Research Question Formulation:

The Pedagogical Approaches of Natural-Science Professors

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Abstract

Questions lie at the heart of science. Scientific inquiry is iterative—questions can emerge before, during, and after a study. Scientists transform these unknowns into funded, researchable questions that their students inherit and pursue. However, a successful academic career cannot rely on the ideas of others—at some point, students will have to generate their own researchable questions to become well-regarded scientists. The present study explores what some mentors do to support their students in developing the ability to find, frame, and formulate questions aimed at discovering new knowledge. Recruited by emails to the science departments of eight North American research-intensive universities, 63 professors were interviewed. The main dataset for the study was 24 science professors purposefully selected because they explicitly described the pedagogical contexts in which research questions arose and represented diverse disciplines across the natural sciences. Five sets of findings emerged from extensive coding and thematic analysis: (a) instances in which students are involved in the design and conceptualization of research, labelled "Student Research Question Formulation" or "student RQF," can be reliably detected across the natural sciences; (b) ten themes that illustrate the teaching and mentorship actions and approaches which reportedly contribute to student RQF; (c) a set of expectations, beliefs, and expectations regarding student roles and responsibility emerges as an eleventh theme; (d) a five-step progressive framework that illustrates how student involvement in research question generation can vary from nearly nonexistent collaboration to full independence; and (e) that scientists across and within disciplines vary widely in how they understand and use common terms in the scientific method (e.g., the research question, research objective, hypothesis, prediction). These findings inform our efforts to research and improve the training of scientists.

Sommaire

Les questions font partie intégrante des sciences. L'enquête scientifique étant un processus itératif, les questions peuvent survenir avant, pendant, et après une étude. Les scientifiques transforment ces inconnues en questions fondées et propices à la recherche que leurs étudiants approfondiront à leur tour. Cependant, le succès d'une carrière universitaire ne peut reposer sur les idées des autres : Tôt ou tard, les étudiants doivent produire leurs propres questions de recherche afin d'obtenir un statut de scientifique respecté. La présente étude explore les mesures que prennent certains mentors pour aider leurs étudiants à développer une capacité à trouver, structurer et formuler des questions visant à acquérir de nouvelles connaissances. À la suite de l'envoi de courriels de recrutement, nous avons interviewé 63 professeurs de sciences de huit universités de recherche. L'ensemble de données principal de l'étude se composait d'entrevues avec 24 professeurs de sciences naturelles, que nous avons délibérément sélectionnés parce qu'ils décrivaient explicitement les contextes pédagogiques dans lesquels les questions surviennent et qu'ils représentaient diverses disciplines dans ce domaine. Un vaste travail de codage et d'analyse thématique a engendré cinq séries de résultats : (a) les cas où les étudiants ont participé à la conception et à la conceptualisation de la recherche, classés dans la catégorie « Formulation des questions de recherche des étudiants » (FQR des étudiants), se décèlent de manière fiable à l'échelle des sciences naturelles; (b) dix thèmes illustrant les mesures et les approches en matière d'enseignement et de mentorat contribueraient à la FQR des étudiants; (c) une série d'attentes et de croyances en ce qui a trait au rôle et aux responsabilités des étudiants ressort en tant que 11^{e} thème; (d) une structure progressive en cinq étapes montre comment la participation des étudiants à la production de questions de recherche peut varier entre une quasi-absence de collaboration et une indépendance totale; (e) les scientifiques, au sein

des diverses disciplines et dans l'ensemble du domaine, présentent des différences notables quant à la compréhension et à l'emploi de termes courants portant sur la méthode scientifique (p. ex., question de recherche, objectif de la recherche, hypothèse, prévision). Ces conclusions éclairent nos efforts d'améliorer la formation des scientifiques et de poursuivre nos recherches en la matière.

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Professor Bruce M. Shore's retirement party was May 30, 2010. Many advisors end their mentorship relationships upon retirement—not Bruce. He stuck with me through the seven years (2651 days) needed to start my PhD, finish my courses, get my proposal approved, and complete a full first draft on September 1, 2017. He still mentors me today and I am ever grateful for his commitment. Bruce, thank you for sticking with me through thick and thin. No matter what life threw at me, I never had to stop the PhD clock because I had your incredible support. I do not know how I would have survived the noise without you. Through it all, you reiterated to me that my health and wellbeing must remain the top priority. This was a very hard lesson to learn, yet I think it finally sunk in near the end of the journey. Also, thank you for cultivating my interest in talent development. Who knew that the modeling that you provided since day one would become the basis for my academic interest and possibly a career path thereafter?

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Though knowledge is situated and co-constructed, a PhD is a test of an individual's ability to create new knowledge. This creation would not be possible if it were not for the supportive academic community behind me. Professor Alain Breuleux and Robert Bracewell led doctoral seminars that helped me learn to pose questions about questioning. Professor Michael Hoover, thank you for commenting on the earliest conceptualization of this study—your course on expertise inspired me to look at differences between the questions asked by novices versus those asked by experts. I am particularly grateful to my committee members Professor Alenoush Saroyan and Professor Marcy Delcourt; thank you for your careful reading of my proposal and manuscripts. Dr. Diana Tabatabai, thank you for teaching me how to do open coding, this task would have been so much more difficult without the foundations that you laid. Thank you to all who helped with the transcription, coding and transferring of the data and the content between software programs and formats. During coding, your ability to stay close to the participants' words and your well-described coding rationales enabled me to test and clarify what I was looking for. Your ability to follow the coding procedures so closely and to discuss your coding decisions so explicitly was the key to the development of the rigorous, reliable, and reproducible construct that is student RQF. Alexia Yeo, Jade Park, and Tiffany Sun, coding and interrater agreement would not be the same without your care, attention to detail, and valuing of this investigation. To all my friends and colleagues who served as sounding boards—those mentioned and those who have left McGill—without you, I would have drowned in the details. You provided me with alternative interpretations and different perspectives, suggested different methodologies to consider, gave feedback generously, highlighted different paradigms to consider, and so on. I am deeply grateful for my community of practice.

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Authorship

I hereby declare that I am the sole author of this dissertation. This is a true copy of the dissertation, including any final revisions, as accepted by my examiners.

Vignette

During a session with an enthusiastic chemist, I opened the interview by inviting the participant to select and describe the most rewarding aspects of her professorship from among teaching, research, and supervision. She chose supervision, elaborating upon how satisfying it was to work with talented emerging scholars. For the next interview question, I challenged the professor with the provocative suggestion that her role in graduate supervision could be replaced by a textbook when it comes to the development of a particular capacity among students—the formulation of research questions: Here is one of many methodology textbooks for natural science students. It contains nine pages on the subject of how to formulate research questions. Is it sufficient for us to give this chapter to your graduate students and expect them to come up with a workable research question on their own, other than some periodic feedback? Alternatively, is there more to the learning and training process for graduate students?

Surprised, the professor proceeded to elaborate at length on her role as an advisor with regard to teaching students how to formulate research questions, explaining that "of course, there is something more to the process." My dissertation sought to fill in this important gap in knowledge by painting the picture of that *something more*.

Chapter 1: Introduction to the Topic of Research Question Formulation

Research questions lie at the heart of scholarly inquiry in the natural and social sciences. Yet, according to Thabane, Thomas, Ye, and Paul (2009), “we have barely begun to explore their characteristics among scientists and scholars” (p. 71). In fact, not much is known about how students find, frame, and formulate research questions that drive the scholarly pursuit of new knowledge—I refer to this ability as research question formulation (RQF). My literature review demonstrated that there has been no systematic attempt to explore the nature of RQF instruction as it is currently carried out in the context of a classroom or supervision. This knowledge is limited to the individuals who apply it and the prescriptive materials that have been written by the authors who have sought to share their personal experiences. When it does exist, the nature of this literature is largely narrative or nonempirical.

My literature review highlighted that most empirical studies have focused on using questions to help students master pre-existing knowledge as opposed to helping them construct questions for the pursuit of new knowledge. This led me to explore how professors developed RQF capacities among students in higher education.

Definitions

Questioning as a skill. “Questioning is both product and process, involving an ongoing interaction between the knower, the known, and sometimes the unknown. It is a branch of knowledge itself. To ask questions is an act of cognition and literacy” (Ciardello, 2000, p. 215). Several authors have proposed definitions for questions, their specific properties, and supporting assumptions. For example, Van der Meij’s (1987) assumptions incorporate a list of requirements that can be used to isolate bona-fide information-seeking questions from similar imposters.

- The questioner does not know the information asked for in the question.

- The questioner believes that the presuppositions of the question are true.
- The questioner believes that an answer exists.
- The questioner wants to know the answer.
- The questioner can assess whether a reply constitutes an answer.
- The questioner believes that the answerer knows the answer.
- The questioner believes that the answerer will not give an answer in absence of the question.
- The questioner believes the answerer will supply the answer.

According to Van der Meij (1987), for a question to be a true question, it must be necessitated by the genuine quest for information and the belief that said question is answerable. This process starts when a person realizes that there is a gap in his or her own knowledge or understanding. He or she then organizes symbolic representation units (e.g., words or numbers) into a sentence aimed at obtaining information to address this personal gap in knowledge. The formulation of questions plays an important role in the personal and social construction of knowledge (Graesser, Baggett, & Williams, 1996; Winters & Alexander, 2011; Wong, 1985). I define question formulation (QF) as the skill or cognitive process that yields the interrogative statements we recognize as questions: the personal and social construction of learners' formulating questions, posing them, and pursuing answers with more competent peers or teachers. The questions formulated in such classroom contexts help students to understand, master, and reproduce known knowledge.

Whereas I use QF to refer to posing questions that address an individual's gap in knowledge, I coined the concept of RQF to specifically apply to the cognitive and scholarly skillset of asking questions that address scholarly gaps in knowledge. The nature of this gap may vary from one field to another, possibly including theoretical, empirical, methodological, or applied gaps. Research questions are expressed in a language that is appropriate for the academic community that has the greatest interest in answers that would address said gap. These interrogative statements serve as launching points for the academic pursuit of new knowledge by directing and delimiting an investigation of a topic, a set of studies, or an entire program of research. The purpose of the RQF skillset is to create knowledge that is new and historically original according to researchers of a discipline (as opposed to QF, the skill of posing general questions to pursue knowledge that is new only to the question-asker).

In the literature, studies on RQF look at how professors and students construct questions that evaluate, replicate, corroborate, synthesize, or extend the current literature (e.g., undergraduate honors project or master's thesis). RQF leads the student or scholar to collaboratively or independently questions for scholarly inquiry (e.g., inquiry that involves systematic, methodical, scientifically rigorous, and transparent processes of collecting, analyzing, integrating information).

Terminology: Student question formulation (SQF) versus research question formulation (RQF) versus student research question formulation (student RQF). There are two ways to conceptualize how educational research has examined students' questioning skills. These two ways are based on the type of knowledge that is sought by the student: knowledge that is new to the student versus knowledge that is new to the discipline. I use the term student question formulation (SQF) to refer to studies on students' ability to pose questions that pursue knowledge that is already known within the discipline but new to the student. SQF helps learners to better understand, master, or reproduce information for their own learning and assessment. Said information tended to be the traditional course content for the discipline. A second set of literature investigated instances of learning in which students generate questions to pursue knowledge that is new to a discipline. Though few and far between, I used these studies to contextualize the term that emerged from my data analysis—student research question formulation (student RQF). Student RQF teaches students to think and function as scholars by formulating tractable, important questions that could produce historically original findings.

Theoretical Paradigm and Pedagogical Models

A social constructivist paradigm. My research is rooted in the theory of social constructivism. A social constructivist sees knowledge as the outcome of an ongoing process of interaction and conference. Knowledge, in this view, is constructed by meaning-makers as they negotiate their social and cultural environment (Vygotsky, 1978). There is extensive support in social constructivism for the role of questioning in discourse and the construction of knowledge (Bearison, 1982; Cobb, Yackel, & Wood, 1992; Damon, 1983; Hatano, 1988; Hawkins & Pea, 1987; Lemke, 1990; Mugney & Doise, 1978; Perret-Clermont, 1980; Pimm, 1987).

Social constructivist studies on questioning tend to converge on a key role outlined for question formulation in problem solving, debate, and argumentation (Aguiar, Mortimer, & Scott, 2010; Barak & Rafaeli, 2004; Denny, Hamer, Luxton-Reilly, & Purchase, 2008; France & Gilbert, 2006; Hmelo-Silver & Barrows, 2008; Lan & Lin, 2011; Pedrosa de Jesus, Teixeira-Dias, & Watts, 2003; Piccolo, Harbaugh, Carter, Capraro, & Capraro, 2008; Veerman, Andriessen, & Kanselaar, 2002; Yu, 2011). According to this theoretical framework, new knowledge is a “constructed synthesis which resolves the inevitable contradictions arising during the course of such interactions” (Moshman, 1982, p. 375). Empowering students to pose and pursue questions that would expose the contradictions can facilitated learning. In this way, social constructivist methods of encouraging student engagement and the social construction of knowledge include a strong focus on the type of scientific argumentation and discourse that is germane to the formulation of research questions.

According to undergraduates' own testimonies, formulating questions while in class improves their learning experience, particularly when there are varied perspectives as in peer-interaction contexts (Yu, 2011). Research question formulation fosters engagement beyond the classroom and into the wider discipline of scholars. This is seen as positive within social constructivism because this increased interaction creates opportunities to build upon the current state of knowledge, regardless of whether said knowledge is historically original or simply previously unknown to the individual.

Questioning is key to the dynamic discourse, training, and practice in scientific argumentation that students need in order to appreciate the fluid and iterative process of knowledge creation. I wanted to understand how instructors incorporate SQF into undergraduate learning and how they develop RQF abilities amongst their undergraduate and graduate students. Two frameworks that fall under the social constructivist paradigm informed my analysis of both SQF and RQF: inquiry-based learning (IBL) and cognitive apprenticeships. I chose these two social constructivist models of learning because they stand out for their prescriptive value at the undergraduate level (IBL) and descriptive value at the graduate level (cognitive apprenticeships). The former prescribes guidelines on how to develop inquiry skills such as questioning amongst students while the latter describes cognitive processes that underlie the mentorship inherent in RQF training.

Inquiry-based learning. Inquiry-based learning (IBL) is a social-constructivist model of instruction that involves the scholarly and systematic pursuit of answers to questions of genuine interest to students (Aulls & Shore, 2008). Inquiry-based learning holds at its core the scaffolding of more complex skills and cognitive abilities into smaller substeps and tasks that can be achieved by the learner with the help of an instructor or more competent peer. Banchi and Bell (2008) outlined four levels of inquiry: confirmation, structured, guided, and open inquiry. In confirmation inquiry and structured inquiry, learners replicate either a known experiment or an explanation for results of such an experiment. Guided inquiry incites students to collectively explore a perplexing result or an unintuitive observation that was provided by the teacher. The first three levels of inquiry do not involve question generation. Open inquiry is the only type of inquiry in this model that is aimed at having students generate their own questions.

Cognitive apprenticeship. Cognitive apprenticeship describes the tools and processes that an expert can use to facilitate students' mastery of the skills required within the discipline by making the expert's tacit knowledge more explicit to the students. I anticipated that professors' descriptions of how their training of RQF among their graduate students would involve cognitive-apprenticeship strategies such as modeling, coaching, scaffolding, articulation, reflection, or exploration (Collins, Brown, & Newman, 1987). Responses regarding the unique role that can only be fulfilled by an advisor can be contextualized within the stages of expert skill acquisition that are supported by cognitive apprenticeships—cognitive, associative, and autonomous. Although textbooks can offer declarative knowledge on how to formulate research questions, I hypothesized that professors would assert that such knowledge is insufficient to move students beyond the cognitive stage. Feedback is required from instructors during the associative stage to help students detect mistakes and misinterpretations before they can refine their ability to formulate research questions during the final autonomous stage. I expected that cognitive apprenticeship theory would be fruitful for contextualizing my findings because it would propose specific strategies and stages that I could look for in my data.

Chapter 2: Literature Review

Literature Search Strategies

Initial search strategy (student question formulation). The first stage in the literature search involved the identification of keywords by casting a broad net. The words *question* or *questioning* in combination with *instruction* or *teaching* and *learning* were sought in any field of bibliographic information of articles in the ERIC database (as queried using both Wilson and ProQuest Online libraries). Q*uestioning Techniques* was identified as the descriptor that yielded articles on questions and questioning as an instructional strategy. Unfortunately, the majority of these studies were about techniques for teachers to use with students. The key terms, *student questions, question formulation, question posing*, and *question finding* were combined with related terms within the theme of instruction. Related instructional terms that were searched for included: assessment, cognitive development, cognitive process, cognitive processes, critical thinking, discovery learning, educational strategies, elementary education, epistemology, experiential learning, habit formation, inquiry, learning activities, learning strategies, problem solving, questioning techniques, reflection, role, science education, science instruction, science interests, student interests, student improvement, student motivation, thinking skills, and transformative learning. Next, the *delete duplicates* function of the *Endnote* software was used as the final filter, creating a list of articles whose abstracts would be carefully sifted, one-by-one. During this last and most important stage, articles that did not engage students in directly formulating their own questions were removed. The final main database comprised approximately 200 articles on students' questions. Articles were considered to be part of the overall review if they systematically investigated a research question using qualitative, quantitative, or mixed-methods approaches, or if they used extensive references (such as is the case with literature reviews) or any type of theory. The editorial, opinion, and instructional *how-to* pieces were set aside as potential sources for additional articles.

Updating the literature search (research question formulation). An initial search for the words "research question" in the abstracts of English publications in ERIC ProQuest yielded 1953 hits. Placing the limiter of "higher education" reduced this total to 176. In the next stage, keywords were identified from these articles that would directly inform the topic of research question formulation. These keywords coalesced around five themes: supervision, thesis and dissertation, literature searching, research processes, and inquiry and question formulation (see Table 2). They were then combined with instruction key words and delimited to our populations of interest to produce individual searches that would yield 100 or fewer hits per search (the number recommended by a reference librarian as the number of hits that merit manual browsing). When a search yielded 100 or fewer hits, the abstracts were manually browsed for articles that had any possibility of content on RQF. These manual searches ultimately resulted in 33 articles, 13 of which were empirical, and 20 of which were not. In subsequently updating the literature search, I also discovered an additional approach to strategically extending the scope beyond educational psychology. I term this strategy "the launching point strategy," an approach that involves using articles that directly involve student engagement in RQF as a launching point to find articles in other fields. At first, this started with reviewing the reference list of these articles and using the "find citing articles" feature in Ebsco and ProQuest. However, because "find citing articles" has limited utility for newer articles, I experimented with tools from publishers' websites (e.g., "find similar articles"). These launching point searches resulted in 153 articles that directly mentioned students' questions (see Table 3 for details), 94 of which were empirical (see Table 4 for details), and directed me toward two promising disciplines in which to search for RQF articles: linguistics, and library and information sciences. The full search processes for both SQF and RQF that unfolded over the course of my study are summarized in Table 1.

Table 1

Literature Search Stages and Phases

Stage	Substeps
Comprehensive examination focused on student question formulation (SQF)	Searched for literature on 'students' questions' in higher education
Updating the literature review for research question formulation (RQF)	Searched for leads to 'research question formulation' using abstracts, citing articles, and reference lists of 'student question formulation' literature
	Created new and comprehensive searches using keywords identified ● Supervision ● Dissertations ● Literature searching ● Research processes ● Inquiry & question formulation
	Selected key articles that explicitly mentioned students formulating their own questions
	Used key articles as launching points for finding additional articles (e.g. by reviewing reference lists, citing articles)
Final literature review	Conducted broad literature search within the natural sciences for: ● Graduate supervision ● Research question formulation ● Problem representation ● Problem solving ● Problem statements ● Problem structure ● Problematization

Table 2

Literature Search Terms

Main themes searched					Terms used to narrow search results	
Supervision	Theses & dissertations	Literature searching	Research processes	Inquiry & question formulation	Instruction keywords	Populations of interest
Mentors Supervisory Methods Supervisor Supervisee Relationship Supervising Research Students Supervision Research supervisor Integrated competing values framework Student role Teacher role Teacher student relationship Faculty advisors Teaching -- research Writing teachers	Theses Dissertation Doctoral Master theses Doctoral dissertations Research topic Research AND topic Student research Inquiry Student projects Student research Research Independent study Research papers (students) Research projects Research skills Research Methodology Methods Courses Science education	Literature Reviews Librarians Library instruction Librarian teacher cooperation Academic libraries Library role Library research Information seeking Information retrieval Online searching User needs (information) Search strategies Reference materials Reference services Peer review Research (major) Gap Spotting Gaps	Epistemology Heuristics Models Definitions Scientific principles Selection Research design Methods Research methodology Writing for publication Writing processes Scholarly communication Rhetoric and composition	Inquiry based learning Scientific inquiry Problem-based learning Students' questions Self-questioning Student generated questioning Question posing skill Questioning techniques Question construction Problem solving -- study and teaching Science education Research problems Research questions Research question construction Problem solving Problem Representation Problem statements Problem Structure Problematization	Metacognitive strategy Higher order thinking skills Understanding skills Active learning Learning methods Training methods Skill development Teaching models	College faculty College students Undergraduate students Student experience Higher education Undergraduate methods Undergraduate study Honors curriculum Research reports Research problems Portfolios (background materials) Performance based assessment Portfolio assessment Graduate study Professional education Doctoral students Scientists

Table 3

All Publications That Mention Students' Questions (Including Both Empirical and Nonempirical)

	Mixed levels [a]	Undergraduate	Graduate, professional, and continuing education	All grade levels
Research question formulation (RQF)	1	18	14	33
Student question formulation (SQF)	23	73	10	106
Problem-based learning (PBL)	0	3	0	3
Inquiry-based learning (IBL)	2	6	3	11
All Subjects	26	100	27	153

Note. Counts in this table reflect all results from the Educational Resources Information Center (ERIC) database, including empirical, non-empirical, peer-reviewed, and non-peer reviewed articles.
[a] Mixed levels refers to studies which include investigated multiple grade levels, e.g., undergraduate and masters students.

Table 4

Empirical Articles That Mention Students' Questions

	Mixed Levels [a]	Undergraduate	Graduate, professional, and continuing education	All grade levels
Research question formulation (RQF)	0	6	7	13
Student question formulation (SQF)	12	55	5	72
Problem-based learning (PBL)	0	2	0	2
Inquiry-based learning (IBL)	0	5	2	7
All Subjects	12	68	14	94

[a] Mixed levels refers to studies which include investigated multiple grade levels, e.g., undergraduate and masters students.

Themes in the Literature

Literature reviews on student question formulation (SQF). There is an old adage that says that one needs to crawl before learning to walk. Although my research interest is on the formulation of questions that lead to new knowledge, there is a set of literature that exists regarding the formulation of questions to help students master known knowledge. This literature outlines the many benefits associated with teaching students to pose and pursue questions that would enhance their own learning (Carlsen, 1991; Chin & Osborne, 2008; Ciardello, 2000; Graesser & Wisher, 2001; Rosenshine, Meister, & Chapman, 1996; Watts & Pedrosa de Jesus, 2005). It also paints the beginnings of the picture of how novices develop the skill to formulate critical questions as they enter a discipline. For example, Chin and Chia (2004) explored the inspiration for, nature, and role of self-generated student questions for ninth graders in high school biology. The authors concluded that teacher modeling, structured tasks, and social supports were required to encourage student question formulation in problem-based learning contexts. In their review of SQF articles in science education at all levels (from elementary to postsecondary), Chin and Osborne (2008) concluded that environmental structure and scaffolding were required for students to formulate questions; without these two elements, said questions would not occur spontaneously. Although recommendations by Chin and Osborne (2008) for future research included how to integrate SQF into instruction, only passing reference was given to the development of RQF for science investigations.

Graesser and Wisher (2001) presented some models of question generation as well as some taxonomies for coding questions. For their review, they selected articles from psychology, cognitive science, linguistics, and cognitive design. They reviewed the theories that predict when and how questions occur in general. Graesser and Wisher's main conclusion was that question generation can improve retention because knowledge gained from one's own questions is constructed in a more complex, detailed, and accessible mental model. Furthermore, the authors selected empirical findings that support effective strategies for the development, encouragement, and refinement of student questions. Although they synthesized nine concrete, tangible practices for immediate use in the classroom and distributed learning settings, divergent use, prevalence in practice, and the selection process of faculty advisors has not been researched.

Rosenshine et al. (1996) conducted a review of intervention studies in which students were taught to generate questions as means of improving comprehension. The authors selected 26 studies that had used either reciprocal teaching or cognitive strategies in which students formulated their own questions to understand new content. The authors did not include studies that lacked a control group or transfer measures. The authors' main conclusion was that students will be better able to comprehend material if they are taught to generate questions. However, the gains from teaching students to formulate questions are not evident when standardized tests are used to measure achievement. Rosenshine et al. suggested that procedural prompts such as signal words (who, what, when, where, why, and how) as well as generic question stems would be helpful to students for the purpose of formulating questions that would improve their reading comprehension yet, similar to the conclusions of other previously mentioned studies, the practice of supporting RQF in the complex context of graduate education has not been sufficiently researched.

Watts and Pedrosa de Jesus (2005) conducted a narrative literature review to explore some of the mechanisms of students' question asking, specifically delving into internal socio-emotional processes that led students to articulate a question in a social setting, the influence of the emotions on the substance of questions, and learners' resulting emotions as a function of how their questions were treated by the instructor. The articles for their literature review included narrative case studies, science teachers' diaries, and empirical articles that examined questioning in the context of class participation. The authors' conclusions converged with those of other literature reviews in that the integration of students' questions into teaching and learning produces measurable gains in comprehension and understanding. Watts and Pedrosa de Jesus used these anecdotal descriptions to claim that students' immediate and long-term experience of producing and posing questions in a social context were characterized by feelings of "aversion, distaste, disaffection, embarrassment, exposure, vulnerability, and distrust" (p. 439). Whereas the majority of student question formulation literature reviews focused on cognitive qualities, Watts and Pedrosa de Jesus extended the discussion to a socio-emotional dimension by concluding that "cognition, affect, and action . . . Each influenc[e] the other in intended and unintended ways" (p. 439) and therefore indirectly make a case to look at the support of RQF within the context of the relationship between faculty and students.

Individual empirical studies informed by inquiry-based learning have focused on using questions to help learners remember, understand, and perform well on content examinations—tools that support an information-transfer approach to learning (Graesser, Person, & Huber, 1992; Lustick, 2010; Marbach-Ad & Sokolove, 2000; Rop, 2003; Yager, Abd-Hamid, & Akcay, 2005). Although these types of questions might help students comprehend and retain content, they are not necessarily the researchable questions that drive further systematic inquiry. In fact, we know that, although there are questions being formulated by undergraduates, such questions tend to be ill-suited for leading students into their own scholarly investigations (Blonder, Mamlock-Naaman, & Hofstein, 2008; Choi, Land, & Turgeon, 2005; Davey & McBride, 1986; Keeling, Polacek, & Ingram, 2009; Mantzoukas, 2008; Nardone & Lee, 2011; Sadker & Cooper, 1974). Herein lies the first important empirical gap in the higher education literature base—current research on the espoused role, applied instructional practice, and subsequent development of students' abilities to formulate questions has yet to include questions that drive scholarly inquiry.

In summary, empirical studies and narrative and systematic literature reviews affirm the clear benefits of SQF in facilitating content mastery and reproduction of previously known knowledge. The underlying theme connecting the vast majority of the SQF literature is how to train students to produce questions to help them understand previously known knowledge, as opposed to questions that lead to the generation of new knowledge. Although the literature conducted to date reveals that direct instruction in SQF helps students to comprehend and retain content, there needs to be more research detailing how to train students to produce researchable questions that drive further systematic inquiry—the pedagogical literature on how to do so is nascent.

Developing RQF in classroom contexts. When it comes to developing student capacities to find, frame, and formulate research questions in classroom contexts, a number of narrative case studies and prescriptive editorial articles abound (Bradley, 2001; Donham, Heinrich, & Bostwick, 2010; Snavely & Wright, 2003) whilst empirical studies that include a control group are virtually nonexistent, save for Strangman and Knowles's (2012) of how to improve RQF among undergraduates in business.

Snavely and Wright (2003) described portfolio-assessment procedures for undergraduate students in a library studies course. This course was taken for credit by honors students conducting thesis research and comprised two sections: one for humanities and social sciences, the other one for sciences, technology, and engineering. The research process for these students included the exploration of a broad research idea of interest, the narrowing of the topic into possible subconcepts, the selection of one of these topics for deeper investigation, the identification of means of answering said question, literature-review preparation, and the final translation of the research interest into a thesis topic or a research question. Using this portfolio-assessment procedure, instructors were able to provide formative feedback while imparting upon the students the iterative and recursive nature of the information-gathering aspect of scholarly research. This article was valuable for its extensive description of how to walk students through the process of RQF, so that the questions they formulate build upon previous research.

Bradley (2001) conducted a case study that explored one instructor's design of a research-methods course that she taught to 20 graduate students in a Master of Gerontology program. The theoretical framework that she used to analyze the students' subsequent learning was experiential learning. Bradley argued that to teach students to move from a research topic to a research question requires numerous tools, practice, and feedback. She designed a very well-defined, scaffolded, and feedback-intensive process that taught students how to refine an interest to make it into a research question for a grant proposal. At every stage of grant-proposal writing, students shared their work with peers and the instructor, integrated suggestions, reflected upon their process and progress, and eventually defended decisions they made in the design of their research. One important contribution of this article was its focus on the importance of prior knowledge, and the role that prior knowledge and understanding play in students' learning processes as they engage in the formulation of questions (whether their focus is old content knowledge or turning the question into a workable one for the empirical pursuit of new knowledge). The main pedagogical contribution of this article was that it clearly outlined an iterative RQF process that was broken down into smaller submissions, with feedback from peers and the instructor integrated on a weekly basis.

Strangman and Knowles (2012) empirically studied instructional efforts to improve students' ability to formulate research questions. The authors collected the first drafts of all 122 research proposals submitted by the students, 51 of which were submitted in semesters prior to the instructional intervention and 71 afterwards. Their investigation stood out as one of the few studies that rigorously controlled for confounding variables such as sex, cumulative GPA, high school class rank, ACT mathematics score (ACT was formerly known as American College Testing), and ACT composite score. Furthermore, rater bias was minimized by ensuring that each of the proposals had a unique random identifier so that raters did not know whether they were assessing work from the intervention versus the control group.

Students in the intervention group fared better in the overall scores on a rating scale devised by the authors to evaluate student research questions. This rating scale included "(1) the scope or vision of the proposal encompasses the relevant variables; (2) the information is useful for decision making or addressing the overall problem; (3) the research questions are well defined; (4) the research hypotheses are well defined; (5) the research hypotheses are measurable; and (6) the research questions and hypotheses are directly related" (p. 4). The intervention group posed research questions that were better defined and had better scope and vision than those posed by students in the control group. Students in the intervention group also wrote hypotheses that were more directly related to their research question, although students in all groups continued to show weaknesses when it came to ensuring that their hypotheses were well-defined, measurable, and testable. Regardless of whether or not they had experienced an intervention, all students did not ask enough subquestions or related questions.

By comparing a control group to an intervention group, Strangman and Knowles (2012) demonstrated that instructional scaffolding enables undergraduates to improve the clarity, vision, scope, and appropriateness of their research questions and hypotheses for undergraduates in a business course. This experimental result converges with the more quasi-experimental studies previously mentioned for undergraduates in library studies (Snavely & Wright, 2003) and master's students in gerontology (Bradley, 2001). That is, students need structured opportunities for both practice and iterative feedback in order to generate their own questions. Instructional scaffolds included templates for writing out research questions and iterative rounds of peer and instructor feedback. The extent to which such scaffolds are used by professors across the natural sciences remains unknown.

RQF in supervision. To date, my search of the supervision literature has yielded few instances of empirical articles that examine the role of supervision in RQF. To recap, "research question" constituted the base search strategy. Search terms that I combined with supervision included training, research skills, dissertation, thesis, faculty, research problems, research projects, master's programs, and doctoral programs. From the search results, I selected three representative articles to depict the articles that emerge from a search on RQF terms related to supervision.

Tan (2007) used narrative inquiry to enable undergraduate students in various research courses to describe their research experiences. She collected data from 10 semistructured interviews and four focus groups, for a total of 27 female and eight male students (the author did not explain this division). These students' stories spoke to the role of strong supervision in helping them move through the various stages of research, which the authors referred to as Groping, Developing, and Accomplishing. The study took place in four research classes, with students writing their research and defending it in a forum. In the initial Groping stage of research, students selected research questions from previous studies, or brainstormed with experts to help them formulate research questions. With regard to RQF, although Tan highlighted the challenge of finding a question that would contribute to the faculty advisor's research agenda, she wrote very little about the actual process of formulating said question. The most important commonality amongst empirical articles on RQF at the undergraduate level was the degree of scaffolding and support that undergraduate students require to help them deal with obstacles posed by their level of cognitive development, their tolerance of ambiguity, and their struggle with ill-defined, abstract tasks during this key period of acclimatizing to scholarly research.

Franke and Arvidsson (2011) explored how professors' experience of supervision varies as a function of the relevance of their supervisees' research. The researchers interviewed 30 supervisors and aimed to establish trustworthiness through member checking for the main themes deduced during their data analysis. The authors concluded that research supervision must include both "a what and a how aspect in the actual learning . . . . The what aspect has been clearly expressed but the how aspect has remained largely implicit" (p. 9).

With practice-oriented supervision, in which the student and professor share their area of interest, the student might even receive a research question from the professor. An important element or quality of this style of supervision is the professor's emphasis on passing down the traditions of his or her field and ensuring the understanding of its rules, practices, and conventions. Relation-oriented supervision is characterized by advisors serving as sounding boards, ensuring quality control, showing an interest in students' emotional and other needs, and possibly even questioning one's own ability to effectively supervise the student in an area outside of one's expertise. Articles such as Franke and Arvidsson's (2011) drew attention to the inherently varied, individualized, context-dependent, and complex nature of any research that attempts to understand supervision in general. The consideration of such dynamic variables is important to the study of supervisory practices related to RQF in particular because it helps us to understand the nuances and paint a more holistic picture.

The articles described above said very little about formulating or refining research questions and had more to do with the overall supervision process, and the roles and needs filled by supervisors as they help doctoral students navigate from the initial interest in a topic to the production of a final dissertation. Franke and Arvidsson (2011) and Vilkinas (2008) applied different models of management and mentorship to illustrate the variety of approaches that can characterize supervision. These empirical articles drew attention to the fact that much variation can exist in terms of both style and quality but stop short of elucidating the role of supervision in the development of RQF capacities amongst students. Therein lies the core of my research interest.

The prescriptive literature: models, tips, and strategies. Advice, tips, and strategies abound when it comes to prescriptions for formulating research questions. Generally speaking, prescriptive writings are targeted at two audiences: supervisors (e.g., commentaries, how-to books, and editorials) and students (e.g., journal articles and textbook chapters).

In her book on supervision, Wisker (2005) dedicated six pages to helping students formulate research questions. She started with a strong definition of a research question: "Research questions or hypotheses . . . [problematize] the statement, . . . [identify] underlying concepts so that the area under study can be interrogated not just described" (p. 74) and suggested that supervisors prompt students with subquestions such as "What is your research question?" "Are there any subquestions?" and "What is your hypothesis?" (p. 74). According to Wisker, the role of the supervisor is to help students problematize an area of inquiry, and then set and maintain boundaries and parameters of their topic. However, her pedagogical suggestions are limited. For example, she suggested that supervisees talk with each other about their research interests, outline the literature using a concept map, and fill out a pie chart that defines their slice of interest within the overall area of possible topics for investigation. However, the vast majority of her advice, targeted at social scientists, presented an elementary overview of topics such as the importance of genuine interest, as well as possible forms of research questions, and a consideration of the same question from different angles and under different theoretical perspectives.

Lei (2009) conducted a literature review to identify successful strategies to find a thesis or dissertation topic and to outline critical factors that influence their topic selection process. He found that faculty, literature, and curriculum constituted the three primary sources for finding topics. When it came to topic selection, several themes emerged: faculty (relatedness to faculty's interest, committee approval, ongoing research), student (familiarity, personal interest), nature of the topic (uniqueness, existing literature, controversy), trends (hot topics, springboard for future research), duration of study (solvable, feasible, participant tractability), and research funding and audience. Lei did not shed light on how a student proceeded from topic selection to research question formulation nor did he emphasize the iterative, nonlinear, and often recursive nature of RQF. Instead, the author's closing remarks were as follows: "Once the topic selection has been firmly made, students are ready to progress to the next major step, which is writing their thesis or dissertation research proposal" (Lei, 2009, p. 1332). This statement missed a critical element of research in the natural and social sciences—the research question itself and its associated methodologies. This article may leave students with possibly unrealistic assumptions about the process of generating a research question.

Ings (2011) proposed an instructional framework to help postgraduate students in graphic design to formulate research-based theses:

> Heuristics comes from the Greek word *heuriskein* meaning 'to discover' or 'find.' It is a qualitative method of solving a problem for which no formula exists. Heuristics relates to the ability to find knowledge, patterns or a desired result by intelligent, informal questioning and guesswork rather than by applying pre-established formulae. As a form of inquiry it utilises sophisticated levels of informed subjectivity and tacit knowledge to solve complex creative problems. (p. 227)

This framework challenged students to connect the investigation to their personal experience to deepen their understanding and intuitive connection with the researcher. At the outset of the research, students are dissuaded from prematurely limiting themselves to a single clearly defined question and, instead, are encouraged to keep an open mind—one that can expand to the many possible areas of investigation. Unlike Lei (2009), who outlined rather simple steps for going from a topic of interest to a research proposal, Ings (2011) advocated a dynamic one to lead to the proliferation of ideas.

Lindeman and Schantz (1982) wrote a detailed instructional article for nurses to understand all the requirements of the research process, and that breaks it down into scientific steps (formulating the problem, framework, and hypothesis; reviewing the literature; defining the variables) and technical steps (operationalizing variables; determining research design, target population, data collection, data analysis; communicating findings). Fernando and Hulse-Killacky (2006) proposed an inverted triangle model for supervisors to facilitate RQF learning for students in counseling by moving them through the following phases: (a) context, (b) what I want to know, (c) the importance of the question, (d) what is known, (e) what is not known, and (f) implications for the field. Thabane et al. (2009) proposed what they termed the *PICOT* model for translating clinical problems into a research question by specifying the target Population, the Intervention, the Comparison variables, the key Outcomes, and the Time frame (PICOT). They used this model to assess the quality of research questions of four major journals in their field of anaesthesia in 2006 and found that 96% of 313 articles that they reviewed did not apply the PICOT model in reporting their research questions. The authors conceded that it remains to be seen whether the application of this model would improve research quality. Thabane et al.'s model did converge with other approaches in that it outlined quality criteria for a question. I agree that its application is promising in its ability to help novices understand what constitutes a well defined and clearly stated research question.

Many people have written extensively about how research questions can and should be formulated, and this advice can sound intuitively useful. However, that which appeals to intuition is not always equally valuable in use. For example, Thabane et al. (2009) found that the research questions reported in articles from the top journals in their field did not consistently include the basic components of an empirical inquiry (e.g., population, variables, timeline). What is the perceived quality of pedagogical advice on how to find, frame, and formulate research questions? Is any of this advice already in use by professors? By asking professors to comment on the quality of the existing advice, I obtained a measure of face validity on this widely available content. An improved understanding of the quality of advice available to professors and students informs our professional development efforts with regard to the needs of both faculty and students. My study sought to be the first empirical attempt to make that applied contribution to knowledge. Furthermore, the majority of the prescriptive writing on RQF has been written in the fields of medicine (e.g., Lindeman & Schantz, 1982; Thabane, Thomas, Ye & Paul, 2009) or education (e.g., Fernando & Hulse-Killacky, 2006; Mantzoukas, 2008). My study was the first to look comprehensively at the natural sciences.

Moderating variables. One size fits all! That was the resounding commonality amidst the prescriptive literature on how to formulate research questions, whether said advice has been targeted toward faculty or students, or was found in a textbook, a how-to article, an editorial, and so on. Few articles have mentioned possible variables that might contribute to an understanding of whether professors vary their mentorship of student RQF, and if so, how, when, why and with whom they vary it. The articles described in this section provide some hint to what these considerations may be. This section starts with a summary of articles that outline the impact of assumptions, particularly differences in assumptions held by undergraduates, graduates, professors, and librarians (Bodi, 2002; Leckie, 1996; Nutefall & Ryder, 2010). Also discussed are epistemological matters that affect the timing and finality of the research questions that students formulate, which could be most evident in research on subject specific or discipline specific differences in RQF and their respective rules for validating and assessing new knowledge.

In an editorial written from a library sciences perspective, Bodi (2002) proposed possible differences between the research process pursued by professors versus undergraduates and the likely impact of such differences. Differences highlighted included the sources and types of motivation, content knowledge, the depth and breadth of tools and strategies that are available to the novice versus the expert. Although such differences in and of themselves are unsurprising, they are often overlooked when it comes to instruction. For example, the assumptions that students hold are likely to affect how students find and focus their topic, their literature search strategies, and what they choose to do with anomalous information that does not conveniently serve their main arguments. Although Bodi's assertions were founded in her reflections and experience instead of empirical investigation, they drew attention to the possibly powerful role of underlying assumptions. An empirical study that systematically probes for such assumptions would lend further credibility to Bodi's assertions. Therefore, it would be fruitful to probe for assumptions that are held by supervisors regarding both undergraduate and graduate students during their RQF processes.

Writing from the perspective of library and information sciences, Leckie (1996) produced a thoughtful piece that outlined the differences in assumptions held by undergraduates versus those of professors during the scholarly research process. Drawing from anecdotal experience and published literature, Leckie examined the resources, background knowledge, tendencies, and inclinations of the two populations that result in problematic issues in the training of scholarly inquiry skills. These assumptions affect the nature of the assignments, instruction, and assessments, the logistics of how to pursue existing knowledge on the topic, search strategies, and important psychosocial, sociocognitive, and motivational variables such as tolerance for uncertainty, strategies for dealing with anomalous information, and one's awareness of becoming engaged in fruitless paths. Since Leckie's publication, improved search tools for online databases have theoretically made information searching easier.

Nutefall and Ryder's (2010) work highlighted the differences in views between professors and librarians regarding another important factor of the research process: When exactly should students be formulating their research questions? The authors interviewed a convenience sample of seven participants—four professors and three librarians—who explored views on the characteristics of good research questions and the timing of research questions. No details were given regarding the nature of the coding used by the researchers to identify the themes found in their pilot study. The authors pointed out that "all the faculty and librarians in the study describe their projects using specific key terms with an awareness of rhetorical purpose; they focus on how or why or what's at stake" (p. 446). Whereas librarians believed that students' research questions should be formulated early in the process to guide their information search efforts, professors emphasized the importance of accepting uncertainty and ambiguity while reading the literature and delaying the formulation of the research question "over the better part of the semester" (p. 444). The resulting disconnect is that professors see an important exploratory phase of information searching and reading, during which they would like students to keep their research topics open. During this phase of keeping an open mind, the students may be inadequately supported if the three parties (students, librarians, and professors) proceed from different assumptions on the nature, timing, and finality of the research questions.

Frankel and Devers (2000) provided a strong, well-written article offering practical advice for clinicians on how to conduct research, describing how a single research topic divides into multiple related subquestions that guide and inform one's search when reading literature. The primary objective of their article was to interest clinicians in qualitative research by offering them clear, concrete advice through the introductory stages of question development, literature review, and the other aspects of designing a study. This was one of the few articles that I have come across that highlighted how the processes for coming up with research questions can differ as a function of the nature and extent of the existing literature. Frankel and Devers pointed out that the development of a research question at the outset may be relatively straightforward if much is already known about the topic while a more iterative process would be necessary if the researcher is pursuing inquiry into an area where the literature is scant:

> [when] the existing theoretical and substantive literature does not adequately capture or reflect their personal experience . . . When relatively less is known about a topic, change is rapid, or discovering new theoretical or substantive knowledge is emphasized, the qualitative researcher may begin with a more exploratory research question and refine it through a series of studies. (p. 254)

A seminal educational psychology study of perceived disciplinary differences was Biglan's (1973) study (1770 citations). The authors asked 54 academics to make judgements on the degree to which two subjects were similar. The participants were given 36 cards, each card containing an area of study, and asked to sort the cards into groups on the basis of similarity. Participants were free to choose as few or as many groupings as possible. Upon completion of the sorting, they were asked to rate each grouping on a set of bidirectional adjectives (pure-applied, physical-nonphysical, biological-nonbiological, degree of personal interest to me, traditional-nontraditional, life science-nonlife science). Using the participants' ordinal ratings, the authors applied a scaling procedure to conceptualize how the ratings coalesced together in a multidimensional space. The best conceptualization of the academic disciplines was along three dimensions: existence of a paradigm, concern with application, and concern with life systems. Given major subject-specific differences in how fields are conceptualized, my research study starts with the presumption that disciplinary differences will also find their way to show up in differences in how faculty see and support RQF.

Shore, Pinker, and Bates (1990) also generated a way of grouping scholarship based on professors' descriptions of their research. The authors demonstrated that scientific disciplines were spread across four types of research—experimental, applied, exploratory, and theoretical—and the role, purpose, format, function, and contribution of a research question varied across these disciplines. In some of these types of research, the hypothesis, predictions, and research questions played a central role; with other types, these served merely as the launching point for the investigation.

Finally, epistemological factors may influence the process by which students come to their research question. In four studies highlighted herein, there was a common thread—specifically the role of previous publications, their characteristics, and how they should be searched and synthesized. Frankel and Devers (2000) suggested that RQF processes might vary as a function of the extent to which a topic has already been researched. Nutefall and Ryder (2010) added to this discussion by finding empirical evidence that scholars would like undergraduate students to maintain an open mind while they become familiar with the literature. Authors in the library sciences believe that there is a disconnection between the assumptions held by students, professors, and librarians (Bodi, 2002; Leckie, 1996), and that these differences have instructional implications (Nutefall & Ryder, 2010). This literature would benefit from empirical testing, replication, and extension to include assumptions that supervisors hold regarding their graduate students as well. Other literature outlines discipline and content-specific requirements regarding the construction of new knowledge within the discipline (Biglan, 1973) or using a specific methodological approach (Tashakkori & Creswell, 2007). The process of formulating research questions differs as a function of several variables (e.g., the amount of existing literature, the methodology in use, the role and experience level of the researcher). We also know that there are differences in the nature, form, and structure and function of research questions used across the sciences. What we do not know is whether any of these differences affect the choices made by scientists during their teaching and mentorship of student RQF.

