3 Discovering How Cognitive Systems Should Be Engineered For Aviation Domains: A Developmental Look at Work, Research, and Practice

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ABSTRACT

Pursuing Cognitive Systems Engineering (CSE) and understanding the implications of what this means for military aviation can be explored through a variety of perspectives and pathways. This review facilitates one perspective that could loosely be classified as a retrospective, developmental viewpoint that traces the author's own learning and discovery of how cognitive systems should be engineered. As part of this view, 15 years of work, research, and practice are examined for threads of consistency, continuity, and clarity as a foundation for learning what the future may hold. To make sense of the multiple directions and diversity within cognitive systems, this chapter is structured in the form of seven major queries to be answered. The answers developed for queries address many issues salient in the aviation domain in particular. The chapter also investigates what is important, valuable, and challenging by tracing the author's own experiential discovery of CSE through five progressive stages of development. As much of the author's experience in cognitive systems is within the domain of military aviation, this nexus is used to describe specific theories, frameworks, approaches, methods, tools, applications, and cases that have been uncovered and thought useful. The review concludes with potential challenges that practitioners need to consider in advancing CSE effectiveness—especially as applied to military aviation domains.

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3.1 INTRODUCTION

Work environments of the 21st Century place users in an information-rich world with little time to make sense out of events surrounding them, make decisions, or perform timely activities. In many cases, computational support and advanced interfaces for work activities have not been designed with cognition in mind. Unfortunately, this lack of "cognitive engineering" may produce what we refer to as *cogminutia fragmentosa*, where the user's cognitive world breaks down into small, isolated strands of thought as unanticipated events transpire (mental stove-pipes). People may experience a loss of meaning and control, become separated from the demands of their work, or fail to comprehend the emerging elements of a situation.

Cogminutia fragmentosa persists when there is no longer an interface between the user's cognitive world and the work he/she is responsible for. In other words, the user cannot properly adapt to the situation encountered (i.e., the user is in a maladaptive state). If this state continues, errors, failure, and even catastrophic disasters may be likely. This state may also contribute to affective and emotional responses by users (e.g., fear, anxiety, and rage) which further complicate agent-environment transactions. However, all is not lost. We are now at a point in history wherein it is not uncommon to observe human factors practitioners referring to Cognitive Systems Engineering (CSE) as their method or tool of choice to respond to work environments that produce cogminutia fragmentosa. As first-of-a-kind systems are proposed for complex environments (e.g., military aviation applications) CSE is now being utilized as a means to elicit various elements of expertise (e.g., cognitive skills, engagement rules, specific knowledge) from users, pilots, operators, or teams. As CSE is applied to real-world settings, expertise is qualitatively modeled (represented) and then used as a basis to predicate elements of a design (e.g., a human-computer interface, cockpit information system). In a typical application, practitioners engage users through a variety of methods that capture multiple facets of how work is transacted from agents to environment.

The preceding prelude functions as one guiding force for integrating chapters that appear in this State-Of-the-Art Report (SOAR). The overall goal is to take a broad overview of cognitive systems engineering. It is our desire to contrast/compare philosophies of use, goals, benefits, methods, tools, experiences, constraints and problems of use, lessons learned, and application examples as a means to generate new levels of understanding—especially as they relate to the specific constraints encountered in the military aviation community.

The hope is that this book provides a forum for what we know about CSE and addresses issues resident in understanding and applying CSE to cogminutia fragmentosa. The intent is to introduce multiple perspectives on this topic while pursuing integration of interests in the CSE area, especially as salient to the military aviation concerns. The international flavor of contributors is expected to produce broadly defined points of view as different practitioners around the world apply CSE to selected domains of interest.

Given this backdrop of overall purpose and objectives of the review, this chapter delves into my own *developmental history* in discovering cognitive systems engineering in aviation (and other) environments.

As the old adage goes, *necessity is the mother of invention*. The last 15 years have afforded multiple opportunities to conceptualize, analyze, design, test/evaluate, and advocate for the role of the human in aviation-related domains. From early work involving field studies to the design of intelligent pilot-vehicle interfaces to current applications of supporting collaborative activity in Airborne Warning and Control Systems (AWACS) operations, there has been the necessity to reinvent terms of engagement. For example, the following questions have repeatedly emerged over the course of time: (1) What does *user-centered* design mean in the face of increasingly complex systems? (2) How do systems come to be more or less cognitive in nature? (3) How are *cognitive systems* requirements implemented as part of the design cycle of technological artifacts? As targets of opportunity change, these queries take on new meaning and may be answered in new ways with greater insight.

This chapter provides a 15-year retrospective history of the author's work in cognitive systems at Wright-Patterson Air Force Base, Ohio. Included are a look at aviation-related projects that provide the necessity for change which in turn have been the basis for innovative learning in the areas of *cognitive science, cognitive work analysis, cognitive modeling, cognitive field studies*, and *cognitive systems engineering*. A survey of various issues, frameworks, approaches, methods, tools, and application examples provides broad exposure to the overall question, "What is the use of cognitive systems engineering?" Using our own perspectives, developments, and case studies (as well as other practitioner approaches in CSE) a number of requirements, trends, and directions are discussed. The organization of the chapter is along the lines of seven systematic but interrelated queries designed to describe and evaluate work in CSE.

To capture a number of different foci and twists which have emerged across time in the development of cognitive system engineering, this chapter addresses "what's coming" with the seven specific objectives (stated as queries) as outlined in Table 3.1. These objectives form the fabric of the chapter and in turn are the waypoints that set up discussion topics. Each query also contains preeminent issues that are addressed as appropriate.

Table 3.1: Continuing Objectives

Considering 15 Years Worth of What

I	**What is it?**	**Defining Characteristics/Core Values**
II	**What are the formative conditions?**	**Background/History/Perspective**
III	**What are the objects of interest?**	**Use/Directions/Applications**
IV	**What are the representative approaches/examples?**	**Theories/Methods/Approaches**
V	**What has transpired?**	**Progress-Influences/Developing Stages**
VI	**What has evolved/ what has been learned?**	**Lessons Learned/Recombinate Themes**
VII	**What is next?**	**Emerging Issues/Future Directions**

3.2 QUERY I: WHAT IS IT?

3.2.1 Orientation

Put yourself in a real-world problem you may have recently experienced. You may have lost your billfold, locked your keys in your car, had your luggage misplaced, or even missed your flight.[2] Recently, I left my camera on board a flight simulator at an amusement park. Once the problem was "realized," I immediately tried to retrace my memory and define just where the camera was lost. Once the situation was defined well enough to assess the camera's predicted location, I had to decide how to get back into the simulator and retrieve it, which immersed me into a new planning situation. These problems may seem minor, but they present a person with an ill-defined, emerging dilemma where (1) understanding/remembering the context is crucial, (2) plans or actions previously considered routine start to break down, (3) problem solutions require innovation, risk taking, uncertainty, and even personal jeopardy.

As a problem solver you are accustomed to exploring solutions relevant to your own experience. Most of us are fairly good at working out our own cognitive engineering solutions in constrained settings. The dilemma arises when

2. This is an excerpt from the *CSERIAC Gateway* Newsletter (McNeese, 1995, Vol. VI, No. 5, pp. 1–4).

we are responsible for providing solutions for other people's problems that require us to know what they are thinking, or to be aware of the context under which they are replanning or taking new actions.

The difficulties experienced in the problem you just simulated can be magnified immensely when we encounter the intricacies of complex problems. When complexity increases, there is a much greater reliance on the cognitive, contextual, and interdependent collaborative factors in human-machine systems. Consequently, there has been an increasing role for cognitive engineering to make interrelated systems elements adaptable with the user's cognitive states. This is most evident in the changes necessitated by the introduction of computing systems into our workday environments.

Cognitive systems engineering is a technical specialty that affords different approaches for capturing users' multiple perspectives of knowledge, experience, and context for a given problem domain, and actively seeks user participation in transforming these elements into real-world design solutions (see McNeese, Zaff, Citera, Brown, & Whitaker, 1995; Zaff, McNeese, & Snyder, 1993). In this sense, the engineering of cognitive systems imparts "knowledge-as-design" for the user, by the user, and with the user. This is one explanation of CSE that I presented in the mid-1990s which takes a particular orientation. However, there are many other perspectives on the subject that one could adhere to. In the process of defining what CSE is and how it is used, it is instructive to assess the *defining characteristics*, *converging themes*, and *different examples* of how it is used. The following sections/queries provide a sampling of some of these items and give the reader a foundation of the more general aspects of CSE.

3.2.2 General Definitions

Before examining situated problems and work domains, and the objects of interest that have developed it is first necessary to explore what we have discovered in the way of defining CSE. Generating a common ground of definitions provides the first scaffold upon which the remainder of this chapter can build. One might think of CSE as a specialty area, a field of endeavor, a movement, or even a discipline. At many junctures CSE knits multiple specialties (e.g., psychology, engineering, and systems design) together to form an interdisciplinary enterprise that—in and of itself—is a work practice intended to generate *designs* that improve worker's effectiveness and well-being. No matter what you think the state of CSE currently is, there must be the realization that in many ways it is still emerging and developing. Best practices are heavily dependent on (1) CSE practitioners and their resident skills, knowledge, and capabilities, (2) the domains and workers which they study, (3) the objects of concern within these domains that workers use, and (4) the methods and tools they use to discover domain-worker specificities and constraints. When one directs CSE towards the aviation *environment*, this provides new levels of influence as *practitioners* may have an aviation psychology background, *domains* involve new dynamic complexities in extreme conditions, *workers* to be studied (e.g., the fighter pilot) provide new kinds of affordances to observe, and innovative *methods and tools* may be developed in accordance with the constraints of these other elements. A main thrust then is for this chapter to look at the environments, practitioners, domains, workers, and the methods and tools I have encountered in the last 15 years with particular attention given to the aviation sector. Given this initial view, lets take a look at some major definitions from some of the top practitioners in CSE.

