# Beyond Intelligent Interfaces: Exploring, Analyzing, and Creating Success Models of Cooperative Problem Solving

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**Abstract.** Cooperative problem-solving systems are computer-based systems that augment a person's ability to create, reflect, design, decide, and reason. Our work focuses on supporting cooperative problem solving in the context of high-functionality computer systems. We show how the conceptual framework behind a given system determines crucial aspects of the system's behavior. Several systems are described that attempted to address specific shortcomings of prevailing assumptions, resulting in a new conceptual framework. To further test this resulting framework, we conducted an empirical study of a success model of cooperative problem solving between people in a large hardware store. The conceptual framework is instantiated in a number of new system-building efforts, which are described and discussed.

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## 3. Success Models for Cooperative Problem Solving

To deepen our understanding of the problems of high-functionality systems and find ways to overcome these problems, we engaged in a search for success models of such systems. The success model idea has proven to be of great value. We have previously analyzed skiing as a success model [4] and derived architectural components for computer-based learning environments [35] from this analysis. In a similar fashion, the ideas behind spreadsheets were used as guiding principles in system-building efforts in other domains [6,36–37]. Studying success models can provide us with equally important insights as studying the role of failures [38] and their impact on the advancement of design.

In this section, we describe a study done at McGuckin Hardware, argue why it is relevant to these issues, and show how the store has successfully addressed the difficult problems mentioned previously. We then place the study in the larger context of research in situated cognition.

### *3.1. McGuckin: An Empirical Study*

A preliminary analysis indicated the McGuckin Hardware in Boulder, Colorado, might be an ideal candidate for a success model. McGuckin carries more than 350,000 different line items in 33,000 square feet of retail space. The store's superior reputation among its customers and its continued growth and profitability make it a success model.

To get a better understanding of just how the "system" operates, we asked McGuckin Hardware for permission to observe and record interactions between customers and sales agents. Some of the dialogues were transcribed from audiotapes and carefully analyzed. Videotapes would have been a superior medium, but would have interfered too much with store operations.

The decision to observe directly as people do problem solving and design in the real world was made as a result of considering the perspective of situated cognition research. Lave [10], Schoen [7], and others have shown how problem solving in daily activity is shaped by the dynamic encounter between the culturally endowed mind and its total context. This leads to a vision of cognition as a dialectic between persons acting and the settings in which their activity is constituted. Lave [10] argued that theoretically charged, unexamined, normative models of thinking lose their descriptive and predictive power when research is moved to everyday settings and relaxes its grip on the structuring of activities.

The following dialogues illustrate the inherent difficulties in high-functionality systems mentioned above (for additional details of our study see Reeves [39]).

**Users do not know about the existence of tools.** In this dialogue, the customer is unsure about how to attach a sign to a metal pole. The customer does not know of self-tapping bolts and therefore cannot ask for them. Even if we assume a complete understanding of the problem, this is not enough to guarantee the knowledge of the best tool for the problem. Here the customer ends up buying a fastener that is introduced and explained by the salesperson.

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**Dialogue$_1$: Attaching a Sign to a Square Metal Pole[1]**

1. C: *I'm looking for a small fastener maybe one-sixteenth.*
2. S: Okay. Plastic? Metal?
3. C: *Well, what I've got is to fasten a sign on to a square pole. I've got a hole in the top and it fits fine and I got to get one on the bottom.*

   After looking at several fasteners, and asking a few more questions, the salesperson suggests a certain type of fastener.

4. S: How about a self-tapping bolt?
   Picks one up and shows it.
5. C: *Well, what uhh, well, this would probably do it, what about, would it come back out?*
6. S: Oh sure. It'd come back out.
7. C: *But once it's in?*
8. S: As long as the hole is smaller than this thing, you can thread it in and out.

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**Users don't know how to access tools.** The next dialogue shows that it can be difficult just to find items you "know" exist. The customer is specific about the wanted item and even seems to know the store fairly well, but still cannot find the item.

