Perspectives on the craft of scientific research: A conceptual organizational framework for creating research pedagogy

By **Frank W. Zok**

What does pedagogy of scientific research involve? Pedagogy is usually portrayed as the creation and the practice of education processes that enable *knowledge transfer* to the learner. But in the context of scientific research, there is more: Pedagogy must include the creation and the practice of processes that lead to *knowledge creation* by the learner. Indeed, the latter represents one of the principal aims of advanced graduate studies in science and engineering.

At a fundamental level, how do those of us who are scholars of science or engineering—not scholars of pedagogy itself—and who are responsible for teaching students the craft of scientific research even *think* about research pedagogy? And what language should we use? These types of questions are rarely discussed in the science and engineering community. Many academicians would probably be hard-pressed to articulate the goals they wish to achieve, not to mention the pedagogic tools they should use in achieving those goals. The easy and most common way out is to opt for the "show them how it's done" approach. While teaching by example is one important component of research pedagogy, the cognitive psychological processes that are used in knowledge creation need to be identified, appreciated, and cultivated. So where do we begin?

At a high level, the nature of scientific knowledge can be examined from several perspectives, including those of epistemology (theory of knowledge), human cognition, and knowledge utility. Here, some of those perspectives are synthesized to suggest one possible conceptual organizational framework of the elements and processes involved in knowledge creation. It is a framework within which educators, learners, and other practitioners of the research enterprise in science and engineering can contextualize their work and within which they can discuss the craft of scientific research using a common language. Such a framework is essential if pedagogic tools that enable transfer of knowledge creation skills to others are to be developed.

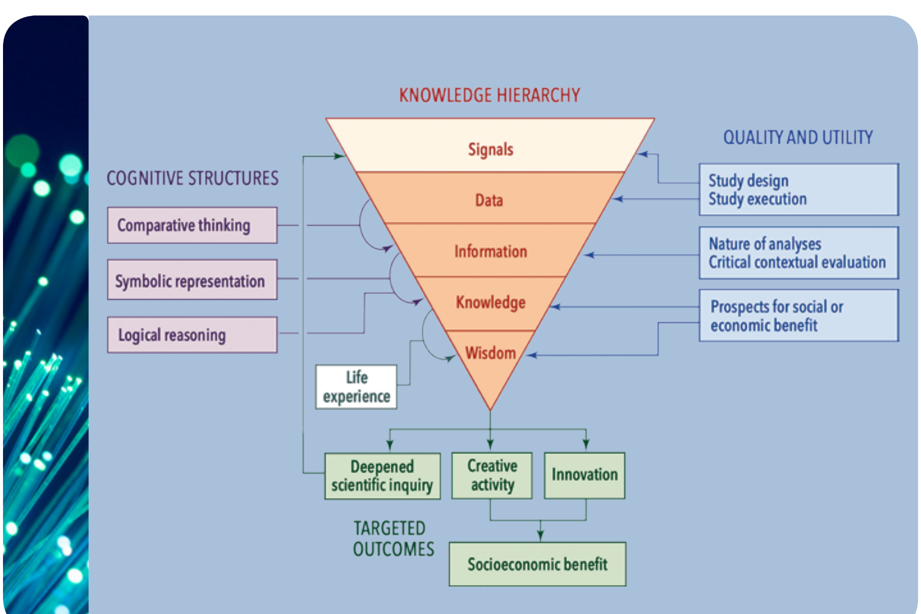

Figure 1. A conceptual organizational framework of elements and processes involved in the creation of scientific knowledge: Synthesis of the knowledge hierarchy, human cognitive structures used in navigating the hierarchy, dimensions of quality and utility, and targeted outcomes of the enterprise.

The knowledge hierarchy: Building blocks of the research enterprise

A useful starting point, taken from the fields of information science and knowledge management, is the *knowledge hierarchy*.[1–4] In its most familiar form, it comprises four elements: data, information, knowledge, and wisdom. The four elements are depicted in **Figure 1** as an inverted pyramid. The arrangement conveys the notion that data flows into information, information flows into knowledge, and knowledge flows into wisdom. An additional element (not

Frank W. Zok, Materials Department, University of California, Santa Barbara, USA.

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usually explicitly shown) involves signals that are recorded in producing data. Thus, signals flow into data, which in turn feed the other elements of the hierarchy.

Data are records of sensory stimuli (e.g., light, sound, electrical signals) and are represented by sets of symbols (e.g., words, numbers, pictures). They are raw, unprocessed, and unorganized and are therefore of no immediate value. Information, on the other hand, is data that has been processed, organized, and contextualized within a framework of understanding of the subject matter.