3.2.3 What Does Cognitive Systems Engineering Consist Of?

As a *systems philosophy*, cognitive engineering brings native user-and-use-centered knowledge to bear on the design of complex systems that subsequently require human interaction. User knowledge is elicited to integrate cognition, context, computation, and collaboration. Consequently, gaps between thinking, knowing, and doing are reduced to achieve more successful interfaces. Cognitive engineering is first and foremost centered on *individual differences* that shape expertise and knowledge as practiced within specific contexts. Integration among these elements systematically addresses functionality and compatibility, within and across different facets of the systems structure. As human-information systems become more involved, more complex, and more intelligent, the role of cognitive engineering looms as paramount first in the *front-end design process*. CSE could be thought of as a catalyst process to confront gaps of understanding among operators, their interfaces, and their contexts. (See Chapter 5 in this SOAR by Scott Potter and colleagues that explores these gaps in depth.)

3.2.4 Viewpoints and Converging Themes

A review of some early cognitive engineering efforts (Card, Moran, & Newell, 1983; Hollnagel & Woods, 1983; Norman, 1986, 1988; Woods & Roth, 1988; Rasmussen, 1986) found several overlapping, representative themes: (1) use-centered philosophies, (2) participatory approaches, (3) real-world problems, (4) elicitation/representations of knowledge, and (5) design processes.[3] Other efforts (Klein & Crandall, 1995; McNeese, et al. 1995; Sanderson, McNeese, & Zaff, 1994) reinforce these themes but suggest new advancements (e.g., mental simulation, collaborative design, and observational video analysis). Throughout the chapter these themes will be present (some will become more salient than oth-

3. Note that the efforts of Card, Moran, and Newell (1983) may be considered, and in fact are referenced, as a cognitive engineering approach although their effort does not exactly fit the confines of our themes. The GOMS model, the heart of their work, may be viewed as an *important bridge* that connects the theoretical principles of cognitive psychology with the practice of human factors engineering within the target area of human-computer interaction. For this reason it plays an important part in the history of cognitive engineering even though it is more of a research-centered approach. The use of GOMS methods today may still be considered one form of cognitive engineering.

ers for a given approach or method). Collapsing across a number of different viewpoints, general conceptualizations of the field can be informative.

As one of the founders of CSE, Jens Rasmussen believes that CSE is a highly interdisciplinary field that is concerned with the design of complex human-machine systems in which humans' cognitive needs are well supported (derived from Rasmussen, 1986). Woods and Roth (1988) suggest that the requirements and bottlenecks in cognitive task performance drive the development of tools to support the human problem solver. Some other views are as follows. CSE concerns design based on the discovery (and articulation) of first principles of how people interact with engineered systems in complex settings (Sanderson, McNeese, & Zaff, 1994). Vicente (1999) suggests CSE is about design that allows operators to adapt effectively and flexibly to unanticipated events. Hollnagel (1998) sees CSE as the basis for determining how we design joint cognitive systems so they can effectively control the situations where they have to function. Obviously these are just capsulated definitions, and one should go to each source for an expanded comprehension of each perspective. For even more definitions and defense of various views of the field of CSE, please refer to the 1998 special issue of the journal *Ergonomics* that contrasts different opinions and rationale of CSE.

As we look at definitions, it is evident that CSE has some shared, overlapping characteristics and core values that stand out. One characteristic suggested by Rasmussen—*well* supported cognitive needs—often gets secondary attention, but has utmost importance for the aviation sector. This is also an attribute that Vicente elaborates in his commitment to safety in work. Woods often addresses wellness through understanding how artifacts shape cognition and in turn become ways to avoid human error. When wellness and safety are not considered, then human errors can be probable. And much of how *well* comes to be is dictated by understanding the cognitive demands in the environment.

The challenges workers face in a domain must be supported by designs of cognitive tools that enable and reify their performance both alone and together. Hence, another characteristic evident is that "what" CSE does is *design with the human in mind*. The endpoint of CSE as a process is a better design for workers in a domain.

Another characteristic associated with these definitions is that designs support cognitive demands if they afford adaptive responses on the part of human and artificial agents (McNeese, 1986). This is what Norman (1993), another early pioneer of cognitive systems engineering refers to as "designing the things that make us smart." Highly brittle and rigid designs do not shape cognition (or collaboration) in ways that make work more effective, efficient, and safe but create a tunnel vision effect that limits human adaptation when emerging and uncertain situations arise in the complexities of work life. In summary, we might conclude that CSE can be defined as supporting distributed cognition through engineering design, designing cognitive technologies to enhance cog-

4. These are definitions I presented at the CSE International Workshop, Dayton, OH, May 19, 2000 that this chapter is predicated on.

Figure 3.1: Capturing cognitive systems engineering.

nitive readiness of workers, and exploring the workplace to design adaptive support systems that mutually enable practitioners in their field of practice[4] (see Figure 3.1).

3.3 QUERY II: WHAT ARE THE FORMATIVE CONDITIONS?

A basic issue to reconcile is how cognitive engineering is different from human engineering and/or knowledge engineering. Cognitive engineering can be thought of as a middle ground existing between human factors and knowledge engineering. As such one might consider it as in service of two masters. It is informative to look at the traditions that led to the formation of cognitive engineering.

3.3.1 Human Factors Engineering

Human factors engineering has typically had a preeminent goal of serving the user but has generally treated the (1) context of work and (2) socio-organizational factors with much disdain (Bannon, 1992). Exceptions to this have played out in the areas of macro-ergonomics (Hendrick, 1986) and ecological interfaces (Flach, 1990). Traditional human factors focuses on *human performance* and emphasizes issues such as workload, anthropometry, control-display integration, lighting, noise, and other factors that highlight design/human compatibility issues. Experiments and models may measure system states and human capabilities-limitations, in the context of ensuing mission-task performance, and vary a number of human-machine interface elements. Although this tradition is vastly important, and has its place in improving users' needs, it may not tell the whole story.

Within human factors practice, *gaps in understanding* occur while reconciling discrepancies among *what users think, what users know, what users do,* and *what users want*. These gaps are evidenced by failures in designs (unfortunately often attributable as "human errors"), clumsy interfaces (see Wiener, 1989; Reason, 1990), or brittle knowledge bases (Lenat & Guha, 1990). As complex systems emerge (e.g., the glass cockpit, nuclear power plants, intelligent highway systems), there is a necessity to modify the old order of human factors business. A reinvention of human factors engineering must accrete more investment in topics involving cognitive engineering, expertise, knowledge, naturalistic decision making, and real-world context to respond to gaps in understanding that are initiated in ill-defined, emergent, uncertain, multi-operator environments.

These gaps are amplified when people interact with each other, with information, or technological systems via various types of interfaces. When the interface involves a computer, the gaps often are irreconcilable as the level of knowledge necessary to complete intelligent interaction increases. And when the computer software comprises (1) knowledge-based, (2) groupware, or (3) evolutionary computing there is an element of "artificial intelligence" cast into the complexity.

3.3.2 Knowledge Engineering

Real-world problems involving human-computer interaction provided one of the developmental threads that gave rise to cognitive engineering. From this end of the spectrum, knowledge engineering was required to "propagate" knowledge (in various forms such as rules, frames, and predicates) within advanced computer technologies designed to perform as if they could reason like humans.

Like human factors engineering, there is a common thread with information requirements analysis, but in this case the analysis typically highlights information as it relates to computer system requirements. Buchanan & Shortliffe (1984) suggest that knowledge engineering is "the process of mapping an expert's knowledge into a program's knowledge base" (p. 5). They trace the term *knowledge engineering* as one coined by Edward Feibenbaum after Donald Michie's phrase *epistemological engineering.* This required engineers to elicit knowledge from subject-matter experts in an attempt to replicate that knowledge in expert systems.

Knowledge engineering practice tries to replicate an expert's knowledge as input into a workable and predefined knowledge structure. Knowledge building tools or even automated knowledge acquisition systems have been developed to streamline this process. Unfortunately, this process became a bottleneck as the knowledge engineer often required an expert to elicit native knowledge in a form (e.g., "if-then" rules) directly exportable to the requirements to knowledge structure. This resulted either in (1) brittle computer systems (what Woods calls clumsy automation) or (2) experts contemptuously rejecting the process or the means by which they were required to "heed knowledge" for a project. How to elicit *user-centered* knowledge from the operator, and how to transform that knowledge to fit information system requirements, initiated the formation of cognitive engineering. This still remains a core issue for the discipline today.

Knowledge engineering generally derives from computer science concerns and is not subject to principles such as "know thy user." Early techniques applied to limited, toy domains wherein "accessed knowledge" was relatively easy to come by. The process became much more difficult for real world systems (e.g., medical diagnosis, see Buchanan & Shortliffe, 1984; pilot aiding, see McNeese et al., 1990). Knowledge engineering usually progressed like most other engineering disciplines in the sense that processes were engaged for the sole intent of building an end product with little regard for how the end product is compatible with human interaction.[5]

When thinking about cognitive engineering, it is informative to point to a common ground that effectively looks at the converging principles and the fundamental ideas that span across different approaches in cognitive engineering. This section is designed to begin conceptualizing the domain along these lines. Specific approaches have much in common but also diverge at various points as we will see later.

