# A Framework for Integrating Cognitive Task Analysis into the System Development Process

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This paper describes a process that orchestrates different types of specific CTA techniques to provide design relevant CTA results and integrates CTA results into the software development process. Two fundamental premises underlie the approach. First, CTA is more than the application of any single CTA technique. Instead, developing a meaningful understanding of a field of practice relies on multiple converging techniques in a bootstrapping process. The important issue from a CTA perspective is to evolve a model of the interconnections between the demands of the domain, the strategies and knowledge of practitioners, the cooperative interactions across human and machine agents, and how artifacts shape these strategies and coordinative activities across a series of different specific techniques. Second, since CTA is a means to support the design of computer-based artifacts that enhance human and team performance, CTA must be integrated into the software and system development process. Thus, the vision of CTA as an initial, self-contained technique that is handed-off to system designers is reconceived as an incremental process of uncovering the cognitive demands imposed on the operator(s) by the complexities and constraints of the domain.

## Introduction

Since at least the early 1980's, the desire to enhance human performance in cognitive work has led researchers to develop techniques for Cognitive Task Analysis (CTA), either as the basis for intelligent tutoring systems (e.g., Bonar et al, 1985) or as the basis for on line computer based support systems (Hollnagel and Woods, 1983). Originally, the focus was to develop specific techniques drawing from basic methods such as knowledge elicitation, critical incident methods, direct observation in the field, walkthroughs and simulation (Roth and Woods, 1989; Cooke, 1994).

To support development of computer based tools intended to aid cognition and collaboration we and others have found that CTA is more than the application of any single CTA technique. Instead, developing a meaningful understanding of a field of practice relies on multiple converging techniques. We have used this approach to model cognition and collaboration and to develop new online support systems in time pressured tasks such as situation assessment, anomaly response, supervisory control, and dynamic replanning across domains such as military intelligence analysis (Potter et al., 1997), military aeromedical evacuation planning (Cook, et al., 1996; Potter et al., 1996), military command and control (Shattuck and Woods, 1997), commercial aviation (Sarter and Woods, in press), cardiac anesthesia (Cook and Woods, 1996), space shuttle mission control (Watts et al., 1996), and nuclear power plant emergencies (Roth & Mumaw, 1995).

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As part of an Air Force sponsored project to develop CSE tools, we are developing a process that orchestrates different types of specific CTA techniques to provide design relevant CTA results, and integrates these results into the software development process.

## CTA as a Modeling Process

CTA is a means to a larger end of specifying ways to improve human and team performance in the domain (be it through new forms of training, user interfaces or decision-aids). From this perspective CTA is best thought of as a process for uncovering the cognitive activities entailed by the field of practice and identifying opportunities for more effective support.

Our approach to CTA is best depicted in Figure 1. The left side of this figure is intended to convey how CTA is an iterative, bootstrapping process focused on understanding both the *domain* (mapping the cognitive demands of the fields of practice) and *practitioners* (modeling expertise and cognitive strategies) through a series of complementary (empirical and analytical) techniques. As indicated by the right side of Figure 1, the CTA process continues into the design/prototype development process. The CTA model (the output of the left side) becomes the *initial hypothesis* for artifacts embodied in the design prototypes which in turn are used to discover additional requirements for useful support (Woods, in press). Phases within the CTA process are represented by vertical columns and the domain world / practitioner distinction (within the field of practice) is represented by the horizontal rows. Time is on the abscissa and growth of understanding is on the ordinate. CTA products/artifacts are represented by the nodes along the activity trajectory.

Critical issues addressed by this framework include the need for:

- multiple, coordinated approaches to CTA. No one approach can capture the richness required for a comprehensive, insightful CTA. However, in an iterative manner, a set of approaches can successively (and successfully) build the required understanding.
- analytical and empirical evidence to support the CTA. Analytical models need to be refined and verified through complementary empirical investigations.
- tangible products from CTA that clearly map onto artifacts used by system designers. CTA must work within a system development process and support critical system design issues.
- the use of prototypes as tools to discover additional CTA issues. CTA cannot be viewed as a standalone analysis. It needs to be an iterative process that learns from subsequent design activities.

