An Introduction to the Handbook, Communities of Practice, and Definitions of Expertise

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Abstract

In this chapter we provide a brief summary of the various communities of practice that have paved the way for current expertise researchers, and are formative of this Handbook. We then provide a synopsis of how expertise has been defined both historically and in present day. Our purpose in this chapter is threefold: To demonstrate the heterogeneity of approaches and conceptions of expertise, to contextualize current views of expertise presented in this Handbook, and to use these views as a springboard to examine how we should examine expertise in the future—which we address in the final chapter. Finally, we present an outline of the chapters that are presented in this Handbook.

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Introduction

The study of expertise weaves its way through various communities of practice, across disciplines, and over millennia. Arguably, Aristotle's writings on the habitual acquisition of virtues were an important impetus for the field as one virtue was *excellence*. Ever since, the polarizing nature vs. nurture debates have held center stage for researchers focused on identifying the catalyst for expertise. While this debate still rages on (e.g., *Outliers; The Talent Code; The Sports Gene*), and is frequently popularized by the media, over the last century the study of expertise has matured into a multidisciplinary field spanning scientific disciplines, such as psychology, engineering, computer science, and education.

To date, the study of expertise has been primarily concerned with how human beings perform at a superior level in complex environments and sociotechnical systems, and at the highest levels of proficiency. Early expertise researchers focused on relatively simple tasks suited to college-level introductory courses in such fields as mechanics and mathematics, and on identifying underlying causal mechanisms—often with a special focus on the cognitive functions, processes, and requirements for operating at an expert level (e.g., Chi, Feltovich, & Glaser, 1981). Others have focused on the pathways leading to the attainment of expertise (e.g., Bloom, 1985; Ericsson, Krampe, & Tesch Römer, 1993). The more recent research has continued the search for better descriptions, and causal mechanisms that explain the complexities of expertise *in context,* with a view to translating this understanding into useful predictions and interventions capable of improving the performance of human systems as efficiently as possible.

Research on expertise is both topical and timely. As the nature of work in today's society becomes increasingly cognitive, and technological advances continue to accelerate the nature of work, the need for proficient and expert workers, and the ability to rapidly acquire skill, has

increased in urgency. This is true not just for key professions that shape future society—including, industry, government, military, and healthcare—but for all walks of public and personal life where learning is central to daily activities.

The purpose of this Handbook is to provide a comprehensive representation of the development of this field of study. As such, we offer traditional and contemporary perspectives, and importantly, a multidiscipline-multimethod view of the state-of-the-science and -engineering research on expertise. Our aim is to present different perspectives, theories, and methods of conducting expertise research, that have been influential in improving our current understanding of expert phenomena across a range of domains. Our second aim is to provide a particular focus on conveying how that understanding has been applied to address *practical* problems and societal challenges. In particular, the Handbook focuses on how this understanding has been translated into reliable predictions useful to society, and into effective interventions that can improve all facets of proficiency, performance, security, safety, health and well-being.

Overview of this Chapter and Structure of the Handbook

In this chapter we provide a brief summary of the various communities of practice that have paved the way for current expertise researchers, and are formative of this Handbook. We then provide a synopsis of how expertise has been defined both historically and in present day. Our purpose in this chapter is threefold: To demonstrate the heterogeneity of approaches and conceptions of expertise, to contextualize current views of expertise presented in this Handbook, and to use these views as a springboard to examine how we should examine expertise in the future—which we address in the final chapter. Finally, we present an outline of the chapters that are presented in this Handbook. First, we provide a brief overview of the structure of the Handbook.

This Handbook is organized into five sections. Section I, edited by Jan Maarten Schraagen, presents frameworks, theories, and models that characterize current views of expertise. In line with the goals of the Handbook, multidisciplinary perspectives are presented that range from early work in cognitive psychology to more recent work, for instance, in cognitive systems engineering.

Section II, edited by Emilie Roth, presents a variety of methods, developed by researchers from different theoretical perspectives, that are vital to advancing our understanding of expert phenomena. These methods are sampled from the full range of methods used to study, test, analyse and represent expertise and, employed collectively, would represent a truly mixed methods approach.

Section III, edited by Julie Gore, presents a diversity of application domains that offer several insights in to the nature of expertise when it matters: when the "rubber meets the road". Chapters are presented that focus on advancing our knowledge in professions, traditional skill domains, decision making under uncertainty in Naturalistic Decision Making (NDM) research areas, and in emerging domains.

Section IV, edited by Paul Ward, presents chapters with the central theme of developing, accelerating, or preserving expertise. Some of the chapters present a review of the current means by which expertise can be achieved and the constraints and barriers to maintaining expertise, whereas others present a challenge to the expertise community to begin to think differently about how we develop and support expertise. In Section V, we conclude with two chapters that examine topical issues of the value and future of expertise. We now turn to setting the scene by providing an overview of the communities of practice that have laid the groundwork for, or been most active in, pursuing studies of expertise.

Past and Current Communities of Practice and Definitions of Expertise

The history of expertise is pluralistic and multi-faceted. Numerous researchers have documented our and related histories elsewhere (e.g., Amirault, & Branson, 2006; Hoffman & Deffenbacher, 1992; Feltovich, Prietula, & Ericsson, 2006; Hoffman & Militello, 2009; Klein, 2008; Ward et al., this volume) and so we will not repeat those here. Instead, we present in this section an overview of various communities of practice that have had an impact on the development of this field of study and comment on past and current definitions and conceptions of expertise.

First, to demonstrate the impact of the study of expertise, we note that several books have already been published that cover some of the topics presented in this Handbook. For instance, some have reviewed expertise theories, methods, and applications, albeit with a specific or narrow focus (e.g., Professional Expertise—Ericsson, 2009; Expertise in Organizations—Wiggins & Loveday, 2015). Others have made recommendations about adopting a particular perspective on what constitutes a science of expertise (e.g., Ericsson & Smith, 1993). Another has provided a specific tribute to a particular individual (William Chase), representing the influence of this work on the field (e.g., Expertise & Skill Acquisition—Staszewski, 2013). Yet others have presented research from a sole or specific theoretical perspective (e.g., Naturalistic Decision Making—Hoffman, 2007, Mosier & Fischer, 2015; Sociology—Mieg, 2001; Philosophy—Selinger & Crease, 2006). Numerous edited texts also exist that have examined expertise in specific application domains (e.g., Sport—Baker & Farrow, 2015; Security—Berling & Bueger, 2015; Technology—Hoc, Cacciabue, & Hollnagel, 1995; Nursing—Benner, Tanner, & Chesla, 2006; Science & Policy—Collins & Evans, 2009). Only one other Handbook exists (see Ericsson, Hoffman, Kozbelt, & Williams, 2018). We think that our Handbook offers

something different—it offers a range of perspectives, is more comprehensive in its scope, and we hope that it is more inclusive in its approach than previous publications. Moreover, in this Handbook we have an eye on both the past *and* the future. Many authors in our Handbook address questions about how future research and practice should and/or may be carried out in order to continue to make the scientific and engineering leaps needed to shape future intellectual discussions and societal contributions of this field.

Communities of Practice

When we started this Handbook project we asked chapter authors to send us some words describing the people who had influenced their careers, especially those that had helped position each of them as world-leading researchers in the study of expertise. What followed was a list of names constituting Ph.D. and post-doctoral advisors, mentors, authors of scholarly works, and practitioners. The names provided did not always reflect an academic lineage—which was, in part, our original goal; to map this Handbook to the original pioneers of the study of expertise. When genealogical maps were provided, predecessors were not always readily identifiable as someone who one many might think of as a pioneer of expertise research. Instead, predecessors and influential figures were pioneers of science, engineering, psychology, sociology, and philosophy—including theoreticians, philosophers, methodologists, practitioners, and stakeholders—that reflected multiple, often disparate, communities of practice in which we operate. Our history is much richer than just a handful of notable individuals.

