Computer-Supported Cooperative Work

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INTRODUCTION

Few contest the claim that modern information technology, supported by computers and communications, contributes to a dramatic improvement in productivity and effectiveness among individuals engaged in a wide range of tasks. Computer-supported cooperative work (CSCW) aims to provide similar improvements for ''multiple individuals working together in a conscious way in the same production process or in different but related production processes.''[1] If achieved, this aim, which has proven elusive during the relatively few years since the term computer-supported cooperative work was coined in 1984, promises to multiply our productivity, perhaps by more than the square of the number of users, as compared against the productivity improvements that personal computers provide to each of us as individuals.

In this article, we consider various definitions for CSCW and related terms, and we draw outlines around the large scope covered by CSCW. In a companion article (see *Computer-Supported Cooperative Work Challenges*), we consider the main challenges that have impeded us from realizing the great promise of CSCW. In both articles, we specifically survey different ground than Mahling[2] covered in his excellent article on CSCW included in the first edition of this encyclopedia. We refer interested readers to the Mahling article for additional, complementary insights on CSCW.

DEFINITIONS

The term computer-supported cooperative work first appeared in 1984 to identify an interdisciplinary workshop organized by Greif and Cashman at MIT in August of that year for invited researchers to consider how computers might be used more effectively to support people in their various work arrangements. A second, open workshop on CSCW followed in December 1986 attracting 300 people. Since then, an international CSCW workshop has been held every two years, starting in 1988. Because CSCW is such a new area of investigation, one might expect significant controversy and fluidity regarding its definition and focus. Surveys of the CSCW literature support this expectation.

Most observers seem to agree that CSCW, an emergent interdisciplinary field, entails some combination of computing and social science. For example, Greif[3] suggests that CSCW is an interdisciplinary endeavor encompassing artificial intelligence, computer science, psychology, sociology, organizational theory, and anthropology. Similarly, 11 years later, Dourish[4] sees CSCW as a highly diverse discipline involving psychology, sociology, anthropology, network communication, distributed systems, user-interface design, and usability. Beyond agreement on the interdisciplinary nature of CSCW, opinions vary widely about a detailed definition and about an exact focus for the field.

Computer-supported cooperative work researchers seem to adopt one of two main viewpoints. One viewpoint is technology-centric, placing an emphasis on devising ways to design computer technology to better support people working together. For example, Greif[3] defines CSCW as a distinct and identifiable research field focused on the role of the computer in support of group work. A second viewpoint is work-centric, placing an emphasis on understanding work processes with an aim to better design computer systems so as to support group work. For example, Suchman[5] defines CSCW as ''the design of computer-based technologies with explicit concern for the socially organized practices of their intended users.'' Similarly, Bannon and Schmidt[6] believe that ''CSCW should be conceived as an endeavor to understand the nature of cooperative work as a foundation to designing information systems to support the work.'' In a subsequent article, Schmidt and Bannon[7] restate their position and identify several important questions, listed below, which they believe CSCW researchers must answer.

1. What characteristics distinguish cooperative work from individual work, and what support requirements derive from those characteristics?
2. Why do people work together, and how can computers by applied to address the requirements arising from the specific reasons?

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3. How can coordination requirements arising during cooperative work be accomplished more easily using computer technology?
4. What do the identified requirements imply for the development of system architectures and services?

The main emphasis of researchers holding the work-centric viewpoint is to understand cooperative work so as to design computer systems to better support cooperative work. The main emphasis of researchers holding the technology-centric viewpoint is to design computers systems to better support the requirements of cooperative work. Further, as Mahling[2] observes, some social scientists also work in the field of CSCW.

Typically, social scientists working in the field of CSCW aim to describe and analyze the behavior that they see as people work together: focusing purely on description, not prescription. On the other hand, work-centric and technology-centric CSCW researchers aim to create computer systems that address the requirements of cooperative work groups. As such, these researchers hope that the social scientists, through their studies, will prescribe the requirements for successful CSCW systems. To date, this expectation remains unrealized, but much energy has been expended as CSCW researchers work to understand and reconcile these different views. The outlooks suggested by Suchman and by Bannon and Schmidt indicate that some researchers are attempting to work across the gap between description and prescription. In fact, some consensus appears to be building among researchers that CSCW is fundamentally a design-oriented research area. Under this view, the main focus of CSCW should be toward the design of systems that embody a deep understanding of the nature of cooperative work and its forms and practices. As we will outline in a bit, the current scope of cooperative work, in terms of forms and practices, proves so large that the challenge for CSCW researchers may be overwhelming. First, though, we need to provide some explanation about the many confusing terms and concepts surrounding the field of CSCW.