Research Question and Objectives

The present study sought to illustrate diversity in pedagogical approaches that foster student research question formulation (RQF) and to identify the facets or dimensions associated with this diversity, specifically:

- What do professors report doing to develop students' capacity to find, frame, and formulate research questions? (Q1)
- How do professors vary their RQF strategies and approaches as a function of students' educational level, of perceived individual student needs, and of any factors associated with the research area itself (e.g., epistemological, methodological, subject-specific factors)? (Q2a)

Over the course of the study Q2a was revised and replaced by Q2b:

- Do professors reportedly vary what they do to help students find, frame, and formulate research questions to meet the perceived needs of individual students? If so, what do professors do differently from one student to another when it comes to developing student RQF and what rationale do they give for differentiating their approaches? (Q2b)

A full discussion regarding the rationale and process behind this revision is presented in the methodology chapter (Data Analysis: Objective five for a discussion of the revision rationale and process).

Approaches to fostering RQF, when they exist, range from those that are tacitly or intuitively generated as the need for them arises to ones explicitly and intentionally designed and systematically applied by professors. Openness to variations in the level of intentionality behind professors' pedagogical approaches is thus important in minimizing researcher bias.

These dissertation questions employed open-ended wording (e.g., "what do professors do . . . ?") while avoiding pedagogical terminology (e.g., "what instructional strategies did professors use . . . ?"). Within the phenomenographic framework, "the idea is for the researcher to be as open as possible to the varying experiences that may be encountered during interviews" (Limberg, 2008, p. 613). The problem with using terms like instructional strategy, mentorship approach, or teaching technique is that these already have predefined meanings and assumptions within the field of educational psychology. Had I used these terms, I would have been pushing my participants to frame their experiences within my educational psychology framework of what constitutes an instructional approach instead of allowing them to freely and openly describe their experiences within each one's own context. Thus, the purpose of the broader and nonspecific wording was to cast a wide net in order to remain open to any type of data that the participants provided, which would inform or address my research objectives of better understanding professors' mentorship experiences with student RQF.

Chapter 3: Methodology

Methodological Framework

The literature review identified the natural sciences as the area with the largest gap in empirical knowledge about how questions are formulated for scholarly inquiry. I therefore chose to explore pedagogy that is believed to support research question formulation (RQF) in the natural sciences at the higher education level. Any single study seeking to investigate the conceptualization and design of inquiry across the sciences would have to contend with a great deal of variation. One major source of variation is how the process of discovery, pursuit, and validation of new knowledge differs from one discipline or subdiscipline of science to another, which means that the processes for identifying, selecting, and designing research necessarily vary as well. A second major source is the degree of variation in student participation in the design of research and the formulation of scientifically testable questions. This occurs due to many contributors such as technical training and requisite knowledge needed, access to resources and technology, or variations in norms for the department, institution, or discipline. Thus, the methodological framework chosen for this study had to be capable of handling the substantial variation in the experience of the phenomenon under investigation.

Phenomenography was selected as the most appropriate framework because it is designed to explore, illustrate, and understand variation in human experience (Marton, 1981). Phenomenography allows researchers to identify the different ways of experiencing a phenomenon and the nuances among and between these ways. These similarities and differences are then used to identify the underlying dimensions. Finally, the dimensions are used to illustrate how the different ways are related to each other (Limberg, 2008). The objective of my study was to understand how students learn to conceptualize and design research questions according to those who are entrusted with producing the next generation of natural scientists. As the methodological framework that guided the design and pursuit of my study, phenomenography prescribed approaches for exploring variation in how natural scientists experience the teaching and mentorship of RQF.

Additionally, the study presupposed that natural scientists would vary in their ability to articulate, describe, and explain the pedagogical events and actions, if any, that they take to promote students' inquiry skills. Indeed, a professor may be transforming implicit intuitions of his or her pedagogy into a more explicit understanding during the interview. Phenomenography expects participants to lack salient, ready-made answers during data collection. Phenomenographic interviews are not intended to elicit preformulated answers; instead they are "a means for the interviewee to think about, reflect on, and formulate ways of experiencing a particular phenomenon. In this way, the various experiences sought in the study are being shaped through the interview for further analysis by the researcher" (Limberg, 2008, p. 613). Phenomenography prescribes approaches to data collection that allowed me to elicit and capture the subtler activities professors—activities that professors themselves may not have linked to how students learn to conceptualize and design research (at least, prior to the interview). Through the lens of phenomenography, I was able to identify themes illustrating the variation in teaching and mentorship approaches believed to support RQF, and to understand this variation in terms of how, why and when the different approaches are used by professors.

Study Design

Research objectives and dissertation questions. The phenomenon of interest was the formulation of research questions in the natural sciences, and professors were the unit of analysis. The objective of the study was to identify the pedagogical experiences that professors associate with developing students' ability to pose research questions. To this end, the main questions for this study were:

- What do professors report doing to develop students' capacity to find, frame, and formulate research questions? (Q1)
- How do professors vary their RQF strategies and approaches as a function of students' educational level, of perceived individual student needs, and of any factors associated with the research area itself (e.g., epistemological, methodological, subject-specific factors)? (Q2a)
- Do professors reportedly vary what they do to help students find, frame, and formulate research questions to meet the perceived needs of individual students? If so, what do professors do differently from one student to another when it comes to developing student RQF and what rationale do they give for differentiating their approaches? (Q2b)

Data reduction tools. During data collection, my goal was to conduct interviews until no new ideas emerged. To do so, I used postinterview memos, precoding and purposeful sampling, and coding to determine saturation points in both data collection and data analysis. Postinterview memos were used to inform my decisions to continue recruitment efforts. Precoding was used to identify interviews where the participant explicitly shared teaching and mentorship actions in the context of student engagement in the conceptualization and design of research questions, as well as mentor beliefs, attitudes and values regarding this topic. Purposeful sampling was used to ensure participants were drawn from a diversity of sub-disciplines across the natural sciences. Extensive coding procedures were used to determine saturation in data analysis; these are described in the data analysis section. See Table 5 for all qualitative research tools used in the study.

Table 5

Overview of Qualitative Research Tools

Research design component	Method
Research questions	● What do professors report doing to develop students' capacity to find, frame, and formulate researchable questions in the natural sciences? ● Do professors reportedly vary what they do to help students find, frame, and formulate research questions to meet the perceived needs of individual students?
Research tradition (paradigm or approach to research)	● Phenomenographic
Data collection tools	● Interviewing
Tools applied to reduce the data set	● Researcher's postinterview memos ● Precoding ● Purposeful sampling
Data analysis tools	● First Cycle coding ● Constant Comparison ● Second Cycle coding
Trustworthiness tools and measures	● Frequent debriefing sessions (contributes to credibility) ● Tactics to help ensure honesty in informants when contributing data (contributes to credibility) ● Interrater reliability (contributes to dependability) ● Researcher's reflective commentary and reflections (contributes to confirmability) ● Rich data and transparency in reporting conventions (contributes to confirmability) ● Saturation (contributes to confirmability)

Data analysis tools. The main qualitative research tools used to make sense of the interview data collected in this study were First Cycle coding, Constant Comparison, and Second Cycle coding.

Coding is a qualitative analysis tool wherein rich, striking, or otherwise important participant words are selected and then labeled with short phrases that capture the most salient attribute of the text segment (Saldaña, 2016). Coding enables researchers to identify similarities and differences among the data, to detect and categorize patterns that enable them to make sense of the data, and to build theories founded in the data. "The data and thus coding processes can range in magnitude from a single word to a full paragraph or an entire page of text to a stream of moving images" (p. 3). Saldaña's First Cycle coding techniques are used to break a data set down into discrete parts for further comparison. These discrete parts—codes—include values, concepts, actions, processes, and other content that represents possible answers to the research questions of a study. Examples of the application of this tool are provided in Table 6.

Constant Comparison is a qualitative tool based on Glaser and Strauss's (1967) analytic work, as well as Saldaña's (2016) explanation on how to detect patterns and interpret First Cycle codes applied by comparing "data to data, data to code, code to code, code to category, category to category, and category back to data, etc." (Saldaña, 2009, p. 45). During the application of Constant Comparison:

- Codes are grouped by similarity.
- Grouped codes are given preliminary working labels that describe the contents of the group.
- Existing and new data are compared to previously existing groupings.
- New groupings are created, or previous groupings are expanded or collapsed together as patterns emerge.
- Codes that were intuitively interesting or potentially relevant but did not fit with any categories are set aside for analysis at a later stage.

Second Cycle coding serves the purpose of "crystallizing the analytic work [into] higher level themes, concepts, assertions and theory" (Saldaña, 2016, p. 233). Focused coding and Axial coding were the Second Cycle coding tools selected for this study. Focused coding facilitates the reorganizing of data into major categories, while Axial coding is used to provide a richer description of the categories. Examples of the application of Second Cycle tools during this study are provided in Table 8.

Table 6

First Cycle Coding Tools (Saldaña, 2016)

Coding method	Description	Examples from the data set in this study
Initial coding	Initial coding (or Open coding) uses detailed, line-by-line analysis to break down qualitative data into discrete parts, and to closely examine and compare them for similarities and differences.	Examples of Initial codes (Open codes) included: • "PhD versus M.Sc. research questions" • "students don't see constraints" • "got fast NSERC funding" • "It's a conversation"
In vivo coding	*In vivo* coding uses words or short phrases from the participants' own language in the data record as codes. These may include indigenous terms from a particular culture or subculture to suggest the existence of the group's cultural categories.	Examples of *In vivo* codes included: • "the problem with students nowadays" • "some students are better at it than others" • "the best students would have their own questions" • "As students progress, they have more freedom to pick their own RQs." • "Features of a good research question are highly customized." • "Master's students do fewer projects than PhDs."
Structural coding	Structural coding applies a content-based or conceptual phrase to a data segment that relates to a specific research question, in order to both code and categorize the data corpus. Similarly-coded segments are then grouped for more detailed coding and analysis.	Q1 was "what do professors do to help students find, frame, and formulate research questions?" • "some senior PhD students eventually find their own questions—organic, dynamic" → Code applied: professors do nothing • "Every three months I make everybody in the lab, including research associates, do Gantt charts . . . to chart their progress on designing their experiments" → Code applied: I do XYZ to develop students' ability to formulate research questions
Process coding	Process coding uses gerunds (-*ing* words) exclusively to connote observable and conceptual action in the data. Processes also imply actions intertwined with the dynamics of time, such as things that emerge, change, occur in particular sequences, or become strategically implemented.	Examples of Process codes included: • "Developing tools" • "Collaborating with other schools / faculty" • "Planning" • "Articulating research" • "Matching research question with student"
Concept coding	Concept coding uses a word or a short phrase to symbolically represent a suggested meaning broader than a single item or action, an idea rather than an object or observable behavior. Concept coding assigns meso- or macro-levels of meaning to data or to data analytic work in progress. Concepts can be phrased as nouns—or as gerunds in the case of conceptual processes. This coding method is usually applied to larger units or stanzas of data. Concept codes can be arrived at by condensing a series of First Cycle codes (such as Process coding or Values coding). Concepts could also be derived from pattern, focused, axial, theoretical, and elaborative coding.	Examples of Concept codes included: • ownership • responsibility • creativity

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Coding method	Description	Examples from the data set in this study
Values Coding	Values coding is the application of codes that reflect a participant's values, attitudes, and beliefs. A value is the importance we attribute to oneself, another person, thing, or idea. An attitude is the way we think and feel about oneself, another person, thing, or idea. A belief is part of a system that includes values and attitudes, plus personal knowledge, experiences, opinions, prejudices, morals, and other interpretive perceptions of the social world.	Examples of Values codes included: • "There's always a challenge from the following perspective: you need to demonstrate that you're actually making progress. . . . To make progress, you have to be able to tell a story; to tell a story you need to have the language sufficiently concise and tight, the conceptualization tight so that you can tell that story." ▪ Belief code: requirements for a research question • "[. . .] and I want to do it in such a way that they're going to learn to be experiments in communication. Me formulating the question for them, that doesn't help them at all. By them learning how to formulate the question, by them having to write up the manuscript and onwards it goes, they're learning the process of communication." ▪ Value code: importance placed on student involvement in the conceptualization and design of scientific research. • "You're not there to publish papers, you're there to train the next generation of leaders. And you can train them so they become leaders or you can train them just to be technical people. . . . I haven't worried so much about the publishing. I'm never going to win the Nobel Prize. That's not the point. Point is, I'm happy because I feel I'm doing my job, my responsibility and I'm doing it well." ▪ Attitude code: feelings about approach to supervision • "[. . .] that's where one formulates the clarity, as a question, as a hypothesis, and the text . . . to answer that. . . You have to look at it from the pedagogical standpoint. What I want my students to do is work in a relatively open environment so they can explore the things that interest them." ▪ Value code: open working environment for student
Provisional coding	Provisional coding begins with a list of researcher-generated codes based on what preparatory investigation suggests might appear in the data before they are collected and analyzed.	Provisional codes generated prior to data collection included: • "Here's what I did in my methods seminar to help students find topics" → A provisional code ("in-class instruction") was applied, this code was researcher driven based on numerous studies on the use of questions in undergraduate teaching.
Subcoding	Subcoding is a second-order tag assigned after a primary code to detail or enrich the entry. Subcoding can be employed after an initial, general coding scheme has been applied and the researcher realizes that the classification scheme may have been too broad, or added to primary codes if particular qualities or interrelationships emerge.	The general code *exposure* was applied to statements about the importance of ensuring students experience a variety of academic, research, and professional environments. These statements were revisited and Subcoded to identify the facets and nuances of this category. Types of exposure: • students to other scientists • students to variety through conferences and seminars • students to other research labs Reasons for exposure: • Get inspiration for new research questions from other people's approaches • Transpose content from one area to another to formulate question • Troubleshoot roadblocks when conceptualizing your research by talking to members of other labs

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Coding method	Description	Examples from the data set in this study
Simultaneous coding	Simultaneous coding is the application of two or more different codes to a single qualitative datum, or the overlapped occurrence of two or more codes applied to sequential units of qualitative data. Appropriate when the data content suggests multiple meanings (e.g., descriptively and inferentially) that necessitate and justify more than one code.	We used multiple codes because our lengthy transcript segments justified more than one code, as there were multiple meanings (both descriptively and inferentially). Here is an example of a single segment where several codes were simultaneously applied: • "go into the literature and read dozens of papers for example in a particular subject area [CODE APPLIED: START WITH LITERATURE] . . . you can ask, then, a question . . . And so one of my students said well, 'What would happen if I switched it around?' [CODE APPLIED: STUDENT INITIATIVE] . . . the literature says that that shouldn't work [CODE APPLIED: CONSIDER FEASIBILITY] . . . Another supervisor might have said, 'Come on. You know, why bother wasting your time with something that everybody knows?'. . . I had no problems with that, because the student had a reasonable concept of why and how it would work . . . it was a proposal . . . a hypothesis . . . something worth exploring [CODE APPLIED: SUPERVISION APPROACH]" The above text represents a single segment in which four meta codes were simultaneously applied during Second Cycle coding: • literature • comments and expectations • feasibility, scope, and specification • supplemental professor strategies
Eclectic coding	Eclectic coding is an initial, exploratory technique whereby the analyst employs two or more First Cycle coding methods to discern a variety of processes or phenomena from the data. After Eclectic coding is done, the process iteratively becomes more purposeful and select as the analyst transitions to a more strategic *second draft* and re-coding based on the learnings from this eclectic exploration.	A number of First cycle coding methods were used at various steps in the analysis (e.g., Open / Initial, *In vivo*, Structural, Process, Concept, Provisional, Values, Simultaneous, and Subcoding)

Note. Descriptions for each coding method are derived from definitions that I shortened from Saldana's *The coding manual for qualitative researchers* book (2016).

Table 7

Second Cycle Coding Tools (Saldaña, 2016)

Coding method	Description of this coding method	Examples of First cycle codes used	Outcome after applying this Second cycle coding method
Focused coding	Focused coding categorizes coded data based on thematic or conceptual similarity, with categories emerging through the reorganization and categorization of the data set. To achieve this, Focused coding searches for the most frequent or significant First Cycle codes. Pre-existent categories may be changed or even discarded if they are found to be in conflict with the results of the Focused coding process. As Focused coding does not address questions of category details such as context, properties, nuances, and dimensions, it is particularly appropriate for the identification of major categories of themes within the data.	The search for the most frequent or significant Initial codes produced codes such as: • Work for other labs to learn new techniques that can inform your own future research questions • Ya gotta study abroad! • Breadth of learning • Expose students to variety through conferences and seminars • Expose students to other research labs	The outcome of Focused coding was the development of codes to represent the main themes in the RQF study. For example, the First Cycle codes highlighted to the left were used to derive a code called exposure. E.g., this theme is about developing students' ability to find, frame, formulate, and refine research questions by exposing them to variety. This variety may include different ideas, research partners, talks, other labs, etc. Exposure is defined as "to make known or to make accessible."
Axial coding	Axial coding extends the analytic work from Initial coding, and to some extent Focused coding, by strategically reassembling data that were *split* or *fractured* during the Initial coding process. The purpose of Axial coding is to determine which codes in the data are dominant, and to reorganize the data set to remove synonyms and redundant codes, in effect *sharpening* the codes to achieve the best possible fit with the data. The outcome of Axial coding is a description of the category's properties (characteristics or attributes) and dimensions (the location of a property along a continuum or range) that refer to characteristics, attributes, contexts, conditions, interactions, and consequences of a process. In this way, Axial coding enables the researcher to explore how the categories and subcategories relate to each other.	Examples of how data was split or fractured during the Initial coding process: • Go to lunch and learn events to get ideas (variety) • Invite colleagues to lab meetings to share their work with your students (role of colleagues) • Go on exchanges (student action) • Spend time at other labs (diversify)	We described the attributes, characteristics, contexts, and properties of the exposure category by adding the details and contexts of the statements grouped within the category. The contexts in which narratives about exposure were shared in the data set include: • Talks: The professor believes that student attendance at conferences, talks, seminars, symposia contributes to student ability to formulate research questions. The professor might even invite guest speakers to come talk to the lab and have research-question-related expectations of students thereafter. • Other labs or other professors: The professor sends students to other professors, labs or universities to help them learn new methods and give them access to different technologies, and then explicitly links these experiences to students' ability to find, frame, and formulate research questions.

Note. Descriptions for each coding method are derived from definitions that I shortened from Saldaña's *The coding manual for qualitative researchers* book (2016).

Data Collection

Participant recruitment. The main objective of my recruitment strategy was to capture the diversity in reported practices of professors across the natural sciences. I also wanted to interview professors who had achieved a level of peer acceptance of their research. The Canadian tri-council funding agencies, such as NSERC, use peer review processes to allocate funding. I therefore recruited participants from a target population of professors who met all of the following requirements: (a) assistant, associate, or professor from faculties of science in research-intensive universities; (b) held a grant with federal funding agencies such as NSERC; and (c) currently supervising students or has taught a course in research methods within the last year. Seven hundred seventy-eight professors at eight research-intensive universities in North America received customized recruitment emails. Sixty-three participants were successfully recruited and interviewed for the study. Eight interviews were conducted in person at the participant's office, while the remaining 55 were conducted remotely using Skype video calls or landline phone calls.

Recruitment efforts ceased when two criteria were fulfilled: a diversity of disciplines across the natural sciences was represented, and additional interviews did not contribute new information about the mentorship of student engagement in the conceptualization and design of research questions. This decision process is described in more detail in the section on data saturation.

Interviewing procedure. Over a period of eight months, 55 interviews were conducted. Each was an hour long on average (range = 31 to 136 min, mean = 64 min). Participants' interview sessions unfolded in the following manner:

- ***Informed consent.*** Consent was generally obtained by email prior to the interview. If consent forms had not previously been signed, the interviewer would inform the participant of their rights to full confidentiality and anonymity, to decline the answering of any questions, and to withdraw from the study. Permission was obtained to proceed with the questions, to audio record the interview, and to protect and store their data for use in future educational research studies.

- ***Opening task.*** The session started with an opening task that lasted five to 10 minutes (see Appendix C: Opening Task). The opening task served two purposes: to collect demographic information and to provide a basis for me to elicit answers at a greater level of depth, breadth, and specificity.
- ***Introducing the study.*** The interviewer introduced herself to the participant after he or she filled out the opening task. The conversation started with the introduction of the study and the clarification of its goals. This introduction was designed based on concerns raised by participants during the pilot interviews regarding two issues: the applicability of their mentorship experiences to the goals of the study and the level of technical or subject-specific detail that would be considered helpful.
- ***Building rapport.*** During this phase, the interviewer aimed to build rapport through open-ended questions designed to elicit positive affect (e.g., What do you love about your work?).
- ***The form and function of research questions.*** In this stage, participants defined and distinguished the research question from similar terms (e.g., research topic, research objective) before describing how these terms affected the design and implementation of research in their lab.
- ***Eliciting relevant contexts and expectations.*** The purpose of this stage was to elicit the context in which research questions arise. This involved open-ended questions from one or more of the following topic areas: the birth and evolution of research questions in the professor's lab; expectations related to the generation and evaluation of research questions; the professor as student and their experiences with generating their own questions; autonomy, creativity, and excellence amongst current and previous advisees. In eliciting and carefully listening to these stories, I actively set aside beliefs and assumptions in order

to examine how the phenomenon presents itself in the world of the participant (Christensen & Brumfield, 2010). Participant narratives shared early on during the conversation allowed interviewers to customize subsequent questions and to probe for specific content in a manner that was sensitive to the context, values, attitudes, and beliefs of the participant (Holstein & Gubrium, 1995).

- ***Probing student engagement in the design and conceptualization of research***. The final step elicited specific approaches and actions taken by the participant to help students learn how to find, frame, and formulate researchable questions for scientific inquiry. I paraphrased participant answers that contained teaching and mentorship actions, strategies, or approaches, and then asked the participant to correct any oversimplifications or misunderstandings.

The full interview guide is detailed in Appendix B: Approach to Interviewing and Interview Questions.

Postinterview memos. After each interview, I briefly summarized the interview and recorded initial impressions regarding the contribution of this interview to understanding the mentorship of student engagement in the conceptualization and design of research questions. Research assistants also recorded postinterview reflections by attending the interview sessions or by listening to the audio transcripts shortly after the interview (See Table 8). Shared, compared, and discussed throughout data collection, these reflections informed my decisions regarding which interviews to transcribe first, and helped me gauge saturation in data collection.

Table 8

Postinterview Memo and Reflection Questions

Topic	Questions
Issues and limitations	What went well about the interview? What could have been done better? What is your intuitive sense of the degree to which the participants' answers reflected their "true feelings and experience?" Consider interview techniques to improve on during the next interview. (This question was specifically and systematically addressed during pilot interviews.)
The conceptualization and design of research questions	How do research questions emerge and evolve in this laboratory? How does the participant come up with research questions? What does the interview contribute to our understanding of the formulation of research questions for scholars in this discipline?
Student engagement	What opportunities were there for students to be involved in the design of research in this lab? What examples, if any, did the participant share about how students found, framed, and formulated research questions, proposed new ideas, future topics, etc.? Based on these stories, would you rate this interview as an example of low, moderate, or high amounts of participant discussion of student engagement in the conceptualization and design of research?
Supervision style	Was the supervisor more constructivist or direct in their approach to mentorship? How student-centred was this participant?
Teaching, learning and mentorship notes	What specific examples, actions or approaches did the participant provide when discussing student engagement in the conceptualization and design of research questions? What were the observable or tangible teaching, learning, or mentorship actions that the participant shared in the context of students learning how to find, frame, and formulate their own research questions? What teaching, learning, or mentorship actions were shared in regard to including students in designing, conceptualizing, modifying, or refining the professor's research questions?
Adjustments, accommodations, individualization	Did this participant vary his or her approach for engaging students in the conceptualization and design of research questions, and if so, how? What were the factors that prompted the participant to vary his or her approaches? To what extent did the participant discuss how he or she adjusted, adapted, or customized teaching and mentorship strategies to meet the needs of individual students, task requirements, project requirements, etc.?
Beliefs about student abilities	Did this participant share his or her values, attitudes, or beliefs regarding whether students can or should be engaged in the conceptualization and design of research questions? Did he or she mention any examples of students proposing their own research questions?
Transcription	What is the *added value* of transcribing this interview? What new information, perspective, or understanding does it add to the data set (when compared with previous interviews or previously transcribed interviews)? Based on your holistic reflections and answers to the above questions, what would be the benefits of transcribing this interview? This interview can be briefly analyzed using the audio only. Should this interview be transcribed?

Sample size. The main data for this study is a set of transcripts from 24 participants that were precoded, coded, and comprehensively analyzed. These 24 participants were selected from the 46 who specifically addressed student RQF (see the upcoming sections on saturation and credibility). On average, these 24 participants had 17 years of experience as a professor (the range was one to 37 years with a standard deviation of 10 years) and had supervised 46 students (the range was 4 to 150 students with a standard deviation of 41). Among these 24 participants, there were four assistant professors, five associate professors, and 15 professors. For more demographic details about the participants and their disciplinary affiliations, please see Appendix A. Two of these 24 participants (an ecologist and a chemist) will be reported in full in order to serve as illustrative cases.

A note on saturation. In a study of sample sizes in qualitative research, Mason (2010) concluded that "while none of the guidelines presented here are intended to be faultless reference tools for selecting qualitative samples sizes, all authors agree that saturation is achieved at a comparatively low level . . . And generally [doesn't] need to be greater than 60 participants" (para. 45). According to Fusch and Ness's (2015) summary of several studies, "data saturation is reached when there is enough information to replicate the study when the ability to obtain additional new information has been attained, and when further coding is no longer feasible" (p. 1408). In other words, saturation is the point at which new ideas, concepts, themes, or codes cease to emerge despite further data collection or analysis (Guest, Bunce, & Johnson, 2006). Practically speaking, saturation is a matter of determining the point of diminishing returns on effort (Mason, 2010). Although additional participants could be interviewed and these interviews could extend the individual, contextual, and disciplinary details available for exploration, such exploration would be tangential to the objective of the study.

The unique or novel contribution of new interviews was assessed by reviewing and comparing postinterview memos. I observed that new ideas about teaching, learning, and mentorship with regard to student participation in the conceptualization and design of research questions became increasingly rare after conducting eight pilot and 20 systematic interviews. In other words, data saturation procedures revealed that I could have stopped after the 20th interview. If my proposal did not stipulate that this was to be a multidisciplinary study, I would have stopped there. Unfortunately, the researcher has little control over who responds to recruitment efforts: biologists (8 participants), other life scientists (6 participants), and physicists (6 participants) were the first to respond to my email—there were no chemists. Hence, I continued to conduct interviews until my interviewee sample was more representative of the diversity of disciplines found in the natural sciences—biology, physics, chemistry, etc. As such, after the 8 pilot interviews, I conducted 55 more interviews using the standardized interview protocol for a total of 63 interviews. Convenience sampling was used to select a subgroup of 46 participants who mentioned my topic. Forty-six interviews are too numerous for a qualitative study. The saturation of ideas was verified using two methods: interview memos and precoding were used to test for saturation during data collection for all 55 of the systematically-conducted interviews. Extensive coding procedures and interrater agreement were used to test for saturation during data analysis for the 24 interviews in the main dataset. This meant that I chose to exclude the remaining 31 interviews from further analysis, a decision which I will explain in the next section.

A note about credibility. The selection and exclusion of data can undermine the credibility of the study. Questions to assess the credibility of the findings include: To what extent does the data and the researcher's interpretations of the data accurately represent the teaching and mentorship experiences of professors across the natural sciences (versus the presuppositions and biases of the researcher)? How complete is a picture that excluded 31 of 55 participants?

I address these credibility questions by revisiting the objective of my study: I sought to describe the full range of strategies that natural science professors can use to develop student research question formulation skills. To do so, I needed to purposefully select interviews that mentioned supervision, students, or learning in the context of how research questions emerged. The first eight interviews were used to pilot test my questions. These eight interviews were not subjected to any further analysis because I was neither consistent nor systematic during my conversations with these participants. This pilot phase enabled me to identify assumptions, problematic wording, and interviewer presuppositions that influenced participant responses. My postinterview memos from this phase were used to rewrite my questions and redesign my approach to data collection. After finalizing my data collection procedure, I excluded these eight pilot interviews from further analysis and proceeded to interview 55 more participants. These 55 interviews were reviewed and precoded to identify transcripts that mentioned my dissertation topic. Three of the 55 participants explicitly stated that students' ability to generate research questions was not applicable or relevant. Six more participants did not mention students at all when they discussed how research questions emerged in their lab, nor did they mention how they learned to generate questions when they themselves were students. In sum, 16% of my sample population (9 of 55 participants) reported that developing students' ability to pose scientifically researchable questions was not relevant, appropriate, or important to them. These nine interviews were removed which meant that 46 of the 55 interviews remained.

"Mentioning" my topic did not necessarily mean that the participants believed it was their duty as supervisors to develop students' ability to formulate questions. The manner in which the 46 remaining participants mentioned student research question formulation ranged from enthusiastically affirming the importance of mentorship when it comes to this skill, to divisions of responsibility between student, supervisor, and the graduate program, to outright disagreement with the idea that professors ought to cultivate such skills amongst their students. From this set of 46 interviews, I selected a diversity of disciplines to ensure that there were participants across the main branches of science (e.g., physics, chemistry, biology). Doing so resulted in a set of 24 interviews. Full details regarding how the 63 interviews were reduced to a main dataset of 24 interviews, the precoding, the data reduction, as well as the selection of the illustrative cases, are recapped in the Data Analysis section (see Table 10, How the Main Data Set Was Created for This Study: The coding of OwnQ).

Data Analysis

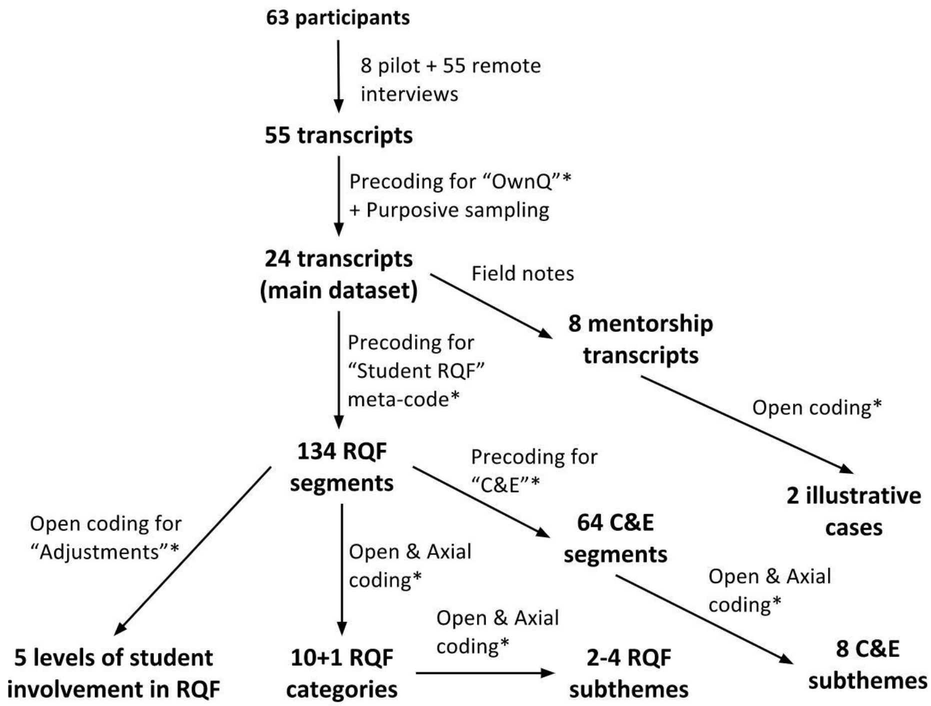
This section describes the stages, steps, and substeps of this study in a manner that approximates the order in which they unfolded. It is important to note that over the course of the two years the actual application of the procedures was highly iterative, recursive, and overlapping. To help readers follow a piece of data from inception to analysis, I have chosen to organize the description of these procedures into six objectives:

- Objective one: Reduce the data.
- Objective two: Operationalize student RQF.
- Objective three: Theme the data.
- Objective four: Ensure saturation in data analysis.
- Objective five: Search for variation.
- Objective six: Explore illustrative cases.

Each objective sets out a context or a challenge that arose in the study, and describes the specific steps taken to address this challenge and the outcome of having taken those steps. My hope is that this level of detail and transparency enables readers to better assess the trustworthiness of this study. See Figure 1 for a graphic representation of the entire flow of the methodology, from data collection to data analysis.

Figure 1

RQF Study Methodology From Data Collection to Data Analysis (Comprehensive Illustration)



*interrater agreement was conducted during this step

Objective one: Reduce the data. The majority of the hour-long interviews were spent on establishing rapport and understanding the participants' context before questions about RQF could be posed. The interviews were also conducted as fluid, dynamic, and organic conversations in which participants elaborated on topics of their choosing (Holstein & Gubrium, 1995), which resulted in extensive, highly technical descriptions of the participants' and their students' research areas and comparatively less discussion of student engagement in the formulation of research questions.

Step One: Finding the most relevant sections of an interview. The first challenge for the analysis of my data set was to systematically identify the transcript sections directly addressing the objectives of the study without prematurely excluding data that could inform my understanding of research question formulation in the natural sciences.

Process. Nine transcripts were reviewed for statements regarding mentor actions that occurred in the context of students establishing their own area of inquiry. That is, rich, important, and striking passages were circled, highlighted, bolded, underlined (referred to as precoding), and then broken down into discrete parts so that the components could be closely examined for similarities and differences (referred to as Initial coding) (Saldaña, 2016). As the construct of RQF had yet to be operationalized at this early stage of the process, I was broadly looking for statements of professor actions that occurred as students were engaged in the conceptualization stages of research. Student engagement in research conceptualization and design included:

- finding researchable topics;
- transforming research interests into researchable topics;
- contextualizing these topics in the literature.

The search for these statements was guided by the cue to find remarks that fit the format of "I did XYZ activities to help my students find, frame, and formulate research questions." I identified 420 such statements across the nine transcripts. Most of these statements contained a description of how students found their research topics and the actions professors took during this process, rather than a direct causal link between specific mentorship strategies and the students' ability to formulate research questions. Thus, the next step was to reread the 420 statements and identify the ones in which the participants drew the most direct links between pedagogical actions and events described, and student engagement in the conceptualization and design of research. I constructed a table to help sort these statements. C*learly linked* statements contained direct associations or direct causal attribution between the professor's actions and student participation in conceptualization and design of the research questions. V*aguely linked* statements were about learning in general, with very little mention of the design or conceptualization of research questions (see Table 9). Statements that fell between clearly linked and vaguely linked were labelled *moderately linked*.

Outcome. The identification of 414 striking statements and their organization into groups that highlighted differences in the degree to which the narratives included student involvement in the conceptualization and design of research. These differences would later become the foundations for operationalizing the construct of RQF, as well as the initial criteria to help further narrow the data set to those participants who were most likely to discuss RQF.

Table 9

Statements Grouped by the Degree to Which Students Were Involved in the Conceptualization of Research

Link between the statement and student engagement in the conceptualization and design of research	Description	Examples
Clear link	The participants themselves explicitly draw clear links between their pedagogical actions and student learning when it comes to the conceptualization and design of research questions and research topics. E.g., "I have students do X because it enables them to come up with their own question."	"It's more about finding something a student is interested in . . . helping them come up with questions. . . . [T]hey don't necessarily know what they're interested in, so maybe I start them off by providing a question, and then [we] collaboratively come up with new questions based on that."
Moderate link	These statements contain the participant's immediate and direct answer to a question about the conceptualization and design of research, although the degree to which the events and actions are associated with student learning are less clear than those in the direct group.	Interviewer: "What are some other ways that your students have contributed to the research questions?" Participant: "Often . . . students will meet and talk with other students, or other people in either my lab or in other labs, and . . . pick up novel approaches that way, which would still relate to the question that they're looking at, but is . . . something that we haven't previously considered because it might be . . . tangential to our focus. It's always great when that comes from the student rather than from me, because I think that's always the most fruitful. And again, it helps them to really feel like this is their project, rather than my project."
Vague or tangential link	Statements are grouped as tangentially linked when there is ambiguity between the events described and student learning or ambiguity in the degree to which students are involved in the conceptualization and design of research.	Interviewer: "Are your students expected to write proposals of what they're going to research?" Participant: "Yeah, because they've been applying for awards, for example. So, one of my master's students, the one who's doing this peer colliculus study, he got an NSERC master's award this year, and yeah. He wrote the

	initial—like it was the project that we had discussed, but he wrote the proposal, and then I did many rounds of editing with him."

Step two: Finding the most informative interviews. The full data set included 55 interviews. While interviews were being conducted, field notes and postinterview memos revealed that some of the participants had few to no opinions, teaching strategies, or experiences to share when it came to student generation of research questions. Thus, the primary goal of this second step became the identification of participant interviews that addressed the objectives of this study (identifying what professors do to engage students in the conceptualization and design of research questions).

Process. The precoding from step one produced 414 statements in which the participant linked teaching, learning, or mentorship actions to the conceptualization and design of scientific research. Saldaña's (2016) First Cycle coding methods were then used to flag action statements, participant values, and concepts that addressed the dissertation question. These First Cycle codes were organized to uncover common themes. The common theme that emerged most frequently was the topic of students posing their own research questions—these statements were flagged with the code *OwnQ*. OwnQ then became the category that was developed further using Axial coding to represent instances in which the participant discussed student generation of independent research questions, professors' efforts to cultivate this ability, or professors' discussion of the value or relevance of the ability. The presence of OwnQ was detected in 46 of the 55 interview transcripts. In other words, 16% of my participants (nine of 55 interviews) either did not discuss student RQF or explicitly said that it was irrelevant. Based on their comments and my need to describe teaching and mentorship experiences, I decided that the 46 interviews were the most relevant for my study.

The next challenge was to reduce these 46 interviews to a minimum sample size that would allow for a diversity of disciplines to be represented and saturation to be tested. During data collection, saturation had been reached after 20 interviews were conducted using the standardized interview protocol. This suggested to me that the data set should include at least 20 participants diversely distributed across the natural sciences. My understanding of diversity was informed by the Natural Sciences and Engineering Research Council of Canada's (2010) list of Evaluation Groups and Research. The NSERC groupings of greatest interest to my study were chemistry, biological systems, physics, ecology, geosciences, and genes, cells, and molecules. Computer science, engineering, mathematics, and statistics were excluded from data collection because these fields were often housed outside faculties of science and I wanted to focus my study on the natural sciences.

To ensure a diverse sample for the analysis, I used a holistic selection process. Items considered in this selection process included the NSERC natural science groupings to which the participant could belong, the disciplinary affiliations provided by the participants themselves in addition to those available in their biographies and awarded grants, the type or nature of the tools and data sources used in their research, and the uniqueness of the approaches to research that they described. For each participant who provided relevant data, I would ask whether the type of scientific inquiry described was already represented in the group. If the answer was yes, the participant would not be added. This selection process allowed me to identify 24 participants broadly distributed across disciplines of the natural sciences. Because the majority of participants were affiliated with several disciplines, I chose not to group them any further during my analysis or reporting. Grouping them also fell beyond the scope of my study as I did not seek to generalize my findings to any subdiscipline. I set aside the remaining 22 interviews as a reserve group. During the data analysis stage of the study I would test whether 24 participants were indeed a sufficient sample size. If saturation was not reached after analyzing the 24 interviews, I would return to the reserve group in order to analyze more interviews.

Outcome. Of the 55 participant interviews conducted, 46 were considered to be relevant to the objectives of the study. These were the interviews flagged (precoded) with the OwnQ code to identify participants who had shared views about, or experiences with, student participation in the generation of research questions. Of the 46 relevant interviews, 24 were selected to comprise the main dataset for the study. These 24 participants were affiliated with main groupings in the natural sciences: chemistry, biological systems, physics, ecology, geosciences, or genes, cells and molecules. Table 10 provides the frequency counts for participants selected at each stage of the data reduction process.

Table 10

How the Main Data Set Was Created for This Study

Variable counted	Count	Total
Participants interviewed		**63**
Less: Pilot interviews removed	8	
Number of interviews that were subjected to any form of analysis		**55**
Less: Interviews in which the participant explicitly stated that students' ability to generate research questions was not applicable or relevant	3	
Less: Interviews in which the participant made no mention of student engagement in the design or conceptualization of research	6	
Interviews considered relevant to the research question		**46**
Less: Interviews not used in subsequent analysis stages because there was already enough representation from these participants' disciplines	22	
Total: Number of interviews in the final data set		**24**

Objective two: Operationalize student RQF. The third step in reducing the data was operationalizing the phenomenon under study. In the proposal, RQF was described as the ability to find, frame, and formulate questions for scientific research. However, I found it very difficult to determine the extent to which students were being invited to contribute to the process of designing research versus carrying out research that had already been designed by their supervisors. During the process of carrying out their supervisor's research, students would sometimes encounter unexpected findings, uncover new leads, or discover a new methodology. These contributions would lead to another research question or the reformulation of the study's research question, thereby creating opportunity for student engagement in the design of research. At other times, participants would talk at length about engaging their students in research question formulation; however, the details of their story revealed that the students were selecting from a predefined list of research questions provided by the advisor. Student engagement in research question formulation needed to be operationalized so that I could reliably detect and distinguish it from experiences in which students had little involvement in the design, conceptualization, or direction of research.

Process. The process of operationalizing student engagement in the conceptualization and design of research questions began with the 414 statements coded as containing professorial actions clearly linked to student participation in the conceptualization and design of research. I returned to the transcripts to look at the extracted statements in the context of the full interview in order to apply additional First Cycle coding methods. The resultant codes were compared to each other and regrouped by similarity using Constant Comparison and Second Cycle coding methods to produce a working definition for the metacode *student RQF*. I continued to refine this definition by measuring the extent to which two independent raters would flag the same sections of an interview as containing student RQF. Once an interrater agreement of 76% was reached, the metacode was applied to all interviews in the main data set. Research assistants were asked to read through each of the 24 interviews, one at a time, and to apply the metacode student RQF to sections of the transcript containing actions, approaches, and contributors that professors associated with student engagement in the conceptualization and design of research questions. Table 11 contains the full coding criteria that were used by the coders and Appendix D contains a detailed description of the interrater agreement process. Sections of the interview that were coded with the metacode student RQF are henceforth referred to as *student RQF segments.*

Outcome. The outcome of step 3 was the operationalization of the key phenomenon under study: student RQF. Student RQF was a metacode for reliably flagging sections of the transcripts that were relevant to the understanding of professor experiences with engaging students in the conceptualization and design of research questions (see Table 11 for the details of this metacode). These were sections of the interview that contained participants' experiences, recollections, and narratives that fulfilled all four of the following criteria (the brackets contain the abbreviation for this criteria):

- It was about the scientific pursuit of new scientific knowledge (NEW).
- It pertained to the focus of the research in that it included one or more of the following: research questions, research objectives, hypotheses, or predictions (FOCI).
- It was about observable student participation in finding, framing, and formulating the focus of the research (FFF).
- It was about the instructor's reflections, expectations, values, and beliefs on the design and conceptualization of scientific inquiry in the context of teaching, learning, and mentorship (TLM).

When the 24 transcripts in the main data set were screened for this metacode, 134 student RQF segments were reliably identified (interrater agreement was 78.8%).

Table 11

Student RQF Metacode—Coding Criteria for Relevant Transcript Segments

Criteria	Basic description	Handle with care	Exclusions
About the scientific pursuit of new knowledge (NEW)	The text segment contains a main idea that concerns the scientific pursuit of new knowledge, including exploratory, or any investigation pursuing a question that has no empirically-established answer. E.g., ● conference presentations of original work; ● journal manuscripts / journal articles; ● grant and scholarship applications that require a proposal for original work.	Not applicable	Close but no: Instances where professors use questions, questioning their own questions or student questions to help students master pre-existing knowledge. E.g., tests, quizzes, exams, or other information transfer tests evaluating student mastery of course concepts.
About the focus of the research (FOCI)	The text segment contains a main idea that involves one or more of the following terms central to delineating the focus of the scientific inquiry. E.g., ● researchable question (RQ); ● research objective / research problem; ● hypothesis; ● prediction; ● field-specific variations of RQ (e.g., problem statement, theoretical problem, mathematical problem).	Handle with care: Participants may use ambiguous, abstract, or broad wording such as ● idea; ● area; ● topic. In and of themselves, these terms do not generally represent examples of terms that determine the focus, parameters, or scope of research. However, this can vary. Always consider the participant's context.	Close but no: Daily problems that arise during the implementation of the study, be they problems in data collection, analysis, or reporting, do not constitute research problems. In order to fulfill the FOCI criterion, the "problem" mentioned must define or direct the objective of the work.
About observable student participation in finding, framing, and formulating the focus of the research. (FFF)	Discusses direct student participation in the design and conceptualization of research. E.g., ● finding a researchable topic; ● framing or contextualizing within the literature a researchable question that is generated by—rather than assigned to—the student; ● formulating the research objective or the research question to be investigated, coming up with the proposal or project; ● formulating hypothesis statements and predictions; ● narrowing a broad interest or a general topic area into a well-defined or tractable line of inquiry (i.e., specification of the problem); ● professor comments about their own experiences with FFF as a student.	Handle the following context with care: ● Reformulations (the process by which students propose changes to the initial research question). ● Changes to the original research question based on data found by the student (did the student propose the changes, either independently or collaboratively?). ● Student participation in selecting, specifying, or extending the project. ● Unexpected results that affect the research approach. Look for the extent to which students are participating in the conceptualization, design, or redesign / redirection of the initial research question.	Close but no: The professor describes the answering of a research question as an example of how the student is 'asking the question.' The activities are daily research tasks needed in the implementation of the study and do not include the student in designing or conceptualizing the research (e.g., gathering data, writing code, running experiments). Close but no: Participant comments about how research foci are found, framed, or formulated without any mention of student.
About teaching, learning, and mentorship, to help students design and conceptualize scientific research. (TLM)	The text segment mentions professorial beliefs, values, expectations, and actions that reportedly support students as they conceptualize and design original research. E.g., ● teaching to current and past students, including attitudes, approaches, actions, expectations; ● how any student, including the professor when he or she was a graduate student, develops the ability to find, frame, and formulate research questions (FFF); ● mentorship actions or approaches to encourage student participation in FFF.	Not applicable	Close but no: Discussion of student learning in general without a participant-described link to FFF. E.g., do not equate comments on how students took ownership of an aspect of the research, such as data collection or data analysis, with student participation in the design and conceptualization stages of research, unless the participant explicitly made this link.

