful information can also be derived from more "hands-on" experiences. Pilot studies can be used to explore the feasibility of an idea while acquainting students with equipment. The development of field-oriented projects can benefit from a trip to a prospective study site, where careful observation and visits with local biologists or residents may provide insights into the biological system being considered.

As students accumulate facts, they will occasionally make intuitive leaps wherein they suddenly generate a new idea or understand something they had not previously. This is the creative step, and it is vitally important because it provides the new thoughts that propel science forward. If the student's insight seems to be a plausible research topic or simply a useful idea, it should be immediately recorded because new insights are also the raw material that the student-advisor team will eventually develop into a thesis topic. But for now, the student must be as creative as possible and intuit numerous ideas because only a fraction will warrant further effort.

Creativity is a mysterious process, but understanding how it functions may increase the number of insights that students generate. Dewey's (1933) analysis of the thinking process suggests that creative insights result from the interaction of three factors: generating a strong desire to solve a problem (in this context, coming up with an idea for a thesis topic), working toward a solution (in this context, accumulating relevant facts),

and allowing time for the subconscious to sort through the information and generate new ideas. When creative insights do occur, they frequently happen when the mind is not consciously focused on the problem (Beveridge 1961).

Once the creative process begins, the student continues to fuel it through continued acquisition of knowledge, but creativity can now be enhanced by exploring new ideas in an interpersonal manner. The advisor and graduate student can start participating in brainstorming sessions in which the student's ideas are discussed. Brainstorming sessions offer numerous advantages. First, the act of verbalizing ideas and getting immediate feedback from another person is a powerful tool for generating new ideas or elaborating existing ideas; second, the advisor can challenge the student's thinking in a constructive way, thereby forcing the student to think more clearly and deeply about ideas; third, the advisor will develop a greater awareness of the student's abilities, which will allow the advisor to provide better advice; and finally, advisors can use their experience to highlight those ideas that seem to have merit. Brainstorming sessions should lead to new or improved ideas and help the student identify which ideas should be further developed.

As ideas for a thesis topic develop, they are objectively assessed by sieving them through a "critical-thinking filter" to extract the best ideas (Figure 1). Much advice has been given about what constitutes a "good" thesis topic, and the student-advisor team can use these suggestions to assess their ideas. For

example, Lawton (1992) and Hunter (1989) suggested that thesis topics be selected based on the quality of the underlying conceptual issues rather than on narrow geopolitical objectives, methodological concerns, or species-specific considerations. Therefore, the fact that no one has calculated gastric evacuation rates of the mule deer herd in a particular mountain range or developed a technique to synthesize sea slug slime does not in itself make these issues valid thesis topics. Focusing on superficial considerations encourages the student to develop a shallow understanding of science that translates to thesis work bearing titles such as: "Use of technique A to measure trait B of species C in state D." As a result, scientific understanding advances in small steps rather than in bounds. Although there is nothing inherently wrong with developing a particular technique or measuring a certain characteristic of a species, these tasks should be undertaken as outgrowths of broader, more abstract considerations.

As an example, perhaps a student reads about—or, better yet, creates a plausible conceptualization of—the relationship between environmental factors and attributes of mule deer digestive systems across the range of mule deer. Once available data are summarized, it becomes apparent that a key combination of environmental factors exists in a certain mountain range. Determination of gastric evacuation rates from the deer herd in the mountain range now becomes an important topic because the combination of environmental factors found at that locale may provide a synthetic understanding of ungulate gastric systems. Similarly,

nothing is wrong with a study developing a method to synthesize sea slug slime if the work is conducted as an outgrowth of the more conceptual aspects of a thesis. When placed in proper context, methods studies can become excellent complementary chapters in a thesis because they ensure rigorous attention to detail in the collection of data. Moreover, the student-advisor team may benefit from an additional publication.

Pollard (1992) suggests that thesis topics focus on problems that are important to a discipline. Simply put, if students want to make significant contributions, their colleagues must think that the problem being addressed is important. Bartholomew (1982) stresses the importance of originality, reasoning that there are too many interesting questions waiting to be addressed to repeat the work of others and squander valuable resources. We echo this sentiment, except in cases where it is necessary to replicate a study to confirm the validity of results. However, replications should not constitute thesis topics; instead, they can be used to provide students with introductions to equipment and methods.

