Science education imparts a method of inquiry and a systematic way of processing knowledge about the physical world. For this reason, science education provides part of the foundation for any knowledge based effort to improve health, nutrition, family planning, environment, agriculture, and industry. Countries around the world recognize the fact that science and technology contribute to the economic prosperity and social advancement and help sustainable development of their nations. Science education has always been a priority in their education planning. Different approaches have been used to address the popularization of science and to encourage curiosity and imagination of scientific phenomena in schools and out of the school environments. However despite all these efforts school systems fail to attract enough students who could take up their career.

This book brings together prominent science educators and researchers from around the world to share their contemporary knowledge about research and trends in improvement of science education and curricula. The chapters provide information on recent trends and developments, effective teaching of science in schools, innovative approaches, advanced curriculum materials and the use of learning technologies. The book will be a critical and specialized source that describes how we can foster scientific habits of mind among young students and what pedagogical knowledge can lead to best practices in science education.

We need more efforts like this one, from a widening circle of contributors addressing the question of what it means to be educated scientifically and to develop scientific habits of mind. The 21st century promises to present a continuing stream of new problems demanding minds capable of addressing them.

Deanna Kuhn
Professor of Psychology and Education
Columbia University Teachers College, USA

This volume does much to advance the intellectual debate regarding scientific literacy within our global society. Collectively, the authors acknowledge that a full understanding of science education requires simultaneous attention to the cognitive, pedagogical, and technological dimensions of teaching and learning, as well as a focus on appropriate science content knowledge. The discussion is informed by inclusion of original research studies as well as the provision of the research bases for exemplary practices espoused by the authors.

Larry G. Daniel
Dean, College of Education and Human Services
University of North Florida, USA

In this book, the authors bring together a diverse range of perspectives and approaches to the study of scientific habits of mind and pedagogical knowledge. The book is organized into several sections, each focusing on different aspects of science education and the development of scientific habits of mind.

The first section, "Fostering Scientific Habits of Mind," explores the importance of fostering scientific habits of mind among students. The authors highlight the role of science education in developing critical thinking skills and the ability to think scientifically. They discuss the importance of promoting curiosity and imagination in the learning of science and the need for educators to create a supportive environment that encourages students to ask questions and engage in scientific inquiry.

The second section, "Pedagogical Knowledge and Best Practices in Science Education," delves into the role of pedagogical knowledge in the teaching of science. The authors discuss the importance of understanding the cognitive and developmental needs of students and the role of instruction in fostering scientific habits of mind. They highlight the importance of using a variety of instructional strategies and the need for educators to continually refine their teaching practices based on evidence of student learning.

The third section, "Innovative Approaches to Science Education," explores innovative approaches to teaching science. The authors discuss the use of technology and other modern tools in teaching science and the potential for these tools to foster scientific habits of mind. They also discuss the importance of collaborating with other disciplines, such as the arts and humanities, to provide a more integrated and holistic approach to science education.

The fourth section, "Advanced Curriculum Materials and the Use of Learning Technologies," explores the role of curriculum materials and learning technologies in fostering scientific habits of mind. The authors discuss the importance of using high-quality curriculum materials that are aligned with the scientific concepts and the need for educators to continually update and refine their materials. They also highlight the role of learning technologies in providing engaging and interactive learning experiences that can help students develop scientific habits of mind.

The book concludes with a section on the future of science education and the role of scientific habits of mind in the 21st century. The authors discuss the need for science education to adapt to the changing needs of society and the importance of fostering scientific habits of mind among students. They call for continued research and development in this area and the need for educators to continually update their knowledge and practices to meet the needs of the 21st century learner.
Fostering Scientific Habits of Mind
Fostering Scientific Habits of Mind

*Pedagogical Knowledge and Best Practices in Science Education*

Issa M. Saleh
*Emirates College for Advanced Education, United Arab Emirates*

Myint Swe Khine
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FOREWORD

This book will inform its readership from a number of perspectives. In fact, it has the potential to do more than just inform and guide on the basis of the table of contents as it has a number of themes or connections between and among chapters in each section of the book. I intend to approach this Foreword not by covering the same ground as the authors in their first chapter as they do this much better than I but to write from the point of view of the connections between chapters and the prevailing themes that underpin the connections. The book is organized into three parts as described by Dr’s Khine and Saleh in their opening chapter.

Predictably, the first section of the book, Contemporary Knowledge and Theories in Science Education, covers the theoretical landscape of science education. Research questions are derived from theory and a selection of research studies are available to the reader in the second section of the book entitled, Contemporary Research and Findings in Science Education. The third section of the book is a focus on Computer Technology and Science Education and is written with a view to enriching the possibilities for teaching science education in well equipped 21stC schools. A review of section one reveals connections between chapters on the role of science in the development of thinking skills and cognitive behaviors. Keith Taber (Chapter 3), for example, discusses ‘student thinking and modeling student cognition’ within the context of constructivist approaches to science education. Roger Anderson (Chapter 4) develops the theme as it relates to higher order thinking skills; Gregory Thomas (Chapter 5) discusses ‘thinking processes’ of students engaged in science learning. Jose P. Mestre, Brian H. Ross, David T. Brookes, Adam D. Smith and Timothy J. Nokes (Chapter 8) explore cognitive science and conceptual understanding and Maria Evagorou (Chapter 6) brings technology into the debate on thinking processes and science education.

These chapters provoke questions on the teaching methods associated with the development of thinking skills in science education and I was immediately drawn to authentic (meaningful and relevant) science teaching discussed in Christopher Harris’s and Ivan Salinas’s (Chapter 7) work. These chapters rely heavily on action and experiential learning in the science classroom which is part of the process of ‘thinking about’ science. Knowledge building discourse is a natural extension of the work on creativity, problem solving, authenticity, thinking skills and of constructivism (Oldham, Chapter 14) as an approach to modern science methods. The work on ‘discourse’ in science classrooms as well as the potential for work on ‘discourse’ in the teaching and learning process is a most fruitful line of enquiry for those looking to fully understand the future of science education content and methods and its impact on students. Making connections and looking for themes and linkages does tend to provoke more questions than it does answers.
The question that comes to mind is what can be done to change for the better the way we approach science education and how do we teach teachers to implement any new approach? Then I came across a persuasive chapter by Roderick Fawns (Chapter 10) on Science Teaching as Theatre. In like manner, this line of thinking ties nicely into the notion of 'discourse', mentioned earlier as it would be the basis for 'stories' that support the various 'plots' (questions) in science education as theatre. I have always considered the interaction between teachers and students and students and students to be a ‘performance of pedagogy’ with the former ‘the actors’ and the curriculum ‘the story’ with the methods used by the teacher and enacted by the student and the teachers to be the ‘plot’ as it unfolds. Each episode throughout the class has a number of sub-plots that come about as a result of student needs which may or may not lead to a conclusion during the classroom episode or it might require continuity. Effective teaching as theatre embodies constructivist (Oldham Chapter 14) approaches and in turn active learning, thinking skills and above all student teacher ‘discourse’ about science. The entire production is enriched these days by the ability of teachers to use technology to help to develop the plots and unravel the stories. Multimedia (Man Fie Tsoi Chapter 16) opportunities and game theory (Khine & Saleh Chapter 15) can add to the theatre and the impact factor in the lesson. These in fact could be seen as the ‘special effects’ of the production and used to augment the quality of the discourse and the depth of the learning experience in line with Harris’s (Chapter 7) work on authentic science education.

The future of science education portrayed in Grotzer and Liu’s (Chapter 2) article explores the nature of science teaching today and the goals for science education in the future. If one agrees with the need to rethink approaches to science education and if both cognitivist and constructivist approaches to science education are essential then how do we find the teachers of science and how do we teach the teachers of tomorrow? Innovative approaches to teaching science and to teaching science educators in higher education including Anila Asghar’s (Chapter 9) article on science subject leaders in K-8 schools. The role of the science subject leader in schools and notes that knowledge of ‘best practices’ in science education are essential to the success of the curriculum. This is connected to the previous discussion of the science lesson as theatre where all the actors engage in action learning, problem solving, group work and constructivist approaches. It is also linked to traditional and inquiry models of teaching presented in Saleh (Chapter 11).

It would be most unlikely for me to read this book from the front cover to the back. Rather, I would look for topics of interest and turn directly to the chapter concerned. However, this book has a number of highly topical ‘centres of interest’ nested in its twenty chapters that hang together on themes. My search for connections identified the theme of ‘thinking skills’ and ‘constructivist approaches’ to science education. Similarly, there is an especially interesting theme of science education as ‘theatre’ which is supported by constructs of ‘discourse’ and ‘authenticity’ in science education. Pedagogically due consideration must be given
to ways in which to excite students about science. In short the question is how to develop scientific skills and thinking processes while at the same time capture the scientific imagination of students.

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PART I
CONTEMPORARY KNOWLEDGE AND THEORIES
IN SCIENCE EDUCATION
1. PROMOTING SCIENCE, ADVANCING LEARNING, AND FOSTERING SCIENTIFIC HABITS OF MIND

INTRODUCTION
Countries around the world recognize the fact that science and technology contribute the economic prosperity and social advancement and help sustainable development of their nations. Science education has always been a priority in their education planning. Different approaches have been used to address the popularization of science and to encourage curiosity and imagination of scientific phenomena in schools and out of the school environments. However despite all these efforts school systems fail to attract enough students who could take up science as their career. In an attempt to foster scientific habits of mind, science educators had investigated in depth understanding of how children learn science and began to experiment with instructional innovations. Coaching, modeling, scaffolding, engaging in authentic learning tasks, collaboration and creating a community of scientific practice are some of the approaches recently introduced in the classrooms. There are still many challenges lie ahead in promoting science education to wider range of students and a multifaceted approach will be needed in formal and non-formal education settings. The chapters in this book present a wide ranging topics in knowledge, theories, research findings and using technology to meet these challenges. This book is divided into three parts, each address to salient features of science education.