Summaries of objectives one and two. The first objective of the data analysis was to reduce the data set to a representative sample of participants in the natural sciences for whom the topic was relevant, and to reduce the codable data down to the portions of the interviews that contained teaching, learning, and mentorship content on engaging students in the conceptualization and design of research questions. These objectives were achieved by reducing the full 600,000-word data set from the 55 participants interviewed to the 24 participants who were selected for the main data set. The 240,000 words from the 24 transcripts in the main data set were then reduced to approximately 80,400 words using student RQF segment, a metacode for identifying 134 transcript sections that pertained most directly to the objectives of this study.

Objective three: Theme the data. After the data set was reduced to 134 student RQF segments from the 24 participant interviews, the next challenge was to uncover the themes illustrating professors' experiences in the teaching and mentorship of RQF. Saldaña (2016) cited Rubin and Rubin's (2012) definition of a theme as "what a unit of data is about and/or what it means," and Auerbach and Silverstein's (2003) function of theme as a way to categorize a data set into "an implicit topic that organizes a group of repeating ideas" (p. 199).

Process. The process used to identify themes in the data was built on Glaser and Strauss' (1967) Constant Comparison principles and Saldaña's (2016) description of how to "theme the data" (p. 198). The approach that I took to theme the data was dynamic, organic, and cyclical. The components of this process included the following:

1. Labeling data.
2. Grouping codes by similarity.
3. Consolidating codes into categories.
4. Applying categories.
5. Refining categories.
6. Elaborating categories.

Labeling data (coding). First Cycle coding methods were used to break the data down into component parts and to apply labels that captured the essential meaning for each of these parts. These codes were then used to annotate the main ideas in the RQF segments with short labels, two to five words in length.

Grouping codes by similarity. The labels were gathered and organized by similarity. Both the labels and the groups were continually compared, arranged, and rearranged until the contents of the intuitively organized groups could be explicitly expressed. The outcomes of this grouping were a preliminary set of main ideas about how students learn to find, frame, and formulate research questions and brief descriptions regarding the contents of these sets.

Consolidating codes into categories. As more and more groupings of participant ideas emerged from the ongoing analysis, the number and nature of the groupings of the ideas changed. Working descriptions were written about each category and the descriptions were compared to each other in order to expand, then combine and collapse the numerous groupings into a smaller number of categories. This process of expanding, merging, combining, and collapsing categories continued until consensus could be reached between myself, my advisor, and my research team on the number and nature of the groupings. Consensus was reached after 10 main teaching, learning, or mentorship categories emerged from the data and the discussion processes.

Applying categories. During the category application stage, the student RQF segments were reviewed, one interview at a time, for the presence of the 10 RQF themes. If a theme was present, the RQF category code was applied. The coding revealed that 127 of the 134 RQF segments contained one or more of the 10 RQF categories. Segments that did not fit any of the 10 RQF categories but were potentially relevant were set aside for further analysis.

Refining categories. Criteria for detecting the presence of themes were refined through an interrater agreement process that involved comparing the coding completed by two independent raters. Interrater agreement testing was conducted on 71% of the data set (17 of 24 interviews). Disagreements between the raters were used to clarify the descriptions of each category until each theme had a well-defined set of inclusion, exclusion, and close-but-no criteria.

Elaborating categories. Student RQF segments that had been grouped into themes were revisited, one theme at a time. The RQF interview segments grouped under each category were carefully reread on a line-by-line basis so that an additional round of First Cycle coding methods could be applied. This recoding allowed recurring ideas, important subthemes, and contextual details to be identified.

Outcome. The first outcome of this objective was the identification of 10 RQF categories that represented the main themes for describing how RQF develops among students. The second outcome was the identification of two to four subthemes for each of the 10 main RQF categories. The third outcome was the identification of content that was deemed potentially relevant to teaching, learning, and mentorship of RQF but did not fit the inclusion criteria of any of the 10 RQF categories. This content was gathered into a new, 11th category. The analysis of this category is described next.

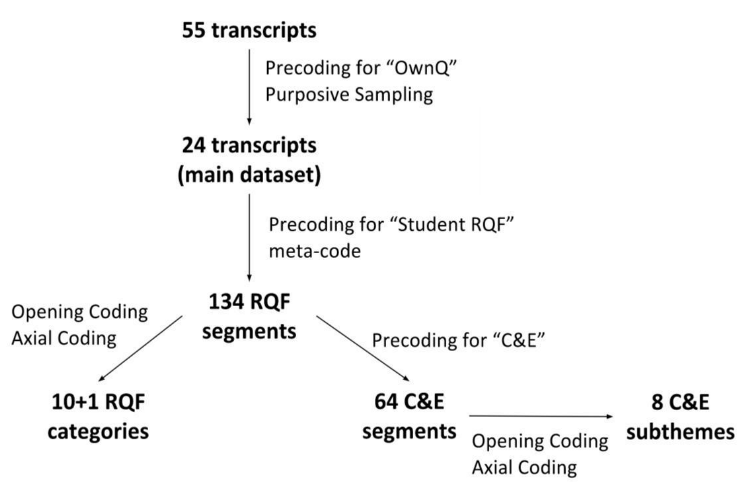
Objective four: Ensure saturation in data analysis. The outcomes of objectives one through three revealed that the teaching and mentorship of RQF could be understood through 10 categories or themes. The fourth objective evaluated the following question: To what extent is the phenomenon of interest comprehensively represented by these 10 themes, and what was done to data that did not fit within them?

Process. Throughout this study, I and my research assistants gathered any and all content that informed our understanding of how students and professors learned to formulate research questions. A segment would be considered relevant to understanding student RQF if it fulfilled all four criteria of student RQF. This approach was followed throughout the coding process and eventually resulted in a set of statements that did not fit into any of the 10 main RQF categories. The uncategorized statements were gathered into a broader group called *comments and expectations* (C&E) and a coding guide was created as more and more segments such as these emerged (see Table 12).

The process used to uncover the 10 main RQF categories was then applied to the C&E category: RQF segments coded with C&E were subjected to a detailed and systematic search for additional RQF strategies through a process that involved identifying main ideas in the segments (Open coding) and then organizing these main ideas into themes that could be used to report the data (Axial coding). Interrater agreement discussions were conducted and researcher memos were compared to reach consensus on the number and nature of subthemes within the C&E category. The entire coding and discussion process is illustrated in Figure 2.

Figure 2

Sample Size, Data Reduction, and Analysis of the Comments and Expectations Category



Outcome. The primary outcome of Objective four was verifying that saturation in the analysis of the data had been reached—and indeed, it was. All segments either fit into one of the 10 main RQF categories or in comments and expectations (C&E). A careful look at the C&E segments revealed that there were no new ideas pertaining to the objective of my study. That is, segments coded with C&E did not contain what the professor could do to support student RQF; instead, it contained professorial expectations, views, and beliefs about student learning. Pedagogical actions, approaches, and strategies were already comprehensively captured by the 10 categories yielded in Objective three. The secondary outcome was the emergence of eight subthemes for the C&E category. These subthemes represented contributors to the development of student RQF that fell outside of teaching and mentorship--Actions to be initiated, driven, and maintained by the students themselves.

Table 12

Coding Criteria for Comments and Expectations (Category 11)

Description	Inclusions and examples	Exclusions	Handle with care
This is a catchall theme to capture an idea that, despite not being captured by any other code, is important to our understanding of how RQF develops in students, according to professors. The idea must be from a segment that fulfills all four RQF criteria.	● Developmental trajectory: How student ability to pose research questions develops among students or in general, especially when students find an area of interest and move toward building their own study. ● Student weaknesses: Initial weaknesses in students' questions. ● Student role & expectations: Anything else that students should be doing—with the professor or on their own—to develop their own RQF skills that is not captured by any other focused theme. ● Responsibility: Whose responsibility is it to develop RQF? E.g., "it's the student's responsibility to learn RQF on their own time—no one will push them to do it." ● RQF Source: How do students learn how to find, frame, and formulate research questions? Does this happen Naturally? Innately? Organically? Dynamically? Intentionally? ● Whom: Among whom does RQF develop? E.g., "the really good ones will be able to come up with their own agendas by the time they graduate; the rest just weren't cut out for this kind of thing." ● Professor as student: Comments related to how the professor themself learned to find, frame, and formulate their own research questions as a student or during their early career days. ● Scientific method & RQF: Comments related to how the scientific method works out in practice for this professor when it comes to how research questions are found, framed, and formulated in his or her subdiscipline.	Ideas, content, stories, views, experiences that are already captured by one of the main RQF codes.	Not applicable: This is the "catch-all" category to flag anything that is potentially relevant to understanding student engagement in the conceptualization and design of research questions, and the teaching, mentorship, and learning that professors associate with this skill set.

Objective five: Search for variation. The secondary question for this study (Q2a) was originally phrased as "How do professors vary their RQF strategies and approaches as a function of students' educational level, of perceived individual student needs, and of any factors associated with the research area itself (e.g., epistemological, methodological, or subject-specific factors)?" With Q1 answered by objectives three and four, the next challenge was to illustrate how professors reportedly varied their strategies for engaging students in the conceptualization and design of research questions.

Process. During pilot interviews, participants were asked about how they varied their teaching and mentorship strategies for developing student ability to formulate research questions. Participants expressed that this question was too awkward or abstract to answer, or stated that they did not vary their strategies (often contradicting stories they had shared earlier about how their supervision strategies varied from one student to another). It is possible that my use of the word "vary" did not reflect the reality of how the participants experienced teaching and mentorship. A scientist could vary an experiment by changing one aspect, controlling other facets, and then examining the results. As a result of these pilot data, I chose to rephrase the question of "How do you vary your mentorship . . . ?" For the rest of my interviews, I asked "What do you do differently from one student to another?" Answers to the latter question were then coded during data analysis to look for examples of variation.

Objective three concluded with the creation and refinement of 10 thematic categories of teaching, learning, and mentorship events, actions, and approaches that professors associated with the development of student RQF. The hunt for variation proceeded with a search within the segments of each category for any instances where participants described how they changed, modified, or customized their pedagogy. Examples of such statements included:

- Explicit comparisons (e.g., “I do one thing with master’s students and set the bar higher when it comes to my PhD students”).
- Conditional statements (e.g., “The amount of contact that I have with a student depends on how much they seem to need”).
- Actions taken with particular students (e.g., “This one student was exceptionally motivated, so I gave him a lot of freedom”).
- Reference to student skill level as a factor in teaching approaches (e.g., “This student’s writing skill was not at the expected level for PhD students, so I sent him to the writing center”).

The review of the segments containing such statements exposed the presumptive and awkward nature of the wording of Q2a. The question assumed that (a) the professors varied their teaching and mentorship strategies and approaches, and (b) it would be possible to detect such variation (e.g., if the pedagogical approach to developing RQF was highly varied in and of itself, how would I detect variation?). Furthermore, the search for variation in *strategies and approaches* was leading me away from capturing nuances and contextual details that informed my understanding of RQF mentorship. This was a pivotal point in my study: Pursue Q2a as originally written and sacrifice the richness of the participant perspective, or revise the question to better reflect this perspective. The latter was more aligned with the phenomenographic philosophy behind my study, and so I chose to revise the dissertation question. The original Q2a, which focused on how professors customized their approaches for individual students, was not pursued beyond this stage. The revised research question, Q2b, sought to identify perceived student needs and characteristics that prompted professors to individualize their teaching and mentorship of RQF (see Table 13 for full wording of the original and revised questions).

The coding processes described in objectives three and four were then similarly applied. That is, exemplary instances of answers to Q2b were identified amongst the RQF segments. These instances were then used to generate criteria for finding more segments. The category "adjustment" was created using these criteria. The purpose of this category was to flag segments that addressed Q2b. The full data set of segments that were coded with RQF was then revisited and coded with adjustment whenever any part of an RQF segment fulfilled the criteria for this category (see Table 14). These adjustment codes were then sorted into groups by similarities. Following phenomenographic approaches, similarities and differences between the groups were identified in order to detect an underlying structure or overall narrative that permeates across all groupings. This narrative was used to arrange the groups hierarchically in order of least to greatest student engagement in the conceptualization and design of research.

Table 13

The Modification of the Dissertation Questions

Dissertation question	Objective of this question	Outcome
Q2a (original question): "How do professors vary their RQF strategies and approaches as a function of students' educational level, of perceived individual student needs, and of any factors associated with the research area itself (e.g., epistemological, methodological, subject-specific factors)?"	To identify variation in the application of strategies and the reasons given by participants for their decisions to vary their strategies	Found RQF segments that discussed the following: ● Norms and expectations for a discipline ● Applications of a broad and highly-varied strategy (e.g., feasibility and scope, supplemental professors strategy) ● Generalizations about the needs of scientific research
Q2b (modified question): "Do professors reportedly vary what they do to help students find, frame, and formulate research questions to meet the perceived needs of individual students? If so, what do professors do differently from one student to another when it comes to developing student RQF, and what rationale do they give for differentiating their approaches?"	To identify perceived student needs that prompted professors to individualize their teaching and mentorship of RQF	Identified participants who adjusted their RQF pedagogy to meet individual student needs. Identified underlying themes behind these adjustments.

Table 14

Coding Guide for Identifying Data That Addressed Q2a and Q2b

Segment identification criteria for Q2a (the original dissertation question)	Segment identification criteria for Q2b (the modified dissertation question)

Look for how a professor may treat one student differently from another based on any factors (e.g., student abilities / aptitudes / achievement levels, student personality [introversion / extraversion, desire for structure versus freedom], their learning and communication styles… anything related to the student).
● Key words: stronger, weaker, more, if, depending, some / most people / students, for / in terms of [X student], usually, difference, exceptional / impressive / outstanding, expectations
 	
Examples may include statements that:
● contained explicit comparisons (e.g., "I do X with one group of students and Y with another group of students"),
● were conditional statements (e.g., "Depending on if the student is X, then I do PQR"),
● focused on students with specific characteristics or qualities (e.g., "For X student, I do or require PQR"),
● were anecdotes of unique students (e.g., "This one student came to me with the condition of pushing for X research direction, so I had no say"),
● mentioned student skill level as a factor in teaching approaches (e.g., "This student's writing skill is still not up to par, so I did XYZ").
 	
Adjustments related to the subject matter
● Epistemological factors: Ideas that relate to how knowledge is constructed in a discipline. How does that discipline know something to be true? What are its rules for validating knowledge?
● Methodological factors: Ideas that relate to the tools, techniques, and methods for collecting and analyzing data within a discipline.
● Research area: Pedagogical needs that relate to the topic that the professor is researching. Possible cues: "You have to understand that in my research area, XYZ is really important," "that would never fly in my discipline, we need to be able to do XYZ in order to secure time on the space station, and so, our students need to…," "materials chemistry is unique in that it's very XYZ, students will do PQR"
● The discipline: Included references to a need that participants felt was unique to their discipline (e.g., "In materials chemistry, research questions only come about from doing X, which is why I train my student in Y related skill.")
  ▪ "In my discipline"
  ▪ "In my field"
  ▪ "For students in X field" / "For students in X subject"
	Exemplary or borderline yes:
	● Explicit comparison: The segment with the adjusted / individualized or adapted strategy contains a sentence in which the participant explicitly compared what he does with one group of students versus another group (e.g., strong versus weak, good versus poor motor skills, undergraduates versus PhD students)
	● Conditional statements: "Depending on if the student is X, then I do PQR"
	● Actions that are causally linked to individual student needs, characteristic, qualities (e.g., "For X student, I do or require PQR; I do X when students demonstrate Y characteristic")
	  ▪ Segments with emphasis on student characteristic (an abstract, creative student) count
	● Variation as a function of student skill / proficiency level, or student background, or competencies developed
	  ▪ Segments that mentioned student skill level as a factor in teaching approaches (e.g., "This student's writing skill is still not up to par, so I did XYZ")
	● Acknowledgement of the need to vary / adapt / adjust pedagogy could include statements such as "I do vary what I do; there is no single protocol for RQF because research is an apprenticeship that is affected by supervisor and student personality"
	● New to lab / introduction / orientation procedures: "I do X with new students"
	● Grade level: "I do X with grade level A students, Y with grade level B students"
	● Borderline yes: "He's a very creative student who loved to absorb the literature. If I wasn't directive, he'd be wandering in the articles forever"
	
	Close-but-no
	● Recognition of different needs amongst students, but no mention of adjusting teaching or mentorship to accommodate these differences: "I do X for all students, Y students benefit most from this [and no mention of what is done differently for students who benefit less from the strategy]"
	● Implied comparisons of students that do not contain explicit professorial actions to describe how pedagogy differed for one group of students versus another: "Some people are really gifted at coming up with ideas. For my grad students, I develop creative thinking in my class using XYZ. Some students find it easier than others"
	● Not about teaching or mentorship: "The difference between average undergrads and outstanding [undergrads] is that the former only do what I ask and the latter come up with additional ideas. Here's what I do to find the outstanding undergrads." (In this quote, the professor prescribes how to recruit talent, not how to teach or mentor.)

Outcome. Three outcomes ensued from the search for variation in professors' RQF strategies. The first was a revised dissertation question that was more responsive to the data (Q2b). The second outcome was the answer to Q2b—the ways in which professors adapted their teaching and mentorship to meet the perceived needs and characteristics of individual students. The third outcome was a framework for distinguishing five levels of student involvement in generating research questions.

Objective six: Explore illustrative cases. Focused coding revealed the teaching, learning, and mentorship experiences that a broad cross-section of 24 scientists associated with students learning how to find, frame, and formulate research questions. The next challenge was to understand how professors might weave these strategies and methods together during their teaching and mentorship experiences.

Process and outcome. Two illustrative cases were systematically selected. First, postinterview field notes were used to locate interview transcripts within which the participants spoke most extensively about the teaching and mentorship of RQF; eight such transcripts were identified. These eight transcripts were then coded with First Cycle methods to catalogue actions, values, attitudes, and beliefs participants had shared as they described their mentorship experiences. Topics that emerged included

- the format and function of research questions within their discipline;
- quality criteria for research questions;
- the professor's own processes for finding, framing, and formulating research questions;
- overall approaches to supervision;
- descriptions of how RQF develops among their own students.

With these five topics as grouping categories, the eight participants were compared with each other in order to determine the most promising candidates for the illustrative cases. A key question that guided the comparison was: "In using this participant as an illustrative case, what more could we learn about the mentorship of RQF that we do not already know from the RQF categories?" As I worked to answer this question, two participant interviews stood out for containing

- extensive discussion of RQF when compared with other interviewees;
- clear accounts of the role of research questions for scientific inquiry in their labs;
- detailed explanations of mentorship approaches, attitudes, and strategies associated with the development of student RQF.

These two participants, a chemist and a biologist, became the illustrative cases to bring the RQF categories to life.

Chapter 4: Results—The 10+1 RQF Themes

The RQF Segments

The largest challenge for this study was the identification of data that were directly relevant to the dissertation questions. The objective of the study was to explore the teaching and mentorship that supported students' involvement in finding, framing, and formulating questions for scientific research (RQF). S*tudent RQF* was the term derived to represent student involvement in the conceptualization and design of questions for scientific research that produces new knowledge. In order to recognize student RQF, I generated an empirically derived and replicable definition for "student RQF segments." Student RQF segments were sections of the interview containing participants' experiences, recollections, and narratives that pertained to all four of the following criteria:

- The pursuit of new scientific knowledge.
- The experiences of teaching, learning, or mentorship.
- The processes of finding, framing, and formulating the focus of the research.
- The focus of the research in that it included one or more of the following: research questions, research objectives, hypotheses or predictions, and research topics for grants, dissertations, and theses.

Student RQF segments tended to include the interviewer question, the participant answer, and any additional transcript lines needed to contextualize the segment. The 24 participants selected for the main data set tended to contribute five RQF segments while endorsing four to five RQF categories. The average number per participant was 5.6 RQF segments and 4.5 RQF categories, respectively. The average length of a segment was 603 words, with a large standard deviation of 307 (segments ranged from 111 words to 1532 words). In total, 134 RQF segments were reliably flagged as borderline "yes" or exemplary instances of RQF (interrater agreement was 78%). Segments were independent of each other in that each segment held a contained narrative about RQF.

Next, each RQF segment was assigned to one or more of 11 RQF categories. An RQF category was a grouping of actions and strategies that reportedly contributed to student RQF. Of the 134 RQF segments, 75 (56%) contained only one category of strategies for developing RQF (these were called single-coded segments). The remaining 59 RQF segments (44%) contained multiple RQF strategies (multicoded segments). The prevalence of multiple strategies in a single segment should not come as a surprise given that the segments were extracted so that the entire context in which the quotes arose could be included. This context served three purposes: It provided information on how RQF strategies were used, it captured how participants themselves connected their actions to student RQF, and it allowed pedagogical strategies for developing RQF to be differentiated from strategies related to the answering of already formulated research questions. The prevalence of multiple codes in each segment suggested that professors used a combination of strategies and approaches for developing RQF. The fact that these multiple strategies occurred in a single narrative suggests that the approaches are dynamic, organic, and integrated. That is, the strategies were usually described in fluid natural contexts in which the participants described events as they occurred with their students and the actions taken by student and professor. The RQF categories themselves were independent in their conceptualization but integrated in practice. For example, ensuring students are exposed to different labs (RQF category exposure) is clearly a different strategy from directing students to specific articles (RQF category literature) or narrowing the scope of research questions with them (RQF category feasibility). During the interviews, a participant would mention all three in a single answer when asked, "How did your student come to study their topic?" This entire answer would be extracted and treated as a single segment in which multiple RQF categories could be identified.

The RQF Categories

Overview. In the upcoming section, the results of the entire coding process are reported one RQF category at a time. First, a category definition is provided along with the coding criteria used to identify transcript sections for the category. Next, the disciplines and supervision experience of the scientists who mentioned the RQF category were summarized in a table. Each category is then richly described through illustrative quotes organized into two to four subthemes that characterize the nuances of that RQF category. Table 15 presents the number of segments that pertain to each RQF category as well as the subthemes for that category.

Table 15

Nuances of Each RQF Category

	Segments		Participants		
RQF category	Number of segments [a]	Proportion of participants (n=134)	Number of participants	Proportion of segments (n=24)	Subthemes within each category
RQF development in the curriculum (Category 1)	9	6.7%	8	33.3%	• Acquire background knowledge • Developing proposals
Starting points for RQF (Category 2)	13	9.7%	10	41.7%	• General topic areas as starting points • Finding starting points through intersections in student-professor interest • Projects as starting points for future RQF
Literature-based approaches to developing student RQF (Category3)	15	11.2%	10	41.7%	• Requiring students to read broadly and critically • Directing students to contextualize their initial inspiration in the literature • Sharing specific articles • Discussing ideas and interests in response to student-initiated explorations of the literature
Peer interaction (Category 4)	11	8.2%	8	33.3%	• Peer training in experimentation allows students to formulate their own research questions • Input from peers provides leads to research questions

(continued)

(continued)

RQF category	Segments: Number of segments [a]	Segments: Proportion of participants (n=134)	Participants: Number of participants	Participants: Proportion of segments (n=24)	Subthemes within each category
Exposure and student RQF (Category 5)	17	12.7%	14	58.3%	• Expose students to other scientists • Expose students to variety through conferences and seminars • Expose students to other research labs
Professor's in-course teaching of RQF (Category 6)	4	3.0%	3	12.5%	• Cultivating creativity that transforms into research questions (graduate chemistry course) • Requiring novel and original research questions (graduate ecology seminar) • Writing assignments to contextualize findings and generate new research directions (graduate biology seminar)
Feasibility, scope, and specification (Category 7)	15	11.2%	10	41.7%	• Directing students away from the abstract toward the actionable • Directing students toward parameter specification • Questioning and listening
Presenting research questions (Category 8)	7	5.2%	6	25.0%	• Graduate conference presentations enable students to elicit feedback • Graduate conference presentations facilitate peer modelling and critical thinking • Preparing and delivering presentations can provide leads for research questions
Additional writing (Category 9)	3	2.2%	3	12.5%	• Participation in grant writing • Other writing
Supplemental professor strategies for RQF (Category 10)	21	15.7%	13	54.2%	• Maintaining an open and encouraging attitude to elicit student ideas and contributions • Encouraging students to try out ideas and follow their leads • Modeling scholarly skills • Directing students toward promising areas of investigation
Comments and expectations (Category 11)	64	47.8%	23	95.8%	Students can or should... • contextualize their questions in the existing research literature or in the ongoing work of their field • build on past projects and previous experiences to come up with new ones • integrate different ideas and perspectives • think about their work from a critical standpoint • consider funding opportunities or career interests, or trends in the field and the broader contribution of their study when selecting a research topic • work with their supervisors to integrate the research interests, strengths, skills, expertise of both parties when formulating a research question • use a testable hypothesis as a starting point for RQF • engage in free explorations of broad topic areas, either with their supervisor or with other researchers

[a]The sum of segments from all categories does not add up to the total number of RQF segments (n=134) because segments could be assigned to more than one category.

A note on conventions used in participant quotes. Extensive participant quotes are used throughout the reporting of the results for two reasons: To provide rich description of the context in which the teaching, learning, and mentorship content arose, and to transparently show how the participants themselves linked this content to the ability to design and conceptualize research. Some illustrative quotes combine sentences from two or more segments in order to present a cohesive image of that participant's views on a given topic. In these cases, "//" is used to denote the pasting together of participant comments from different sections of the same interview. To improve readability without misrepresenting participant views, certain colloquialisms such as "gonna" were corrected to their grammatically correct equivalent ("going to"). Ellipses were used when parts of a participant's quote were omitted, and square brackets were used for inserting explanatory text not mouthed by the participant, as per the American Psychological Association's conventions for omitting and inserting material (2010, pp. 172-173).

Category 1: RQF development in the curriculum. This theme refers to aspects of graduate and undergraduate curriculum that professors see as contributing to students' ability to find, frame, formulate, narrow, and refine research questions. The purpose of this theme was to capture student activities that occurred as part of usual graduate or undergraduate programming, and that were not specific to things done by the professor in his or her own teaching.

Focused coding using the coding guide presented in Table 16 revealed that the RQF development in the curriculum category applied to eight of the 134 RQF segments, which came from interviews with seven of the 24 participants (see Table 17 for demographic details). Open coding conducted on these eight segments produced 13 codes that represented approaches, methods, and means for developing student RQF through the use of programming. Axial coding on these 13 codes produced two recurring themes:

- Acquire background knowledge.
- Developing proposals.

Table 16

Coding Guide for RQF Development in the Curriculum (Category 1)

Description	Inclusions and examples	Exclusions	Key question to ask
This theme refers to aspects of graduate and undergraduate programming that professors see as contributing to students' ability to find, frame, formulate, narrow, and refine research questions. The purpose of this theme is to capture student activities that occur as part of usual graduate or undergraduate programming and are not specific to things done by the professor in his or her own teaching. Little extra intervention is needed from the professor because students will develop RQF abilities just by following their courses and their program.	This includes undergraduate and graduate classes, seminars, tests, exams, thesis, proposals, class discussions, coursework, or any other program requirements. Negative sentences like "For the PhD program, we don't have much structure. And I think the reason we do that, we're comfortable with it, is so that people, students are not constrained. They can actually move quite freely to you know, inquire and formulate their own research questions whereas in other programs students may be more constrained." In this segment, the lack of structure is a feature of the program that allows for the exploration of possible research questions.	If a segment fits both in RQF development in the curriculum and professor's in-course teaching, label the statement as professor's in-course teaching as the latter is more specific than RQF development in the curriculum.	Will students develop RQF abilities by following the typical program as outlined for most students? If the answer is no, then there is likely a better theme that captures that which the professor believes is necessary for students to develop RQF. In 10, students could use their electives to find courses that would give them the background knowledge to pursue their own research questions. However, the student and the professor are not taking additional initiatives to find these courses to serve a particular end. The typical program simply includes electives. The professor did not say that the fact that programs include electives is sufficient for the development of student RQF, so the segment would be considered a "close but no" for RQF development in the curriculum.

Table 17

Demographics of Participants Coded With RQF Development in the Curriculum (Category 1)

Participant ID	Branch of science	Discipline-specific identifier	Gender (for pronoun purposes)	Faculty position	Years worked as a professor	All undergraduates supervised to date	All master's students supervised to date	All doctoral students supervised to date
3	Biology	forest ecologist	Female	Professor	25	30	10	3
17	Biology	molecular biologist	Male	Professor	13	20	5	10
10	Chemistry & Biochemistry	analytical chemist	Male	Professor	30	100	25	25
12	Chemistry & Biochemistry	inorganic chemist	Male	Associate Professor	12	30	2	7
21	Chemistry & Biochemistry	materials chemist	Male	Professor	30	20	6	12
11	Other Life Sciences	biophysicist	Male	Assistant Professor	5	15	0	3
18	Physics	geodynamicist	Male	Professor	15	26	6	6
24	Physics	theoretical physicist	Male	Professor	27	20	10	20
				Averages	19.6	32.6	8.0	10.8

Acquire background knowledge. Three participants mentioned the role of courses in helping students acquire the background knowledge or broad overview of the field before they can meaningfully engage in research question formulation. For example, a materials chemist (Participant 21) listed the knowledge obtained through coursework as one of the key ingredients needed for research question formulation:

> The other thing I want is for them to be creative, to have ideas, to say "Why not? Why, if I would try this or that?" Because this is the driving force for research . . . . We are not training people as future lab technicians. They need three things . . . skills, knowledge, and creativity. Knowledge is a part of what they get in class, what they get by reading things.

Similarly, a forest ecologist (Participant 3) spoke about the importance of building foundations for research question formulation through coursework:

> [They lack] critical thinking or critical awareness . . . [of] the evolution of the research and the questions, right? So most of them do not know the deep history—research history of their own field. . . . Which is why we have an introductory course for all the graduate students where they have to learn that.

When asked to describe how research questions emerged amongst the students in his lab, a theoretical physicist (Participant 24) redirected the conversation as follows:

> Let me first of all say some general things . . . students typically start out by taking a supervised reading class. These are for graduate students, it's at a formal level, [it's a specific class] . . . . And for undergraduate students, it's independent reading. And so in that class, the students get familiar with the broad overview of the field . . . then when a student is ready to do research, then they typically have a preference for one or the

> other of the subfields which I'm working on . . . see, I don't just take on a student for a project, but I take on a student based on their qualifications. And then the student and I come up with a project, sort of in discussion, taking into the account the strengths of the student and what they seem to be interested in. . . . I think that this is a very important aspect, because it puts the responsibility for the project already from the beginning on the student.

In the above quote, the physicist described how research question formulation started with the development of background knowledge that enabled students to demonstrate their interests and qualifications. In fact, all three of the above participants listed developing foundations through coursework as a necessary prerequisite to meaningfully engaging in research question formulation.

Developing proposals. Quotes from three participants illustrated the role that proposals played in helping students develop the ability to formulate research questions. For example, a molecular biologist (Participant 17) talked about how the expectations for research question formulation changed as students attempted to transfer from the master's to the doctoral level:

> If they start as a master's and they want to transfer as a PhD—the expectation I think for all transfer exams is that, if you're spending two years in the lab, when you come up for a transfer, you should really take ownership of your project. So the questions that you're asking are your questions, the experimental design is your experimental design. I mean that's what you expect from a transfer. And we have a lot of students who don't pass their transfers the first time around because they're just at a master's level, they just go, "well, I'm just going to continue on with this project. I'll do what my supervisor tells me

> to do." And we're the ones who say, "No, that's not how you transfer to a PhD. Really, you got to take ownership, and you're the one who's got to take it forward now."

From the above quote it appears that the role of those in charge of evaluating student transfer requests was to reiterate the expectation for ownership, independence, and originality in student research questions. If students failed to meet these expectations, the program coordinators would prevent students from advancing to the PhD level. The molecular biologist continued to describe the expectations for the transfer exam:

> They have to write a five to 10-page proposal about what their PhD will entail, then they walk into the exam and give like a 20-minute presentation, and then we just grill the bejesus out of them . . . it would be similar to defending your master's research, but on top of it, not only do they have to defend the research that they've done, they defend their proposed experiments.

In the above quote, the role of examination evaluators was to question and critique the student's work. In doing so, they created the opportunity for students to defend the research question they formulated and the approach they chose for answering it. An inorganic chemist (Participant 12) listed the benefit of the doctoral seminar—a requirement to write proposals:

> [In] our department . . . they have to give in their PhD1 . . . [a] proposal . . . About planned future research, assuming they were to apply for faculty positions . . . the best students . . . reuse them in the future when they apply for jobs . . . [they write a] three or four-page proposal as if they were sending it to a granting agency right away . . . they're even encouraged to come up with a budget. It's sometimes funny to see how they think—how much, or how little cost their chemicals, or how much they have to pay a postdoc, or an undergraduate. But they're encouraged to think about their future

> research, as if they were an independent researcher. . . . They basically have their research objective laid out: “we want to make this and we want to make this, that would be perfectly fine.” It doesn’t have to be formulated as a question. . . . It’s actually made to widen their horizons. So it’s supposed to be a topic that’s not currently investigated in their supervisor’s group.

In the above quote, the chemist explained that the proposal simulated being an independent researcher who needed to consider both the costs and logistics of carrying out a research program in addition to the clear communication of said program. The requirement for ownership and originality stood out as students were asked to propose a new research question outside of those already being investigated by their supervisor’s research group.

When asked for examples of students who proposed their own research questions, a geodynamicist (Participant 18) explained how the capstone project in his undergraduate program required all students to generate their own questions and projects:

> In engineering they have to do this capstone project which is something, you know, innovative and so forth. So they come up with some kind of very crazy ideas. Saying, “Can I do this? Can I do that?” I say, “sure,” because I want to let them, you know, find out or imagine new situations like in engineering. “Can I build this? Can I do that? Can I build that?” And they take all these examples from their experiences.

In the above quote, the participant noted that senior engineering undergraduates drew on their experiences to propose creative research ideas during their capstone project. When asked whether students who participated in the capstone project experience were selecting from available research questions or generating their own questions, the participant provided the following reply:

> I can tell you it's not only with my students, it's with all the students here at X university in engineering. [When] we launched the program, . . . our professors had one or two ideas, and they explained them to [the students] . . . The second year [of the program], [that] did not work. 50% of the students came up with their own ideas . . . And then we said, "forget it, we're not going to tell them anything." These guys, they [want to] develop some . . . ideas . . . during their undergraduate studies. Whatever they want to do, they will do it. . . . In only exceptional cases, if the students . . . cannot find other colleagues to work with, they may ask, "what do you think about that," or "do you have a general idea about a project?" But nothing specific, they just generate their own.

In the above quote, the role of the professor was to recognize that senior engineering students preferred to define their own research questions and projects over choosing from a pre-established set proposed by the professor. The participant and his fellow professors then opted to give students the freedom to explore and find their own research questions, remaining available to students who might need a sounding board.

It is important to note that research proposals were mentioned by other participants. In fact, keyword search for the word "proposal" revealed that 19 of the 24 participants mentioned proposals during the interview. The quotes selected from the above participants stood out as instances where the professor made a direct link between proposing research projects as part of normal graduate programming and being able to generate one's own research questions.

Synthesis. The act of proposing new research involves creative and critical thinking. According to my participants, proposals served as important, authentic simulations of the conceptualization and planning for a program of research. This premise converges with Fister's (1992) finding that formally verbalizing the focus of a project was "the single factor that most frequently spurred a student's movement" (Formulating a focus for research, para. 6) beyond the preliminary stages of exploring a topic. Writing proposals enabled students to build their portfolio of independent research interests and their identities as scholars.

The purported benefits of writing proposals found in the present study suggest that students should be engaged in writing research proposals early and often. In comparing the quotes and subcategories to each other, I was struck by the following question: How much prior knowledge was needed before students could start to engage in the design and conceptualization of research? Comments that valued student engagement in designing research proposals implied that early and frequent engagement in designing research was beneficial. Conversely, comments about the role of the curriculum in developing students' background knowledge could imply delaying engagement until students have acquired the prerequisite knowledge. What I would like to highlight is not that prior knowledge contributes to RQF, but rather how much knowledge is needed, when is it needed, and to what extent can it be acquired concurrently with student engagement in RQF. The amount of prior knowledge needed before students are invited to engage in the design and conceptualization of research varies dramatically based on a number of factors, which will be revealed when this topic is revisited in section "Customizing or Individualizing RQF pedagogy." For now, let us move the discussion to examples of introductory levels of student engagement in the absence of said prior knowledge—starting points for RQF.

Category 2: Starting points for RQF. This theme describes how introductions and starting points in a research lab can contribute to the development of student RQF skills. It includes starting points provided by the professor that allow students to begin exploring possible topics within, or converging with, the professor's research interests.

Focused coding using the coding guide presented in Table 18 revealed that the starting points for RQF category applied to 11 of the 134 RQF segments. These 11 segments came from interviews with nine of the 24 participants (see Table 19 for demographic details). Open coding conducted on these segments produced 28 codes that represented approaches, methods, and means of developing student RQF through the use of a professor-provided starting point. When Axial coding was used to group these 28 codes by similarity, three types of starting points for engaging students in student RQF emerged:

- General topic areas as starting points.
- Finding starting points through intersections in student-professor interest.
- Projects as starting points for future RQF.

Table 18

Coding Criteria for Starting Points for RQF (Category 2)

Description	Inclusions and examples	Exclusions	Handle with care
The professor gives the students a starting point for pursuing their own research question.	• Starting points provided by the professor that allow students to begin exploring a curiosity that they had. • Starting points regarding how to merge the student's interest with the professor's interest.	• Excludes examples of professors giving students journal articles to read to become familiar with the current topics in the lab. These should be coded as literature instead. • Excludes starting points that students find on their own. This theme is only for those suggested by the professor. • Excludes instances of the professor giving the student a list of pre-formulated research questions from which to choose (this action, in and of itself, does not constitute student involvement in the process of RQF).	• Tread carefully with descriptions that sound like ways to make the entire project more feasible which include a concrete starting point. Consider the extent to which students are conceptualizing and designing research. • Distinguishing starting point from feasibility: If the starting point is more about being introduced to a lab or a topic area, then code it as starting point. If the professor mentions several steps after the starting point and a plan for making an abstract interest or project more feasible, code it as feasibility, scope, and specification.

Table 19

Demographics for Participants Coded as Starting Points for RQF (Category 2)

Participant ID	Branch of science	Discipline-specific identifier	Gender (for pronoun purposes)	Faculty position	Years worked as a professor	All undergraduates supervised to date	All master's students supervised to date	All doctoral students supervised to date
2	Biology	systems biologist	Male	Professor	15	20	11	3
4	Biology	molecular ecologist	Female	Associate Professor	7	10	5	1
16	Biology	genomicist	Female	Assistant Professor	5	15	6	4
5	Chemistry & Biochemistry	protein biochemist	Male	Associate Professor	10	13	2	2
10	Chemistry & Biochemistry	analytical chemist	Male	Professor	30	100	25	25
1	Other Life Sciences	cognitive neuroscientist	Male	Associate Professor	10	6	4	1
14	Other Life Sciences	comparative physiologist	Female	Assistant Professor	2	8	3	0
18	Physics	geodynamicist	Male	Professor	15	26	6	6
19	Physics	materials physicist	Male	Professor	15	20	10	12
20	Physics	astrophysicist	Male	Professor	25	15	12	8
				Averages	13.4	23.3	8.4	6.2

General topic areas as starting points. Five participants mentioned assigning students a general topic area rather than a specific research question. An analytical chemist (Participant 10) provided a page of possible topics to his new students and explicitly told them, "this is not your project, all you're doing is you're choosing an area to explore and we will resolve your project, your direction of the first chapter, in the next six months." A cognitive neuroscientist (Participant 1) described how the starting point opens up numerous areas of research so that supervisor and student can then formulate a question together:

> We'll try to find something that they're interested in . . . it might be a topic that I give to them . . . there's . . . hundreds of things they could potentially do . . . often it's the case where they don't necessarily know what they're interested in, so maybe I start them off

> by providing a question, and then . . . collaboratively come up with new questions based on that.

In the above segment, the neuroscientist spoke of helping students identify their individual areas of interest by providing an example of a research question. The students were then expected to collaborate with him on identifying questions that truly interested them.

Similarly, a genomicist (Participant 16) emphasized the importance of ascertaining student interests before collaboratively establishing the focus of the research together:

> When new students start . . . I start talking about some of my interests, telling them a little bit about the lab . . . and some of our most exciting recent findings. . . . I point them to some papers to read, and then we . . . proceed with a conversation from there. So I find out from them . . . what they think was most interesting, and we . . . keep that going back and forth until we sort of settle down into a focus that I am happy with and that fits within the umbrella of my funding . . . [giving students] the time to work through what we've talked about and develop their own ideas and focus.

For the genomicist, student research question formulation began with the professor sharing her own interests and then developing student curiosity through various activities that expose the students to the lab and the field. This quote was coded as starting points for RQF, literature, and supplemental professor strategies because the professor provided the student with literature as part of her starting point, and then explicitly expressed her expectation for mutuality and collaboration with the student.

Conversely, when it comes to undergraduate research question formulation, a comparative physiologist (Participant 14) described guiding students to specific gaps in knowledge instead of broader topic areas:

> [F]or an undergrad, obviously, I'm not going to say, "Just go find a question!" I usually give them a rough frame of what my overall question is, and give them little openings of . . . "we don't know a lot about it in this area, maybe this molecular project, if that's what you're interested in," and then they get to . . . take it from there.

Similarly, upon being asked about when graduates get to see research questions, a materials physicist (Participant 19) described how he treated strong students and weak students differently when it came to starting points for research question formulation:

> The moment they begin, I usually have an idea of a topic I want to explore for some reason. I'll give them reading material on that, give them my ideas on this . . . the weaker students more or less hang their hat on every word you say . . . for them . . . you have to make sure your research question is rock solid, and you have enough steps to get to it. The good ones, you just need to sort of put it out there as a general question and a bunch of ideas around that, and they usually take it to a direction of their own.

The physicist further explained that weaker students imposed a significant liability, because they could only progress if the assigned research question was "rock solid," detailing all the steps involved in answering it. In contrast, the stronger students could take ownership of the RQF process after being given general topic areas.

Finding starting points through intersections in student-professor interest. Three participants mentioned how the starting point for student involvement in RQF entailed finding the overlap between the professor's area of funding and the interests that students brought to the table. For example, a cognitive neuroscientist (Participant 1) talked about how questions emerged as "students' interests kind of overlap" with the "whole list of things [professors] want to know." A molecular ecologist (Participant 4) spoke of the role of overlapping interests in greater detail:

> She came in my lab saying that she wants to study speciation. . . . I said, "This is my model organism. This is what I would like to understand about this. These are the most exciting studies on speciation that I am aware of. What do you think?" . . . I try to put that a lot on their shoulders, try to . . . ask them, "What do you think about this? . . . What do you think are difficulties?" . . . I think we help the students [find] careful situations in which they have to react and provide another approach.

By introducing her area of work and presenting the student with compelling literature on the topic, the molecular ecologist sought to bridge her interests with those of the student, and then to engage the student in critical reflection in order to find possible research topics and approaches to study these topics.

Whereas the molecular ecologist was working from within her area of expertise, a geodynamicist (Participant 18) described how he was able to find overlapping research areas with a student whose interests fell outside of his expertise:

> The student wanted to study another topic I hadn't dealt with—[topic x] . . . [and he said] "I see that you're doing something with satellites; can we combine that?" I said, "Sure . . . we can combine [satellites] with [topic x]" . . . But I told him, I'm not expert in [satellites] and you're not expert either, and what we want to do—we're both moving in the dark so we'll be helping one another.

The professor's role was to find an area of overlapping interest with the student and then to guide the student as they both developed new expertise and a research question together. The geodynamicist continued:

> He learned and I learned a lot of things; so amazing. And that was an area that was very new . . . these topics were coming from discussions. We had amazing discussions. "How do you do this? How do you do that?" And we let our imaginations . . . create all this. "Can we do this? Oh yes, that's a good idea. . . ." So we developed these kind[s] of ideas, obviously discovering things.

In the above quote, the geodynamicist enthusiastically described how the professor and student not only shared interests, but jointly embarked upon an imaginative and rewarding journey that led to new discoveries. The student also fared well after this experience: "He's working with NASA . . . they were waiting for him to finish his PhD for 10 months. I told them, 'This is a great guy, I don't want to lose him.'" In all three segments, the participants talked about the importance of ensuring that there is overlap between the interests of the professor and those of the students. Segments in which the professor talked about providing students with preformulated research questions would be coded as a starting point if the participant explicitly indicated that starting with these professor-generated questions helped the students to later be able to develop their own questions. The idea of projects as starting points for future RQF is elaborated more fully in the upcoming quotes.

Projects as starting points for future RQF. Two participants mentioned using projects with previously formulated research questions as starting points for students. In these cases, the starting point was seen as a project to develop competencies and model the process of RQF for students so that they could later find and define their own projects. For example, a cognitive neuroscientist (Participant 1) spoke of how he gave research projects as starting points to students whose interests were not well defined when they joined the lab:

> It varies depending on whether the student comes in with a question of their own or not. So they have a vague idea of what they want to study, and maybe for the first project, the professor has some ideas in mind, and . . . assigns something, and then ideally . . . for their dissertation, they'll have done some project already, and then they'll develop their research questions based on that.

In other words, the cognitive neuroscientist assigned contained projects to his master's students, which became the starting points for the students to develop into fully fleshed-out research questions during their PhD. Similarly, a protein biochemist (Participant 5) outlined how he used the same strategy, but offered a fuller explanation of the logic behind it:

> Most students will start as a master's, and I'll give them . . . a project, which is fairly well-defined, with . . . techniques which are already working, and we need to add these particular things on, that need to be developed and established. And that will have kind of an opening towards longer-term. . . . And then, if the student promotes . . . I just take a step back . . . because . . . they're usually running that project by themselves anyway. . . . And then you . . . guide them toward the next thing, and . . . give them a bit less guidance. They get a bit scared, and they kind of work it out.

Here, the biochemist described a longer path toward independent RQF, one that began from a preformulated research question. The student's responsibility started with helping further define, refine, and specify the assigned research question. Vygotsky (1978) specifically described the role of problem solving in collaboration with instructors and more capable peers as a means of eventually mastering tasks that initially lay beyond the learner's capacity. Vygotsky referred to this as learning that occurred within the student's zone of proximal development

(ZPD). The above quote illustrates how the supervisor scaffolded student RQF so that the learning would occur within the student's ZPD.

This first project enabled the student to develop competencies while allowing the supervisor to simultaneously test the student's aptitude for further advancement. Guidance from the supervisor was slowly withdrawn for students who passed this test, encouraging them to venture out of their comfort zones and take on greater responsibility for defining their own research questions. At this stage, rather than provide instructions, the supervisor expected the students to make more and more judgement calls based on prior experience.