Selected CSCW Terms

Due to its broad scope and relative youth, the field of CSCW encompasses a wide array of specific and sometimes confusing terms. In this section, we introduce and attempt to distinguish between some of the more common terms. People often use *groupware* as a catchy term to refer to CSCW. More specifically, we can think of groupware as computer software and related computer networks that enable collections of people to work cooperatively.[8] Groupware might include application-sharing programs, videoconferencing software, software for tracking document changes, electronic-mail software, and software to support the collaborative viewing of web pages. *Workflow* is another term often used to refer to CSCW.[9] Workflow deals with the specific issues surrounding movement of transactions through a set of people who must act together to complete some required work. In this sense, workflow is a more specific term than groupware; however, workflow software typically supports formal work processes and so is often excluded from the scope of groupware, which is usually considered to be software that supports less formal forms of collaboration. *Team computing*, a term coined at Xerox PARC,[10] refers to collaborative systems to support group meetings. In general, such meetings are envisioned to occur in face-to-face settings. More recently and more conventionally, another term, *electronic meetings*,[11] has been used to describe group meetings enhanced through the use of computers, networks, and software. A less common term, *media spaces*,[12] occasionally appears in discussions of CSCW. The intent of media spaces is to provide a virtual meeting space where distributed collaborators can congregate electronically, meet informally, and gain all the advantages of collaborators who work together within the same physical location.

KEY DIMENSIONS OF CSCW

As indicated in the brief discussion of definitions and selected terms, CSCW involves a broad, multidimensional scope. Here we aim to distinguish some of the important dimensions inherent in CSCW and to clarify the essential features that must be supported by CSCW systems. Table 1 lists 10 key dimensions of the complex design space for CSCW; for each dimension, the table indicates two extreme design points. One important dichotomy facing designers of CSCW technology occurs along the *time* dimension: Is there a requirement to support cooperative work that occurs simultaneously (synchronously) or separately (asynchronously) or both? Another decision relates to *space*: Must the individual collaborators be physically located at the same site, such as a room or an auditorium? Of course, a more complicated requirement might also exist for multiple, physically distant, sites of collocated collaborators to be brought together virtually. A third important dimension is *group size*: Must the system support a small team, a department, an enterprise, or a mass audience? A fourth dimension must consider *interaction style*: Does the group require support for planned or impromptu interactions or both? A fifth dimension covers *context*: Do group members participate in many distinct collaborations or do they tend to participate in only one or a few? A sixth

Table 1 Ten key dimensions in the CSCW design space

Dimension	Extreme design points
Time	Fully simultaneous vs. fully disjoint
Space	All collocated vs. fully distributed participants
Group size	Small team vs. mass audience
Interaction style	Assigned workflow vs. ad hoc
Context	Single vs. unlimited collaborations per participant
Infrastructure	Fully homogeneous vs. fully heterogeneous
Collaborator mobility	All in fixed locations vs. all mobile
Privacy	Assigned by authority vs. controlled by participant
Participant selection	Assigned by authority vs. free for all
Extensibility	None vs. all functionality defined by participants

dimension relates to *infrastructure*: Will the group permit the deployment of homogeneous computing platforms tailored to collaboration, or must the CSCW system operate across already deployed, heterogeneous computing systems? A seventh dimension defines *collaborator mobility*: Will the collaborators remain at fixed locations or will some or all of the collaborators move among locations? An eighth dimension considers the degree of *privacy*: How much information can be made available about the collaborators and who should control the release of information? A ninth dimension considers *participant selection*: Must the group's participants be assigned by existing group members or by some external authority, or can participants self-select or search for additional participants from a larger population? A tenth dimension covers *extensibility*: Does the CSCW system define the complete functionality available to collaborators, or can the collaborators extend the functionality to support changing needs? These ten dimensions provide a rich design space through which the developers of CSCW technology must navigate. Such extreme complexity also presents a great challenge to CSCW researchers. Despite such complexity, CSCW researchers have been able to focus on some essential features that CSCW systems must provide.