Next, we describe some of the communities of practice that reflect or have emerged from these influences, and that represent the majority of perspectives, theories, methods and applications presented in this Handbook. Many of these communities are overlapping with other communities (e.g., numerous NDM researchers use verbal reporting methods; perceptual-motor

expertise researchers also conduct deliberate practice research), and some have been largely superseded by other communities or other areas of research (e.g., expert systems by AI). Although some of the early research occurred around the turn of the 20th century, the 1970s and 1980s were a particularly busy time for the emergence of many of these communities.

Verbal Reports of Thinking Community of Practice. The verbal reports community is arguably one of the earliest communities of practice relevant to the study of expertise. The methods that unite this community have their roots in introspection—the history of which as it pertains to the study of expertise is presented in detail by Ward et al. (this volume). Hence, we refer the reader to that chapter for more information.

Despite Brentano's (1874/2009) observation that "outstanding people" (p.26) are an important focus for introspective studies of psychological laws (see Ward et al., this volume), the history of these methods is far longer than their application to the study of expertise. De Groot (1946/1965) was arguably the first person to seriously study chess experts using methods employed by this community. However, and arguably, following Duncker (1935; who leveraged Selz's (e.g., 1924/1981) work before him), De Groot is also the source of a division in this community. On the one hand, there are those who employ verbal report methods almost exclusively as a process tracing methodology (e.g., Ericsson & Simon, 1980, 1993)—so-called think aloud reports. On the other, there are those who also employ knowledge elicitation methods to better understand expertise more broadly, as well as to represent expertise so that process-traced verbalizations can be interpreted in context (e.g., Crandall, Hoffman, & Klein, 2006; Hoffman & Militello, 2009). Generally speaking, this division also reflects those who have studied simpler tasks (e.g., chess) and those that have studied more complex ones (e.g., firefighting), respectively.

Regardless of the theoretical, methodological, and practical approach adopted, as a whole this community has given rise to several treatises that have paved the way for this community of practice to employ these methods to better understand expertise more systematically, and with greater rigor. Moreover, these methods have also played a large part in developing theories of expertise (e.g., long-term working memory theory—Ericsson & Kintsch, 1995; Recognition-primed decision making—Klein, 1989). Various chapters in this Handbook describe these methods, their products, and/or their application to the study of expertise (e.g., Harris et al., this volume; Hutton, this volume; Militello & Shilo, this volume; Ward et al., this volume).

Skill Acquisition Community of Practice. This community of practice emerged from early research on learning (e.g., Ebbinghaus, 1885/1964) and transfer of training (e.g., Thorndike & Woodworth, 1901) where, amongst other things, researchers were interested in the *savings* from engaging in prior learning when relearning the same task, and the degree of transfer from having previously learned a similar task. One of the landmark studies with respect to expertise was conducted by Bryan and Harter (1987) who studied the acquisition of telegraphic language in field operators. Their research suggested that some skills were acquired more rapidly than others (i.e., sending rate was acquired faster than receiving rate), and habits were hypothesized to be acquired hierarchically—i.e., letters, then words, then clauses, then sentences, etc.—suggesting an automation of some aspects of the task before others are acquired. This phasing of skill acquisition is, perhaps, most representative of this community of practice, and exemplified in the framework proposed by Paul Fitts (e.g., 1964). Fitts argued that skill acquisition progresses through phases, from cognitively demanding, to more direct (i.e., less verbally mediated) associations between stimulus and response that are typically accompanied with decreases in error rates and time to respond. The final phase, in contrast, is assumed to be more

characteristic of automatic behavior and not to be consciously mediated. This is a point of departure for some communities of practice, who speculate that experts actively defer automating skill in order to maintain conscious control and/or access to underlying representational structures, especially those involving higher-order thinking (e.g., see Ericsson & Ward, 2007).

Many parallel lines of skill acquisition research emerged around the same time, including research focused on contextual interference (e.g., Battig, 1966), the power law of learning (e.g., Snoddy, 1926; Crossman, 1959; Newell & Rosenbloom, 1981), and reasoning more broadly (e.g., Bartlett, 1958). Some of this research has been instantiated subsequently as computational models of skill acquisition, with some emphasis on expertise and expert learning. Examples of approaches emanating (jointly) from this community of practice (and others) can be found in the Handbook (e.g., see Arthur & Day, this volume; Gobet, this volume; Kirlik & Byrne, this volume).

Individual Differences Community of Practice. The individual differences community has its roots in early efforts (pre-WWI) to develop tests capable of measuring verbal, non-verbal, and performance-based tests of intelligence and mental ability, as well as physical and motor proficiency. The goal was often pragmatic—to be able to classify individual differences in various types of ability, to diagnose intellectual or performance disabilities, and to predict future accomplishment from current levels. Although many of these efforts would have been designed to differentiate "the best from the rest" on a range of ability measures, a landmark study in the area of individual differences as they pertain to the development of expertise was conducted by Ackerman (1988). Ackerman (1988) showed that different abilities (e.g., general intelligence, perceptual-motor speed) changed in their degree of contribution to skill development as

individuals progressed through different phases of learning. As individuals become more skilled with training, ability measures tended to do less well at predicting *job* performance than those related to skill or knowledge.

More recently, however, there has been a resurgence in interest in the role of individual differences in expertise. Where previously discounted, researchers have recently asserted that some of the variance in skill is explained by domain-general factors, challenging the widely held conception that 10,000 hours of deliberate practice is sufficient to attain expertise. This community has been active in the last decade in their attempts to redress this balance (e.g., see Hambrick, Burgoyne, & Oswald, this volume; Ullen, de Manzano, & Mosing, this volume).

The Knowledge and Classic Expertise Approaches Communities of Practice. Two interrelated communities, often treated as one, emerged in the 70s; one at the Learning Research and Development Centre (LRDC) at the University of Pittsburgh, and one at Carnegie Mellon University (CMU). Arguably, these communities of practice had the earliest concentration of effort on the experimental study of expertise, and provided specific methodologies that could be used by others to study expertise. These lines of research clearly motivated those that followed to test the ideas put forward, but often at the cost of omitting other emerging frameworks that used different methods and/or had alternative theoretical orientations (e.g., Rasmussen, 1983, 1986).

Although equally known for his work in standardized testing, Robert Glaser, the first director of the LRDC, was instrumental in establishing a line of research focused on how people learn and, especially, how they progress within a particular field of expertise from novice to expert. This work led to a range of experimental and verbal report-based research (e.g., see Chi, Glaser, & Farr, 1988), including some citation classics (e.g., Chi, Feltovich & Glaser, 1981) that

examined the structure of *knowledge*, and the associated cognitive strategies and memory skills that support the transition to expertise.

Arguably, the expertise work at CMU was made possible by Herbert Simon and William Chase, and Allen Newell (e.g., Newell & Simon, 1972); which built on work by Adrian de Groot (1965; which in turn built on research by Karl Duncker and, indirectly, Otto Selz; see Ward et al., this volume). The *classic expertise approach* adopted by the CMU researchers is covered in some detail in the chapter by Gobet (this volume), hence will not be repeated here. Suffice to say, that this work, amongst many other concepts, led to the concept of *chunking,* a mechanism used by chess experts to circumvent the limits of short term memory by grouping individual units of information (e.g., chess pieces) in to constellations of information (e.g., patterns of chess pieces). Skilled memory theory followed (e.g., see Ericsson & Staszewski, 1989), as did the concept of a retrieval structure to elaborate on the explanation of chunk storage in long term memory, and subsequent derivations of this theory (e.g., Ericsson & Kintsch, 1995; Gobet & Simon, 1996). This community also explored differences between experts and novices in problem understanding, problem-solving strategies (e.g., forward-chaining versus backward-chaining), and differences in problem representations. As such, this work foreshadowed some of the later work on recognition-primed decision making (see Schraagen, 2018, for a discussion of the relations between these lines of work).