3.4 QUERY III: WHAT ARE THE OBJECTS OF INTEREST OF CSE?

Success or failure of joint cognitive systems is inextricably tied to the situation context, conditions, processes, and measures that compose any given orchestration. In particular, *situated context* is increasingly becoming a salient foundation to understand real-world problem solving in a variety of domains (education, design, medicine, aircraft operations, see Hutchins, 1995; Young & McNeese, 1995; Zsambok & Klein, 1997). Such situated problems and envisioned designs to support workers context are the objects of interest for CSE. A more practical way of looking at this is stated by Woods (1998) where he indicates that "designs are hypotheses about how artifacts shape cognition/collaboration."

Situated problems and socio-cognitive factors are prevalent in many complex systems the U. S. Air Force is engaged in (e.g., space operations, information dominance, unmanned air vehicles, mission planning). These contexts are

5. Most expert systems were designed to be used by operators engaging the system—therein the end products were human-computer interfaces. But relatively little credence was given to this perspective in the early design of these systems. Exceptions were Buchanon's and Shortliffe's (1984) chapter on human engineering medical expert systems. Today, this has changed as the evolution of human-computer interaction and computer supported cooperative work has essentially redefined our vision of information systems in contrast to the notion of 'artificial intelligent' systems from the early-to-mid 1980s. Still, the engineering of knowledge within human-computer interfaces may proceed from traditional knowledge engineering standards resulting in impoverished or problem-

highly interdependent, collaborative in nature, highly integrated with multiple aviation concerns, and require global awareness in response to changing conditions and multiple uncertainties. The context most recently targeted in our studies involves Command, Control, Communications, and intelligence (C^3I) and planning operations (McNeese, Rentsch, & Perusich, 2000). Within the AWACS command and control domain, we have been applying cognitive engineering and modeling to the study operator intentionality, interrelated causality, contextual variation, boundary constraints, and emergent contingencies.

The vision of making situated problems (such as AWACS command and control) and envisioned designs the objects of CSE is historically related to the ideas and research approach of Suchman (1987) who suggests that cognition and collaboration come about—not by symbol systems—but through situated actions arising during the course of events that occur in a context. This is about cognition—not bounded by the individual brain or mind—but cognition constructed by social processes (Resnick, Levine, & Teasley, 1991). This view highlights "qualitative and naturalistic" components of what people actually do when they work together. In this sense, CSE is bound to approaches that are described as *situated cognition*, *ecological*, *participatory*, and *ethnographic* in nature. Inherently, this vision prescribes to the same basic view elaborated by Greenbaum and Kyng (1991) as it highlights situations and breakdowns, social relationships, knowledge, tacit skills, mutual competencies, group interaction, and experienced-based work. However, the vision also includes using the inductive insights gained from naturalistic views of cooperation to inform (1) experimental research paradigms that focus on quantitative, empirical studies and (2) design prototypes/infrastructures that may be evaluated through the use of both qualitative and quantitative tools.

3.4.1 Understanding Collaboration In Context

Much of the work that occurs today in the military, government, or private sector is done in teams or teams of teams. Teams may be continuously emergent, ad hoc and transient, and may contain smaller units that we term "multi-operator enclaves." Individuals who form a team may simultaneously be members of several other enclaves that disperse time, resources, and relationships in unexpected ways. Hence, teams may operate in layers of complexity and change. There is evidence that teams can fail in their endeavors (e.g., the Vincennes incident, the O-ring problem in the space shuttle disaster). Such failure exists as targets of opportunity for the CSE profession. CSE must assess the social-organizational, psychological-cognitive, and technological components of collaboration. Too often human factors fails to take a broad, systems approach to a problem and encounters a nearsightedness in research and guidelines. When the artifact of concern involves complex systems (e.g., computer-supported cooperative work) it is imperative that a broader approach be utilized. In response to this concern, we address collaboration problems through the lens of ecological psychology and naturalistic decision making. Attempts to view collaborative systems more broadly have been made by Hinsz, Tindale, and Vollrath (1997) and others (Wegner, 1987) but primarily look at team function in terms of information processing or memory systems.

In addition to Suchman's (1987) situated cognition research, Thordsen and Klein's (1989) work on team mind is representative of early approaches that put more weight on the naturalistic components of collaboration. Even more salient is the work on "cognition in the wild" (Hutchins, 1995) which provides extensive knowledge on ship navigation from the vantage point of social-cultural practice. Young and McNeese (1995) define situated cognition as representative of real-world problem solving wherein group members spontaneously generate knowledge in the context of a situation; coordinate multiple cognitive processes, applied through multiple paths; and pick up critical perceptual cues for potential solutions. Collaboration directed towards solving real-world problems is often interpersonal, ill-structured, involves interwoven problems, extended timeframes, requires discovering problems and subproblems, and invites the social construction of knowledge. Simply put, an ecological psychology perspective emphasizes the interaction between an agent(s) and an environment wherein the attributes of each constrain the "interaction." This reciprocity is often referred to as agent-environment mutuality (Gibson, 1979; McNeese, 1996a). This may take the form of what an agent can effect (effectivities) or what the environment can afford (affordances). Affordances and effectivities are always in terms of each other. This systems-based view can be extrapolated to interpret cognition and collaboration in various forms

3.5 QUERY IV: WHAT ARE REPRESENTATIVE APPROACHES/PREMIER EXAMPLES OF CSE?

Theories, methods, and tools are often portrayed as consistent with (or even distinguished as) cognitive systems engineering approaches including knowledge acquisition (Cooke, 1994), cognitive task analysis (Gill & Gordon, 1997), naturalistic decision making (Klein, Orasanu, Calderwood, & Zsambok, 1993; Zsambok & Klein, 1997), operator modeling (Card, Moran, Newell, 1983), systems engineering (Rouse & Boff, 1987), field studies (Xiao, 1994), and ethnographic studies (Hutchins, 1995) to name a few. Within these areas, specific methods have migrated into the CSE focus. This includes, but is not limited to, repertory grids, protocol analysis, exploratory sequential data analysis, process tracings, direct observation, weighted networks, concept maps, design storyboards, Ishikawa diagrams, the decision ladder, means-ends hierarchies, retrospective reports, cognitive walkthroughs, and critical event logs. Various approaches and methods evolved into different tools (e.g., the TAKE/COGENT tool; see Sanderson, McNeese, & Zaff, 1994; emerged from our AKADAM techniques and continued to evolve on the basis of both our use of the method and then subsequent use of the tool in practice). In many instances, CSE approaches may form through an amalgamation of theories, methods, and tools in these pre-existent areas. On the other hand, approaches are distinctively defined by the CSE label from their inception. As customary in science, there is a progression from theory-to-method-to-practice-to-tools-to-theory and so on. By looking at the roots of premiere CSE programs and tracking evolutionary paths, one can gain insights. Early practitioners (Card, Moran, & Newell; Hollnagel; Norman; Rasmussen; Woods;) may trace their roots to human information processing theory which subsequently influenced their conceptualization of cognitive systems engineering.

Yet, in every case the impetus came from real-world problems or application domains (e.g., process plant dynamics, Rasmussen, et al., 1994; robotics, Sheridan, 1992; the Pilot's Associate, Zaff, McNeese, & Snyder, 1993). This early emphasis suggests a lineage that is inherently related to ecological psychology (see Gibson, 1979) or more recently to naturalistic decision making (Zsambok & Klein, 1997). Early practitioners mainlined their own research in cognitive psychology as a scientific basis for CSE, but still paid attention to contextual issues. Perhaps in the book *The Psychology of Everyday Things*, Norman (1988) created mergers among human information processing, ecological psychology, and design issues. Rasmussen (1988) states that "human abilities and capabilities with respect to information processing behavior are closely related to the symbolical information features of the environment, and cognitive science will, therefore have to be akin to Brunswikian ecological psychology" (p. 332).

A major theoretical shift that occurred in the 1990s put even more emphasis on ecological precedence (e.g., situated cognition, Suchman, 1987; Young & McNeese, 1995). This shift consequently also influenced the development of new methods, tools, interfaces, and support systems, for example, computer-supported cooperative work (Whitaker, 1994), ecological interface design (Vicente & Rasmussen, 1992), naturalistic decision making (Zsambok & Klein 1997; Xiao, 1994), Scandinavian design work (Greenbaum & Kyng, 1991), and learning science (Rogoff & Lave, 1984).

Consequently, evolution in cognitive science has influenced cognitive systems engineering as well. Norman takes up the cause of "affordances" in design work. Rasmussen argues for the ecology of human-machine systems. Woods studies cognition in the wild. Sanderson, McNeese, and Zaff (1994) reference multiple data streams in sociotechnical systems. This shift also influences proliferation of CSE methods and tools. Klein employs the critical decision method/cognitive task analysis tools. McNeese applies the AKADAM method/COGENT tool to military situations. Sanderson explores new settings with the MacSHAPA tool. As new ideas perpetrate the "old guard" of cognitive science, CSE continues to evolve and leave contrails for new theory, methods, and tools.

The following descriptive sections provide a limited, yet broadly specified perspective of different approaches to CSE. In many instances, a practitioner's designation under one of the constructs may seem arbitrary as they have gone on to develop many avenues of their programs that in fact propagate across many different levels of theory-methods-tools-practice-design. The examples presented herewith are classified with respect to *initial starting points* and/or the *primary area of influence* emanating from their work.