Essential Features in CSCW Systems

Much of the CSCW research literature focuses on providing collaborators with tools to support *articulation work*: establishing and evolving organizational structure, plans and schedules, standard operating procedures, and conceptual schemes for classifying and indexing information objects.[7] In other words, CSCW aims to support the overhead that arises when work is conducted among distributed, independent agents. Articulation work includes two important threads: construction and management of a common, shared information space and workflow management. In the past, designers of workflow systems automated written procedures as maintained by each target organization, which in all cases turned out to be a fictional, idealized version of the real work process. Now, CSCW researchers understand that most work situations entail a continuous renegotiation of task descriptions and allocations. Further, researchers understand that collaborative communication must allow for ambiguity in the negotiation processes surrounding articulation work.

To support articulation work, CSCW researchers investigate essential design features in five main areas: communication, configuration, coordination, information access, interaction, and usability. Table 2 indicates some of the specific features encompassed by each of these areas. We discuss these features further below.

Communication

Successful negotiation on issues related to organization, planning, and control requires provision of an effective system for communication among the individuals involved. For this reason, human-to-human communication

Table 2 Five CSCW design areas and some key design features in each

Design area	Key features
Communication	Asynchronous, audio, data, private, shared, structured, synchronous, text, unstructured, video
Configuration	Adaptation, composition, evolution, extension
Coordination	Access control, concurrency, consistency, delegation, scheduling, versioning
Information access	Distribution, filtering, retrieval, structure
Interaction	Attention management, awareness, context management, relationship establishment and maintenance
Usability	Boundary crossing (cyberspace, physical space, logical space), cross-device interaction, cross-mode interaction

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is one of the key features needed for CSCW. Previous research[13] suggests that audio is the most important channel for successful communication. Some CSCW researchers[14,15] have investigated the effectiveness of conference calls, or open-loop multiparty audio channels. Other researchers[16] have shown the value of shared audio channels even when a group of workers is physically collocated. The importance of collaborating around data or documents is also well established. For this reason, a group audio channel is sometimes augmented with a separate distribution channel for sharing views of a document and for highlighting on the document. More sophisticated communication systems integrate audio and data distribution channels together with video channels to compose a form of multimedia conferencing. Whether communicating live (synchronously) or in playback mode (asynchronously), humans can benefit from such multimedia channels.

For live communication, multimedia transmissions often stream data among multiple points in some form of videoconferencing arrangement so that all parties can simultaneously see and hear each other, along with any relevant documents. Satisfactory video viewing usually requires a rate of at least 15 frames per second. Typically, multimedia communication includes an associated audio channel that requires reasonably tight synchronization with the video, within at least 200 milliseconds. These factors place a premium on the quality of service (QoS) provided by the underlying data transmission channels. For this reason, much of the research related to networking for CSCW has investigated techniques to provide the necessary QoS transmission characteristics (see for example Ref. [17]). Currently, the required QoS usually can be arranged by configuring a conference topology to support multiparty communications at the speeds provided by integrated-services digital networks (ISDN), which typically range between 144 Kbps and 1.5 Mbps. Satisfactory multimedia conferencing typically requires two ISDN channels, providing around 300 Kbps total. Unfortunately, most collaborators must use the more ubiquitous Internet, which does not provide built-in mechanisms to request and achieve specific targets for quality of service. For this reason, much of the current network research related to CSCW has focused on establishing quality of service for multiparty transmissions on the Internet (see for example Ref. [18]).