A comprehensive CTA needs to encompass analysis and modeling of both the domain and how domain practitioners respond to it. The focus is on building a model that captures the analysts' evolving understanding of demands of the domain, knowledge and strategies of domain practitioners, and how existing artifacts influence performance that can be used to guide specification of requirements for improved performance

In performing CTA, two mutually reinforcing perspectives need to be considered (as depicted by the two "dimensions" on the ordinate axis in Figure 1). One perspective focuses on the *fundamental characteristics of the domain* and the cognitive demands they impose. The focus is on understanding the way the world works today and what factors contribute to making practitioner performance challenging. Understanding domain characteristics is important both because it provides a framework for interpreting practitioner performance (why do experts utilize the strategies they do? What complexities in the domain are they responding to? Why less experienced practitioners perform less well? What constraints in the domain are they less sensitive to?) and because it helps define the requirements for effective support (what aspects of performance could use support, what are the hard cases where support could really be useful) as well as the bounds of feasible support (what technologies can be brought to bear to deal with the complexities inherent in the domain, which aspects of the domain tasks are amenable to support, and which are beyond the capabilities of current technologies).

The second perspective focuses on how today's practitioners respond to the demands of the domain. Understanding the knowledge and strategies that expert practitioners have developed in response to domain demands provides a second window for uncovering what makes today's world hard and what are effective strategies for dealing with domain demands. These strategies can be captured and transmitted directly to less experienced practitioners (e.g., through training systems) or they can provide ideas for more effective support systems that would eliminate the need for these compensating strategies. Examining the performance of average and less experienced practitioners is also important as it can reveal where the needs for support are.

## CTA AS A BOOTSTRAP PROCESS

We contend that CTA is fundamentally an opportunistic bootstrap process. The selection and timing of particular techniques to be deployed will depend on the detailed constraints and pragmatics of the particular domain being addressed. While Figure 1 provided an overview of this process, Figure 2 illustrates additional details of this idea. One starts from an initial base of knowledge regarding the domain and how practitioners function within it (often very limited). One then uses a number of CTA techniques to expand on and enrich the base understanding and evolve a CTA model from which ideas for improved support can be generated. The process is highly opportunistic. Which techniques are selected, whether one starts by focusing on understanding the domain or by focusing on the knowledge and skills of domain practitioners, depends on the specific local pragmatics. The key is to focus on evolving and enriching the model as you go to ultimately cover an understanding of both the characteristics of the domain and an understanding of the way practitioners operate in the domain. This means that techniques that explore both aspects will

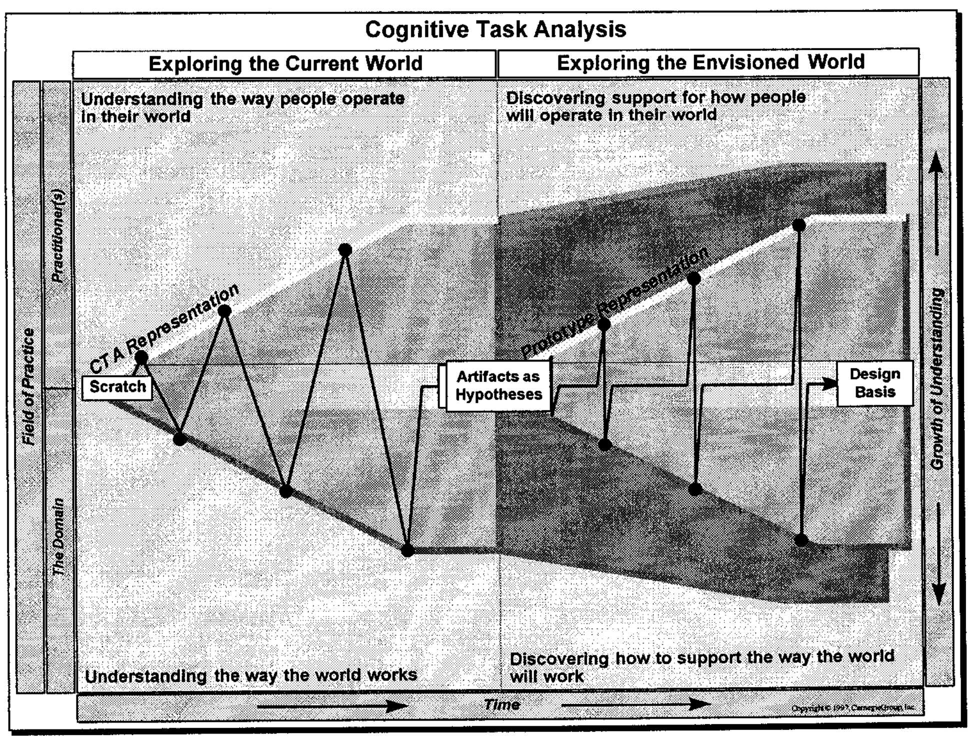


*Figure 1. Overview of an integrated approach to CTA within an iterative system development process.*

most likely need to be sampled, but where one starts, and the path one takes through the space will depend on what is likely to be most informative and meet the local constraints at any point in time.