In Part I, researchers presented contemporary knowledge and theories in science education and in Part II, contemporary research and findings in science education are covered. It is a common practice in teaching today in applying various types of technology assisted learning and Part III featured the use of computer technology in science education.

CONTEMPORARY KNOWLEDGE AND THEORIES IN SCIENCE EDUCATION
In Chapter 2, Liu and Grotzer from Harvard University caution science educators not to be trapped in teaching the nature of yesterdays’ science. The authors draw attention to the importance of teaching the nature of science in this chapter. They point out in the chapter that by studying the nature of science student will be aware of the source and limits of scientific knowledge. As the result, students will have a deeper understanding of science. They support their argument by looking at the work that was done by Carey and Smith (1993). The authors also look at the shift of science education over the years. They interview three scientists and they make a
recommendation for science educators. They advise that science should be looked as a dynamic rather than static and they make a prediction that science curriculum will play a catch up because of the changing nature of the nature of science.

In Chapter 3, Keith S. Taber from the University of Cambridge looks at some of the reforms that need to take place and some of the concerns in science education. He warns within the chapter the danger of ‘top-down’ curriculum planning. The author also points out the common failures of students cannot be put to incompetent teachers and lazy students but has to do with the abstract nature of science contents and human cognition. He illustrates this point by looking at specific examples form physics, biology, and chemistry.

In Chapter 4, O. Roger Anderson from Columbia University Teachers College begins the chapter by looking at the relationship between the organization of knowledge in memory and higher order cognitive operations. He points within the chapter the work that was done by Tsai in 1999 that shows that knowledge networking is dynamically interrelated with students’ epistemological orientation toward science. He gives a specific recommendation for science teaching and learning by looking at the cognitive sciences. Some of his suggestions are for teachers to help students construct rich networks of knowledge during class discussion. He cautions teachers not to move from one topic to another too fast. This is because students need time to process the information they learned in a daily bases. He farther suggests that teachers should spend time listening to students discussion in class that will give teachers insight on students understanding or misunderstand. He looks at the work that was done by Long, Anderson, and Wicht in 2002 that shows evidence for the importance of incorporating visual graphics by students can help to improve science learning.

The author starts Chapter 5 by pointing out the objective of science which is to improve science understanding and also thinking processes of students. He argue that in spite of the substantial research findings little change in the students’ management of the cognitive processes in classrooms. He looks at two major variables in science education that need to be considered the socio-cultural nature of school science education and the hegemonic nature of science education as a form of human activity. The author uses activity theory as framework to look at these variables.

In Chapter 6, Maria Evagorou from King’s College looks at two different thinking skills. These are systemic thinking and argumentation. She starts the chapter by pointing out the challenges of not finding a single definition of thinking skills. She uses Kuhn’s (2005) definition of thinking skills a ‘the process that enables us to make informed choices between conflicting claims’ (p. 33). By using this definition the author was able to argue that systemic thinking and argumentation are thinking skills. She uses the work of Cho and Jonassen (2003) to advocate that higher-level argumentation can be achieved by using computers based tools and teachers scaffolding students. She further argues the precedence of thinking for and about science over knowing science. She also looks at the work of Zohar (2004) that teachers are more inclined to hold a transmission of knowledge view from them to students rather than a constructionist of knowledge view point.
The focus of Chapter 7 is authentic science learning. It looks at reasons why authentic science learning became the spotlight for contemporary theory and research. The author argues that authentic science provides opportunities for students to conduct scientific inquiry in a manner similar to how scientists conduct their work. The author looks some research that deals with authentic science learning in primary and secondary classrooms. The author acknowledges some of the challenges and advantages for teachers and students. The author looks at science programs that support authentic science learning. Finally, the author concludes the chapter with challenges and future directions in the plan of authentic science learning environments.

In Chapter 8, Jose P. Mestre, Timothy J. Nokes, and Brian H. Ross try to connect science education with cognitive science. The authors try to point out some of the flaws in student understanding of basic physics. They use the work of Bowden, Dall’Alba, Martin, Laurillard, Marton, Masters, Ramsden, Stephanou and Walsh from 1992 and Mazur from 1997. They argue in the chapter that physics educators are doing a poor job in teaching conceptual understanding to students. However, they point out that teachers are doing fairly good job in teaching problem solving skills. They point out within the importance of having both (Conceptual and problem solving skills) to be effective science educators. They explain and give specific example how physics educators send a mixed message to students that can be counterproductive for conceptual understanding of physics concepts for students. This Chapter also looks at the finding of cognitive sciences to improve instructional activities in science classrooms.

CONTEMPORARY RESEARCH AND FINDINGS IN SCIENCE EDUCATION

The Chapters in Part II delve with contemporary research and findings in science education. In Chapter 9, Anila Asghar from Johns Hopkins University begins the chapter by looking at the significance of teacher leadership in science education in elementary and middle school settings. She then looks at two area of research in leadership as the conceptual framework for her study in this chapter. She argues that teachers can improve science knowledge and teaching skills by being intellectual leaders. She collected data by doing interviews, observational notes from interviews, class interactions, course feedback and evaluations, participants’ plans for seminars and workshops to enrich their colleagues’ science knowledge in their specific contexts, teachers’ reflective journals in which they wrote about their work context, and their emerging roles as leaders. The author was able to reveal some of the major challenges for science teachers with in the schools. She also outline some to the initiatives that where suggested by the Science Lead-Teachers.

In Chapter 10, Roderick Fawns argues that demonstration in science classrooms are ‘invitation to a conversation about a way of thinking’ but can’t provide prove of empirical truth. He points out the importance of storyline in science classrooms. He recommends that the expressive social order in teachers should dominate the practical social order. He advocates for ‘aesthetic awareness’ that will enable teachers to be more expressive when covering the instructional objectives in classrooms. He illustrates within the chapter how teachers can be expressive using specific examples.
According to the author, when science teaching is presented as a theatre, it mimics how science works in real social setting. He advocates for science to be taught as a human activity that focus on human experience and imaginations.

The focus of Chapter 11 is to compare Florida Comprehensive Assessment (FCAT) Science scores for traditional chemistry and Chemistry in the Community (ChemCom) students. Data were obtained from archives of the research and evaluation office at Duval County Public Schools. The sample consisted of 87 students with ChemCom as their high school chemistry background and 87 students with a traditional chemistry program as their background. The population examined in this retrospective study consisted of all 11th grade students for 2004-2005 school years at one of the schools in Duval County, Florida who completed a chemistry program on the fall of 2004-2005 school years before the administration of the FCAT Science test in 2005, a total of 174 students. The school guidance counselor assigned the students to ChemCom or traditional chemistry without any preference for either program. Therefore, the study did not use any specific purposeful design of sampling. However, the sample was examined to make sure that it was not biased in terms of gender, achievement, and socioeconomic status. All the students in the sample took the FCAT Science. No significant difference in achievement was noted between the inquiry-based verses traditional chemistry students.

In Chapter 12, Plummer and Barrow look at line graphing skills and attitudes of freshman biology non majors. After looking at the result of the study, they make several suggestions for educators who are involved in teaching laboratory sciences courses. One of the suggestion they give is that the teaching of graphing skills should be as early as possible to students (Cohn, E., Cohn, S., Balch, D. C., & Bradley, J., Jr., 2004). They give suggestion to teachers to let students’ generate data in experiments to make graphs.

In Chapter 13, Linda S. Behar-Horenstein, Alice C. Dix, Kellie W. Roberts, & Melissa L. Johnson look at undergraduate honors’ science scholars and the students’ research and course experiences. The chapter is based on a three qualitative studies. The result of the study was consistent with other researchers such as Mabrouk and Peters in 2000, Stevens and Reingold in 2000, Zydney, Bennett, Shahid, and Bauer in 2002 who also suggested that research start as early as the freshman year. The result of the study also shows indicated that students skills has increased as the result of the mentorship. The students show some sign of autonomy in their work as the result of the experience. This result is also consistent with Mabrouk and Peters when they did the study on Student perspectives on undergraduate research experiences in chemistry and biology.

In Chapter 14, Oldham deals with a case study of mathematics and science education in Ireland. She looks at the paradigm shift of focus in Ireland’s education system. This shift is basically moving away from transmission teaching and rote learning to more constructivist practices. The focus of the chapter is on teachers rather than students. Hence, she looks at the support that is provided to teachers to accommodate this change. Finally, the author looks at the different path that was taken in the development of science education by Ireland and also looks at some of the successful projects that are outside the formal curriculum.
The Chapter 15 analyses some of the recent studies in game-based learning in science education. The chapter looks at some of the studies that explain how interactive computer games enhance concentration, promote thinking, increase motivation and encourage socialization. The chapter argues that game-based learning in science education can help students in teaching difficult concepts and fostering scientific habit of mind.

In Chapter 16, Raymond Mun Fie Tsoi looks at the Piagetian Science Learning Cycle Model and the Kolb’s Experiential Learning Cycle. He argues that TSOI Hybrid Learning Model to be a better model. His argument is based on the notion that TSOI Hybrid Learning Model has the ability to cater to student different learning styles better than the Piagetian Science Learning Cycle Model or the Kolb’s Experiential Learning Cycle Model. Moreover, he also argues that TSOI Hybrid Learning Model helps to facilitate active participation of students in learning than both the models.

In Chapter 17 the author looks how to development innovative science and its role in the scientific process. The author also looks at the relationship between creativity and problem solving. Finally, she discusses what creativity in science education means for pedagogical knowledge and best practice.