In the absence of either multimedia conferencing support or audio communication channels, successful collaboration can still be conducted through the use of text-based interaction systems, known variously as chat applications or chat rooms. Text-based chat applications can also provide private channels for a subset of collaborators to hold side conversations outside the purview of the main proceedings. As chat applications become more sophisticated, they can also provide a convenient means to distribute documents, data, and images related to a collaborative session. Beyond free-flowing text-based chat applications, CSCW researchers have developed and assessed a number of techniques for enforcing structure on the dialog and interactions associated with a collaborative session. Such systems, which include news groups, dialog-threading applications, and indexed electronic-mail lists, have proven useful in limited ways. Studies have shown that the rather fixed capabilities provided by most of these systems can sometimes impede their effectiveness as a collaboration tool.[19,20]

Configuration

Whether supporting small or large groups, CSCW systems have proven difficult to set up and configure. The scope of such systems is large, covering several layers of system and application software and many points in a distributed topology, both within the network and at network end points. Though relatively few CSCW researchers have chosen to investigate these issues,[21] we suspect that the viability of CSCW systems depends in some large measure on the ease with which collaborative sessions can be established. A number of researchers have investigated the difficult problems associated with: 1) extending the capabilities of CSCW systems after deployment;[22] 2) automating adaptation to changes in available resources for transmission and display of data;[23] 3) composing CSCW systems from a range of supporting components;[24] and 4) evolving system components to suit the changing needs of collaborators.[25,26] Research surrounding the configuration of CSCW systems has not yet received the attention it warrants. Successful adoption of CSCW technology will certainly require an ease of configuration that at least equals and tracks the ease with which desktop computer software can be configured.

Coordination

Much of the communication associated with CSCW is used to coordinate work among the disparate, independent parties engaged in a collaborative endeavor. For this reason, CSCW researchers investigate features and mechanisms to help groups coordinate their activities. A major aspect of group coordination involves scheduling, whether of people, processes, or resources. While some CSCW researchers[27] have investigated techniques to more tightly integrate calendaring software with other aspects of collaboration, such as document distribution, situation awareness, and personnel location tracking, more of the research to date has focused on process or workflow scheduling and coordination. For example, Glance, Pagani, and Pareschi[28] investigated process-structure grammars as a means to introduce flexibility into workflow languages. Such grammars describe the relationships among documents and tasks and use constraints to express soft dependencies rather than the hard dependencies more often introduced with process-flow languages. Similar goals motivate related research by Dourish and his colleagues.[29] Other researchers[30] focus on mechanisms that permit coordination policies to be established and changed as collaboration unfolds. Computer-supported cooperative work researchers should also be interested in techniques for expressing, catching, and handling exceptions during the processing of workflows. The need for such techniques arises because, to date, implementing workflow procedures has proven brittle. Researchers must also take interest in the issues surrounding delegation of authority and work within a workflow. Such techniques are often used by people in day-to-day work but are usually not supported well in automated workflow systems.

Aside from coordinating direct activities among people, CSCW requires mechanisms to coordinate indirect activities as individuals asynchronously access and updated shared documents, files, objects, and other resources. The needed mechanisms include control of access and concurrency and maintenance of versioning and consistency. A number of researchers have investigated concurrency control techniques. For example, Prakash[31] has uncovered a range of concerns that arise when providing concurrency control for concurrent editing applications. These concerns include: 1) ensuring adequate response time for shared edit operations; 2) maintaining consistency of results under simultaneous updates; 3) providing adequate capabilities for a per-user ''Undo'' feature; and 4) ensuring effective awareness of the activities of others engaged in editing the same files. Adopting a formal approach, Ressel and his colleagues[32] use a transformation-oriented scheme to represent and reason about concurrency and ''Undo'' operators, as used within group editors. In a more general look at the relevant issues, Munson[33] and Dewan[34] discuss the larger design space, encompassing a framework for consistency control in synchronous, shared-access applications.

Achieving effective concurrency and consistency control in information-sharing applications requires two underlying foundations: access-control policies and versioning policies. Access-control policies establish the ground rules under which various users may access shared information objects. Versioning policies define the ground rules under which different versions of the same object may be combined into a single, consistent copy. In a typical desktop computer, a small set of standard access-control policies is applied to each directory and file that a user creates. Should the user need to extend access to various groups for particular objects, the access-control policies can become quite difficult to establish, understand, and verify. This is one aspect of the problem that faces designers of access-control policies for CSCW. As discussed by Keith Edwards,[35] another aspect of this difficult problem is that access-control policies must be changeable during run time as the requirements of a collaboration change.