The work at LRDC and CMU has been extraordinarily influential yet has tended to focus on providing computational and/or theoretical explanations of simpler domains of expertise, and of the study of single tasks. Various chapters in this Handbook have adopted one of the perspectives that emerged from the LRDC or CMU, or describe work that is consistent with it

(e.g., Gobet, this volume; Harris et al., this volume; Kirlik & Byrne, this volume; Resnick, Russell, & Schantz, this volume)

Dreyfus-ian Community of Practice. The Dreyfus-ian community emerged in the 1980s, in part, in response to the expert systems and computational model-based approaches to studying cognition, including those associated with the classic expertise approach. Rather than propose a model of expertise per se, Hubert Dreyfus extended traditional phase-based theories produced by the skill acquisition community by proposing particular stages of expertise development (see Dreyfus & Dreyfus, 1986). Learners were assumed to progress from performance that was verbal, rule- and problem-solving-based, to a form of thinking that was based on experience—where experts recognize important and relevant aspects of the situation and know intuitively what to do without any need to engage in effortful and deliberative thinking or problem solving. This approach has been most notably advocated in the domain of nursing (e.g., see Benner, 1984; Benner, Tanner, & Chesla, 1996) but its influence has been felt in other areas too (e.g., see Baber, this volume; Fadde & Jalaeian, this volume; Ross & Phillips, this volume) (cf. Ericsson, Whyte, & Ward, 2007; Gobet & Chassy, 2008).

Social Studies of Science Community of Practice. Somewhat akin to the Dreyfus-ian community, the social studies of science community reacted to the expert systems and artificial intelligence communities' failure to consider the situated nature of human knowledge. Specifically, Harry Collins (e.g., 1990, 2018; Collins & Kusch, 1998) argued that these researchers had neglected the fact that humans and computers were socially embedded, which is needed for intelligence to emerge—because knowledge and understanding are societally determined (for a summary of this argument, see Hoffman & Militello, 2009). The strongest proponents of this view would argue that knowledge, including scientific facts, is socially

constructed. For instance, rather than physical laws being universal, this community of practice might argue that they are a reflection of the received view of the world at a particular moment in time that is culturally and contextually specific, rather than a truly universal phenomena. These views are captured in current definitions of expertise that have been forwarded by this community, such as contributory and interactional expertise—respectively, they reflect the practical competence within a domain and "the ability to master the language of a specialist domain in the absence of practical competence" (Collins & Evans, 2007, p. 14). Approaches that tap in to the social nature of expertise are reviewed in multiple chapters within the Handbook (e.g., Collins & Evans, this volume; Yardley et al., this volume).

The Deliberate Practice Community of Practice. The deliberate practice community emerged, initially, with the publication of a book by Bloom (1985) that contained several chapters examining the support mechanisms leveraged, and developmental pathways taken by current experts from a range of domains. In 1993, Ericsson et al. published a seminal paper on deliberate practice, which they defined as those solitary practice activities designed by a coach specifically to improve performance, that require substantial effort, and are not inherently enjoyable. Ericsson et al. (1993) claimed that engagement in these activities is related monotonically to the level of expertise attained, and that the greatest improvements in performance are likely to be associated with the largest weekly amounts of deliberate practice. Therefore, individuals who have accumulated the largest number of practice hours throughout their career and consistently and deliberately engaged in high levels of practice for sustainable periods are more likely to attain expertise. The general rule of thumb to attain expert status reiterated in this research is 10 years or 10,000 hours of deliberate practice (see also Hayes, 1985; Simon & Gilmartin, 1973).

The concept of deliberate practice has permeated the expertise literature in the past quarter of a century and the influence and application of this community has been demonstrated in fields as diverse as soccer (Ward, Hodges, Starkes, & Williams, 2007), clinical psychology (Rosenberg, 2000), teacher education (Dunn & Schriner, 1999), and with insurance agents (Sonnetag & Kleine, 2000). Several chapters in this Handbook discuss this research (e.g., Mishra, this volume; Fadde & Jalaeian, this volume). Notably, the strong claims of this research, that deliberate practice is sufficient (rather than just necessary) to explain expertise have recently been challenged (see Hambrick et al., this volume; Ullen et al., this volume).

Perceptual-Motor Expertise Community of Practice. The perceptual-motor expertise community grew out of other communities of practice, such as: the individual differences community, and their early emphasis on general and specific motor abilities; the skill acquisition community, with its focus on a shift from deliberative to automatic behavior with increases in perceptual-motor skill; and the classic expertise approach, with its emphasis on intuition as a mechanism of perceptual automation. Arguably, the latter approach had most influence with early sports expertise researchers attempting to test chunking theory by building on Chase and Simon's recall studies using sport-specific stimuli. Poulton's (1957) work on perceptual anticipation was also influential in providing a pragmatic point of focus for researchers who realized that anticipation played a significant role in sporting expertise. Following the trend in motor control and sport psychology more broadly, a division in this community occurred with sports expertise being investigated largely from two dominant perspectives: ecological (e.g., Araujo & Kirlik, 2008) and cognitive psychology (e.g., Starkes & Allard, 1993). The work of this community led to numerous texts on expertise (e.g., Williams, Davids & Williams, 1999;

Starkes & Ericsson, 2003; Baker & Farrow, 2015) and is well represented in this Handbook (see Fadde & Jalaeian, this volume; Harris et al., this volume; Williams et al., this volume).

Naturalistic Decision Marking and Macrocognition Community of Practice. The Naturalistic Decision Making (NDM) and Macrocognition community emerged in the mid 1980s, pioneered by Gary Klein and colleagues. The impetus for this community came from the military's desire to better understand high-stakes decisions under extreme time pressure and in dynamic, uncertain, and complex environments. The Army Research Institute for the Behavioral and Social Sciences supported several lines of NDM research during the mid-1980s, and incidents such as the 1988 USS Vincennes shoot-down led the US Navy to want to better understand naturalistic decisions. The first NDM conference was held in 1989 in Ohio and, over the years, the NDM community came to appreciate that its purview should not be on naturalistic decision making alone but on all aspects of cognitive activity in actual work environments (e.g., see Gore, Ward, Conway, Ormerod, Wong, & Stanton, 2018). Hence, NDM evolved to focus on macrocognition—or the way in which individuals cognitively adapt to complexity.

This community gave rise to the development of a host of cognitive field research-based methods (e.g., see Crandall et al., 2006), including the Critical Decision Method (Klein et al., 1989) and a range of models of expert thinking including the Recognition-primed Decision Making model (Klein, Calderwood, & Clinton-Cirocco, 1986; Klein, 1989), the Data/Frame model of Sensemaking (Klein, Phillips, Rall, & Peluso, 2006), and the Flexecution model of Adaptive Replanning (Klein, 2007a, b). Its impact has been far reaching (see Hutton, this volume) but like other communities of practice, it has not been without its critics (e.g., see Yates, 2001). These critics argue, first, that the explanations provided for expert performance by the NDM community are descriptive rather than predictive, and that these descriptions over-

represent the importance of aspects of performance that are easy to verbalize; second, that the more mundane, daily decisions that people make are ignored because of its emphasis on expert performance in complex environments; third, that NDM relies on a case study approach that limits generalization to the population at large (Markman, 2018).