Synthesis. Starting points can be broader topic areas that invite students to explore and discover their own interests within a professor's overall research agenda. This result converges with the findings of Nutefall and Ryder's (2010) study of differences in how librarians and faculty members guide students through the initial stages of research. Nutefall and Ryder found that, for professors, "the starting point is not a narrow question but rather a large and admittedly unwieldy one that must be honed down through research as the student becomes familiar with the materials and the discourse of the issue" (p. 444). When the students bring their own interests to the table at the beginning of a supervisory relationship, starting points may be a series of discussions in which the professor and the student find ways to bridge their respective interests and expertise areas. Starting points can also be projects to develop competencies and cultivate curiosity, so that the students can one day formulate their own research questions.

Once students have developed a basic understanding of the supervisor's lab and their area of research, they can begin to explore inspirations for researchable topics and new research directions. The next category examines how students are asked to test the originality and significance of these ideas against previous publications.

Category 3: Literature-based approaches to developing student RQF. This category encompasses all beliefs and practices that explicitly mention the professors' reported actions in helping students navigate, understand, assess, and contextualize research questions in the literature. I defined literature as the searchable body of scholarly knowledge that is available to students and researchers within the discipline (including Wikipedia, Internet, and textbooks).

Focused coding using the coding guide presented in Table 20 revealed that the literature category applied to 11% of the extracted dataset (15 of the 134 RQF segments). These 15 segments came from interviews with 10 of the 24 participants (see Table 21 for demographic details). Open coding conducted on these segments produced 33 codes that represented approaches, methods, and means of developing student RQF through the use of literature. When Axial coding was used to group these 33 codes by similarity, four types of literature-based strategies for developing student RQF emerged:

- Requiring students to read broadly and critically.
- Directing students to contextualize their initial inspiration in the literature.
- Sharing specific articles.
- Discussing ideas and interests in response to student-initiated explorations of the literature.

The existence of a category for statements related to literature and the mentorship of student RQF is not surprising considering that scientific findings cannot be validated as new knowledge without considering the empirical literature that previously existed. It would be surprising if no scientists mentioned strategies that related to literature. As it stood, 19 of the 24 interviews contained the term "literature." In some of these cases, the transcript section in which the word literature appeared did not qualify as an RQF segment, for example, it was about the professor's overall research or was off-topic in some way. In other cases, literature was mentioned in a context that was more relevant to another RQF strategy, for example, students should discuss literature with their peers—this was coded as peer interaction, or students are required to do a literature search as part of their seminar, which was coded as RQF development in the curriculum. At the end of the day, segments from 10 of the 24 participants were coded with the literature category (41% of the participants).

Table 20

Coding Criteria for Literature-based Approaches to Developing Student RQF (Category 3)

Description	Inclusions and examples	Exclusions	Handle with care
This theme is about how the professor helps the student navigate and contextualize research questions in the literature, in either a directive or nondirective (supportive, facilitative) way. Literature is defined as the searchable body of scholarly knowledge that is available to students and researchers within the discipline (including Wikipedia, Internet, and textbooks).	Literature & RQF includes all beliefs and practices that explicitly mention the professor's actions in helping students navigate, understand, and contextualize research questions in the literature. The professor does not need to be directive; he can be facilitating and supporting student literature searches, student questions about literature, and student-directed explorations of the literature. This includes but is not limited to: • Professor directs the students to the literature (including Wikipedia, internet, and textbooks); • Professor suggests articles; • Professor helps student with literature searches; • Professor expects students to navigate and apply the literature; • Professor answers students' questions about the literature; • Discussions the professor has with students about literature that students find; • Negative sentences about literature, such as "I don't give them literature to read, they should find it themselves," because this is a professor expectation.	Literature represents any written material (peer-reviewed or not) that is publically searchable to the student and scholars in that discipline. Literature does not include the professor's own instructional material and notes or anything that is not publically searchable.	Not applicable.

Table 21

Demographics for Participants Coded as Literature-based Approaches to Developing Student RQF (Category 3)

Participant ID	Branch of science	Discipline-specific identifier	Gender (for pronoun purposes)	Faculty position	Years worked as a professor	All undergraduates supervised to date	All Master's students supervised to date	All doctoral students supervised to date
3	Biology	forest ecologist	Female	Full Professor	25	30	10	3
16	Biology	genomicist	Female	Assistant Professor	5	15	6	4
17	Biology	molecular biologist	Male	Full Professor	13	20	5	10
12	Chemistry & Biochemistry	inorganic chemist	Male	Associate Professor	12	30	2	7
23	Chemistry & Biochemistry	theoretical chemist	Male	Full Professor	18	20	3	6
13	Other Life Sciences	neurophysiologist	Male	Assistant Professor	1	4	0	0
14	Other Life Sciences	comparative physiologist	Female	Assistant Professor	2	8	3	0
18	Physics	geodynamicist	Male	Full Professor	15	26	6	6
24	Physics	theoretical physicist	Male	Full Professor	27	20	10	20
19	Physics	materials physicist	Male	Full Professor	15	20	10	12
				Averages	13.3	19.3	5.5	6.8

Requiring students to read broadly and critically. Three participants mentioned expecting students to read the literature broadly, carefully, and critically to establish their foundations for finding researchable questions. For example, a theoretical physicist (Participant 24) asserted, “Before the topic is chosen, the student has done the reading, the general reading of the field.” This participant mentioned that students acquired this general reading of the field through directed reading courses or seminars that he would sometimes teach.

A forest ecologist (Participant 3) talked about the importance of directly teaching students how to carefully peruse and understand the articles that they read: “What I always say to my students is, ‘You should always be able to answer about any research paper that you just read . . . Who? What? Why? Where? When?’” The extensive and original strategies that this forest ecologist developed for helping her students find research questions from the published literature will be further shared in the Illustrative Cases section of the results.

An inorganic chemist (Participant 12) mentioned having his students use the literature as a source of modeling to help them learn to assess the quality of research questions:

> So you're looking at good research, you're looking at not-so-good research, and not everything that's published in the literature is good. And so eventually an idea, what is a good question and what is a not so good question [emerges]. . . . [The] key is they have to read the literature.

In all three of these examples, the professors expected that the reading of the literature would occur prior to finding the research question.

Directing students to contextualize their initial inspiration in the literature. Four participants mentioned having students use the literature more for contextualization after the initial inspiration for a research question has been discovered. For example, a genomicist (Participant 16) spoke about how she directed students to the literature after discussing their initial interests and inspirations with them: "When they identify something that they think might be interesting, then I really encourage them to go and look—you know, go and develop that further by looking in the literature." This participant proceeded to give an example of one student who "did quite a lot of reading of the literature to look into possible mechanisms and ways that we could then further follow up her initial observation."

When asked about how a supervisor could help students to search the literature for researchable questions, the forest ecologist (Participant 3) rephrased the question with, "or you can go in with a question and then read the research literature." The genomicist (Participant 16) mentioned, "so in our weekly meetings, she would sort of report what she'd found in the literature, and we would look at it together and kind of make sure that we agreed on the interpretation of the findings." A geodynamicist (Participant 18) spoke about how he and his student used the literature to make sense of unexpected findings that could lead to new research questions: "We examined a number of studies and literature, and so forth, and we realized that the observations from the satellites were somewhat affected by some kind of an unknown cause. . . . We say, okay, so let's investigate that." In all four examples, the reading of the literature occurred after students had found an inspiration for a research question.

Sharing specific articles. Three participants mentioned giving specific articles to the student when asked about how to help students find researchable questions. A comparative physiologist (Participant 14) spoke of how the practice of guiding students toward researchable questions through specific articles came from her own supervisor:

> [My supervisor said that my hypothesis was] a good place to start, but . . . it didn't advance knowledge enough to be what he considered a good hypothesis. He would come and sort of ask questions, and try to push us in helpful directions, and give us the background information that he had that we didn't have yet. . . . [He was giving us] good papers and saying, "This just came out and it's pretty impressive." . . . He would always send us papers that were sort of tailored to our interests, and he would say, "Well this just came out, look at it."

When asked what he did to help his own students through the process of generating viable research questions and hypotheses, this comparative physiologist mentioned that he gave his students specific articles and expected them to "read [the articles], analyze how they fit into the existing literature, how they advance what we didn't know before, and what the next question would be coming out from them." A molecular biologist (Participant 17) talked about how giving students articles and requiring them to generate their own research question was part of his interviewing process with potential students:

> Typically, before they accept graduate work, I interview them. I email them all my grant applications, email them all my papers, and I say, "well, you know, read up, read what we're doing, read what we've done, and come back to me with your own research question."

A genomicist (Participant 16) mentioned that with new students, "I point them to some papers to read, and then we meet the next week and sort of proceed with a conversation from there." This comment was made in the context of an elaborate strategy that involved keeping the dialogue open with current students, being patient and nondirective to encourage new ideas, and making students explicitly aware that she expected them to generate research questions. Her statement is described in more detail in the sections on *starting point for RQF* and *supplemental professor strategies*. All three of the above participants shared specific articles while holding the expectation that students would find and discuss possible research directions with their supervisor after reading these articles.

Discussing ideas and interests in response to student-initiated explorations of the literature. Two participants mentioned how students should initiate explorations of the literature on their own. The role of the supervisor is then to respond to these student-driven efforts by discussing ideas and interests with the students. A geodynamicist (Participant 18) reported finding time for potential mentees more readily if they had previously read his published papers, explaining that these students usually had already identified some areas of common interest.

> Most of the students in science are interested in the supervisor's research area obviously. Let's say someone's interested in geodynamics, usually he goes and finds information

> about the professor doing geodynamics and perhaps reads a few papers to see what . . . interest that the student may have, match the supervisor.

A theoretical chemist (Participant 23) described how he made himself available on a weekly basis for explorations of the literature that were initiated by one of his students:

> He was reading the literature and he had these little questions. And we talked for, you know, three hours. And this was happening every Saturday for about two years. And so these questions were totally his, he went throughout all the literature, and this is kind of how we operated. And this all had nothing to do with his research, he was just asking, thinking, asking questions, digesting, you know, what is happening in this field.
> . . . What's my role in this? We had these discussions of course, but it's triggered by the student. I am not telling students, you know, "You need to read the literature and then you have to come with your little booklet and ask me questions." No, that's not how it works. It's just he does this and so that's how it went.

In the above quote, the theoretical chemist provided two to three hours in his weekend schedule to discuss possible research questions that the student found in response to the student's high level of motivation. He also voluntarily mentioned that he does not assign readings to his students, nor does he expect this level of student engagement, but rather, is willing to respond openly and encouragingly when it occurs. Throughout the interview, the participant did not report sharing this willingness with his students, so it is unclear as to whether his students were aware that this level of initiative was appreciated by their supervisor. Both participants were willing to create a space to discuss possible collaborations and future research questions if and when students initiated the exploration of the literature.

Synthesis. Participants assisted students in using the literature to establish foundations, find inspirations for research questions, as well as contextualize and frame these inspirations as researchable questions. At times the professor was more directive, requiring students to read specific articles. Professors also made themselves available for student-driven explorations of the literature; during such meetings, potential advisees could be invited to join the lab while current advisees could find themselves engaged in extensive discussions of research ideas and possibilities for existing students. The results of the present study converge in some ways with those from Tan's (2007) study on the perspective of students taking an undergraduate research class. Although my study examined the mentors' perspective and focused mostly on the graduate level in the natural sciences, my findings converged with Tan's on the following point: Mentors' guidance and iterative feedback are important to helping students navigate the earliest stages of finding research questions. My findings diverge from those of Tan when it comes to the student emotions. According to Tan, students described how the earliest stage of defining research topics was characterized by fear, apprehension, insecurity, and feelings of inadequacy, despite the support of their advisors. In the present study, the professors rarely mentioned the role or implications of such emotions when describing their mentorship of student RQF, whether at the undergraduate or graduate level. The mentees either did not discuss matters related to emotional turmoil with their mentors or, if they did, these were not salient to the mentors.

As a whole, the literature category gathered teaching and mentorship actions related to the role of literature in finding, framing, and formulating research questions. The next category contains the actions related to the development of student RQF skills through interactions with, and mentorship by, their peers.

Category 4: Peer interaction. This theme is about how interaction among peers and lab members contributes to the development of student RQF skills. It includes comments that make a direct link between peer discussions or peer mentorship with developing the ability to find, frame, formulate, and refine research questions.

Focused coding using the coding guide presented in Table 22 revealed that the *peer interaction* category applied to nine of the 134 RQF segments that, in turn, came from interviews with six of the 24 participants (see Table 23 for demographic details). Open coding conducted on these segments produced 15 codes that represented approaches, methods, and means of developing student RQF through the use of peer interaction. Axial coding on these 15 codes produced two recurring themes:

- Peer training in experimentation allows students to formulate their own research questions.
- Input from peers provides leads to research questions.

Not all segments that mention peer interaction are shared in this section; some were multicoded with other categories and shared in their respective results sections because they were more representative of those other categories. The quotes highlighted in this category are ones that make a direct and explicit link between peer interaction and the formulation of research questions.

Table 22

Coding Criteria for Peer Interaction (Category 4)

Description	Inclusions and examples	Exclusions	Handle with care
Interaction among peers and lab members contributes to students developing RQF skills.	Peer interaction: Professor makes a direct link between student RQF and the role of peer interaction. • The role of lab members in helping students find, frame, formulate, refine, and modify their research questions by helping each other out through training and troubleshooting. • The role of peers as sounding boards to test out research ideas (outside of the context of presenting research questions for feedback). • Any other interaction among lab members: cooperation and collaboration that leads to the exploration of ideas, possible research topics, or other RQF processes. Peer discussion: Professor makes a direct link between student RQF and the importance or occurrence of any of the following: • Lab members talking to, cooperating with, helping out, or collaborating with each other as they engage in RQF. • Peers providing help that cannot be provided by the professor (or that cannot be provided as well by the professor) for RQF. • How lab dynamics contribute to student RQF. • How interpersonal factors on the team affect student RQF. Peer mentorship: Professor makes a direct link between student RQF and the role of peer mentorship. • Senior students mentoring newer or younger students on how to find good research topics.	Interaction or mentorship in general without RQF link. Examples: • Comments on the overall importance of peer interaction. • Lab members talking to, cooperating with, helping out, or collaborating with each other, providing help that can be provided by the professor (or better provided by the professor). • Lab dynamics or interpersonal factors on the team which the professor does not link to RQF itself..	Interactions between the professor and several students where everyone is interacting with each other. Pay careful attention to the wording.

Table 23

Demographics for Participants Coded as Peer Interaction (Category 4)

Participant ID	Branch of science	Discipline-specific identifier	Gender (for pronoun purposes)	Faculty position	Years worked as a professor	All undergraduates supervised to date	All Master's students supervised to date	All doctoral students supervised to date
4	Biology	molecular ecologist	Female	Associate Professor	7	10	5	1
9	Biology	cancer biologist	Male	Full Professor	24	50	14	11
16	Biology	genomicist	Female	Assistant Professor	5	15	6	4
10	Chemistry & Biochemistry	analytical chemist	Male	Full Professor	30	100	25	25
14	Other Life Sciences	comparative physiologist	Female	Assistant Professor	2	8	3	0
15	Physics	theoretical atomic physicist	Male	Associate Professor	12	5	10	6
24	Physics	theoretical physicist	Male	Full Professor	27	20	10	20
22	Physics	applied physicist	Male	Full Professor	31	39	30	41
				Averages	17.3	30.9	12.9	13.5

Peer training in experimentation. Three participants mentioned how peers play an important role in training and the development of lab skills needed to eventually find one's own researchable question. For example, a comparative physiologist (Participant 14) talked about the role of more advanced peers in the following segment:

> I didn't really know how to make a research question, and also, I was rather intimidated by the literature that was out there. It's very extensive, and you don't really know what's going on. You don't know that there's already 30 papers on this particular topic, and how to distil those down into an original question was just very difficult. But [my supervisor] had an extremely large lab. He had—when I joined, there was 23 people in it. And there was a number of postdocs—he had, I think, 10 or 11 postdocs when I started, so they were immensely valuable.

The comparative physiologist continued to elaborate on how peer support enabled students to troubleshoot and learn essential lab skills:

> You never actually spoke to [the supervisor] until you had results. You took the results to him, or you had your question finalized and you went to him, and you said, "This is the question that I want, this is my hypothesis," and he would either tell you it's crap, or tell you to go for it, and then you went to him with the results at the end. . . . And so he had built a little empire, and he had delegations, so you would speak to the postdocs about the troubleshooting, you'd speak to the postdocs about sample preparation and protocol, . . . you don't talk to him. He just didn't have time for it.

In the physiologist's view, her supervisor was able to overcome the constraints of available time by cultivating an atmosphere of peer interaction, training, and mentorship. A biologist

(Participant 9) similarly outlined the necessity of developing experimental skills in order for researchable questions to emerge from the data:

> So initially, [the student] doesn't know how to do anything, right? He is tasked with a specific question, and he learns from my professional staff how to do the various experiments, and he gets better and better at that, and his data becomes more and more polished. . . . So it's a continual evolving process . . . that provokes questions and hopefully he can go away and try and address those questions with new experiments.

The cancer biologist explained that, through refining lab skills with senior lab members, newer students learned to gather better data. With better data, new research questions would emerge alongside the students' ability to run experiments that address those questions.

A theoretical physicist (Participant 24) mentioned that such peer training must be accompanied by the student's own avid curiosity:

> [Students] have office space in the building. . . . And we have group meetings, and students see that the ability to develop independent questions is a good thing. . . . I think that's where a very important point enters. One has to be curious. So genuine curiosity will lead the students to develop questions, and joint with training, through classes and through group discussions, you will then also be able to even formulate an actual project.

In the above examples, new research questions emerge as students are immersed in experimentation, data collection, and troubleshooting with peers (often peers at higher degree levels). The supervisors value independence but do not leave the students entirely on their own—the students are able to rely on peers for training and assistance. The formulation of research questions does not happen discretely but rather continuously as experiments evolve over time.

Input from peers provides leads to research questions. Three participants mentioned how the act of seeking input from peers can help provide students with leads for new research questions. For example, an applied physicist (Participant 22) said that the task for new researchers is to identify specific problems and noted that this usually comes about as they interact with peers. A comparative physiologist (Participant 14) reflected on the importance peer interaction played in her own work as a graduate student:

> I was reading the literature and I was talking to people in the lab, basically. I was talking to people that already had questions . . . . Talking to the other people helped a lot. So right now I have a very small lab, so it's very important for [my students] to talk to people in other labs.

The physiologist's quote also highlighted the importance of being exposed to a sufficiently wide range of peer voices, something she felt was not possible with her current small lab. A genomicist (Participant 16) similarly described the role peers can play in helping students find researchable questions and avenues to investigate:

> Something that [the student] did that people don't always do is . . . talk to other people in the lab as well . . . . And some of the aspects of her project came about through her conversations with other people in the lab that didn't involve me at all. . . . I like that because it's nice when people come up with new ideas that don't involve me . . . . So that was really nice to see her take that initiative and seek advice and kind of synthesize input from other people and then decide on something that she wanted to pursue.

In the above quote, the genomicist described how impressed she was when a student took the initiative to seek out peer advice and to synthesize that advice before presenting the research question to the supervisor.

Synthesis. Research questions in many areas of the natural sciences require knowledge of experimental techniques and approaches in order to know that the questions are indeed testable. Three participants talked about the importance of developing those lab skills and the role that more advanced peers can play in that developmental process. Research questions can also emerge from using peers as sounding boards. In the above quotes, we saw that talking to peers is important to problem solving and defining research directions. Peer interaction, whether within the student's lab or in other labs, and across all degree and experience levels, is a resource students can use as they conceptualize and design their research. The use of this tool is valued because it facilitates the training, exposure, and modeling that the participants explicitly link to students' ability to formulate their own researchable questions.

Peer scaffolding and support are grounded in social constructivist theories of learning (Bruner, 1996; Vygotsky, 1978). Vygotsky specifically outlined the role of problem solving in collaboration with more capable peers as a means of eventually mastering tasks that initially lie beyond the learner's capacity, a concept he termed the Zone of Proximal Development. The value of peer interaction for student engagement in research is also well established in existing literature (Aulls & Shore, 2008; Donham et al., 2010; Gautier & Solomon, 2005; Todd, Bannister, & Clegg, 2004; Waite & Davis, 2006; Xia, 2013).

Examples of possible benefits of peer interaction in structured settings come from the work of several researchers (Donham et al., 2010; Gautier & Solomon, 2005; King, 1990; Waite & Davis, 2006). Waite and Davis (2006) in their action-research study asserted that the collaborative instructional format was linked to motivation for education students learning how to do research. Gautier and Solomon (2005) empirically found that high-achieving undergraduate students chose to brainstorm as a group before settling on any particular research.

Donham, Heinrich, and Botswick (2010) found that students began to articulate their research questions after considerable time and effort was invested in large and small group discussion of the observations, curiosities, other inspirations for research, or a combination of these. King (1990) found that peer interaction in groups in which instructors structured the sessions so that students were provided with generic guides to generate their own task-specific questions resulted in more critical thinking, more explanatory reasoning, and higher achievement compared to peer-interaction groups that were unstructured.

In unstructured settings, conversations with peers and professors who were not the students' advisors were noted as helpful to the process of selecting dissertation topics (Xia, 2013), and social science undergraduates described the benefits as well as the limitations of reaching out to peers during their struggle to define thesis topics (Todd et al., 2004). All of these studies stopped short of describing what mentors can do to help facilitate the kind of peer interaction that would contribute to students' abilities to find, frame, and formulate researchable questions. My study addressed this gap in knowledge by providing specific examples of the infrastructure, opportunities, and collaborative cultures that mentors can facilitate in order to develop a culture that supports the student generation of research questions. Infrastructure elements for peer support include the provision of shared lab space, encouraging students to seek out and provide peer guidance, delegating the training of new students to more senior students, and making lab staff available to students who are in the earlier stages of designing their research. Opportunities for peer interactions that contribute directly to students' ability to conceptualize and design their own research are facilitated when mentors hold group discussions on student-generated research interests and structure peer feedback sessions. From the data that emerged in Category 4 and from the previous literature, I inferred that mentors can also make their support for collaborative peer culture explicit to students by structuring guided interaction and feedback sessions. Category 4 addressed the various forms of students' exposure to peers. The next category focused on exposure to scientists, topics, tools, and techniques outside of the students' immediate lab.

Category 5: Exposure and student RQF. Exposure is defined by the *Cambridge English Dictionary* as "the conditions that make available an opportunity to learn or experience new things" ("exposure," n.d.). In my study, *exposure and student RQF* (Category 5) emerged as a group of statements that were all concerned with developing students' ability to find, frame, formulate, and refine research questions by exposing them to a variety of ideas, areas of research, and approaches. This variety may come from research partners, colleagues, collaborators, seminars, talks, or conferences. Although such exposure is already a part of the graduate experience for many students, the key thing to note is that the participants themselves made the links between these experiences and student RQF. That is, participants elaborated on the importance of exposure when asked questions that directly probed for student RQF experiences, for example, "What experiences enable students to start bringing in their own questions?" "What activities helped your students through the process of formulating their own questions?" "What aspects of their master's program contributes to their ability to formulate their own question during their PhD?"

Focused coding using the coding guide presented in Table 24 revealed that the exposure category applied to 14 of the 134 RQF segments. These 14 segments came from interviews with 11 of the 24 participants (see Table 25 for demographic details). Open coding conducted on these 14 segments produced 33 codes. Axial coding of these revealed three different types of exposure that reportedly contributed to students' ability to find inspirations for their own research questions:

- Expose students to other scientists.
- Expose students to variety through conferences and seminars.
- Expose students to other research labs.

Table 24

Coding Criteria for Exposure and Student RQF (Category 5)

Description	Inclusions and examples	Exclusions	Handle with care
This theme is about developing students' ability to find, frame, formulate, and refine research questions by exposing them to variety. This variety may include different ideas, research partners, talks, other labs, etc. Exposure is defined as "to make known or to make accessible."	Talks: The professor believes that student attendance at conferences, talks, seminars, symposiums contributes to student RQF. The professor might even invite guest speakers to come talk to the lab and have RQF-related expectations of students thereafter. Other labs or other professors: The professor sends students to other labs, other universities, other professors for exposure, variety, learning new methods, access to technology, and explicitly links these experiences to student RQF.	Statements about the importance of gaining a broad or diverse education without mentioning the contribution of this goal to developing students' ability to find, frame, and formulate researchable questions.	Statements that mention the importance of learning new lab techniques and methods, consider whether the participant connected this learning to RQF

Table 25

Demographics for Participants Coded as Exposure and Student RQF (Category 5)

Participant ID	Branch of Science	Discipline-specific identifier	Gender (for pronoun purposes)	Faculty position	Years worked as a professor	All undergraduates supervised to date	All Master's students supervised to date	All doctoral students supervised to date
3	Biology	forest ecologist	Female	Full Professor	25	30	10	3
4	Biology	molecular ecologist	Female	Associate Professor	7	10	5	1
17	Biology	molecular biologist	Male	Full Professor	13	20	5	10
8	Chemistry & Biochemistry	green chemist	Male	Full Professor	19	114	18	10
10	Chemistry & Biochemistry	analytical chemist	Male	Full Professor	30	100	25	25
12	Chemistry & Biochemistry	inorganic chemist	Male	Associate Professor	12	30	2	7
1	Other Life Sciences	cognitive neuroscientist	Male	Associate Professor	10	6	4	1
11	Other Life Sciences	biophysicist	Male	Assistant Professor	5	15	0	3
14	Other Life Sciences	comparative physiologist	Female	Assistant Professor	2	8	3	0
15	Physics	theoretical atomic physicist	Male	Associate Professor	12	5	10	6
18	Physics	geodynamicist	Male	Full Professor	15	26	6	6
24	Physics	theoretical physicist	Male	Full Professor	27	20	10	20
20	Physics	astrophysicist	Male	Full Professor	25	15	12	8
22	Physics	applied physicist	Male	Full Professor	31	39	30	41
				Averages	16.6	31.3	10.0	10.1

Exposing students to other scientists. Four participants mentioned the importance of ensuring students interact with scientists outside of their immediate lab, stating that this type of exposure enables students to contribute to and benefit from scientific dialogue. The type of dialogue that stood out from these quotes were conversations on the conceptualization and design of new research, whether it be the students' research or that of the other scientists with whom they interacted. For example, a biophysicist (Participant 11) described the process of collaboratively developing research questions. When I probed further about how students get trained on the various aspects of coming up with research questions, he further explained:

> A lot of the research question development is done in a lab meeting with input from all 14 members of the lab. . . . All three of our labs come, and from that we openly discuss all of our progress in the last week and what we need to do in the next week to ensure that progress of the research questions is addressed, and if anything needs to be modified. So with that, we have lots of input from graduate students, trainees, RAs, PIs, everything. So that's probably as useful as anything.

The research question development process described by the biophysicist is both collaborative and ongoing. Research questions get posed, their answers are pursued in subsequent investigations, but crucially, the research questions themselves are expected to change along the way. The collaborative development of research questions fits the social-constructivist idea of inquiry curriculum being co-constructed by teacher and student (Aulls & Shore, 2008).

When talking about how his PhD student formulated a research question, an astrophysicist (Participant 20) described what sounded like the student aimlessly wandering from one topic to another. After I probed about this impression, the participant corrected me and summarized the learning process as follows:

> It's not wandering, but it is sampling. It's more like sampling a series of subjects. . . . That means for instance, at our collaboration meetings, going into different sessions and listening to what your colleagues are talking about with respect to the analysis of different objects, sitting in on the conference calls, contributing when you can . . . . And you may do that for six to eight months, helping other processes progress, and going

> "Okay I can do this, but it's not really a life that's exciting for me; it's interesting but it's not where I want to do my thesis." So you move on to different topics, a slightly different group of people. You listen to their conversations and eventually you understand their issues and how you can contribute and, you know, suddenly you think, "Oh yeah, this is way more exciting for me." And so you jump in and you become one of the prime movers in that area.

In the above quote, the process of research question formulation starts with "sampling" different topics and can end with the student developing not only interest and expertise, but also making major contributions to an area of research. In all of the above quotes, students were expected to not only learn from collaborators, but to increasingly participate and contribute as well. The importance of collaboration came up frequently during interviews with scientists. A simple keyword search of the transcripts revealed that 19 of 24 interviews contained "collaborator," "collaborate," or "collaboration." Uniquely in the above two quotes, both participants made a direct link between exposure to collaborators and the students' ability to come up with their own research questions.

Whereas the above physicists talked about the importance of exposure to collaborators, two other participants mentioned exposure to top researchers. These two, a forest ecologist (Participant 3) and an inorganic chemist (Participant 12), drew from their own graduate careers when reflecting on the experiences that contributed to their ability to independently come up with research questions. For example, when asked how she developed the ability to formulate her own research questions, the ecologist shared the following:

> I wanted to ask questions [about my topic] . . . so this is the guy . . . widely recognized as one of the greatest evolutionary theorists of the 20th century . . . he advised me on . . .

> research that I did during my PhD. . . . He is basically the kind of person who is constantly asking questions. . . . I started out as an undergraduate doing field work . . . where there were constantly top global academics coming and going. So I was interacting with and having academic conversations with some of the most famous biologists in the world from the age of 19.

This participant later talked about the importance of engaging her students in the scientific community through discussion and dialogue, proactively eliciting feedback, and testing out ideas with others.

Similarly, the inorganic chemist also spoke about the influence of top researchers when asked to recall the first time that he had posed his own research question:

> Back then I decided to work on [my topic] with the leader in the field . . . and I actually suggested to [my supervisor], "Can I do an exchange . . . in her group?" And [my supervisor] was quite sympathetic, and I got a fellowship to work at that university. . . . That's how [my supervisor] helped [me] in developing my own project.

After describing his own experience, this participant made a direct link between working with other researchers, exchange programs, and student RQF:

> I've had people actually be successful on exchange fellowships, and I've seen people actually coming back and really liking it, and that doesn't necessarily mean that the country where they're doing research is better than Canada, it might be equally good or on average superior or on average inferior, it doesn't matter. If you see something different, it broadens your horizon to the degree that you have it easier to find an interesting question.

This quote is powerful in its succinct and clear articulation of a direct link between acquiring different experiences outside of the lab and finding inspiration for researchable topics.

Exposing students to variety through conferences and seminars. Five participants mentioned that sending students to conferences helps to expose students to different ideas and approaches, and that this exposure is important for developing student RQF. Some briefly mentioned conferences in response to questions on how students eventually develop the ability to find their own research questions: "Reading papers and going to conferences" (Participant 17), "internationally, going to conferences, looking at what the others are doing" (Participant 18).

Others were more explicit. For example, when asked about the kinds of things that students should be doing at these conferences, a comparative physiologist (Participant 14) replied that students should initiate conversations that use other experts as sounding boards. She continued to elaborate that students should engage the experts in the following ways:

> [students] should be talking about the difference between, sort of, a good hypothesis and not a good hypothesis. Like, "Is this hypothesis good, you think? Do you think this is interesting enough? Do you think this is a good idea?"

Similarly, an inorganic chemist (Participant 12) stated that attending seminars allows students to learn "from other students what other people find interesting." Getting a sense of what others are researching and testing out new ideas speaks to the importance of helping students learn what a field considers worthy of investigation.

An applied physicist (Participant 22) expressed a desire for his students to take their exploration one step further by describing what students should bring back from their seminars and conferences: "When they hear what somebody's doing, it can give them an idea for their own work. 'Hey, so and so said this at a seminar. Why don't we consider this problem or this approach for what we're doing?'" This idea of finding inspiration through exposure to different ideas and approaches was also present when participants talked about sending students to other labs.

Exposing students to other research labs. Four participants mentioned sending students to other labs as a means of granting them access to knowledge, resources, and facilities not available at their own labs. For example, a molecular ecologist (Participant 4) told her students, "Here is a list of collaborators that could help us get other populations and here are regions where you can go and sample." The analytical chemist (Participant 10) also described facilitating access to other labs for his students. These comments will be described in the Illustrative Cases section of the results. When asked what students should be doing with what they learn at other labs, the comparative physiologist (Participant 14) provided the following reply:

> [Students should ask] "Does anybody know anything about this? Has anybody looked at this before?" That sort of thing. . . . There's quite a lot of invertebrate physiologists here while we're a vertebrate lab. Just learning . . . what those guys are doing, and seeing if there's a chance to say, "Well, if invertebrates are doing it, you know, what would be different in a vertebrate? Would it be different? Why would it be different?"

The comparative physiologist highlighted exposure to other labs as giving students the opportunity to inquire about the originality of possible research questions. Exposure to different labs also enables students to transfer ideas and methodologies from other areas of study to their own, which could lead to new researchable questions. An inorganic chemist (Participant 12) echoed this idea of transposing learning from one lab to another:

> It's hard to explain, it's somewhat indirect, but if you see different places, it makes you better at developing independent research questions. That doesn't mean you steal questions from the other place. The best-case scenario would be more like a synthesis. Say somebody comes from an inorganic chemistry background, and they go into an environment that's more biological, they might come back with ideas that are related to, say, inorganic, and to, say, biological . . . [using] none of the tools . . . your supervisors had ever thought of. . . . My advice to students [is to] try many experiences in different groups, including different countries.

In the above quote, the chemist described how exposure to different labs enables students to integrate and synthesize ideas from disparate areas, a skill that enables them to improve upon their ability to generate their own research questions. He continued to elaborate with a specific example:

> Even if the chemistry was very related on paper, the techniques they're using are different. So there's kind of a lab culture. . . . There are at least five different ways you can have an atmosphere of dry nitrogen. You can use it in a glove box, you can use it a so-called flank line, you can use a balloon with nitrogen attached—these little things.
>
> Just [leave] one particular research group to see how is research done at different places.

According to the chemist, preferences and subcultures at different labs contribute to different interpretations and applications of techniques, but these differences are not readily apparent without firsthand experience.

Synthesis. When asked about experiences that would contribute to student RQF, the majority of participants (14 of 24) talked about the importance of ensuring student exposure to a diversity of knowledge, facilities, experts, and experiences. Examples of how their own students gained such exposure included working with collaborators, going to conferences and seminars, working in other labs, or engaging in exchange programs with professors at other universities.

Inspirations for research topics expanded when students encountered new lines of inquiry, approaches, and methodologies they could adapt from other areas. Interactions with experts who were not their supervisor gave students the opportunity to test out the popular appeal or the scientific rigor of the research questions they were formulating. The varied experiences gained through such exposure also allowed students to begin developing their identities as scientists. The mentor's efforts to facilitate such exposure included securing student access to experts, knowledge, data sets, tools, and facilities that the mentor could not provide.

The benefit of ensuring that researchers at all levels of experience are exposed to a variety of topics, media, and experts is well established in the literature. For professors, inspirations for future research came from numerous sources that included seminars, talks, conferences, and scholarly conversations with students and colleagues (Hua & Shore, 2014; Moody, Vera, Blanks, & Visscher, 1989; Shore, Pinker, & Bates, 1990). For students, conversing with scientists in informal settings such as science cafes helped undergraduates to better conceptualize research tasks (Streitweiser, Light, & Pazos, 2010). Students also benefited from consulting additional experts when formulating their research questions (Tan, 2007). Exposure to different topics, contexts, and experts is deemed important because "the learner must be able to discern aspects or dimensions of phenomena in the surrounding world by experiencing variations in these aspects or dimensions . . . without variation, there is no discernment and no learning can take place" (Dahlgren & Öberg, 2001, p. 279). Although it is not difficult to find support in literature for the general benefits of exposing students to variety, the results of my study extend this notion by providing direct, participant-generated links between such exposure and student ability to conceptualize and design research. Whereas Category 5 contained largely student-driven means of making progress on their paths toward RQF, the next category is very professor-driven and formal as the RQF learning occurs in classroom contexts.

Category 6: Professor's in-course teaching of RQF. This category was used to capture statements regarding how participants themselves explicitly taught RQF skills to a group of students in formal course or classroom settings. The teaching must have unfolded as part of a course that is delivered to more than one student (e.g., a research-methods course, an undergraduate or graduate-level seminar) to qualify as in-course teaching. Teaching that occurred in the context of courses that were taught on a one-on-one basis, such as self-directed reading, research or thesis courses, or in the context of the participant's own supervision were considered mentorship activities and therefore were not coded in Category 6. RQF strategies that unfold as a part of the typical graduate or undergraduate program, or as a part of courses that are not taught by the participants themselves, were coded as RQF development in the curriculum (Category 1).

Focused coding using the coding guide presented in Table 26 revealed that four of the 134 segments were coded as professor's in-course teaching. These were contributed by four professors: a materials chemist (Participant 21), a molecular ecologist (Participant 4), a cancer biologist (Participant 9), and a forest ecologist (Participant 3). See Table 27 for additional demographic details on these four participants. The forest ecologist shared strategies she used with her own supervisees and with students in the research methods courses that she taught. Because she was selected as an illustrative case, her strategies will be shared in the Illustrative

Cases section. Hence, only the segments from the three remaining professors will be reported in this section.

Table 26

Coding Criteria for Professor's In-course Teaching of RQF (Category 6)

Description	Inclusions and examples	Exclusions	Handle with care
Classroom teaching of RQF skills by the professors themselves. It must be something that the professor explicitly does in front of a classroom or in a seminar setting for a group of students; not for courses that are taught one-on-one with students, nor for teaching that occurs with a few students in his or her own lab. The essence of this theme is to capture RQF teaching that happens as part of courses that the professor gives to more than one student at a time. The teaching can occur through supplemental out-of-class materials, or through meeting students during office hours. It does not need to be in front of a class.	Includes: meeting with students from the course during office hours, which at times may be a one-on-one meeting. Differentiation: To distinguish between RQF development in the curriculum (Category 1) and professor's in-course teaching of RQF (Category 6): When the instructional strategy being mentioned is used by the professors themselves in their own teaching, apply Category 6. If the professor talks about teaching in the program in general (as opposed to their own teaching), apply Category 1.	• Courses that are based on mentorship, such as one-on-one directed reading courses, one-on-one independent study courses, one-on-one special project courses, etc. • Any one-on-one courses fall under mentorship and should be captured by themes such as Feasibility, scope, and specification; Literature; Exposure; Starting Point; Additional writing; Supplemental professor strategies; etc.	Not applicable.

Table 27

Demographics for Participants Coded as Professor's In-course Teaching of RQF (Category 6)

Participant ID	Branch of science	Discipline-specific identifier	Gender (for pronoun purposes)	Faculty position	Years worked as a professor	All undergraduates supervised to date	All Master's students supervised to date	All doctoral students supervised to date
4	Biology	molecular ecologist	Female	Associate Professor	7	10	5	1
9	Biology	cancer biologist	Male	Full Professor	24	50	14	11
21	Chemistry & Biochemistry	materials chemist	Male	Full Professor	30	20	6	12
				Averages	20.3	26.7	8.3	8.0

Cultivating creativity that transforms into research questions (graduate chemistry course). A materials chemist (Participant 21) talked about the importance of developing creativity and critical questioning skills because he believed these are essential to problem solving in chemistry. The area of chemistry in which he worked was applied, and research questions were problems that needed to be solved through the development of substances or techniques to create such substances. However, the participant felt that the importance of creativity was not reflected in the way chemistry was being taught:

> We don't do [anything] in our training to develop techniques for students to be creative. . . . Chemistry is more creative than physics, more than biology, etc. And this creativity—chemistry, the way we teach it, it's the most boring way. And I don't understand why . . . we don't manage to put some creativity in the way we teach chemistry, and we just teach chemistry as [if] it's something to just memorize. . . . We, as chemists, suck at teaching chemistry.

The chemist then went on to describe an exercise he did in class with his graduate students to develop creativity:

> Something I did [was] . . . functional analysis. . . . I said, "In a sense you have to look beyond the battery itself. If you look at the batteries—what is the purpose of a battery? [It is for storing] some energy that can [be] transported . . . and delivered. So the function of the battery [is] . . . transportable energy storage. It's not about electricity. So we could say that one option would be [to] build a micro- or nano-nuclear reactor . . . [that you could] have in your car." The example [depends on describing] the functions . . . and [asking], "what are the connections between the components?" And you could, in your process maybe, say, "okay, I could change this component." . . . [I had my students] use a mind concept map . . . and say, "what is important is not the component, but the component and the relation here between the component[s]. So you take a chemical synthesis and you convert it into a concept map, you plot the connection." . . . There are different models in your synthesis, you must prepare that, and you must filter it, you must

> add your solvent, you must heat, you must mix. And by doing that you can see where . . . you should look.

The critical thinking and creativity required involved understanding not only the desired outcome but the components of the problem, and how these components were connected to each other. Concept mapping was then used to identify the chemical components and relationships between the components that could be manipulated in order to achieve the desired outcome. Through these exercises, the chemist prepared his students to use the same techniques in their search for research questions. The students were then able to convert real-world problems into research questions in materials chemistry. The chemist then elaborated further with another concrete example:

> I wish we could do it much more. I did it in the class with PhD and master's students actually, where I asked them to develop this functional analysis with different things . . . I want to show them that you can take any problem. So the first thing was about . . . the wrinkle. . . . One thing in cosmetics is to get rid of them. And what does it mean to get rid of them? Is it to get rid of them or is it that people won't see them? . . . You have to redefine the problem . . . . Do you want to get rid of them or do you just want to make them more discreet? [This] is actually a very big issue in cosmetic industry. It's not a dream, it's a realistic issue because you will [have to find] ways [to address the wrinkles]. Either you will fill them with something, like you will inject something . . . or you will create [a cream] that will reduce the reflection of things. . . . So this is a type of example where I say, "if you get rid of them it's not the correct description of the problem. The problem is not to get rid of them, it's that you, yourself, or others, won't see them as much."

The above example illustrates the participant's point that the manner in which a problem is understood and described affects the nature of the research that is pursued thereafter. He later explained that his subdiscipline uses an inter- and transdisciplinary approach in the chemical sciences, wherein both general chemistry and the physical chemistry of complex fluids are combined to design advanced functional materials. In a classroom context, students began to practice using functional analysis on problems ranging from how to make a baby laugh to how to build an igloo in Africa. Regardless of how the question is framed, an applied problem is still not a research question in this area of chemistry until the technical characteristics of the problem are included in the question itself. Therefore, the materials chemist's students were taught how to perform a functional analysis of the problem in order to formulate a researchable question for the chemical synthesis of materials.

Requiring novel and original research questions (graduate ecology seminar). A molecular ecologist (Participant 4) described a course in which she made RQF part of the course requirements for a 500-level (combined senior undergraduate and first year graduate) seminar. The topic arose when she was asked about the advice that should be contained in a guide to help students in her discipline with generating their own research questions: "With the class that I am now coordinating where I ask students to come up with a research question and a research project, I encourage students to think about the topics that fascinate them." Not only did the molecular ecologist require the student to pursue original research, she emphasized the importance of their authentic interest in the topic. The following three quotes have been gathered together to form a single excerpt because they illustrate her rationale for requiring novelty from her students:

> If you push them [toward finding something new], they have to explain why that is new, so they have to make sure that . . . they don't replicate, and in doing that, they have to do quite a bit of reading // [a] question that is not well-formulated . . . generally indicates that the student is unclear about the technique or what they can do with the particular technique, so they have a question that cannot be answered with that particular technique that they proposed . . . I have to generally figure out what it is that they don't understand // and when we think that it's not feasible, we want to make sure that the student did . . . the background work.

Demonstrated in this above spliced segment is the idea of using novel research question formulation to ensure that students read the literature and understand the techniques. Poorly formulated questions can highlight gaps in student knowledge, gaps in student understanding, or a failure to do the legwork necessary to know what methods are appropriate. The segment also suggested that the participant's area of study considers the selected technique to be part of the research question itself (without which there is no tractable research question). The molecular ecologist continued by sharing the first submission that is required of the students:

> The first thing we ask them to provide [is] a very brief report. Like half a page, not more, because I think with that, we can get a sense of the direction that they want to take, if they manage to formulate a question. We are actually surprised that most of the questions are quite elegant, quite advanced.

She then talked about the importance of formal deadlines and ungraded formative feedback:

> To encourage them, I don't grade each proposal. I tell them that they did it for their own benefit. . . . As early as they are ready, they can submit it. That helps them, but then we have a deadline, too, and I encourage them to send it to us, we read it . . . we go over and

> provide comments like, "the research question is not well-formulated," or "the topic that you selected is too close to your PhD topic." You don't want them to replicate something that is already part of their thesis.

Feedback in the earlier stages helps with the direction of the students' projects. The following spliced segment illustrates how ongoing feedback helps students determine the feasibility and scope of their research questions:

> Sometimes we have to just remind them that this is just a course and [they] can't [do] all that, because they come up with questions that look like studies that you will want to publish. // Some of the questions are actually . . . quite ambitious. // Or, "this might not be feasible," and then we try to give them direction: "Did you consider trying only this aspect, or did you consider . . . ?"

The above segment illustrates that the role of the professor is to help students to gauge what is realistic and doable within the time constraints, as well as to give suggestions for alternative options.

Students are also encouraged to participate in research question formulation on a smaller scale in the following way:

> We also encourage them to implement in this research project things that they learned in our class, because we have a lab that is incorporated in this class, and we run a series of lab exercises that demonstrate how you go in these databases, how you download data, how you analyse data, what type of questions you can now ask. So the lab is part of the class, and then we ask them to pick one of those questions and pick one of those approaches and do their own research . . . take it a little bit farther. . . . There are some other projects where there is no question, so students want to do something because they

> want to, like, "I would like to work with that type of data because I need bioinformatic expertise in that particular technique." "Okay, that's fine, so I will download that data set and do the filtering steps and the analytical steps, but you have to come up with a question. You have to ask a question that is different of the question of the original author. You have to do something else."

The above quote describes one approach that requires students to find a research question and another approach from a database and a set of procedures that have already been defined in advance. Although the set of possible research questions has been narrowed, the professor emphasized that the requirement remained to generate an original question. This requirement appeared throughout the participant's description of the course and was seen as key to ensuring students read the literature and understand the techniques.

Generally, students must start by finding areas of genuine interest, contextualizing their interest in an understanding of the boundaries of current knowledge and the tools available for pushing those boundaries to uncover new knowledge. Students are free to find, frame, and formulate their own questions based on their interests or a question that can be answered using a data set given by the instructor. This data set allows the instructor to scaffold the steps and model the procedures. The role of the professor is to help the students determine the feasibility, scope, and direction of their research questions while reiterating expectation that the research question is a novel and original one. Early and frequent feedback allows the professor to identify misconceptions, gaps in understanding, and failure to read the literature. Feedback that is ungraded may also play a role in encouraging students, according to this participant.