CONCLUSION

Science education imparts a method of inquiry and a systematic way of processing knowledge about the physical world. For this reason, science education provides part of the foundation for any knowledge-based effort to improve health, nutrition, family planning, environment, agriculture, and industry. The soul of civilization depends on education. Specifically, science education is a key to unlock the gate of civilization in the technological world we live in. From the invention of the light bulb to the invention of computers, the fundamental principles for these advancements lay in the heart of science education. Hence, to increase inventions like these, science literacy must be a priority if a nation is to compete globally. The backbone for science literacy is effective curriculum. It is our hope that this book will be a useful resource for educators who wish to advance their pedagogical knowledge, practices and future research in science education.

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2. LOOKING FORWARD: TEACHING THE NATURE OF SCIENCE OF TODAY AND TOMORROW

ABSTRACT

The “nature of science” (NOS) refers to the epistemology, or the values and beliefs inherent to scientific knowledge and its development. It has been argued by numerous science education literature and organizations that teaching NOS in K-12 settings should be a major goal in science education, as it is of equal, if not greater, importance than traditional subject matter. Understanding NOS is believed to be crucial for scientific literacy and critical in preparing students to participate in a discovery-oriented field. However, it would be easy to fall into the trap of teaching the nature of yesterday’s science. This chapter examines key shifts occurring in the epistemology of science—from approaches that are reductionist to integrative/systems-based, from biological to mechanistic, and from hypothesis-driven to data-driven—by identifying emerging trends in current-day scientific practice from interviews with scientists working at the cutting edge of experimental research. The identified trends portray forms of thinking relevant to 21st century science—systems thinking, mechanistic (engineering) thinking, interdisciplinary thinking, quantitative thinking, and distributed thinking. We consider the implications of these particular thinking patterns and argue for the necessity of a general stance of epistemological flexibility for educating the next generation of scientists.

INTRODUCTION

The founders of modern natural science realized that they would have to begin afresh. This was a bold resolve, but not so bold as must be that of the student of mankind today if he expects to free himself from the trammels of the past. James Harvey Robinson, 1921

The “nature of science” (NOS) refers to the epistemology of science, or the values and beliefs inherent to scientific knowledge and its development (Lederman, 2006). Broadly construed, it takes into account what is considered to be scientific knowledge, the characteristics of scientific inquiry, and the processes, rules or assumptions for how science is conducted and how scientific knowledge is substantiated and evaluated as fact. Significant research underscores the importance of teaching NOS in K-12 settings (e.g., Lederman, Abd-El-Khalick, Bell, & Schwartz, 2002; Sandoval, 2003; Sandoval & Reiser, 2004) and it has been argued that
teaching NOS should be a major goal in science education, as it is of equal, if not greater, importance than traditional subject matter (Lederman, 2006). Understanding NOS is believed to be crucial for scientific literacy and critical in preparing students to participate in a discovery-oriented field.

However, it would be easy to fall into the trap of teaching the nature of yesterday’s science. As elaborated below, historical perspectives on the nature of science reveal clear shifts in how science has been conducted in the past and the patterns and trends that have characterized the nature of science at different points in time. Looking forward, we can anticipate shifts that reflect new knowledge and paradigms for framing scientific inquiry. Teaching NOS to today’s students requires a vision of what the science of today and tomorrow looks like. This chapter considers what scientists working at the cutting edge have to say about the nature of the science that they participate in and the implications for educating the next generation of scientists.

There is a growing interest in what the nature of science looks like through the voices of scientists rather than as science educators might define it based upon the philosophy or history of science. Samarapungavan, Westby and Bodner (2006), Schwartz and Lederman (2006), and most recently, Wong and Hodson (2009) have interviewed scientists in an attempt to define a more authentic sense of NOS and a more up to date vision (Wong & Hodson, 2009) of the epistemology of science. The work reported here, carried out over the past year, fits with this trend and introduces shifts in scientific reasoning that extend beyond those reported in the earlier research.

This chapter examines key shifts occurring in the epistemology of science—from approaches that are reductionist to integrative/systems-based, from biological to mechanistic, and from hypothesis-driven to data-driven—by identifying emerging trends in current-day scientific practice from interviews with scientists working at the cutting edge of experimental research. The identified trends portray forms of thinking relevant to 21st century science—systems thinking, mechanistic (engineering) thinking, interdisciplinary thinking, quantitative thinking, and distributed thinking. These forms of thinking are considered through the lens of science within a socio-historical culture and as a set of epistemological assumptions and tools that must bend and change with the winds of time. We consider the implications of these particular thinking patterns and argue for the necessity of a general stance of epistemological flexibility for educating the next generation of scientists.

We begin by discussing the nature of science and reviewing science education research to illustrate why it is so important that students learn NOS. We explore historical shifts in how the nature of science has been construed, and argue that this supports a need for epistemological flexibility. Through the analysis of interviews with contemporary scientists in cutting-edge fields in the sciences—genomics, nanoscience, synthetic biology—we offer a detailed vision of how science in this century has shifted from that of the past, and how such change impacts and is impacted by the current socio-cultural timeframe in which it is located. Finally we consider the implications of these epistemological shifts for science learning in the future.
In order to teach the nature of science, one needs a guiding vision of what the nature of science entails. While there is disagreement amongst philosophers, historians, sociologists, scientists, and science educators about the specific elements of NOS (Alters, 1997; Lederman, 2006), there is a growing consensus in the K-12 education community about what some of the understandings should entail. It includes understanding that scientific knowledge is 1) tentative, 2) empirically-based, 3) subjective (i.e. being theory driven), 4) based on human inference, imagination, and creativity, 5) socially and culturally embedded, and so on (Lederman, 2006).

This view of science is in stark contrast to the commonly held belief that scientific knowledge is a just natural product of following the scientific method. The highly touted “scientific method,” in which one starts with a hypothesis followed by a hierarchical set of steps of experimentation, is commonly taught in science classrooms and textbooks as the correct way to conduct scientific investigations. This leaves students with a stereotyped version of a much more subtle set of authentic scientific processes (e.g. Dunbar, 1995; Dunbar, 2002; Koslowski, 1996), giving them the impression that all science proceeds in much of the same way. Perhaps some scientists might conduct their work in this manner, but rarely do they use it in the stereotyped, step-by-step way as commonly taught in schools—despite the fact that scientists present their work in this linear sequence in journals. For instance, Koslowski (1996) has persuasively argued that scientists often use working hypotheses that they bootstrap between theory and data, and that science proceeds as the generation and modification of working hypotheses. Wong and Hodson (2009) quoted a physicist who argued that experimentation is not what he or most physicists do in their work nowadays; instead, they work with more theoretical issues—a startling finding given the strong emphasis on experimentation in science classrooms. As Rudolph (2000; 2003) has argued, we must reconsider the epistemology taught in classrooms.

Further, any account of the nature of science needs to consider the generation of scientific questions—what kinds of thinking patterns, processes, and experiences lead to them—and yet, this is entirely missing in most school accounts of the nature of science. It is especially important to recognize that scientific discovery and thinking is a highly nuanced and opportunistic endeavor specific to its particular socio-cultural context.

The U.S. national science standards do address specific understandings regarding the epistemology of science. They call for an awareness of the ways of knowing in the discipline, for instance, “scientists develop explanations using observations (evidence) and what they already know about the world (scientific knowledge). Good explanations are based on evidence from investigations.” And “scientific explanations emphasize evidence, have logically consistent arguments, and use scientific principles, models, and theories. The scientific community accepts and uses such explanations until displaced by better scientific ones. When such displacement occurs, science advances” (NRC, 1996).
Research in science education suggests that understanding NOS is essential to scientific literacy; if students understand the source and limits of scientific knowledge, they will be better equipped to make informed decisions about personal and societal problems that are scientifically-based. Carey and Smith (1993) argue that participating in a society that requires them to make decisions relating to science is a compelling enough reason, but that the reasons extend far beyond this. They found that 7th graders put forth views quite at odds with the prevailing theory-based notions of science. Rather, they held commonsense, inductive notions (as elaborated below) (Chalmers, 1978). Sandoval and Reiser (2004) have argued that students need to understand the epistemological commitments that scientists make—the processes they value for generating and validating knowledge. They call for foregrounding these commitments in the context of inquiry-based approaches.

Not understanding “the big picture” can impact the learning of specific epistemological skills and deep conceptual understanding. Peoples’ ability to reason about evidence appears to be limited by their epistemological development (Lederman, Abd-El-Khalick, Bell, & Schwartz, 2002; Sandoval, 2003; Sandoval & Reiser, 2004). Further, students with more epistemological knowledge generally learn science content better (e.g. Linn & Songer, 1993). Having a dynamic view of science has been shown to be particularly important. Songer and Linn (1991) found that students who view science as dynamic were more likely to integrate new knowledge successfully than students with less advanced notions.

While most research shows that students tend to have limited notions of NOS (e.g. Griffiths & Barman, 1995; Lederman & O’Malley, 1990; Smith, Maclin, Houghton, & Hennessey, 2000), research shows that students can learn to think about epistemology (Smith, Maclin, Houghton, & Hennessey, 2000). Carey, Evans, Honda, Jay, and Unger (1989) found that challenging student’ understandings of NOS and offering specific experiments to encourage building, reflecting upon, and testing their own science theories results in modest improvements in understanding. Explicit reflection on epistemology is important in supporting more informed NOS views (Khishfe & Abd-El-Khalick, 2002).

Technology-based, epistemic tools have also been used to scaffold students’ framing of their epistemological beliefs (e.g. Bell & Linn, 2000; Sandoval & Reiser, 2004; Scardamalia & Bereiter, 1993/1994). In classrooms using these resources, students have, for instance, demonstrated the ability to negotiate the terms of explanations, engage in planful investigation (Schauble, Glaser, Raghavan, & Reiner, 1991), and evaluate whether or not the evidence fit with their explanations (Sandoval & Reiser, 2004). This kind of classroom support is especially important given that teachers often have minimal epistemological knowledge.

