Negotiation Architecture for Large-Scale Crisis Management Using NII

by
Carl Hewitt & Carl Manning
hewitt@ai.mit.edu, carlmanning@ai.mit.edu

This paper reports on research sponsored by ARPA and monitored by ONR.

1. Introduction

Negotiation is an important activity in arranging future joint activities, particularly those involving multiple organizations. It is of great theoretical and practical interest to develop technology which participates in social worlds. A critical challenge is to develop an information systems architecture which facilitates negotiation.

Progress in negotiations depends on representing and communicating the existing and proposed joint activities of the participants. Ongoing activities are continually in progress and continually evolving. A representational approach based on describing the ongoing processes (rather than snapshot states) of the participants has the potential to better capture the concurrency and indeterminacy of the world.

Mobile telecomputer hardware technology is available now and improving rapidly. It enables people to carry and use information systems technology throughout their day, enabling both the people and the information systems to keep better informed about ongoing activities. This technology enables people to include information systems where ever they negotiate, whether in meetings, halls, or in the field. It enables Mobile Distributed Telecomputing, a paradigm shift in the interaction of people and information systems technologies.

Multiple organizations may be able to use *negotiation architectures* in their information systems to more efficiently, flexibly, and robustly to negotiate their future joint activities. In a negotiation architecture, participants in joint activities may agree to negotiate with each other before taking certain actions. Unsatisfactory negotiations can be brought to the attention of other parties. Carrying this negotiation architecture into the information systems, information system negotiations can help crisis management organizations to coordinate the flow of messages based on available resources, freeing valuable human time for other tasks.

In this paper, we lay out a framework of issues and requirements that need to be addressed by information systems for large scale joint activities such as crisis management. We sketch an approach; this preliminary work remains to be fleshed out and implemented.

2. Crisis Management Using NII

The construction of national information infrastructures is changing the paradigm for communication. During a major crisis, this new infrastructure can enable many more people to simultaneously send messages to request or offer assistance. Crisis management organizations can use information technology to better track and coordinate their own activities with each other in response to ongoing events. However, this capability can also quickly inundate crisis teams with tens of thousands of messages, potentially delaying important communications. We are developing a negotiation architecture to enable crisis management teams to manage such information flows.

Future crisis teams must use information technology to deal with floods of messages. The communications infrastructure is changing from a primarily voice-based telephone and radio conversations to include electronic mail messages. Currently the number of circuits (e.g., phone lines, radio channels) and the requirements of human conversation limit the number of communications. Resources are managed both by switch controllers (e.g., during a crisis, a radio dispatcher can prioritize service requests, and phone companies can limit long distance calls to keep local lines open) and by luck (timing determines who gets a busy signal and who gets through). Not only can few callers get through, but it takes precious human time to prioritize and deal with every caller, urgent or not.

As the NII connects to people's homes and businesses and to personal wireless devices, an increasing number of people in a crisis will simultaneously have the capability to send messages to crisis centers. During a major crisis, crisis centers can be inundated with messages. At such times, human expertise is precious, so information technology which can prioritize, route, and respond to some of these messages will help alleviate the load on humans, keep communications available for urgent messages and unusual cases requiring human expertise or authority, and provide quick responses.

For example, during the recent L.A. riots, a member of our staff happened to be caught in an elevator lobby in the ISI building in Marina del Rey. Calls to the police resulted in many busy signals. Eventually persistence was rewarded with short conversation ending in a curt reply to call back in four hours or so — the police had more urgent matters to deal with. In the future such requests can be sent as messages from a mobile personal communicator, and information technology in crisis management centers could provide quick responses without taking up precious human time.

Crisis management teams' information systems must collaborate and negotiate to manage message flow. Many organizations must work together to deal with a crisis, including police, medical, and fire personnel; relief organizations such as the Red Cross; local governments, schools, and churches; and organizations responsible for property involved, such as natural gas lines, power lines, etc.

Crisis management teams must track resource availability, shifting the flows of requests to organizations which may have the resources to deal with them. Each organization directs its own resources, so it must be involved in determining how they are used. Thus, the information systems for managing the flow of messages must allow each of these organizations to be involved in the process. In light of the crisis at hand, it is especially important that changes be made robustly and quickly, and mostly without requiring much human intervention.

To build these information systems, a crucial technology will be the representations of joint activities. These representations will enable the organizations (humans and computers) to communicate about these activities, and will be the basis of processes for creating new proposals, and for analyzing and comparing them.

3. Representations in Negotiations

Negotiation is discourse influencing future joint activities of participants. In this broad sense negotiation may, for example, arrange deals among equals, or clarify or recommend changes to orders between captain and crew. Participants may represent organizations as well as themselves.

Representations of (future) joint activities are critical to negotiation participants. The extent to which information systems can process these representations limits how fully they can participate in negotiations.

Anselm Strauss has eloquently stated some assumptions that we will use for guidance in our representations:

> "...we are confronting a universe marked by tremendous fluidity; it won't and can't stand still. It is a universe where fragmentation, splintering, and disappearance are the mirror images of appearance, emergence, and coalescence. This is a universe where nothing is strictly determined. Its phenomena should be partly determinable via naturalistic analysis, including the phenomenon of men [and women] participating the construction of the structures which shape their lives" From [Strauss 1978, p. 123], as quoted in [Strauss 1992, p. 20].

He goes on to characterize the nature of the universe assumed in the quotation above as follows:

> "a world that is complex, often ambiguous, evincing constant change as well as periods of permanence; where action itself although routine today may be problematic tomorrow, where answers become questionable, and questions produce ultimately questioned answers?" [Strauss 1992, p. 20]

Our challenge is to develop representations of interactions that do not contravene the above assumptions. For example, we must be able to represent the indeterminacy of interactions because we assume that "this is a universe where nothing is strictly determined." Limitations in the ability to represent indeterminacy in activities can cause limitations in the ability of information systems technology to participate in negotiations about these activities.

Our representations build on a notion of "process" that extends over space and time because we assume "a universe marked by tremendous fluidity; it won't and can't stand still." The concept of "process" is in contrast to the usual computer science notion of the "state" of a system in which it remains until the "next" state transition occurs. Particularly in the case of complex entities such as organizations or humans, "state" is not well defined.

Ongoing joint activities form complex webs of relationships with their participants. Engineering diagrams are an important part of human interfaces to representations of complex activities. Diagrams enable us to more readily communicate and perceive relationships. They also make these relationships concrete in forms which can be used by computer systems as well as humans. Diagrams are an important communication medium between humans and computer systems as well as between humans.

Representation in Crisis Management We now turn to a preliminary example of how we might represent activities for crisis management, and how these representations might be used.

Representing activities. Consider figures 1 and 2 which represent the process of being stranded in and escaping from a building during the L.A. riot, as mentioned earlier. The process is modularized into a hierarchy of *joint activity episodes* ("Negotiation with LAPD" contains both phone calls). Each joint activity has several participants, each with their own timelines progressing from left to right. Before and after the activity, relevant ongoing processes for each participant are described, summarizing the impact of the activity on the participants' processes.