3.5.1 Theory-Driven Examples

3.5.1.1 The Work of Don Norman and Colleagues. Although Norman's work certainly flows into method and suggests ideas for tools, it primarily is theoretical and was foundational in establishing the field. Classifying Norman's work in the theoretical category is based upon his seminal work in cognitive systems engineering (specifically, Norman, 1986; 1988). Since then his work has actually been more attuned to ecological psychology, real-world concerns, and the design of artifacts (see Norman, 1993). It is also interesting to note that much of his early work in CSE evolved from his research in cognitive psychology. In fact, Lindsay and Norman (1977) wrote a classic book on the human information processing approach to psychology.

One way to trace Norman's view on CSE is to make an analogy to mechanical engineering, wherein theory, first-order principles, and laws (e.g., statics and dynamics) contribute as a science to the design of machines. Likewise, CSE is an approach to the design of human-information systems predicated upon the statics and dynamics of human behavior within an environment of action. The "act-in" aspect is important as a basic indicator of Norman's theory of interaction. At the heart of this theory is the principle that the intentions of humans must be translated into physical actions in the environment. The interpretation and translation required to do this involves a complex mapping problem; in other words, maps between the physical mechanisms (e.g., human-computer interfaces) and system states, and system states and correspondent psychological interpretation.

A theory of action focuses on doing things and the ensuing discrepancies between the psychological and physical. Discrepancies thus become anchors that open inquiry into major issues regarding design, analysis, and use of systems. Norman represents discrepancies as execution and evaluation "gulfs." Gulfs can be bridged by moving a system state closer to user's needs through the application of design, or by moving the psychological state closer to the system by use of plans, action sequences, and interpretation that move goals and intentions in alignment with system states. Literally, the action taken to "move" towards intention is determined by what a person can do through his/her input alternatives. Hence, the degree of match/mismatch transpires through this gulf of execution. On the other hand, the gulf of evaluation requires a match between user goals and intentions through interpretation of the system state by the user. This gulf is revealed by output displays and is bridged through seeing the display, perceptually processing of display objects, interpretation, and evaluation in terms of how well initial intentions are carried out. As Norman indicates, complexity in the form of many levels of outcome and lack of immediate feedback play havoc with bridging these gulfs and eliminating discrepancies. Within this theory, behavior may be goal or event driven.

In addition to the theme of gulfs, Norman places emphasis on the user's *mental model* of the system, and the designer's model of the system and how these views interact to impact artifacts and discrepancies. Indeed, he notes that the user's model helps guide human behavior and thus transform confusing, difficult tasks into simple ones.

It is interesting to note that the evolutionary stance provided by Norman's work over the last 25 years represents the forces present in cognitive psychology, ecological psychology, human factors, and engineering design. As previously mentioned all these areas contribute as tributaries to what we have come to know as *cognitive systems engineering*. Norman's work is heavily influenced by cognitive psychology, human-computer interfaces, and design practice but does not really transition into the knowledge engineering/artificial intelligence areas as much. In this sense, it is very similar to the early Card, Moran, and Newell (1983) work. Yet, their work has progressed more as a method (the Goals, Operators, Methods, and Section Rulers model) which has been used and adapted by a variety of groups.

It is also informative to note that the theory of interaction historically is a cousin to basic human factors models related to control theory, and as Norman points out, to theories related to servomechanisms and cybernetics. So as tradition has it, Norman's approach represents a logical progression from psychology to design, from theory to practice. The influence of this approach has been voluminous in a variety of venues but one of the lasting values is that the work itself is elaborated based on first-order principles of human interaction.

3.5.1.2 The Work of David Woods and Colleagues. Like Norman, Woods' work has been very substantial in defining and developing the scope of CSE as a discipline. The "New Wine in New Bottles" paper (Hollnagel & Woods, 1983) is probably referenced more often than any other paper in the CSE discipline, and is considered a preeminent reference on the topic of CSE. Woods and his colleagues have had a continuing and major impact on the applications of CSE in real-world environments (e.g. flight, medicine, information analysts, etc.). Perhaps the best example of this is in the field of human factors. For the first time at the 1995 Annual Meeting of the Human Factors and Ergonomics Society, a number of sessions, panels, and papers were approved by a newly formed technical group in Cognitive Engineering and Decision Making. Through the efforts of David Woods, Gary Klein, and many other practitioners, the dream of CSE is finally becoming a force in the way human factors is practiced. Woods has been very active in translating initial investments into actual methods and cognitive tools while continuing to wave the "cognition in the wild" flag to signify the importance of dynamic worlds.

In some ways, because of the early focus on dynamic worlds as a critical piece of the cognitive engineering scenery, Woods perhaps began with more of an ecological appreciation than some of his peers. Therein, we see impressions of this through such characterizations as dynamic worlds, distributed cognition, cognition in the wild, and natural environments surface to the forefront in Woods' publications. Although this is not necessarily indicative of a strict Gibsonian approach, it is certainly predicated on the role of context. As Woods refers to dynamic worlds there is a point that research in CSE is subject to the interdependencies/symbiotic nature of real-world problems. In this sense, Woods classifies CSE as being "problem driven."

From the problem comes the basic elements by which cognitive systems engineering unfolds—challenges, descriptions, agents, inadequacies, successes, demands, performance, computation, available resources—that in turn specify requirements for a cognitive engineer to follow. Often these elements are explored and defined by use of cognitive task analysis (Gill & Gordon, 1997) or cognitive work analysis (Vicente, 1999). By this attraction then, it is not surprising that Woods has also made much progress in the study of human error (see Woods, Johannesen, Cooke, & Sarter, 1994 for review), an area that could be considered either a part of or a cousin to CSE. The Woods approach then at least conceptually is related to Norman's (1981) work on action slips and errors as well as Reason and Mycielska's (1982) work in this area. Human error may very well be the lens that allows theory and practice to meld together, wherein cognition meets up with design.

One theme that resonates at the heart of Woods' approach (Woods & Roth, 1988) is the idea that the impact of computers in dynamic worlds results in operators experiencing more mental work and more complexity in general. As a consequence, these demands require creation of the appropriate cognitive descriptions and environments to avoid pending failures/errors. Unfortunately, this is easier said than done. Descriptions and representations frequently may produce brittle rule-based systems that cannot adapt to the dynamism experienced in the real world. Woods captures this dilemma through use of a tri-factor model that looks at problem-solving as interaction among dynamic worlds, agents that act upon that world, and the representations the agent uses to experience that world. Hence, CSE must put *cognitive tools* in the hands of problem solvers to cope within their natural problem solving habitat and avoid mismatches that can occur between the world, agent, and representation. This occurs by focusing on what is missing (or incomplete) in a habitat that could lead to patterns of errors.

Another important issue that Woods refers to in his work (not utilized as much as other aspects of his position) is the problem of *activating knowledge* under natural conditions of "uninformed access." Informed access conditions occur when operators are "told what to do" without activating knowledge on their own (uninformed access). When cognitive tools are only designed from an "informed access" perspective, the operator may not understand what the tool is doing and consequently be led into situations where error is likely. However, if the designer is aware of the conditions that lead an operator to overcome inert knowledge, then the cognitive engineering of the tool is more likely to lead to success in a real-world setting. This view of CSE derives from the tradition of research by John Bransford on spontaneous access of knowledge (see Bransford, Sherwood, Vye, & Rieser, 1986) and serves as a theoretical link in knowledge acquisition. In fact, the work by McNeese and colleagues (McNeese et al., 1995; Young & McNeese, 1995) is strongly predicated from this tradition and in this sense, historically similar to Woods' theoretical stance.

There is one other thread that co-occurs with the discussion of dynamic worlds that does not appear as much in other approaches. CSE is not simply a single operator endeavor. It must take into consideration the effects of multiple cognitive agents, distributed decision making, group processes, and organizational constraints. If one is true in allegiance to dynamic worlds then it is difficult to avoid contact with collaborative work settings. Because Woods' approach highlights this component of emerging cognitive systems, this is a testament to his early insights in this area. This focus has been carried through as many of his colleagues' work has taken place in collaborative, naturalistic settings. The focus on collaborative agents resonates quite well with Klein's and McNeese's work in military environments involving group processes (McNeese et al., 1995; McNeese, Rentsch, & Perusich, 2000). In fact, much of my own work from the last five years involves complex worlds that include multiple, active agents (e.g., battlefield management and planning, AWACS command and control, design teams, crew station interaction, cooperative learning teams).

Even though Woods' work is heavily focused toward creating cognitive tools, the work is considered here as a theoretically driven, principled approach to design which in turn the practitioner must pursue. In contrast (for this chapter) tool-driven approaches refer more to actual products that enhance CSE application. They are still cognitive tools in the Woodsian sense, but cognitive aids for cognitive engineers. The presumed application of Woods' approach will in fact lead to actual tools in a specified environment (Woods, 1998).