Cognitive Systems Engineering Community of Practice. The Cognitive Systems Engineering (CSE) community emerged in the early 1980s, pioneered by Neville Moray, Thomas Sheridan, and Jens Rasmussen, among others. Based on some early verbal report work on electronics trouble shooting and plant diagnosis (e.g., Rasmussen, 1981; Rasmussen & Jenson, 1974), Rasmussen (1983) developed a model of cognitive control to identify the different ways in which humans at different levels of expertise exert cognitive control of performance (i.e., knowledge based, rule-based and skill based control) and the resulting heuristic strategies and workarounds used by skilled performers. Following some of the pioneers in ecological psychology and dynamic systems theory (e.g., Brunswik, 1956; Bernstein, 1967), cognitive systems engineers who were most influenced by Rasmussen adopted an ecological and systems perspectives with subsequent models (e.g., Abstraction-Decomposition Hierarchy) of the work environment. This community views expertise not as an individual phenomenon or a particular stage of information processing, but rather as a coupling between an expert with a problem ecology through a representation. After two seminal books on Cognitive Systems Engineering (Rasmussen, 1986; Rasmussen, Pejtersen, & Goodstein, 1994), Kim Vicente synthesized this work into an accessible treatise detailing Rasmussen's collection of methods, known as Cognitive Work Analysis (see Vicente, 1999). This and related perspectives, and the associated methods in particular, are detailed throughout this Handbook (e.g., Burns, this volume; Flach & Voorhurst, this volume; Naikar & Brady, this volume). This work has led to numerous

elaborations and offshoots of this perspective that are relevant to the study of expertise, including work on joint cognitive systems, applied cognitive work analysis, and resilience engineering (e.g., see Havinga et al., this volume).

The above list of communities is not exhaustive and others surely exist (e.g., Ethnomethodology, Expert Systems, and Resilience Engineering Communities of Practice). In the next section, we examine the different ways in which expertise has been defined in this handbook across communities of practice. We begin with a short discussion of the value of performance-based definitions.

Definitions of Expertise

We would need a book dedicated to this topic to record completely the range of definitions that have been used to capture what it means to be an expert. Rather than provide an exhaustive review of this literature without doing it justice, we focus on some of the common definitions of expertise and attempt to capture the variety of definitions presented in this Handbook. Perhaps the most widely cited definition of expertise is one of *reliably superior performance on representative tasks*—a key tenet of the Expert Performance Approach (e.g., Ericsson & Smith, 1991). One could argue that this is one of the best approaches for studying expertise—where measurable differences in performance between those performing at different levels of proficiency are reproduced and scrutinized under standardized and controlled conditions (e.g., see Ericsson & Ward, 2007).

This definition of expertise is exemplified in Morrow and Azevedo's (this volume) chapter where they describe expertise as "superior levels of performance on representative tasks" and as "performance improvements with increasing task-related experience… skills, knowledge, interests, and other changes that accompany improved performance" (see also, Harris et al., this

volume; Williams et al, this volume). However, one could argue that this and related performance-based definitions, while popular, do not easily apply in the study of cognitive work in many complex domains where performance cannot be measured or simulated easily, or reduced to single tasks.

Winning a chess match, serving a tennis ace, typing without error at speed, or playing a piece of music flawlessly (or innovatively) are relatively easy tasks to simulate and standardize under controlled conditions—and this is likely one reason why much research has focused on these domains. Studying performance in these domains and on such tasks may retain the functional complexity of work without compromising its ecological validity, making what is captured during experimentation a good representation of actual performance in these domains. But this does not help us to understand expertise in the vast array of complex domains (such as many of those discussed in this Handbook) where performance measurement on a given task is either difficult, impossible or does not reflect the totality of the domain expertise. This is not to say performance measurement should not be part of a definition of expertise. Perhaps, it always should be, at least, when it is possible. The real question is: What do you do (and how should one define expertise) when working in the majority of complex domains where performance measurement is particularly challenging or impractical? We address this issue in more detail in the final chapter.

How does one measure, for instance, expertise in those individuals or teams whose task is to contemplate a dilemma (i.e., where there is no right or wrong answer)? What about those areas of work that are purely knowledge based, or where the environment is highly uncertain, the problem or goals are ill-defined, or where there are high stakes? Other authors in this Handbook suggest a slightly revised definition, still relevant to performance, but where the emphasis is on

the measurement of performance goals or the associated knowledge, skills and/or attitudes; and the emphasis is on using a multi-measures approach as well. For instance, Matthews et al. (this volume) suggest that expertise is about cognitive and/or psychomotor skill competence, where those skills are central to accomplishing performance goals. Burns (this volume) suggests the emphasis should be on the "expert's deep knowledge and experience that brings about significantly different and more effective behaviors than novices." Feldon (this volume) suggests that expertise in scientific fields is more about "mastery of the knowledge and skills capable of bringing about new knowledge that meets or exceeds current standards." Moreover, Crichton adds another dimension to a definition of expertise in the Nuclear and Oil and Gas industries, suggesting that the ability to demonstrate and implement relevant knowledge and skills competently as well as *confidently* are what really matters.

Baber (this volume) and Ross and Phillips (this volume) both draw on Dreyfus' and Dreyfus' or Klein's conceptualizations suggesting that expertise is defined by the ability to see the signal in the noise—the critical situational elements—and intuitively generate the appropriate, or at least an effective, course of action. Ross and Phillips (this volume) go one step further suggesting that in times of uncertainty expertise is defined by the ability to mentally simulate those actions and *see* their success. Emphasizing similar elements but also highlighting the social nature of expertise, Yardley et al. (this volume) add:

> Experts need a fine-tuned moral compass and the ability *to navigate complex social situations where power is at play* as well as intellectual and psychomotor skills. They have to be tolerant of ambiguity and have a capacity to withhold action or act in the face of uncertainty, based on a fine balance of risks and benefits [emphasis added].

Collins and Evans (this volume) operationalize expertise along these same lines, and include the role of *Individual accomplishment* of the type described by Dreyfus and Dreyfus

(1986) and others. In addition, they add two social dimensions: *Exposure*—the ease with which tacit knowledge within the domain of expertise can be accessed in general and from others; and *Esotericity*—the ease with which social aspects of expertise can be accessed. This is consistent with Otte, Knifer, and Schippers' (this volume) definition of team expertise: "the ability to effectively leverage …the knowledge and expertise of all team members."

In their definition of expertise, Ross and Phillips (this volume) also allude to the expert's ability to immediately recognize changes in the scenario and to flexibly apply knowledge and experience, even when the situation is novel. Baber and Flach and Voorhorst suggest that expertise is a matter of "sensitivity to environmental constraints and opportunities". These adaptive and context-sensitive components of expertise are not new. For instance, Hoffman (e.g., see Hoffman et al., 2014) has described expertise as context-dependent choice amongst alternatives and Bohle Carbonell and Van Merriënboer (this volume) describe how routine expertise should be differentiated from what Hatano and Inagaki (1984, 1986) termed adaptive expertise. They describe the former as high level performance on representative tasks, and the latter as the same but in unfamiliar situations, where adaptivity is attributed to a deeper conceptual understanding of the fit between a specific procedural skill and a specific situation (see also Ward et al., 2018).

Conversely, Fletcher and Dehais (this volume) differentiate the type of (routine) *expert* performance of real experts from that which is more representative of competent journeymen—"the ability to successfully perform job-relevant duties and solve common problems quickly, reliably, and accurately." They suggest that, by definition, expertise conveys an "ability to successfully solve uncommon, unusually difficult, and/or strategic problems that others cannot." This perspective is consistent with Hoffman's (1998) delineation of proficiency across the skill

continuum, which was amongst the first to present a proficiency scale—based on the Craft Guilds of the Middle Ages—that captured this adaptive feature within a definition of expertise.