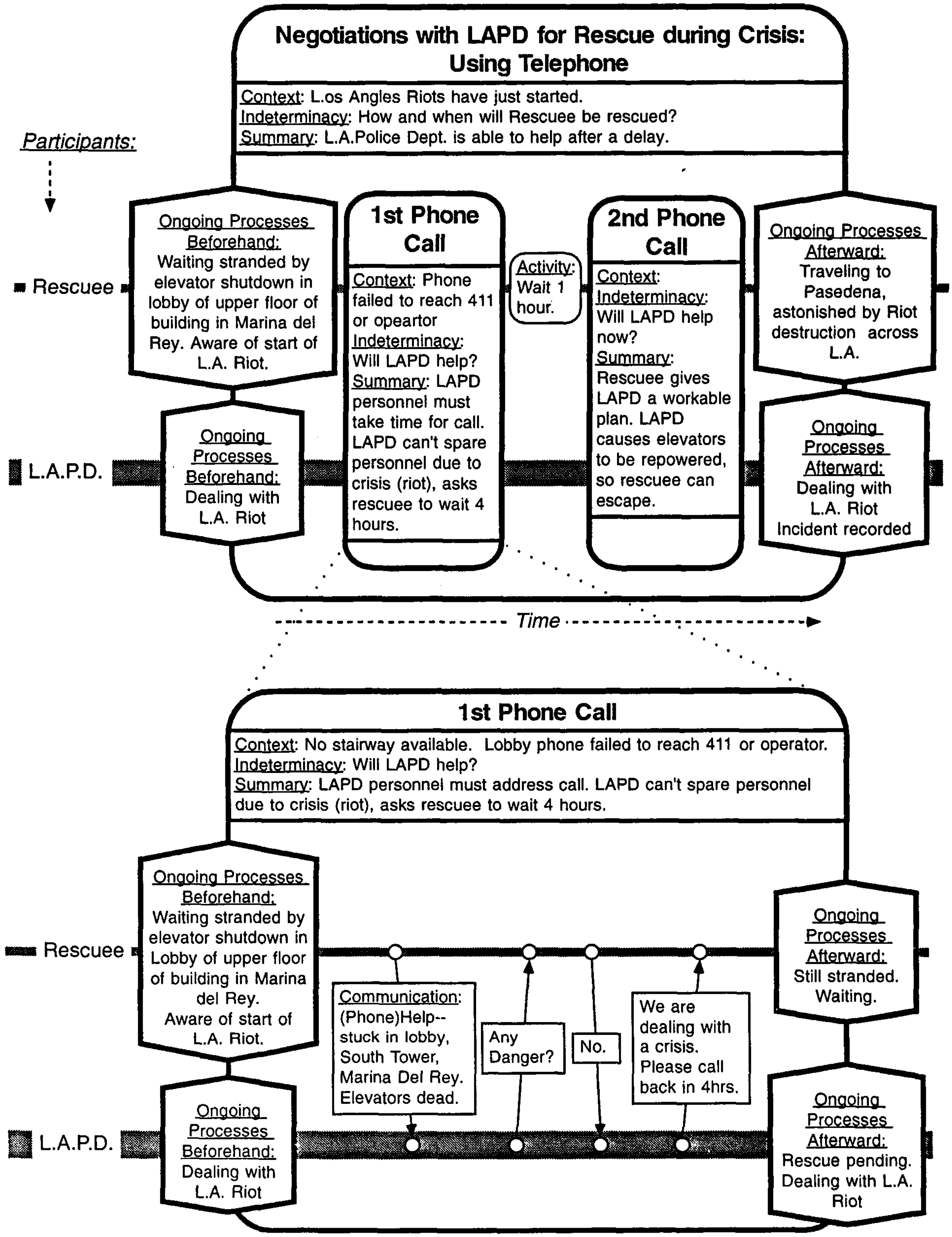
All details of communications and subactivities need not be be shown within an activity. The subactivities can be further described by diagrams elsewhere; for example, the first phone call is expanded at the bottom of figure 1, and the second phone call is expanded in figure 2. The same could be applied to the ongoing processes beforehand and afterward, or described in the context. Where detailed instantiated descriptions are not available, more general descriptions can be used. Those aspects which do stay the same can be described by processes which keep them the same (e.g., we expect a guard to still be there since it's part of the job (process) of guarding the premises).

Using Representations to Communicate. Consider figures 3 and 4 which illustrate how cases like the one above can be handled in the future with the aid of Mobile Distributed Telecomputing technology. Rescuees carry mobile telecomputers which can send and receive messages using wireless communications. They will have increased ability to request help during a crisis. However, as we noted above, this means that crisis centers can be inundated with messages during a crisis. Information systems can help prioritize and handle such messages.

In this particular example, the rescuee negotiates for help with LAPD message routing and prioritization information systems. The information systems can provide electronic forms to prompt the sender for information. The rescuee also has the capability describe situations beyond common cases covered by the forms. In figure 4 we propose that, just as in the phone negotiation with human, proposing a workable plan should reduce the effort required by the LAPD information systems. Communicating representations of plans offer opportunities for quick attention (agreement and performance). In order to evaluate the rescuee's plan, future information systems must use representations of other information about the situation. Where the capabilities of the information systems break down, cases can be forwarded to (now less inundated) humans. This is an example where joint activity representations can be used by a crisis management activity to communicate and analyze proposals.

These representational diagrams can also be used as records of activities as they occur. These records can then be studied and presented in negotiations to improve handling similar cases in the future, as we have done here. Keeping such records and make them available during meetings can be facilitated by Mobile

Figure 1: Representation of a crisis management episode.