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**Dialogue$_2$: Finding Tool Clips**

1. C: *I need clips for tools where you shove it up in them and it holds*
2. S: Yeah.
3. C: *I mean not just a single clip, a bunch of them. We tried in housewares, the cheap little ones, tools only have like funny kind of ones. Where else could they be?*
4. S: Garden center, for rakes and shovels and things like that
5. C: *Would it be there?*
6. S: Yeah.
7. C: *Okay, I know where that is, thanks.*

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**Users do not know when to use tools.** The interaction shown in Dialogue$_3$ involves a search for scales to weigh small animals and illustrates the concept of *applicability conditions*: the conditions under which an item can be used, especially for "unintended" purposes. The salesperson is able to recognize a crucial element: namely, that there be a platform large enough to hold something of a certain approximate size and weight. He helps the customer to know *when* to use a given tool, even though that use might not have been intended by the designer of the tool. The fact that a scale is intended for food is less important than those features.

Dialogue$_3$ also illustrates the use of *differential descriptions*. The customer describes the intended item "differentially" in terms of an example, building on what the environment has to offer. The customer uses an example item (the "little tiny ones over here") to differentially describe the intended solution. The salesperson extracts the crucial information and suggests an item intended for a different domain, yet useful for accomplishing the described task.

In Dialogue$_4$ the customer wants strength, but the salesperson has to point out a crucial feature of that strength: that it comes at the expense of brittleness.

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**Dialogue$_3$: Scales for Small Animals**

1. C: *I'm looking for some scales and I saw some little tiny ones over here, but I need something that has a large platform on it, to weigh small animals on.*
   Holds hands about 18 inches apart.
2. S: I would think something in our housewares department, for weighing food and things like that. Go on down to the last isle on the left.
3. C: *Okay.*

**Dialogue$_4$: Hardened Bolts**

1. C: *So if I were going to hook something would this be the best thing? What I'm going to have is I'm going to drill into the cement and have it sticking out.*
2. S: You going to have this sticking out, just the shaft of the bolt? holding a bolt and pointing to the unthreaded shaft.
3. C: *Right.*
4. S: Hmm. Interesting problem.
5. C: *A hardened bolt would give me more . . .*
6. S: Yeah, but it'll shear, they're more brittle. I don't know if you'd be any better off with a hardened.

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**Users can not combine or adapt tools for special uses.** Although the combination in Dialogue$_5$ is simple, it does illustrate how tools can be combined in various ways. The customer doesn't know why the salesperson suggests a certain combination of tools, but ventures a guess. The salesperson allows the suggestion, but then states his reason.

**Dialogue$_5$: Combining Simple Tools**

1. S: After deciding that a three-sixteenth inch wire is to be looped around a half-inch bolt, which is mounted in cement
   You want a small enough loop, put it between two washers. Picks up two washers and places them on the shaft of a bolt.
2. C: *Small enough loop.*
3. S: Yeah.
4. C: *Why between two washers, so it won't rub?*
5. S: Yeah, so it won't slide off. Probably won't.

Observing interactions like these confirmed the previous analysis of the difficulties of using high-functionality systems. In addition, it raised several other issues that must be considered in building cooperative problem-solving systems.

**Incremental problem specifications.** Dialogue$_6$ shows that there is a close relationship between defining specifications incrementally, as seen here, and establishing shared knowledge, as will be seen in the next dialogue. The distinction is a subtle, yet useful one. Shared knowledge has more to do with establishing a common reference point with which to discuss a situation, and less to do with the specific process of identifying relevant parts of the problem domain.