The phrase 'bootstrapping process' is used to emphasize the fact that the process builds on itself. Each step taken expands the base of knowledge providing opportunity to take the next step. Making progress on one line of inquiry (understanding one aspect of the field of practice) creates the room to make progress on another. For example, one might start by reading available documents that provide background on the field of practice (e.g., training manuals, procedures), the knowledge gained will raise new questions or hypotheses to pursue that can then be addressed in interviews with domain experts, it will also provide the background for interpreting what the experts say. In turn, the results of interviews may point to complicating factors in the domain that place heavy cognitive demands and opportunities for error. This information may provide the necessary background to create scenarios to be used to observe practitioner performance under simulated conditions or to look for confirming example cases or interpret observations in naturalistic field studies.

The selection of which technique(s) to use and how many techniques to employ should be motivated by the need to produce a model of the field of practice and how domain practitioners operate in that field. In practice the modeling process generally requires the use of multiple converging techniques that include techniques that focus on understanding the domain demands as well as techniques that focus on understanding the knowledge and strategies of domain practitioners. The particular set of techniques selected will be strongly determined by the pragmatics of the specific local conditions. For example, access to domain practitioners is often limited. In that case other sources domain knowledge (e.g. written documents) should be maximally exploited before turning to domain experts. In some cases observing domain experts in actual work practice (using ethnographic methods or simulator studies) may be impractical, in those cases using structured interview techniques (such as concept mapping) and critical incident analysis may be the most practical methods available. Still in other cases domain experts may not be accessible at all (e.g., in highly classified government applications), in those cases it may be necessary to look for surrogate experts (e.g., individuals who've performed the task in the past) or analogous domains to examine.

It should be stressed that studying the practitioner vs. the domain are merely different access points that provide complementary perspectives. We present them here as distinct to stress the importance of considering both perspectives, but in practice the lines are not so clearly drawn. It is possible to uncover characteristics of the domain through interviews with domain practitioners or field observations. It is also possible to gain perspective on expert strategies by understanding the affordances provided by structural characteristics of the domain.

As a heuristic, if resources are limited, it is likely to be more effective to utilize several techniques that sample from both portions of the space (analysis of the domain and analysis of practitioner) even if done cursorily, that to expend all resources utilizing one technique. Unexpected complexities and surprises are more likely to be uncovered when multiple techniques are employed than when the focus is on only on one technique. When the results using several techniques reinforce each other and converge, it increases confidence in the adequacy of understanding. If differences are found it signals the need for a deeper analysis.

## USING PROTOTYPES AS TOOLS FOR DISCOVERY

The introduction of new technology necessarily transforms the nature of practice. New technology introduces new error forms; new representations change the cognitive activities needed to accomplish tasks and enable the development of new strategies; new technology creates new tasks and roles for people at different levels of a system. Changing systems change what it means for someone to be an expert and change the kinds of errors that will occur.