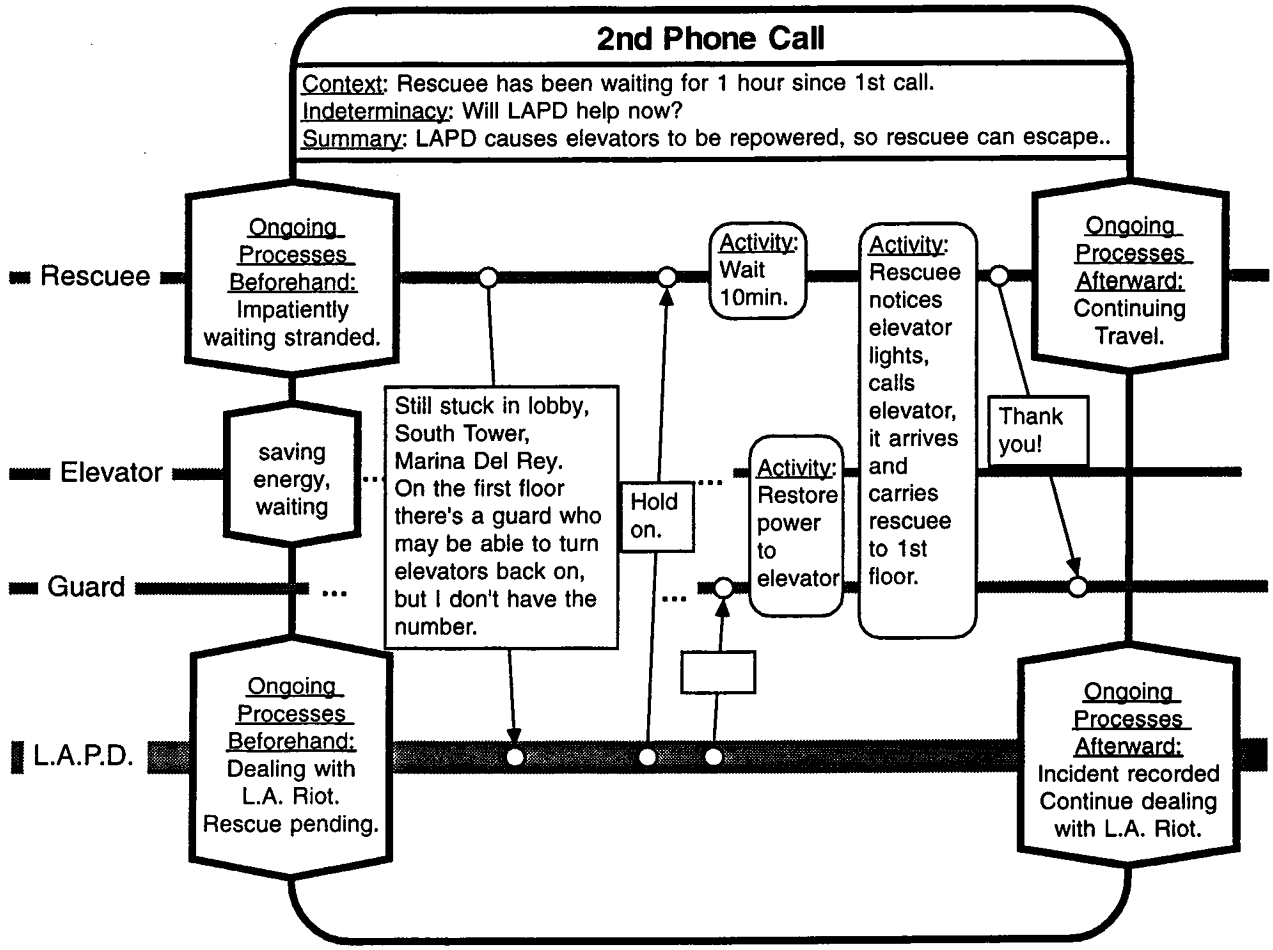


Figure 2: Representation of a crisis management episode (cont).

Distributed Telecomputing technology, which can help keep everyone up to date and available, both human and machine.

4. Paradigm Shift: Mobile Distributed Telecomputing in NII

Mobile Distributed Telecomputing is a paradigm shift of interaction for participants in the new information infrastructure. Current paradigms include:

The **Distributed** paradigm, characterized by:
Go to available device(s), *stop* to use them.

The **Mobile** paradigm, characterized by:
Take device(s) with you, use them *anywhere*,
making use of available wireless services.

Mobile Distributed Telecomputing shifts the nature and kind of interaction among people and information systems technology:

The **Mobile Distributed** paradigm, characterized by:
Take device(s) with you, use them *anywhere*,
making use of wireless services *in conjunction with* available distributed devices.

Figure 3: Proposed use of representations in future crisis management information systems.

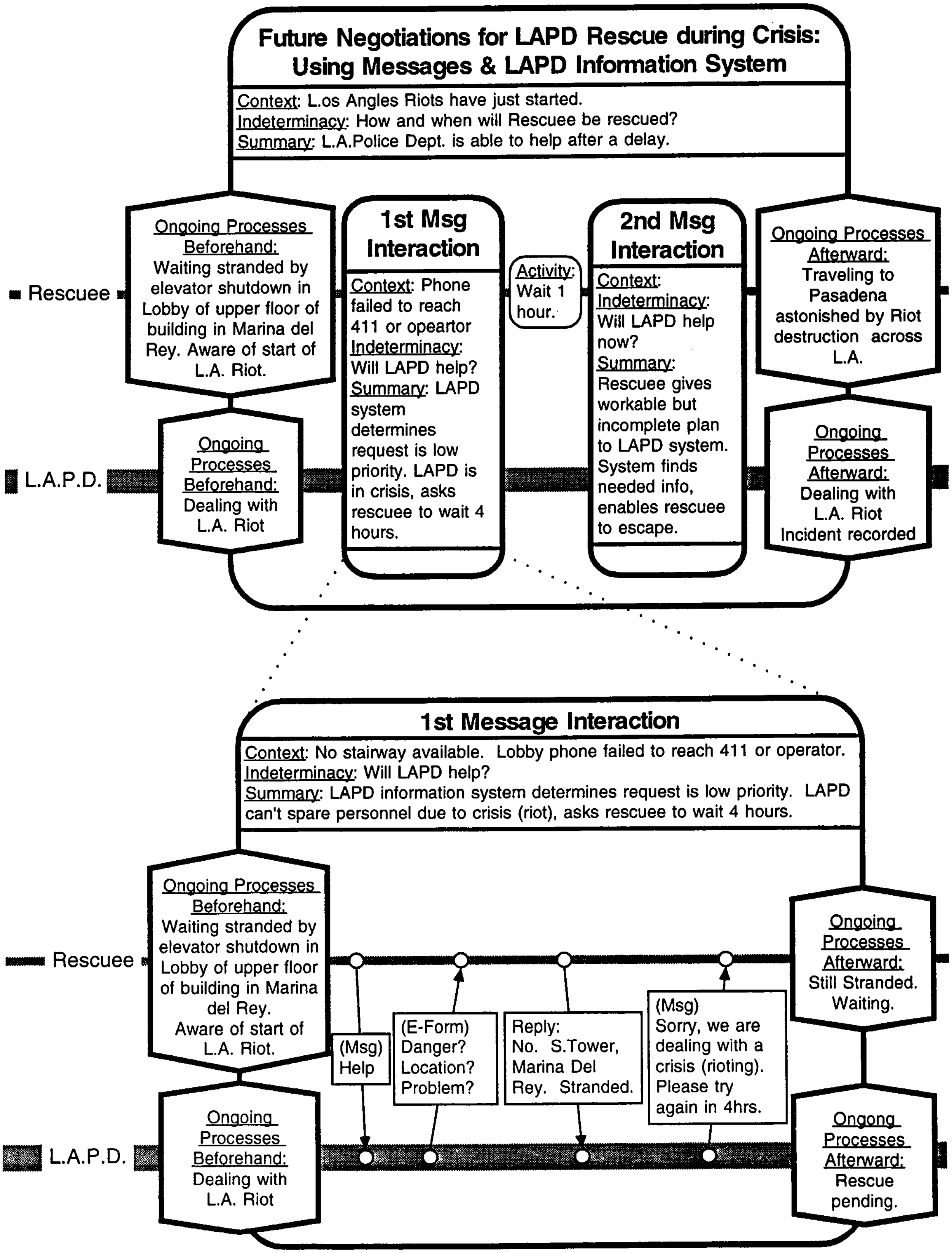
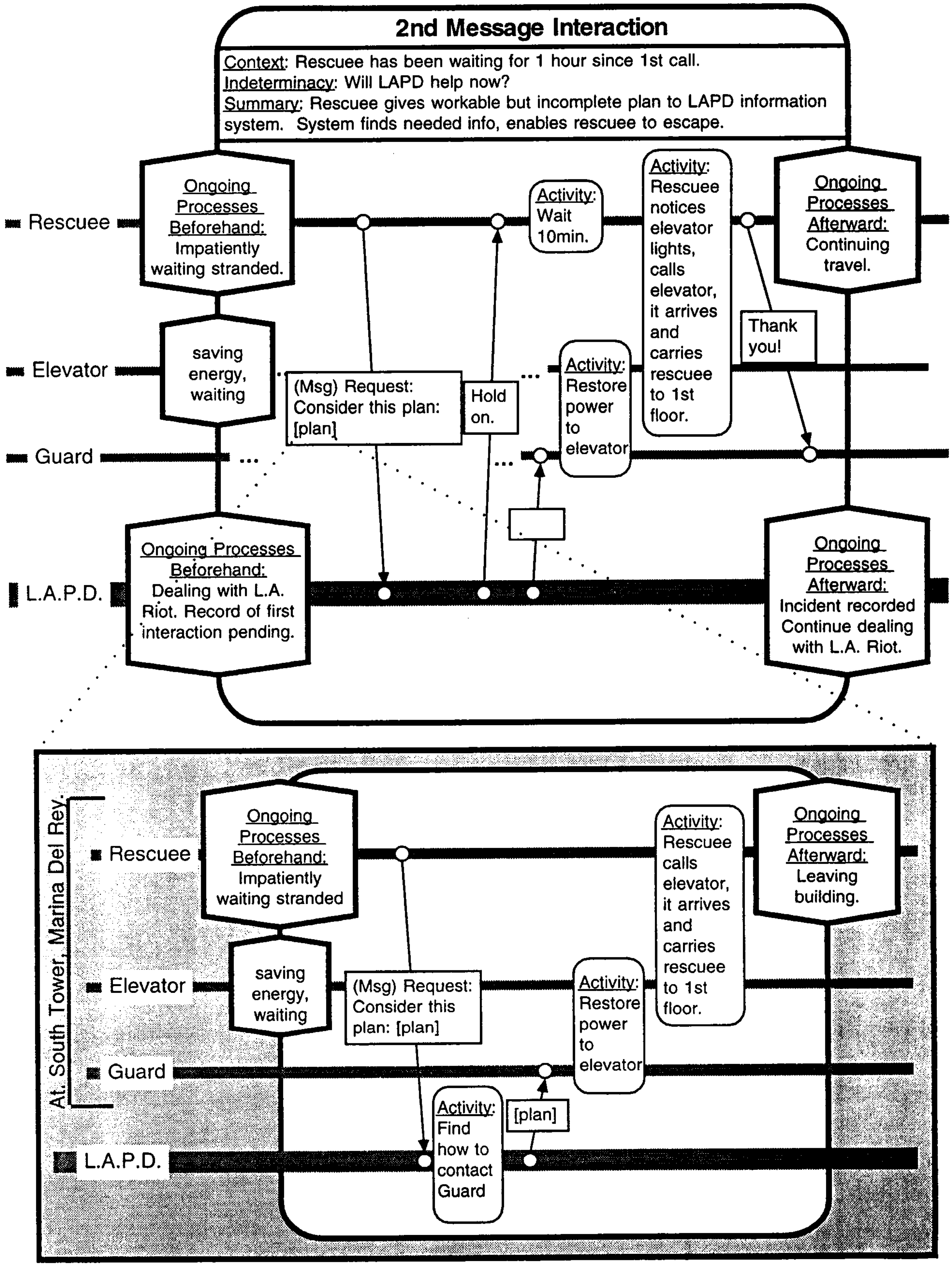