**Dialogue$_6$: Incrementally Refining a Query**

1. C: *I need a cover for a barbecue.*
2. S: (Leading customer down an isle where several grills are lined up and accessories are displayed) Okay . . . what have we got here . . . chaise, chair barbecue grill cover. . . . Does that look kind of like what you got? (Pointing to one of the grills.) Similar? No?
3. C: *No.*
4. S: Take any measurements?
5. C: *No.*
6. S: That's a good guess there. (Pointing to a one-burner grill.)
7. C: *It's a double burner one.*
8. S: 52 inches. That's the total length it'll cover. (Measuring with the tape and holding the tape over one of the grills.)
9. C: *Yeah. I know it's not that big at all.*
10. S: You saying about 18 by 18. Well, this is 27, it'll cover up to here. (Using measuring tape again and pointing.)
11. C: *I need two.*
12. S: A couple . . . in that brand, that's all I have. Here are these Weber ones, thicker material and all that. Here are some smaller ones.
13. C: *I'll take this one.*
14. S: We'll be getting more of these pretty soon.
15. C: *You'll have them by Christmas?*
16. S: Hopefully Thursday.

**Achieving shared understanding.** Between the time a customer begins to interact with a sales agent and the time the customer leaves with a "satisficing" solution [23], a shared understanding must be created between the two cooperating agents. The customer must begin to appreciate relevant parts of the solution domain and the sales agent must understand the problem in enough depth to make reasonable suggestions. Dialogue$_7$ shows how establishing shared understanding is a gradual process in which each person participates, sometimes ignoring questions, sometimes volunteering information, and sometimes identifying miscommunications. Illustrated also are the problems of knowing about the existence of tools and understanding the results that they produce. The customer wants to fasten a sign to a square metal pole. The top of the sign has been fastened via a preexisting hole, but the bottom is still unattached. The customer learns about certain fasteners while the salesperson learns about the specific problem. Their shared understanding increases as each in turn asks questions and makes suggestions that are critiqued by the other.

**Dialogue$_7$: Attaching a Sign to a Square Metal Pole[2]**

1. C: *I'm looking for a smaller fastener. Maybe one-sixteenth.*

2. S: Okay. Plastic? Metal?
3. C: *Well, what I've got is to fasten a sign onto a square pole. I've got a hole in the top and it fits fine and I've got to get one on the bottom.*
4. S: Pole have holes in it?
5. C: *Yeah. I had a one-eighth bolt, but it's too big. Need something smaller than that.*
6. S: Round pole? Square Pole?
7. C: *Square pole.*
8. S: (Picking up a fastener and showing it) You tried these?
9. C: (Scrutinizing the fastener.) *Hmmmm.*
10. S: You've got to have a five-sixteenths hole and you fold this thing up and stick it in. Would that work?
11. C: *It's got to be five-sixteenths?*
12. S: Yes. The size of the shaft on this thing. (Pointing to the fastener.)
13. C: *It's not that big.*
14. S: No way to drill it?
15. C: *No.*
16. S: No. What did you use the first time?
17. C: *I tried a one-eighth inch.*
18. S: How thick is the metal in the pole?
19. C: *Oh, probably about one eighth inch.* (Pointing to a certain fastener.) *How about these?*
20. S: (Picking one up and showing the moving parts.) These work on hollow-core doors.
21. C: *Yeah.*
22. S: (Walking over to a different kind of fastener and picking it up) I don't know if this would be strong enough. Still need a three sixteenth hole. If the wind is blowing hard it might give way. Just putting it in with a screw-driver?
23. C: *Yeah.*
24. S: How about a self-tapping bolt? (Picks one up and shows it.) Put that in, tighten it down, (points to tip), that's a thread cutting thread there.
25. C: *Well, what, uhmm, well, this would probably do it. What about, would it come back out?*
26. S: Oh sure. It would come back out.
27. C: *But once it's in?*
28. S: As long as the hole is smaller than this thing, you can thread it in and out.

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**Integration between problem setting and problem solving.** Dialogue$_8$ shows an interaction in which a customer wanted to buy heaters, then decided to reconceptualize the problem from one of "adding heat," to one of "retaining heat." This appears to be a trivial reframing and hardly worth notice, but we will argue that understanding exactly this kind of reframing is crucial to building cooperative problem-solving systems. The problem *itself* was redefined.