Writing assignments to contextualize findings and generate new research directions

(graduate biology seminar). A cancer biologist (Participant 9) described a course in which graduate students were taught to generate new research by completing a set of writing assignments. He introduced this course as follows:

> When I took over the graduate program in my department 10 or 11 years ago, I guess, as director, I implemented a new course, and the course was really designed to help people formulate research questions . . . and develop critical learning—critical thinking skills.

The central set of writing assignments for this course was inspired by an article format that the cancer biologist described as follows:

> A lot of journals—scientific journals have emulated this approach in recent years, but I think *Nature* was the first to do it. . . . When some important publication gets submitted . . . the editors—they decide, "OK, this is the greatest thing since sliced bread, this is really moving the field forward" . . . And then very often what they do is they ask one of the reviewers of the manuscript to write a "News and Views" [article] about it. The reason that they ask that reviewer is presumably they are experts in the field. . . . They would have a good appreciation of how that paper has moved the field forward.

According to the participant, "News and Views" are brief articles authored by an unbiased expert reviewer, explaining the significance of a groundbreaking study conducted by other scientists. The participant required students in his class to write three such articles. Below is the participant's rationale for requiring the graduate students in his seminar to complete these writing assignments:

> So I get our students to start right at the beginning of their program with papers that are relevant to what they're going to be doing—hopefully, [for] their PhD . . . and I get them to write a "News and Views" about it. And they become the experts—so they're

challenged to actually become—and you don't expect them to become an expert overnight on it. . . . I get them to do three of them over the course of two semesters. . . . And they get feedback from me and from other faculty, and their supervisor—but by the end of that process, they hopefully will have built a bibliography in the area that included several hundred papers, presumably. So that first paper is just sort of a jumping-off point. They presumably have to read several other papers to even be able to write that "News and Views," and then sort of a spider web from there, they have to go back—so it gives them a way of building that foundational knowledge, but also open up in different areas to try and understand what are the most important, innovative, perhaps controversial areas in the field, and get up to a point where, within a couple of semesters, they can engage their supervisor in a conversation where they're not just listening and doing what they're told to do. They actually know enough about it that they can start to have a rapport, and they can start to intellectually contribute to design and talk about the design of experimental questions. So what we want them to do is to develop the knowledge, but also the confidence, to be able to do that. And so that's an important aspect of them being able to, in the final stages, to develop a research project. So they do three "News and Views" essays, but then they write a research proposal. And so that's the hypothesis, experimental aims, approaches, and then, you know, significance, rationale—all that sort of stuff. And that's a very common format for university courses nowadays in a lot of areas, because we all realize, "yep, if you're going to stay in this field, you're going to have to be able to apply for money." And that's the format of a grant application.

This above text was included in its entirety to illustrate how the participant himself made clear, coherent, and direct links between the writing assignments and student ability to generate research questions (only two ellipses were used to replace a few redundant words that interfered with the readability of the text). These links will be summarized shortly. For now, I would like to note that the biologist also described the structure of the "News and Views" articles in another segment of the interview that was 1100 words in length. He mentioned that each section of a typical "News and Views" article serves an objective. Using this participant's words, I was able to infer implicit learning outcomes for the assignment. Those outcomes, along with the participant words from which I inferred them, and an illustrative example taken from an actual "News and Views" publication, are shared in Table 28.

The participant used the words "hopefully" and "presumably" twice in this 370 word segment. This stood out because it suggested that there is a level of difficulty involved in the task of bringing students up to high level of expertise on the topic within only two semesters. His decision to involve the students' supervisors and other professors in giving feedback on such articles seems wise because it might be difficult for a single instructor to evaluate the extent to which all the graduate students in a class have mastered content that falls outside of the instructor's area of expertise.

Table 28

A Cancer Biologist's In-course Instructional Strategy Inspired by the Nature Journal's "News and Views" Articles

Section of News and Views article	Purpose of the section of the News and Views article (and by extension … the implicit learning outcome achieved by students who successfully write a News and Views article)	Participant quote [Cancer biologist (9)]	Illustrative example from one randomly selected "News and Views" article (Snowden & Janssen, 2016)
First three sentences	To summarize the article and entice reader interest.	go and read some of these News and Views . . . you communicate in the first three sentences or so—kind of like the beginning of a New York Times article—. . . what the story is. . . . That's why I say go look at the New York Times, assuming they're good writers . . . and it's in the title, and they read that first paragraph, and they know what it's about. So, okay, the greatest thing in electrophysiology this year is this thing. And if they're more interested, they go further.	A receptor and its associated hormone are often thought of as a lock and key, in which the hormone key fits perfectly into the receptor lock, leading to a biological response — with the key ultimately being released intact from the receptor. [The two papers described in this article] show that the reality is different for [the phenomenon] . . . This triggers a dramatic change in . . .
Background	To contextualize the study within existing and important gaps in knowledge, gaps that render the study groundbreaking.	The format after that is to dig a little bit deeper, to set the background stage . . . [for] why is this an important area, or why is this paper so important and innovative, why has it changed the way we look at things?	Strigolactones regulate aspects of plant development such as the growth of branches and the programmed death of leaves . . . [it is] one of the fastest known enzymes . . . [but] is unusual in that it acts both as a receptor and as an enzyme . . . Even stranger, the rate [related to the receptor] is very slow . . .
Findings	To summarize the accomplishment achieved by the results of the study and how it was achieved.	And then they may spend a little bit of time drilling down into very specific things they show in the paper, but generally they don't get too much into the micro-details of it, because it's meant to be a more general description of the work.	The authors accomplished the difficult task of solving the [problem] . . . which is important because [of a related phenomenon]. . . . The greatest surprise is [discovery x], because . . .
Critical assessment	To evaluate the strengths, weaknesses and importance of the work in order to identify the gaps in knowledge that remain in spite of this study.	But the real important part of these things is after that. It's when those guys critically assess it, and they really tell the reader what's good or bad about it, and . . . At this stage, why it's important . . .	Although these studies answer some questions . . . they also raise new questions. We do not yet know the sequence in which [steps in the plant process happen] . . . Nor is it known whether [phenomenon y is related to x] . . . In particular, does it involve linkage of [discovery x, phenomenon y and something else]? We also do not know . . .
Directions for future research	To generate future research directions and "if statements" that speculate on possible discoveries should these directions be pursued.	And then usually they finish with something about, "Okay, where do we go from here?" . . . And what's the significance of that? And that will include things like, "If this is true, if these findings are true and are validated by independent work, then what does it mean?" It means we oughta do this, and this. . . . So the flashlight gets pointed over there now, instead, because of what they show.	A broader question is how does the [phenomenon appear in the larger system] . . . Has this mode of receptor action evolved to cope with [phenomenon y] . . . Only time will tell if [the author's method can be successfully applied to improve our understanding of topic z] . . .

Synthesis. In-course teaching is the only category that illustrated how professors bring together a set of strategies in the single learning context of a course. The instructional approaches to developing student RQF included isolated strategies for transforming real-world problems into scientifically testable topics (functional analysis in chemistry), developing and answering original questions for real data (the ecology seminar project), and writing assignments that involved synthesizing literature concisely, comprehensively, and accessibly (the News and Views article in biology).

Using functional analysis and concept mapping, the materials chemist taught students how to examine a topic from different angles, because the manner in which one frames a problem affects the nature of the inquiry that can be pursued thereafter. Students then structured the problem as a question that could be researched in materials chemistry. The molecular ecologist engaged her students in the scholarly processes of reading the literature, learning the techniques, finding areas of genuine curiosity, and then justifying the scholarly pursuit of these curiosities by identifying gaps in knowledge. The cancer biologist developed students' ability to contextualize a study in the literature, as well as to understand, synthesize, and communicate that literature. The participant had his students practice this skillset by writing three accessible summary articles before proposing their own research question.

The materials chemist and molecular ecologist engaged in continual questioning to help students uncover unaddressed assumptions or misconceptions in their thinking. These two participants made their tacit discipline-specific knowledge explicit to their students by scaffolding and modeled the process of finding, framing, and formulating researchable questions or future research directions. All three participants created the context for students to explore their personal interests, and nudged that exploration towards the search for relevance, be that an applied interest, a personal interest, or the broader implication of a particular investigation on a field. By the end of their course, these participants expected their students to gain extensive practice with delimiting and (re)defining a problem as a research question.

My findings converged with in-class approaches for developing RQF found in the literature. Features shared across previous studies include providing iterative feedback, directing students to pursue topics of genuine interest, training students in the use of subject-specific tools for problematizing a concern, and an emphasis on generating novel research questions (Donham et al., 2010; Lundstrom & Shrode, 2013; Marbach-Ad & Sokolove, 2000; Strangman & Knowles, 2012). The in-course efforts to develop student RQF in this existing literature tended to unfold over a single semester while the assignments described in my study spanned more than one semester or trickled into graduate students' overall research interests to be pursued after the course. Some of my findings add to this existing literature by laying out a clear path toward developing scholarly expertise; one that includes in-class assignments, mentorship, and graduate program components.

The previous literature also focused on developing student skills through assignments such as using taxonomies describing different types of research questions (Donham et al., 2010), brainstorming activities (Strangman & Knowles, 2012), and take-home exercises in which students self-generated research questions to be discussed within peer groups (Marbach-Ad & Sokolove, 2000)—tasks that were divorced from the tasks frequently undertaken by mature researchers. Conversely, the participants in my study structured the course assignments to mirror authentic scholarly tasks: Student proposal formats were structured like grant proposals, written assignments were structured in the format used by leading publications, participants required feedback to be integrated from multiple experts (not just the instructor or peers). These differences between my findings and those from the existing literature cited here may lie in the fact that the majority of studies on RQF found by my literature review were conducted at the undergraduate level across multiple subject areas whereas all of my participants are speaking about RQF experiences in the natural sciences, and most often, they are sharing experiences with senior undergraduate or graduate-level students.

Professor's in-course teaching of RQF (Category 6) was concerned with RQF instruction that occurred in a classroom context with one instructor and multiple students. The next category will discuss activities that occurred in a more individualized, one-on-one mentorship context.

Category 7: Feasibility, scope, and specification. This theme is about the professor's role in helping students understand the parameters and constraints of a research topic by helping the professor specify the project details, scope, and boundaries. Included are statements about how professors help students render projects more doable within assigned time frames and with the available tools, technology, and methodologies.

Focused coding using the coding guide presented in Table 29 revealed that *feasibility, scope, and specification* (Category 7) applied to 15 of the 134 RQF segments (11% of the extracted set of RQF segments). These 15 segments came from interviews with 10 of the selected participants (41% of the 24). See Table 30 for demographic details on these participants. The challenge of ensuring that research questions are scientifically testable and interesting, as well as feasible and tractable arose in nearly every interview. What differentiated the 10 participant transcripts coded with Category 7 was the fact that these participants discussed the challenge in the context of teaching, learning, and mentorship strategies for students. Selected quotes from this group of 10 participants will be shared in the upcoming subsections to highlight specific, concrete, or observable actions of the mentors as they helped students through the challenge of determining the feasibility, specification, and scope of their research questions. For reporting purposes, these segments were organized into three sections—the first two are recurring themes, while the third presents a single segment that merited independent description:

- Directing students away from the abstract toward the actionable.

- Directing students toward parameter specification.
- Questioning and listening.

Table 29

Coding Criteria for Feasibility, Scope, and Specification (Category 7)

Description	Inclusions and examples	Exclusions	Handle with care
These statements outline the professor's role in helping the student understand research question parameters, methodological constraints, how to focus on the specific, and how to specify the details of the project.	Statements that refer to a professor's role in: • Helping the student make his or her project more doable. • Helping students to specify the details of their project. • Students meeting deadlines when it comes to finding, framing, formulating, and reformulating research questions.	Statements about how to meet deadlines in general (that are not specific to the finding, framing, formulating, and reformulating of research questions).	Not applicable.

Table 30

Demographics for Participants Coded as Feasibility, Scope, and Specification (Category 7)

Participant ID	Branch of science	Discipline-specific identifier	Gender (for pronoun purposes)	Faculty position	Years worked as a professor	All undergraduates supervised to date	All Master's students supervised to date	All doctoral students supervised to date
10	Chemistry & Biochemistry	analytical chemist	Male	Full Professor	30	100	25	25
12	Chemistry & Biochemistry	inorganic chemist	Male	Associate Professor	12	30	2	7
21	Chemistry & Biochemistry	materials chemist	Male	Full Professor	30	20	6	12
1	Other Life Sciences	cognitive neuroscientist	Male	Associate Professor	10	6	4	1
11	Other Life Sciences	biophysicist	Male	Assistant Professor	5	15	0	3
13	Other Life Sciences	neurophysiologist	Male	Assistant Professor	1	4	0	0
14	Other Life Sciences	comparative physiologist	Female	Assistant Professor	2	8	3	0
18	Physics	geodynamicist	Male	Full Professor	15	26	6	6
24	Physics	theoretical physicist	Male	Full Professor	27	20	10	20
19	Physics	materials physicist	Male	Full Professor	15	20	10	12
				Averages	14.7	24.9	6.6	8.6

Directing student attention toward the actionable. Three quotes stand out for describing how participants directed student attention away from brainstorming and toward actions that were concrete and immediately executable. For example, an analytical chemist (Participant 10) said, “the thesis to me is the vision of the program. The chapters in the thesis are the projects. And so what we do is we steer away from the program to a project, to get [the students] going.” A neurophysiologist (Participant 13) drew from his own graduate experience to describe how novice enthusiasm can lead to a proliferation of research possibilities:

> I did this as a grad student and postdoc as well, you sort of come with a very broad idea . . . You’re tying in so many different things, you’re very excited about it, so you’re like, “it’s this, and it’s that, and it’s this.”

He then shared an example of how he helped his student move from the abstract to the specific:

> So, broadly, he was interested in multisensory integration. So, how does the brain combine multiple senses into unified representations? And our initial conversations were . . . high-level: “What does this mean in terms of our actual subjective experience of the world?” Like, how is multisensory integration important, etc. And then it was initially me starting to provide him with papers and readings to learn more about what is known about it on the neurophysiological level.

Because the neurophysiologist used this sharing of specific articles to direct the student’s attention toward the task of identifying specific gaps in knowledge, the segment was also coded as literature.

A cognitive neuroscientist (Participant 1) described having similar conversations with his own student:

> There are so many different ways to develop this population-receptive field technique, and so many different ways it could be applied, and so many different ideas. Like, you have to say, “OK, you need to concentrate on doing a small number of things for your

> dissertation, like, OK, let's do this, this, and this." It's straightforward and feasible and you can get it done in year two, something like that. And there's often some directing like that.

The neuroscientist helped his student move away from being overwhelmed by the vast range of possible projects toward a limited number of clear and achievable tasks that would contribute to the timely completion of the degree. As with the previous two participants, the supervisor played a very directive role in guiding the student toward concrete, actionable steps.

Directing students toward parameter-specification. Segments from two participants stood out as descriptions of how the professor outlined and modeled the process of laying out the details of a research question. A theoretical physicist (Participant 24) described helping his student set up a problem in order to turn an ambitious research question into something more tractable:

> So, there was an overriding, very ambitious question, namely, "can you avoid the Big Bang singularity by using one of the main advances in superstring theory?" . . . It's a very ambitious question. Now, we—as a first step—we decided, let's do it a little bit less ambitious . . . . Let's try to only look at small fluctuations about something that's homogeneous and isotropic. . . . So that's already a little bit more manageable. And then the question was, how do we set up the problem? And the problem is—it's identifying the different steps. And then each step has some complications. And then some steps can only be done approximately, so you have to learn how to do an approximate analysis.

In the above quote, the theoretical physicist suggested a very specific subquestion that fell within the student's broader question, and guided the student in creating a plan that anticipated possible complications along the way. The above segment continued as follows:

> The only problems that you can solve exactly mathematically [in my field] are uninteresting, simple problems. So the challenge is to develop an approximation which is realistic and treatable. And that's an art which students in my field need to learn.

In other words, good research questions in theoretical physics depend on "approximations." Students need to learn how to use approximations in order to transform problems into researchable questions. The mentor's role during this process was to reduce the enormous scope and ambitiousness of the project by proposing smaller subquestions to help the student identify procedures, to anticipate possible complications, and finally to ensure that the student knows the subject-specific tools, techniques, or approaches for framing the research question.

In this next segment, a materials chemist (Participant 21) similarly outlined for his student what is required to set up and define a researchable problem in chemistry:

> What is important is to define the problem, to define the field of our test, so the parameters, to set the parameters, and to ask the good question. . . . Probably a good question would be "What is the nature of the particle? What is the crystal state of the particle? What is the size of the particles?" And for me these are the questions . . . something I keep repeating to students in lab and in class: "A description in science means quantitative." . . . So, if you have the good question, you define your stuff and you say, "these are the parameters for my synthesis, and these are the features I should look at to be able to describe and after to identify which technique you will have." . . . I don't want them just to play with the toy and equipment because the machine is in the lab. I want them to plan. . . . The other thing I want is for them to be creative, to have ideas, to say, "why not? [What would happen] if I would try this or that?" Because this is the driving force for research. . . . And the third one will be

> that define within the constraints of the equipment access, and [within the] time frame, [what] would be the priority. So I would say—define. On one side being creative, hav[ing] ideas, after defin[ing] what should be the work plan, and being able to decide whether they should keep going on or whether they should stop it because they don't have time for that.

The materials chemist used a set of questions that required students to describe and quantify a researchable problem. He described three things that he wanted from his students: (a) a detailed, quantitative description of the problem; (b) a plan that shows elements of creativity; and (c) exploration and consideration of constraints, contingencies, and end points. He noted how the level of directiveness in his approach would depend on the ability level of the student:

> [I] say, "OK, you cannot explore hundreds of parameters, you cannot make thousands of samples. So we have to refine it." This is where I'm supposed to be able to help them in the best-case scenario. In the worst-case scenario I just tell the student, "do this and do that."

The above quotes from the theoretical physicist and materials chemist are similar to those in the first section in that participants directed students' attention toward the actionable. In addition, these two quotes specified the parameters required to transform a topic into a researchable question.

Questioning and listening. One participant, a geodynamicist (Participant 18), reported questioning and probing her students' projects to help evaluate their feasibility. She started by explaining how students were encouraged to brainstorm and pursue innovative ideas:

> In engineering they have to do this capstone project which is something . . . innovative . . . So they come up with some kind of very crazy areas. Saying, "Can I do this? Can I do

> that?" I say "Sure" because I want to let them, you know, find out or imagine new situations like in engineering. // The weakness is, I think, they don't actually see the implications of what it takes to complete such a project right. And their enthusiasm prevails in that, "Oh, I want to do this," but they cannot size up the difficulties, the challenges that this task may involve.

When asked what she does to help her students improve the initial research questions or objectives proposed in their undergraduate capstone projects, the geodynamicist replied:

> My approach is to question things. In other words . . . I don't jump into criticizing or critiquing what somebody tells me. I say, "OK, why are you saying this? Can you give me some more information about this? Why did you think about this? How did that come about?" Listen, and so by probing this way, I give them the opportunity to really explain further how they thought about it, and what they believe can be thought about it. . . . [Then students] usually discover what the weakness was, and then I start mildly putting it in front of them saying, "OK, you said you wanted to do this; now do you know how that is going to be done?" or "do you know how difficult that will be?" . . . And so forth, rather than saying, "oh, that cannot be done," or "it's too different," or "I don't do that."

By using questions, the geodynamicist created opportunities for students to reflect and identify weaknesses in their thinking. This less didactic approach set the geodynamicist apart from the other participants in this category. Specifically, the geodynamicist was the only participant to emphasize the importance of probing and listening carefully to the student in order to hone in on gaps in the student's own understanding of the research project. Especially consider these words: "I don't jump into criticizing or critiquing." Telling the student that something cannot be done falls well within the purview of a research supervisor, yet the geodynamicist made a point of scaffolding the process of considering constraints in a supportive and encouraging manner.

Synthesis. Three strategies were identified for helping students specify and define the feasibility and scope of their research questions: (a) Directing students away from the abstract toward the actionable, (b) directing students toward parameter-specification, and (c) questioning and listening.

The first strategy involved directing students' exploration toward inquiries that were more appropriate to the skill level, time, and resources of the student. The three professors espousing this strategy offered smaller, more feasible questions that fell within the student's broader interests. For the second strategy, two professors helped students learn to evaluate the tractability of their research questions by having them anticipate and plan for possible difficulties and constraints. The last participant asked students to explain the reasoning behind their research questions as the professor probed for details, gaps in their knowledge, and unsupported assumptions. By deliberately holding back on criticism, the professor guided the students toward uncovering the weaknesses in their research question on their own.

All three strategies were meant to keep novices from floundering amidst endless possibilities by enabling them to benefit from the expertise and experience of their supervisors. Additionally, participants included in this category reportedly trained students to use subject-specific tools for transforming research topics into research questions.

These findings converged with those of previous studies in that novice and intermediate researchers need support in focusing their broad initial ideas. Dissertation advisors have stated that the specification of the research question is one of the most challenging aspects of the thesis for undergraduate students in the social sciences (Todd et al., 2004). Clinicians learning how to do research also benefit from consulting with more senior researchers and research supervisors when narrowing the scope of their inquiry (Bragge, 2010). Lundstrom and Shrode's (2013) study of undergraduate research noted students' appreciation of an instructor's overall level of supportiveness, availability, and encouragement as they selected and refined their research topics. Although previous literature noted that mentors play an important role in helping students assess the feasibility of their projects, it stopped short of sharing what mentors actually do within these roles. The present results extend the literature by identifying a set of specific actions reportedly in use by mentors to help students define the scope and details of their research question. In sum, feasibility, scope, and specification (Category 7) encompassed a relatively broad range of mentor strategies. The next category offers a narrower view because it centers on a single student activity: the presentation of research questions.

Category 8: Presenting research questions. The act of articulating and sharing one's research questions, especially while the study is still being designed, allows a researcher to elicit feedback. Such feedback can help a researcher to improve his or her research questions, to clarify the research focus, to highlight possible weaknesses and unsupported assumptions, or to identify new research directions. RQF development in the curriculum (Category 1) and peer interaction (Category 4) also mentioned the importance of eliciting peer feedback. However, unlike these two categories, segments coded with *presenting research questions* (Category 8) involved student presentations in more formal or unfamiliar contexts such as conferences. Category 8 also intersects with exposure (Category 5) in that quotes from both categories placed value on exposing students to presentations by researchers outside of their own lab. However, presenting RQs is unique in that it requires the students themselves to be the presenters so that they can benefit from the new perspectives that emerge from the process of preparing and delivering presentations.

Focused coding using the coding guide presented in Table 31 revealed that Category 8 applied to seven of the 134 RQF segments (5%). These segments were provided by six participants (25%; see Table 32 for demographic details), all of whom talked about the role of student research question presentations in developing RQF. Open coding conducted on these segments produced 11 codes representing main ideas within the category. These 11 codes could not be reliably organized into recurring subthemes because the Axial coding process did not identify enough recurring ideas to facilitate such organization. When searching for the most illustrative quotes to report within this category, I found that some of the quotes had already been earmarked for sharing in other sections of the Results chapter (e.g., in the Illustrative cases section). The quotes that remained to be shared in this category were those that highlighted participant explanations of how the activity of presenting one's own research questions contributed to students' ability to conceptualize and design research. These quotes will be reported in the following three subsections:

- Graduate conference presentations enable students to elicit feedback (molecular ecologist, 4).
- Graduate conference presentations facilitate peer modeling and critical thinking (theoretical atomic physicist, 15).
- Preparing and delivering presentations can provide leads for research questions (applied physicist, 22).

Table 31

Coding Guide for Presenting Research Questions (Category 8)

Description	Inclusions and examples	Exclusions	Handle with care
Student presentations of researchable topics and researchable questions to the lab, to other people, or to the supervisor, prior to conducting their study. We are searching for examples of students sharing questions that they have to some extent developed. The purpose of this sharing is to elicit feedback (from anyone) that can help them to improve their research questions, to clarify their focus, and to identify possible weaknesses and unsupported assumptions in these questions.	• Presentation as a way of learning to articulate your topic, its importance, the why and how behind what you are doing, • Presenting your topic to your lab or peers so that you can defend it. This includes all FOCI terms used during the conceptualization phases of research: research questions/ research topics/ hypotheses (before testing them).	• Presentations done as part of program requirements should be coded as Programming instead. • Presentations of results should be excluded, as then the research study has already been framed and the question already formulated. • Informal discussions about more generalized research ideas and possibilities, like possible research topics that are still in their early stages. These should be coded as interaction instead.	Students sharing more general research interests or possible topics does not capture the essence of this theme and thus needs to be treated on a case-by-case basis.

Table 32

Demographics for Participants Coded as Presenting Research Questions (Category 8)

Participant ID	Branch of science	Discipline-specific identifier	Gender (for pronoun purposes)	Faculty position	Years worked as a professor	All undergraduates supervised to date	All Master's students supervised to date	All doctoral students supervised to date
3	Biology	forest ecologist	Female	Full Professor	25	30	10	3
4	Biology	molecular ecologist	Female	Associate Professor	7	10	5	1
9	Biology	cancer biologist	Male	Full Professor	24	50	14	11
12	Chemistry & Biochemistry	inorganic chemist	Male	Associate Professor	12	30	2	7
15	Physics	theoretical atomic physicist	Male	Associate Professor	12	5	10	6
22	Physics	applied physicist	Male	Full Professor	31	39	30	41
				Averages	18.5	27.3	11.8	11.5

Graduate conference presentations enable students to elicit feedback. When asked what would happen to her students if they did not have her supervision during their process of formulating research questions, a molecular ecologist (Participant 4) replied, “I don’t think that much would [change] . . . graduate students come [to] large meetings and present their plan and present their ideas and they get a lot of feedback from each other." Although this participant minimized the importance of supervision to the process of finding, framing, and formulating one's own questions, she highlighted the importance of peer feedback and suggested that presentations are a good way to elicit that feedback.

An inorganic chemist (Participant 12) also outlined the value of having students plan, write, and present proposals. His views are shared in the RQF development in the curriculum (Category 1) because he referred to presentations given in seminars that were part of the doctoral curriculum. Four other participants mentioned having students elicit peer feedback through presentations of student research projects that were in progress or completed (forest ecologist, Participant 3; analytical chemist, Participant 10; theoretical atomic physicist, Participant 15; applied physicist, Participant 22). These four segments were not considered examples of the Category 8 because this category requires that the research question is still being formulated, and the study had not yet been conducted. From the initial planning and proposing stages, to later stages at which students are presenting preliminary results, participants expressed that it is important for students to elicit and receive feedback on their work.

Graduate conference presentations facilitate peer modeling and critical thinking. A theoretical atomic physicist (Participant 15) also spoke about graduate student conferences when asked about experiences that contribute to students' ability to come up with their own questions:

> Here at [this university], in the physics department, [there is] something like a graduate student conference that takes place every year. The idea is that they give presentations about their research, but basically it's from the grad students for the grad students. And I think that's a very good thing, where the grad students see what is it that the others are doing, what questions are they tackling. And that helps, I think, to become a bit more

> critical about all these things. I think that's something important. Interaction with peers, not just with a supervisor, but also with peers.

The above quote, multicoded as peer interaction and presenting RQs, described how presentations facilitate peer exchanges that expose students to other examples of research questions and help them more critically assess the merits and faults of research.

Preparing and delivering presentations can provide leads for research questions. An applied physicist (Participant 22) discussed the importance of eliciting different perspectives by preparing and presenting one's research. When asked about how students can formulate their own research questions, he described four ways. The first three were learning about different content and techniques outside of one's lab or field and bringing these ideas back to the research group (exposure), persisting in the face of difficulties to identify contradictions in thinking (comments and expectations), and finding new ways to do calculations and apply theories (comments and expectations). He then added:

> A fourth one, when you actually present your work to other people. And often . . . you understand something one way when you do a calculation, but you understand it in a very different way when you have to present it to somebody else. And so . . . students generate their own ideas by going through the exercise of presenting their work to a new audience. . . . I encourage them to rehearse by themselves, and then when they present to the group, that's sort of a rehearsal for when they present to a conference . . . what I've found is . . . in the course of preparing seminars—it forces [students] to think about what they were doing in a different way, and can sometimes raise new research ideas or new questions.

The above quote illustrates how the act of preparing to present research questions and the presentation itself contributed to student RQF by exposing students to perspectives that could yield leads for future research questions. A cancer biologist (Participant 9) also mentioned that new research questions can emerge when students are presenting their studies or sharing their data as it is being collected (this quote was shared in the section on peer interaction).

Synthesis. The presentations mentioned in this code are largely optional ones, such as those given at graduate student conferences. Throughout the quotes, there was an emphasis on organizing and communicating one's ideas, plans, and preliminary results. The student outcomes valued by the participants were the abilities to clearly articulate one's research, to see the articulated research questions of others, to elicit feedback, and to engage in discourse.

These results converge with those from Seymour, Hunter, Laursen, and DeAntoni's (2004) study of undergraduate science and engineering students' independent research experiences in several ways. Both sets of results underscored the value of preparing and presenting one's own research in progress. Both mentioned helping students identify gaps in their knowledge and become comfortable navigating those gaps. Both sets of studies also converged on the importance of building student confidence and identity as a scholar—something that purportedly happens as students are required to think about how to communicate their work and to reflect on what they know and what they do not know yet need to know. The raw participant data of both studies also referred to the perspective taking that happens when students need to prepare and present their work. Taking the perspective of the audience or hearing random, but sometimes profound, audience questions leads the presenters to rethink their work.

Conversely, Seymour et al.'s (2004) study looked solely at the student perspective, whereas the present study complemented their results by adding the mentor perspective. The role of the mentor is to encourage students to take part in these optional presentations, possibly even making time for them within their own labs. The next category, additional writing, continued the current category's theme of learning how to pose research questions by participating in the articulation of research through activities that fall outside the required graduate curriculum. However, whereas Category 8 focused on the role of oral communication in developing student RQF, category 9 addressed written communication.

Category 9: Additional writing. This theme is about student engagement in the writing process related to publications, scholarships, grants, or any other supplemental writing tasks that contribute to RQF but fall outside usual undergraduate and graduate program expectations.

Focused coding using the coding guide presented in Table 33 revealed that the additional writing category applied to five of the 134 RQF segments. These five segments came from interviews with five of the 24 participants (see Table 34 for demographic details). Though the additional writing category was created from earlier interviews with the intention of capturing possible links between research question formulation and co-authoring publications, such links either did not exist in the data selected for the final analysis or were too subtle or tangential to be considered compelling participant endorsements. In hindsight, this is not surprising considering that co-authoring publications would represent the final stage at which the findings are to be communicated to a larger audience after a question had already been formulated and the investigation completed. The recurring themes that did emerge from the quotes on additional writing were as follows:

- Participation in grant writing.

- Other writing.

Table 33

Coding Criteria for Additional Writing (Category 9)

Description	Inclusions and examples	Exclusions	Handle with care
Student engagement in the writing process related to publications, scholarships, grants, or any other supplemental writing outside of undergraduate and graduate program expectations, that contributes to RQF.	Scholarship writing: • Professor makes an explicit link between RQF and students' scholarship writing processes. • Professor makes a direct link to RQF by responding with "scholarship writing" in response to a question that directly asked about RQF. Student grant writing: • Any student involvement in the grant writing process that the professor believes contributes to RQF. • Professor's rationale for not including students in grant writing if there is a link between grant writing and RQF anywhere in the interview. Publication: • Professor makes an explicit link between publication and RQF. • Professor makes a direct link with RQF by responding with "publication" in response to a question that directly asked about RQF. Other: Interesting professor strategies for thesis writing that extend above and beyond the actual requirement to write the thesis itself like in the following example: "Think of it as writing a thesis chapter. If you can formulate the question starting from the vision of what your thesis will be, write the chapter so that each chapter is a question, but it's a broad question and then you dig and find the nuances to make it happen. Your thesis will assemble itself, as will your publication . . . And I want to do it in such a way that they're going to learn to be experiments in communication. Me formulating the question for them, that doesn't help them at all. By them learning how to formulate the question, by them having to write up the manuscript and onwards it goes, they're learning the process of communication."	• Writing for comprehensive exams, proposals, seminars because those comments are coded as programming. • "[Jotting down ideas for future reference or for possible future writing" is not writing in and of itself. Scribbling ideas is what happens before the writing happens. The theme additional writing & RQF is about engaging students in writing for the purpose of producing a formal document for the scientific community, for scholarship applications, for grant applications.	Not applicable.

Table 34

Demographics for Participants Coded as Additional Writing (Category 9)

Participant ID	Branch of science	Discipline-specific identifier	Gender (for pronoun purposes)	Faculty position	Years worked as a professor	All undergraduates supervised to date	All Master's students supervised to date	All doctoral students supervised to date
4	Biology	molecular ecologist	Female	Associate Professor	7	10	5	1
10	Chemistry & Biochemistry	analytical chemist	Male	Full Professor	30	100	25	25
11	Other Life Sciences	biophysicist	Male	Assistant Professor	5	15	0	3
				Averages	14.0	41.7	10.0	9.7

Participation in grant writing. Two participants (8%) made links between RQF and grant writing. When asked about the stage at which students in her own discipline were expected to come up with their own research questions, a genomicist (Participant 16) stated that "by the time they write their thesis they are expected to propose future directions which could theoretically be a new grant proposal based on their work." In response to probing about student involvement in the professor's own grant proposals, the genomicist replied as follows:

> One thing that I usually do is I do brainstorming sessions with my group when I'm starting to write a new grant, so that I can get their input and feedback on where they think that we should go next with our research. So we'll do brainstorming sessions, and then I'll kind of write an outline and share it with them, and get their feedback. I usually try not to actually ask them to do the actual grunt work for the grant because they've got other things to do, so I usually do that. But also, as I'm generating a more completed draft, then I ask them to read it and give me some feedback and—so I do try to get their input as much as possible. And the brainstorming sessions are really fun, that's something that my PhD supervisor did with me that I really enjoyed at the time, so I try to make sure to always do that with my group as I'm thinking of new research grants. . . .

> And again, I think that's a really great way for people to feel like we're really working as a team. And—so, you know, it's the sort of bottom-up led rather than top-down led approach. So I really, really appreciated that aspect of what he did, and I try to incorporate that as much as possible.

In the above quote, the genomicist described how her students were engaged in collaboratively finding researchable questions during meetings, and then gave feedback on early outlines and drafts that were shared by the supervisor. In essence, the supervisor modeled how to find and frame a research question that can attract funding, and then provided opportunities for students to gain practice with editing and refining the description of a program of research.

The second participant who spoke about involving students in grant writing was a biophysicist (Participant 11). He described the involvement as follows:

> Together, we formulated the hypothesis and aims, and then he really filled in a lot of the methodology and the expected outcomes from that methodology. So he guided the main parts of it, and we came up with the hypothesis together. And he does a lot of independent reading and independent research, and comes to me with lots of different ideas and hypotheses as to how things could work. He's a very impressive student, actually. So I anticipate—he has a lot on his plate, so he's not helping with grants right now, but I anticipate in the future that he would help a lot with grants. The other girl, my other doctoral student—she will, in the future, be able to do that. She has absolutely input right now on directions of research and how we formulate questions, and how those questions change on a day-to-day basis. But she's not really to a writing level yet that's up to what you would expect in a grant. So she needs to work on that—and I've . . . tried

> to help her with that, and we actually sent her to a grant writing course just for her own professional development.

In the above, the biophysicist described creating opportunities for students to contribute to grant writing in different capacities based on their abilities. The first student identified testable hypotheses, specified methodological details and wrote sections of the grant—tasks that were considered central. The second student helped to formulate research questions but did not yet have the skills to contribute written sections. The contribution of written sections to grant writing was so important to this biophysicist that he invested in professional development in order for more students to participate in the formal writing process.

Other writing. Three participants (13% of 24) linked other types of student writing to the development of RQF. The forest ecologist (Participant 3) required her students and supervisees to submit a short written summary of the research that they would like to pursue; one that included a research question (explicitly phrased as a question) and another a research objective. The analytical chemist (Participant 10) had students transform the questions that they were asking as they designed a research project into a broader question that could be used to organize the chapters of their thesis, and later be converted into publications. Because these two participants were selected for the illustrative cases (see the Illustrative Cases section), their strategies will be elaborated in more detail in that section. The molecular ecologist (Participant 4) used writing as part of her recruitment process:

> When I recruit students, often I give them . . . a small assignment . . . to write a small proposal. Recently, the student from China, for his scholarship, he had to go and write something. [It] allowed the student . . . to go and come up with the question and write something, and I was just editing so that makes sense. And then I mentioned to him

> when he writes. . . . "Take this and arrange something that would be that—to the C standard."

The participant factored a student's research question formulating abilities into her recruitment decisions by evaluating the questions that he asked in a small grant proposal. New students in her lab also got to formulate research questions when they were writing scholarship applications. For second-language learners, the role of the professor was to help with editing.

Synthesis. Engagement in grant writing, be it during the brainstorming, conceptualizing, or the actual writing stage, enables students to practice collaboratively finding not only feasible, but fundable research questions, and then frame these questions for external evaluation. The task is an authentic one, and the involvement can be scaffolded to meet students' different ability levels. Opportunities to practice individually formulating research questions can be created by requiring students to submit a brief piece of writing that includes the research question and research objective, or more extensive writing such as that required for a scholarship application. Whether the students are writing their own research questions or helping their supervisors to find, frame, and formulate fundable research questions, the process is iterative and involves feedback in both directions.

Category 10: Supplemental professor strategies for RQF. Focused coding revealed that the supplemental professor strategies for RQF category applied to 24 of the 134 RQF segments (18%). These 24 segments came from interviews with 13 (54%) of the 24 participants. Focused coding was used to allocate the statements to the 11 categories identified during earlier rounds of open and Axial coding. The RQF categories described thus far are:

- RQF development in the curriculum.
- Starting points for RQF.

- Literature-based approaches to developing student RQF.
- Peer interaction.
- Exposure and student RQF.
- Professor's in-course teaching of RQF.
- Feasibility, scope, and specification.
- Presenting research questions.
- Additional writing.

The above categories represented the activities, actions, and engagements that participants explicitly linked to their students' ability to find, frame, formulate, and refine their research questions, research objectives, and hypotheses. Category 10, supplemental professor strategies for RQF, is a grouping to capture participant actions and attitudes that did not fit into any of the aforementioned RQF categories. With 24 of the 134 RQF segments, this was the second largest category after comments and expectations (64 segments).

Table 35 shows the coding guide, inclusion and exclusion criteria that were used to distinguish these statements. Statements made regarding contributors to student RQF that did not directly involve the professor were not included here but allocated to the eleventh category—comments and expectations.

Table 36 depicts the demographic details of participants who made statements found to fit this theme. Open coding of these 24 segments produced 63 codes that were rearranged by similarity into four subcategories that represent the nuances of Category 10:

- Maintaining an open and encouraging attitude to elicit student ideas and contributions.
- Encouraging students to try out ideas and follow their leads.
- Modeling scholarly skills.
- Directing students toward promising areas of investigation.

The next section presents quotes from each theme to assemble a narrative that illustrates the nature of the theme (participant identification numbers are listed in parentheses).

Table 35

Coding Criteria for Supplemental Professor Strategies for RQF (Category 10)

Description	Inclusions and examples	Exclusions	Handle with care
A catch-all theme to capture any and all approaches, methods, strategies that professors use to help students to find, frame, formulate, and refine their research questions, research objectives, and hypotheses which have not been captured by other categories.	• How professors help students to assess the importance and impact of students' research questions. • Discussions that professors have with students to improve students' questions. • Professors' replies to the interview questions that directly probed RQF but could not be assigned to other categories. • How professors help students contribute new ideas or improve students' initial research questions. • Attitudes a professor holds that facilitate and encourage RQF. • Anything else professors do, believe, make possible, or facilitate, through their actions, attitudes, etc. that makes room for student RQF.	• If the professors themselves were not involved in the activity described as contributing to RQF, code the segment as comments and expectations. • If the strategy falls under general supervision and is not clearly directed at developing RQF, do not code as supplemental professor strategies. • Exclude statements related to the professor's logistical role (and not RQF). • Managerial and logistical issues related to running a lab. • Funding issues and navigating systems-level constraints • Administration.	Tread lightly when the professor uses words such as creativity, innovation, new idea, new methodology, new computational modeling. Consider such segments holistically within their context because they may be too broad to qualify as examples of developing student RQF abilities.

Table 36

Demographics for Participants Coded as Supplemental Professor Strategies for RQF (Category 10)

Participant ID	Branch of science	Discipline-specific identifier	Gender (for pronoun purposes)	Faculty position	Years worked as a professor	All undergraduates supervised to date	All Master's students supervised to date	All doctoral students supervised to date
3	Biology	forest ecologist	Female	Full Professor	25	30	10	3
4	Biology	molecular ecologist	Female	Associate Professor	7	10	5	1
16	Biology	genomicist	Female	Assistant Professor	5	15	6	4
8	Chemistry & Biochemistry	green chemist	Male	Full Professor	19	114	18	10
10	Chemistry & Biochemistry	analytical chemist	Male	Full Professor	30	100	25	25
23	Chemistry & Biochemistry	theoretical chemist	Male	Full Professor	18	20	3	6
1	Other Life Sciences	cognitive neuroscientist	Male	Associate Professor	10	6	4	1
7	Other Life Sciences	biomedical physiologist	Male	Full Professor	15	10	8	3
11	Other Life Sciences	biophysicist	Male	Assistant Professor	5	15	0	3
15	Physics	theoretical atomic physicist	Male	Associate Professor	12	5	10	6
18	Physics	geodynamicist	Male	Full Professor	15	26	6	6
24	Physics	theoretical physicist	Male	Full Professor	27	20	10	20
19	Physics	materials physicist	Male	Full Professor	15	20	10	12
				Averages	15.6	30.1	8.8	7.7

Maintaining an open and encouraging attitude to elicit student ideas and contributions. Six participants spoke of maintaining an open and encouraging attitude in which students are expected to interact with the supervisor as a colleague (instead of hierarchically, as supervisor and student). The participants described how students' research interests were being transformed into research questions during discussions between the student and supervisor. Such discussions were described by a theoretical physicist as "a back-and-forth between me and the student, where we are at the level of equals" (Participant 24). A genomicist spoke of how her students were made "repeatedly [aware] that I want to get their input, that I want the project to be a collaboration between us in terms of what the focus is" (Participant 16). A green chemist (Participant 8) described how he expected his students to apply their critical thinking skills when he introduced possible research projects:

> I've got some cool new idea I thought of and I'm hoping it's a good one, but it might be a bad one, I tell them at group meetings, "I thought of this, what do you think?" They'll say, "Oh, well, that part is good, but this is going to be a real problem over here." And we discuss it.

A cognitive neuroscientist (Participant 1) shared how he remained flexible as his student moved from one topic to the next:

> She was working on . . . various sexuality topics . . . but she got frustrated because she was working with these deviant populations. . . . So she decided she didn't want to do that anymore . . . and wanted to study the visual system. . . . She started working on a project that I assigned to her. . . . [Later] she decided she didn't want to study vision so much anymore, and . . . went back to this sexual research (which is totally not my expertise, but I can help her with the brain imaging). So really [she developed her questions] without much help from me at all. . . . My helping to design some of the stimuli, the structure of the experiments, the control groups, and things like that, helped her in collaboration with her other advisors.

In the above quote, the professor supported the student as she sampled multiple topics. During this exploration, the student learned more about her interests, strengths, and weaknesses as they pertained to the pursuit of different research questions. When the student settled on a topic outside of the professor's area of expertise, the neuroscientist allowed her to be cosupervised by other professors while continuing to help her with the research design and methodological details of her study.

The genomicist (Participant 16) also noted how an open and encouraging attitude can require patience, as he spoke about holding back on one's own ideas in order to make room for student contributions:

> I basically ask them what they're interested in, directly, and then I try not to talk, because sometimes . . . I get excited, and I have a lot to say, but I find that I do try to sort of sit back a little bit and let them tell me what they've found that they thought was interesting.

A green chemist (Participant 8) expressed similar beliefs:

> When it's coming up with the idea, I don't want to help them too much because there's a tendency for me, and perhaps any other professor, to give them too much information and say, "OK, here's my idea, why don't you come up with it?"

A geodynamicist concurred with the idea of being nondirective: "With my students, I follow some kind of a meta-approach. I guide them, but discreetly. I don't want to interfere very much with their imagination" (Participant 18). When asked about instructional strategies for helping students come up with research questions in a course that she was teaching, a molecular ecologist (Participant 4) replied that she used "close discussions to the student because students are so intimidated, especially undergraduate students." An analytical chemist (Participant 10) also spoke about how supervisor attitudes will affect whether or not students are comfortable with sharing their ideas. Because this chemist was selected as one of our illustrative cases, his quotes will be shared in the Illustrative Cases section.

All these six quotes showed an awareness of the importance of professorial attitudes in supporting students' ability to find researchable topics. Students may find themselves feeling uncertain, intimidated, discouraged, or hesitant to share their thoughts and ideas. In other words, power differentials in the mentor-mentee relationship and students' emotional needs may inhibit student research question formulation. The above quotes suggested strategies that mentors can use to help students work through these feelings. The mentors built critical thinking, confidence, and risk-taking abilities by reminding students of the collaborative role they are expected to play, by directly asking the students to critically evaluate the mentor's ideas, and, when conversing with the student, by patiently holding back on sharing the mentor's own ideas until the students have had a chance to share their ideas.

Encouraging students to try out ideas and follow their leads. Whereas a patient, open, and nondirective attitude can create a space for students to share their ideas, a more directive approach may be useful in encouraging students to actively explore ideas. For example, a materials physicist (Participant 19) asserted:

> I don't discourage [my student] from following these leads because they may deviate from the original material that posed the question, but rather I say, "run with it! . . . In answering that one question, you've found many sets to pull on—this will create a career for you, this will create a lot of curiosity in these questions."

Note the enthusiasm in this participant's words as he helped his student perceive and appreciate the value of the area of inquiry that was discovered. Such enthusiastic support was also evident in the words and tone of an interview with a green chemist (Participant 8): "I also encourage them to try it a bit even if they haven't got a lot of time left in their degree. I say, 'well, take off some time, and at least try this idea.'" He then jovially commented on how he consoled and encouraged his students after giving them frank and critical feedback on their ideas:

> [I say], "come up with something new." And they do, and some of them suck [laughs] . . . . They come up with their ideas, they come and tell me, and I say, "I love that you

> come up with new ideas. This one's probably not worth working on, because of this reason. But it doesn't matter, don't get discouraged, come back again next week with another idea."

As seen in the above quote, enthusiasm for student ideas does not mean that the mentor is blindly providing uncritical support. Instead, constructive criticism is combined with explicit encouragement to try again.