Figure 4: Proposed use of representations in future crisis management information systems (cont).



Thus, people will use not only distributed stationary devices (workstations, servers, etc.), and mobile, relatively location-independent devices and services (notebook computers, cellular phone service, etc.), but also use mobile devices in conjunction with relatively location-dependent services (e.g., high bandwidth infrared communication among meeting members' devices in a room, local wireless communication with nearby shared wall display or printing services, etc.)

Mobile Telecomputing Hardware and Wireless Network Infrastructure are now becoming available. Mobile Distributed Telecomputer Hardware and Networks are here and improving. Small notebook (Powerbook, Thinkpad, etc.), clipboard (EO, Thinkpad, DTR-1, etc.), and notepad (HP100LX, Newton, etc.) computers are here and getting lighter, more powerful, and more useful each year. Low bandwidth digital wireless communications is here in the form of Ram Mobile Data and Ardis cellular networks. Technology continues to develop towards higher bandwidth, smaller cell networks in the Personal Communications Service (PCS) frequencies. Another technology available is diffuse infrared, which currently provides 1Mbit/sec in an office, and will soon provide 10Mbit/sec.

This paradigm shift affects the architecture of distributed workstations as well as mobile platforms. People will use mobile distributed telecomputing to interact with other people and also with applications and services provided by stationary platforms.

This Mobile Distributed Telecomputing paradigm shift both requires and enables a shift in information systems architecture. Trends in shrinking hardware for computing and wireless digital communications are enabling a fundamental paradigm shift for information systems. People will be able to carry mobile telecomputers every where, to provide information systems services in all their activities, especially their interactions with other participants in the field. To provide these information service interactions requires not only communications and mobile computation infrastructure for transferring and storing human understandable text, audio, and video, but also open architectural standards for organizing and managing semi-structured representations of Interactions.

Several important new requirements on information systems architectures which come with this paradigm shift can be characterized as follows:

- *Shared coordination of interactions*: Creating shared representations can be facilitated by tools with which multiple participants may display, point to, modify, and transfer representations. Currently applications, such as project management tools, are largely designed with single users (the project manager) in mind, rather than for active use by multiple participants during negotiations. In the Mobile Distributed Telecomputing paradigm, people at a meeting can interact by displaying, pointing to, modifying, and transferring representations (such as those provided by project management tools). They may interact using a large shared display, or more discreetly through their mobile telecomputers.

  The Mobile Distributed Telecomputing paradigm can provide not only tools for manipulating representations at the focus of a meeting (e.g., using a large shared display), but also can provide tools for participants to discreetly interact with each other and with project members away from the meeting. These additional communication paths can enable participants to keep up to date on ongoing activities and investigate issues which arise during the meeting, allowing them to be resolved at this meeting rather than waiting for the next one (or waiting for a break make contact).

  However, this can lead to second order effects, namely interruption, distraction, or overload. With communication services nearly continually available and with new information potentially arriving at any time, the following problems must be addressed:

  - *interruption*: Notifications are desired during some activities may be unacceptable interruptions during other activities.
  - *distraction*: Messages which are mixed together without regard to topic, importance, or priority can make it difficult to stay focused on an activity.
  - *overload*: Personnel can be inundated with more information than they can make effective use of, diminishing their performance as time and effort are diverted to deal with the flood.

Organizing the communications by the activities which they affect, their priority or urgency, the authority of the people involved, etc., will make it easier to limit interruptions to higher priority messages, stay focused on an activity, and find important information. The participants will have different perspectives on these aspects, so shared representations of communications themselves may need to be negotiated by the participants (or their information systems).

- *Autonomy:* Mobile units may be only intermittently in contact with each other, so mobile units must be able to operate without connections. They cannot be required to be continually accessing remote distributed databases. Personnel away from their home turf should be able to operate using just their own mobile equipment. When responsibilities or tasks are assigned, the relevant organizational modules must be able to be migrated to/from mobile platforms.

  Many implementations of distributed services today assume that clients and servers will continually be connected unless there is a rare failure, in which case the entire service can be temporarily halted. For example, many distributed databases are implemented with a centralized lock server or schema server; if a client becomes unavailable, all its operations in progress are aborted. More generally, mobile users with intermittent connections will need to transfer their ongoing information system activities to their mobile unit and leave, breaking contact with the server. Some current persistent object servers address this issue by enabling systems of objects to be checked out persistently, surviving disconnections and downtime. More generally, systems should be created out of modules which can be migrated and reorganized as needed, so they can be used in changing mobile networks as well as static networks of workstations.