Some approaches to teaching NOS have focused on teaching students the history of science. Examples of this approach include Harvard Project Physics (Rutherford, Holton, & Watson, 1970) and the History of Science Cases for High Schools (Klopfef & Watson, 1957). According to Khishfe and Abd-El-Khalick (2002), evidence in support of these approaches is inconclusive at best. Students appear to have improved in their ability to understand the basic tenets of science such as
differentiating theories from facts. However, students had a very difficult time adopting past views or expressing understanding or empathy for how scientists arrived at such views. They appeared unable to appreciate the socio-historical cultural context of the discoveries. More recently, Lin and Chen (2002) found an increased understanding of NOS with preservice teachers when historical cases were integrated into their program.

While historical cases can be an important part of a broader program, careful attention must be paid to how the cases are presented. It is all too easy to skew students’ sense of the discipline by only sharing examples that warrant historical recognition or stand out for some reason. Revolutionary science that cuts across disciplinary boundaries or that shifts the current paradigm is far less common than everyday science, which involves solving smaller scale puzzles and slogging through data. It is also all too easy to succumb to 20/20 hindsight bias. In retrospect, it is easy to believe Judah Folkman’s theory of angiogenesis since evidence has been amassed to support it and therapies based upon it have shown success. It is much harder to step back 20 years and put oneself into the shoes of his colleagues who were faced with a new, revolutionary theory that contradicted all of the common wisdom and hence felt that he was a heretic.

THE NEED FOR EPISTEMOLOGICAL FLEXIBILITY

As educators consider what forms of epistemic knowledge make the most sense to teach, these decisions must be framed within the broader cultural framework. Any vision of NOS is defined within the historical, and often, political, context in which it falls. Here, we take a brief look back in time at historical examples to offer educators a sense of just how deeply the tenets of science can shift over time and to foreshadow the need for flexibly defining the epistemology taught in schools.

The History of Science

Major shifts in how science is conceived and what constitutes its principal ways of knowing can be illustrated through past changes. Consider the following four shifts in the predominant notions of what constitutes science—from authoritarian to Empiricist/Positivist to Popperian to Kuhnian notions—as explained below.

Early sources of scientific knowledge were rooted in the teachings of the Church and the prevailing ideas of Aristotle as authorities. Aristotle (384-322 BCE) was a scholar and a philosopher and is considered by many to have had the most impact of any one mind on the way that we think and frame subjects today. Aristotle reasoned using deductive logic to figure out what necessarily must be so.

This “handing down” of science knowledge was eventually displaced by views that we would more likely recognize today: in particular, the ideas of two schools of thought that held some common tenets, the Empiricists and the Positivists. They portrayed the discipline as one of knowledge based on facts that are directly given to careful unprejudiced observers that provide the basis for inductive reasoning (Chalmers, 1978). According to Chalmers (1978), the view that science can be
derived from facts and observation is a strong aspect of many people’s commonsense notions of how science proceeds. This vision had great appeal in the assumption that facts were considered to be prior to and independent of theory. Therefore, they could constitute a firm and reliable foundation for scientific knowledge.

However, this view of science ran into difficulties in the idea of unprejudiced observers given the “extent to which perceptions are influenced by the background and expectations of the observer, so that what appears to be an observable fact for one need not be for another” (Chalmers, 1978, p. 17). The broader concept, that one could collect facts by observing patterns inductively over time also ran into problems. Even if a certain outcome occurred repeatedly, it didn’t necessarily inform what would happen in the future. A well-known story attributed to Bertrand Russell considers the dilemma of the inductivist turkey. The farmer comes to his pen each day at 9:00 a.m. and brings feed. This might lead a reasonable turkey to expect feed at 9:00, but on Christmas Eve, the farmer comes and instead chops off his head. Interestingly, despite the subsequent shift to Popperian and Kuhnian notions outlined below, it has been argued that induction is still a very strong part of the epistemology of science (e.g. Chalmers, 1978; Koslowski, 1996; Wong & Hodson, 2009). For instance, current Bayesian analyses—how we sum across experiences to develop theories of the world—are based upon induction as a central human cognitive process (e.g. Gopnik & Glymour, 2002).

The next significant shift in the tenets of science grew out of the work of Karl Popper. To address the problems of induction, Popper put forth the idea of “falsificationism.” He argued that one could only disprove, and not ever really validate, a scientific theory with absolute certainty. With this view, a valid scientific theory is one that can be argued and falsified (in contrast with a philosophy, which is not as easily disproved). Through falsificationism, he reasoned that only the fittest theories should survive. According to Chalmers (1978, p. 79), “It was urged that science should progress by the proposal of bold, highly falsifiable conjectures as attempts to solve problems, followed by ruthless attempts to falsify the new proposals.” The problem with this, according to Chalmers, was that little is gained from falsifying bold, risky conjectures or from confirming cautious conjectures. Further, “bold” and “novel” are historically relevant notions. They have to be measured against the background knowledge at the time. Further, falsificationism works with simple absolute statements, but runs into all sorts of problems in real life where there can be multiple necessary causes.

In 1962, Thomas Kuhn put forth a paradigm shift model for how science proceeds. Challenging an accumulation model for advancing scientific knowledge, it defined science as having a revolutionary character, where one theoretical structure is abandoned and replaced by another incompatible one. Scientific communities play an important sociological role in recognizing and allowing for (or disallowing) paradigm shifts. This notion of a paradigm as a particular conceptual framework had been put forth by Conant, a mentor of Kuhn’s, in which Kuhn elaborated the notion and set forth the non-accumulation aspects of the model (Miller, 2009). According to Chalmers, “A revolution involves not merely a change in the general laws but also a change in the way the world is perceived and
a change to the standards that are brought to bear in appraising a theory” (1978, p. 121). This means that the advancement of science is largely non-cumulative (but also involves the accumulation of facts and laws) and that observation is theory dependent. It involves periods of “normal science” when there is tacit agreement upon the epistemic rules. Eventually, rival models surface. These rival models regard different kinds of questions as legitimate or meaningful. In this context, the scientifically accepted knowledge of today may well be tomorrow’s misconceptions.

This historical overview reveals how, at a very fundamental level, our notions of scientific epistemology change with time. The shifts described above are very broad shifts in the notion of what science is. Below, we examine shifts at a finer level of grain—not so much in terms of what defines science as an enterprise—but more at the level of the epistemological tools and ways of knowing or thinking that can shift over time. But again, the necessity of epistemological flexibility as the sciences fits within a broader socio-historical framework becomes evident.

LOOKING FORWARD: CONSTRUCTING A VISION OF CURRENT SCIENCE

Despite the lack of consensus on exactly what NOS entails in the sciences (Alters, 1997; Lederman, 2006), there is a growing body of research on scientific thinking to help inform our notions of NOS. The work of Kevin Dunbar (e.g. 2002) and other researchers who study scientists in vivo as they are dealing with data, discussing evidence, making decisions, and so forth offers an important window into the cognitive science of scientific discovery. This work is a start towards a more nuanced notion of how real-world scientists proceed in their work, in contrast to the publicly perceived notion of the common scientific method as portrayed in school textbooks.

However, current conceptions of the nature of science and scientific thinking—presented as a list of discrete items in the science curriculum—seems too general and too broad to be productive for good learning in science (Elby & Hammer, 2001). As previously mentioned, the nature of science and scientific thinking is commonly presented as a set of vague characteristics: empirically-based, subjective, imaginative, creative, socially and culturally embedded, etc. (Lederman, 2006). Other studies on scientific thinking usually refer to broad and general cognitive processes, speaking more towards generic thinking skills than thinking patterns that are situated uniquely in science such as induction, deduction, analogical and causal reasoning (e.g. Dunbar & Fugelsang, 2005b). Equally general is the framing of scientific thinking as a set of procedural processes such as problem solving and hypothesis testing.

Thus, rather than focusing on the more general cognitive operations, we will focus on specific patterns that are unique for 21st century science research. Given the rapid advances in scientific knowledge and technology in the past several years, and a history of shifting scientific epistemologies, it is our belief that the current consensual notions of NOS may no longer fully reflect 21st century practices. Hence, over the past year, we interviewed scientists who are involved in rapidly growing, innovative fields of experimental research, to elicit insight into contemporary
science and the processes by which it is conducted. Interviewing scientists at the frontiers of science should illuminate aspects of NOS that may call for greater attention in the near future. Recently, Wong and Hodson (2009) published work that similarly argued for the importance of interviewing cutting-edge scientists. This collective interest promises to contribute to a nuanced and elaborated sense of what the science of today looks like.

**Scientist Interviews**

This chapter draws upon data from three scientists from three different disciplines that are currently at the frontier of science. Our selection of scientists—the geneticist, the materials scientist, and the synthetic biologist—is not meant to be representative of all science, but rather provide a window into contemporary scientific practices in key fields. The geneticist is a post-doctoral researcher in Advanced Studies in Genomics, Proteomics and Bioinformatics and is currently working on various genome sequencing projects. The materials scientist is a third year doctoral student in Materials Science and Engineering and is currently working on a nanobiotechnology project. The synthetic biologist is a second year doctoral student in Biological and Biomedical Sciences and is currently working on a synthetic biology project. The years of research experience among the scientists range from 7 to 10 years. It was our priority to select scientists who are actively involved in contemporary experimental research, which meant that extensive years of research experience was not a crucial factor in our selection process, as such scientists may not have more accurate insights of contemporary science. This is especially true with cutting-edge fields like bioinformatics/genomics, nanoscience, and synthetic biology, which really only came to the forefront of science and made big splashes in the scientific community near the turn of the century. By working with two relatively younger scientists who are becoming familiar with the tenets of their fields, we hoped that they would be more acutely aware of the tacit knowledge and assumptions that typically guides the work of their mentors and more senior scientists. All three scientists are from three different major research universities in the United States. While all three scientists were most strongly affiliated with the biological sciences, science disciplines used by these scientists also included chemistry, physics, and computer science due to the interdisciplinarity of these particular scientific fields.