3.5.2 Method-Driven Examples

3.5.2.1 The Work of Gary Klein and Colleagues. Klein (1990) suggests that cognitive engineering is the attempt to design systems that are better adapted to the thought processes of users. His work has been very influential in defining how people make decisions in everyday naturalistic environments. From that perspective, decision systems and human-information interfaces may be designed to enhance the power of the user. Outcomes associated with Klein's work (see Klein, Woods, & Orasanu, 1993) have strengthened the ties between the cognitive engineering and naturalistic decision making areas while emphasizing (1) inherent demands and strategies in temporally evolving events, (2) the role of action in cognition, (3) the coupling of perceptual recognition with action, (4) the role limited resources play in cognitive effort, (5) how experience and reasoning strategies affect courses of action, and (6) the competence rather than the failure of decision makers. Klein (1993) developed a recognition model of decision making, highlighting cognitive task analysis methods/tools, all of which derive from study of real-world situations and subject-matter experts. More recent work poses how team processes and mental simulation are important to engineering cognitive systems. Examples of application include assessment of neonatal nurses, designer support analyses, hacker profiles, systems required for battlefield operations, firefighter strategies, and team coordination in aircraft crews.

Obviously, given space considerations, these approaches and applications could be significantly broadened and described in more depth. Yet, one can begin to get a feel for the definitions, features, differences, and similarities that mutually establish what is meant by a cognitive systems engineering approach to human-information systems.

Although the work of Woods and Klein both employ contextualist views that harbor the advantages of engaging expertise, making cognitive descriptions based on problems encountered in real-world settings, and designing tools that are participatory in nature, the approaches are laced with cognitivist references such as mental simulation, attention, knowledge activation, cognitive representation, etc. that signal crossover effects from cognitive psychology rather than carrying the ecological psychology banner of Gibson. The approaches may bear more lineage to the work provided by Brunswick than Gibson, and therein are not oppositional per se but somewhere between cognitive and Gibsonian-based ecological psychology.

3.5.2.2 The Work of Jens Rasmussen and Colleagues. Rasmussen, Pejtersen, and Goodstein (1994) define the scope of cognitive engineering as (1) *cognitive* because thinking, problem solving, and decision making maintain a greater level of influence in our everyday lives than physical strength and dexterity; and (2) *engineering* because the development of concepts, methods, and tools can positively impact system designs that help users carry out daily activities. Historically, the work of Jens Rasmussen has contributed more to the field of CSE than that of any other person.

His activities in CSE encompass broad dimensions covering such topics as work domain representation, mental strategies, distributed decision making, social-organizational processes, and the division/coordination of work. These dimensions frequently analyze domains at several levels of abstraction by looking at parts that form a whole, or means that establish ends. Decomposing worker domains allows engineers to design in response to complexities inherent in the context. Rasmussen et al. (1994) suggest a function (*what* is used) can be seen both as goal (*why* it is relevant) or as a means for a lower level function (*how* it is realized). The model of expertise and decision making (Rasmussen, 1986) portrays an adaptive use of skills, rules, and knowledge to govern different types of behavior necessary while experiencing demands in a complex setting. His approach has been applied to the design of nuclear power plants, library retrieval systems, electronic trouble shooting, unmanned air vehicles, and medical decision making in hospitals, to name just some of practice he has investigated.

A few of the leading luminaries' approaches have been briefly described to show examples of how CSE has developed in similar yet different ways. The chapter will now change from discussing other practitioner perspectives to outline how we have discovered and developed CSE through work, research, and practice over the last 15 years, primarily in military and aviation contexts.

3.6 QUERY V: WHAT HAS TRANSPIRED?

3.6.1 A General View

One of the ways to capitalize on understanding CSE is to create a general framework that covers some of what we have reported already. Figure 2.2 shows a framework in which there are four major components that practitioners must consider in consort to practice CSE: (1) work in context, (2) analysis of cognitive activities, and (3) engineering of cognitive systems, and (4) first-of-a-kind artifacts. A cascading flow of activity is spawned from the study of work in context and how artifacts influence the context and the work. Using various methods to analyze different cognitive activities complements observing a field of practice. As analysis of cognitive activities ensue they must feed and be the foundation for engineering designs of cognitive systems.

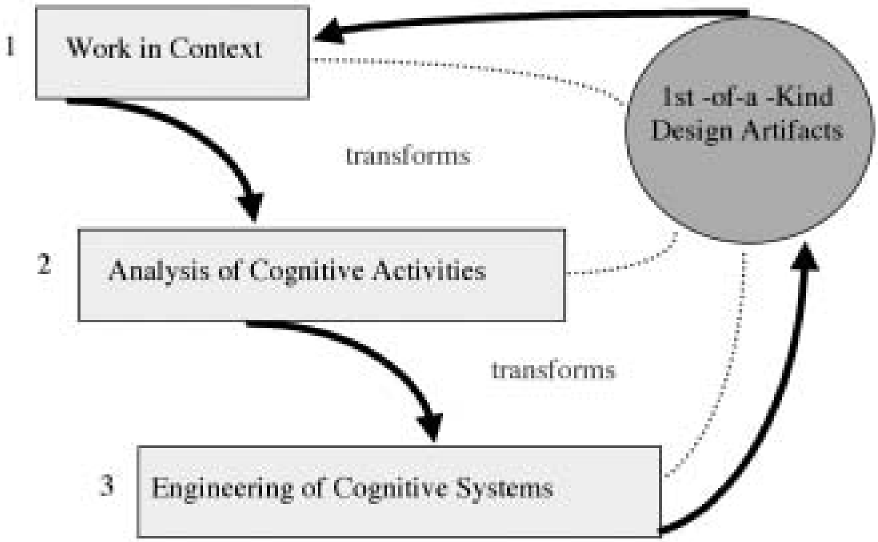

Figure 3.2: A general framework of cognitive systems engineering.

Engineering cognitive systems is the basis for deriving various first-of-a-kind artifacts which in turn are tested as *in situ* interventions. The relationship among these components is governed by multiple transforms that allow various versions of artifacts to emerge as solutions to solve situated problems.

In considering this general framework as we look over 15 years of activity, it is clear that at times the research has clearly not been balanced with multiple transforms but has been directed at examining different components at different times. One major challenge and an issue that have arisen is how to create and maintain balance among cognitive science, cognitive systems engineering, cognitive modeling, cognitive ergonomics, and software engineering while still keeping the field of practice as a primary object of interest. More often than not these specified areas can be at odds rather than showing any sense of integration. As we review different threads of activities it is clear that there needs to be a crosswalk to bridge these voids. However, such a crosswalk at this time is just beginning to unfold.

The following stages represent distinct growth patterns in my own discovery of CSE. They are used to communicate what I have learned and value as important, and provide a trajectory of development with varying sources of influence.

3.6.2 The Neonatal Stage

Upon reviewing my first ventures in CSE there is a clear sense of connectedness to some of the representative perspectives and converging themes presented earlier. My first venture into this area was a field study conducted at the University of Dayton in 1977 as part of a senior thesis project. The study entitled, *How People Space Themselves Out in University Places* (McNeese, 1977), used ethnographic methods and falls into the work in context component of the framework. This study was conducted with streams of influence from Barker (1968) relating to designed ecologies, and Gibson (1979) relating to perceptual learning. The gist of this early work was the nature of the design of spaces. Ironically, many of the issues of interest 25 years ago—how people produce spaces and effective space design as a function of social, cultural, and political use of space—are still a cogent topic of concern today.

My study investigated different people in different settings engaged in different activities (from an observational approach) and posed innovative design ecologies for given intents. At the time, "systems engineering" pointed more towards the *physical use* of places. Today, the study of *information spaces* and how people share information spaces at various places is a hot topic for CSE in general.

One other early direction ensued during my first five years of employment at Wright-Patterson Air Force Base (WPAFB), Ohio. I was placed in charge of developing the Aeronautical Systems Division's *Human-Computer Interface Mil-Prime Standard* (a set of guidelines for implementing and managing HCI for aviation concerns). During the early 1980s I was also assigned to two programs (based at the Aerospace Medical Research Laboratory at WPAFB) as a liaison for human factors and cognitive systems to work on the systematic development of different kinds of automation to be integrated into the cockpit (the *RAM/ACE* and early *CAT* programs; see McNeese, Warren, & Woodson, 1985).

This was a time when cognitive science, artificial intelligence, expert systems, situation awareness, and Human-Computer Interaction (HCI) were beginning to build with momentum and be incorporated into the plans and programs of the aeronautical/aviation systems of the future. The streams of influence for this time were first—Jens Rasmussen. I was greatly influenced by his "Human as a System Component" paper (Rasmussen, 1980), followed by other papers of his in the early-to-mid 1980s (e.g., Rasmussen, 1983). Another influence during this neonatal period was recognition of early human performance modeling efforts in aviation systems (Pew, Baron, Feehrer, & Miller, 1977) and the potential role it could have in simulating complexities. This was looked upon in terms of technology assessments of automation but directed towards how the technology supported cognitive abilities. In sum, this period set the stage for much of my work in CSE even though I was not fully aware of this at the time.

3.6.3 The Toddler Stage

In 1984 I transferred from the Air Force Aeronautical Systems Division to the Air Force Aerospace Medical Research Laboratory (AAMRL) while still on-site at WPAFB. Work began as part of a research group called COPE—C^3 Operator Performance Engineering. The goal of the COPE program was to study and produce user-centered command posts that incorporated human information technologies. COPE as the name indicates was an early form of CSE but with a unique vision of working with teams and collaborative units in real-world operative domains. Like the neonatal stage, the importance of situated problems in context was at the heart of a lot of activities; however, work under COPE provided many innovative facets of research that were both qualitative and quantitative, and pointed towards a true balance of work-analysis-engineering-design-intervention transforms indicated in the general framework. COPE work also generated exposure to some very innovative information technologies (e.g., large group displays, speech recognition systems, adaptive interfaces, and video teleconferencing).