Finally, practical considerations must be taken into account when selecting a thesis topic. A good thesis topic should have growth potential and facilitate career goals because the topic will be the student's specialty when the thesis is finished (Pollard 1992). Stock (1985) suggests that the match between research requirements and the abilities and past experiences of the student be considered. A thesis project requiring a skill the student already possesses will reduce the learning curve associated with a portion of the thesis work, but the student will not have the opportunity to develop new skills. Of ultimate practicality is whether a potential thesis topic is tractable given time and money considerations. Often, a potential topic is too broad and must be narrowed.

Step 2—Scoping statement

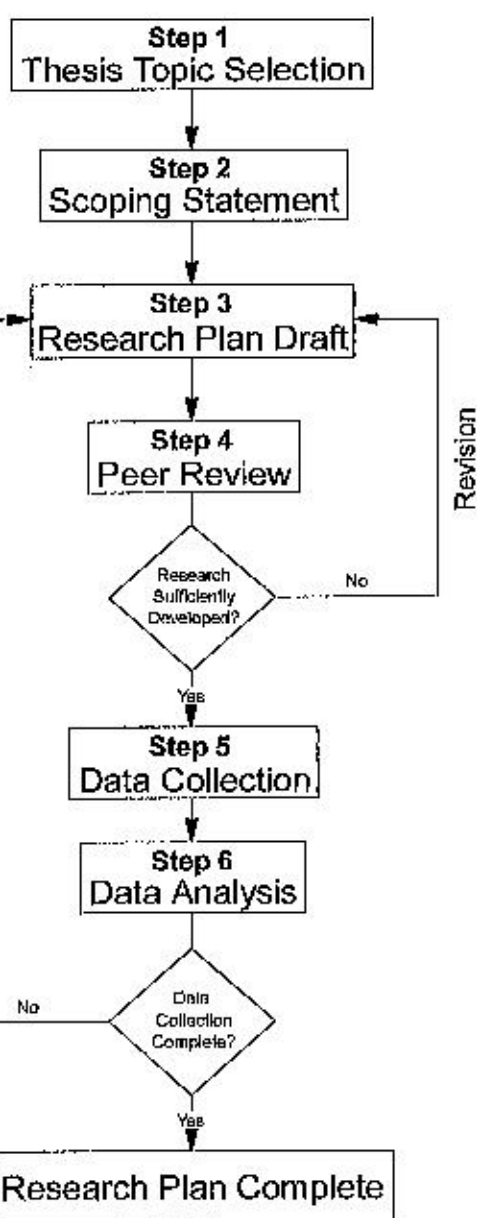
Once the student-advisor team has selected a thesis topic, the student should write a scoping statement summarizing thoughts pertinent to the thesis topic. A scoping statement

Figure 2. Flow chart depicting an idealized process of graduate research plan development.

is useful in several respects. First, writing such a statement gives the student an opportunity to develop critical-thinking and writing skills because the act of writing is a powerful tool for ordering and clarifying thoughts (Woodford 1967). Second, the statement makes the student's understanding of the research topic obvious, allowing the advisor to structure advice accordingly. Third, the existence of a document makes it possible for others to assess and constructively criticize the thesis topic.

The scoping statement need not be long, just long enough to develop the rationale behind the thesis topic. A good statement would introduce the thesis topic, describe underlying conceptual issues, and establish the originality and importance of the proposed research. At this point, it is important to make distinctions between logically discrete units of the research because these distinctions will help focus later efforts to develop the research. In a simple case, a thesis might consist of two units: one involving the development of a new technique, and one that uses the technique as a data-collection method to address a broader question. If the student experiences difficulty discerning what constitutes discrete units of the research, he or she should seek the expertise of the advisor.

After a draft of the scoping statement is completed, the advisor should review it and provide criticism. The student then modifies the document accordingly. Once both parties are satisfied with the scoping statement, comments can be obtained from committee members, graduate students, or faculty members to ensure that a



wider audience detects no fundamental flaws in the thesis topic.