- *Changing location, and thus available bandwidth and latency:* Mobile telecomputers move with their owners, so even when wireless contact isn't complete broken, the bandwidth available can significantly degrade as the units are moved from being plugged into the wired network at the owners' desks, to roaming the halls, neighbors' offices, and conference rooms of the campus/workplace, to visiting collaborators in the metropolitan area, to visiting customer sites across the country and internationally. Systems or parts of systems may need to be migrated and reorganized to provide acceptable service. Addressing must be independent of physical location.

- *Organizational Scalability:* For mobile distributed telecomputing to become a widespread paradigm used in organizations large and small, the architecture must be designed with organizational scalability in mind: it must permit larger systems to be created by composing smaller ones, and it must permit system organizations which match the human organizations.

Part of our challenge in developing a Mobile Distributed Telecomputing Architecture for NII is to address these challenges.

5. A Negotiation Architecture

An architecture identifies components and their relationships, interfaces, and behaviors. A negotiation architecture is the architecture of a negotiation (a discourse influencing future joint activities of the participants).

To deal with the issues and requirements explored above, we are developing an information systems negotiation architecture. Key features of this architecture include:

- Joint Activity Representation services, to enable communication and storage of joint activity representations, among information systems and humans. (discussed above)

- ORGs, to provide organizational modularity for scalability and autonomy.

- Negotiation Forums, to enable multiple organizations to "plug-in" to negotiations.

For instance, these features can be used to create information systems which help crisis management teams handle greater message traffic during a crisis. These information systems can be modularized as ORGs mimicking the organization of each crisis management team. Each organization's information system, communicating with people and equipment in the field and in crisis centers, helps track and manage its activities and resource usage plans (e.g., electrical crews, medical supplies, etc.). Organizations will use Negotiation Forums to route, prioritize, and respond to messages quickly during a crisis, e.g., directing requests for medical attention to nearby services with available appropriate resources. Negotiation Forums enable participants to be added or removed from ongoing negotiations.

ORGs provide for Scalability and Autonomy. Large-scale work requires organization. The 'largeness' of large-scale work means that it must be divided among many resources, which are distributed across space and time, and these divisions must be organized to accomplish the work. For example, to develop and market a new commercial computer, it is not sufficient to find a few good people and immediately set to work. Instead, the product designers must cooperate with the marketing department (which is responsible for developing potential customers) and the manufacturing department (which is responsible for efficiently building the new machines). Each of these is a distinct organization within the larger organization. Each contains both humans and telecomputer systems, and is often organized into smaller suborganizations as well.

Thus, a large distributed organization is not simply a sea of people communicating with each other, but is comprised of organizations and sub-organizations, each with its own (ever-changing) responsibilities and resources for carrying them out. Similarly, scaling up mobile distributed telecomputing services will produce not a sea of objects communicating with each other, but organizations of objects with associated policies, procedures, and resources.

Our architecture will provide ORG services which enable the development and maintenance of *scalable* organizational systems. ORGs encapsulate concurrent processing, storage, and communications resources, allowing subsystems to be migrated as a unit to mobile hosts for *autonomous* operation [Hewitt & Inman 1991].

Negotiation Forums provide "plug-in" capabilities. A key idea in this architecture is the *negotiation forum*. Like a hardware bus, the negotiation forum provides a protocol for participants (like hardware boards) to cooperate using a common communications resource. Unlike early hardware buses (such as the ISA bus of the PC world), the negotiation forum should allow participants to be added easily without knowledge of the internals (e.g., dip switch settings) of the other participants on the forum. Like more recent busses such as the PCMCIA bus, it should automatically perform any reconfiguration needed to enable participants to be plugged in or removed while the system is in operation.

Negotiation Forum participants may agree to negotiate before taking certain actions. A hardware bus enables cooperation by requiring each board to make requests and receive permission before taking any bus action. Participants in negotiation forum may agree to request permission by making proposals and negotiating with other participants before certain actions will be carried out. However, hardware bus protocols manage a simple resource (access to the bus to transfer a short data or signal burst in the immediate future) and thus can get by with protocols composed of a few request, priority, grant, acknowledge, etc., signals. Negotiation forums will be used to manage resources and resource use requirements with much greater complexity, requiring symbolic representations of the participants and resources, and their relationships, constraints, behavior, and interactions.

Negotiation Forums Services. Some common negotiating needs can be met by negotiation forum services. We are investigating services to analyze, evaluate, and learn from negotiation situations including the following:

- Constraint propagation to propagate the consequences of actions and to detect conflicts.
- Case-based reasoning to generate proposals and support claims on the basis of precedents.
- Explanation-based learning and statistical learning to capture and generalize experience.

To process a message, participants propose ways how to prioritize, route, and/or respond to the message, and then share recommendations, preferences, and concerns about each other's proposals, and propose revisions.

Negotiation Forums can refer problematic negotiations to other authorities. If the negotiation peters out or times out without a clear agreement, then the negotiation can be summarized, appealed, or passed on to other authorities (e.g., a human, an information systems service, another Forum, etc.) for more processing.

We will validate the results from our work by using it to provide recommendations and prototype technology to the Massachusetts emergency response organizations.

6. Summary

Negotiation is an important activity in arranging joint activities, particularly those involving multiple organizations. Quickly changing conditions, as during a crisis, mean that joint activity must be negotiated among the organizations involved with knowledge of contemporary activity.

Representations of joint activity are key tools for creating proposals for, communicating, analyzing, and negotiating future joint activities. The ongoing nature and complexity of concurrent large scale organizational activities leads us to an representational approach of relating these ongoing processes rather than trying to reduce them to transitions between states.

Mobile telecomputer hardware technology is available now and improving rapidly. This technology enables Mobile Distributed Telecomputing for NII, a paradigm shift in the interactions between people and information systems technologies.

A key issue is how to create an architecture which provides means for these interactions. Interaction, Mobility, and Scalability introduce several requirements for the architecture which aren't easily addressed by current technology:

- Shared coordination of interactions: Frameworks for developing interfaces for interactive use by negotiating participants, perhaps controlled through their mobile telecomputers, would facilitate the development of applications with shared control.
- Continual accessibility: Information services used in conjunction with other activities, such as negotiations, must be quickly accessible or risk delaying those activities. However, interruption, distraction, and overload can result from being continually accessible to coworkers through the electronic infrastructure. Organizing messages/access according to the importance of the activity it regards is an important way of managing this problem, but determining what is or isn't important *now* can be a challenge.
- Autonomy: services and components must be redesigned and sometimes migrated to the mobile platform to provide services in the face of intermittent connections.
- Changing location, latency, and bandwidth: As people move, the network bandwidth available to them changes. Migration of information can help move components closer to use when availability is critical.
- Organizational scalability: The architecture must enable larger systems to be created from smaller ones through composition, and it must allow these systems to be concurrent and distributed so the performance of processing and other resources can scale with the size of the system.

Negotiation architectures provide opportunities for managing the NII. The NII will create a paradigm shift in electronic communications from mostly voice and FAX to multi-media. During major crises, this shift will worsen the flood of incoming requests to emergency response agencies. Information technology can provide help to manage the flow of messages However, it must be cooperatively managed by multiple organizations involved.