**Methodology**

There are a number of approaches to collecting data for NOS research. Kevin Dunbar and Jonathan Fugelsang (2005a) adopted a biological taxonomy to categorize the various methods used to investigate the scientific mind, each with their own advantages and disadvantages. These methods include: *In vivo*, *Ex vivo*, *In vitro*, *In magnetico*, *In historico*, and *In silico* methods. We have chosen an *Ex vivo*, interview, approach. This allows us to directly interact with scientists and converse openly about what 21st century scientific practices look like to them, rather than through observation, which is the bases of all other methods. As with
all interviews, there is no way to ensure that participants are not presenting biased interpretations of their work, or leaving out details that they take for granted as part of the tacit knowledge of the field. However, the first author had prior experience with each of the interviewees and chose them specifically because they stood out as being exceptionally reflective about the nature of their work. In-person interviews were conducted with two of the scientists, while the other over online audio conferencing. The interview questions were open-ended to allow for the scientists to structure their responses and to give salience to what they deemed to be important. For instance, scientists were asked: Have you seen any changes in the way you or scientists in your field approach research problems and conduct research? What do you think is characteristic of the 21st century in how we do science and think in science? Are there any differences in the way we use technology now versus before? Do you use other disciplines in your work? Knowing what you know now, what do you think would be beneficial to learn if you were to go back to high school?

All interviews of 60 minutes duration were digitally recorded and transcribed for analysis. The interviews explored scientists’ views on their day-to-day practices and the practices of their field. Interview transcripts were coded for overarching patterns found in the data. An open coding system was used in which two different researchers read the transcripts separately and noted emic patterns in the language and issues that were brought forth by the scientists. They also noted the prominence of how often particular kinds of statements were made. Then the researchers discussed the patterns each had detected to determine the areas of overlap.

Five prominent themes or patterns of scientific thinking contextualized in the 21st century were identified. These point towards three key shifts in the epistemology of science. 1) Systems thinking which points towards a shift from a reductionist to systems approach to scientific inquiry; 2) mechanistic (engineering) thinking and 3) interdisciplinary thinking which highlight the shift from a biological to mechanistic (engineering) approach to science; and 4) quantitative thinking and 5) distributed thinking which underline a shift from hypothesis-driven to data-driven science.

FROM REDUCTIONIST TO SYSTEM APPROACH

Systems Thinking and Complex Causal Patterns

Systems thinking can be described as an approach by which a system of interacting entities is analyzed as a whole, rather than by analyzing its individual constituent entities separately (Hood, 2003). It is assumed that to fully understand the functioning of cellular processes, it is not enough to simply assign functions to individual genes, proteins, and other cellular components. The organization and control of the system must be analyzed in an integrated way by looking at the dynamic networks of genes and proteins, and their interactions with one another. Predicting the behavior of complex systems also involves a broad repertoire of concepts for dealing with causal complexity. These include understanding negative
and positive feedback and feed-forward control, linearity and non-linearity, non-additive effects, and so forth.

When speaking of their research, the scientists shared a predisposition towards such systems thinking. They spend most of their time investigating the behavior and relationships of all of the elements in a particular system, how individual parts come together as a whole, the interactions between components, and network dynamics. For example, referring to his research on engineering viruses to self-assemble into battery parts, the materials scientist commented, “There are multiple components working together. So I can’t look at each component totally separately, because their interactions ultimately affect the bottom line, which is the performance of the battery or solar cell.”

This emerging systems way of thinking in the 21st century can be contrasted with the reductionist approach that dominated 19th and 20th century biology (Woese, 2004). Reductionism is an approach that dissects biological entities or systems into its constituent for analysis. A systems way of thinking is a result of a growing awareness, by the scientific community, of the limitations of reductionism and the value of balancing reductionist studies with those that embrace biological complexity. Thus, the driving force behind systems thinking is a quest to seek a global, and hence more comprehensive and accurate representation of what is happening within and across complex biological systems. For example, the synthetic biologist said, “now that we have that global picture, we can measure them all at once, and try and see if they behave the way we thought they did,” referring to components within an organism. The geneticist’s interest in cross-species comparisons is demonstrated when he described his work as “trying to understand [transducers] more globally. Before most people were focusing on one organism only…[Whereas] we were trying to see if there are any similar proteins in different organisms.” However, beyond his own work, the geneticist affirms that the systems approach may be dominating 21st century biology as a whole:

Nowadays, you can’t study something individual anymore because, well you can, but you’re not going to publish anything…Before if you study, discover a protein, and understand the function of the protein, you can have a really good paper. But now, you may not be able to publish it. You need to have a global picture of this protein, how this protein interacts with totally different things.

While the concept of systems thinking is not new, it is emerging as a dominant way of thinking in 21st century science as a result of recent developments in advanced high-throughput technologies and the ability to sequence whole genomes. This belief is fostered by scientists in the study and is also well supported in scientific literature (Hood, 2003; Ideker, Galitski, & Hood, 2001). The materials scientist commented that, “the ability to model more complex processes has never been available before [now]. Without modern technology, I could work only on things that I can imagine in my head or write on a piece of paper.” Similarly, the synthetic biologist also attributed the recent possibility for global analyses—observing everything at once—to technology:
There is a lot of technology that exists now that allows us to look at the output of an entire set of data from a system. So there’s all sorts of new “omics” things coming out [like genomics, proteomics, and metabolomics], and that’s really just because we have ways to measure everything at once. So we’re getting to the point where we can actually predict and then do experiments on the whole network rather than at one enzyme at a time.

Leroy Hood (2003) and his colleagues (Ideker, Galitski, & Hood, 2001) explain how enabling technologies such as high-throughput automated DNA sequencers, microarrays, and high-throughput proteomics allowed scientists to carry out global analyses for rapid and comprehensive assessments of biological system properties and dynamics. The development of the first automated DNA sequencers in 1986 by Leroy Hood, allowed scientists to sequence whole genomes more efficiently, leading to the completion of the Human Genome Project in 2000. The availability of large genome databases and hence catalogs of all the genes and proteins in various organisms, allowed scientists to study the role of all genes or all proteins at once, directing biologists toward a more global and systems perspective on life processes.

While 20th century biology focused on intensive analysis of the individual components of biological systems, the 21st century discipline is focusing increasingly more on the study of entire biological systems at their full complexity (Lander & Weinberg, 2000). Although biology has always been a science of complex systems, complexity itself has only recently acquired the status of a new concept because of the advent of computational tools and the possibility of simulating complex systems and biological networks using mathematical models to supply new ideas and solutions (Van Regenmortel, 2004; Wake, 2008). Likewise, the scientists we interviewed seem to display this integrative way of thinking, striving to understand how components interact to create a whole, and displaying a more nuanced perspective towards their work with greater sensitivity to context variables.

FROM BIOLOGICAL TO MECHANISTIC (ENGINEERING) APPROACH

Mechanistic (Engineering) Thinking

Another common theme was the scientists’ display of mechanistic thinking, or thinking that had a mechanical/engineering undertone. This is shown through their regular use of mechanical analogies to conceptualize their work, and their modular, synthetic, and purpose-driven approach towards their research problems; all of which is in the quest for greater manipulation and control over the object/organism they are working with.

Examples of mechanical analogies included the synthetic biologist’s reference to genes as biological parts and organisms as biological machines, “One common thing about synthetic biology is that…we want to use standardized biological parts to build these biological machines, biological processes that kind of do things that we want to do.” The materials scientist went on to explain why thinking mechanistically is becoming more common in biology, “Mechanics is a part of
biology because stresses affect everything biological. Biology have also stepped over the boundary [of what has been traditionally defined as biology] by using nanomechanical probes to understand biological phenomena.”

Speaking of how his research question was generated, the synthetic biologist explained, “So if we have yeast that can make hydrogen, you can insert that new hydrogen making yeast into existing processes that we use to make ethanol, and change the output from ethanol to hydrogen.” From this, we see how he thinks synthetically and modularly by the fact that he sees natural biological organisms as made up of interchangeable parts, which can be used to assemble into systems that function in new ways, never existing before in natural living systems, hence synthetic. Similarly, the materials scientist conceived his research as “building a better solar cell by having viruses assemble a certain component’s material… a very mechanics-based problem: just get the viruses to snap certain parts together in a certain way like Legos, and we get the desired structure.”

Much like how engineering is purpose-driven, or with an ultimate goal in mind, as opposed to being hypothesis-driven, the interviews suggested that the work of current scientists often takes on this purpose-driven approach. Referring to his work, the synthetic biologist shared, “[In] traditional biology, you’re trying to understand how a certain process, biological process, works—[but] we’re more trying to say, ‘we want to take a biological organism and accomplish this, but then how are we going to do that?’” Along the same lines, the materials science commented, “A lot of times, you’re conducting science for a certain application or to reach a certain goal that is not necessarily scientific.”