While most access-control policies seek to enforce consistency by limiting access to a single user at once, many collaborative activities, such as joint authoring of documents, proceed more efficiently when multiple users can access the same information simultaneously. In such cases, consistency among independent, concurrent updates becomes a key concern. In an attempt to provide an effective system for co-authoring of documents, Rees and his colleagues[36] describe a mechanism that separates proposed changes to a shared document space from the orthogonal issues of concurrency control and repository management. Specifically, as a collaborator updates a copy of a shared document, the updates are recorded in change proposals that track information the collaborator expects to revise and that record consistency relationships that must be maintained. Once recorded, change proposals can themselves be treated as shared documents. At an appropriate point, multiple versions of shared documents can be combined and residual inconsistencies can be raised for case-by-case consideration. The area of concurrency and consistency control within multiuser distributed systems remains fertile territory for research, whether applied to CSCW or other relevant applications.

Information Access

All collaborations require access to information in two classes: subject-matter information and collaboration-support information. Subject-matter information includes the data, images, video clips, spreadsheets, and web pages that contain content related to the subject being discussed in a collaborative session. Collaboration-support information encompasses overhead data, such as session transcripts (which can include all media types: audio, video, text, images, and interaction events) of previous discussions and agreements about plans, procedures, and schedules for the work. Computer-supported cooperative work requires the ability to structure, retrieve, distribute, filter, and index information in both classes, whatever the media type. Computer-supported cooperative work researchers, as well as researchers in the related fields of information management and digital libraries, work on all of these techniques.

Bush[37] provided one of the earliest discussions of automated structuring and retrieval of information when he outlined the possibility of the memex, an associative memory enabling the retrieval of information encoded on microfilm and permitting people to construct an associative web of trails through the information. The ideas behind Bush's memex foreshadowed several later developments, such as the World Wide Web, publish-subscribe tuple spaces,[38] and globally accessible persistent storage. These later developments (discussed in subsequent sections of this article) seem poised to provide CSCW with a tremendous increase in capabilities to structure and access information. For example, hypertext, a direct descendant of Bush's memex, possesses some significant strengths exploited early on by researchers of Web-based systems for collaboration[39–42] and later adopted in several commercial products, such as Netscape Collabra™, WeMeeting™, eAuditorium™, and TEAMcenter®. Unfortunately, as discussed by Jeff Conklin,[43] hypertext has two significant drawbacks as an information access technique. First, users often experience disorientation while navigating through hypertext, finding it difficult to identify their current place in the information, such as their route to the current page and routes to return to previous pages. Second, users who structure information as hypertext often report a significant cognitive burden associated with creating, naming, and tracking a large number of hyperlinks. For these reasons, information structuring and access remain important research topics.

Information distribution provides one possible alternative to information retrieval. Information distribution aims to automatically promulgate relevant information to people who might be interested. Such capabilities can be very handy for disseminating information in collaborative sessions. In general, information dissemination systems require some means of description, coupled with mechanisms for matching and delivery. Information subscribers must be able to indicate the characteristics of information they would find interesting and producers must be able to indicate the essential characteristics intrinsic to the information that they create. With these characteristics properly expressed, an automated computer program can identify matches between subscriber needs and producer data. Once matches are made, distribution can be carried out through a communication system.

The key issues in information distribution surround description techniques. As discussed by Malone and his colleagues,[44] semistructured messages enable computers to process automatically a much wider range of information than would be possible with free-form text messages alone. In addition, semistructured messages enable people to communicate nonroutine information, which would be impossible within the confines of rigidly structured messages. Malone points out that much of the processing that people already undertake reflects a set of semistructured messages, so even if no automated processing is anticipated, people can benefit from having an available set of semistructured message templates to help them formulate messages that contain all relevant information for particular tasks. Further, by adopting a set of semistructured message templates, automated systems could be adopted and incrementally enhanced more easily over time. Malone and colleagues also illustrate that semistructured message templates can be arranged in a type hierarchy that can then be supported with a consistent set of display-oriented editors to help people construct messages. Semistructured messages seem particularly appropriate for collaborative systems because both computers and people can create, read, interpret, and act on the same messages. Semistructured messages foreshadow the later development of XML (extensible markup language), a means to specify computer-interpretable messages that can also be read by people.