Negotiation architectures will make it possible for participants from different organization to dynamically join and leave negotiation forums. Participants may agree to negotiate with each other before certain actions are taken. Problematic negotiations can be brought to the attention of authorities. Participants may make use of common negotiation services such as the following:

- Constraint propagation to propagate the consequences of actions and to detect conflicts.
- Case-based reasoning to generate proposals and support claims on the basis of precedents.
- Explanation-based learning and statistical learning to capture and generalize experience.

Negotiation architectures have the potential to enable multiple organizations to efficiently, flexibly, and robustly arrange their future joint activities. They have to potential to enable crisis management organizations to efficiently, flexibly, and robustly process conflicting requests from different organizations.

7. Status and Future Work

The work presented in this paper is preliminary and unimplemented, and many of the ideas need to be fleshed out.

In particular, the diagrams shown in this paper rely on English descriptions and the background knowledge they evoke to convey much of their semantics. We will be working to develop process-based[1] machine representations, reflecting a "universe ...[that] won't and can't stand still".

8. Related Work

Research on negotiation has occurred in a variety of settings including: Anthropology, Artificial Intelligence and Law, Business Process Management, Computer-Supported Cooperative Work, Concurrent Engineering and Development, Cooperating Knowledge-Based Systems, Distributed Artificial Intelligence, Economics, Enterprise Integration, Group Decision Support Systems, Intelligent Cooperating Information Systems, International Relations, Parliamentary Procedure, Management Science, Multi-agent Systems, Organizational Science, Sociology (of science and technology), Software Engineering, and Voting Systems.

9. Acknowledgments

This research was sponsored in part by ARPA and monitored by ONR. We thank Kirstie Bellman, Tice DeYoung, Gary Koob, Chris Landauer, Bob Powell, and Andre Van Tilborg for their help and support.

Bibliography

[Adler, Davis, Weihmeyer, and Worrest 1989] Adler, Davis, A. B., Weihmeyer, R., and Worrest, F. W. "Conflict Resolution Strategies for Non-Hierarchical Distributed Agents," in [Gasser and Huhns 1989, p.139–162].

[Agha 1986] Agha, Gul., *Actors: A Model of Concurrent Computation in Distributed Systems*, MIT Press, Cambridge, MA, 1986.

[Agre88] Philip E. Agre. *The Dynamic Structure of Everyday Life.* PhD thesis, Department of Electrical Engineering and Computer Science, MIT, Cambridge, MA, 1988.

[Becker 1960] Becker, Howard S., "Notes on the Concept of Commitment," *American Journal of Sociology*, Vol. 66, July 1960, pp. 32–40.

[Becker86] Howard S. Becker. *Doing Things Together.* University of Chicago Press, Chicago, IL, 1986.

[Bentley54] Arthur F. Bentley. The Human Skin: Philosophy's Last Line of Defense. In Sidney Ratner, editor, *Inquiry into Inquiries*, chapter 10, pages 195–211. Beacon Press, Boston, MA, 1954.

[Bond 1990] Bond, A., "Commitment: A Computational Model for Organizations of Cooperating Intelligent Agents," *Proceedings of the 1990 Conference on Office Information Systems* Cambridge, MA. April 1990.

[Bond and Gasser 1988b] Alan H. Bond and Les Gasser, *Organizational Analysis of Distributed Artificial Intelligence Systems* Computer Research Institute, University of Southern California. Technical Report CRI-88-33. July 1988.

[Bond and Gasser 1988] Bond, Alan H. and Gasser, L. (Editors), *Readings in Distributed Artificial Intelligence*, San Mateo, California: Morgan Kaufmann, 1988.

[Bond88a] Alan H. Bond and Les Gasser. An Analysis of Problems and Research in Distributed Artificial Intelligence. In [Bond and Gasser 1988].

[Buss87] Leo W. Buss. *The Evolution of Individuality.* Princeton University Press, Princeton, NJ, 1987.

[Chapman87] David Chapman and Philip E. Agre. Abstract Reasoning as Emergent from Concrete Activity. In Michael P. Georgeff and Amy L. Lansky, editors, *Reasoning About Actions and Plans: Proceedings of the 1986 Timberline Workshop*, pages 411–424. Morgan Kaufmann, San Mateo, CA, 1987.

[1] in contrast to state-based

[Clarke90] Adele E. Clarke and Elihu M. Gerson. Symbolic Interactionism in Social Studies of Science. In Howard S. Becker and Michael McCall, editors, *Symbolic Interactionism and Cultural Studies.* University of Chicago Press, Chicago, IL, 1990.

[Cohen79] Philip R. Cohen and C. Raymond Perrault. Elements of a Plan-Based Theory of Speech Acts. *Cognitive Science*, 3(3):177–212, 1979.

[Cohen87] Philip R. Cohen and Hector J. Levesque. Intention = Choice + Commitment. In *Proceedings of AAAI-87*, pages 410–415, 1987.

[Collins85] Harry M. Collins. *Changing Order: Replication and Induction in Scientific Practice.* Sage, Beverly Hills, CA, 1985.

[Collins90] Harry M. Collins. *Artificial Experts: Social Knowledge and Intelligent Machines.* MIT Press, Cambridge, MA, 1990. (in press).

[Conklin & Begeman 1989] Jeff Conklin and Michael L. Begeman, "gIBIS: A Hypertext Tool for Exploratory Policy Discussion", *ACM Transactions on Office Information Systems*, Vol. 6, No. 4, October 1988, p.303–331.

[Corkill, Gallagher, & Johnson 1987] Daniel D. Corkill, Kevin Q. Gallagher, and Philip M. Johnson, "Achieving Flexibility, Efficiency and Generality in Blackboard Architectures", in *Proceedings of AAAI-87*, p.18–23; Reprinted in [Bond and Gasser 1988, p541–546]

[Curtis, Kellner, & Over 1992] Bill Curtis, Marc I. Kellner, and Jim Over, "Process Modeling", *CACM*, Vol. 35, No. 9, Sept. 1992, p.75–90.

[Davis 1982] Davis R., "Expert Systems – Where Are We? And Where Do We Go from Here?" in *AAAI Magazine*, Spring 1982.

[Davis83] Randall Davis and Reid G. Smith. Negotiation as a Metaphor for Distributed Problem Solving. *Artificial Intelligence*, 20(1):63–109, 1983.

[Davis, Shrobe, & Szolovits 1993] Randall Davis, Howard Shrobe, and Peter Szolovits, "What Is a Knowledge Representation", *AI Magazine*, 14(1):17–33, Spring 1993.

[Decker89] Keith S. Decker, Edmund H. Durfee, and Victor R. Lesser. "Evaluating Research in Cooperative Distributed Problem Solving". In [Gasser and Huhns 1989, p.487-519].

[Dewey96] John Dewey. The Reflex Arc Concept in Psychology. *Psychological Review*, III:357–370, July 1896.

[de Jong 1991] de Jong, Peter, "A Framework for the Development of Organizations," *Journal of Computational Computing*, February, 1991

[Drexler and Miller 1988] Drexler, K. Eric and Miller, Mark S., "Incentive Engineering for Computational Resource Management," in [Huberman 1988, p.231–266].

[Durfee and Lesser 1989] Edmund H. Durfee and Victor R. Lesser, "Negotiating Task Decomposition and Allocation Using Partial Global Planning," in [Gasser and Huhns 1989, p.229–244].