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**Dialogue$_8$: Generating Versus Containing Heat**

1. C: *I want to get a couple of heaters for a downstairs hallway.*
2. S: What are you doing? What are you trying to heat?
3. C: *I'm trying to heat a downstairs hallway.*
4. S: How high are the ceilings?
5. C: *Normal, about eight feet.*
6. S: Okay, how about these here?
   They proceed to agree on two heaters.
7. C: *Well, the reason it gets so cold is that there's a staircase at the end of the hallway*
8. S: Where do the stairs lead?
9. C: *They go up to a landing with a cathedral ceiling.*
10. S: Ok, maybe you can just put a door across the stairs, or put a ceiling fan up to blow the hot air back down.

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**Summary.** The findings of the McGuckin study can be summarized as follows:

*Natural Language is less important than Natural Communication.* People rarely spoke in complete, grammatical sentences, yet managed to communicate in a natural way. In fact, most of the dialogues shown here had to be "cleaned up" for readability. The study provided convincing evidence that the support for *natural communication* [29], allowing for breakdowns, clarifying dialogues, explanations, etc., is more important for cooperative problem solving than being able to parse syntactically complex sentences. One objective of future human-computer communication research should therefore be to understand the processes of intention communication and recognition well enough to enable a system to participate in a natural dialogue with its user [40].

*Multiple Specification Techniques*. Customers used a great variety of specification techniques such as bringing in a broken part, pointing to an item in a catalog or in the store, and giving general descriptions such as "I need a lock that qualifies for cheaper insurance rates."

*Mixed Initiative Dialogues*. People were flexible in the roles they played during a problem-solving episode. They easily switched from asking to explaining, from learning to teaching. Because Dialogue$_7$ is the longest, it probably shows this best. The structure of these dialogues was determined neither by the customer nor by the sales agent, but clearly indicated mixed initiative [28] determined by the specifics of the joint problem-solving effort.

*Management of Trouble*. Many breakdowns and misunderstandings occurred during the observed problem-solving episodes, but in almost all cases clarifying dialogues allowed their recovery. Problem solving among humans cannot be characterized by the absence of trouble, but by the identification and repair of breakdowns [8]. Dialogue$_6$ and Dialogue$_7$ contain examples of this.

*Simultaneous Exploration of Problem and Solution Spaces*. Customers and sales agents worked within both problem and solution spaces simultaneously, or at least alternatively. Typically the problem owner (customer) had a better grasp of the problem space and the problem solver (sales agent) had a better understanding of the solution space, but over time these spaces converged until there was a large enough intersection of shared knowledge within which potential solutions could be evaluated. This is seen in Dialogue$_7$ in which the customer knows what needs to be done but needs a better understanding of the possible solutions, and the salesperson knows how many different fasteners work but needs to understand the specific application.

*Humans operate within the physical world*. Although perhaps obvious, system designers overlook the fact that people use elements of the physical world as sources of information, as reminders, and in general as extensions of their own knowledge and reasoning systems. In most of the dialogues that deal with fasteners, both the customer and salesperson held the items and used them to guide and clarify the discussion. For example, in Dialogue$_6$, the salesperson picked up two washers and placed them on the shaft of the bolt, leaving a small gap between them to show where the cable would go, and how the loop needs to be small enough to be guided or constrained by the washers.

*Humans make use of distributed intelligence*. Much of people's intelligent behavior results from the interaction of mental processes with the objects and constraints of the world, and much behavior takes place through a cooperative process with others. Collaborators challenge each other's analysis of the problem and help to achieve creative solutions. One thing that surfaced in discussions with salespeople is that when they send a customer to another department, they count on the customer being able to find the items, but also expect another salesperson to be available there.

### *3.2. A Situated Cognition Perspective*

The perspective of situated cognition researchers is important in this analysis of cooperative problem-solving success models. McGuckin Hardware provides an example of what situated cognition researchers have been claiming: much of problem solving is fundamentally related to the larger context in which the problem gets perceived, framed, and eventually resolved. Suchman [8] argued that plans are just one of the resources in the problem-solving process, not *the* guiding principles. The McGuckin study confirms this view of plans: customers do have plans, but these plans are just one resource, not the primary guide.