Since the introduction of new technology transforms the nature of practice,

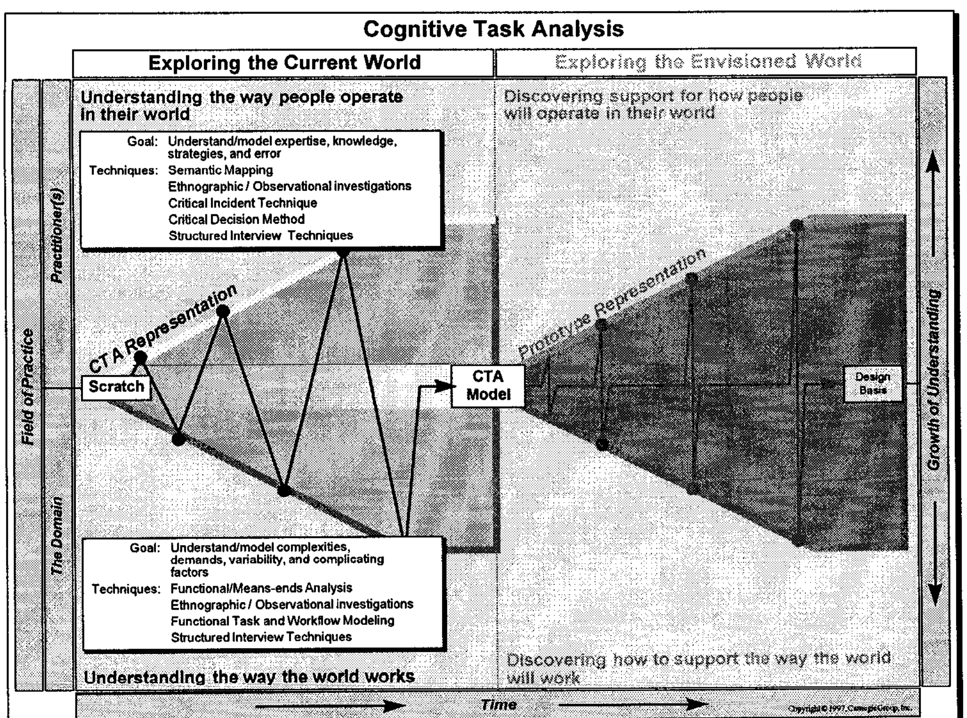


*Figure 2. Detailed depiction of the first phase of an integrated approach to Cognitive Task Analysis within an iterative system development model. The critical issue is the mutually reinforcing analyses that, in combination, work toward an understanding of the practitioner(s) and the domain.*

developers face the *envisioned world* problem (Woods, in press):

- How do the results of CTA that characterize cognitive and cooperative activities in the current field of practice inform or apply to design activities that will produce a world different from the one studied?
- How does one envision or predict the relation of technology, cognition and collaboration in a domain that doesn't yet exist or is in a process of becoming?
- How can we predict the changing nature of expertise and new forms of failure as the workplace changes?

The envisioned world problem means that effective CTA must face a challenge of prediction: how will envisioned technological change shape cognition and collaboration and how will practitioners adapt artifacts, given mismatches to the actual demands and pressures they experience, to meet their own goals (Woods, in press). The goal of such predictions is to influence the development process so that new tools are useful, support practitioners, and are robust since such predictions of a co-evolutionary dynamic are inherently limited.

One approach to dealing with the envisioned world problem is to extend the CTA process into the design/prototype development phase. This is illustrated in Figure 3. The CTA model (output of the first phase of effort) becomes the initial hypothesis for artifacts embodied in the design prototypes which in turn are used to discover additional requirements for useful support (Woods, in press).

As indicated by the figure, each opportunity to assess the utility of the design artifacts provides additional understanding of requirements for effective support but also additional understanding of our initial CTA model. Thus, designs – among other levels of analysis – embody hypotheses about how technology change will shape cognition and collaboration.

An important issue from this perspective is that the vision of CTA as an initial, self-contained technique that is handed-off to system designers needs to evolve into a process of modeling not only the interconnections between the demands of the domain, the strategies and knowledge of practitioners, but also the cooperative interactions across human and machine agents, and how artifacts shape these strategies and coordinating activities.

A second equally important claim, then, is that it is only when we are able to design appropriate support that we truly understand the way the world works and the way people will operate in this world. This is the flip side of the claim by Winograd (1987; p. 10) that designing 'things that make us smart' depends on "...developing a theoretical base for creating meaningful artifacts and for understanding their use and effects."

## INTEGRATING CTA INTO THE SYSTEM DEVELOPMENT PROCESS

In developing and evaluating a CTA process the focus should be on the products to be derived from the CTA. The question one should ask is 'Are the demands of the domain and how domain practitioners are responding to those demands being captured in a way that enables concepts for improved support to be generated?'