[Durfee87] Edmund H. Durfee and Victor R. Lesser. Using Partial Global Plans to Coordinate Distributed Problem Solvers. In *Proceedings of IJCAI-87*, pages 875–883, 1987.

[Ferber88] Jacques Ferber and Jean-Pierre Briot. Design of a Concurrent Language for Distributed Artificial Intelligence. Technical Report LITP-88-57-RXF, Laboratoire Informatique, Theorique, et Programmation (LITP), Université Pierre et Marie Curie, 4 Place Jussieu, 75252 Paris, France, 1988.

[Fikes82] Richard E. Fikes. A Commitment-Based Framework for Describing Informal Cooperative Work. *Cognitive Science*, 6(4):331–347, 1982.

[Fisher, Ury, & Patton 1991] Roger Fisher, William Ury, and Bruce Patton, *Getting to Yes: Negotiating agreement without giving in* (2nd ed.), New York: Penguin Books, 1991

[Fox 81] Mark S. Fox. An Organizational View of Distributed Systems. In IEEE Transactions on Systems Man and Cybernetics SMC-11, pages 70–80, January, 1981.

[Fujimura87] Joan H. Fujimura. Constructing Doable Problems in Cancer Research: Articulating Alignment. *Social Studies of Science*, 17:257–293, 1987.

[Garfinkel67] Harold Garfinkel. *Studies in Ethnomethodology.* Prentice-Hall, Englewood Cliffs, NJ, 1967.

[Garfinkel81] Harold Garfinkel, Michael Linch, and Eric Livingston. The Work of a Discovering Science Construed with Materials from the Optically Discovered Pulsar. *Philosophy of the Social Sciences*, 11:131–158, 1981.

[Gasser and Huhns 1989] Gasser, L. and Huhns M.N. (Editors), *Distributed Artificial Intelligence, Volume II* Pitman/Morgan Kaufmann, London, 1989. pp. 229–244.

[Gasser86] Les Gasser. The Integration of Computing and Routine Work. *ACM Transactions on Office Information Systems*, 4(3):205–225, July 1986.

[Gasser89b] Les Gasser, Nicholas F. Rouquette, Randall W. Hill, and Jon Lieb. Representing and Using Organizational Knowledge in DAI Systems. In [Gasser and Huhns 1989, p.55–78].

[Gasser90] Les Gasser and Randall W. Hill. Engineering Coordinated Problem Solvers. In *Annual Reviews of Compuer Science*, volume 4. Annual Reviews, Inc., Palo Alto, CA, 1990.

[Gasser91] Les Gasser. Social Conceptions of Knowledge and Action. *Artificial Intelligence*, 47, January/February, 1991.

[Gasser93] Les Gasser. Social Knowledge and Social Action: Heterogeneity in Practice. In *Proceedings of IJCAI-93*, Cambery, France, August 1993.

[Georgeff87] Michael P. Georgeff. Planning. *Annual Reviews of Computer Science*, 2:359–400, 1987.

[Gerson 1976] Gerson, Elihu M., "On the Quality of Life," *American Sociological Review*, Vol. 41, October 1976, pp. 793–806.

[Gerson and Star 1986] Gerson, E. M. and Star, S. L., "Analyzing Due Process in the Workplace," *ACM Transactions on Office Information Systems*, Vol. 4, No. 3, July 1986, pp. 257–270.

[Gerson77] Elihu M. Gerson. Scientific Work and Social Worlds. *Knowledge*, 4:357–377, 1977.

[Grudin 1994] Jonathan Grudin, "Groupware and Social Dynamics: Eight Challenges for Developers", *CACM*, Vol. 37, No. 1, January 1994, p.93–105

[Hayes-Roth 1987] Hayes-Roth, B., "Blackboard Systems," in *Encyclopedia of Artificial Intelligence, Volume 1* Shapiro, S. C., (Editor in Chief), John Wiley & Sons, 1987. pp. 73-79.

[Hewitt84] Carl E. Hewitt and Peter de Jong. Open Systems. In *On Conceptual Modeling*, pages 147–164. Springer Verlag, New York, 1984.

[Hewitt85] Carl E. Hewitt. The Challenge of Open Systems. *Byte*, 10(4):223–242, April 1985.

[Hewitt86] Carl E. Hewitt. Offices are Open Systems. *ACM Transactions on Office Information Systems*, 4(3):271–287, 1986. Reprinted in [Bond and Gasser 1988, p.321–329] and [Huberman 1988, p.5–23].

[Hewitt 1989] C. Hewitt, "Organizations of Restricted Generality." In *1989 IFIP Congress Proceedings*, IFIP, August 1989, San Francisco, CA.

[Hewitt & Inman 1991] Carl Hewitt and Jeff Inman, "DAI Betwixt and Between: From "Intelligent Agents" to Open Systems Science.", *IEEE Transactions on Systems, Man, and Cybernetics*, Vol. 21, No. 6, November 1991.

[Huberman 1988] Huberman, B. A. (Editor), *The Ecology of Computation*, New York: Elsevier Science Publishers (North Holland), 1988.

[Hudlicka87] Eva Hudlicka and Victor R. Lesser. Modeling and Diagnosing Problem Solving System Behavior. *IEEE Transactions on Systems, Man, and Cybernetics*, SMC-17(3):407–419, May/June 1987.

[Huhns87] Michael N. Huhns, Uttam Mukhopadhyay, Larry M. Stephens, and Ronald D. Bonnell. DAI For Document Retrieval: the MINDS Project. In Michael N. Huhns, editor, *Distributed Artificial Intelligence*, pages 249–284. Pitman Publishing/Morgan Kaufmann Publishers, San Mateo, CA, 1987.

[Jarke, Jelassi, & Shakun 1987] Matthias Jarke, M. Tawfik Jelassi, and Melvin F. Shakun, "MEDIATOR: Towards a negotiation support system", *European Journal of Operational Research*, Vol. 31, p.314–334, North Holland, 1987

[Katz and Rosenschein 1989] M.J. Katz and J.S. Rosenschein, "Plans for Multiple Agents," in [Gasser and Huhns 1989, p.197–228].

[Kersten et al 1991] Gregory E. Kersten, Wojtek Michalski, Stan Szpakowicz, and Zbig Koperczak, "Restructurable Representations of Negotiation", *Management Science*, Vol 37, No. 10, October 1991.

[King90] John Leslie King and Susan Leigh Star. Conceptual Foundation for the Development of Organizational Decision Support Systems. In Jay F. Nunamaker Jr., editor, *Proceedings of the Twenty-Third Annual Hawaii International Conferenc on System Sciences*, volume III, pages 143–151, Los Alamitos, CA, January 1990. IEEE Computer Society Press.

[Kornfeld and Hewitt 1981] Kornfeld, William A. and Carl Hewitt, "The Scientific Community Metaphor," in *IEEE Transactions on Systems, Man, and Cybernetics*, Vol. SMC-11, No. 1, 1981.

[Kuhn 1969] Thomas S. Kuhn, *The Structure of Scientific Revolutions*, Chicago, IL: U. Chicago Press, 1969

[Kuwabara and Lesser 1989] K. Kuwabara and V.R. Lesser, "Extended Protocol for Multistage Negotiations," in [Gasser and Huhns 1989, p.129–162].