Lave [10] argued that the problem-solving context plays a crucial role in problem framing. The McGuckin study confirmed this finding. As customers interacted with the wide variety of hardware (e.g. two isles of fasteners), they were able to recast their perception of the problem they came in to solve.

In a critique of the approach technical rationality has encouraged professional practitioners to take toward ill-defined problems. Schoen [7] argued against abstract principles and for skills developed in domain-specific problem solving, emphasizing the role that problem setting plays. Real problems are never given, but "must be constructed from the materials of problematic situations which are puzzling, troubling, and uncertain."

**The setting of a problem is as important as the problem itself.** The word "setting" means two things: (1) the physical and social environment (the "context") in which a problem solver acts, and (2) the process of defining the problem. The problem context provides key resources in solving the problem, because it affects how we come to perceive the problem and the resources available to us.

Carraher, Carraher, and Schliemann [41] described how important the setting was to Brazilian school children who worked as street vendors. On the street, they were quite accurate in their calculations (98 percent correct), but when given mathematically identical problems outside the marketplace context, their accuracy dropped to a dismal 37 percent.

Attempts have been made to bring more of the environment into consideration in analyzing problem solving. Larkin et al. [42] studied several issues, such as the interaction between the person solving a problem and external memory aids such as paper and pencil, and representing situations that change over time. Situated cognition appears to push this concept of setting and problems that change over time even further into our physical environment and social relations.

When people encounter problems, these problems are embedded in an environment that provides ways in which the problem is perceived and resources with which to analyze it. Problems can be divorced neither from the social settings in which they occur, nor from the process of problem defining. The former provides structuring resources to the problem solver and the latter affects how the problem is allowed to evolve.

**Problems and solutions coevolve—one cannot exist without the other.** Empirical studies of people developing complex computer systems [21] have confirmed that often the problem is not to implement a given specification, but rather expressing the problem itself: deciding what problem to solve.

In the context of design problems, Rittel [43] argued that "*you cannot understand the problem without having a concept of the solution in mind; and that you cannot gather information meaningfully unless you have understood the problem but that you cannot understand the problem without information about it.*" Taken literally, this leaves no room for a beginning, but there is a way in which this view nevertheless makes sense. If one cannot begin one without the other, then the only way to proceed is with both simultaneously. In problem solving, people cannot proceed until they have a "resolution shape—a sense of an answer and a process for bringing it together with its parts" [10, p. 19].

John Dewey noted that "discovering a problem is the first step in knowing" (cited in [44]). And Wertheimer [45] observed that: "Often in great discoveries the most important thing is that a certain question is found. Envisaging, putting the productive question is often more important, often a greater achievement than the solution of a set question" (cited in VanGundy [44, p. 102]).

We are trying to understand what this means to designers of cooperative problem-solving systems. Success models of these systems provide a new perspective that informs the design of such systems built on a computing platform. Studying people at McGuckin provided an opportunity to observe "everyday cognition." These observations confirm the importance that the situated cognition perspective brings to the design of cooperative problem-solving systems.

## 4. Second Generation of Cooperative Problem-Solving Systems

In this section, findings from the McGuckin study are related to the framework suggested in the first section. This is followed by a description of a prototype of an integrated, domain-oriented, knowledge-based design environment.

### *4.1. Requirements for Cooperative Problem-Solving Systems*

**Beyond user interfaces.** Effective human-computer communication is more than creating attractive displays on a computer screen: it requires providing the computer with a considerable body of knowledge about the world, about users, and about communication processes. This is not to say that the user interface is not of crucial importance to knowledge-based systems. Analysis of expert systems (such as the DIPMETER advisor [46]), has shown that the acceptance and real use of expert systems depends on far more than a knowledge base and an inference engine. The developers examined the relative amount of code devoted to different functions of DIPMETER and found that the *user interface portion was 42 percent* compared to 8 percent for the inference engine and 22 percent for the knowledge base. Similar data are reported for commercial knowledge-based system tools (e.g., in Intellicorp's tools, 55–60 percent of the code is interface related [47]). A good user interface is important for two groups: for the developers of knowledge-based systems and for the end-user of these systems.