Knowledge, distinct from information, can be viewed as the product of a synthesis process in which information is passed through a personal "belief system": an internalized understanding of the subject matter informed by experience and guided by intuition.[5] A key outcome of this process is the abstraction of general truths from curated collections of information. But, being a product of the human mind, the synthesis process is inherently prone to personal bias; the same information processed by two minds can lead to subtle (or perhaps not so subtle) differences in the resulting truths. Of course this seeming contradiction calls into question whether purported general truths are indeed truths or simply personal perceptions of a reality that is too complex to grasp by the human mind. One important lesson here is that it is a dangerous leap of faith to believe that all knowledge, as we perceive it, is absolute.

Paradoxically, knowledge is both essential to the effective conduct of research and is a product of the research itself. This paradox undoubtedly underpins the mentor–apprentice model most commonly employed in teaching the craft of scientific research. But here again, we find the potential for personal bias to infiltrate the process. Such bias can compromise decisions made at all stages of research, from research design and execution to analysis and interpretation of data, thereby reinforcing existing biases. And because of the nature of the mentor–apprentice relationship, these biases can be readily promulgated from one generation to the next. As such, the presence of bias—scientific and personal—must play a central role in discussions of research pedagogy.

Wisdom has long been considered one of the most cherished human qualities and the pinnacle of human development.[6] Yet its meaning remains subject to debate. One common view is that wisdom involves ways of thinking that enable application of knowledge, guided by a sense of moral responsibility.[7,8] It is accompanied by a mastery of handling uncertainty (recognizing that knowledge is incomplete), intellectual humility (including the recognition that knowledge is not absolute), acceptance of various viewpoints, and an aptitude for compromise and flexibility.[7,8] These attributes evolve from a synthesis of diverse life experiences (both positive and negative) through reflective and contemplative practice. It should be noted that, while knowledge plays an essential role in the development of wisdom, even the most prodigious accumulation of knowledge does not on its own constitute wisdom.

Human cognition: Navigating the knowledge hierarchy

While the knowledge pyramid provides a useful classification scheme for the elements involved in knowledge creation, navigation within the hierarchy occurs in the realm of human cognition (**Figure 1**, purple). Understanding the navigation process therefore requires a different set of conceptual models.

The human cognitive structure can be broken into three broad levels.[9] The first, *comparative thinking*, involves recognizing similarities and differences, classifying data, and identifying spatial and temporal relationships. It is the principal cognitive structure through which useful information is derived from raw data. The second, *symbolic representation*, involves codifying information in socially recognized formats. It is, in essence, the embodiment of information. The third, *logical reasoning*, is the most advanced cognitive structure and is at the heart of knowledge creation. It includes inductive reasoning (whereby information is synthesized to form hypotheses), deductive reasoning (whereby hypotheses are assessed by examining information), and hypothetical thinking (e.g., thought experiments in which hypotheses are tested against conjectured data). Logical reasoning is essential in identifying cause and effect relationships and in the processes of problem framing (i.e., distilling a complex problem down to an examinable problem statement) and problem solving.

Integration of these structures into the conduct of scientific research is accomplished through the cognitive process of communication. In general terms, the communication process can be viewed as two sequential information-processing steps: one of coding and another of decoding.[10] In the first, the sender converts thoughts in their mind into words and symbols derived from a socially recognized language. This coding, sometimes considered the creation of explicit (formulated) knowledge from tacit (personal) knowledge, is invariably imperfect. (Michael Polanyi, a renowned chemist, social scientist, and philosopher, made this point eloquently:[11] "We can know more than we can tell.") In the second, the message is decoded by the receiver. In the process, explicitly formulated knowledge

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is converted into tacit knowledge in the receiver's mind. This, too, is imperfect. Whether the receiver successfully converts the message into mental representations that bear close resemblance to the intended thoughts in the sender's mind depends on both the fidelity of the coded message and the receiver's ability to decode that message using, as a basis, existing knowledge of the subject matter. Recognizing the imperfect nature of the transmission, the receiver must practice mindful listening during decoding, remaining cognizant of the hazards of personal bias and hasty judgment. One important implication of the information-processing steps involved in communication is that the message itself is not knowledge; rather, it is the successful coding and decoding within human minds that constitute transmission of knowledge.[10]

Knowledge transmission is critically dependent on the efficacy of coding of internal thoughts into communicable language. Moreover, the very act of coding plays an important contributing role in knowledge creation in that it enhances and solidifies comprehension of ideas in the mind of the sender. Herein lies one of the underappreciated challenges in scientific research: *communicating newfound knowledge that resides in one's mind to others*. While communication among laypeople in daily life may rely heavily on inference and a high degree of uncertainty may be tolerated, communication of scientific knowledge requires the highest precision in language usage and minimal reliance on inference if it is to succeed in its intent.