The display of mechanistic thinking by these scientists appears to be a result of the merging of biology and engineering practices that is increasingly observed in 21st century biology, as compared to a time when most of biology—traditionally known for its pure, basic research—remain clearly demarcated from engineering—a purely applied research field. In the past, the connection between a scientific discovery and its practical application was not always made. Recently however, our understanding of biological mechanisms is opening up entirely new realms of technologies that can have significant impact on society. For example, the synthetic biologist mentioned the creation of biological machines to produce cheap hydrogen fuel to help alleviate the world energy crisis; and the materials scientist discussed his research involving building better solar cells by leveraging biological assembly processes. Thus, with more potential discoveries having increasingly large societal implications, it is not surprising that these particular scientists are adopting more of an engineer’s, or purpose-driven and applied research, mindset when conducting their work, as opposed to a pure quest for fundamental understanding of life with little practical applications for society. In Donald Stokes’ (1997) terminology, these scientists are operating within the Pasteur’s Quadrant, or practicing use-inspired basic research, but with a slight twist. While Louis Pasteur strove to both achieve a fundamental understanding of bacteriological processes and develop a way of controlling the effects of those processes in humans and animals, the primary goal of these scientists is to accomplish an engineering, or practical, feat. Indeed, the scientific research conducted by these scientists can still lead to a better
understanding of basic biological processes and interactions, but it is not the main motivation behind their research.

Along with an engineering mindset, comes the quest of 21st century biologists to have more manipulative control over the machinery of organisms, a trait traditionally belonging to the field of engineering. This is reflected in the synthetic biologist’s description of his research goal, which is “not just [to] move new genes into organisms but also have switches so that these genes are turned on at specific times or be able to process inputs so that when something changes in the environment, the system responds accordingly.” As with systems thinking, a mechanistic way of thinking is coming to the forefront now because of recent developments in new technologies and knowledge that enable scientists to manipulate biology more directly, allowing them to engineer and create novel biological systems for the benefit of society.

Interdisciplinary Thinking

As can be seen with the merging of biology and engineering, scientists are tapping increasingly more into multiple disciplines in their work, demonstrating flexibility in utilizing methods and tools from different disciplines. The materials scientist went on to say that beyond his own work, overall, “the nature of science is evolving to involve more disciplines.” He recognized that the utilization of multiple perspectives is dependent on the type of research one does; however, the most innovative fields today calls for interdisciplinary thinking, making it a distinctive 21st century scientific habit of mind:

It depends on what you’re working on. But it happens that some of the hot topics nowadays involve a lot of integrated thinking...Energy-related research, for example, involves a lot of chemistry since you are dealing with fuels, and sometimes biology and physics. Many of the important topics of the day stress this kind of thinking.

A main reason why this trend may be coming to the forefront now is because the questions and problems scientists are interested in today are more complex than before. This is not surprising given that the more problems we solve and more knowledge we gain within scientific disciplines, scientists are naturally pushed to ask more and more complex questions that cross the artificial boundaries between various scientific disciplines. As the materials scientist pointed out, “Chances are that, with these tougher and more complex problems, multiple disciplines would naturally be involved. To be ready to address those challenges, researchers need to have that kind of [interdisciplinary] perspective.” He described this natural progression towards complexity and interdisciplinarity as overlapping disciplinary circles:

Imagine you have three circles in a knowledge plane: physics, chemistry, and biology. They are expanding, and all the sudden there are intersections among two or all three of the circles. Those intersections are growing with time as each discipline advances. At this point, you can get away with knowing only
biology, etc., because there are areas that are not covered by the other disciplines. I don’t think there will be a day when you must know everything, but it’s becoming increasingly important to know multiple disciplines just so you can access those overlapping areas.

The new frontier is the interface. Science has long existed as a collection of narrow disciplines with well-defined territories, and is now undergoing a consolidation of ideas and concepts with the potential to stimulate tremendous innovation.

The drive behind this form of integrated thinking is the quest for a more comprehensive understanding of a phenomenon, which can only be achieved by thinking beyond one discipline. An example given by the material scientist presents this nicely:

There is a mechanical engineer at MIT, Dr. Subra Suresh, who used to model aircraft fatigue and damage. He then started looking at biological cells through the mechanics perspective; specifically, the mechanical physics of blood cells. Blood cells deform just as metals in airplanes deform. By using tools familiar to mechanical engineers, he started to understand blood cell diseases better because disorders such as malaria are a result of altered blood cell mechanics. By doing this, he crossed the line between physics and biology.

Implied from the three scientists’ discussion of their ability to use interdisciplinary thinking skills, is their ability to flexibly adapt to new situations and aptly acquire new knowledge and skills that may be characteristic of another unfamiliar discipline, or something entirely new to the scientific community. As both the synthetic biologist and geneticist attested, to be on the cutting-edge of research, you must constantly update your knowledge and skill sets to include the newest technologies in your field—this includes technologies transferred over from other disciplines: “the cutting edge of science is always going to be how do we apply these new tools to learn new things and do new things,” the synthetic biologist commented, while the geneticist expressed the same sentiment by reflecting on his own work, “I’ve been working on research for 8, 10 years…and our center has always been working on something new. We try to use new technology – whatever is available…because nowadays it is more and more competitive to get funded for research projects. To be able to do cutting edge research, it is impossible without new technologies.”

Possible catalysts for the emergence of interdisciplinary thinking include the development of the internet and the complexity and quantity of data and questions scientists are dealing with in the 21st century. The materials scientist spoke of the ease of reviewing literature over the internet, and the power of the internet to disseminate a vast array of information, both of which promoted him to think in an interdisciplinary manner:

I think the ability to conduct research efficiently online promotes multidisciplinary thinking because one can now more easily access journals outside one’s field through a few mouse clicks. When I research a certain topic on the
internet for my research, I often come across research not directly related to materials science. This has exposed me to a lot of information from different disciplines and has helped me see the topic from a broader perspective through other disciplines.

The complexity and quantity of data present-day scientists are up against may yet be another reason for the emergence of interdisciplinary thinking trends. For example, complex systems-level thinking inherently encourages scientists to think in an interdisciplinary manner. As biology becomes increasingly more complex, scientists are pushed to cross conventional disciplinary boundaries to use the knowledge and skills of other disciplines (e.g. mathematics, computation, and the physical sciences/engineering) to help them organize and analyze their complex research problems.

FROM HYPOTHESIS-DRIVEN TO DATA-DRIVEN APPROACH

Quantitative Thinking

As scientists are looking at ever more complex phenomena, math naturally becomes an increasingly vital part of science. Reflected in the scientists’ views, is the growing importance of thinking with mathematics in 21st century science. Math is becoming more and more necessary to validate science, to increase its predictive power, and to manage the complexity and exponentially accumulating amounts of scientific data. Speaking to the necessity of math to validate science, the materials scientist explained:

Science can be an art that’s very subjective. Math basically helps people defend their ideas…Anyone can imagine anything, but if you have a mathematical model that is founded on principles that people have worked with in the past, and you show that the modeling results match up well with your data, [then] that supports your hypothesis, theory, or statement. In that sense, math is a language, a tool you use to describe and qualify your idea.

Mathematics has historically been less intrusive in the life sciences, and has been until recently largely descriptive. The materials scientist’s explanation highlights the recent transformation of a largely descriptive field of scientific practice into a more quantitative and predictive interdisciplinary endeavor. Scientists now frequently demonstrate their findings in mathematical equations to justify and explain their work. For example, when scientists talk about a molecule moving along a DNA strand or diffusing through a cell, a mathematical model is often included, and even required by some scientific journals.

Undeniably, math has always been some part of science. However, it is the recent demand for quantitative descriptions within the scientific community, and the indispensability of math to analyze and process the complex problems and data sets of contemporary science that makes quantitative thinking a distinctive quality of 21st century science. As the materials scientist noted, “Without math, you can perhaps look at only one percent of the universe’s phenomena and have it be
interesting enough that people will pay attention to what you’re saying.” The synthetic biologist reiterated the importance of math in science going forward, as it is being reflected in newer scientific domains such as synthetic biology. He also hinted at how the quest to increase precision using math, in turn increases the predictive power of scientific claims:

A big part of synthetic biology is trying to make biology quantitative; ‘can we measure and come up with an absolute amount?’ And a lot of biology up until this point has been qualitative just because we haven’t had the tools to really measure things that accurately. But now we’re interested in mathematically modeling biology. We’re coming up with ways to very precisely measure things and making sure that we can use that developed model. So yea, that’s going to be a huge part of biology going forward.

Math is also needed to manage the complexity of problems current-day scientists are exploring. According to the scientists, the large part of the scientific community is no longer satisfied with studies or answers that do not place individual units of analyses within a larger context, as seen through systems-based thinking. However, beyond just a tool, quantitative thinking provides a new lens and perspective through which new questions and answers that were once invisible are revealed. The materials scientist reflected this sentiment as he explained how the mechanisms being studied today are more complex, and hence truer to reality, than can be explored with the simple diagrams of old science.

We’re able to look at more complex phenomena, which means that we can look at more things, since most phenomena in the universe are complex…As a result of us being able to look at more complex things, science is becoming more real. Old science could only take you so far because it couldn’t describe very much of what’s actually going on, since what’s really going on is too complex to be described by a few simple equations or drawings. But now we’re able to investigate life and how things work in the world a lot more accurately.

In addition to the necessity of math to manage and model complex phenomena, it is needed to manage the growing wealth of biological information (e.g. genome, proteome, and metabolome databases). Specifically, statistical tools in math are essential in separating signal from noise in high-throughput studies where huge data sets are generated, as summarized by the synthetic biologist:

So there’s the math at the modeling level, which is trying to use math to model how biological processes are actually occurring. And then at the other end, the network end that we’ve been talking about, statistics are very important there, like separating the signal from the noise is really important in these huge data sets.

Thinking with mathematics is emerging as a 21st century scientific habit of mind as a result of recent trends in system-level analysis, mass data production, and increased computing power (Bialek & Botstein, 2004; Cohen, 2004; Steen, 1988;
The growing pervasiveness of mathematics in the sciences is taking on many different forms: for example, statistics in experimental design, pattern seeing in bioinformatics, models in evolution, ecology, and epidemiology (May, 2004).