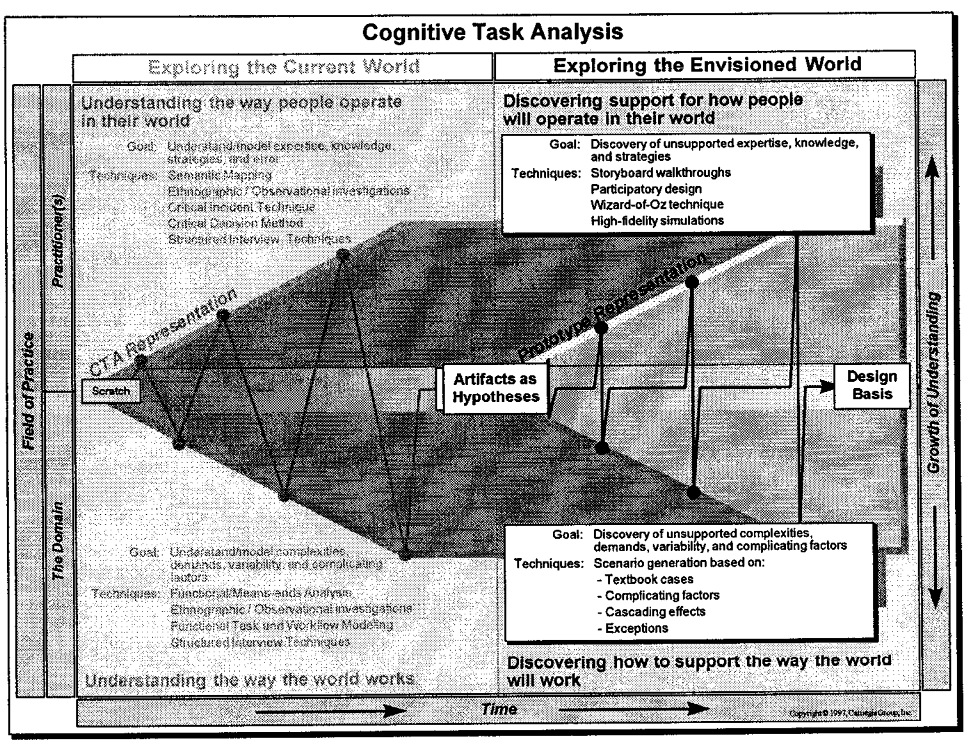


*Figure 3. The transition to the second phase of CTA. This figure indicates how prototypes are used as tools for discovery and enrich the understanding achieved through the initial phase.*

Criteria to consider in developing and evaluating a CTA process should include:

1. **efficiency** of the CTA in itself (Are the resources being invested in the CTA activities commensurate with the value of the results being obtained? )
2. **validity** of CTA (Does it capture what it is like to function in the field of practice?)
3. **effectiveness** of CTA in design (Does the CTA point to what is likely to be useful support? Does it help generate new aiding concepts and innovations? Does the CTA help to identify the bounds of aiding? Does it help avoid typical design errors? Does it generate ideas that can be readily converted to system requirements to guide system design and testing?)
4. **tractability** of CTA results in design (Are the products of the CTA documented in a way that can be meaningfully reviewed, tracked, and updated not only throughout the CTA phase but also throughout the entire system design life-cycle? Does it

support distributed communication and coordination of design team members within and across organizational boundaries? Do the products of the CTA make contact with artifacts utilized in the software design process and can the results of the CTA be integrated into the software and product development process?)

5. **predictive power** of CTA (Does it help anticipate the impact of the introduction of new technologies and aiding concepts on practitioner performance? Does it predict how new technological power can change roles, expertise and error? Does it help address the envisioned world problem;)

The criteria presented above help elucidate the requirements for software tools to support the CTA process. The major benefits of applying software technology to the CTA process will not come from improving the efficiency of use of any given CTA technique. The real value of applying software technology comes from providing tools to support the modeling and documentation activities that are the products of the CTA that feed into the system development process.

Our vision is to develop software tools that aid the CTA analysts in the modeling and documentation aspects of the CTA process to yield a more useful product that makes direct contact with the software development process and supports communication and coordination of CTA results among design team members distributed within and across development organizations.

We envision a tool that:

- streamlines the production of software engineering artifacts (i.e., provides support for directly contributing a CTA perspective into established software engineering artifacts).
- makes these software engineering artifacts more focused on defining requirements for building effective, practice-centered decision support (i.e., system requirements that defines solutions to the cognitive demands imposed on the user by the complexities of the domain);
- provide a mechanism for updating and maintaining related downstream design stages (e.g., a change in the underlying CTA structure triggers a change in the information requirements and thus a change in the resulting display and vice versa).

In this way it would support cognitive task analysts in capturing and maintaining the essential cognitive issues and relationships developed through a CTA yet will also be a tool for software developers to maintain awareness of the "design basis" underlying the resulting system requirements and specifications by forming a maintainable, traceable component of the functional design. The primary benefit of an integrated, tool-supported process will be the radical advance in the impact of CTA results on the resulting decision support system design

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