Despite the limited evidence for positive skill transfer with expertise, the flexible and adaptive nature of expertise is emphasized by several authors in this Handbook. One view which exemplifies many is that of Resnick, Russell, and Schantz (this volume) who suggest that experts "draw fluidly and flexibly on the information at hand and on the complex set of skills and attitudes (including the willingness to change one's mind) that comprise reasoning." We will revisit the concept of adaptive skill in the final chapter of the Handbook. In the next section of this chapter, we provide a brief summary of the chapters within each section of the Handbook.

Outline of the Oxford Handbook of Expertise

Characterizing Expertise: Frameworks, Theories and Models

Section I provides an overview of frameworks, theories and models used to characterize expertise. The chapters range from the classic approach to expertise, as exemplified by Chase and Simon's research on chess expertise in the early 1970s, to more recent approaches focusing on macrocognition and cognitive systems engineering. Although the study of expertise has been dominated by research in cognitive psychology, and most chapters build upon this tradition, this section also includes chapters from a sociological and neural point of view. A brief overview of each of the chapters in this section is presented next.

In chapter 2, Gobet describes the classic expertise approach and its evolution. He starts off by briefly discussing early research on expertise that influenced the classic approach. He then describes in some detail Chase and Simon's classic papers and chunking theory. This leads the way to a presentation of some of the key experimental and theoretical research that was

characterized by detailed analyses of the cognitive processes involved, use of verbal protocols, and a small number of participants. The chapter then discusses more recent theories that can be considered as outgrowths of the classic approach, providing a good opportunity to try to understand not only its key characteristic but also why it had such a large impact. The chapter concludes by a discussion of what this approach tells us about the means to address the challenges currently facing research on expertise.

In chapter 3, Hambrick, Burgoyne, and Oswald review evidence concerning the contribution of cognitive ability to individual differences in expertise. Their review covers research in traditional domains for expertise research such as music, sports, and chess, as well as research from industrial-organizational psychology on job performance. The specific question that they seek to address is whether domain-general measures of cognitive ability (e.g., IQ, working memory capacity, executive functioning, processing speed) predict individual differences in domain-relevant performance, beyond beginning levels of skill. The authors note that evidence from the expertise literature relevant to this question is difficult to interpret, due to small sample sizes, restriction of range, and other methodological limitations. By contrast, there is a wealth of consistent evidence that cognitive ability is an important and statistically significant predictor of job performance, even after extensive job experience. The authors discuss ways that cognitive ability measures might be used in efforts to accelerate the acquisition of expertise.

Chapter 4 provides a sociological perspective on expertise. Collins and Evans build upon a research program they refer to as Studies of Expertise and Experience (SEE), often referred to as the *Third Wave of Science Studies*, which treats expertise as real and as the property of social groups. This chapter explains the foundations of SEE and sets out the theoretical and

methodological innovations created using this approach. These include the development of a new classification of expertise, which identifies a new kind of expertise called *interactional expertise*, and the creation of a new research method known as the Imitation Game designed to explore the content and distribution of interactional expertise. The authors conclude by showing how SEE illuminates a number of contemporary issues such as the challenges of interdisciplinary working and the role of experts in a *post-truth* society.

In chapter 5, Pfeiffer discusses giftedness and talent development in children and youth, with a focus on talent development as a path toward expertise and eminence. The chapter briefly discusses a history of gifted education and then tackles some big picture issues and future possibilities. The chapter addresses a number of questions, including: Who is gifted? How are gifted individuals identified? Is giftedness domain-specific or domain-general? How malleable is giftedness? Does giftedness represent a qualitative or quantitative difference? How does the concept of expertise fit into gifted education? The author proposes a tripartite model of giftedness that offers three distinct lenses through which high ability students can be viewed: (1) high intelligence; (2) outstanding accomplishments and (3) potential to excel.

In chapter 6, Ullen provides an overview of some of the neuroanatomical and functional correlates of expertise, concluding that expertise is related to macroanatomical properties of domain-relevant brain regions and ultrastructural properties of both the gray and white matter. The consequence of these neural adaptations is a capacity for vastly more efficient performance of domain-specific tasks. In functional terms, this depends on multiple mechanisms that are situated at different levels of neural processing. These mechanisms include automation and alterations in functional connectivity, as well as specializations within memory systems and sensorimotor systems that optimize the processing of information which is relevant for the

particular domain of expertise. The author concludes by a discussion of neural mechanisms of expertise from the perspective of new models that emphasize a multifactorial perspective and take into account both genetic and environmental influences on expertise and its acquisition.

In chapter 7, Hoffrage provides an overview of the *fast-and frugal heuristics* program of research on expertise. According to the program reviewed in this chapter, people—including experts—use fast-and-frugal heuristics. These heuristics are models of bounded rationality that function well under limited knowledge, memory, and computational capacities. These heuristics are ecologically rational: they are fitted to the structure of information in the environment. While studying experts in the context of this program amounts to modeling them with fast-and-frugal heuristics, studying the acquisition of expertise focusses on how laypeople learn such heuristics. Because fast-and-frugal heuristics do not require complex calculation and are typically easy to set up, this program offers a straightforward way to aid experts: After the heuristics' performance has been determined under various environmental conditions, experts can be educated about these results.

In chapter 8, Flach and Voorhorst advance the claim that expertise is not a property of any particular stage of information processing, nor is it a property of an individual. Rather it is the property of a triadic semiotic system where the quality of performance depends on the coupling of an agent with a problem ecology through a representation. The dynamics of this coupling is akin to a self-organizing, adaptive control system. The authors argue that many of the debates about the nature of expertise arise from the different ways that people have parsed the triadic system into sub-components (elements or dyads). Thus, the fundamental point of this chapter is that expertise is not something that can be isolated as a property of a mind, independent from a problem ecology, or vice versa.

In chapter 9, Hutton provides an overview of so-called macrocognitive models of expertise, of which three are discussed in some detail: the Recognition-Primed Decision model, the Data-Frame model of sensemaking, and the Flexecution model of replanning and adaptation. Macrocognitive models are models of experienced, often expert performers and have been developed primarily from the study of decision making and cognitive work in naturalistic settings, as opposed to well-controlled laboratory experiments. They describe how people manage uncertainty and complexity in the world of work. The limitations and applications of these models are also illustrated in order to provide a future-oriented perspective on how the models might be improved and how they might be applied to support more effective cognitive work and more resilient work systems.

In chapter 10, Naikar and Brady present a perspective of human expertise in sociotechnical systems based on the phenomenon of self-organization. Consistent with the ideals of the field of cognitive systems engineering, this perspective is based on empirical observations of how work is achieved in complex settings and incorporates an emphasis on design. The proposed perspective is motivated by the observation that workers in sociotechnical systems adapt not just their individual behaviors, but also their collective structures, in ways that are closely fitted to the evolving circumstances, such that these systems are necessarily self-organizing, a phenomenon that is essential for dealing with complexity in the task environment. Accordingly, the chapter explores in depth the theoretical and design implications of the phenomenon of self-organization for understanding and supporting human expertise in sociotechnical systems, and draws attention to the broader implications of this phenomenon for advancing a social basis for human cognition.

In chapter 11, Baber reviews theories that explore the relationship between action and performance. These theories ask whether our cognitive activity depends on *internal representations* or whether it can be explained by our interaction with the world around us. In other words, rather than projecting a model of the world outwards in order to plan and guide our actions, these approaches see physical interaction with the world as a form of cognitive activity. These theories focus less on using mental representation and more on perception-action coupling between us and our world. Baber concludes that this points to an account of expertise which sees it as a matter of sensitivity to environmental constraints and opportunities, together with the ability to focus on optimal parameters in a given situation. From a practical point of view, he considers ways in which such sensitivity could be probed through field study and interview with experts.