The communication requirements are even more important for cooperative problem-solving systems. Because the user is actively involved in the problem-solving and decision-making process, there is an increased necessity for the interface to support the task at a level that is comprehensible by the user. In order for a knowledge-based system to support cooperative problem solving, the following components depend critically on each other:

- the structure of the knowledge and problem-solving system itself—how a system represents its problem-solving activity and retrieves the relevant portion appropriately in response to user queries
- the generation of views of this knowledge which corresponds to the needs and the knowledge of the user; for this a system must contain a model of the user
- the presentation of this knowledge on the screen; this part is mostly (explicitly or implicitly) associated with user-interface research.

**Problems can be fully articulated only in the context of solving them.** The McGuckin study clearly indicated that problems in realistic situations are not fixed targets. The combination of a large selection of objects and knowledgeable sales agents creates an environment in which customers can produce partial solutions and get feedback from the items in the store and from the sales agents in the form of critiques. As problem solvers tentatively explore possible solutions and evaluate how those affect their perception of the original problem, they shape the situation: in accordance with their initial appreciation of it, the situation "talks back," and they respond to the situation's back-talk [7].

**The fidelity of the design situations' "back talk" must be increased.** Many of the problems that are discussed at McGuckin are ill-defined. The artifacts and inventory at McGuckin are powerful to the extent that the sales agents are knowledgeable. Providing rich functionality without domain-specific expertise is not enough. In our system-building work, we originally believed that domain-oriented construction kits would be powerful enough to "talk back" by themselves, but this turned out not to be the case [31]. Construction kits support the construction of an artifact, but they do not provide any feedback on the quality of the design. Knowledgeable sales agents provide this higher level expertise and so help the situation to "talk back."

McGuckin hires experts in the various departments and considers previous experience within a field, such as plumbing, to be more important than previous sales experience in that field. The difference between working and selling experience in a field is crucial. Behind the surface or syntactic layer of the inventory, there is a semantic understanding of trade-offs, and experience in mapping specific problems to multipurpose tools.

**There is a need for specialization and putting knowledge in the world.** Simon [23] predicted that when a domain reaches a point where the knowledge for skillful professional practice cannot be acquired in roughly a decade, a burden on mastering all the tools and the knowledge will occur [48]. Simon predicted that the following adaptive developments will occur: (1) specialization will increase and (2) practitioners will make increasing use of books and other external reference aids in their work [49]. McGuckin addresses the tool mastery burden by (1) organizing functionality according to external task domains, and (2) incrementally making the information space relevant to the task at hand by an evolving shared understanding between customers and salespeople.

**Supporting human problem-domain communication with domain-oriented architectures.** The

McGuckin study illustrates the need to respond to a diverse set of tasks. There is an important need in computer science to develop domain-oriented architectures in order to avoid the pitfall of excess generality. Instead of serving all needs obscurely and insufficiently with general purpose programming languages, domain-oriented architectures serve a few needs well. The semantics of our computing environments need to be better tuned to specific domains of discourse; this involves support for different kinds of primitive entities, for specification of properties other than computational functionality, and for computational models that match the users' own models. Human-computer communication needs to be advanced to human-problem domain communication, where the computer becomes "invisible" and users have the feeling of interacting directly with a problem domain.

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4. R.R. Burton, J.S. Brown, G. Fischer, "Analysis of skiing as a success model of instruction: Manipulating the learning environments to enhance skill acquisition," in *Everyday Cognition: Its Development in Social Context*, edited by B. Rogoff, J. Lave. Harvard University Press: Cambridge, MA—London, pp. 139–50, 1984.