Step 3—Research plan draft

The ideas presented in the scoping statement are developed in detail and linked to specific predictions and methods in the research plan. The body of the research plan should be prefaced with the information from the scoping statement to provide readers with an overview and conceptual context for the research. Students conducting field studies should follow this overview with descriptions of study-site components that are relevant to the research, such as characteristic flora or fauna, climate information, present or his-

toric land uses, natural disturbance regimes, or underlying geologies. The rest of the research plan should be used to elaborate the discrete units recognized in the scoping statement.

We suggest that each discrete unit be developed as a chapter modeled after a journal article, with introductory, prediction, and methods sections. Although the composition of individual chapters will evolve as the research proceeds, this evolution is expedited when students remain actively immersed in research design, as the thorough development of each chapter requires. Furthermore, research development becomes less overwhelming when broken into a series of well-defined pieces. Students also gain valuable practice putting thoughts into journal format, and future extraction of chapters for publication or grant submissions will be facilitated.

Introduction. Each chapter of the research plan begins with an introductory section. A chapter introduction performs an important function by defining the scope of a chapter and giving direction to subsequent sections in the chapter. The amount of writing in the chapter introduction does not have to be exhaustive, but the thinking going into the words put on paper does. As the introduction is written, care should be taken to ensure that each phrase and sentence are concise and logically linked and convey the necessary message. Appropriate references should be included in the text and cited accurately. When integrating literature, the student should attempt to synthesize and express the work of others in an original way rather than simply summarizing.

In many regards, the process of developing a chapter introduction is simply a more specific and detailed repetition of thesis topic development. Facts are acquired as the student conducts a thorough assessment of the literature relevant to the chapter topic. Creativity supplies new ideas regarding voids in the current knowledge base or how relevant facts may fit together. Critical-thinking skills are used to extract the best ideas and present them logically and accurately.

The completed introduction should

be a seamless thread of logic that does three things: establishes the importance of the topic for an informed reader, provides a context for the study by describing the status and shortcomings of present knowledge, and describes how the study will supplement current knowledge (Peters 1991). For example, a paper exploring the molecular basis of algal cell lysis by bacteria (Kato et al. 1998) begins with a statement establishing the topic's importance:

Harmful algal blooms cause severe damage to aquacultured fishes and shellfishes (Imai et al. 1995) and are also responsible for killing other marine organisms (Sieburth 1979).

The status of current knowledge is then assessed through a brief literature review. Knowledge voids that the current research is designed to fill are noted:

Although the mechanisms of algal bloom outbreaks is [sic] not clearly understood, the alga-lytic activities of bacteria may be a useful factor for controlling excess growth of marine algae in nature (Burnham et al. 1981). Algal lysis by bacteria may be brought about by the production of extracellular products (Fukami et al. 1992) or cell-to-cell contact mechanisms (Sakata 1990, Mitsutani et al. 1992). However, virtually nothing is known about the mechanisms of algal cell lysis at the molecular level.

The introduction ends with an explanation of how the research will fill this knowledge void:

In this paper, we describe the isolation of cryptic indigenous plasmids from *Asteromonas* sp. strains which are able to lyse the diatom *Sketetonema costatum*.

Predictions. A series of predictions related to the chapter topic follows the chapter introduction, but before the reasoning behind predictions can make sense, the student must understand the concept of a hypothesis. Scientists use the term "hypothesis" to describe the abstract conceptualization underlying a research topic (or chapter topic). In more concrete terms, a hypothesis defines the elements composing the system being

studied and describes how system elements interact. For example, many species of wild animals are thought to exhibit metapopulation structure (Hanski and Gilpin 1997). In a metapopulation, a series of discrete populations are connected by the occasional movements of individuals among populations. Interactions among populations result in the persistence of many species that would otherwise be extirpated. In this conceptualization, system elements include each of the populations, the individuals within the populations, and the movement corridors connecting populations. The movement of individuals among populations constitutes interaction between system elements.

Despite data suggesting that the concept of a metapopulation or numerous other hypotheses are valid, hypotheses are still abstractions of reality. No one will ever actually see or otherwise experience a metapopulation. This situation results in two questions: Why are hypotheses important? How can an abstraction such as a hypothesis be studied? Hypotheses are important because they plausibly synthesize the facts relevant to particular systems and, in so doing, largely define systems and how they are studied. Before the metapopulation hypothesis, biologists envisioned populations as discrete entities and focused most of their attention on measuring within-population attributes, such as the birth, death, and growth rates of individuals; they ignored or thought irrelevant the processes that occurred among populations. Once the metapopulation hypothesis was developed, wild populations of animals were studied differently because attention was focused on processes occurring among populations, such as immigration and emigration.