Cognitive and collaborative system work in those days provided exposure to informational and organizational analysis, fieldwork to redesign real command posts, interactive and scenario-driven simulations, conflict resolution in cognitive systems, decision aids, and knowledge acquisition. In the COPE program team analysis was used to develop new large-group display technologies. In turn, these technologies were used for in-house experiments to assess theories of group process and team performance. This would be my first experience with what I would later refer to as a "living laboratory" approach (McNeese, 1996a).

Major streams of influence during the COPE experience were Jens Rasmussen and his way of modeling systems, Gary Klein and his preeminent work with expertise and field research (Klein, Calderwood, & Clinton-Cirocco, 1986; Klein, Calderwood, & MacGregor, 1989), William Rouse and his research on mental models and diagnosis in natural settings (Rouse & Morris, 1986), and Kenneth Hammond and his cognitive continuum theory (Hammond, McClelland, & Mumpower,1980) that suggested cognition lies on a continuum between analytical and intuitive poles, and varies according to situations. COPE hence became a time of grounding myself in various venues, with new theories and methods, while working in real world domains of (1) command and control, and (2) aviation support systems.

3.6.4 The Formative Years

As I continued to work at WPAFB in aviation and military-based C^3 settings, and then continued my graduate education at Vanderbilt University, several new streams of influence extended my understanding of CSE. One of the key elements that proved to be a useful method for modeling agent-environment transactions was protocol analysis. As modeling continued to be valued, protocol analysis became one methodological bridge between cognitive science and CSE. The pioneering work of Herb Simon in analyzing and modeling cognition using protocols (Ericsson & Simon, 1984) informed my own dissertation work which was also enhanced by a protocol analysis tool, SHAPA (Sanderson, James, & Seidler, 1989) designed by Penny Sanderson to analyze and encode transcripts. One of the key insights at this time centered on creating a situated model of activity from the data itself using the protocol analysis tool as the basis to explore real-world transactions.

A very strong influence during this time was the work of my Ph.D. dissertation advisor, John Bransford, and his research on learning, problem solving, and the role perception plays in how people acquire and use knowledge (Bransford et al., 1986). The more theoretical work of the late 1980s became the basis for our cognitive task analyses of the 1990s.

This time also provided opportunities at Vanderbilt to work on macro-contexts and scaled world problems. Macro-contexts (e.g., the Jasper paradigm, see Young & McNeese, 1995) provided much of the affordances and perceptual learning of real worlds but within an experimental environment. This period continued to place much emphasis on distributed collaborative activities both at WPAFB (Snyder, Wellens, Brown, & McNeese, 1989; Wellens & McNeese, 1987; Wilson, McNeese, & Brown, 1987) and at Vanderbilt. Also the work of David Woods on cognitive demands and process tracings provided evidence of what CSE was coming to mean to me. As far as the components of the general framework, this period opened up new possibilities in the analysis of cognitive activities both with tools and with scaled worlds.

3.6.5 The Preteens

The early-to-mid 1990s was really a time when much of our solid work in CSE was established and where my group carved a niche as part of the whole CSE movement. At this point I was back at WPAFB and was working on a new program, the Pilot's Associate (PA). This program had as an intent to integrate much of the new research and technology into the fighter cockpit. However, one of the major problems experienced in knowledge engineering was that of the knowledge bottleneck. Our group at AAMRL was employed to advance new ways to develop intelligent cockpits from a user-centered philosophy. As I mentioned, the way people learned, the process by which individuals acquired, constructed, and accessed knowledge in natural, situated problems significantly influenced the methods we created for the Pilot's Associate, (see Zaff, McNeese, Snyder, & Lizza 1991). The set of techniques we used for the PA—termed the Advanced Knowledge And Design Acquisition Methodology

(AKADAM)—would be used in many other domains and become the anchor for our work throughout the 1990s (McNeese et al., 1995).

AKADAM (McNeese, Zaff, Peio, Snyder, Duncan, & McFarren, 1990; Zaff, McNeese, & Snyder, 1993) first and perhaps foremost utilized concept mapping as a user-centered knowledge elicitation method that employed different elements of cognitive task analysis to represent the complexities of user beliefs about their work setting, advanced technologies, and the context of work itself. AKADAM, as a CSE technique, was used to elicit knowledge and convert that knowledge into useful design artifacts. AKADAM covered all the elements of the general framework and highlighted the principle of "knowledge as design." Although very participatory in nature, AKADAM was very much "off-line." That is, users heeded knowledge about past experiences, cases, or stories which would be relevant for a given mission area (e.g., pilot target acquisition).

The AKADAM approach employed use of task networks (such as Integrated computer-aided manufacturing DEFinitions [IDEF]), concept mapping, and design storyboarding as multiple perspectives that yielded user-centered representations that could evolve into interface designs. Concept maps were developed in consort with experts (pilots, engineers, and designers) as a mapper explicitly represented expert knowledge drawn out as a concept map on a whiteboard. In essence, it was an interactive, graphic diagram of an expert's mental model about a situation—developed over various timeframes. We would do at least two interviews with an expert at different times to draw out different takes on knowledge. The experts—after they were done with their map—would take the map home and review it some more whereupon they could change it even further. Once we completed interviewing an expert we would summarize all the experts' maps as part of a summary map which often consisted of over 1000 concepts and relationships. Concept maps could be adapted to represent both declarative and procedural knowledge.

In addition to the concept mapping element of AKADAM we also utilized a functional decomposition/task network modeling technique (IDEF) to capture detailed elements of a mission. The third element, design storyboarding, placed experts in the role of designers to translate concepts into design interfaces for each leg of the mission geometry. These three techniques, concept mapping, IDEF, and design storyboarding, formed AKADAM. We used and adapted AKADAM in many different ways over the years and have used it successfully with different kinds of experts in unique fields of practice.

One other important aspect of AKADAM was that it became the impetus for us to develop a toolset (TAKE—later named COGENT) based on the concept mapping element (Sanderson, McNeese, and Zaff, 1994). Part of my group at WPAFB used TAKE to develop some significant design work for helicopters and other domains. This was part of the overall AKADAM philosophy—to develop CSE tools as we applied them in the field. This time was also prime for discussion of new tools both with Penny Sanderson and John Flach to generate effective new approaches to work domain analysis—predicated on Rasmussen's abstraction hierarchy. The intent behind all these tools was to test and apply them in the field.

During this "preteen" period the lab also assisted in funding, and helped develop another significant CSE tool, MacSHAPA, through the expertise and guidance of Penny Sanderson (Sanderson, McNeese, & Zaff, 1994; Sanderson, Scott, Johnston, Mainzer, Watanabe, & James, 1994). This was a tool from the tradition of exploratory sequence data analysis and utilized comprehensive video analysis—coupled with the protocol analysis functions in SHAPA. It significantly enabled videotapes of human activity in context to be analyzed in new ways. It allowed efficacious models to be built based on in-situ data. By juxtaposing MacSHAPA with the AKADAM methods and the TAKE/COGENT tools we had an effective observer-participant approach to CSE (Sanderson, McNeese, & Zaff, 1994).

These various methods/tools formed a core for conducting a comprehensive cognitive engineering analysis of complex systems (McNeese, 1996b). They placed much of the responsibility for design on the user and were focused on acquiring user knowledge that spanned the gap to performance in context.

One final major event during the 1990s which significantly empowered our CSE approach in a specific domain was the establishment of the Collaborative Design Technology Laboratory (CDTL) (seeWhitaker, Selvaraj, Brown, & McNeese, 1995). This lab really covered all the elements of the general framework and practiced a "living lab" philosophy. The intent was to develop user-centered collaborative design technologies (Whitaker, Longinow, & McNeese, 1995) to enhance design teams in real-world settings (Citera, McNeese, Brown, Selvaraj, & Whitaker, 1995). The CDTL afforded multiple opportunities to put into practice many ideas of CSE and allowed ethnographic study, reconfigurable testbeds, as well as experimental lab projects (see Brown, Selveraj, Whitaker, & McNeese, 1995; Citera, Selveraj, McNeese, Brown, & Zaff, 1995). True to the spirit of the 1980s, the focus was absolutely on situated, complex problems, distributed collaboration, and developing technology to support teamwork. The thread relating CSE to teams continued to be assuaged but in new ways with new fields of practice.

3.6.6 The Restless Teenager

From the mid-1990s to 2000 many events coupled with CSE took place at the Air Force Research Laboratory. Methods certainly matured but there were other questions, issues, and challenges that have remained unanswered. First, let's take a look at some of these events that composed my continued discovery of the meaning of CSE from my own personal perspective.

One of the main events was the intent to use cognitive models and develop models as informed from cognitive task analysis. Task network modeling continued (informed by the use of concept mapping as a *cognitive task analysis*) as we developed models of fighter pilots engaged in target acquisition (Bautsch, Narayanan, & McNeese, 1997). This research used a Maverick launch mission task in a synthetic task environment to compare actual performance results of pilots (given different experimental conditions) with (1) an extended air defense simulation (a model without "user" parameters), (2) cognitive models as informed and built as a function of HCI guidelines and behavioral-based task analysis, (3) cognitive models informed and built as a function of cognitive task analysis, and (4) a cognitive architecture-based simulation, SOAR (Darkow, Marshak, Woodworth, & McNeese, 1998).

Modeling cognition in applied contexts is informative for knowledge acquisition, establishing a basis for design, and for exploring constraints of the problem space itself. Our results found that the type of task analysis performed influences the performance of the model created in reference to the baseline pilot performance. The research demonstrated that adaptive cognitive capabilities (e.g., in SOAR) were really not needed to capture some of the well-defined procedural sequences of the mission. However, on more advanced, ill-defined requirements these capabilities would absolutely be necessary to capture activities.