This section concludes with chapter 12 on adaptive expertise by Bohle Carbonell and Van Merrienboer. The authors start by noting that the increasing number of changes at the workplace created through automation, political upheavals, and new technology frequently exposes individuals to unfamiliar situations. According to the chapter authors, mastering these situations requires individuals to possess adaptive expertise. By being an adaptive expert, individuals are able to deal with novel situations and remain performing at their original level. By drawing on recent literature, the goal of this chapter is to describe what adaptive expertise is. The authors contrast the concept of adaptive expertise with routine expertise to clarify when adaptive expertise produces superior performance to routine expertise. Subsequently they compare adaptive expertise to other expertise concepts. Following this, they describe how adaptive expertise can be developed and measured. The chapter ends with a number of recommendations of how individuals can be stimulated to develop adaptive expertise.

Methods to Study, Test, Analyse and Represent Expertise

In Section II we present a range of methods that have been used to study expertise. These methods provide a sampling of techniques that draw from multiple theoretical perspectives and communities of practice. In combination they provide an excellent introduction to the variety of theoretical approaches and practical methods available for analyzing, representing, and testing the knowledge and skills associated with expertise. Several of the chapters provide practical *how to* guidance and describe pitfalls to avoid when conducting research on expertise.

In chapter 13 Harris, Foreman, and Eccles provide an introduction to design of representative tasks, tests and simulated task environments for use in uncovering the basis of expertise. The authors describe how well-designed representative tasks can be used to discover the mechanisms that underlie superior performance, to stratify performers based on skill, and to discover the developmental steps involved in reaching superior levels of performance. The authors describe how representative tasks and simulated task environments can be used to understand the basis for expert performance as well as to develop training on the basis of expert performers. The authors present recent research illustrating the use of representative tasks and simulated task environments.

In Chapter 14 Ross and Phillips describe the origin, development, and application of a Mastery Model approach to the acquisition, representation and assessment of expertise. The framework of the Mastery Model originates from the Dreyfus and Dreyfus general model of cognitive skill acquisition. Development of a Mastery Model is based on a semi-structured interview of experts and a qualitative analysis process. The model specifies the hallmarks of performance, characterize the progression of skill, and provide performance indicators for each

key area, categorized in five progressive levels. The chapter includes specific examples and discusses differences between the Mastery Model and competency modeling approaches.

In chapter 15 Kirlik and Byrne provide a comprehensive introduction to computational models of expertise, reviewing both the foundational and contemporary body of research. The chapter discusses and provides examples of computational models built within the framework of a unified cognitive architecture as well as models that are more domain or task specific in their psychological assumptions. It highlights the requirements for effective computational modeling of expert behavior, including the need for extensive analysis, and possibly expert-level knowledge of both tasks and the environments in which expert behavior is manifest. The chapter ends with a discussion of promising future directions for research using computational modeling, as well as other emerging techniques such as neuroimaging, that can be combined to advance the scientific understanding of human expertise.

In chapter 16 Salmon, Stanton, Walker, and Read discuss the use of Hierarchical Task Analysis (HTA) to represent expert behavior and the factors influencing it. HTA is among the most widely used methods for conducting task analysis and a variety of ergonomics methods build on HTA outputs to provide in-depth analyses of behavior. The chapter describes HTA and its origins, discusses its' strengths and weaknesses, and provides practical guidance on how to apply the method. Two rail level crossing cases studies are used to illustrate how HTA can be employed to describe and analyze both the behavior of individuals at the sharp end (i.e., at the rail level crossing itself) as well as the behavior of the overall sociotechnical system (i.e., the rail level crossing *system*).

In chapter 17 Ward, Wilson, Suss, Woody, and Hoffman provide a historical examination of the philosophical roots and long-standing controversies associated with one of the most

widely used methods for understanding expertise – elicitation and analysis of verbal reports. The chapter serves as a comprehensive introduction to the variety of introspective-type methods discussing their validity and utility. It begins with a historical review of the perspectives and contributions of the pioneers of introspective methods, highlighting key motivations, arguments and disputes that have driven methodological development over the past 100+ years. It then turns to a review of current methods that rely on *thinking aloud* and other types of verbal reports to study expertise. It offers cautions and guidance on appropriate use of verbal reports, and ends with reflections on the future of introspection methodology and opportunities to improve the state-of-the-science and escape the legacies of behaviorism.

In chapter 18 Yardley, Mattick, and Dornan provide an introduction to qualitative research methods, particularly as part of research grounded in practice. The authors argue that expertise is inherently linked to the context in which experts work. Qualitative methods enable researchers to examine the broader context, including social practices, within which expertise is manifest and to uncover and pursue unexpected findings. The chapter describes different qualitative methods and discusses their distinct contributions to understanding expertise development in professional work. The authors provide examples to illustrate how qualitative methods can be used to answer *how* and *why* questions, to disentangle the impact of different factors in complex and uncertain situations, and to explore the messiness and complexity of expertise more generally.

In chapter 19 Militello and Anders provide a comprehensive introduction to incident-based interview methods for discovering and characterizing expertise. Incident-based methods are among the best known and easily applied methods for understanding expertise. The chapter presents four types of incident-based interview methods: critical decision method, knowledge

audit, simulation interview and cued-retrospective interviews. It describes strategies for analyzing the outputs of incident-based interviews, and provides examples of the types of products that are generated. Among practical applications described are uncovering requirements for training; identifying requirements for support tools; as well as developing testable hypotheses and descriptive models to inform basic research on expertise. The chapter ends with discussion of practical issues associated with the use of incident-based interview methods and experience-based advice in how to address real-world challenges.

In chapter 20 Burns reviews the roots of the cognitive work analysis (CWA) framework and how it can be used to represent expertise. CWA methods are best known as tools for the design of novel displays that improve performance in complex domains such as process control, health, and military operations. Displays built on CWA principles have proven to be particularly effective in supporting performance in unanticipated complex situations where expert *knowledge-based* strategies are most useful. Less improvement in performance has been found in routine situations that are well supported by conventional displays and procedures. Burns argues that this may be because CWA focusses on the needs for expert performance. She points out that CWA was originally founded as part of attempts to understand human expertise and transfer the knowledge of human experts into a design so that those who are *less expert* could benefit. As a result, CWA methods are useful for understanding and transferring expertise. Burns reviews the steps of CWA and discusses their various contributions to the understanding and development of expertise. The chapter ends with a discussion of how CWA can be used to develop and transfer expertise through design.

In chapter 21 Moon provides an invaluable perspective on how to understand and represent expertise through reflections on his own experiences in the professional practice of

knowledge-capture. The chapter describes the scope, uses, and origins of knowledge capture methods. Most particularly it covers protocols and methods for knowledge elicitation, focusing on the elements common to all capture methods – structure and probing questions. The issues of cognitive burden sharing across the capturer and holder, how purpose guides execution, and how constraints can shape practical developments in approaches to knowledge capture, are also discussed. Throughout, the chapter offers insightful, first-hand stories of knowledge capture and provides invaluable advice in dealing with pragmatic complexities that inevitably arise when going out *into the field*. The chapter concludes by looking at future directions for the profession.

In chapter 22 Matthews, Wohleber, and Lin examine the complex relationship that exists between stress, skilled performance and expertise. Stress generally impairs attention and working memory, increasing vulnerability to cognitive overload. The authors present a model characterizing the inter-relation between stress and expertise called the Standard Capacity Model (SCM) derived from theories of attention resources and cognitive skills acquisition. Matthews and colleagues argue that SCM, while having some empirical support, has serious limitations including neglecting contextual factors that can alter the pattern of findings. As an illustration, the authors describe the interplay between stress and expertise across four domains: test anxiety, sports performance, surgery, and vehicle driving. Consistent with the SCM, in some cases stress is associated with cognitive overload and expertise is shown to buffer the effects of stressors. However, the authors also provide evidence that expert performance is subject to domain-specific influences beyond cognitive capacity, including strategies for emotional regulation, choking under pressure, and aggressive behaviors that mediate the relationship between stress and expertise. They conclude that the relationships between stress and expertise must be examined contextually.