The answer to the second question lies in the use of predictions. Hypotheses may be ethereal entities, but they are systems composed of tangible elements that interact in observable ways. By using hypothetical understanding to make a series of insightful and measurable predictions about how system elements interact and then testing the correctness of these predictions, it is possible to draw inferences about the accuracy of hy-

potheses. Thus, predictions serve two purposes: They form a bridge between the abstract and concrete, and they make explicit the attributes of the study system that are important to measure. As a result, appropriate methods can be selected and ideas tested rigorously (Figure 1).

In addition to yielding helpful insights, good predictions are specific and testable (Stock 1985). Predicting that "The DNA of bacterial species will differ between species" is not a good prediction because it does nothing to focus research efforts (i.e., are all species of bacteria being tested? Which genetic characteristics will be examined, and how will they be assessed?). Furthermore, the prediction is not testable because it is already true (i.e., the DNA of every organism differs at some level of genetic analysis). A better prediction would be, "Allele *a* frequency at the *PGI-2* loci of bacterial species A will be half that of bacterial species B." Because this prediction is not already known to be true, it can be tested and the results of the tests used to draw inferences about the hypothesis under consideration. With the second prediction, efforts are focused on two bacterial species and on specific genetic characteristics, both of which limit the number of possible methods to those providing information about bacterial allele frequencies. Once introductions and associated predictions are completed, comments should again be solicited from others and the research further refined before time is spent designing methodologies.

Methods. The methods that will be used to test the stated predictions are described in the final section in each chapter. The methods section contains enough detail that a knowledgeable reader could replicate the study. It is useful to split the methods section into two subsections, one describing how data will be collected and one describing how data will be analyzed.

Data collection. Study-system attributes (hereafter referred to as variables) that must be measured are specified in the series of predictions associated with a chapter. Frequently, more than one method can be used to obtain data on each variable of interest. Each method has strengths and weaknesses, often

documented in the primary literature, that must be critically evaluated before the most appropriate method can be chosen. To help discriminate among methods, answers to the following questions should be sought: What is the quality of data derived from each method? How costly, with respect to both time and money, is each method? What assumptions are associated with each method? Can assumptions be met or violations minimized? Occasionally, the answer to one question (e.g., how costly is it?) overrides all other considerations, but often the answer is not clear-cut, and the above questions should be used to select the most appropriate method.

Data analysis. Data analysis methods are used to objectively describe patterns in data sets so that the accuracy of predictions can be assessed. Beginning researchers often neglect data analysis considerations until after data have been collected. Such an approach is a mistake, however, because knowing which analysis methods will be used can increase the efficiency of data collection and the subsequent quality of results. For example, if ANOVA or regression will be used to analyze data, a power analysis can often be conducted before data are collected (Cohen 1988). A power analysis tells the researcher exactly how much data are needed, making it possible to avoid collecting too much or too little data. Similarly, when using regression analyses it is often desirable to obtain data that are spaced as evenly as possible over a wide range so that the relationship between variables is characterized accurately (Neter et al. 1989). Comparable considerations apply to all data analysis methods, and knowledge of each method's nuances should lead to critical evaluation and further modification of data collection methods until the most efficient study design is achieved.

Step 4—Peer review

Once the research plan draft is completed, it will benefit from extensive peer review. The peer-review process should always begin with the advisor. After the advisor's concerns are addressed, criticism can be sought by presenting the research plan at an

informal seminar, sending the plan to experts in the discipline, or distributing the plan to committee members, other faculty, or interested graduate students. We have obtained excellent results from brainstorming sessions held among small groups of graduate students and faculty familiar with a research plan. The relaxed atmosphere lends itself to detailed lines of questioning, and the free exchange of ideas often exposes new opportunities or previously overlooked weaknesses. After obtaining criticism, the student-advisor team should critically assess the comments received and identify valid criticisms. If peer review suggests that the research is insufficiently developed or contains serious flaws, another iteration of research plan development should be conducted (Figure 2).