While semistructured messages work well for text data, much of the information associated with collaborative systems exists in the form of image, video, and audio information. Such rich, but unstructured, information presents significant problems with respect to access. The key problems revolve around indexing multimedia information so that people can access it through filters and queries. Some researchers[45] investigate techniques that employ speech-recognition technology to create text transcripts from audio streams. Once an unstructured text database exists, additional technologies can be applied to create multiple indices that identify people, places, dates, and topics included within the data. Using this approach, an audio stream, or repository of audio streams, can be indexed for retrieval or filtering. Some researchers[46] consider audio and video together. Video presents new challenges associated with automatically segmenting video clips into scenes or segments. While the audio indexing techniques can help in this process, other techniques can also be applied. For example, if an audio-video stream comes with an associated closed-caption text stream, then information can be extracted directly using topic and subject identification techniques. Other techniques can be applied directly to the video frames in an attempt to identify scene changes. Further, some researchers[47,48] attempt to look inside video frames to identify objects and to extract text, for example on trucks, buildings, and street signs. While analysis and indexing of multimedia streams is typically tackled off-line, some researchers[49] are attempting to perform a rough level of filtering in real time. The challenging problems surrounding automated indexing of multimedia data continue as targets for active research; however, progress along these lines promises to boost substantially the capabilities of CSCW systems that include video and audio conferencing.

Interaction

Computer-supported cooperative work must include support for people-to-people interaction at a distance: maintaining awareness of the state and activities of others, managing attention and context when a collaborator becomes involved simultaneously in multiple distinct collaborative sessions, and building and maintaining relationships among people who meet infrequently, if ever. These problems might be among the most difficult that CSCW researchers must address. Still, some progress can be discerned.

An important focus of interaction research deals with awareness at a distance. In order to stimulate ad hoc discussions or to coordinate work, collaborators working in distinct locations must maintain some awareness about the availability and progress of others. This can also extend to awareness about the state of collaborators in multiple, distinct collaborative sessions. The issue is further complicated by the fact that people seem averse to allowing others to peek into their personal space or activities. In a sense, there appears to be a fine line between maintaining awareness and allowing unwanted intrusions. Hudson and Smith[50] have considered associated tradeoffs. Several researchers[51,52] investigate video-based techniques that can reduce the problem of intrusiveness, while simultaneously facilitating ad hoc interactions among distributed groups. Nomura and colleagues[53] experiment with techniques to provide peripheral awareness through shared work spaces. Others[54–56] propose mechanisms to provide awareness within the context of application sharing and groupware systems. Some researchers[57] even imagine that desktop computers can be used successfully for impromptu interactions. Taking a less constrained view, Tollmar and colleagues[58] have designed and experimented with several techniques intended to enhance social awareness within the work place. Awareness in CSCW systems remains an important and fertile area for research.

Another difficult challenge for CSCW researchers involves development of techniques to effectively manage the attention of collaborators, especially when individuals may become involved in multiple, but separate, collaborative sessions at the same time. Belotti and Bly[59] examined the problem of context management in an environment where people move among physical locations to engage in various collaborations. Fitzpatrick and her colleagues[60] studied the problem for virtual collaborations; specifically, they investigated the issues that arose as a group of system administrators collaborated remotely with each other and with system users to identify and solve problems with the configuration of computer systems. Results from the study influenced the design of Orbit,[61] a research system to support desktop collaboration where the user engages simultaneously in multiple collaborative contexts. Other researchers attempt to solve the problem of context management through the use of various metaphors, such as ''virtual places'' and ''virtual spaces''[62] and ''team rooms.''[63] Even in a physical work space, many people find it difficult to manage multiple working contexts, as well as to manage their own time and attention. Computer systems bring the possibility for people to engage in many more activities at once. Aiding people to effectively manage these more numerous contexts remains a challenging research issue.