In the past, biological processes and the underlying genes, proteins, other molecules, and environmental factors were studied one by one in relative isolation. In the present, with science taking on a more systems perspective, math (in the form of robust mathematical models and computer simulations) is required to measure multiple variables simultaneously and predict the behavior of entire biological systems over different biological conditions or time (Bialek & Botstein, 2004). For example, the constituents of a complex system interact in many ways, including negative feedback and feed-forward control, leading to dynamic features that cannot be predicted by linear mathematical models that disregard cooperativity and non-additive effects (Van Regenmortel, 2004). In turn, mathematics will be inspired by the sciences much like how scientific knowledge and technology drives one another (Cohen, 2004; Stewart, 2002).

The recent ability to sequence whole genomes led to a rapid expansion of our information technology. Math, such as statistics, is needed to help scientists make sense of large data sets of information by separating signal from noise and extracting meaningful patterns. For example, soon after the human genome was sequenced, it became clear that a large database of DNA codes is not enough to understand the functional processes of life. Genes are part of a complex dynamic system and often behave in nonlinear and adaptive ways. Scientists must use mathematics in order to see high-level patterns and make sense of the high-level dynamics of complex systems within such large data sets. The geneticist provided some perspective on the exponentially growing amount of genetic information, as he compared the process of DNA sequencing over four years:

…”one run of genome sequencing generates like 20 gigs base pairs. That’s like a million times more than before, you know? For example, four years ago we started the papaya sequencing project, using the most powerful sequencer at the time...We had six of these machines, six of these sequencers. It took us 18 months, day and night, 24/7, for these machines to run. We generated one gig of data. One gig only, a thousand million base pair. Right now, with the [newest sequencer], it can generate 20 gigs in one run, couple of days only! So you think about this technology, and how much it improved…it’s hard to imagine even for most biologists. They can’t even imagine how much more data is going to be available.

Much like the other patterns of thinking, the increasing employment of quantitative thinking in the 21st century is made possible with technological advancements. As pointed out by the geneticist, the ability to generate mass data in the first place, starts with supercomputers with high computing power. Other technological advancements include the development of sophisticated computational approaches related to data management, statistical inferences, and mathematical modeling.
A consequent of being able to generate large amounts of data efficiently and with low cost is the reversal of conventional hypothesis-driven science, towards a more information- or data-driven approach to science. In the words of the geneticist:

…the sequencing technology and the computer power is getting better and bigger, and doing genome sequencing is becoming cheaper…Think about 7 years ago, when we started off our first project…We spent maybe $20,000 for the small microbe genome. Now, [with] $20,000 you can do a couple of huge projects already. For the microbe, you may need like $5,000 only. So during the past 7 year, that’s what happened. So genome sequencing is becoming a lot easier than before. That’s why people prefer to get the genome first, and then view the genome.

Science as traditionally practiced and taught in schools emphasizes the generation of a hypothesis at the start of a scientific investigation to direct what information needs to be collected. This made sense when scientists had limited resources and time to gather data, and hence little room for “mistakes,” or the collection of irrelevant information. However, contemporary scientific processes allow for data to be obtained without the need for prior hypothesizing. Recent advances in technology, especially in the biological sciences, leaves the majority of data collection to automated high-speed machines, reducing data generation time and hence enabling scientists to first obtain mass amounts of data, then data-mine for interesting research questions and develop sound hypotheses and theory. This data-driven approach to science is becoming much more common in 21st century scientific practice.

**Distributed Thinking**

In light of the increasingly complex problems scientists are working with, distributed thinking becomes even more crucial today than ever before. We named this pattern “distributed thinking,” based on the theory of distributed cognition, where it is believed that cognition is not limited to an individual’s mind, but can be extended beyond the individual by involving other persons and tools or technology. The idea that cognitive processes can be stretched over onto one’s physical or social surround is known as distributed cognition (Perkins, 1997). Perkins coined the term person-plus to refer to the person plus their surrounding physical and surrounding resources as one cognitive system. People employ the surround to support, share, and undertake aspects of cognitive processing, where outputs from such a distributed cognitive system would not be possible had cognition resided just in the individual. In this chapter, we take a person-plus perspective on scientific thinking.

The scientists demonstrated distributed thinking in their work by recruiting other people and technology to help them think through research problems. The materials scientist referred to the technological distribution of cognition when he said, “With more powerful tools, we’re able to do a lot more, and go beyond the limitations of the human mind through computational tools.” He recognized that
without these tools, his cognitive abilities are limited, “I wouldn’t be able to do my research without the microscopes I mentioned, and the research many other people are conducting wouldn’t go very far without computer tools.” The geneticist referred to the social distribution of cognition when he said, “We have maybe 20 different labs from all over the country, and the data are all analyzed by different groups of people.”

Similar to interdisciplinary thinking, possible catalysts for the emergence of distributed thinking include the development of the internet and the complexity and quantity of data scientists are dealing with in the 21st century. The internet promotes a social distribution of thinking by making it easy for scientists to collaborate and exchange ideas across space and time, as the materials scientists reiterated:

The internet has had two major affects. One is to help us access information more easily; the other is to help us collaborate. Now I rarely see people going to the library to look at papers. They do all their literature research online. And people are getting smarter about managing their papers on the computer and sharing knowledge online.

The complexity and quantity of data present-day scientists are up against also makes it harder and harder for an unaided human mind to process and organize. As DNA sequencers, microarrays, and other large-scale technologies begin to generate vast amounts of quantitative data, computer systems are required to store, catalogue, and condense this rapidly accumulating mass of data. Automated tools are also needed to assimilate these data into network models, which allows scientists to better predict network behaviors and outcomes that can then be tested experimentally. Thus, as can be inferred from the scientists’ interviews, technology is often the limiting factor to the scientist’s cognitive ability.

EDUCATIONAL IMPLICATIONS

In practice, helping students learn the epistemology of science holds a number of challenges: 1) understanding what the epistemology of science looks like; 2) preparing teachers to understand the epistemological assumptions; and 3) finding ways to make epistemological assumptions accessible at the right level for students without reducing them to a stereotyped set of steps. By interviewing scientists in fields that are at the frontier of 21st century science, we are able to develop a more authentic representation of the nature of contemporary scientific work.

Incorporating the Themes in K-12 Education

What are some of the implications of our findings for education in the near term? While these interviews represent only a small set of scientists, what direction might their observations about the nature of the fields that they work in suggest for what we should be doing in K-12 education? The paragraphs that follow sketch some possibilities.
Learning to Think About Systems and Causal Complexity

The interview analyses suggest the critical importance of helping students learn to think about systems and the embedded complex causal concepts. Systems thinking and reasoning about causal complexity entails concepts that are typically not taught in schools. A long time movement by the advocates of systems-thinking (See for instance, The Creative Learning Exchange) has yielded interest by teachers and schools, but little systematic change in mainstream educational practice. However, as science and a complex world continues to demand the ability to reason about systems and causal complexity, developing approaches that teachers can adopt and put into practice is an imperative. Grotzer and colleagues (e.g. 2000; Grotzer & Basca, 2003; Perkins & Grotzer, 2005) have met some success teaching complex causal concepts in service of deeper understanding of science concepts that students are already expected to learn.

Research on reasoning about systems and causal complexity reveals that students frame their explanations very differently than scientists do (e.g. Chi, 2005; Driver, Guesne, and Tiberghien, 1985; Ferrari & Chi, 1998 Grotzer, 2003; Grotzer, 2004; Hmelo-Silver, Pfeffer, & Malhotra, 2003; Perkins & Grotzer, 2005; Wilensky & Resnick, 1999). The patterns that students and lay persons use tend to simplify phenomena in a type of reductive bias (Feltovich, Spiro, & Coulson, 1993; Grotzer, 2004).

Research suggests that student can learn to reason about causal complexity. For instance, Wilensky, Resnick and colleagues (e.g. Resnick, 1996; Wilensky, 1998; Wilensky & Resnick, 1999) conducted numerous studies on the concepts of emergence using multiagent modeling. They have demonstrated that constructionist opportunities to work with dynamic, object-based models that reveal complex causal concepts result in new insights into the nature of complex phenomena such as the gas laws, ecology concepts, and behavior of slime molds. Grotzer and colleagues (See e.g. Grotzer & Basca, 2003; Grotzer, 2000; Perkins & Grotzer, 2005) contrasted three pedagogical conditions across a number of science concepts (electricity, ecosystems, air pressure, and density) that engaged students in thinking about simultaneity, multiple causes and effects, non-obvious causes, nonlinearity, and outcomes due to balance or imbalance between multiple variables. They found that a combination of activities designed to reveal the underlying causal concepts and explicit discussion about the nature of causality (what is hard to grasp about it, how it differs from other causal forms) led to deeper understanding. These students significantly outperformed students who participated only in the causally-focused activities or had “best practices” science units that included having students build extensive models, evaluate evidence, and participate in Socratic discussions. The differences were especially dramatic for science concepts in which the causality departed the most from being linear, sequential, and direct. Chiu, Chou and, Liu (2002) found that Cognitive Apprenticeship made a significant difference in students’ ability to grasp concepts of simultaneity and randomness as they relate to understanding chemical equilibrium in contrast to students in a control group. These efforts suggest the promise of the endeavor.
Learning to Think Across Disciplines

Underlying all three key shifts in the epistemology of science, with its five prominent patterns of scientific thinking, is the increasingly interdisciplinary nature of modern-day scientific practice. As the basic goal of scientific research is changing, demanding scientists to look at more complex and truer-to-life problems, scientists are crossing disciplinary boundaries to gain new perspectives, whether it is a more systems-based, mechanistic, or quantitative perspective. It is not a coincident that today’s most cutting-edge fields of science are all very interdisciplinary; scientific advancement is ultimately based on the unification rather than fragmentation of knowledge (Kafatos & Eisner, 2004). For example, nanoscience combines elements of physics, chemistry, and at times biology, to find new solutions to old problems: cheap, efficient solar cells, access to clean water, etc. Combining the ideas of computer science with molecular biology opens the door to bioinformatics, or genome research. Applying engineering principles of simplicity, standardization, and modularity to biology in the construction of synthetic biological “machines” leads to the innovative field of synthetic biology.