More current work in cognitive systems engineering/modeling focuses on addressing one of the wicked problems we encountered in our early work. It is coupling the knowledge elicitation processes and model representation to transform early concept maps into dynamic models (McNeese, Bautsch, & Narayanan, 1999). Early work was beneficial in transforming conceptual knowledge of the user (and his/her context) into design artifacts for a given mission (Zaff, McNeese, & Snyder, 1993). However, the concept mapping component of AKADAM—although very good for eliciting early issues, constraints, and design requirements—was too *loosely coupled* (as a knowledge representation typology) to directly transform knowledge into dynamic models. This is especially the case for situated contexts that require a high degree of interdependent, collaborative activity.

One recent project (McNeese, Rentsch, & Perusich, 2000) focuses on modeling C^3I operations using the *fuzzy cognitive map (*Perusich et al., 1999) method. Note the field of practice of interest has now switched to the area we initially started with in the original COPE projects—one of the ironies of this developmental process. However, the domain is much changed, is more global and multi-team focused, and includes use of many new information technologies (not the least of which is the internet and associated telecommunication technologies). Perhaps the term "battle management" connotes the broader level of coverage. The battle management domain absolutely incorporates many aviation-level contingencies (e.g., addressing new cognitive system concerns attributed to remotely controlled, unmanned air vehicles).

The initial assessment of the fuzzy cognitive map technique indicates it is an efficacious way of eliciting knowledge in a form that is easily and directly transformed into models of team processes/team decision making. Our assessment is based on contrasts with previous cognitive task analyses and cognitive engineering techniques we have applied to various fields of practice. The method can be generalized to many "collaboration in the wild" problems and is useful for simulating the differential effects of socio-cognitive and factors as they influence team effectiveness.

Our intent, given the tradition of the living lab philosophy, is to develop models (individual or team-level) that are used as the basis to (1) design decision support systems, cognitive aids, human-computer interfaces, or intelligent agents embedded in complex systems and, (2) be a way to easily test interface designs, support systems, and agents for how well a human (or a team) interacts and performs given certain constraints. Part 1. allows CSE to incur as it takes the "knowledge as model as design" view whereas part 2. exploits the model as a tool to be used to test/evaluate designs without having to do full-blown, timely experiments. One may also use these test/evaluations as preliminary data before the "intervention" part of the living lab cycle. That is, the model can help assess problems in a proposed design prototype and therein suggest improvement prior to actually embedding it in a field of practice for testing and usability analysis. Fuzzy cognitive maps have been the main technique and advancement to the early 1990s work on concept mapping and allow us to use models to capture "knowledge as design."

Fuzzy cognitive maps are directed di-graphs that contain (1) fractional edge strength values among variable concept states, and (2) feedback that affords a qualitative model of a complex system. They may be used to build a model of team— environment transactions wherein goals, information, physical attributes, value judgments, behaviors, decisions, and quality valuations are all needed to represent boundary constraints and emergent complexity (Perusich & McNeese, 1998a). They capture the causal reasoning of the expert constructing a system (or decomposing a problem) and are especially useful in situations where a variety of variables must be compared that lack a common numerical metric. Therein, they can be used to model decision making in teams that involve complex tradeoffs between disparate causes and effects because "apples and oranges" comparisons can be seamlessly made (Perusich & McNeese, 1997). Rather than forcing comparisons by transforming the measures of each variable to some artificial numerical scale, such as utility, each is represented by its states.

In contrast to traditional concept maps (McNeese et al., 1995) which tend to facilitate more surface-level maps of knowledge, fuzzy cognitive maps enable a deeper structure of knowledge (within the knowledge elicitation/data abstraction process and the subsequent qualitative modeling activities). Intentions, causes, and effects are represented as nodes in the map. A cause-and-effect relation ship is represented in the map by a directed edge from one node to another. In a cognitive map, the strength of these edge strengths is limited to the values 1, –1, and 0, representing “A causally increases B,” “A causally decreases B,” and “A has no effect on B,” respectively. In a fuzzy cognitive map, degrees of causality are incorporated by allowing edge strengths of any fractional value in the closed interval [–1,1]. Fuzzy causality, such as “A somewhat causes B” or “A causes B a little,” is incorporated in the map by letting the edge strengths have an appropriate fractional value, such as 0.4 or –0.6.

As an “associate memory,” inference in FCM is conducted by applying a set of input variables and allowing the map to equilibrate a stable output or observing a limit cycle. The presence of feedforward and feedback mechanisms in the associative memory creates causal loops that help understand and model the dynamics of complex systems (Perusich & McNeese, 1998b).

One of the advantages of the FCM representation was that it was fluid enough to capture many of the front-end constraints in problem finding but sophisticated enough to transform knowledge representations (captured from the elicitation process) into active, dynamic models. FCM can be applied to individuals but more importantly it has a unique capability to integrate many of the qualitative judgments that multidisciplinary team members need to make. The method can make conflicts explicit (as part of the representation) and equilibrate the consequences of conflicts in the overall problem space. Likewise, the multiple constraints of interdependent collaborative actions, the modeling of emergent complexity, and the effects of expectation and causality can be represented (using aspects of fuzziness) and equilibrated to simulate teamwork and socio-cognitive factors given a specific situated context.

Our initial assessments of FCM have been very positive. In contrast to many of our previous methods of cognitive engineering, the FCM approach provides a dynamic model of collaborative activity—directly instantiated from knowledge elicitation activities while maintaining user-centered, participatory principles. It also affords users the opportunity to directly experience (and incrementally change) their mental model in a way that resonates with their expectations.

The goal of our research is to understand socio-cognitive factors in situated contexts with specific application to military or other operational domains. As mentioned, FCM is just one component of our overall vision. Future work will integrate results of our team models with team schema similarity measurements (Rentsch, McNeese, Pape, Burnett, Menard, & Anesgart, 1998) using the living lab perspectives (McNeese, Perusich, & Rentsch, 2000). These models are envisioned to evolve into *embedded software mediators* that can assist in managing global, battlespace, and shared situation awareness, that is, can systematically be inserted as team members as part of a crew. With the reduction in crew size (a major issue to be addressed in the military), the capability of having software mediators available to a reduced-size crew will be very important for enhancing shared situation awareness in distributed environments. The use of FCM-based software mediators to assist in C^3I teamwork with a reduced crew size is the next phase of our research. Obviously, we are interested in how the teamwork schemas of crew members will vary when software mediation is present, and as a consequence, how this can feed back into the development of fuzzy models.

As work continues there is recognition of a need for various kinds of collaborative task analyses within CSE (see McNeese & Rentsch, 2001). To this end, we have been eliciting and assessing team schemas/team member models as new kinds of knowledge to model and in turn to use for design.

One other major development has been the need to develop a Computer-Aided Cognitive Systems Engineering (CACSE) tool that acts as a support system to the cognitive systems engineer. Through the use of a Small Business Innovation Research-based development operating under the program leadership of Scott Potter, Emily Roth, and David Woods, we developed CACSE for that purpose (Potter, Roth, & Woods, 2000; Potter, Roth, Woods, & Elm, 1998). A main intent in this project was to take the knowledge developed in cognitive task analysis and make it useful and relevant for software engineers using their CASE tools. The project was very successful and produced a prototype tool which in turn was tested in a real-world application. Although the tool itself is a design hypothesis about how as an artifact it shapes CSE activities (Woods, 1998) (and requires revisions to go to the next level of development), a new path has been established.

Tools such as CACSE are perhaps the future as to where CSE will lead. Tools are necessary to make CSE work easier and doable given various constraints in place. The CACSE tool also provided a culmination—personally—as it is predicated on Rasmussen's abstraction hierarchy and much of Wood's understanding and contributions to CSE. However, by creating a real tool to be used by the software engineers who actually create designs for human-computer interfaces and support systems, much new knowledge about how to advance and use the abstraction hierarchy was produced (see Potter, et al., 1998; Potter et al., 2000 for more information on CACSE).

The development of CACSE reveals a future requirement for the CSE field. It is that CSE is not an island unto itself. As a continually evolving profession there is much necessity to migrate into work with other specialties such as was demonstrated with software engineering. One must continually ask the question of what CSE, cognitive modeling, and cognitive field studies point to and what is the "plan" to get from here to there(see McNeese, Baustch, & Narayanan, 1999). The degree of relationship and utility to other tangential specialties will establish credence and validity for the field. As has been told in this query—there is an absolute need to make "design" a core value in CSE.

3.7 QUERY VI: WHAT HAS EVOLVED/WHAT HAS BEEN LEARNED?

Obviously, the last query had many peaks and valleys, traversed uncharted territories, and some cases ended up in vast wastelands rather than productive fields of practice. Still, the value of discovery is that you come to recognize limits, failures, and boundary constraints of practice. Through discovery you make right and left turns to go in new directions. This query and the next assess what exactly evolved over the last 15 years and what has been learned as a function of the journey.