Computer-supported cooperative work researchers must also address a subtler problem: how can people find appropriate collaborators and then build and maintain effective relationships without much physical contact? These issues will become increasingly important as business interactions move more and more to the digital realm, which can reduce the inconvenience, cost, and other inefficiencies associated with physical travel to face-to-face meetings. One typical problem confronting people, even within the same organization, is to find appropriate experts to answer a specific question or problem, or to apply a particular body of knowledge. For this reason, several researchers[64–66] have investigated systems to facilitate finding knowledge and expertise through a social network. Other researchers[67–69] have explored the use of collaborative filtering systems, which do not necessarily include information about the expertise of the participants but which can be applied on a large scale, such as the World Wide Web (the Web). Since the Web encompasses millions of users, some researchers attempt to leverage typical behaviors among Web users to help connect them to possible collaborators without incurring additional cognitive overhead. For example, Payton and colleagues[70] devised a novel way for people to discover potential collaborators based on comparisons among individual patterns of Web browsing, which are typically logged by a computer. After converting logs of Web accesses into graphs associated with each user, a matching program can measure similarities and differences and then bring people into contact through electronic mail. Included within this research are several mechanisms intended to protect individual privacy, a concern that might be raised by potential users when a computer system is applied to passively monitor their activities. Even in some face-to-face situations, such as large conferences or meetings, electronic systems can be used to help stimulate new collaborations. For example, Borovoy and colleagues[71] developed ''meme tags,'' wearable devices with displays that enable conference attendees to electronically share succinct ideas or opinions. Based on the shared information, conference attendees could form into groups with similar interests. Behind the scenes, a server system monitors and collects information about tag exchanges and then reflects the information back to conference attendees in ''community mirrors,'' which are publicly visible displays that present real-time views of the unfolding dynamics within a community. Similar ideas have been used within cyberspace to permit groups of individuals with related interests to form and interact from among millions of undifferentiated participants. Usenet, pioneered in 1979 by Jim Ellis, provides one of the earliest examples.[72] Usenet enables the creation of newsgroups focused on particular topics. Individual users can discover the existence of such groups, subscribe to those of interest, and then participate in asynchronous conversations through threaded, text postings. The more popular newsgroups sustain interactions among hundreds or thousands of users. Newsgroups continued in popularity as tens of millions of users moved onto the Internet during the 1990s. In fact, newsgroups have helped to form the ocean of Internet users into smaller collections of folks with similar interests. From these smaller collections, some individuals form and sustain deeper connections, a human art that can require additional assistance in the digital domain.

Establishing, developing, and maintaining human relationships typically relies on: 1) informal social contact; 2) chance encounters in hallways; 3) chats before and after formal meetings; 4) discovery of shared interests; 5) feelings of community; and 6) implicit knowledge of the state of others.[12] While many of these factors occur naturally among collocated people, some researchers[73] have observed that social responsibility and commitment appear to diminish when people do not meet face to face. For this reason, CSCW researchers often attempt to recreate these relationship-building factors when people must interact at a distance. We have surveyed much of the relevant research already. A few CSCW researchers[74,75] have focused specifically on building relationships with significant depth and trust while working at a distance. Research surrounding these topics will increase in importance as work becomes more reliant on digital interaction at a distance.

Usability

While most CSCW research concerns interaction among humans, some researchers focus on issues related to interaction between humans and computers. Though such research mainly occurs in the context of human-computer interaction, a separate discipline that focuses on the relationship between individual users and their computers, the CSCW research community pays special attention to issues arising from interactions among groups of people who share computer-controlled devices. One subtle problem arises from the need to share viewpoints among distant collaborators. In particular, how can one collaborator ensure that other collaborators are seeing as they are seeing? This question has led to substantial research[56,76,77] aimed at providing a ''what-you-see-is-what-I-see'' capability. Other researchers investigate interaction among groups of people in face-to-face meetings, supported by sets of shared, computer-controlled devices operating within the same room. Perhaps the earliest related research was conducted at the Xerox PARC Colab, where researchers[10] applied computer technology to provide enhanced support for face-to-face meetings. One result from this research was the LiveBoard, which allowed people to interact through a computer system that drove a large-screen display and that also provided network connectivity to other information resources. The LiveBoard became a commercial product, which led to several competing products. Today, such capabilities can be found selectively in meeting rooms around the world, but the capability remains far from ubiquitous.