Demonstrating scientific inquiry skills. Quotes from three participants stand out as examples of the importance that participants assigned to the act of exposing students to scholarly inquiry as it unfolds among experts. A green chemist (Participant 8) started by saying that students tend to receive the objectives for their research projects from their supervisors. Given this supervisor-defined context, the participant was asked how students develop the ability to come up with their own research questions as independent scientists. The chemist replied, "first . . . they'll learn from me how new projects get started." A geodynamicist (Participant 18) provided a similar reply to the same question by pointing to the importance of "exposure [to] the supervisor's [questions] . . . and description[s] of the research problems." The importance of modeling in an RQF context was also mentioned by a theoretical atomic physicist (Participant 15):

> What we sometimes do in these group meetings is that we discuss a paper . . . . My colleague and I are often involuntarily leading this discussion, but maybe it also helps the students a little bit to see how we read a paper, and how we are critical about some results that are presented there . . . so they see how we approach it.

The value of exposing students to expert processes of thinking and research emerged throughout the interviews as participants discussed student learning in general. What stood out about the above quotes was the fact that these three participants explicitly and directly associated said exposure to the student RQF. In other words, these participants believed that, in seeing how a project gets started, how research questions are described, and how to critically discuss previous research, students would learn how to eventually generate their own lines of inquiry.

Directing students toward promising areas of investigation. The theoretical physicist, molecular ecologist, and green chemist all spoke of guiding students toward more fruitful avenues of investigation, with comments such as “push them to develop the ones which look most promising” (Participant 24), “[I tell them] I think this would be the way to actually go to” (Participant 4), and “I try and help them to vet the idea to see if it’s one of the good ones or one of the bad ones” (Participant 8). A materials physicist (Participant 19) talked about ensuring that his students selected questions that were amenable to contingency plans: “You always want to have . . . A question that’s grounded in real-world applications, have some need in it to discover stuff, have a bailout plan so you can always write something up with it.” All four of these quotes speak to how professors evaluate, vet, and select research questions, and they do so either with their students or for their students.

Synthesis. Overall, nine participants made statements regarding what they did to help students find, frame, and formulate researchable questions. The specific actions they shared varied—some were more instructor-centered and didactic than others. More didactic mentor actions included telling students how to start a research project and exposing students to scholarly discourse between the mentor and other professors. Less didactic actions included proactively soliciting critiques and ideas for future research from the students, as well as assisting with the methodology for a student-selected topic, even when this topic fell outside of the mentor's area of expertise.

The mentor perspective in the present study converged with the student perspective described in previous literature in two respects: the value assigned to directive guidance and the value assigned to modeling. For directive guidance, the participants in the present study noted that they directed or redirected students toward the most compelling research topics. Similarly, Fister (1992) found that students sought instructor input when struggling to focus their research topics. These students reported that they appreciated the "nudge in the right direction" from their instructors. Students also saw as beneficial their advisors' efforts to model typical scholarly processes such as consulting with colleagues, dealing with setbacks, and making complex decisions, as contributing to their ability to think and work like a scientist (Seymour, Hunter, Laursen, & Deantoni, 2004). Implicit in these mentor actions were roles for students that may have ranged from passive to active. Students could be playing a more passive role if they were merely observing two professors leading a discussion on how to critique an article. The act of accepting a supervisor's advice regarding the most compelling lines of inquiry could be seen as more active, but still less so than learning how to identify the most compelling areas by oneself.

The professorial participants in this study and the student participants of previous studies valued what they referred to as "modeling" by mentors. Other studies used modeling in classroom exercises, which exposed students to expert thought processes (e.g., brainstorming, identifying constraints, narrowing a testable research question), and then gave the students opportunities to practice and get feedback on their application of the skills they had seen modeled by the expert (Gautier & Solomon, 2005; Strangman & Knowles, 2012). The examples of modeling in previous studies were largely written for classroom contexts by researchers who were using data from their own in-class examples. The pedagogical examples that they described were deliberately designed with the intention of developing student ability for posing research questions. In the present study, similarly rich and detailed examples were present in RQF Category 6, professors' in-course teaching, as well as in RQF Category 3, literature-based approaches to developing student RQF. In Category 10, supplemental professor strategies for RQF also contained the mention of modeling, comments that came from three participants. However, unlike the manner in which modeling was described in categories three and six, modeling examples in Category 10, supplemental professor strategies for RQF were much briefer, lacking any reference to scaffolding, guided practice, expert thinking aloud, or iterative feedback. In fact, it appears that the modeling described by these participants was far closer to didactically demonstrating something as opposed to pedagogically modeling it as per the examples in the literature (Gautier & Solomon, 2005; Strangman & Knowles, 2012). In sum, it is fair to say that participants' mentioning of modeling should be taken with a grain of salt because not all "modeling" is the same.

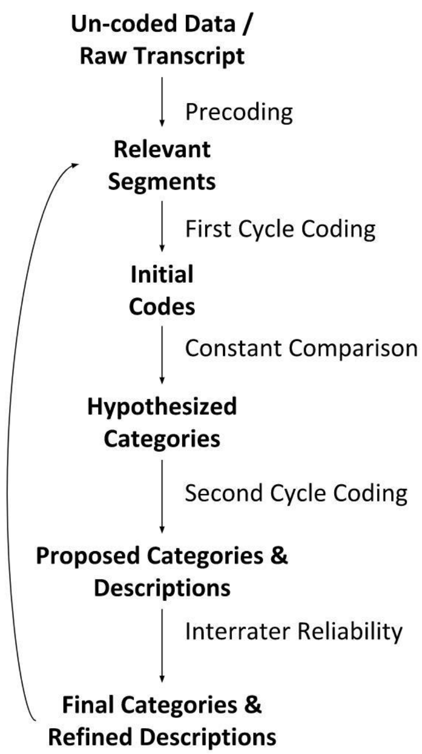
Students experience a range of difficult emotions during their early stages of research. For example, in Tan's (2007) study of undergraduate research experiences, students expressed feelings of insecurity, fear, and inadequacy as they initially faced the tasks of conceptualizing their research interests. Seymour et al. (2004) also found that students appreciated it when their instructors were open and encouraging as the students navigated the challenges of the undergraduate research process, carried out important research tasks, and made independent research-related decisions. Todd, Bannister, and Clegg (2004) found that students struggled when determining a precise and feasible focus for their dissertation question, experiencing feelings such as uncertainty. In a study of motivational variables supplementing undergraduates' learning of research skills, Waite and Davis (2006) found that students perceived the task of individual research projects to be daunting and isolating. The undergraduate students in Lundstrom and Shrode's (2013) study also expressed feelings of confusion about how to choose and refine research topics for successful research papers. The results of the present study extended the previous findings by providing specific actions that mentors believed would alleviate student anxieties, encourage students to take risks, share their ideas, and try again when they fail. The mentors in the present study reported specific, concrete, observable actions that invited students to overcome traditional role hierarchies (professor versus student) to a relationship based on collaboration and increasingly higher levels of collegiality—an apparent prerequisite to developing independent research questions.

Category 10 exclusively contained a broad set of mentor-driven actions to support student RQF. The next category contains only student-driven actions.

Category 11: Comments and expectations. Comments and expectations (C&E) is a catch-all theme to flag sections of participants' transcripts that are potentially important to the understanding of how RQF develops (see Figure 3: Coding procedures that generated 10+1 RQF categories for a graphic representation of how raw data was processed into the 10+1 RQF categories).

Figure 3

Coding Procedures That Generated 10+1 RQF Categories



As with the other categories, these segments must also fulfill all four RQF criteria (i.e., the segment pertains to the focus of the research, to student RQF processes, to teaching or mentorship, and to the shared discovery of new scientific knowledge). C&E captures values, beliefs, wishes, hopes, and expectations related to student RQF. C&E does not contain actions, approaches, or strategies that professors could apply in their own teaching or mentorship to develop student RQF because such statements would be coded as supplemental professor strategies. Segments were flagged as comments and expectations if they contained any of the following: the developmental trajectory of student RQF, roles and expectations of students related to RQF, beliefs about how and among whom the ability to formulate research questions develops, weaknesses in the research questions that students initially posed, the professor's own experience as a student learning to formulate research questions, and comments on the scientific method and RQF, or about aspects of RQF that the participant believed to be unique to their own discipline. As the 11th category, C&E was coded for 64 RQF segments from interviews with 23 of 24 participants. The remaining participant's interview transcript was entirely coded into the 10 main categories. Table 37 contains the full criteria used for the identification of sections of interview transcripts that constitute instances of C&E. Table 38 contains the demographic details for all participants who contributed segments for C&E.

Table 37

Coding Criteria for Comments and Expectations (Category 11)

Description	Inclusions and examples	Exclusions
This is a catchall theme to capture an idea that, despite not being captured by any other code, is important to our understanding of how RQF develops in students according to professors. The idea must be from a segment that fulfills all four RQF criteria.	• Developmental trajectory: How student RQF develops among students or in general, especially where the students find an area of interest and move towards building their own research question. • Student RQF weakness: Initial weaknesses in students' questions. • Student role & expectations: Anything else that students should be doing, with the prof, or on their own, to develop their own RQF skills which is not captured by any other focused theme. • Responsibility: Whose responsibility is it to develop RQF. E.g., "it's the student's responsibility to learn RQF on their own time; no one will push them to do it." • RQF Source: How does student RQF happen. Naturally? Innately? Organically? Dynamically? Intentionally? • Whom: Among whom does RQF develop. E.g., "the really good ones will be able to come up with their own agendas by the time they graduate, the rest just weren't cut out for this kind of thing." • Professor as student: Comments related to how the professor himself or herself learned to find, frame, and formulate their own research questions as a student, or during his or her early career days. • Scientific method & RQF: Comments related to how the scientific method works out in practice for this professor when it comes to how research questions are found, framed, formulated in his or her subdiscipline.	None listed. If the segment fulfills all 4 RQF segment criteria and does not fit in any other RQF category, it is coded in this category.

Table 38

Demographics for Participants Coded as Comments and Expectations (Category 11)

Participant ID	Branch of science	Discipline-specific identifier	Gender (for pronoun purposes)	Faculty position	Years worked as a professor	All undergraduates supervised to date	All Master's students supervised to date	All doctoral students supervised to date
2	Biology	systems biologist	Male	Full Professor	15	20	11	3
3	Biology	forest ecologist	Female	Full Professor	25	30	10	3
4	Biology	molecular ecologist	Female	Associate Professor	7	10	5	1
9	Biology	cancer biologist	Male	Full Professor	24	50	14	11
16	Biology	genomicist	Female	Assistant Professor	5	15	6	4
17	Biology	molecular biologist	Male	Full Professor	13	20	5	10
5	Chemistry & Biochemistry	protein biochemist	Male	Associate Professor	10	13	2	2
8	Chemistry & Biochemistry	green chemist	Male	Full Professor	19	114	18	10
12	Chemistry & Biochemistry	inorganic chemist	Male	Associate Professor	12	30	2	7
21	Chemistry & Biochemistry	materials chemist	Male	Full Professor	30	20	6	12
23	Chemistry & Biochemistry	theoretical chemist	Male	Full Professor	18	20	3	6
1	Other Life Sciences	cognitive neuroscientist	Male	Associate Professor	10	6	4	1
6	Other Life Sciences	neurobiologist	Male	Full Professor	37	90	13	6
7	Other Life Sciences	biomedical physiologist	Male	Full Professor	15	10	8	3
11	Other Life Sciences	biophysicist	Male	Assistant Professor	5	15	0	3
13	Other Life Sciences	neurophysiologist	Male	Assistant Professor	1	4	0	0
14	Other Life Sciences	comparative physiologist	Female	Assistant Professor	2	8	3	0
15	Physics	theoretical atomic physicist	Male	Associate Professor	12	5	10	6
18	Physics	geodynamicist	Male	Full Professor	15	26	6	6
24	Physics	theoretical physicist	Male	Full Professor	27	20	10	20
19	Physics	materials physicist	Male	Full Professor	15	20	10	12
20	Physics	astrophysicist	Male	Full Professor	25	15	12	8
22	Physics	applied physicist	Male	Full Professor	31	39	30	41
				Averages	16.2	26.1	8.2	7.6

Note. The analytical chemist (Participant 10) was the only participant out of 24 who did not have any segments coded as C&E. All eight RQF segments extracted from his interview neatly fit into seven of ten main RQF categories. This participant was later selected as an illustrative case.

Recurring themes. Eight recurring themes were identified among the 64 C&E segments; all relating to student roles and responsibilities when it came to developing their own RQF abilities (see Table 39 for details). The first C&E theme represented participants' recollections of their own RQF. These recollections included explorations with their colleagues or explorations that were facilitated through the supervision they received as graduate students. Three of the recurring themes in C&E—*Contextualize*, *Integrate*, and *Use past experience*—are student actions that can be linked to professorial strategies that were found among the main RQF categories. For example, C&E comments about contextualizing represent the appropriate student response for the RQF category literature—students should be contextualizing their research questions in the literature as the professor helps them to select and navigate this literature. Integrate can be considered the student complement of the RQF category exposure in that students should integrate different ideas and perspectives as professors create opportunities for them to be exposed to other labs, research partners, talks, etc. *Use past experience* might be relevant to starting points for RQF (Category 2) in that students can or should build upon past projects to come up with new ones, after which the professor can help them to identify a starting point for pursuing their own questions. The remaining four themes contain other actions that students can or should take when engaged in RQF: starting RQF with a hypothesis, finding the overlap between professor and student interests, considering additional factors when selecting a research topic, thinking critically when engaged in research in order to uncover new research directions.

Table 39

Recurring Themes Among Segments Coded as Comments and Expectations

Recurring theme	Description	Number of participants	Illustrative quote
Contextualize	Students can or should contextualize their questions in the existing research literature or in the ongoing work of their field.	9	I knew a lot about that element from the Master's, but I knew that studying more ligand substitution reactions I wouldn't find satisfying, because in my opinion, enough is known already. So . . . what is cutting edge? What are hard problems? . . . what is the most interesting question that is currently being addressed with the element platinum? So, in a sense, using what you know already, which was an element, but taking it into something which is cutting edge. Inorganic chemist (Participant 12)
Use past experience	Students can or should build on past projects and previous experiences to come up with new ones.	11	It followed on specific findings, right? I find [chaperone protein X], I find its co-chaperone, that leads me to mitochondria, I find other things related to the mitochondria [. . .] I find [protein Y] relates to folding, and I ask how that protein relates to CFTR. And . . . this is just one of the grants, right? There's another grant which related to a potassium channel where we kind of take the same approach, right? Here's [protein Y] and [chaperone protein Z], let's look at another human protein, the potassium channel, right? Protein biochemist (Participant 5)
Integrate	Students can or should integrate different ideas and perspectives.	11	So what he did was take the idea of innovation and the idea of colonization and he took that to . . . A pretty nice level. . . . So a good topic is a topic where—or [a] question, or whatever you . . . Bring together the ideas and the expertise of two people. Neurobiologist (Participant 6)
Think critically	Students can or should think about their work from a critical standpoint (about their data, results, assumptions, understanding of processes, calculations, models, etc.).	7	I: [Interviewer probes on the topic of contradictions because the participant mentioned it earlier] Can you just elaborate how not understanding and her persistence in [it] . . . led to the ability to come up with your own questions? P: Well, it comes, I guess, by finding contradictions in your own thinking. And the problem is, if you find a contradiction in your own thinking, . . . is that because you don't understand it yet, or is it because there's an actual contradiction in the method or in the approach or in the science? And sometimes the contradiction is powerful, but sometimes it's more mild, in which you've made assumptions that are more restrictive than you thought they were, that's the case for this one. So that's another way, is by persisting in understanding when you think something doesn't make sense or is contradictory. Applied physicist (Participant 22)

(continued)

(continued)

Recurring theme	Description	Number of participants	Illustrative quote
Consider additional factors	Students can or should consider funding opportunities or career interests, or trends in the field, and the broader contribution of their study when selecting a research topic.	13	you always have to see what you add to the field. And so what I add to the field, or what people like me add to the field, is the ability to link two areas. And to link two things you have to . . . Be able to zoom out and not get caught up in your own little microcosm of interests. . . . the research questions that we needed to look at and formulate and investigate, we have to keep in mind the impact of them on a broader scale. . . . within your little microcosm, some question may seem particularly interesting. On the scale of what impact it would have, it would be relatively small. So then you need to decide and prioritize what is of particular interest—not just to you, but to a broader community. And those are the higher impact publications, by definition . . . Biophysicist (Participant 11)
Find the overlap	Students can or should work with their supervisors to integrate the research interests, strengths, skills, expertise of both parties when formulating a research question.	5	I: OK, so once she arrived in January 2014, were these questions self-evident or did they emerge out of discussion? How did these questions come about? P: She had read my papers and she wanted to do that. I: OK so she read your papers, and she said "I want to look at how innovative birds differ from other birds." P: "I want to see whether innovations from one species are transmitted to others, or to birds of that species, or to birds from other species . . ." I: So she read your work and she came to you with the research question? P: Yes. Neurobiologist (Participant 6)
Hypothesize	Students can or should use a testable hypothesis as a starting point for RQF.	2	We do experiments until we find something interesting, and then we publish it. . . . often it fits in with the hypotheses, the broad hypotheses we've formulated to fund that research, and sometimes not. To be quite honest, big chunks of my research are based on . . A chance finding. Scientific serendipity, where something happens that you weren't expecting, or . . . you can't explain your phenomenon entirely with the following results, so you investigate it further, and then that branches out into something. . . . Or someone asks you, "Did you ever try this on your prep?" And you go and try it, and literally there's four papers that emerge from that, or a whole PhD, or several Master's theses. Biomedical physiologist (Participant 7)
Explore	Students can or should engage in free explorations of broad topic areas, either with their supervisor or with other researchers. Professors recall benefitting from such pursuits when they were students themselves.	3	I: So in your interactions with your supervisor, like when you're working on those grants and formulating the research questions, like what things stand out about those discussions? P: . . . when we were discussing things and discussing research ideas, the amount of insight that he would have, even from some seemingly unrelated topics, was really surprising to me at time. Because at that time he was 74, and you'd think a guy like that would be in his comfort zone and sort of know everything that he needed to know, and I was in my-I started university when I was 15, so I only would've been about 19 at that time—and for me, talking to this guy who was really the first protein structure biologist in Canada—talking to him and realizing that even at his age, he was still trying to get outside his comfort zone on a regular basis-that showed me what the importance of being broad is. Biophysicist (Participant 11)

Synthesis. Comments and expectations was a catch-all category to minimize the risk of missing mentorship approaches that did not fit in the 10 main RQF categories. Sixty-four transcript segments were coded as comments and expectations (Category 11), constituting 48% of the entire dataset of 134 RQF segments. When the ideas contained in these 64 segments were analyzed, they were all discovered to be student-driven. That is, in all eight of the recurring themes identified within the category, the student was the actor. At the end of coding and interrater discussions, none of the Category 11 segments contained strategies that professors reported as actions they explicitly or intentionally took to promote student RQF development. Professorial actions were comprehensively represented by the 10 RQF categories, suggesting that these categories provided a compelling framework for understanding mentorship approaches that supported and promoted student RQF. Results from Category 11 served the purpose of demonstrating that saturation had been reached in the data analysis.

Additionally, particularly striking about this category was the fact that statements about roles and responsibilities for students often emerged in response to questions regarding what the mentor ought to do to develop student RQF. These comments suggested that mentors were consistent in assigning the responsibility for initiating, cultivating, and refining RQF skills to both student and mentor, though their opinions varied as to the amount of responsibility borne by each.

Synthesis of the 10+1 RQF categories. The first dissertation question was, “What do professors report doing to develop students’ capacity to find, frame, and formulate research questions?” (Q1). What started out as a search for what professors themselves do ended up producing a full-fledged framework of how scientists see RQF development in students. The framework captured elements relating to teaching, to mentorship, and to the curriculum. In addition to these, the framework highlighted mentor expectations for student-initiated, student-driven, independent learning of RQF. Mentors and students shared the responsibility for the process and for achieving the final goal of enabling students to formulate new research questions in collaboration with professors and, eventually, independently.

Table 40

Number of Participants who Mentioned Each RQF Category

RQF category	Number of participants who explicitly mentioned this RQF category during the interview	Percentage of sample population that explicitly mentioned this RQF category during the interview (n=24)
Starting point for RQF	10	41.7%
Feasibility, scope, and specification	10	41.7%
Literature & RQF	10	41.7%
Presenting RQs	6	25.0%
Additional writing	3	12.5%
Supplemental professor strategies for RQF	13	54.2%
Professor’s in-course teaching of RQF	3	12.5%
Exposure & RQF	14	58.3%
Peer interaction & RQF	8	33.3%
RQF development in the curriculum	8	33.3%
RQF comments & expectations	23	95.8%
Grand Total	24	

I identified 10 broad themes that addressed the first dissertation question (see Table 40 for details on which participants mentioned each theme). Of these, one theme (Category 6, professor’s in-course teaching) described activities taking place in a formal classroom setting rather than within a mentorship relationship. Similarly, Category 1, RQF development in the curriculum, described activities that were part of the graduate or undergraduate curriculum but did not always require mentor involvement. Additionally, there were statements that were relevant to the dissertation question, but did not fit the existing 10 categories. These statements were grouped into an eleventh category, comments and expectations. Careful examination of this category revealed that it contained professor's expectations for student-initiated, student-driven, independent learning of RQF. Because Category 11 did not contain professorial actions or approaches to developing student RQF that were not already captured by the framework, I concluded that saturation had been reached. To highlight the distinct status of Category 11, I referred to the entire set of themes as "10+1 RQF categories." From the 10+1 RQF categories, I inferred that student RQF required

- concrete starting points for eliciting students' interests and strengths, particularly those which would contribute to the professor's research agenda;
- prerequisite content knowledge, the extent of which varied greatly by mentor, student, and area;
- training and guidance in procedural knowledge (such as wet lab skills or navigating the literature);
- an advisor-advisee relationship in which students are invited to share their ideas, explore different topics and approaches, and are allowed to make mistakes;
- a collegial lab environment that encourages students to give and receive criticism;
- a diversity of sources for potential research ideas (e.g., peers, other labs, talks);
- opportunities both within and beyond the mentor's lab for presenting research questions and eliciting feedback; and
- guidance and direction from the mentor regarding the value, feasibility, and scope of student-proposed projects.

What professors did to facilitate such opportunities varied from one student to another. The nature and reasons for this variation are explored in the next section.

Customizing or Individualizing RQF Pedagogy

Overview. Thirteen participants shared experiences in which they explicitly compared and differentiated their approaches to RQF in response to perceived needs and characteristics of individual students. The narratives they shared contained actions and approaches that were multicoded across several RQF Categories: starting points (Category 2); literature (Category 3); peer interaction (Category 4); exposure (Category 5); feasibility, scope, and specification (Category 7); presenting research questions (Category 8); supplemental professor strategies (Category 10); comments and expectations (Category 11). The challenge that remained was attending carefully to the data to discern what had been varied across these multiple themes. The answer I identified was the invitation to formulate research questions.

In other words, when the comparison narratives provided by the 13 participants were re-examined through open, axial, and focused coding, a new theme emerged. The mentors in my study described varying the degree of freedom permitted to students as part of the research conceptualization and design process. I grouped these variations into five distinct levels, ranging from lowest to greatest degree of freedom and independence (see Table 41 for details). At the lowest level, students were assigned preformulated research questions and specific tasks. At the highest level, students were explicitly invited and expected to generate their own research questions. The intervening levels were marked by granting students progressively more freedom to explore.

Although the lowest (level 1, most restrictive) and the highest (level 5, least restrictive) levels were clearly delineated, the distinctions between levels two, three, and four were subtler. These intermediate levels shared many commonalities in both the approaches participants reported using, and their rationales for choosing these. The level divisions were meant to illustrate a progression toward ever-greater student contribution and participation in the research question formulation process. In contrast, the differences that distinguished the levels at the ends of the spectrum were more pronounced (e.g., assigning versus offering questions in level 1; co-constructing questions versus inviting independent student question formulation in level 5).

Table 41

Levels of Student Involvement in the Design and Conceptualization of Research

Level name	Description of level	Student participant in the conceptualization and design of original research
1 - Assigning research questions	The professor develops a research question and assigns it to the student. The student develops lab skills and familiarity with the area of study as part of pursuing the project as conceptualized by the professor.	Little to none
2 - Offering research questions	The professor provides the student with a set of possible research questions or studies to undertake. The student explores different topic areas and scientific techniques in order to select and pursue a research question from this set.	Possibly some
3 - Providing general areas for exploration	The professor provides the student with a general area of inquiry, within which the student is expected to explore relevant topics; the student identifies and refines a research question that falls within the professor-provided area.	Moderate
4 - Co-constructing research questions	The professor and student identify an area of study based on shared interests and collaboratively construct research questions for the student to pursue within the selected area.	Moderate to high
5 - Expecting and inviting independent research question generation	The professor expects and/or invites students to independently generate research questions for scientific inquiry. Mentor prefers but does not require these student-generated questions to fall within the funding or program of research. The mentor's role is limited to offering feedback or removing support entirely as students are expected to assume greater self-direction.	High

Level 1: Assigning topics. Six participants described how they assigned preformulated research questions or topics to some of their students: "The supervisor already has those [research] questions in hand [for the masters students]" (Participant 9); the questions are then given to the students as "the beginning of their project" (Participant 8); the advisor tells the students, "Here's what we need you to do" (Participant 16); and concedes that he relies on a "dictatorial approach" (Participant 7). The wording in these quotes was selected to convey the highly directive role that professors described when relating these narratives. Two participants emphasized the importance of ensuring that the project "is fairly well-defined" (Participant 5), explaining how the advisor has "to make sure [the assigned] research question [has] enough

steps" (Participant 19). In all cases, these professors explained how they assigned some very specific, well-structured inquiry to some but not all of their students.

A single theme emerged as the resounding rationale for assigning research questions: the limitations of what could be expected of a novice in their scientific community. All six participants described the high levels of prerequisite procedural and content knowledge needed for inquiry in their respective fields. For example, a green chemist expanded on degree level expectations with "the first couple of months is simply learning how to do experiments and they're doing what I told them to do" (Participant 8). A cancer biologist's quote (Participant 9) drew an even closer link between mastering experimental techniques and formulating research questions:

> We don't typically expect that, by the time that they finish, [master's students] will have gotten to [the] point of being able to formulate and carry out an independent research program . . . you expect by the time they're finished that they can figure out how to do experiments.

The above quote implies that mastery of experimental techniques is a requirement for formulating research questions. A biomedical physiologist expressed a similar sentiment with regard to foundational knowledge, explaining that students could not simply dive in and start generating research questions independently without mastering "reams of details you need to know just to have a conversation" (Participant 7). A genomicist used preformulated research questions to address the urgency of launching novices into her research: "Students don't really have any framework. So they really just have to get started on something" (Participant 16).

Extending the theme of prerequisite knowledge and experience, two other participants emphasized the amount of support and structure needed by those who are new to the field. For example, a neurophysiologist noted that students who “were kind of earlier in their career. . . needed a bit more guidance” (Participant 13). A materials physicist explained why he gave stronger students the freedom to explore general topic areas while assigning well-defined questions to his weaker students: “The weaker students more or less hang their hat on every word you say . . . . And it’s tough, because it’s a big liability. You have to make sure your research question is rock solid” (Participant 19). Regardless of the rationale, all the actions shared in statements grouped in this level are very didactic: Students are instructed, assigned, and delegated tasks and projects by the supervisor. In the next level, the mentor’s actions provide greater consideration of student interests.

Level 2: RQ menu / RQ exploration of different topics. When reflecting upon how their experiences with supporting student RQF differed among mentees, three professors talked about offering different possible research questions to their students: “I don’t let master’s students necessarily find their own projects . . . . I usually provide a couple of options” (Participant 7), and “we did a bunch of different things and it was a process that took some time before he discovered what he really was excited . . . to do for his PhD thesis” (Participant 20). A comparative physiologist (Participant 14) elaborated on the strategy of introducing students to different possibilities as follows:

> There’s different levels of what I allow students to do. So for an undergrad, obviously, I’m not going to say, “just go find a question!” I usually give them a rough frame of what my overall question is, and give them little openings . . . . And then they get to sort of take it from there.

In above quote, the physiologist emphasized degree level as her reason for letting students choose from a set of possibilities, yet the exploration is still very limited:

> And that's really more for an undergrad though, like, "here's the list of transporters, find one of the transporters that you really are interested in, and why, and then we can teach you how to clone them and sequence them and then that's your project." (Participant 14)

Alternatively, a biomedical physiologist (Participant 7) elaborated on the importance of using different topic areas to identify student strengths: "See what [students are] good at, physically, since what we do has a lot of fine motor control, steep learning-curve type tasks." A quote from an astrophysicist extended the student-centred conversation from degree level and strength toward student interests:

> There are students who come in knowing exactly what they want to do and there are other students who say they want to work in this area of astro particle physics but . . . don't know enough about it to know what [they] want to do with it. (Participant 20)

The astrophysicist went on to describe the above process as one in which students were not only permitted, but actively invited, to explore different topic areas as a fundamental part of the process of transforming into leaders in the field:

> Remember it's not wandering . . . . It's more like sampling a series of subjects . . . that means for instance at our collaboration meetings, going into different sessions and listening to what your colleagues are talking about . . . sitting in on the conference calls, contributing when you can . . . you may do that for six to eight months, helping other processes progress and going "okay, I can do this, but it's not really a life that's exciting for me, it's interesting but it's not where I want to do my thesis," so you move on to different topics, a slightly different group of people. You listen to their

> conversations and eventually you understand their issues and how you can contribute and . . . suddenly you think, “oh yeah this is way more exciting for me.” And so you jump in and you become one of the prime movers in that area. (Participant 20)

The above quote illustrated how and why the participant chose to invite his students to explore different topic areas—he believed exploration as a novice to be essential to becoming a trailblazer in that field. The three participants’ quotes highlighted a common expectation that students at a particular degree level are not yet able to play a significant role in formulating appropriate research questions, but can—and should—be allowed to explore and select a topic from a list of options provided by the mentor.

Level 3: Provides general topic area. In the first two levels (assigning and offering research questions), students worked within parameters that were well defined by the professor, but with the second level incorporating a greater focus on exploration. The theme of exploration continues in this level; what differs between levels two and three is the degree to which the parameters of the students’ inquiry are specified in advance by the professor. In level 3, instead of assigning or offering research questions, participants spoke about launching students into scientific inquiry using a broad topic area. For example, a comparative physiologist described how she provided master’s students with a general topic area in the form of an interest/gap in knowledge:

> For the master’s students, it was more . . . for magnesium, we know that . . . dietary magnesium is important, but we don’t know how it gets transported, we don’t know where it gets transported, we don’t always think about it. So go read up on what happens in mammals, what happens in invertebrates, and then come back with a proposal for what’s happening in fish. (Participant 14)

In the above example, the physiologist's student was expected to turn this general gap in knowledge into a specific research proposal. Similarly, a materials physicist said "you just need to sort of put it out there as a general question and a bunch of ideas around that . . . the good ones . . . [they] usually take it [in] a direction of their own" (Participant 19). The same participant had mentioned providing weaker students with tightly-defined research questions. He explained that strong students did not need well-defined research questions because they could be trusted to expand, explore, and direct the scientific inquiry.

Reasons for entrusting students with a general area of exploration converged with those provided in the previous category: The alignment of the research project with student strengths and degree-level expectations. For example, a theoretical physicist talked about the advisor's responsibility to guide students toward their strengths:

> I pointed out the basic topic that I want to study, it's a very ambitious project—yes I know that this student is technically strong, and the student is going to work on it. So he—even within his subfield, there's a huge variety in terms of how a project comes about. And this is tailored to the student. . . . Some students are technically very strong, some students are very imaginative. I think the responsibility of the advisor is to pick up on the strong points, and to try to work with the strong points. (Participant 24)

The three participant quotes that were gathered to form this level allow for student exploration and the tailoring of professors' research interests to the needs of the students. Missing from the first three levels is the quality of collegial collaboration.

Level 4: Collaboratively constructing research questions. When asked to compare how RQF mentorship experiences differed among their students, four participants talked about a back and forth collaboration process between the professor and student.

A biomedical physiologist (Participant 7) described how he, as the mentor, directed the student to "tell me what you want to do, give it to me, I'll cover it in red ink and give it back to you and we'll do this several times. And you're going to see exactly what this is about." The physiologist described the process as more student-driven and collaborative with mentees whom he described as more competent or senior in degree level:

> The good students—even the good master's students, but the good PhD students, by year four or so . . . [find a source of inspiration] on their own. . . . And they go, "okay, I'm going to try this." They run it by [me] and they try it or they do some simple experiment, get some preliminary data, bring it to me . . . [and say] "what do you think?" And it becomes far more collaborative.

The comparison highlighted the increasing levels of collaboration that occur as students acquire more hands-on experience and more independently generate leads for research questions.

Three of the four participants explicitly mentioned an iterative process in which they provided starting points upon which they expected the students to expand. A neuroscientist (Participant 1) described how he started "them off by providing a question, and then . . . collaboratively come up with new questions based on that." He reasoned that this approach allowed his students to explore and uncover their interests when they were new to a field. This participant also mentioned that "the best students would have their own questions, and . . . I would just kind of facilitate," but that these constituted a minority of his students. From this I inferred that the professor engaged in the more hands-on collaborative process in order to bring the majority of his mentees closer to the same level as the stronger, more-focused students.

A genomicist (Participant 16) described how much she appreciated one student's self-directed efforts to explore and expand upon the professor-assigned starting point. When the student expressed a desire to continue working on the topic she was originally assigned by the professor as an undergraduate research project, the genomicist said:

> Her project came about through her conversations with other people in the lab that didn't involve me at all . . . that was really nice to see her take that initiative . . . [to] synthesize input from other people and then decide on something that she wanted to pursue // she proposed a . . . novel experimental approach . . . a novel way to address her research question.

The genomicist concluded by explicitly sharing her appreciation for this type of student-driven refinement of research questions, saying "it's nice when people come up with new ideas that don't involve me, because obviously we need all of our brains working on solving these problems" (Participant 16).

A materials physicist (Participant 19) talked about how he wanted his students to "start asking their own questions and answering them and relating it back to the question that [they started with]." It was more difficult to discern a rationale for this participant because he did not explicitly use words such as "because" or elaborative causation statements such as "it's about." The earlier context in which the physicist's quote arose provides a hint as to why he values a student-directed collaborative mindset among his students:

> She still . . . takes out her pencil when I talk, and assumes there's going to be closure to her answers. And I can see still the undergraduate student in her, that she assumes she's going to leave my office with answers. . . . I've talked to her openly about that, saying, "As you move forward . . . I want you to make your own suggestions about what you think might be going on, to explain your data, or explain why it's not what we think it is. Right now I'm sort of . . . telling you to do these steps, even trying to interpret it for you,

> but eventually I want you to come back and tell me your ideas about it as well." . . .
>
> And she's waiting for the answers [because she is still] seeing me as the instructor.

In the above quote, the participant describes his frustration with a highly competent student who expects him to have the final say as to what answers are correct, rather than view him as a collaborator with whom she should be sharing her own questions and answers.

The underlying theme around which the above four participant quotes coalesce is the desire for student-driven collaborative effort. The contexts in which the quotes arose suggested that participants would like students to uncover and work on projects that appeal to their strengths and interests, to engage in the design and direction of the inquiry, and to have progressively increasing contribution as their skills and mastery increase.

Level 5: Removing support. Six participants expected students to generate their own research questions—an expectation they applied to students who were more senior, experienced, independent, or imaginative. In each of the six statements, the fact that the professor held the expectation was clearly expressed in the interview transcript. Less clear were the actions and strategies used for supporting students in meeting this expectation. For example, when asked about the level at which scientists in his field start to develop their own research questions, a cancer biologist replied:

> Some students like to work autonomously; . . . they can generate a good solid thesis and publications. And some can't. Some require more guidance. In the absence of a supervisor, they might not know what to do next. And so as the students mature, generally they become more autonomous. . . . Certainly by the time they're in the first year of a PhD program . . . they're starting to learn how to [develop research questions]

> themselves // [at the postdoctoral level I can say] “Here’s the project, I’ve got five years of funding . . . here’s my grant, take [it] and do it.” (Participant 9)

In the above quote, the participant explained how he differentiated the level of support he provided based on student characteristics of maturity and the ability to make progress independently. This transcript segment did not spell out the details of what the biologist did differently from one student to another. When this participant’s comments were compared with those of other participants, what emerged was a theme of mentors removing support when they expected their students to formulate their own research questions. For example, a geodynamicist stated: “When I detect that a student has more imagination and a willingness to discover something and inquire something different, then I let them all by themselves” (Participant 18). The rationale provided by the geodynamicist for giving particular students more autonomy was that “some students have more imagination than others . . . I [didn’t] want to interfere very much with their imagination” (Participant 18). Whereas previous participants emphasized degree level, the cancer biologist and the geodynamicist differentiated their mentorship of student RQF based on student characteristics of maturity and imagination. Neither participant elaborated on the specifics of how they removed or phased out their support as a mentor.

In contrast, the statement provided by a comparative physiologist (Participant 14) was much more explicit regarding the manner in which she removed support for students. This participant trained her students in experimental procedures and helped them navigate the literature when they needed such training at the undergraduate and master’s level. The guidance that she provided decreased dramatically at the doctoral level. She stated: “I don’t expect to help them as much with forming their questions” because “[I] expect them to be incredibly independent.” Not all support was removed, as she continued to provide her doctoral students with feedback on their research questions and their plans for pursuing the questions, but her postdoctoral students were expected to generate full topics and complete plans on their own.

The descriptions provided by the first three participants painted a picture of the four student characteristics and abilities that prompted these mentors to differentiate their mentorship strategies: maturity, self-directedness, imagination, and degree level. Whereas some participants talked about student characteristics associated with independent student question generation, other participants related the benefits thereof. For example, a neurophysiologist related the mentorship practices that he inherited from his own advisor:

> Don't tell the granting agencies this, because I don't think they like to hear it—but basically, you design a research question, you kind of come up with a project, but then you fully anticipate that the final actual questions you ask might be quite different. As long as they're roughly in the same vein of what you're interested in—so when I say my supervisors let me design my own projects, they totally did, but it was of course within the remit of what their lab was studying, right? And likewise, I will kind of do that with my own students. (Participant 13)

In the above quote, the neurophysiologist described how he allowed students to deviate from questions in his grant in order to generate their own research questions. He continued to share the following:

> I think it's important . . . because I think the best results . . . come when a student is really engaged in a project. Because, at the end of the day, I'm too busy to really be on top of everything in a project. . . . I feel like what happens if you have a student who's just

> doing a project that you have fully crafted for them . . . they will not be as . . . keen as if it was their own project. (Participant 13)

The above quote related two participant-defined benefits of student engagement in research question formulation: enhanced student motivation and more efficient allocation of the mentor's finite time and attention. In the absence of explicitly shared causation statements, these benefit statements can be considered a proxy for understanding participant motivations for providing some students with opportunities to conceptualize scientific inquiry. Another benefit or rationale was provided by a green chemist:

> I don't do this for my master's—but for a PhD student I tell them, "Some of your time should be spent coming up with something new. . . . Think of a new project. I might steal it and give it to a new grad student after you're gone, but come up with something new." (Participant 8)

The above quote illustrates how new and creative research directions can be a benefit of having students independently generate research questions. This benefit was so valued by the green chemist that he extended an explicit invitation to his students.

In other examples, the communication of this expectation was less clear. In this next example, there was ambiguity regarding the extent to which an expectation is shared with the student. The quote started with a theoretical physicist (Participant 15) expressing his disappointment with one of his doctoral students:

> What I would like to hear from him actually is that he would come with his own ideas. . . . He has worked on a very specific topic . . . and he knows a lot about it, but I would really like him to formulate his own questions that he wants to pursue. // It's just not happening. // He is mostly executing my ideas.

When probed by the interviewer about whether this expectation was shared with the student, the participant hesitated and discussed his uncertainty regarding the student's level of interest and motivation in his research.

This category contained participants' expectations for the highest level of engagement in the conceptualization and design of scientific inquiry in the present study: the independent formulation of research questions by students themselves. From the six participants who held this expectation, the mentor actions that could be discerned for supporting students in fulfilling the expectation included the communication of the expectation, permitting students to pursue questions outside of the mentors' grants, and the removal of supervisory guidance and support. This expectation was not applied by the mentors to all of their mentees; students had to either reach the doctoral level, or to display a certain degree of self-directedness, maturity, or creativity.

Synthesis. To connect the five levels of student engagement in RQF back to the objectives of this study, here is a restatement of the dissertation objective from Q2b that led to these results:

- Do professors reportedly vary what they do to help students find, frame, and formulate research questions to meet the perceived needs of individual students?
- If so, what do professors do differently from one student to another when it comes to developing student RQF?
- What rationale do professors give for differentiating their approaches?

Yes, professors in my study did vary their mentorship of student RQF. Specifically, they individualized the extent to which they invited each student to conceptualize and design future research. The participants did so by changing the specificity of research topics that they offered to the individual students. At the highest level of inquiry, professors expected students to formulate their own research questions with little guidance. The opposite end of the spectrum showed how some professors would assign tightly-specified research questions to students who were new to their lab or their subject area. In between the extremes, students and professors constructed research questions collaboratively.

In parallel with the degree of specificity, professors also varied the amount of direct training they provided to students in lab skills, writing, or searching the literature. In the five identified levels of student engagement, mentorship strategies that were explicitly applied by participants to students at the most restrictive level were much more difficult to detect at the least restrictive level. At this advanced stage of student participation, professors largely removed support as they deemed students ready to formulate own research questions.

Degree level was the most frequently mentioned rationale for participants varying their approaches—an unsurprising finding because I often used prompts about degree level to elicit more concrete examples during the interviews. Other factors that determined the level at which professors scaffolded student engagement in RQF included students' familiarity with the field, the degree of procedural- and content-knowledge mastery, and their fine motor skills or technical abilities in the lab. Finally, characteristics such as creativity, initiative, imagination, maturity, and self-directedness also emerged as mediators that affected the opportunities mentors were willing to extend to students when it came to the design and conceptualization of research.

Mentors scaffolded the level of student engagement in the conceptualization and design of scientific inquiry. The value of such scaffolding was confirmed by previous research on the student perspective. For example, Gautier and Solomon (2005) evaluated an intervention for undergraduate students in earth sciences that included modeling, concept maps, as well as discussion and feedback as students generated research questions within the topic area provided. The authors found that students needed to be guided within the parameters given by the professor before they were sufficiently experienced and comfortable with the open-ended challenge of generating research questions. Similarly, participants in the present study guided students within parameters that limited the open-endedness of challenges and expectations given to students. Streitwieser, Light, and Pazo (2010) also evaluated a workshop in which biology and chemistry undergraduates proposed their own independent, original research projects. The authors designed their workshop based on Vygotskyan scaffolding (Vygotsky, 1978) and the situated-learning principle of legitimate peripheral participation (Lave & Wenger, 1991). Streitwieser et al. (2010) contended that students learned what it meant to work as a scientist when they were supported in undertaking authentic and legitimate activities that facilitated their entry into a community of practice. Mentors' efforts to customize the amount of guidance and training provided to students during this process were essential to building student confidence and identity. The types of starting points and training outlined by participants in the present study provided examples of legitimate peripheral participation. Such activities transitioned students from the periphery of their community of practice (in which the students were learning lab skills while familiarizing themselves with the topic) to a more central role in the community (in which students were collaboratively or independently generating leads for future research).

Thiry and Laursen's (2011) study of undergraduate research experiences in STEM confirmed the importance of striking a balance between providing guidance and removing support. Students in this study were frustrated when exploring new topic areas if their advisors provided too little or too much supervision. The mentors in my study provided narrow and specific parameters for novices to their lab, guided students who were functioning at intermediate levels, and then removed support for advanced students whom they expected to generate their own independent questions. This outcome of a continuum for inquiry instruction is consistent with those reported by Herron (1971), Martin-Hansen (2002), and Banchi and Bell (2008). While these other continuums exist at the elementary or secondary school level, my study is the first to present a continuum for inquiry instruction at the postsecondary education level. The present results inform practice by providing five levels of student engagement in RQF, levels that can be determined by the mentor's assessment of student needs, interests, and experience, as well as the subject matter and procedural knowledge required at each level.

Illustrative Cases

Overview. For each of the two illustrative cases, I constructed a narrative from the following information: the participant's profile, a description of the nature of his or her research, how he or she used terminology central to the design of scientific research (e.g., research topic, research objective, research question, hypothesis, prediction), his or her values and beliefs related to RQF, and his or her methods for developing student RQF. The narrative was richly illustrated with quotes, the interview context in which each quote arose, and the contribution of that quote to our understanding of the participants as scientists and as mentors. What emerged from these two illustrative cases was a picture of how the development of student RQF might look when it is highly valued and intentionally pursued by mentors.

Ecologist (Participant 3). Information for this first illustrative case was provided by an ecologist, a professor who exuded extraversion, warmth, and intense interest in my research topic. Unique about this interview, compared to those not selected as illustrative cases, was how articulately she spoke about developing RQF skills in her students. Her graduate training was completed at an internationally recognized university where mentorship and frequent interaction with leading scholars were the norm. Over her 20-year career as a professor, she had supervised approximately 30 undergraduates, 10 master's, and three doctoral students (see Table 42 for more details). According to the participant, she studied "lots of different things" and has "published across a very wide range of fields, in different journals." This participant spoke emphatically about empiricism, and so was given the pseudonym "Professor Emp."

Table 42

Supervision Experience for Professor Emp

Level	Total number of students supervised to date (self-report)	Average *n* = 24 (6 physics, 6 chemistry and biochemistry, 6 biology, 6 other life sciences)
Undergraduate	30	27.8
Master's	10	8.8
Doctoral	3	9.3
Postdoctoral	0	8.2
Totals	43	46

Role of research questions. For Professor Emp, the role of the research question was to drive her research agenda. When asked about how she narrowed broader topic possibilities down to actual research questions, she provided the following answer:

> I: So how do you go from [your initial research interest] to the actual research question?
>
> P: How did we formulate questions? Well, you do a lot of reading. . . . I was already an expert in the first and second research areas that I previously described to you . . . so, basically, I just read the research literature . . . and applied it to an ecosystem that I had an opportunity to work in and stated it as a question. . . . When I write my research

> up, I'm really driven by questions. I'd like to see people focusing; I'll always ask, "What is the question you are asking?" Because I think that a lot of people actually don't know what the research question is and they haven't reflected or formulated it clearly. So, I think this is the easiest way for people to get traction, or interest from other people, is simply to state it as a question. So it never takes me very long because I'm always asking questions.