Quality and utility: Toward effective outcomes

The value of scientific research hinges in large part on the quality of data and information and the utility of ensuing knowledge and wisdom[4] (**Figure 1**, blue). Data quality can be assessed in terms of two aspects: study design and study execution. The quality of study design is judged by a combination of (1) the appropriateness of the working hypotheses to the problem of interest; (2) the selection of signals monitored and recorded; (3) the selection and control of independent variables; and (4) the breadth of the parameter space probed by the study. In turn, the quality of study execution is determined by the precision and accuracy of resulting data, dictated by limitations of measuring devices and control systems, and the degree to which the test methodologies employed conform to accepted standards in the cognizant research community.

Information quality is naturally limited by data quality—the adage "garbage in, garbage out" being apropos. Assuming data quality is high, information quality is determined by the nature and depth of analyses performed on the data in deriving information. The analyses require due consideration of all potentially meaningful relationships between data elements, culling patterns and trends from potentially large sets of raw measurements and observations, and testing of the statistical significance of correlations within and between data sets. They also require critical evaluation of the information in the context of the prevailing understanding of the subject matter and the working hypotheses. This evaluation—often the heavy lift in bringing a research activity to fruition—is key to generating useful knowledge.

It is worth noting that the quality of information can only be assessed and judged to be good if that information is communicated effectively to others, starting with research collaborators, mentors, and other immediate stakeholders. Information that is not communicated or poorly communicated, however high its quality may appear in the eye of the beholder, is of little use in knowledge creation.

By its very nature, knowledge cannot be readily reduced to practice outside the human mind. As a result, its utility in isolation is difficult to measure objectively. But, in the context of scientific research, knowledge is usually judged by the value of actions it enables in pursuit of social or economic benefit. Wisdom is even more difficult to reduce to practice. Methods for characterizing its utility in a broad sense and strategies for cultivating it remain active topics of study in the fields of psychology and philosophy.[12,13] Notwithstanding, the utility of wisdom, like knowledge, can be judged in the context of scientific research by the value of actions it enables, especially actions that are morally justified.

Actions that reflect the utility of both knowledge and wisdom include (1) creative activity—the conception of new ideas with value potential; (2) innovation—the reduction to practice of new ideas and hence the realization of value; and (3) deepened scientific inquiry through formulation of new questions and hypotheses for further exploration (**Figure 1**, green), which creates a feedback loop that is a hallmark of scientific research.

Expanding the framework: Elements of pedagogy that lead to effective researchers

A conceptual organizational framework of elements and processes involved in the creation of scientific knowledge based on synthesis of concepts in epistemology, human cognition, and knowledge utility has been outlined. Even in its nascent form, it provides a language that may facilitate dialogue between those involved in teaching and those involved

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in learning the craft of scientific research. The framework also helps to highlight important aims of research pedagogy that should be the focus of future discussions. Among these, two examples stand out:

(1) Much anecdotal evidence suggests that the science and engineering community has come up far short in providing students with tools and experiences for elevating their communication skills to the levels needed for them to become effective researchers. This deficiency is arguably one of the most critical and impactful in all areas of the research enterprise. Despite challenges in balancing research output with students' curricular needs, educators should provide students with resources (e.g., books, time) for learning to write well and prepare effective presentations (going beyond the creation of elaborate slides) and opportunities for practicing these skills in various social contexts (peer-to-peer, with non-experts, with subject matter experts) and various modalities (spoken, written).

(2) Cultivating wisdom in the research realm requires allowance of time and space for thinking deeply about what was learned recently, about what was learned years ago, about experiences in other facets of life, and about one's values—not separately, but together. It also requires integrity and humility in the face of the many challenges in academia. With the pressures of generating numerous publications and the extreme competition for research funding, conversations have become rife with hyperbolic claims of great accomplishments and grandiose ideas; self-promoters with questionable ethics seem to outnumber exemplars of wisdom by a large margin. Cultivating wisdom will require educators to heighten awareness of these issues among students and to provide students with ample exposure to positive role models.

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