As computer systems become smaller and, therefore, more embeddable, while also retaining the capability to communicate with other computer systems, the design space for usable collaboration-support systems continues to expand. Mills and Scholtz[78] survey some key opportunities and related research. Here, we focus on two main issues: 1) crossing the human-computer boundary and 2) coordinating interaction across devices and modes.

People working in groups have proven quite productive when exploiting a set of physical aids: whiteboards (or chalkboards) and large paper tablets mounted on easels. Using such aids, small groups of people can create, view, annotate, share, and evolve a visual record of an interactive discussion. While these techniques have proven familiar and effective, they remain solely within the physical (human) domain. For this reason, CSCW researchers have begun to explore ideas that can bridge the techniques people find effective and the unique advantages of the digital world. One set of techniques, reminiscent of the LiveBoard, aims to provide direct, real-time capture of digital information as users create it. Lakin[79] describes one attempt to create a digital medium that can support blackboard-like activity that permits the live manipulation of graphics and text. The aim of this research was to enable people to perform in a digital medium the work that they typically do with whiteboards, paper lists, tape, and tacks in a physical space. Other similar ideas appear in the research literature. For example, Len and colleagues[80] are developing an electronic environment that enables people to sketch the design for a user interface that can be made operational by a computer. Such a technique might prove valuable because it will enable users to easily construct task-specific interfaces, a capability that other researchers[25] have found to be essential to support ad hoc collaborative applications. In another example, Arai and colleagues[81] developed technology that enables people to insert electronic links directly into paper documents. Pursuing a similar strategy, Harrison and colleagues[82] devised electronic staples, which permit bits of electronic information (such as a uniform resource locator, or URL) to be embedded into physical objects; thus, permitting users to obtain information about an object from direct query of the object. Thinking further into the future, Holerer and colleagues[83] investigate augmented reality, the use of wearable computers that can track a user's location and orientation and use that information to superimpose virtual data into a heads-up display to provide information about the physical surroundings.

Several products on the market today also address the boundary crossing between physical and digital worlds. One example is the Cross Pad™, which combines regular paper and a digital pen with automatic capture of digital information. As a user writes on the paper, the pad captures electronic signals representing strokes made with the pen, and stores those signals as digital information. Later, when the user connects the pad to a computer, the digitized notes can be transferred, as bitmaps, to a computer disc. From there, optical-character recognition can translate the bitmaps into searchable and editable text documents. The natural writing board (NWB) provides another example. Using ultrasonic and infrared sensors, coupled to algorithms for signal processing, filtering, and positioning, the NWB captures marks and sketches drawn on a whiteboard with a standard, dry-erase Expo™ marker and digitally transfers the data into electronic format. Because it can be used with any whiteboard found in conference rooms and offices, the NWB holds some potential for ubiquitous adoption. Another example can be seen in the products, such as electronic signage and publishing with paper, under development at E Ink. The linking thread in these products is the use of flexible, reusable displays populated with a grid of dots that each encapsulates an electrophoretic ink technology developed by researchers at Massachusetts Institute of Technology.[84] The resulting outcome is a black-and-white display, resembling a sheet of paper, which can be electronically altered to display specific content.

While the future appears bright for technologies that aim to cross the boundary between physical and digital worlds, widespread success for such technologies will increase the need to address problems that arise when multiple users can collaborate across many devices with various interaction modes. These problems become even more difficult under two circumstances: 1) when distributed groups collaborate through computer-mediated devices that have differing capabilities, such as desktop computers versus personal digital assistances and 2) when collaborators can move among various devices during a collaborative session. Some researchers are already looking into a few of the issues. For example, researchers at Rutgers[85] have integrated into a single desktop interface a range of multimodal technologies, including gaze and gesture tracking, voice recognition, and speech synthesis, along with the more typical display, mouse, and keyboard. Success in such research will permit gestures, and maybe eventually even facial expressions, to be used as interaction modes. Other researchers aim to enable a room[86] or building[87] to become an enveloping user interface that can track people and resources within physical spaces and adapt the form and location of information presentation to suit the physical circumstances. To fully realize the possibilities for multidevice and multimodal interaction, human-computer interfaces will have to be redesigned to separate the logical intent of an interaction event from its physical manifestation. Such redesign suggests a fertile area for further research.

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