[Lander & Lesser 1990] S. Lander & V.R. Lesser, "Conflict Resolution Strategies for Cooperating Expert Agents" *Draft Proceedings of International Working Conference on Cooperating Knowledge-Based Systems* University of Keele, England. Oct 3-5, 1990. pp. 129–162.

[Latour 1987] Bruno Latour, *Science in Action*, Harvard University Press, 1987.

[Latour79] Bruno Latour and Steve Woolgar. *Laboratory Life: The Social Construction of Scientific Facts.* Sage, Beverly Hills, CA, 1979.

[Lave88] Jean Lave. *Cognition in Practice.* Cambridge University Press, New York, 1988.

[Lax & Sebenius 1986] David A. Lax and James K. Sebenius, *Manager as Negotiator: Bargaining for Cooperative and Competitive Gain*, New York: Free Press, 1986

[Lee 1991] Jintae Lee, *A Decision Rationale Management System: Capturing, Reusing, and Managing the Reasons for Decisions*, Phd. Thesis, MIT EECS Dept., Cambridge, MA, September 1991

[Lenat and Guha 1990] Lenat, Douglas B. and Guha, R. V., *Building Large Knowledge-Based Systems* New York, NY: Addison-Wesley, 1990.

[Lesser80] Victor R. Lesser and Lee D. Erman. Distributed Interpretation: A Model and Experiment. *IEEE Transactions on Computers*, C-29(12):1144–1163, December 1980.

[Lesser81] Victor R. Lesser and Daniel D. Corkill. Functionally Accurate, Cooperative Distributed Systems. *IEEE Transactions on Systems, Man and Cybernetics*, SMC-11(1):81–96, January 1981.

[Lesser83] Victor R. Lesser and Daniel D. Corkill. The Distributed Vehicle Monitoring Testbed: A Tool For Investigating Distributed Problem Solving Networks. *AI Magazine*, pages 15–33, Fall 1983.

[Lesser87] Victor R. Lesser and Daniel D. Corkill. Distributed Problem Solving. In Stuart C. Shapiro, editor, *Encyclopedia of Artificial Intelligence*, pages 245–251. John Wiley and Sons, New York, 1987.

[Lesser88] Victor R. Lesser, Jasmina Pavlin, and Edmund H. Durfee. Approximate Processing in Real Time Problem Solving. *AI Magazine*, 9(1):49–61, Spring 1988.

[Levesque, Cohen, and Nunes] Hector J. Levesque, Philip R. Cohen, and Jose H. T. Nunes, "On Acting Together", in *Proceedings of AAAI-90*, p.94–99.

[Maes88] Pattie Maes. Computational Reflection. *The Knowledge Engineering Review*, 3(1):1–19, March 1988.

[Malone87] Thomas W. Malone. Modeling Coordination in Organizations and Markets. *Management Science*, 33(10):1317–1332, 1987.

[Matwin et al 1989] Stan Matwin, Stan Szpakowicz, Zbig Koperczak, Gregory E. Kersten, and Wojtek Michalowski, "NEGOPLAN: An Expert System Shell for Negotiation Support", *IEEE Expert*, Winter 1989, p.50–62

[McCarthy77] John McCarthy. Epistemological Problems of Artificial Intelligence. In *Proceedings of IJCAI-77*, pages 1038–1044, 1977. Reprinted in Ron Brachman and Hector Levesque, eds., *Readings in Knowledge Representation*, Morgan Kaufmann Publishers, 1985, pages 24–30.

[Mead34] George Herbert Mead. *Mind, Self, and Society.* University of Chicago Press, Chicago, IL, 1934.

[Messina 1988] Angelo John Messina, *Negotiation theory and computer models: application in the context of a hypothetical U.S.-Soviet joint venture case*, Master's thesis, MIT Dept. of Management, Cambridge, MA, 1988

[Minsky 1985] Minsky, Marvin, *The Society of Mind*, New York, NY: Simon and Schuster, 1985.

[Newell 1990] Newell, Allen, *Unified Theories of Cognition*, Cambridge, Mass: Harvard University Press, 1990.

[Rein and Ellis 1990] Rein, G.L. and Ellis, C.A., *rIBIS: a real-time group hypertext system* MCC Software Technology Program. Report STP-095-90. March 1990.

[Robert 1876] Henry Martyn Robert, *Robert's Rules of Order*, revised 1970, Glenview, IL: Scott, Foresman, Co., 1970

[Rosenschein85] Jeffrey S. Rosenschein and Michael R. Genesereth. Deals Among Rational Agents. In *Proceedings of IJCAI-85*, pages 91–99, August 1985.

[Sathi, Morton, & Roth 1986] Arvind Sathi, Thomas E. Morton, Steven F. Roth, "Callisto: An Intelligent Project Management System", *AI Magazine*, Winter 1986. Reprinted in *Computer Supported Cooperative Work: a Book of Readings*, Irene Grief, ed. San Mateo: Morgan Kaufman, 1988.

[Sathi89] A. Sathi and M.S. Fox. Constraint-Directed Negotiation of Resource Reallocations. In [Gasser and Huhns 1989, p.163–194].

[Smith and Davis 1981] Smith, R. and Davis, R., "Frameworks for cooperation in distributed problem solving," *IEEE Transactions on Systems, Man, and Cybernetics*, Vol. SMC-11, 1981, pp. 61–70.

[Star 1989] Star, S.L., "The Structure of Ill-Structured Solutions: Boundary Objects and Heterogeneous Distributed Problem Solving," in [Gasser and Huhns 1989, p.37–54]

[Stefik 1986] Stefik, Mark., "The Next Knowledge Medium," in *AI Magazine*, Vol. 7, No. 1, Spring 1986, pp. 34–46. Reprinted in [Huberman 1988, p.315–342].

[Strauss 1978] Strauss, Anselm, *Negotiations*, Jossey-Bass, 1978.

[Strauss 1992] Anselm Strauss, *Continual Permutations of Action*, unpublished manuscript, Dept. of Social and Behavioral Sciences, University of California, San Francisco.

[Suchman87] Lucy Suchman. *Plans and Situated Actions: The Problem of Human-Machine Communication.* Cambridge University Press, New York, 1987.

[Sycara 1987] Ekaterini P. Sycara, *Resolving Adversarial Conflicts: An Approach Integrating Case-Based and Analytic Methods*, GIT-ICS-87/26, (Phd. Thesis), School of Information and Computer Science, Georgia Institute of Technology, 1987.

[Sycara 1990] Katia P. Sycara, "Negotiation Planning: An AI Approach", *European Journal of Operational Research*, v.46 p.216-234, North-Holland, 1990.

[Sycara89] Katia P. Sycara. Multiagent Compromise via Negotiation. In [Gasser and Huhns 1989, p.119–138]

[Weiser 1993] Mark Weiser, "Some Computer Science Issues in Ubiquitous Computing", *CACM*, Vol. 36, no. 7, July 1993

[Werkman and Hillman 1991] Werkman, K. J. and Hillman, D. J., "Designer Fabricator Interpreter System."

[Werner 1989] Eric Werner, "Cooperating Agents: A Unified Theory of Communication and Social Structure," in [Gasser and Huhns 1989, p.3–36]

[Winograd and Flores 1987] Winograd, Terry, and Flores, Fernando, *Understanding Computers and Cognition*, Reading, MA: Addison-Wesley, 1987.