Step 5—Data collection

Initial data collection efforts are an exploratory process as the student develops familiarity with methodologies and equipment. The student should anticipate this process and prepare for data collection by conducting practice runs before attempting to collect meaningful data. Once a routine has been established, however, the process of data collection often leads to creative insights as the subconscious works to make connections between what is actually being observed and what hypothetical understanding suggests should be observed. As noted earlier, creative insights and associated thoughts should be recorded because they may later prove valuable in the evolution of the student's research.

Step 6—Data analysis

In most graduate research projects, data are collected through a series of laboratory experiments or field studies. Breaks between data collection efforts should be used to refine and intelligently redirect research. Exploratory data analyses can be conducted to describe patterns present in initial data. It often happens that predicted patterns do not exist or unexpected patterns are detected. In all cases, the student-advisor team should discuss the implications of preliminary results and brainstorm

to determine options that exist. Certain avenues of the planned research may no longer be tenable, whereas previously unanticipated dimensions may unfold. If preliminary results suggest major research revisions, another iteration of research plan development is conducted.

Conclusion

Our goal in this article has been to provide advisors and beginning graduate students with a model of graduate research training that helps catalyze the transition of students into scientists. Although hopefully providing utility, the model should be viewed as a simple but flexible template. As experienced scientists know, the process of research design is decidedly nonlinear, characterized by complex interactions, and closely akin to an art. This complexity is difficult to portray in a coherent fashion, and it will become apparent to beginning researchers only as they develop intimacy with their research. In addition, our model is unlikely to have universal appeal, given the idiosyncrasies of various disciplines within the biological sciences and the personal preferences of individuals. We find the model useful, however, even in creatively constraining situations, in which students agree to work on projects for which grant funding has already been obtained. Similarly, the model has proven applicable to students with a wide range of abilities and working at both the Master's and PhD levels. It is here that the role of the advisor becomes pivotal because advice must be tailored to ensure that the student gains an understanding of science while developing a thesis topic of appropriate scope and substance for the degree being sought.

Whatever the setting, several components of our model should become ubiquitous parts of graduate research within the biological sciences. Proposed thesis research should be described in detailed research plans. The development of research plans gives students much-needed opportunities to practice critical-thinking and writing skills. But more important, students become actively immersed in their research, with the result being a continuation of creative insight gen-

eration and honing of the critical-thinking skills needed to fully refine the research. Peer review should be an integral part of research plan development. Only by addressing difficult questions before data are collected can research design be improved and the quality of research ensured. In addition, exposing students to the review process early in their graduate careers accustoms them to receiving criticism and provides a strong incentive to develop defensible answers to criticisms of the research. Finally, the scientific method should be an explicit theme in graduate research. Thesis research often suffers because beginning researchers do not understand the application of the scientific method well enough to perceive the role it should play at each stage of research design. Inexperience can be quickly overcome, however, if advisors emphasize the roles of curiosity in acquiring new facts, creativity in generating new ideas, and critical thinking in refining ideas, as well as the interplay that occurs among hypothetical understanding, predictions, and methods.

Development of a solid research plan is a time-consuming and involved task, but doing good science is not a trivial task. For most graduate students, however, a major hurdle has been cleared once the research plan is completed. The scope of the thesis has been narrowed from an amorphous mass of possibilities to a well-refined and tractable research topic. With little additional effort, portions of the research plan can be appropriately formatted and submitted as grant proposals, or individual chapters can be finished (as data collection efforts become complete) and presented at scientific meetings or submitted for journal publication well ahead of a thesis defense. At this point, students can go as far as their minds will take them because, similar to the metamorphosis that occurred as disparate thoughts and ideas were forged into research plans, students have transformed themselves into critically thinking and creative individuals who have earned the title of scientist.

Acknowledgments

We thank Stanley Anderson, Rebecca Chasan, Shellie DuBay, Gregory Hay-

ward, Lance Heddon, Kirk Krueger, Carlos Martinez del Rio, Mark McKinstry, Brian Murphy, Timothy Patton, Frank Rahel, and three anonymous reviewers for comments on earlier drafts of this manuscript.

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