Thus, to equip students with the tools and skills to face complex problems that may not have straightforward solutions embedded in a single discipline, students must be encouraged and given the opportunity to apply different disciplinary perspectives and tools in science classrooms. Students must be taught how to borrow intelligently from different disciplines to help advance their understanding of a complex phenomenon and seek pragmatic solutions. The materials scientists explained how he developed such an interdisciplinary “attitude” in high school:

That might just be an attitude…When I started seeing how one set of principles, tools, or perspectives applied to another field, that really engaged me because it made me see how science is not that narrow. Scientific principles can be broad, and a lot of things we talk about are universal. What helped me was seeing examples of principles being taken outside the mental boundary I had set for them.

This is not to say that students should not be centered in a discipline of interests to which they can make significant contributions, but rather to say those contributions will be even more significant if students are able to use the techniques, ideas, and the expertise of people in other disciplines to help them tackle their scientific investigations.

Mechanistic and design thinking. Mechanistic thinking, or thinking with an engineer or design perspective, is a current-day example of how the disciplinary boundaries between the physical and natural sciences are becoming arbitrary and irrelevant. An example of an effective way for teachers to promote students’ interdisciplinary thinking, especially with engineering and design thinking, is to practice designed-based learning in the classroom. Design-based learning (DBL) is a form of problem-based learning (Krajcik & Blumenfeld, 2006), where students work together in teams to solve a problem. With DBL, students work together specifically to design and create a new invention or prototype that is applicable to real life situations, while
learning content along the way (Ellefson, Brinker, Vernacchio, & Schunn, 2008). This type of instruction incorporates design thinking with scientific inquiry, and encourages students to learn information in a more meaningful way by simulating authentic scientific practices. For instance, Ellefson, Brinker, Vernacchio, and Schunn (2008) has successfully created and implemented an eight-week Designer Bacteria DBL unit where high school students genetically modify bacteria so they are able to express new traits that can be used to improve students’ lives. The task of genetically modifying bacteria with new DNA to display new traits provides opportunities for students to meaningfully engage with the content of gene expression. Apedoe, Reynolds, Ellefson, Schunn (in press) also created an eight-week high school curriculum unit, the Heating/Cooling System, in which engineering design is used to teach students central and difficult chemistry concepts such as atomic interactions, reactions, and energy changes in reactions. DBL has also been shown to be a more effective approach for teaching science concepts to middle school students as compared to the traditional scripted inquiry approach commonly practiced in science classrooms (Mehalik, Doppelt, Schunn, 2008).

Quantitative thinking. Problem-based learning can also be used to effectively infuse quantitative thinking, or any other disciplinary tools and skills, into the science curriculum. It may be that math and science teachers need to work together to introduce mathematics materials using relevant biological problems, or vice versa (Bialek & Botstein, 2004). However, at the K-12 level, students may not have the mathematical competence to truly simulate the way modern quantitative scientists work. What is most important then, is to have students understand how quantitative thinking contributes to the understanding of scientific knowledge. By recognizing its importance in scientific work, student can then approach their math learning with an awareness of its applicability in science rather than seeing it as an obstacle (i.e. as course requirements) to be overcome on the way to science. Students should come to see math not as a collection of abstract equations, but as a lens and perspective through which new questions and answers that were once invisible are revealed. Scientists who can think quantitatively have an “extra sense” as Charles Darwin once wrote, “I have deeply regretted that I did not proceed far enough at least to understand something of the great leading principles of mathematics; for men thus endowed seem to have an extra sense” (May, 2004).

Learning to Thinking outside the Individual Mind

As science become increasingly interdisciplinary, it is impossible and arguably unnecessary for students to learn everything in the ever-growing and -expanding array of scientific knowledge. As the synthetic biologist reminded us, what makes a good scientist is not one’s ability to memorize large quantities of information, but one’s flexibility to adapt to new situations and learn new things efficiently; or in his words, “good scientists aren’t good at memorizing big data sets; they are good at coming up with new things to do with the existing data sets.” To do this, students need to learn and practice the art the thinking outside of one’s mind, what
we have been calling distributed thinking, or utilizing the cognitive abilities of others and the tools of the culture (Perkins, 1997).

Students are usually trained from the beginning of their education to be independent, even competitive, and often hold a stereotypical view of the lone scientists. However, with the rapid growth in the volume of information, collaboration is critical in teaching students to socially distribute their thinking (Wake, 2008). For example, the use of jigsaws in learning, where each student takes on a part of the learning and then communicates it to others simulates the distributed nature of discovery in science. Many cutting-edge practices in science education, such as the use of multi-user virtual environments for distributed learning, make use of this approach (Dieterle & Clarke, in press). It must be emphasized to students that unlike conventional notions of collaboration, where it is a mere means of dividing up work and reducing work time, collaboration in the view of modern day science is a means of achieving an understanding or creation that otherwise would not be possible had thinking resided in the individual mind.

At the K-12 level, the technological distribution of cognition is most often practiced as a way of managing heavy cognitive loads, where students can download their ideas and mental processes onto external objects (e.g. paper and computers) to help them with their memory. In this chapter, we emphasize a different reason for the practice of technological distribution of thinking relevant for contemporary science, which is the necessity of utilizing external cognitive operations such as computer-generated representations and calculations to reach a level of understanding that is otherwise impossible. Students should be encouraged to maximize the use of the tools around them and utilize technological tools in such ways that advance their mental representations and processes, rather than using technology to merely reflect their mental representations, as what we have been traditionally asking students to do.

In addition to the above adjustments to how and what we teach, the following adjustments to how we as educators think about teaching epistemology are warranted.

The On-Going Building of Visions of Current Science

As we explored in this chapter, advancement of technology has changed science through the centuries—and vice versa—and consequently changed the way scientists conduct their inquiries, or their way of thinking and knowing. Especially in a digital informational age where an unprecedented amount of technology is at our disposal, and where scientists are able to organize and conceptualize massive amounts of information in various ways, it is pertinent that we look at what scientific thinking means today in light of the rapidly changing environment of the 21st century, rather than trying to emulate yesterday’s science. Clearly, a critical piece of the educational puzzle involves continuing to develop relevant visions of current science and how it proceeds. This is an on-going challenge as new insights, technologies, and patterns of working create new possibilities for science as a field.
While there is no one science static with time and fitting all disciplines and context, helping educators understand the nuances of science as practiced in the expert community is a critical part of helping educators avoid stereotyping the ways of knowing in the sciences. Ongoing efforts by cognitive scientists are needed to 1) characterize the types of problems that the field grapples with; 2) to reveal key ways that scientists frame and engage with scientific problems; and 3) to offer a sense of what different forms of expert thinking about a particular problem type might look like.

Recognizing the Necessity of Epistemological Flexibility

It is important to help students discover that while there may be general ways of thinking and knowing that are shared among scientists across time and context, there are also distinguishing differences in the way modern and past scientists go about their work. Studying trends in scientists’ way of thinking and knowing can help students in their own thinking in science class; students can analyze the modes of inquiry that scientists engage in and reflect on what this means for their own thinking in science. But more importantly is that it helps students view the ways of knowing in science as flexible, and recognize the changing nature of NOS.

It may be that the science curriculum will always be playing catch up with the changing nature of NOS, and hence the most current day NOS can never be fully taught. One might look at the five prominent thinking patterns we have identified in scientists working in today’s most innovative fields, and use it as a laundry list of what we should be teaching our science students. While such attempts may work in the short term, current trends are fallible guides for longer periods where the socio-historical culture may be dramatically different, especially when science is developing and changing at the rapid pace we are experiencing now. This attitude is reflected when the materials scientist said, “Systems thinking might be unique today for certain fields just because of the requirements of today.”

Thus, we suggest an educational approach to NOS that promotes students to see science as a dynamic entity as opposed to a static field of study, or as the synthetic biologist saw as developing a type of mindset for scientific flexibility:

…it’s more about developing a mindset I think, rather than knowing the specific tools that we’re using at any one time. It’s more like, these are the [cognitive] tools we have – what are we going to do with it. It’s not like learning a trade; the tools that I’m using now are not going to be the tools I’m using 10 years from now.

Science is a dynamic discipline in which scientists are highly influenced by the scientific Weltanschauung of the time, as dominant thinking patterns and scientific practices shift and change over time.

In this chapter, we examined key shifts occurring in the epistemology of science due to changing socio-cultural contexts over time, and identified emerging trends in current-day scientific practice from interviews with scientists working at the frontier of experimental research. The implications of these epistemological shifts
and thinking patterns for science teaching and learning argue for a view of the nature of science as epistemologically flexible and an eye to the future as we educate the next generation of scientists.

ACKNOWLEDGMENTS

The authors would like to thank Amanda Heffner-Wong and Rebecca Miller for their help in preparing for this chapter. Special thanks to the scientists who participated in the study, whose helpful insights contributed greatly to the chapter.

NOTES

1 Investigate scientists as they think and reason live about their research.
2 Interview scientists about how they do their research, or diary studies of scientists.
3 Conduct controlled experiments on an aspect of scientific thinking.
4 Scan brains of people as they reason scientifically using functional magnetic resonance imaging.
5 Use historical data to reconstruct thought processes that led to a particular discovery.
6 Write computer programs that simulate scientific thinking or discovery.

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