Domains and Applications

Section III is focused upon the wide variety of domains and applications exploring expertise. The chapters highlight great diversity of application and provide a range of insights from disparate domains. Two chapters focus on advancing professions of business and science, technology, engineering, and mathematics (STEM) education. Three chapters focus on advancing skill in domains in which expert performance has been studied traditionally: games, music, and sports. Seven chapters focus on advancing decision making under uncertainty in traditional naturalistic decision making (NDM) areas of research: spaceflight, nuclear, oil and gas operations, healthcare, firefighting and emergency responding, weather forecasting, aviation, railroad transportation, law enforcement, and military. Two chapters focus on decision making under uncertainty in the emerging domains of cyber security and intelligence analysis. Notably, the authors who have contributed to this section are located in academia and practice across many disciplines around the world. A brief overview of each of the chapters in this section is outlined below.

In chapter 23, Feldon, Jeong, and Franco provide a synthesis of literature which is most relevant for enhancing expertise in STEM. This synthesis focuses upon relevant findings from cognitive psychology and the psychology of science, sociology and anthropology, and educational research. The authors present the fundamental mechanisms of thinking and problem-solving practices in science and engineering that underlie expert performance within these disciplines. The chapter also examines issues pertaining to assessment and recognition of expertise in STEM fields, and the impact of training and education. The chapter ends by suggesting that further work is needed to explore and question the nature of expertise, the dynamic nature of STEM disciplines and interdisciplinarity.

Mueller, in chapter 24, examines word game expertise from a cognitive perspective and proposes a general taxonomic space of word games where the primary organizing axis distinguishes letter versus meaning-centered games. His critical review of the area concludes with the hypothesis that word game expertise is supported by both practice *and* prior skills and ability, and suggests predisposition-opportunity may be a fruitful framework for understanding skilled performance in this domain.

Chapter 25, by Mishra, suggests that music is a foundational domain in the development of the theory of expertise. Similar to Mueller's conclusions, Mishra reports that current thinking is that whilst deliberate practice is important, it is insufficient to entirely explain expertise. Mishra conjects that future research will aim to determine how genetics and practice interact in the development of experts.

In chapter 26, Williams, Fawver, Broadbent, Murphy, and Ward provide a historical overview of research focusing on the topic of anticipation, with a particular emphasis on its importance in various high-performance domains, including sport. They review more than five decades of research which has highlighted some of the key perceptual-cognitive skills underpinning anticipation and how these interact and vary in importance from one situation to another. In the second half of their chapter, they highlight the need for methodological improvements and identify ways in which conceptual understanding may be enhanced.

Patel, Kaufman, and Kannampallil (chapter 27) report on the study of diagnostic expertise which initially focused on characterizing the reasoning process and, later, on understanding the nature of expert knowledge and its impact on performance, including memory, comprehension, and reasoning. This chapter highlights that medical expertise is not a simple construct, and its development is characterized by non-linear growth in skills and knowledge.

Facilitated by new technology, recent research has moved toward real-world studies (or a combination of both laboratory-based and naturalistic studies), with automated and often precise methods of data collection and analysis.

Chapter 28 examines the study of expertise in the context of firefighting and emergency responding. The outcomes of existing research initiatives are examined emphasizing the importance of accurate and precise mental models, that are acquired through active interaction within the operational environment. Future research directions are proposed that will ensure the development of a continued comprehensive understanding of the nature expertise in firefighting and emergency responding.

Wickens and Dehais (chapter 29) explore proficiency and make the distinction between the experience of aviation professionals, often quantified in terms of hours of flight time, or flight qualifications, and expertise; proficiency at aviation tasks. They conclude from an extensive review of the literature in this area that experience of skills such as situation awareness, decision making, task management and crew resource management, may be only loosely coupled with proficiency and explore why this may be so.

Another well-established research area is covered by Roth, Naweed and Multer in chapter 30, who summarize methods used to uncover expertise in railroad research, followed by a review of the types of strategies that railroad workers exhibit. By providing a discussion of the impact of ongoing technological changes on the requirements for expertise the authors speculate on longer term changes in railroad technologies and the nature of expertise.

Thomson (chapter 31) describes the historical and continuing evolution of the cyber domains, and how we can operationalize current research in cyber expertise. Research into cyber expertise is in its infancy; in fact, there is no clear definition of what constitutes cyber expertise

or how it may be unique when compared to other technical fields. Thus Thomson describes the work roles of cyber operators and review results from Cognitive Task Analyses of their workplace. Finally, topics are presented for future research, including the use of realistic synthetic environments to study cyber operations with more ecological validity.

Jenkins and Pfautz (chapter 32) focus upon intelligence analysis (IA) and highlight past research methods that have been applied to characterize the domain of IA from a high-level workflow perspective down to low-level models of analyst information processing. They argue that such characterizations of the domain provide opportunities to highlight different characteristics of expert behaviors throughout the IA process. They conclude with implications for the design of training and propose new types of technologies to aid in IA and analogous domains.

In chapter 33, Suss and Bolton examine expertise in Law Enforcement and provide guidance for those planning on conducting research in this field. Illustrative examples cover a broad range of methods and highlight the subtleties that researchers new to the domain should consider when designing and conducting expertise research.

Fletcher and Kowal (chapter 34) review characteristics of expertise common to all domains as a context for the expertise needed by military personnel. Cognitive qualities needed for military expertise are discussed, including the emerging issue of cognitive readiness required for irregular as well as regular military operating environments. The chapter emphasizes that military expertise is similar to expertise elsewhere, however, the volatility, uncertainty, complexity, ambiguity, and lethality of the environment in which military decisions are made that affect large numbers of individuals may be unique.

Chapter 35 illustrates DiBello's work, which shows changes in society have influenced a greater need for expertise in business. DiBello's chapter provides an exceptional insight into her work with organizations over the past two decades, helping them adapt their expertise to an increasingly complex and interconnected world of business. DiBello's chapter suggests that the new *expert* in business may not be an individual at all, but rather a high performing and highly efficient team. The chapter ends with reflections about how business organizations may learn from expertise.

Fisher and Mosier's chapter (36) on teams in space captures the complexities associated with human space flights' multiteam effort requiring the coordination and collaboration not only of individuals within a team (mission control or space crew), but importantly also between teams. The chapter discusses the strategies and procedures these expert teams have established to ensure common task and team models, and to facilitate their communication and joint performance. The teamwork challenges of future long-duration space exploration are discussed, as are the continuing advancements and research needed to address them.

Chapter 37, by Crichton and Moffat, describes the current status of expertise development in nuclear power production and oil & gas facilities, both for routine operations and emergency response. They note simulator-based exercises increasingly being introduced. The chapter summarizes existing research into the content and format of the skills required by operators in these settings, highlighting many questions yet to be answered, including how do we measure this combination of task, duration of experience, and level of performance to determine expertise?

The final chapter of this section by LaDue, Daipham, Pliske, and Hoffman (chapter 38) captures the latest insights on weather forecasting. The chapter summarizes four research

programs ranging from organizational to individual analyses to provide unique, complementary insights about expertise in this highly technologically focused domain. Like many areas of expertise the forecasters have extensive, complex knowledge about each type of weather process they forecast, a knowledge that may be lost if not captured and passed on to the next generation. LaDue et al. suggest that the empirical work on professional activity in context that they report here, has the potential to invigorate studies of expertise.