One way to examine the extent of evolvement is to look at different kinds of outputs and products as the lasting contributions in the field of cognitive systems engineering. The research and development in CSE during my tenure with the U.S. Air Force focused on the mutual interplay of understanding, modeling, and measuring teamwork and individual activities within complex systems. At the heart of this research has been the desire to apply innovative *theoretical orientations* (humane intelligence, McNeese, 1986; situated cognition, Young & McNeese, 1995; group sensemaking, Nosek & McNeese, 1997; socio-cognitive factors, McNeese, 2000); *cognitive systems engineering frameworks/techniques* (AKADAM framework, Zaff, et al., 1993; McNeese et al., 1995; cognitive fieldwork, McNeese et al., 1999; fuzzy cognitive mapping, Perusich & McNeese, 1997; collaborative task analysis, McNeese & Rentsch, 2000; Living Lab, McNeese, Perusich, & Rentsch, 2000); *CSE tools* (COGENT/MacSHAPA, Sanderson, McNeese, & Zaff, 1994; CACSE, Potter et al., 2000); *cognitive modeling methods* (Bautsch & McNeese, 1997, Perusich & McNeese, 1998a); and *scaled world research paradigms* (Automate, Citera et al., 1995; Maverick Mission, Bautsch et al., 1997; Jasper, McNeese, 1992, DDD, McNeese, Rentsch, & Perusich, 1999; Patriot, McNeese & Perusich, 2000; TRACES, Brown, et al., 1995; CITIES, Wellens, 1993; TRAP, Wilson, McNeese, & Brown, 1987); *designs* (team display-group interface, McNeese & Katz, 1987; McNeese & Brown, 1986; Whitaker, 1994; PA interface, Fraser, Hipel, Kilgore, McNeese, & Snyder, 1989, McNeese et al., 1990). Other outputs exist as well but these are the major objects that have evolved.

Upon looking at these various objects there are some "recombinant themes" that have been learned that may be critical for addressing challenges and issues for the future of CSE (to be discussed shortly). As we search for invariance across the evolutionary development of CSE from the first field study of the student union to the most current model employing fuzzy cognitive maps, there are some insights that stand out. First, the *design of spaces* is a key element of CSE—whether it be physical, informational, collaborative, or global-oriented. CSE is about knowing the constraints of a space and how a space is used to enable and advance human activities. Second, studying *fields of practice* with new tools always leads to new insights about what is wrong or what could make a practitioner more effective. So much can be learned from fieldwork studies by use of a different—yet integrated—set of CSE tools. *Protocol analysis* is very important to capture different kinds of perspectives and acts to bridge some of the gaps we have mentioned. One of the newer advances that is showing an increasing rate of return for research is experimental scaled worlds (predicated on knowledge from CTAs that inform with respect to the context and user constraints). We are seeing more and more examples of scaled worlds that emulate real-world problem spaces but are to scale for efficiency and effectivity. Finally, we have learned that a loosely coupled, eclectic set of techniques without the ability to tie analysis to design, and without the ability to integrate with each other in a meaningful way, can leave the CSE specialist asking more questions than she/he answers. This can also lead to sloppy approaches to fieldwork and participant-observer methods. With respect to these various themes, there are two summary ideas that I would like to posit.

In the introduction to the query on what I have done over 15 years I posed a generic framework to simply capture the many directions I have pursued in the different periods of my CSE life. That framework has been specifically reified to be known as the living laboratory approach to CSE. We first introduced it in the mid-1990s (Whitaker et al., 1995; McNeese, 1996a) but have been using it quite a bit as a shield representing our beliefs concerning CSE. At the heart of this approach is a pulse which is repeated throughout this paper—the value of learning, discovery, and improvement. The living lab is a way of research life that places value on discovery through different venues, concurrency, ecological validity, feedback, mutually informative processes, technological intervention, and the willingness to broadly approach complex problems without dogmatic, doctrinaire biases.

As reflected upon CSE—the goal of the living lab is to enable CSE practitioners (working with specified fields of practice) to become a community of learners. As an active research community there is always the presence of the specific and how to attune support in that way. However, a more challenging goal is to recognize how the particular folds into the universal (Woods, 1998). CSE can make more effective and safer interfaces for a given project and domain, but the real goal is to learn principles across many fields of practice that point to universal findings about cognitive systems. One might say it is necessary to go from a field of practice to a *field of knowledge*. If we only address the particular and specific, CSE as a field of knowledge will suffer. This is not only true for a domain but may be applicable to other elements as well (e.g., tools used, technology intervention, scaled worlds, etc.). By spanning specific targets to abstract what is similar across contexts, learning, discovery, and the meaning of CSE can rise to new heights.

The most recent manifestations of a living lab view are the CACSE framework/toolset (Potter et al., 2000) and a new systematic approach for conducting cognitive field studies (McNeese, Bautsch, & Narayanan, 1999). Although there is not enough space in this chapter, these new directions show how we have used what we have learned to advance the state of CSE.

3.7.1 Summary

In concluding this query, I wanted to state explicitly specific things learned along the way—that I consider of value for other CSE practitioners. These thoughts are not unique per se and I am sure they have been discovered by others in this field as well:

- Nothing is perfect—especially in a complex world
- Several integrated, bootstrapped approaches are better than single, or piecemeal approaches
- There are various gaps that CSE can help to fill, (e.g., What people intend vs. what people know vs. what people do which are all complicated by teamwork settings, in other words, CTA →cognitive modeling →cognitive design →software engineering →decision-based test & evaluation)
- Gaps are filled by people who pick up and transfer context in spaces (physical, perceptual, informational, social, cultural, emotional)
- Context rules! Constraints have to be known to control adaptive process but they often are perceptually bound
- Individual differences are very active and must be considered but so too are social norms, cohesiveness, and teamwork activities
- It takes time to develop accurate models of users at work and to develop the underlying engineering of joint cognitive systems
- CSE as a scientific endeavor is lagging behind but as an engineering specialty is moving forward
- Time in a field of practice is usually constrained—time with practitioners is short and often restricted—plan accordingly, practical, proprietary, security, safety concerns
- Practice of CSE often is not integrated with ongoing design engineering practice—CSE becomes an island
- Reliability, validity, and verification issues still nag practitioners but answers are slow to come forth—there often is a bias explosion on the part of the approach and the practitioner conducting a study
- Science/Philosophy/Engineering faultlines—"turn the crank" mentality pervades often
- Too much CTA—not enough design
- How to predict beyond what is given based on cases/domains not known—the envisioned world problem
- "What is the meaning of this" issue—multiple paths, beliefs, percep-

tions may be difficult to capture and then represent as models.

These are a few of the discoveries made that have informed continuing evolution.

3.8 QUERY VII: CONCLUSIONS—WHAT'S NEXT?

Getting beyond where we are going or where we are heading is a nontrivial task. It requires reaching into the future on the basis of what we have learned from the past. If we look at CSE as a whole, it is evident that the field has multiple personalities from multiple levels of inheritance that result in multiple meanings of where it is headed. Many examples of CSE are put forth that may only fit subsets of the definitions, themes, and example approaches provided in earlier queries. On the one hand perhaps this results in a dilution of CSE as field in its own right. For example, those who say that it is nothing more than "glorified human factors" or a subset of knowledge engineering (see McNeese, 1996b, that describes how CSE is different from these areas). Alternatively, there are those who want such a narrow definition that perhaps many current practitioners would be excluded. In the final hour we simply need to remember to ask ourselves several things that keep us on the right road to discovery as a reason for what is next:

- What is the use of CSE?
- What specific directions should CSE head towards (places where it has not been previously)?
- What inherent weaknesses require the greatest attention?
- What have we learned as an evolving field from given standpoints
- What have we learned in given domains across multiple domains?
- Is CSE science, engineering, anthropology? All or neither?
- How shall we teach and communicate with others the inherent worth, value, and impact of CSE?

Too, the question of how and how well the field addresses the universal principles—as derived from multiple domains of practice—determines the quest of future evolution. As we consider these basic questions and reflect on the queries throughout this chapter it is instructive to end with what I think are legitimate challenges for CSE to pursue to strengthen its position and to look for what is next. The following are an initial set of challenges—certainly incomplete—to begin considering and answering as a community of learners. Because the intent of this book aims toward the aviation setting as a target, many of the challenges are clothed with that context.

3.8.1 The Challenges

3.8.1.1 Philosophy/Value.

- For aviation projects, how is cognitive systems engineering different from human factors engineering—what is the value added for applying CSE to aviation?
- What is the inherent relationship of cognitive science to cognitive task analysis to cognitive modeling to cognitive systems engineering? How can these areas all be used systematically in addressing prime military aviation concerns?
- How does one address collaborative, team level issues with CSE?
- In your practice of CSE, what are the current weaknesses and limitations? How would you improve these for the next generation of CSE methods and tools?

3.8.1.2 Methodology/Tool-Use.

- What is the nature of translating the output of cognitive task analysis into design visualizations? Is this creativity? Does CSE suggest a specific process for doing this?
- What specific tools do you use as a practitioner in applying CSE to specific contexts? What computer-based tools (or other tools) would you like to see come on to the horizon?
- What do verification and validation mean in the context of CSE applied to aviation domains—for cognitive task/work analysis; for designs created from CSE process?
- What is the form and basis for the kind of modeling you do in CSE? How do you assess/validate/test models?

3.8.1.3 Aviation Application & Field of Practice.

- Is there anything unique about military aviation contexts that changes the application of cognitive system engineering principles?
- What are the crux of the issues involving specificity of context (e.g., a given military aviation domain such as the F–22) and generalizability of findings to other domains—what transfers and how do you know this?
- What are the objects of your study in aviation-based CSE? How do you begin a project? How do you deal with first-of-kind, unfielded sys-

tems design? How do you address uncertainty of data, info, knowledge, etc. with the CSE process?

- In conducting aviation-based fieldwork as part of the CSE process, what lessons learned could you share that would be informative to other practitioners?

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