Questioning was such a ubiquitous way of thinking for Professor Emp that she found it relatively easy. Her formulation and selection of research questions was grounded in practical considerations around the data that she could gather to answers questions that, in turn, emerged from her reading of the literature both within and beyond her immediate areas of expertise. Furthermore, probing for RQs was a part of her interactions with other researchers, helping these researchers articulate their questions. She elaborated on the second point when describing her methods for developing student RQF abilities: For Professor Emp the process of probing for the underlying question enabled one to better specify, clarify, direct, and communicate one's research.

Values and beliefs related to RQF. Four criteria could be discerned regarding characteristics that Professor Emp valued in research questions. The first criterion started as follows:

> I'll write down here what I just said to all the students as those trying to get them to articulate the thesis topic—exactly with all of these hypothesis, what it is, and I'll make them all restate, and restate, and restate. And the thing I—that I said about the research question has to be a question mark in it because you won't give me research questions without a question mark.

Professor Emp was one of the few participants to insist on the importance of ensuring that her students stated their research problem in the form of a question. She continued to extend her comments on research questions in general to questions that were specific to ecology. This quote provided the second requisite or quality criterion—multidimensionality:

> As a researcher, [you] are forced to do research that simultaneously addresses different scales: either of time or space. If you don't do that, if you try to zero in on one scale, say a population, or an individual, or a community, and try and explain the ecology of the situation that you're observing with that research question, if you haven't also asked the question of what's happening in a different scale which could be the ecosystem scale or the individual, you probably missed what's driving or determining what you're seeing.

Professor Emp stipulated that research questions in ecology were multidimensional—they simultaneously addressed both micro- and macro-level factors while maintaining a longitudinal view of how the phenomenon unfolded. She then compared her discipline with history to emphasize the unique importance that ecologists placed on this multidimensional approach to inquiry:

> A systems view is one aspect of ecology and the individual view is the other aspect. So either being more individualistic or more systematic, you have to do both of them simultaneously. This is, as far as I can tell, actually not required for any other scholarly field that I have ever had a conversation with. It is not de rigueur, it is not essential. You can still somehow manage to be a well-respected historian and be the uber-world expert on the year 1814, September 1814, and you can know as much as you could know about one place on the planet and something then, and people will still respect you as a historian. If you did that in ecology, you will have no respect from anybody. So you'd

> have to have studied not just that village, but that country, but that continent, but the 10 years, but the 100 years, and the history and the evolution, you know, you just can't know something about something that happened at that one time. You might do it for one paper, but if you do that, you'll get nailed.

A subsequent exchange illustrated a difficulty that I commonly encountered as I tried to elicit additional quality criteria for research questions—the overlap between research questions, hypotheses, and predictions:

> I: Are there structural or semantic features of a research question in ecology? Like, it should have, you know, can you make a checklist of, "make sure . . . ?"
>
> P: Well it should have hypothesis predictions, models, statistical analysis, all the things that you gave in that template.
>
> I: Okay, so the research question:
>
> P: And if it's not there, and if a grad student is going into defense without that, they'll get nailed.
>
> I: Okay. And then what else are features of a good research question in ecology?
>
> P: Tons of data and excellent analysis, statistical . . . .
>
> I: In the research question? Not the topic, the question itself.
>
> P: No, I think that that's it.

From the above exchange, it sounded like a third requirement for research questions was the inclusion of terms central to the design of scientific studies (e.g., "hypotheses and predictions"). When specifically probed about the research questions themselves, Professor Emp expanded on the point by elaborating the importance of statistical analyses. Quotes such as this one are scattered throughout the entire data set, suggesting that, for scientists, the research question itself must include terms such as hypotheses and predictions, or that they were answering interview question with reference to the entire research study as opposed to the “research question” itself, what I had conceived of as the problem statement in scientific inquiry.

The fourth characteristic that can be deduced from the transcript is clarity. The following exchange illustrates how this characteristic can also be interpreted as a quality criterion for research questions in general:

> I’d like to see people focusing; I’ll always ask “What is the question you are asking?” because I think that a lot of people actually don’t know what the research question is and they haven’t reflected or formulated it clearly. So, I think this is the easiest way for people to get traction, or interest from other people, is simply to state it as a question.

She continued, sometimes tangential but always emphatic, elaboration on the importance of clarity of focus, and accessibility of the wording also recurred later in the interview:

> I: Okay. So what role does the research question play, like you were telling me how?
>
> P: Key, key. Any research talk that you go to, if the person cannot clearly articulate their research question—in ecology—and walk away, which doesn’t seem to be the case in molecular and cell biology and cancer research, and, you know, I frequently go to research—so one of the things that I say to all of my students, undergraduate, graduate, and my colleagues, is, if I’m going to, in theory, I may not know the jargon, but I should be able to go into any research lecture in any field in any university and understand what that person’s research question is. I don’t care what faculty or department they’re from, but if they cannot articulate it, they’re a crap researcher, end of story.
>
> I: Because the research question gives you. . . . .

> P: Because, as Einstein said, if you can't explain it to a six year old, you don't understand it! Pretty simple. I'm going to look at you and go, "Wow, those people over there say you're smart, but I think you're stupid, because I can't understand a word that you're saying." Like, I don't care, so this whole idea that we're in the ivory tower and there are experts—experts who can't explain things clearly, to me they're not an expert if they have to rely on transparent jargon.

According to Professor Emp, research questions in ecology should fulfil the following criteria:

- The problem statement that guides the scientific inquiry must be stated in the form of a question (a research question!).
- Research questions should simultaneously address multiple levels or dimensions (e.g., time, geographic space, micro and macro scales).
- Research questions must contain hypotheses, predictions, and statistics.
- They must be clearly formulated and accessibly communicated.

Her elaboration of the uniqueness of her field led directly into how she cultivated students' understanding of different terms from the scientific method.

Research questions and related terminology. At the beginning of the interview, Professor Emp was busily searching for her favorite research methods textbook while describing how students struggled with understanding terms from the scientific method. The following exchange illustrated how, without prompting, she shared a teaching strategy for facilitating that understanding:

> P: I'm trying to [inaudible]. I mean I used to teach, I taught once a first-year course about where do biological facts come from and we spent a lot of time talking about

scientific methods, so on and so forth. [inaudible] Where is her book? The problem is I keep lending them to people.

I: [laughs]

P: She has—it's at home, that's—

I: That's okay.

P: Because there is, there is sort of more walking you through.

I: Which book is it? Author?

P: I'll look it up for you.

I: Okay.

P: It's a statistics book actually.

I: Oh, okay. Stats book. I haven't looked in there yet. They would have it too, descriptions on how to come up with your question.

P: You should be teaching the course almost, that's why I actually do. Anyway, here we are. So this is—here you go, at least you can see. So this is *Introduction to Statistics for Biology*, third edition. And it's fantastic—how to sample a population, normal distribution, expressing variability. Then it has planning an experiment, principles of solving, first catch a worm, objectives, replication, testing the hypothesis is from a statistical point of view, but it really does walk you through. It's a great book and it sort of gets—it sort of deals with those concepts.

I: Okay, thank you.

P: Some other things, basically what I had them do, I had them write down, say, the title of the honors thesis so, up there we were just doing things on the whiteboard and they had to express it as a hypothesis, that they had to express it as a research objective. Then, had to express it as a research question. Then they had to express the predictions.

I: You help them work through it.

P: Oh, my god, yes. I kept saying the same thing. It's really restating the same ideas in slightly different ways for slightly different purposes. And I can tell you that even our grad students—because I taught the intro grad course—can't do it.

I: Hmm.

P: In fact nobody can do it really, really well and it really has to do, let me see. He'll get you a cup of coffee.

The most important message in the above quote is the fact that Professor Emp reported having students restate or reframe their research questions as research objectives, predictions, and hypotheses because doing so "is really restating the same ideas in slightly different ways for slightly different purposes." In this next exchange, Professor Emp revisited these key terms from the scientific method as she shared how she helped students to delineate the scope of their research.

I: For their original research questions that they come to you with? What do they look like, in the very beginning? They're vague . . . .

P: No, no, they're very specific. So I'll just give you an example. There's one guy, he's doing a master's.

I: One of these?

P: So he's asking questions about a general question of, what is the number of, what's the number of birds that are dying from flying into windows. Window, it's called window kills, right? Window kills. It turns out that the building, on the camp at night, when the lights are on, birds fly into windows and they die, you know this story. During the day we have a woodlot over there. Birds are flying across. They're seeing the sky reflected in these windows and there are leaves and vines on the outside of the windows so they're bouncing off here, and you go in the morning or late morning, and there's all these dead birds, especially during migration time. So that's the topic of his master's, which is very important for bird conservation, is, what's the role of buildings in bird mortality? So this guy shows up in this course and he has to—and that's his basic research question, but then he has to frame that as a hypothesis, he has to—he has to think about it from hypotheses about the mortality. He has to have a research objective: What's the objective to do this? He has to have some predictions. You know, it could be that birds on the north side of buildings are more likely to, or birds on the east side, whatever, there has to be directionality, but he has to be able to put that research into the historical context of long-term ecology research of that area of study. So this guy, smart kid, comes to me and says, "I can't do a deep history because the first journal paper about window kills in birds was only published just over 20 years ago." And I'm like, okay, this is not what we're talking about. We're talking about the general, the broader research questions and the concepts that you're working with—the ecological concepts. I said, "You can go back 150, 200, 300 years." He said, "No, I can't, because I looked on Google Scholar," or "I looked in SCOPUS and there was just nothing." So every single student was like this, so they had a very specific research question, "I'm looking at lakes, fish in lakes, to see whether in warming lakes with climate change, the fish distribution changes." Okay, that's your research question. It is incredibly specific. That has got an entire ecological theoretical concept.

Table 43 uses excerpts or inferences from the above quote to better portray how Professor Emp viewed concepts that were central to the scientific method.

Table 43

Examples of Terms That are Key to the Scientific Method in Ecology

Scientific method term	Example (inferred or expanded based on participant's text)
Research topic/ research objective	The objective of this study is to explore the role of buildings in bird mortality [inferred from participant excerpt].
Research question	What is "the number of birds that are dying from flying into windows"?
Statistical hypotheses (H_0 and H_1)	H_0 (Null hypothesis): There will be no significant differences between the number of window kills found at any side of the building. Or more precisely stated in statistical terms, the null hypothesis would be "The test statistic (e.g., F) for the difference between the mean number of window kills on different sides of the building will fall within the selected confidence interval and therefore not differ from zero beyond change at the alpha level selected." H_1 (alternative hypothesis): There will be at least one significant difference in the number of window kills found between two or more sides of the building. [Both hypotheses were inferred from participant transcript]
Predictions	"Birds from [this particular] side of buildings" are more likely to be subject to window kills than birds on the east of the building.

Throughout the interview, directing the participant's focus toward the research questions and toward processes of finding, framing, and formulating these questions themselves, as opposed to the formulation of hypotheses and predictions, was challenging. Table 43 illustrates how these terms are interdependent. My conversation with Professor Emp also helped me realize that, as a researcher, I had presumed that one had to first pose a research question before generating the hypotheses and prediction statements that could answer it. The following exchange illustrates how this presumption did not align with the participant's view:

> I: Okay. So the research question gives you a hypothesis that you can test, and falsify, or—[Participant interrupts interviewer]
>
> P: The research question comes out of the hypothesis. You have you start with your hypothesis. Your, um, Popperian hypothesis as opposed to your hypothesis, H_1, H_0. Then that hypothesis is what generates your models and your predictions, which

generates your research question, which—your research question formulates—is formulated out of your all your hypothesis and conceptual thinking.

I: So you have a research interest, a curiosity, in a broad area, and then you go to hypothesis, and then from that you come up with a research question?

P: Yeah. That's how I think it should be. And students obviously jump in at different points along the route, but they have to be able to backtrack to that. They have to be able to put it in that framework. If they can't, then they're really going to get into trouble and do bad research.

I: And I'm finding even with natural scientists that the role of the research question differs a little bit from one discipline to another. So, an example of—one person might tell me that a research question is just kind of a starting point, like a launching point to pursue an area, and then from the data that emerge, they see what kinds of answers and what kinds of questions can be answered by their data, and

P: Oh, god! That's post—[inaudible], oh my god, that's horrible! Okay.

I: And then, from that, they come up with research questions. So, a research question is a guidepost.

P: Yeah, it's iterative, it [inaudible], and you can start anywhere along that route. But you've got to always backtrack to what the hypothesis is, what the working hypotheses are.

This exchange illustrated how Professor Emp viewed the hypotheses as the starting point for the design of scientific studies, out of which research questions, models, and predictions can be generated. Although she later conceded that the process is iterative, this concession might have been in response to my probing. Her initial unprompted answer, combined with her shock at the notion of collecting data before posing research questions, illustrated the primary role she envisioned for the hypothesis.

Methods for developing student RQF. Professor Emp stood out amidst other participants in the explicitness, comprehensiveness, and integrated coherence of the methods and approaches she reported using for developing student RQF. Main ideas in her extensive answers were identified through her use of transition and explanation words such as “also,” “the other thing,” and “so.” She started by describing how she helped students with the scope of their research:

> They really struggled about scaling their question—very specific question that their master’s supervisor or whatever gives them. They come into a lab. There’s research funding to study why birds are dying around here, whatever, you know, but that is—that is not a master’s or a PhD because it’s completely lacking in conceptual theoretical framework, which is the same for any field because you have to set it in the literature pertaining to that so they just couldn’t get it. So I had them doing mind maps. I published a paper that one of my students [started] . . . . Basically, it’s like the literature review of your thesis, it’s like the Chapter One context, he then published it and then he had all the different concepts and how the concepts were evolving over a hundred years and then we published, co-published it with a bunch of people. So I show them, I say, “here is a research journal paper based, rooted exactly in this essay assignment that you’re doing. It got published.”

In the above example, Professor Emp had one student create a concept map as part of a paper on the evolution of research questions on a particular topic. She then used the paper as a model to help other students better contextualize their own research interests in the literature. She proceeded by describing the challenges that students encountered when asked to pull out the research questions in a journal article:

> [*directly continued from previous quote*] So I kind of said, well, mind mapping over time how one research question in that research paper is leading—is evolving. You pick them out of the journal papers, what is the research question? How do you deconstruct a journal paper? So that's another big thing you find is most people don't know how to deconstruct a journal article and how to pick out from a journal article, any journal article or even a book or a chapter, what is the research question? What is the hypothesis? What is the objective? People can't do that, so I spent a lot of time teaching . . . [laughs].

Throughout this interview, Professor Emp's perception was that students are ill-prepared, in both content and procedural knowledge, when it comes to understanding the scientific method, critically engaging with literature of the field, and contextualizing their research within this literature. Professor Emp addressed this problem by having students deconstruct the end-products of their discipline (the studies presented in journal articles) into their component parts (research question, hypothesis, prediction). Next, she had them map out the history of the field, noting how these concepts progressed over time. In doing so, students would be better able to theoretically and conceptually frame their own research questions. In this next exchange, we can see the intentionality behind her process and strategies.

> I: [Interviewer and participant are looking at the table of students currently supervised by Professor Emp] Okay, can we grab a student where the research question changed significantly from the beginning to where it is here? Or changed more so than the others, so that we can look at the process of—?

> P: So you're really interested in process. So what I'm trying to do a lot with my weekly lab meetings—
>
> I: Process and strategy, yeah.
>
> P: —is to streamline process. So the thing is that what I find is pretty much all students—except for in the last five to six years—the bulk of students have huge problems formulating their research in terms of their research question, hypothesis, the objectives, the statistical hypothesis, all that stuff that you're asking about.
>
> I: They have huge problems? What do they do?
>
> P: They just can't do it. So what we do in our weekly lab meeting is we really focus. . . .

The above exchange demonstrated that her approaches were intentional, explicitly and directly linked to help students through "their huge problems formulating their research in terms of their research question, hypothesis, the objectives." She further described how she addressed these problems by having students engage in scientific dialogue during their weekly lab meetings:

> [*directly continued from the above quote*] So the main technique that I am using is getting them to speak about it. Articulate, open their mouth, and say something, because as I mentioned earlier, science is a dialogue. You know, could I have done my experiment better, is the research question good? It's a debate. You know, the science is never resolved. I mean, it might be 99.9% but then something will come up that will throw it out. So they have to do really, really regular presentations where they take turns to present and each other is questioned. They have to be able to state, "What is my research question?" So they have to be able to say all of this to anybody that they meet.

This above quote concerned engaging in scientific discourse face-to-face, in an informal setting of a weekly lab meeting. In doing so, students were expected to develop their ability to articulate their research question "to anybody that they meet." She then built on the theme of engaging in scientific discourse in a group setting to an activity completed individually by students as they read journal articles:

> [*directly continued from the above quote*] The other approach that I really press on is, they have to be able to read the peer-reviewed research literature and they have to be able to recall who wrote what paper and what was the research question in that paper? What was the hypothesis, what were the results? Did it support the original question or not? You have to be able to say that for papers. They also have to be able to mind map, map out these conceptual maps. So I really like mind mapping as something that is a good way to get people to visualise what's going on. So I'd say that those are my main ways of trying to get research questions refined and revisited. And I do [mumbles and then starts on a new idea].

This above quote was a brief recapitulation of the two strategies that she mentioned earlier during the interview—deconstructing journal articles and concept mapping. After she summarized her "main ways" of developing student RQF, she proceeded to comment on students' anxiety when it came to experimental failure. Professor Emp shared how she coached students through their risk-aversion:

> [*directly continued from the above quote*] What I've now realized is that most students today, as opposed to 10 years ago or even 20 years ago, when—they need to be micromanaged. So, in other words, students, to—so science is about jumping in at the deep end, trying something, and failing. Experimental failure, let's give it a whirl. I'd say that the bulk of young people today are anxious. It's the zeitgeist. Of course this doesn't apply to everybody, but when you have over-parented—and I am a parent—and

young people, they are remarkably unadventurous. And science is about being adventurous and asking questions and taking risks, but if you think, you're going to get a Nobel prize at the end of your fourth year, that's a problem. The other thing that I really work a lot with them on is writing up papers, entering contests, going to conferences, um, just being judged to get peer-reviewed feedback or feedback from as many different sources as possible and to learn to take criticism and act on it, so I work a lot in my teaching on giving students feedback and then coaching them through taking the feedback, because so much of what's going on here is about listening and taking feedback. So I would say that if you're constantly anxious because you have come to university with massive grade inflation, that you secretly know that you're not a Nobel prize candidate, therefore you are anxious because you've been told that you're an A+ student but you kind of know not everyone can be an A+ student. So how do you, how do you risk failing if you've experienced failure very little? So science is about kind of going into the experiment and going, "Well, I've got these research questions. I've got this experiment that's going to totally fail," and this is what I say to everyone coming here, "You're now going to redo an experiment that you redo an experiment that we tried five times before, we got so-so results. We're still doing the same experiment because there wasn't a big enough sample size, or the plants died or this or that, or something happened. We keep trying this." So science is about persistence, and it's boring; it's really boring 99% of the time and it's about attention to detail, so answering your research questions, you have to be prepared, if you're in the field, say you go to the Arctic and things aren't working out. You have a research question and everything dies,

> well you'd better come up with another research question really fast that is anchored in the work that you've done to some extent.

By having students elicit and integrate feedback, both informally through their weekly lab meetings and formally through peer-review processes, students learned "to take criticism and act on it." Working through risk aversion can be a general supervision strategy (as opposed to RQF). However, the comment emerged within the same quote as the one in which she shared her strategies for developing RQF and then ended with the participant drawing a direct link back to RQF.

During the focused coding, the above segment (P [1:07:22]) was assigned multiple codes: literature, feasibility and scope, presenting research questions, peer interaction, additional writing, supplemental professor strategies, as well as other comments and expectations. Throughout the answer, the participant was able to outline a procedure for helping students to gain a stronger understanding of both individual articles and a body of literature, articulating and defending one's own research questions, and eliciting and integrating feedback.

Synthesis. The two themes that permeated the interview were (a) the need for students to acquire a deep and applied understanding of the scientific method, and (b) to actively engage in the scientific discourse of a community. According to Professor Emp, these two themes are central to the development of student RQF skills. In a single uninterrupted answer, she coherently outlined her four main approaches to helping students develop RQF: (a) expanding the scope of a literature review beyond one's own taxonomic groups; (b) deconstructing journal articles into their research question, hypotheses, predictions and results; (c) concept mapping the historical development of a research topic; and (d) presenting research questions for the purposes of clarifying one's focus and eliciting feedback. The rationales that she gave for valuing these four approaches coalesced around her wanting students to contextualize, articulate, justify, and defend their research questions. Several points stood out about this interview: (a) Her answers directly addressed student RQF; (b) her strategies were comprehensively, coherently, and explicitly described; and (c) this set of strategies represented her way of helping students target specific weaknesses when it came to developing their own research questions.

Professor Emp also talked about the importance of eliciting and integrating feedback, but at times it was unclear as to whether she was talking about student RQF in particular or supervision and research in general. Furthermore, despite attempts to direct or redirect the conversation away from scientific research design in general and toward the formulation of research questions, Professor Emp responded in ways that illustrated the substantial overlap in how she applied the terms such as research question, research objective, hypotheses, and predictions. This overlap suggested that RQF may be a process that is dynamic and fluid, and at times inseparable from general supervision or other aspects of designing a scientific study.

Chemist (Participant 10). This next participant is a professor with 30 years of experience. Not only did he work more years as a professor than the average participant in this study (Mean = 16 years), he had also supervised more students (e.g., 25 PhDs; see Table 44 for details). The nickname given to him was Professor Launcher because he believed that research questions set the process of exploration in motion, and because his strategies for developing student RQF clearly started with the launching points that he gave to his students. Although I never explicitly asked him for his motivation for participating in my study, it appeared it may have been his interest in the topic, because he commented that "I think your project is really, really cool, very interesting."

Table 44

Supervision Experience for Professor Launcher

Level	Total number of students supervised to date (self-report)	Average *n* = 24 (6 physics, 6 chemistry and biochemistry, 6 biology, 6 other life sciences)
Undergraduate	100+	27.8
Master's	25	8.8
Doctoral	25	9.3
Postdoctoral	20	8.2
Totals	170	46

Professor Launcher was selected for the illustrative cases because he was a chemist who spoke passionately about an integrated set of strategies for developing student RQF. The methods and approaches that he used for developing student RQF were highly reflective, intentional, specific, and concrete. He also had a consistent record of high achievement as a researcher—the databases from major federal granting agencies indicated an uninterrupted record of competitive funding. During the interview, he talked about diversifying sources of funding, always ensuring that he had grants and projects from industry for his students to work on. Here is his description of this work:

> And the question we pose to ourselves is, what, today in analytical chemistry, would be really exciting? What's sort of, the big question—the grand challenge-type question? And we've decided that the grand challenge would be getting inside a living cell and actually watching the chemical communication process in real time! Say, what's the onset of cancer? We actually want to be able to watch that process take place. Now, to do that, to get inside a living cell and not disturb it, you have to find a pretty small scale; that's where [subcellular technologies come] into play. And so we build technologies around [particles of the subcellular level]. These are [special] technologies so we don't

have to stick wires and probes into [the] cell. The particles are basically eaten by the cell, the particles go to specific sites in the cell because of the materials we put on the particles, it's dragged to certain sites, and we can actually watch the chemistry that's taking place.

Professor Launcher and his students worked towards the grand vision of simultaneously diagnosing and treating cancer by following chemical processes at the subcellular level.

Role of the research question and related terminology. Professor Launcher stated that, for studies in analytical chemistry, research questions are open-ended, broader explorations of the topic. The following exchange outlined how Professor Launcher defined and distinguished research questions from similar terms:

P: A research question could be much more open-ended than a specific hypothesis. It would be in a sense an exploration of a concept. . . . It could be in a statement, it could just be—it doesn't even have to be stated per se. There's a general interest in terms of looking at a particular phenomenon. You don't have to necessarily describe it in detail but you know what it is, what the phenomenon area is, and you just start digging in.

I: Okay. So then, [are] the research question and the research objective the same thing? Or are they different?

P: A question would be in a sense posing what the unknown is. . . . An objective would be to actually say where we're going to be at the end of that exploration. What is it that we want to accomplish?

The key information from the above segment lies with how Professor Launcher distinguished the research question as the "posing of what the unknown is" and the research objective as "the end of that exploration." Professor Launcher proceeded to distinguish the implicit subquestions that are related to the main research question from the explicitly stated research questions that are seen in the communication of the research to the scientific community:

> I: So you said sometimes the question doesn't have to be stated, it's just implicit.
>
> P: It can be implicit in the sense that it's part of a—I'll try to put this in context: When you're moving towards a particular goal, there are going to be numerous elements wrapped around it to actually achieve that particular goal. . . . Each of those could be expressed, if you will, as a question, but basically you know that you have to tackle all of these things, you don't necessarily have to state it. Just do it, because it's all part of the same problem.
>
> I: Okay. And so when do you actually have to state it? On your grants and where else?
>
> P: Publications and presentations. If you're trying to convey ideas to other people, particularly a public audience, then you better have a good story to tell.

In this next exchange, Professor Launcher described that the role of the research question is to provide a launching point for further exploration:

> I: What role does [the research question] play during the course of your research?
>
> P: Um, not much. I mean, one can imagine that in a highly-managed organization, the research question limits or defines the silo that you're going to be working in. . . . But in a fundamental research laboratory, the last thing you want to do is silo. You want to have the opportunity to explore beyond the original question because what will happen if you're good at this, is that you're going to come up with other questions along the way and the last thing you want to do is be constricted or constrained by the initial question. So it doesn't play much of a role other than setting, uh, if you will, the process of exploration in motion.

Early during the interview, Professor Launcher described a limited role for research questions. He said that the role is “not much” beyond setting “the process of exploration in motion.” However, 15 minutes later, as he talked more about his research, he broadened his description for the role of research questions. Professor Launcher volunteered the following unprompted statement after sharing a summary of his current research:

> I: [Your research] sounds really exciting and fascinating, thank you.
>
> P: Yeah, well I’ll give you the same thing I tell everybody. We haven’t done it. We have this grant idea. I may not live long enough to see it, but the point is it does give us a very—an interesting focus in terms of what would be the idea. We set ourselves a research task and in that sort of, you know, realm, there’s all kinds of questions that can be asked. These are the research questions, right? This is the goal, this is defined, this is really what you’re asking about. How does one move forward? We have a vision of what we’d like to be able to achieve. And knowing what the vision is, we break it down into pieces and say well what do we need to do to get there? And this is where research questions come into play, by understanding what you need to do, you realize most of what you want to do, nobody knows how to do. So now you ask research questions.

In the above segment, Professor Launcher described how research questions represent the subquestions posed in pursuit of a greater goal. In essence, research questions are the subsidiary components that enable researchers to chart their progress toward a greater vision.

In this next excerpt, we see how Professor Launcher responded to “research questions” as if they were synonymous with broader thematic areas within which students find and select research objectives and are told to “make it happen!”

I: Do you remember when you were posing your own research question independent of a supervisor's work for the first time?

P: Yeah, it's, it started very shortly after the undergraduate, uh, short of, senior year thesis project. As soon as I became a graduate student, you know, it was just, you know, make it happen!

I: So as soon as you became a graduate student, you were posing your own research question as well in addition to the one you were working on?

P: Yeah.

I: What question was it?

P: Keep it, uh, I try to put this in perspective—it's not so much a question as thematic area. . . . We know what we want to do and in a sense the student is asking the question and posing the challenges, what do I need to do to move ahead in this thematic area?

Professor Launcher equated his selection of a broader thematic area with the formulation of research questions: "My supervisor said to me: 'You know what you want to accomplish and I have confidence that you want to make it happen. So just do it. And you figure it out from the standpoint of your timeline.'" The theme of empowering students with choice and then giving them the freedom to "make it happen" continued with his own supervision:

> And that's what I tell all my people. I don't have a clock, I'm not watching whether you're here in the morning, here in the evening, or—doesn't matter! You know what you need to do, you have it, you know, your own goal, your own aspiration to get out of here within four, five years for your thesis if you're in PhD or whatever. You make it happen!

Research questions are open-ended, broader explorations of the topic.

Professor Launcher differentiated research questions as the "posing of what the unknown is" from the research objective, which he saw as "the end of that exploration." He described three roles for the research question: (a) research questions set "the process of exploration in motion" by providing the launching point for students and researchers to find and pursue both implicit subquestions and new but related questions; (b) explicit research questions enable researchers to better communicate the study and its results to the scientific community upon completion of the study ("If you're trying to convey ideas to other people, particularly a public audience, then you better have a good story to tell"); (c) research questions could also represent subquestions that allow a research team to chart progress towards a greater vision or ultimate goal ("knowing what the vision is, we break it down into pieces and say well what do we need to do to get there? And this is where research questions come into play . . .").

See Table 45 for a summary of Professor Launcher's definitions of key scientific method terms in chemistry.

Table 45

Definitions of Terms Key to the Scientific Method in Chemistry

Scientific method term	Definition (inferred or expanded based on participant's text)
Research focus/ topic	The research focus/ topic is the "long-term goal" of the research. It is a "thematic area" within an "area of interest" from which research questions are derived: • "We have this grant idea. I may not live long enough to see it, but the point is it does give us a very–an interesting focus in terms of what would be the idea. We set ourselves a research task and in that sort of, you know, realm, there's all kinds of questions that can be asked." • "once [students] know the area of interest, then they start reading and we refine a topic and that's our only, if you will, the first chapter of the thesis so that they have a place to start. And from that first exploration they'll define what they want to pursue."
Research question	The research question is defined within the larger context of the research focus/ topic: • "knowing what the vision is, we break it down into pieces and say well what do we need to do to get there? And this is where research questions come into play, by understanding what you need to do, you realize most of what you want to do, nobody knows how to do. So now you ask research questions." • "When you're moving towards a particular goal, there are going to be numerous elements wrapped around it to actually achieve that particular goal. . . . Each of those could be expressed, if you will, as a question, but basically you know that you have to tackle all of these things, you don't necessarily have to state it." The research question functions as a launching point: • "setting uh, if you will, the process of exploration in motion" • It asks "what do I need to do to move ahead in this thematic area" Thus, the research question can be defined as: • "an exploration of a concept" • "a general interest in terms of looking at a particular phenomenon" • "posing what the unknown is" • "open-ended, broader explorations of the topic" In practice, the question may be more or less explicit: • "It could be in a statement, it could just be—it doesn't even have to be stated per se." • "you don't necessarily have to state it." But when stated explicitly, the questions helps to communicate the research: • "If you're trying to convey ideas to other people, particularly a public audience, then you better have a good story to tell."
Research hypothesis	Less "open-ended" than a research question.
Research objective	"where we're going to be at the end of that exploration [of an unknown]. What is it that we want to accomplish."

Values and beliefs related to RQF. Professor Launcher firmly believed in not only allowing, but proactively inviting and encouraging students to come up with their own questions. He poignantly asserted that, "Me formulating the question for them, that doesn't help them at all." He shared the following mentorship philosophy:

> What you're asking, in a sense, is how does one create an environment that can nurture the creative potential of individuals and lead to the next generation of leaders in the sciences. . . . And you can train them so they become leaders or you can train them just

> to be technical people. I've chosen my particular route. . . . So I haven't worried so much about the publishing. . . . I'm never going to win the Nobel Prize. I have no interest in that. . . . That's not the point. [The] point is, I'm happy because I feel I'm doing my job, my responsibility, and I'm doing it well.

The above quote revisits a recurring theme in the interview, which was the priority that this participant placed on mentoring scholars instead of training technicians. Professor Launcher also spent a fair amount of time discussing supervision in the context of innovation:

> You can't just structure everything for academic, you can't structure just for industry. You have to set them up for life so that they can move and do the things they want. And that's what I think, you know, they take away from this particular experience in the team. It doesn't—you know it's not focused to just teach them how to crank out papers and be excellent academics, nor at the same time is it ignoring the concept of what I'll call innovation.

This above quote is important because it illustrates how Professor Launcher's supervision style aimed to give students a balanced approach that included giving students experiences that would benefit them in both academia and industry. In this same segment, the quote leads into this professor's description of innovation:

> I laugh because I can walk up and down the halls here at this institution and say, you know, "Who's innovative?" And everybody will have their hands, hands come out. When's the last time that something you published was actually used for good by someone else? As opposed to just an interesting tidbit of information. And of course most everybody says, well we don't work in that space. But that's what innovation is about, innovation is taking a creative idea and moving it into something that has practical

> good. . . . What we try to do is teach innovation because somebody who's good at that can be good at virtually anything they set their mind to.

The key take-home point from the above quote is how Professor Launcher strived to instil among his students an appreciation of innovation as something that moves research into the sphere of application. When asked about how he develops this appreciation amongst his students, he responded as follows:

> I: Yeah. What are the experiences they have while working on your research team or working with you that you think contributes to that ["that being innovation"]?
>
> P: Well it's quite broad. The questions we ask—and again, because of my field—my field lends itself very naturally to applications. Analytical chemistry, you're not just asking what it is but how to make it, you know. Make that happen. There's a very natural tendency in my field to always be looking of what can I do with this information. How can I make a difference? But I've, uh, in fact, surrounded the group for many years with this idea of working with industry, working with government, we've held major contracts with the [departments in the federal government], with groups in hospitals, with groups in industry, and so on. It's always in my group, an undercurrent of the discovery research and the more applied research. Maintain that at all times because every student needs to see that balance across the spectrum. You know, so that's I think been very revealing for [inaudible]. Basically, [it] encourages them to be creative but realize that as they're being creative, not to ignore the potential to move ideas into public good.

In the above quote, Professor Launcher emphasized the importance of ensuring students are exposed to a variety of research projects because this exposure helps students learn to pursue innovative research (wherein innovation was conceptualized as "moving ideas into the public good"). The take-home point regarding all of these quotes on innovation and ensuring high student engagement is the professor's emphasis in training the next generation of scholars and scientific leaders, "not technicians."

The conversation continued toward the broader topic of funding contexts that have enough flexibility to allow students to formulate their own research questions. The next three quotes addressed an issue that many participants raised, namely, the premise that students cannot pursue their own research questions because professors need to make progress on the grants for which they are funded.

> I: I still don't understand how, how do you make progress on the grants that you—because these students need to be funded if they don't come with their own funding, so you have your own grants and the grant has specific objectives, and they provide the funding for the students, so then do the—how does it work out in practice?
>
> P: If you're dealing with grants such as the Natural Sciences and Engineering Research Council, NSERC Discovery grant, the understanding with the discovery grant is you're not held to the particular grant proposal tightly at all. . . . Many people don't realize that. NSERC has these different compartments in terms of—probably provide funding. The Discovery grant, that name, the discovery process, sends a signal that there are no constraints. Even if you have a change of heart. Remember, these are five year[s] long. In the first year, you may discover what you thought would work won't work at all. So what are you going to do for the next four years? You change the path and you keep exploring and you refine it and it's the obligation of the faculty members and the students to make the best use of that time and the financing that has been resolved to make something happen of it. But it's very open-ended.

After relating the open-ended nature of NSERC Discovery Grants, he continued to describe some other grants that are also very flexible. As a caveat, Professor Launcher also shared a strategy for advancing his research agenda when progress needs to be made on specific, preformulated research questions:

> [When] you have to meet certain specific dates and specific objectives . . . the kind of people you put on [the task] are not necessarily graduate students. This is where you would put a postdoc. And the postdoc would say, I need this for my training, my academic career, I want to learn specific things and I can work in this environment [to] move a project forward and demonstrate I can do that with management techniques now that would be required—for example, in industry: timelines, meeting the goals, the financial responsibility and timing. So this is a training platform that's somewhat different for different purposes. . . . If you know that you have deliverable and a target, you can't rely on some—for example, a graduate student that has courses to do and teaching of undergraduate labs and this type of thing. You bring professional researchers like a postdoctoral fellow who will use it as a stepping stone for their own career development . . . .

Professor Launcher was the only professor in the entire group of participants to mention that he hired postdocs to pursue his research question in order to leave his graduate students with enough room to explore their own interests and attend to their graduate student responsibilities. Next, he commented on values and professional objectives that might prevent professors from allowing their students freedom to explore their own research questions despite holding flexible grants that make it possible to do so:

> I think there's so much flexibility in the system, you'll find that professors, they define how they want to run their operations. You know, what you've told me is what I would've expected from the reply of a more junior faculty member even on a Discovery Grant. If they tell you that their students are working on a specific project and they have to meet milestones, that's because that particular individual needs to have a productivity record, they want to ensure that their publications are out the door for tenure and promotion purposes. Look at me, I'm an old guy; I've been in the system for so long, I don't have any of that baggage to worry about at this point, right? So I can change the way that I do business in the lab to really make it encouraging to the students and have a great time doing it!

In the above quote, Professor Launcher outlined how he was able to carve out a student-centric supervisory role for himself that may not be available to newer faculty members who are concerned with their publication record for promotion and tenure. Of central importance to Professor Launcher was the creation of "an environment that can nurture the creative potential of individuals and lead to the next generation of leaders in the sciences." With his strong interest in ensuring students are career-ready, he warned that, "You can't just structure everything for academic" purposes but, rather, you need to expose students to a variety of projects. This variety helps to "set them up for life so that they can move and do the things they want" as well as helping them to pursue innovation, something that he defined as moving "research into the public good." Professor Launcher shared the caveat that there were some affordances that came from the fact that he was an older professor as opposed to one who is concerned with a publication record on track for tenure and promotion. Nevertheless, one of Professor Launcher's strategies for making progress on his more restrictive grants—the hiring of postdoctoral researchers—is a strategy that is also available to funded professors who are still pursuing tenure.

Professor Launcher's values and beliefs were conducive to allowing students to formulate their own research questions. The strategies he used for making this possible may also be available to other professors, tenure track or not. Such ideas will be further explored in the discussion.

Methods for developing student RQF. Six segments were coded as RQF for Professor Launcher, which is slightly higher than the average number for most participants [5.6]. The segments were coded as starting point, peer interaction, supplemental professor strategies, and exposure. What emerged from looking at how a single participant speaks ardently about training the next generation of scientific leaders is a narrative illustrating how important RQF is to that training process.

From starting points for RQF to "resolving a project," to frameworks for grant writing. When asked about the student's contribution to research-question formulation, Professor Launcher started by outlining his overall strategy for introducing students to topical areas of interest that set the process of research question formulation in motion:

> When students come and interview me for things that are, you know, they'd like to work in my lab, what I do is I give them a page and it talks about the different topics that are ongoing and projects that I would like to start and they can choose from that the recipe, that menu, anywhere that they want to get going. And I tell them this is not your project, all you're doing is you're choosing an area to explore and we will resolve your project, your direction of the first chapter in the next six months. So [I] give them a starting point. . . . What they'll do is they'll enter the lab, talk to the students that are

> already there, and they will formulate an area that excites them, an area of interest without a thesis. Without a specific topic. And once they know the area of interest, then they start reading and we refine a topic and that's our only, if you will, the first chapter of the thesis so that they have a place to start. And from that first exploration they'll define what they want to pursue.

The above quote illustrates that Professor Launcher does not expect his students to come into his lab with their own well-defined research questions, nor does he assign research questions to them. The process of research question formulation starts with stimulating students' curiosity and creativity by introducing them to possible areas of research, having them interact with other students in the lab, and becoming familiar with the literature. In this next quote, Professor Launcher elaborated further on how students continue to narrow down their topics of interest:

> [Later] they have to, in a sense, resolve more tightly than what it is that they actually see themselves—what their long-term vision, their goal, is for their thesis. Not putting a title on it but putting a very clear direction as to what they want to do. . . . And, in a sense, that becomes important and limiting because it will take them years to actually build the thesis. And so, if they choose a topic area, long-term goal that's not going to mesh with what their interests are over that period of, you know, four or five years, they're going to have a very unpleasant experience and that's what we try to avoid. That's why I don't want to stick anybody on a project from the outset. What they do is they resolve the project that they get excited about and we give them a license to design what project they want to pursue. I don't tell them what their project is.

The above quote illustrates the importance Professor Launcher placed on ensuring that the student envisions a long-term goal that will retain their attention over the course of the degree.

Instead of assigning projects to students, he viewed his role as helping students to identify areas of continued interest and empowering them to pursue these areas. Ultimately, a student who has successfully resolved and carried out a research project becomes an expert in the topic:

> The reality is, when you go for your PhD exam at the end, as much as you know, the PhD candidate may not appreciate it, they are actually the expert in the room. No one else in that room has looked at that problem at the level or depth that student has, eh? And that's important for students to understand even at the early outset.

This above quote illustrated something that stood out about Professor Launcher: his expectation for his students to become experts on the topic started from day one.

As students explored topics in the lab and developed this expertise, they integrated the early conceptualization stage of research with the writing process itself.

> That's where one formulates the clarity, as a question, as a hypothesis, and the text, and how to answer that. Beyond, it's exploration in the lab until you find a path that's going to lead you to that type of resolution. And, in many ways, this is what I tell my students: You're not trying to tackle a particular project. Think of it as writing a thesis chapter. If you can formulate the question starting from the vision of what your thesis will be, write the chapter so that each chapter is a question, but it's a broad question and then you dig and find the nuances to make it happen. Your thesis will assemble itself, as will your publication.

This above quote showed how Professor Launcher's students are taught to integrate the processes of exploring, finding, and formulating the central design elements in their research study "as a question, as a hypothesis," through the process of writing down these questions to frame each thesis chapter. Professor Launcher continued to explain why it is so important to ensure students engage in these processes:

> You have to look at it from the pedagogical standpoint, then it probably makes sense. What I want my students to do is work in a relatively open environment so they can explore the things that interest them. . . . And I want to do it in such a way that they're going to learn to be experts in communication. Me formulating the question for them, that doesn't help them at all. By them learning how to formulate the question, by them having to write up the manuscript and onwards it goes, they're learning the process of communication.

In essence, Professor Launcher engaged his students in research question formulation so that they would become skilled at communicating. This mentorship in scientific communication started early through the use of grant writing terminology:

> And, in fact, what I start doing without telling the students, is feeding them the philosophy that the granting councils have. The granting council philosophy is you will run projects and the projects in combination define your research program—and that's the wording that they use. Programs and projects. The thesis to me is the vision of the program. The chapters in the thesis are the projects. And so what we do is we steer away from the program to a project, to get them going. And that gives the student the confidence to actually move a problem forward and as soon as they start building confidence and seeing the thought process in particular with others in the lab, they become, uh, astute at driving that themselves.

In the above quote, Professor Launcher explained how students map the grant writing terms, programs, and projects to equivalents in thesis writing—the vision of the thesis and its individual chapters. In doing so, Professor Launcher expressed the belief that by using grant writing terminology as a framework for writing their own theses, and by seeing the same process through their peers, students become empowered to drive their own progress forward. This importance of peer-interaction and exposure are soon revisited when Professor Launcher talked about the laboratory environment and how to overcome material and resource limitations.

Peer interaction and the collaborative generation of research questions. Professor Launcher was asked how coherent progress is made in his research lab if his students are all working on different projects. He answered this question by sharing how lab members generated research questions collaboratively:

> So the students are working as a– I call it a relatively cohesive team. They know what the other students are working on, they're looking for opportunities to complement the group. You have to understand that the thought process, at least in my team, is that it really is a team. These people, they work together very closely. They offer shared authorship on publications, they have interests in common, and so when they choose projects, they actually not just do it as the individual, they do it as collectives to solve a particular task that each of them or even more can gain benefit from. So it's a very collaborative environment. What you're asking is, in a sense, how does one create an environment that can nurture the creative potential of individuals and lead to the next generation of leaders in the sciences, whether it's in research or, if you will, the concept of innovation, moving the creativity into something that's an application. And so that's the kind of environment that I try to nurture.

This quote and many other quotes in this illustrative case highlighted the central role of nurturing an environment that makes RQF possible. The quote ended with Professor Launcher revisiting the topic of training the next generation of leaders in the sciences—a goal that is tightly associated with allowing graduate students the opportunity to find, frame, and formulate their own research questions. The next section illustrates the professorial attitudes that make such explorations possible.

Supplemental professor strategies: Encouraging student exploration. Several segments of the interview with Professor Launcher were coded as supplemental professor strategies. The first of these supplemental strategies was encouraging student exploration. The topic started with his discussion of how a supervisor's attitude could affect the degree to which students are willing to share their ideas:

> If you have an openness to the students and you recognize you're a facilitator as opposed to a dictator, then the students behave very differently. If the students feel that you're going to be resistive to change, ideas that are new, ideas you didn't come up with yourself, they're going to be reluctant to put that to you. So right away, you change the nature of the dynamics in the group by your attitude coming in.

The above quote speaks to the importance of the supervisor's attitude. The participant's word choice illustrated one of the key challenges in determining what segments of the interview could be considered relevant to RQF. In some cases, a participant's mention of words such as "new ideas" or "new possibilities" would not be sufficient for the text segment to be considered relevant. In this above example, Professor Launcher's use of the words "new ideas" was considered to be relevant to research questions because he also talked about how new ideas from the student lead to new knowledge.

> I: Wow, okay, thank you. You mentioned explore and another chemist mentioned explore, too, but he wasn't able to give me an example of what it meant, means to

give your freedom, give your students the freedom to explore. Can you help me understand that a bit better?

P: Yeah, I'll give you maybe one example; I don't know if it's a good one. Um, one can go into the literature and you can read dozens of papers for example in a particular subject area, subcellular particles, for example. And it'll tell you things work in a certain way. And you can ask, then, a question, you know, I wonder what would happen if we flipped it on its head. And I'll give you an example. . . . [In my field], everybody [puts one particle in the middle and a different type on the outside] for [better results]. . . . And so one of my students said well, "What would happen if I switched it around? The particle in the middle, it becomes the type on the outside, and the one on the outside, we put it in the middle." Now the literature says that that shouldn't work. But I think this needs to be tested because if it's done in just the right way, it could work really well. Another supervisor might have said, "Come on. You know, why bother wasting your time with something that everybody knows?" Well, the reality is that it did work very well, just as the student predicted, if you did it in a certain way, all right? And I had no problems with that, because the student had a reasonable concept of why and how it would work, and it was a proposal, it was a hypothesis if you will, and it was something worth exploring, right?

In the above example, Professor Launcher precisely described how new knowledge was created when he allowed his student to challenge the status quo. After requiring his student to provide a compelling rationale for this challenge while grounding said rationale in the literature, Professor Launcher allowed the student to proceed with the study. The results of this study were fruitful, leading to new findings for the field and speaking to the importance of the supervisor's openness in student research question formulation.

Supplemental professor strategies: The supervisor updates his background knowledge. The second segment that was coded as supplemental professor strategies related to how Professor Launcher updated his background knowledge to support his students' research question formulation processes. The topic arose when the interviewer asked Professor Launcher about his role during the period in which students were narrowing down their research interests.