Developing, Accelerating, and Preserving Expertise

Section IV presents a collection of approaches that have been used, broadly speaking, to develop or maintain expertise. The chapters range in emphasis from envisioning new pathways for educating our children and teachers to leveraging our knowledge of how experts learn and adapt in complex environments. Chapters cover important topics from improving expert performance individually and in teams, to accelerating the development of expertise, maintaining or retaining expert skills, and avoiding breakdowns in system performance.

Resnick, Russell and Schantz (chapter 39) argue that current methods of classroom teaching may be unfit for purpose—they do not adequately prepare students to thrive and excel in a complex world. As an alternative, they discuss the role of argumentation in developing expert reasoning skills, and point to an emerging body of research which suggests that teaching these skills in the classroom can lead to the acquisition and retention of general knowledge, beyond the topics taught through discussion. They review the ways in which *dialogic* reasoning can be used as a form of teaching to support the development of argumentation skill, and discuss some of the barriers to extending these methods beyond those students already considered gifted. In addition, they examine the role of educational, organizational, and social systems in facilitating a transition toward greater adoption of these methods in the classroom and beyond.

In chapter 40, Fadde and Jalaeian provide an overview of the concept of deliberate practice and review the associated research in teacher education, medicine/surgery, and sports. They examine the difference between domains that have a culture of *practice*—like sports and music—versus a culture of *study* or a culture of *experience*. They highlight that while strong correlations have been found between expertise level and domains that have a culture of practice, much weaker correlations have been found in those with a culture of study or experience, such as education or professions. Accordingly, they present an alternative to deliberate practice, termed deliberate performance, which captures the kinds of learning activities in which professionals might engage to deliberately improve their performance. Last, Fadde and Jalaeian compare three models of training based on related research and review their effectiveness and conclude that consciously incorporating deliberate practice during college-based professional education and deliberate performance during the career work of professionals (who typically have little time to *practice*) can accelerate the development of professionals to expert levels.

In chapter 41, Spiro examines expertise in complex and ill-structured domains from the perspective of *Cognitive Flexibility Theory* (*CFT).* His emphasis is on *adaptation* in modern situations that deviate from novelty in relatively ordinary yet unexpected ways. Spiro builds on and extends the adaptive skill framework proposed by Ward et al. (2018) by further specifying how one prepares for situational novelty via meta-features of an *adaptive mindset* that generalize across cases in ways that content does not. Spiro's view also specifies how these features support the novel rearrangement of previously encountered case features in ways that are adaptive to new situations. Computer-supported case-based learning environments are used as a means to apply CFT to *expertise acceleration,* and a theoretical rationale and empirical examples are provided for structuring these computer systems in terms of the principles of case and concept selection

and sequencing. *New modes of deliberate practice* that foster *adaptive readiness* are proposed, including skill at situation-adaptive assembly of knowledge and experience for *adaptive performance* that require a rethinking of what constitutes deliberate practice. Spiro concludes with a discussion of a wide range of practical *implications* to the accelerated fostering of adaptive response to novel situations.

In chapter 42, Moore and Hoffman present a view of proficiency scaling in the domain of intelligence analysis. They highlight the role of what are termed essential competencies, and detail the many distinct analytical roles entailing a specialization of expertise in this domain. Moreover, they discuss models of analyst reasoning and knowledge as a function of proficiency level and consider the stability of individual differences in styles, and distinctiveness of approaches to critical thinking across proficiency levels. In an era when the intelligence community is calling for robust measures of performance, they review how analysts make sense of situations and events for which there is no single cause, and discuss the role of human agency and motivations in causal reasoning. Last they present implications of this research for training future analysts.

Otte, Knipfer, and Schippers put forward the claim, in chapter 43, that team reflection is a major driver for the development and attainment of expertise in teams. They define team reflection as the collective evaluation of prior team activities, review the associated research, elaborate the mechanisms that link team reflection to expertise in teams and discuss multiple catalysts of team reflection. In the final part of their chapter, they investigate the shortcomings of previous team reflection research. These include the level at which this research has been analysed and the short-term and long-term consequences of engaging in this activity, and make

suggestions for future research in this area to deepen our understanding of the effects of team reflection on the development of expertise in teams.

In chapter 44, Petushek, Arsal, Ward, Hoffman, and Whyte focus on the role of mentoring in the development of expertise and discuss the multifactorial nature of mentoring, coaching, and related learning enhancement methods. They pursue a specific goal of unpacking the complex interactional relationship between developmental functions and roles to more fully describe what it means to be an effective coach/mentor. They review the meta-analytic and empirical evidence supporting the effectiveness of developmental and mentoring-type roles on a range of outcomes, such as job performance and career progression, and provide some specific examples of studies that have documented mentoring activities in action. They conclude by summarizing some of the major issues yet to be resolved in this field, and make specific suggestions for how to advance this area of research.

In chapter 45, Morrow and Azevedo focus on the relationships between expertise and aging. They begin their chapter by considering how experts excel on domain-relevant tasks despite cognitive limitations. Further they examine how these expertise-related advantages develop, providing possible ways that adults can offset age-related cognitive constraints to maintain performance in later years. Their chapter centers around two key issues related to expertise and aging: the extent to which superior levels of performance can be maintained by experts as they continue to age; and the extent to which knowledge and skill associated with experience can offset age-related declines in abilities and function.

Arthur and Day (chapter 46) focus on the issue of skill and knowledge decay and retention and how this intersects with expertise. Their review highlights several important conclusions: First, decay is affected more by interference than forgetting of information. Second,

decay is highly dependent on task and situational factors. Third, there is less decay on complex tasks than is observed for simple tasks. Fourth, retention is a function of expertise—it is stronger with practice, elaborative rehearsal, and greater mastery of the task. Fifth, retention and transfer are distinct concepts. Sixth, there is a limited amount of empirical research on decay and expertise in complex real-world performance domains. They conclude by suggesting that much could be learned by closer integration of the literature on expertise and skill decay and make recommendations for how to proceed in this regard.

In chapter 47, Havinga, Bergström, Dekker, and Rae present an argument for expertise from a resilience engineering perspective, suggesting that this has changed the value of expertise from meeting required standards to helping organizations adapt. They begin by introducing the concept of resilience and its application to safety in sociotechnical systems. Then they explore how to manage expertise in complex systems, considering both its costs and benefits to engineering resilient organizations. Their review considers the role of expertise at multiple levels of the system, including frontline workers, teams and management, and on an organizational systems level.

In chapter 48, Conway and Gore focus on the role of expertise in developing complex policy interventions for government. They begin by providing some context on the nature of government work and its challenges; and then examine the role of expertise across the system, including the overlap in expertise between different roles, how this has evolved over time, and how the evidence is derived, from whom, and how it is shaped by values. They highlight the difficulties of identifying and incorporating true expertise into policy interventions and consider whether expertise itself is under threat in this process. Last, they identify research gaps that if addressed would support the further professionalization of the policy function in government.

Current Issues and The Future of Expertise Research

Section V presents two chapters that address the current and future challenges of expertise research. In chapter 49, Klein, Shneiderman, Hoffman, and Wears highlight the seeming irony that although expertise is increasingly sought out and needed in today's society, at the same time several communities have actively begun to disparage experts! They present a series of arguments that demonstrate why their criticisms are misguided and assert that the criticisms made can help the research community discover better methods for supporting experts and for developing expertise.

In the final chapter, Ward, Schraagen, Gore, Roth, Hoffman and Klein discuss some of the future directions that the field of expertise studies might take in order to continue to allow people to thrive in a world whose complexities are ever increasing. In particular, they present a particular view of expertise focused on adaptive skill—a concept that has often been discussed but is an empirically neglected aspect of expertise research—as a potential remedy for advancing the field and better preparing individuals to cope with the uncertainties and complexities of tomorrow's society.

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