6. G. Fischer, C. Rathke, "Knowledge-based spreadsheet systems," in *Proceedings of AAAI–88, Seventh National Conference on Artificial Intelligence (St. Paul, (MN))*, Morgan Kaufman Publishers, San Mateo, CA. 1988, pp. 802–807.

7. D.A. Schoen, *The Reflective Practitioner: How Professional Think in Action*. Basic Books: New York. 1983.

8. L.A. Suchman, *Plans and Situated Actions*. Cambridge University Press: New York, 1987.

10. J. Lave, *Cognition in Practice*, Cambridge University Press: Cambridge, UK, 1988.

21. B. Curtis, H. Krasner, N. Iscoe, "A field study of the software design process for large systems," *Communications of the ACM*, vol. 31, pp. 1268–1287, 1988.

23. H.A. Simon, *The Sciences of the Artificial*, The MIT Press, Cambridge, MA, 1981.

28. J.R. Carbonell, "Mixed-initiative man-computer instructional dialogues," Report 1971, BBN. 1970.

29. D.G. Bobrow, R.M. Kaplan, M. Kay, D.A. Norman, H. Thompson, T. Winograd, "GUS, A frame-driven dialog system," *Artificial Intelligence*, vol. 8, pp. 155–173, 1977.

31. G. Fischer, A.C. Lemke, "Construction kits and design environments: Steps toward human problem-domain communication," *Human-Computer Interaction*, vol. 3, pp. 179–222, 1988.

35. E. Wenger, *Artificial Intelligence and Tutoring Systems*. Morgan Kaufman Publishers: Los Altos, CA. 1987.

36. K.-Y. Lai, T.W. Malone, "Object lens: A 'spreadsheet' for cooperative work," in *Proceedings of the Conference on Computer-Supported Cooperative Work (CSCW '88)*, ACM, New York, 1988, pp. 115–124.

37. N. Wilde, C.H. Lewis, "Spreadsheet-based interactive graphics: From prototype to tool," in *Human Factors in Computing Systems. CHI '90 Conference Proceedings (Seattle, WA)*, ACM: New York, 1990, pp. 153–159.

38. H. Petroski, *To Engineers Is Human*. St. Martin's Press: New York, 1985.

39. B.N. Reeves, "Locating the right object in a large hardware store—An empirical study of cooperative problem solving among humans," Technical Report CU-CS-523-91, Department of Computer Science, University of Colorado, Boulder, CO, 1991.

40. T. Winograd, "A Language/Action Perspective on the Design of Cooperative Work," *Human-Computer Interaction*, vol. 3, pp. 3–30, 1988.

41. T.N. Carraher, D.W. Carraher, A.D. Schliemann, "Mathematics in the streets and in the schools," *British Journal of Development Psychology*, vol. 3., pp. 21–29, 1985.

42. J. Larkin, et al., "Expert and novice performance in solving physics problems," *Science*, vol. 208, pp. 1335–1342, 1980.

43. H.W.J. Rittel, "Second-generation design methods," in *Developments in Design Methodology*, John Wiley & Sons: New York, 1984, pp. 317–327.

44. A.B. VanGundy, *Stalking the Wild Solution: A Problem-Finding Approach to Creative Problem Solving*, Bearly Limited: Buffalo, NY, 1986.

45. M. Wertheimer, *Productive Thinking*, Harper & Row: New York, 1959.

46. R.G. Smith, "On the development of commercial expert systems," *AI Magazine*, vol. 5, pp. 61–73.

47. M. Stelzner, M.D. Williams, "The evolution of interface requirements for expert systems," in *Expert Systems: The User Interface*, Ablex Publishing Corporation: Norwood, NJ. pp. 285–306, Chapter 12, 1988.

48. F.P. Brooks, Jr., "No silver bullet, essence and accidents of software engineering," *IEEE Computer*, vol. 20, pp. 10–19, 1987.

49. D.A. Norman, *The Psychology of Everyday Things*. Basic Books: New York, 1988.