> I: Okay, so during those six months they need to find a clear direction of where their thesis is going to go. Um, and then what happens during those conversations between you and the student as they're trying to do this? They come back to you, "I want to do this!" Then what happens?
>
> P: Oh, I say, "Okay! What do we need?" You know, and then they come to facilitation, right? And what we do, what I do, is I go away and read a little bit about it so at least I have some background in terms of what, you know, we're getting into. . . . When they start reading, they probably have in the first few weeks of reading more knowledge and insight than the supervisor has about that particular area, right? And so what I do is I get enough background so that I can speak with at least some intelligence about it and then in a sense because of experience I can sit back and say, well what would happen, and how does this work, and what do we need to know to be able to move it forward, to get them started? . . . And then it gives them a sense of how to create a structured inquiry. Start thinking about here's where I want to be, how do I get there? And break it into pieces, right? And then they learn that themselves.

What is particularly interesting is the way Professor Launcher shared how he would read just enough to model and scaffold the type of thinking that he expected from the students before removing his support and letting the students continue with the inquiry on their own. Whereas some professors are less comfortable allowing students to explore outside of their areas of expertise, Professor Launcher would take the initiative to update his knowledge in order to support his students' forays into new topics.

Securing access to funding, facilities, and knowledge for RQF. "Exposure" is a theme from the focused coding whose purpose was to capture attempts to send students to other labs for any reason or to introduce them to different areas, models, theories, and ideas. Professor Launcher provided several answers that spoke to the importance that he placed on this practice. The topic was introduced when Professor Launcher was asked about whether the level of prerequisite knowledge needed by students could be a barrier to engaging students in research question formulation. Here is how the conversation unfolded.

> I: Okay. Two other constraints that are often mentioned: One is the level of knowledge that students need before they can formulate original questions, it's just too—it's much too high, which is why professors say "That's why I didn't start doing it until I was a PI." And this is why, you know, she continues to train students this way. Do you have any comment on that? Students just need a lot of foundation knowledge before they can do this. What you're saying, they would just tell you students don't have enough knowledge to do it yet.
>
> P: Yeah, that's what they can say. The reality is, what's to prevent a student from gaining that knowledge? To say they can't work in an area because they don't know that area would be the same as pointing to myself saying I shouldn't work in cells

> because I never had a formal, you know, graduate biology course. The question is not so much whether you can't; the question is how you will resource that type of individual to be successful. And you can't expect somebody without the knowledge to immediately take up a project and be successful in the project. So, you know, if a research supervisor, PI, is asking that, that's ridiculous, but if a student in my lab has expressed interest to work in an area and it's completely new to them, I encourage them! That's why you're here, you're here as a graduate student or a postdoc because you want to learn something.

The interesting perspective illustrated in this quote is the premise that a lack of knowledge need not be a barrier to formulating original research questions. After providing an example from his own experience, Professor Launcher affirmed that the purpose of graduate study is to expand one's knowledge. He continued to describe how he connected students with the knowledge that they require:

> The trick is, how to get them resourced to really learn that something so what we'll do is we'll look around for core courses that they could take, sometimes that's to their advantage to get credit while putting in the effort. But typically it's done through mentoring or by connection with other colleagues. You find the people with the right expertise and they become teachers of my graduate students. So we'll work with other faculty members, and what we do is we make arrangements from the outset that everybody's satisfied. If this works, you become a co-author on the paper, right? It's worth your time and effort. Nobody's asking you to put your own money and your own grants into my student. I'll pay for everything, yet you can participate in this project. Maybe you'll become interested and we can collaborate on another one, another project

> and we'll get new funding in the future. The real trick in these things again is the leverage, right? Sometimes you run into these situations where you can't get the right equipment, the particular instrumentation. This is where your colleagues become so important. Often—especially at an institution like [participant's university], this is a big place. You can find almost anything as instrumentation somewhere in this university.
>
> It's a matter of reaching out and creating a relationship with the people that control that.

In the above quote, we see how Professor Launcher leveraged the background and experience of other faculty members to help students gain the knowledge and other resources that they needed to engage in RQF. There is an element of negotiation and appealing to the interests of his colleagues in order to secure appropriate training opportunities for his students. He continued to provide a concrete example of how this works.

> As [an] example, if you don't have the right facilities or the right connection to make things happen. So this an impediment to my group. I do not have a biocontainment facility. So how does one actually work with cells? You want to get inside liquid cells to see what's happening. We don't have the facilities to do that in the group, and so my job then is to facilitate the group. So what I do is I work with other colleagues in other departments that do have that type of expertise. So my students are actually graduate students on certificates of other people in other departments within our physical complex here, to be able to access cell culturing and biohazard containment.

In addition to securing access to facilities, knowledge, and equipment, Professor Launcher also sought funding to support students in their explorations:

> It's a very open environment, so what I have continually going is, the students will approach me and say, "Dr. [name], this is what we want to try. Do we have the budget

> to do it?" And I cannot recall any issue in the last year where I've actually turned something back. I've always said to them, "Okay it's expensive but it's exploration and I'll find the money to do it somehow it's worth doing. Your idea, we'll support your idea."

Professor Launcher's example demonstrated how the lack of knowledge or resources does not have to be a barrier that prohibits students from engaging in RQF. In fact, the lack of foundation knowledge can motivate students to explore and seek new knowledge. Professor Launcher saw his role as helping to find that knowledge through course selection. More importantly, he talked about his role in creating and facilitating beneficial partnerships with other faculty members. These partnerships gave his students access to knowledge, facilities, and scientific equipment that they required. Finally, Professor Launcher proudly shared how he would even work to allocate funding toward supporting the original research questions that his students proposed.

Hints of student roles from the participant's pronoun usage. At first glance, Professor Launcher shared some similarities with professors who assign questions or who offer a set of questions from which students can choose. However, the degree of student ownership and responsibility in the construction of the question that Professor Launcher aspired to contained a quality not seen in the responses of most other participants. In other transcripts, we could see many statements regarding how participants valued collaboration and a proliferation of the plural "we" pronoun. As for Professor Launcher, he spoke articulately about the pedagogical activities outlined for his students at each stage, and the learning outcome or rationale behind each activity. Professor Launcher's use of pronouns reflected clear roles and active student engagement at every stage.

Synthesis. The RQF process started as students made initial contact with Professor Launcher. He then presented a menu of topics or thematic areas that were being researched by his lab at that point in time or that he would like to pursue in the future. Peer interaction became important as students shared their research ideas and plans with each other. At times, this sharing led to research questions being collaboratively chosen by the group. In the initial stages of the RQF, Professor Launcher also encouraged students to get better acquainted with these topics by reading the scientific literature. From interactions with the supervisor and peers, as well as from readings, students would get a better sense of the thematic area that they would like to explore further. Professor Launcher adamantly let the students know that the option chosen from the menu was not their thesis topic, but merely a starting point that was to be further "resolved." As students explored possible research questions, they started to lay out the chapters of their thesis during the first six months of their research. During this time, the students also became better acquainted with the literature and laid out their long-term goals. If a student picked an area that was unfamiliar to Professor Launcher, he took it upon himself to do the necessary background reading so that he could engage in the topic well enough to guide the students through the inquiry to a point at which they were self-sufficient.

Professor Launcher saw his role as setting in motion and facilitating the process of exploration by remaining open to new ideas and removing technical and financial constraints. It is important to note that Professor Launcher was exemplary in his eagerness to support his students' forays into new areas, making student engagement in research question formulation possible by leveraging whatever relationships, time, funding, and other resources that he had available as he trained "the next generation of leaders in science."

Synthesis and Comparison of the Two Illustrative Cases

The broad purpose of the present study was to document and illustrate the variation in mentorship approaches for developing student RQF. In this illustrative case section of the results, I had the opportunity to focus on some of the contextual factors that could accompany said variation by looking at the differences between two exemplary RQF mentors (see Table 46 for participant profile information). The experiences described by Professors Emp and Launcher differed in four ways:

- How they defined, distinguished, and applied terms central to the design of scientific research (e.g., research topic, research question, research objective, hypothesis, prediction). (See Tables 43 and 45 for details on how each participant defines key scientific terms.)
- The role they ascribed to the function and format of research questions. Both participants concurred that research questions should help clarify and focus one's research, yet differed in their interpretations of the extent to which research questions should guide, narrow, and delimit the research (see Table 47 for details).
- The level of directiveness they adopted and the extent to which they provided mentorship in discipline-specific content knowledge: Professor Emp chose to be more explicit and didactic in her RQF strategies, whereas Professor Launcher adopted the role of facilitator, focusing on providing support for student-driven research activities (see Table 48 for details).
- The focused versus generalized nature of the techniques used: Professor Emp opted for a more explicit set of procedural strategies, while Professor Launcher preferred developing students' ability more holistically and implicitly (see Table 49 for details).

The illustrative cases showed that pursuit of science and the form and function of research questions could differ dramatically from one scientist to another. Quotes throughout the Results chapter show that such differences exist among scholars within the same discipline (see Appendix E: Differences in how biologists conceptualized opening tasks for details).

The differences I found in scientists' conceptualization of research questions converged with some previously published findings but diverged from others. For example, my results converged with those of Hernon and Metoyer-Duran (1993) who found that researchers within a single discipline, that discipline being library sciences, disagreed over the purpose, content, and form of a problem statement, stating "it would seem that researchers referred to whatever they want as the problem statement" (p. 71). Similarly, Shore et al. (1990) found that the role, purpose, format, function, and contribution of a research question varies across disciplines due to the nature of inquiry in those disciplines. In some of these types of research, the hypothesis, predictions, and research questions play a central role (e.g., experimental) while, with other types, they are merely the launching point for the investigation (e.g., exploratory).

There is variation in how scientists define and use terms that are generally considered basic to designing scientific research. The existence of differences is not surprising considering the variation in tools, techniques, assumptions, and paradigms among scientists. What is surprising is that multidisciplinary studies about designing research have failed to operationalize an important construct in their study—the research question itself. Furthermore, these authors did not acknowledge the variation in how scientists define, understand, and use the research question. Instead, these studies explored posing scientific questions, finding dissertation topics, formulating hypothesis, the early stages of designing research, quality criteria for research questions, and so on as if these terms are distinct or well-defined (Fister, 1992; Isaac, Koenigsknecht, Malaney, & Karras, 1989; Nutefall & Ryder, 2010; Pedrosa de Jesus, Almeida, & Watts, 2004; Seymour et al., 2004; Sutherland, Meslin, Da Cunha, & Till, 1993; Tan, 2007).

The case studies also drew attention to the importance of context, nuance, and disciplinary differences. Scientists' conceptualization of that which constitutes a research question versus a research topic not only varies, but can contradict each other. What one scientist views as student participation in research question formulation fits another scientist's description of providing students with no opportunities for research design by assigning them pre-formulated research questions. Both scientists could be using the same wording: "I teach my students to ask research questions." Attempts to understand and compare student participation in scientific inquiry across subjects could be more trustworthy if they acknowledged individual and disciplinary differences in the use of terms for focusing and specifying scientific research.

Table 46

Participant Profile Information

Characteristic compared	Professor Emp (biology) (Participant #3)	Professor Launcher (chemistry) (Participant #10)
Professor as student	As graduate students, both participants experienced supervision in which they were given much freedom to explore their areas of interests.	
Academic career	Both worked more years as professors than the average participant in this study (mean=16 years).	
Funding history	Both had uninterrupted funding histories during the time in which they held positions as a professor (which does not include time spent in full time administrative positions).	
Years worked as professor	20	> 30
Number of students supervised	43	170+

Table 47

Participants' Views on RQF

Viewpoint compared	Detail compared	Professor Emp (biology) (Participant #3)	Professor Launcher (chemistry) (Participant #10)
RQF for the expert	Role of RQs in professor's own research	Both believed research questions enabled one to better clarify and communicate one's research.	
		● Research questions (RQs) should be clearly defined and set in advance of the investigation so that they can direct and delimit one's research. ● RQs are explicit in everyday lab activities. ● Research questions served two roles: (a) RQs drove her own research agenda, (b) probing for RQs was a part of her interactions with other researchers.	● RQs are important for opening up an area for exploration: "the last thing you want to do is be constricted or constrained by the initial question." ● RQs are understated or implicit in everyday lab activities. ● RQs become the smaller research projects that enable one to make and chart progress toward a greater goal or vision.
Views about research questions	RQF terminology	● Described significant overlap between research questions, hypotheses, and predictions as they are "restating the same ideas in slightly different ways for slightly different purposes." ● The design of scientific research starts with the hypothesis.	● Differentiated research questions as the "posing of what the unknown is" from the research objective, which he saw as "the end of that exploration". ● The design of scientific research starts with the research question.
	Format of research questions	● RQs must be stated in the form of a question, and must include hypotheses and predictions. ● RQs should simultaneously address multiple levels or dimensions (e.g., time, geographic space, micro and macro scales). ● RQs must be clearly formulated and accessibly communicated.	● RQs do not need to be in the form of a question, they can be a statement or a general interest. ● Gave no quality criteria for research questions.

Table 48

General Supervision

<table>
<tr><th>Themes compared between illustrative case participants</th><th>Professor Emp (biology)
(Participant #3)</th><th>Professor Launcher (chemistry)
(Participant #10)</th></tr>
<tr><td>Shared values and beliefs</td><td colspan="2">● Student engagement in the discourse of their scientific communities.
● Active interest in students’ career path: Professor Emp reported doing a lot of “life-coaching,” career-orientation and “individualized pedagogy” with her students. Professor Launcher envisioned raising a new generation of leaders in science that would produce creative research, later applied in industry and elsewhere.
● Believed that students working in a team environment will complement each other.
● Believed that RQF is a gradual and iterative process that happens at the beginning of their PhD degree.
● Both emphasized the pursuit of new and important research directions: Professor Emp believed students should choose interesting riskier topics instead of settling for “safe” topics; Professor Launcher believed students should strive for innovation, which he defined as moving research “into the public good”.</td></tr>
<tr><td>Approaches to supervision</td><td colspan="2">Both shared a student-centered approach to supervision. However, when it came to helping students find, frame, and formulate research questions, the level of their engagement with students differed in a number of ways:</td></tr>
<tr><td></td><td>● Spoke extensively and explicitly about teaching students RQF, understanding the scientific method, training students how to read articles, search the literature, define a research question.
● Spoke about the importance of empowering students, especially female students, to think independently.</td><td>● Facilitated RQF for students as well (as opposed to teaching students the RQF skills).
● Spoke more about autonomy and creativity, than on instruction of content and procedural knowledge.
● Offered his students freedom to explore, because he believes that it will spur creativity and allow them to advance science.</td></tr>
</table>

Table 49

Methods for Developing RQF

Methods compared	Professor Emp (biology) (Participant #3)	Professor Launcher (chemistry) (Participant #10)
Perception of students' needs	● Students are ill-prepared when it comes to understanding the scientific method. ● Students need to be explicitly taught how to critically engage with literature of the field.	● Students need technical and financial barriers alleviated. ● Students need to see a balance of pure and applied research. ● A lack of knowledge need not be a barrier to formulating original research questions—supervisors can help connect students to that knowledge. ● Professorial attitudes can hinder student question formulation if students do not feel comfortable sharing their ideas.
Shared perception of students' needs	Both participants mentioned how students need to… ● Have dissertation research questions that hold their long-term interest and benefit their career path. ● Take risks in science	
RQF categories only applied to one participant	Professor's in-course teaching of RQF; Presenting research questions	
RQF categories applied to both	Feasibility, scope, and specification; Literature-based approaches to developing student RQF; Peer interaction; Supplemental professor strategies for RQF; Comments and expectations (C&E)	
Writing and scientific communications	● Explicitly spoke about working with students to help them convert assignments and thesis chapters into conferences and publications. ● Emphasized ensuring students proactively seek out feedback from a variety of sources so they "learn to take criticism and act on it."	● Taught students to integrate the processes of exploring, finding, and formulating research questions into the writing of each thesis chapter. ● Introduced grant writing terminology to student writing early in their training.
Shared views on student writing	● Both encouraged students to write and share their findings from an early stage. ● Both expected students to communicate clearly and accessibly as they develop expertise in their areas	
Peer interaction	Both participants discussed the value of peer interaction for students who are in the design and conceptualization stages of their research.	
Guiding students through the literature	● Worked with students to help them contextualize their work in the literature and in the theoretical conceptual background of their field. ● Used concept mapping to help students understand how the line of scientific inquiry on a topic evolved. ● Explicitly taught students how to critically engage with individual journal articles by deconstructing them into their component parts: the research question, hypothesis, predictions, main findings.	● If a topic fell outside of his area of expertise, Professor Launcher would read enough about the topic to scaffold the type of thinking that he expected from the students before removing his support and letting the students continue with the inquiry on their own.
	Both participants described how students need to explore areas of interest yet also contextualize those explorations in the literature.	

Chapter 5: Discussion and Conclusions

The Dissertation Questions

The purpose of this dissertation was to explore the mentorship of research question formulation in the natural sciences. This purpose was pursued with the following two dissertation questions:

- What do professors report doing to develop students' capacity to find, frame, and formulate research questions? (Q1)
- Do professors reportedly vary what they do to meet the perceived needs of individual students? If so, what do professors do differently from one student to another when it comes to developing student ability to find, frame, and formulate research questions and what rationale do they give for differentiating their approaches? (Q2b)

During the pilot interviews, participants struggled to describe how they intentionally develop research question formulation skills in their students, rendering it counterproductive to continue the search for intentionally pursued pedagogical strategies. In accordance with the phenomenographic framework of my study, I proceeded to answer the dissertation questions by illustrating the variation in teaching and mentorship experiences in which students were involved in the conceptualization and design of research questions.

The Answer

The answer to Q1, "What do professors report doing to develop students' capacity to find, frame, and formulate research questions?" was that participants in my study described a diverse set of teaching, learning, and mentorship actions and approaches as contributors to the development of student RQF (the 10+1 RQF categories in 'The RQF Categories' section). The processes that yielded the categories are richly described so future researchers can evaluate the trustworthiness of the findings. The categories themselves varied from the narrow (such as specific exercises in creativity and critical thinking) to the broad (such as supervisor attitudes to promote student confidence and identity development). Pedagogical components shared across the set included guided practice, iterative feedback, the development of content and procedural knowledge, exploration, and ongoing encouragement. Scattered among the narratives were hints that professors continued mentorship practices that they found helpful when they themselves were students.

All 10+1 RQF categories in the framework were systematically derived and dependably reproduced by independent raters. The tenth category, supplemental professor strategies, made it possible to include observable or concrete actions on the part of the mentor which were not captured by any of the aforementioned teaching and mentorship categories (categories 1 to 9). Analysis of the eleventh category, comments and expectations, revealed that the ten-category framework comprehensively captured all observable actions that related to teaching or mentorship. The new ideas in the comments and expectations category were not about the directive or intentional development of student RQF by faculty—instead, they contained the expectations, roles, and responsibilities that professors outlined for students.

The answer to Q2b, "What do professors do differently from one student to another when it comes to developing student ability to find, frame, and formulate research questions, and what rationale do they give for differentiating their approaches?" was that participants intentionally varied their mentorship of student RQF to fit the characteristics of individual students. Mentors gave preformulated research topics to some students, opportunities to collaboratively design or direct future research to others, and invitations to generate independent research questions to a select few. These opportunities and invitations were partly mediated by individual factors such as degree level, students' level of procedural and content knowledge, and characteristics such as initiative, maturity, and self-directedness.

Significance of This Study

Applied contribution. Student RQF is about the pursuit of new scientific knowledge; it involves students in finding, framing, and formulating the focus of scientific inquiry; it describes pedagogy believed to support students in conceptualizing and designing original research. The 10+1 framework represents the expectations, mentorship approaches, and teaching strategies that scientists believe to be in use, and useful, to helping students become scientists. The illustrative cases provide a hint of how such actions and approaches may come together as coherent pedagogical strategies for development of student RQF abilities. Professors who browse this manuscript can see the strategies in the words of their own peers and scientific community throughout the results section. By informing practice, this rich description makes an applied contribution to knowledge.

Methodological contribution. I began this study with an assumption that was prevalent throughout the literature on the conceptualization and design of the early stages of research. I assumed that terms from the scientific method were self-evident and the understanding shared amongst scholars. The previous literature did not account for disciplinary differences in what scholars referred to as predictions, hypotheses, dissertation topics, study objectives, and research questions. Interviewers asked about research questions, how to generate and refine them, quality criteria for them, and how to encourage and support students in designing academic inquiry. The researchers reportedly asked the same question to physicists as they did to philosophers. My study revealed that what one biologist deems to be promoting student question-asking can be dismissed by another biologist from the same subdiscipline as the didactic assignment of research questions to students. Explicitly asking professors for the strategies that they use to develop student RQF produced answers that were not comparable due to differences in how scientists understood and used words such as “research question.” I stopped asking about pedagogy and started asking the researchers about research instead. Scientists then described the events, characters, and contexts that they associated with discovering directions for scientific inquiry when they were students and in their present-day activities. During data analysis, I operationalized the construct of student RQF to identify components of these narratives that directly addressed whether students were formulating their own—rather than executing their professor’s—research questions. With an interrater agreement of 78.8%, the operationalized construct can be used for educational research across diverse scientific disciplines. This definition and the approach I designed to study student RQF represents a methodological contribution to knowledge.

Empirical contribution. Saturation was achieved in both data collection and data analysis. No new ideas, actions, or approaches emerged that did not fit the 10 plus one RQF categories (see Table 15). This saturation suggests that the 10 plus one RQF categories provide a comprehensive picture of the variation in mentor experiences with developing student RQF in the natural sciences. The participants in my study identified a number of things that mentors can do to help students learn how to find, frame, and formulate their own research questions. In terms of actions and approaches, mentors can:

- Provide students with starting points to launch their exploration (Category 2).
- Help students use the literature to find or contextualize new ideas (Category 3).
- Facilitate cooperation in the lab so that peers help each other to discover new leads or to refine research questions (Category 4).

- Expose students to variety, which can come from working in other labs, collaborations with other scientists outside of the lab, different ideas at conferences and seminars (Category 5).
- Use questioning and listening to direct students toward that which is actionable, specific, feasible, and appropriate in scope (Category 7).
- Have students present and defend their research questions both within and outside of the lab (Category 8).
- Engage students in writing grants and scholarships (Category 9).
- Proactively create an environment in which students are comfortable sharing new ideas and are encouraged to pursue their leads (Category 10).
- When it comes to proposing one's own research question, the onus lies with the students. Interestingly, professors may or may not communicate said expectations to their students (Category 11).

Emerging from data that were carefully elicited, systematically analyzed, and then transparently reported—these findings were produced through rigorous empirical inquiry. No prior empirical study has provided a framework of mentor actions, approaches, and strategies for developing student RQF across multiple disciplines: not within or outside of the natural sciences and education; at the elementary, secondary or higher education level; or from the student or the mentor perspective. The student RQF framework represents a significant empirical contribution to new knowledge.

Limitations

As in most studies, my investigation began with a number of recognized and accepted limitations. The first was the exclusion of engineering and mathematics from data collection (although some professors did have cross-appointments). The second was that only reported practices were examined, not actual observations. The third known limitation was the absence of the student perspective. Considering the dearth of empirical literature and the desire for the study to be multidisciplinary, the beliefs and experiences of professors were deemed a good starting point for exploring the teaching and mentorship of RQF.

The diversity of the disciplines represented within the main data set suggests that the results will be of interest to professors seeking to develop student ability to conceptualize and design research in many scientific disciplines. A major limitation of my study is that the results do not necessarily generalize to all areas of the natural sciences. The reason for this limitation is multifold and can be traced to the following assumptions:

- Professors intentionally develop student RQF.
- Professors will describe how they develop student RQF when directly asked to do so.
- Professors from all disciplines of science develop student RQF.
- Professors use common terms for delineating the focus of scientific inquiry similarly across disciplines (terms such as research questions, objectives, hypotheses, and predictions). Any differences in the usage of these terms have little bearing on the investigation of teaching, learning, and mentorship.

I was initially unaware of these assumptions. The first and second assumptions were exposed as professors talked about student RQF as developing holistically, dynamically, and organically—many did not have targeted learning outcomes and pedagogical strategies they could explicitly describe when directly asked to do so. As a result, data-collection procedures needed to be modified so that participants could provide useful, contextualized responses. The third assumption became clear while some professors talked about the irrelevance of student RQF to careers outside of academia. The generation of novel research questions was less important to areas in which the research questions were self-evident as labs across the world raced to solve the problem. The existence and importance of the fourth assumption became clear as inconsistencies arose in how professors described classic terms for designing research: research questions, objectives, hypotheses, and predictions. Within a single discipline, individual professors differed in what they considered to be a research question and how they used research questions in their work. Scientists across disciplines also differed in how they formulated research questions and the scope of student activities that they believed to be directly relevant to the development of this skill. In order to study this phenomenon among scientists from many disciplines, I needed an operational definition that could be used regardless of discipline. No such definition existed in the previous literature. Without such a definition, my sampling strategy had to be broad. Furthermore, because the objective of the study was to illustrate approaches for developing student RQF, I was limited by the number of participants who addressed the phenomenon: 16% of my original participants (9 of 55 interviews) either did not discuss student RQF or explicitly said that it was irrelevant. Among the 46 usable interviews, there were not enough participants to create groupings that adequately represented all six major divisions of the natural sciences in Canada (NSERC, 2010). Thus, to reiterate, the major limitation of my results is that they do not necessarily generalize equally to all disciplines in the natural sciences.

Future Research Directions

Other important future questions also emerged from data collected but have not yet been analyzed. Some participants suggested that the skill of generating original research questions was not equally useful across all scientific disciplines. Similarly, student RQF skills were relevant in only some of the career paths pursued by those who completed graduate studies in science. The comments and expectations section revealed that professors believe that the responsibility for learning how to formulate researchable questions lies largely with the students. The sample that I analyzed represented views of professors who reported, mentioned, valued, or acted upon their desire to mentor students toward generating their own research questions. The question of how representative these views were of the scientific community as a whole fell outside the scope of this study, yet it is a very important avenue for future research. I remain surprised by the fact that 16% of scientists in this study (9 of 55 participants) reported that developing students' ability to pose scientifically researchable questions was not relevant, appropriate, or important to them.

Future research should examine whether there is a discrepancy between the proportions of the scientists who reportedly value student RQF versus those who actually do something about this value. When is RQF development desirable? Whom do we want to acquire this skill set? What are the roles and responsibilities for those who could be involved in developing it? Other directions for future research include:

- What value do students place on opportunities to collaboratively develop new research questions with their advisor or to develop their own questions? How does student participation in the design and conceptualization of research questions correlate with other desirable student outcomes (e.g., attraction, dissertation completion times, motivation, minority group participation, creativity)?
- What mentorship or instructional efforts do students find helpful in developing RQF and who should provide it (advisors, course instructors, librarians, more advanced peers)? To what extent do mentors' intentions and reported actions converge with the realities experienced by their advisees?

- To what degree does student RQF require an individualized or personalized approach to learning student RQF?
- If RQF is a desired outcome to the scientific community and is seen as a skill that ought to emerge through direct involvement of academic research labs, to what extent are principal investigators incentivized to develop these skills among their student lab members?
- How do the form, function, role, and generation of research questions differ among scientists? What are the differences between the various branches of science, the individual disciplines of each branch (e.g., within the subdisciplines of chemistry), and among the individual scientists of a single discipline? What implications do these differences have on the teaching, learning, and mentorship of RQF? Despite these differences, are there similarities that could inform faculty development efforts or large-scale policy and practices that support the creation of opportunities for student RQF?

Based on the social dynamics of the interviews, methodological and epistemological research questions may also merit investigation. For example, the fact that I am a social science researcher studying scientists might have contributed to how scientists prepared or filtered their answers. As an educational psychologist, the wording I chose may have reflected my presuppositions about the design of research and the scientific method. What were the scientists trying to tell me when they responded awkwardly to questions about how they “varied” their teaching and mentorship? Future studies that look at pedagogy within different disciplines ought to consider the extent to which words such as “vary” carry a shared or overlapping meaning.

An old adage states that a good PhD is one that opens up more questions than it answers. While the present study has answered a number of important questions, it has brought up many more that await future investigation.

Conclusions

To date, our knowledge of student RQF has been largely informed by the following three sources: (a) the learner's perspective in empirical studies of student engagement in independent research, (b) the constructivist paradigms that prescribe parameters for meaningful student engagement, and (c) the views of many participants in the present study. All three converge on a single premise: Opportunities for creativity, autonomy, and contribution are valued when scientific inquiry is appropriately scaffolded. Professors create these opportunities when they invite students to collaboratively or independently find, frame, and formulate researchable questions.

The importance of being able to pose tractable, testable, and valuable questions for scientific inquiry is rarely contested. Knowledge of how to instruct students in RQF, the difficulties they are likely to encounter, and the best strategies to help students work around these difficulties, is confined to researchers who are passionate about teaching and mentorship. The literature search suggested that, to date, few of these individuals have shared this knowledge with the wider scientific community. In this study, I have elicited, collected, and synthesized the components for mentors to build the foundations for student-directed research question formulation. This foundation is composed of opportunities for students to explicitly learn more about the form and function of research questions, for collaboratively formulating research questions with mentors and other lab members, for guided practice with independently formulating research questions, and for testing research questions with internal and external audiences. The study also presented ways in which the mentor can interact with the students in order to create environments in which students are comfortable taking risks and making use of such opportunities.

Increasing graduate student enrolment and decreasing university resources allocated for training students augments the need for efficient and effective instruction, training, and mentorship. The scientists who volunteered their time to talk to me about student RQF were dedicated, passionate, and accomplished scholars and mentors. I share their belief that student participation in conceptualizing and designing scientific inquiry moves us toward a more active and inclusive approach to training our next generation of scientists.

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Appendix A

Participant Demographics for Main Data Set

Discipline (participant ID#)	Rank	Years worked as a professor	All undergraduates supervised to date	All graduate students supervised to date	All students supervised to date
cancer biologist (ID# 9)	Full	24	50	25	75
forest ecologist (ID# 3)	Full	25	30	13	43
genomicist (ID# 16)	Assistant	5	15	10	25
molecular biologist (ID# 17)	Full	13	20	15	35
molecular ecologist (ID# 4)	Associate	7	10	6	16
systems biologist (ID# 2)	Full	15	20	14	34
analytical chemist (ID# 10)	Full	30	100	50	150
green chemist (ID# 8)	Full	19	114	28	142
inorganic chemist (ID# 12)	Associate	12	30	9	39
materials chemist (ID# 21)	Full	30	20	18	38
protein biochemist (ID# 5)	Associate	10	13	4	17
theoretical chemist (ID# 23)	Full	18	20	9	29
biomedical physiologist (ID# 7)	Full	15	10	11	21
biophysicist (ID# 11)	Assistant	5	15	3	18
cognitive neuroscientist (ID# 1)	Associate	10	6	5	11
comparative physiologist (ID# 14)	Assistant	2	8	3	11
neurobiologist (ID# 6)	Full	37	90	19	109
neurophysiologist (ID# 13)	Assistant	1	4	0	4
applied physicist (ID# 22)	Full	31	39	71	110
astrophysicist (ID# 20)	Full	25	15	20	35
geodynamicist (ID# 18)	Full	15	26	12	38
materials physicist (ID# 19)	Full	15	20	22	42
theoretical atomic physicist (ID# 15)	Associate	12	5	16	21
theoretical physicist (ID# 24)	Full	27	20	30	50
	Average	16.8	29.2	17.2	46.4
	Minimum	1	4	0	4
	Maximum	37	114	71	150
	Standard deviation	9.9	30.0	15.9	40.8

Appendix B

Approach to Interviewing and Interview Questions

1. Informed Consent.

- As a participant in this study:
  - you may decline to answer any question;
  - you may withdraw from the study at any time without penalty;
  - you are guaranteed absolute confidentiality (neither your name nor any personal information will be released or published).
- All data you provide will contain no identifying information and be linked to your consent form with a numerical code, with the key accessible only to the primary investigator.
- The data you provide must be stored for archival purposes in accordance with McGill's research policy for five years.
- You may ask any questions related to this study, to receive satisfactory answers to your questions, and any additional details you want, prior to or after your participation.
- Consent
  - Audio recording.
  - Use in future studies.

2. Opening task.

- See appendix C for details.

3. Introducing the study.

- Introduce topic. Here's what we know:
  - The initial source of inspiration for research questions.

  - How to support the generation of research questions for graduate students in the social sciences; teachers; medical students; and medical professionals.
  - For natural scientists, we know very little when it comes the processes of question formulation (after the initial inspiration for the question is discovered); methods textbooks for students provide cursory coverage on topic selection, supervision books provide generic one size fits all advice.
  - Black box: How do questions get developed, implemented, and modified in the natural sciences?
- Disclaim: what I am not doing:
  - Not testing any hypotheses in the present study (as there are no theoretical or empirical grounds upon which to generate such hypotheses, and formulating and testing hypotheses prematurely would only lead to tainted results).
  - Not looking for huge, profound, or field-changing questions.
  - Not looking to identify or generalize best practices, generalizations across disciplines is beyond the scope and feasibility parameters of this study.
  - Open to examples of how students contribute directly to the research agendas of their principal investigators and to examples of student research questions that complement such agendas more tangentially, if at all.
- Clarify: What I am striving to do in this study:
  - Explore how research questions unfold, are developed, pursued, and further modified in research labs.
  - Illustrate these processes in a manner that is comprehensive, accurate, and sensitive to the contexts, research areas, lab environments, and subdisciplines in which they occur.

    - Demonstrate the diversity (or lack thereof) in professors' approaches to the development of research questions in the natural science.
    - Identify differences in the importance of intentionally developing this skill.
- Affirm: Detailed answers are good (I have a RA from natural sciences to help with the analysis).
- Outline: Rough flow of interview:
    - About RQ in your discipline.
    - The past.
    - The present (your current grant).
    - The future...your students.

4. Building rapport.

- **Promoting positive affect**: What are some of the most enjoyable aspects of your job?
- **Easy question:** I see you look at topic X, tell me something fascinating about this topic.
- **Identifying participant motivation:** What prompted you to reply to our email?

5. The form and function of research questions.

- **Terminology according to participant:** Within your subdiscipline, how do you delimit and define a focus for research? (e.g., research topic; research objectives; research question).
- **Format of RQ:** Does the research question need to be phrased in the form of a question?
- **RQ Usage:** When do you use research questions? When do your students use research questions? What role do research questions play in your discipline?
- **Role of RQ:** So it sounds like the role of RQ's in your lab is xyz for students and pqr for professors, are there other additional roles played by the RQ?

- **Differentiating terminology:** How would you differentiate the research topic versus the research objective versus the research question?
- **Posing research questions in this discipline:** In some areas, the research questions are the well-known gaps in knowledge pursued by numerous research teams racing to be the first to find the tools and techniques to solve it. In other areas, the research questions are slowly uncovered and meticulously specified. When it comes to finding, framing or formulating research questions, what are the difficulties or challenges for your area?

6. Eliciting relevant contexts and expectations.

Topic: The birth and evolution of research questions in the professor's lab.

- **Inspiration for research to RQF**: What inspired you to become interested in your research topic? How did this interest transform into a testable research question? How do you go from an inspiration to something more focused, scientifically testable, and tractable?
- **Gap in knowledge to RQF**: For the grant or research project that you described in the opening task, what is the gap in knowledge? How did your lab come to discover this gap? Amidst the many research questions and methods that you could have used to address this gap in knowledge, how did you come to the research question that you chose? How do you go from a gap in knowledge to something more focused, scientifically testable, and tractable?
- **RQ's in this lab:** Tell me about your current grant. Are any of your students working on research questions from this grant at present? How did your lab arrive at or develop that research question? (Probe: What did the student do? What did you do?)
- **Student contribution to professor RQF**: What should students bring to the conversation when you are coming up with a research question or in the process of coming up with a

research question? What does the master's student bring? What should the PhD student bring?

- **Evolution of RQ:** Can you think of a time when a research question become better developed, further modified, or redirected after a student had taken on the project? I am looking for an example where the research question that was eventually pursued differed dramatically from the one that was originally proposed and assigned to the student. What caused the question to change? What did the student do during this process? What did you do?

Topic: expectations related to the generation and evaluation of research questions.

- What are **quality criteria** for a research questions in your area? What distinguishes average research questions from outstanding ones? What are quality criteria for research questions at different grade [degree] levels?
- **RQF expectations:** In your discipline, when do students formulate their own research question for the first time (questions that are independent from the selection offered by their supervisors)? How important is it for these students to pose their own research questions? (provocative probe: Are research questions not readily available from previous studies or easily extended from their graduate work with their supervisor?)

Topic: The professor as student and their experiences with generating their own questions.

- **RQF and grant writing:** Do you recall writing your first grant as a PI? How did that go? Was that the first time you wrote your own research questions?
- **Professor's first time:** Do you recall the first time you wrote your own research question, one that fell outside of the research questions given to you by your supervisor? What aspects of that process stood out to you?

- **Prof as student:** Over the course of your graduate training, what things contributed to your being able to formulate your own research questions?
- **Professor as supervisee:** Do you recall what your supervisor did to support you while you were formulating your own research questions?

Topic: autonomy, creativity, and excellence amongst current and previous advisees.

- **Student RQ table:** Let's look at the table of research questions currently pursued by students in your lab.
  - Out of all the student projects below, which ones changed the most from the initial starting point / introductory discussion you had with them?
  - How has their topic been modified or refined since the discussion first started?
  - What specific things did you do to during this process to help your student?
  - What specific things did this student do?
- **Creative students**: Of all the students whom you've supervised over the years, can you think of one who was creative and productive? A student who kept coming to you with different possibilities, original topics, interesting avenues, or new directions for research?
- **General mentorship expectations:** Ownership, independence, creativity… What do these things look like in your best students? Tell me about one of your most productive / creative / outstanding students. What are your expectations of them this year? What skills or areas would you like to see this student develop further?

7. Probing student engagement in the design and conceptualization of research.

- **Direct RQF:** You mentioned how important it is for students to learn how to propose their own research questions. How do you help students come up with research questions?

- **From topic to question:** After students have found an interest, what do you do to help them move them from interest to something researchable?
- **RQF through graduate program:** What aspects of graduate student training contribute to developing students' ability to pose their own research questions?
- **Lab activities & RQF**: What other experiences and activities do students do as your supervisees or as part of your lab that may contribute to their ability to formulate their own questions one day?
- **Weaknesses in student RQF**: When students come to you with initial ideas for possible research questions, what are some of the weaknesses in these ideas? How do you help them improve on the initial weaknesses in their research questions? What you do to help them to arrive at a stronger question than the one they came in with?"
- **Adjustment:** So it sounds like during your supervision you do xyz. How do you vary this approach from one student to another?
- **Other factors:** Are there any factors related to the topic, the tools, the status of research on the field or anything else that require you to do additional things as a supervisor to help students as they generate research questions?
- **RQF through other lab activities:** What other experiences and activities do students do as your supervisees or as part of your lab that may contribute to their ability to formulate their own questions one day?
- **Grant writing and students:** Do you ever involve your students in grant writing; if so, how?
- **Additional details**: Responses to an interviewer's line of questioning that probes what participants THEMSELVES previously mentioned: "You mentioned that students really struggle judging the feasibility of their ideas. What do you do to help them improve on this

ability? . . . [Participant provides answer with regards to helping students to narrow focus] . . . Okay. And then, to teach students the skill of how to narrow their focus, “This is how you narrow your focus, you have to do A, B, C,” what does that look like?

Appendix C

Opening Task

Opening Task

Instructions to participants: This exercise can be completed during the first few minutes before we start our interview. Your answers will become the basis for the interview.

Basic Info

Form 1

Basic Info

Years worked as a professor	Discipline and subdiscipline	Faculty position (Assistant Professor, Associate Professor, Professor, etc.)

Current Grants

Is this an accurate list of your current grants? You are welcome to list any other grants that your students are working on.

Research Questions Pursued in Your Lab

Form 2

Research Questions Pursued in Your Lab

	Gender	Student's start date	Degree level	Student's current research topic
Student A				
Student B				
Student C				
Student D				
Student E				
Student F				

Current Project or Grant

Instructions to participants: Delete or replace any terms so that they suit your project.

Form 3

Current Project or Grant

	Enter info from a single and current project or approved research grant [only if applicable] . . .
Research topic [or title of grant]	
Initial inspiration • Graduate work • Previous research • Unexpected findings • Conference / symposium / talk • Literature • Collaborators • Undergraduate / graduate students	
Research goals or objectives(s)	
Research questions(s)	
Hypotheses	
Predictions	
Other?	

Approximate Number of Theses Supervised to Date

Form 4

Approximate Number of Theses Supervised to Date

Level	Current # of students supervised (academic year 2014-2015)	Total # students supervised to date (over your whole career)	Program requirements with regard to RQ's ● Exposure? ● Expectations?	Activities which contribute to students achievement of these expectations ● program requirements ● within your lab ● other?	Characteristics of good research questions at this level	Notable example of a student contribution to a RQ that was subsequently pursued in your lab (either by this student or others) ● Initial finding/ suggestion ● Making question tractable ● Subsequent development / evolution of RQ
Undergraduate						
Masters						
Doctoral						
Post-Doc						
Total						

Appendix D

Interrater Agreement Procedure

Interrater agreement was conducted by two trained research assistants and reviewed by the principal investigator for 17 of 24 interviews (70% of the main data set). The outcome of this process was that 56% to 78% of the time, two trained raters reliably identified content that is directly relevant to how participants perceive the development of student RQF. The purpose of this appendix is to describe that process.

All coding was documented in a spreadsheet and began with individual coding. During the first stage (before), each coder was asked to listen to the interview recording in order to flag sections they believed to be about student RQF. They then did a close reading of those flagged sections of the transcript (segments) in order to verify that they were in fact about RQF. For segments confirmed to be about RQF, coders wrote a summary for the segment, explained why they thought the segment was about RQF, attributed the segment to one or more RQF category(-ies), and explained why they thought it fit that RQF category. Interrater agreement calculations involved three stages: before, compare, after.

Interrater agreement (before). In the before stage, interrater agreement was calculated to identify the difference between the coding of two independent raters after they had completed their individual coding and before they had looked at each other's coding. This ratio, which I termed the "10+1 Segment-based Agreement ratio (includes Comments & Expectations - [B4])" was 56.46%. That is, before looking at the other person's coding, 56.46% of the time, both coders agreed that a particular segment fit all 4 RQF conditions.

Interrater agreement (compare). During this second stage of evaluating our coding, raters would look at each other's individual coding and respond to the other coder's comments about which there were disagreements. Two types of disagreements were of interest:

- Whether or not the code is affirmative (borderline yes or exemplary) or non-affirmative (close but no or not coded at all). It is important to note that a code is affirmative if it is about RQF and fits the relevant category definition.
- Whether or not the code related to one of the 11 RQF categories.

The coders would respond to the other coder's comments by doing one of two of things:

- Agree with the other coder's coding and change their own coding so that it would match with that of the other rater.
- Disagree with the other coder about whether or not the segment is RQF or about whether that particular RQF code is applicable to the segment. In this case, with an explanation for why they do not agree with the other rater's code.

In other words, for this stage, interrater agreement (compare) was calculated after the coders changed or maintained their individual coding decisions for each segment within the interview as a result of reading the other's coding. The interrater agreement (compare) value was 75.84%. That is, after looking at the other person's coding and adjusting one's own coding accordingly, 75.84% of the time, two coders agreed that a particular segment fit all four RQF conditions.

Interrater agreement (after). During this third and final stage, raters responded to the comments made during the second stage. The final interrater agreement after this stage was calculated by identifying the difference between the coding of two independent raters after they had discussed disagreements that had remained after stage 2 (compare). After this interrater agreement was calculated, the PI would resolve persisting interrater disagreements. Two segments produced disagreements that the PI did not resolve, these segments were removed from the data set under the rationale that two individuals could not agree that particular section of the transcript contained information relevant to RQF. The interrater agreement (after) value was 78.80%. That is, after discussing disagreements that remained after the compare stage, 78.80% of the time, two coders agreed that a particular segment fit all four RQF conditions.

Appendix E

Differences in How Biologists Conceptualized Opening Tasks*

Participant ID (discipline)	Definition of "research topic"	Definition of "research question"	Definition of "research objective"	Definition of "hypothesis"	Definition of "predictions"
201503111500 (ecology)	Very general: keywords in here wide scope	Could be general or specific. Ends with a question mark!	To do . . . something. Again, general or more specific.	More than one type: e.g. general idea/ guess/ explanation. OR Statistical Hypothesis: Ho/H1	We don't test hypotheses, but rather the predictions arising from them, which are 'directional'
201503121100 (biology)	General area of the research	Specific long-term goal	Short-term goal of the particular grant	Statement that will be tested by experiment	What I expect the outcome of an experiment will be
201504071400 (evolution, molecular ecology)	The area under study	The formulated questions that are addressed in a particular research	Are generally broader than the specific questions and can go beyond specific questions. Research objectives are also not as concrete as the research questions.	A proposed explanation/ phenomenon that can be tested using specific predictions	A forecast that we can make if we have a well formulated hypothesis
201504081400 (neurobiology)	General field of interest	What specifically you want to understand better; can consist of a broad hypothesis.	What experiment you want to do to address the hypothesis	Specific scientifically formulated questions	The specific predictions depending on whether a hypothesis is true or false, or which model applies
201504151100 (structural biology)	[The research topic] is the same as research objective	[The research question] is the same as research topic	Research objective is not applicable	More specific	Don't use
201504291100 (biology, plant ecology, ecology)	Broad context of the work	Focus of discovery efforts	Scientific and/or utilitarian outcome motivating the work	[The hypothesis is] not applicable	[The prediction is] not applicable
201505121101 (physiology, biomedical science, neuroscience)	A field of study, often associated with said methodologies. Overall focus. All grants are written with a topical interest.	N/A	N/A	[The hypothesis is] not applicable	[The prediction is] not applicable
201504301530 (biochemistry, molecular biology)	The topic is the local intersection of the field (e.g., which biological systems are being studied), the technical approaches used (many are possible but I have my own strengths), and the types of biomedical problems usually addressed by the combinations.	Note objective and question sometimes mean the opposite of what it seems here. Objective here is the unifying goal that the research works towards, usually based on a central hypothesis, the objective is more specific than simply advancing knowledge in the field. The objective is often stated as a clear question to be answered.	The objective or hypothesis is usually broken down into parts or steps which often can be addressed relatively independently of each other, but which all fit together. The specific questions or aims are often built around sets of techniques, or sets of experiments, that form a project by themselves. Each specific aim is usually intended to be a separate paper, or papers.	[See answer in previous column]	[The prediction is] not applicable

* All answers were directly transferred from participant written responses in the opening task.