Task Knowledge Structures and the Design of Collaborative Systems

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Psychological Theory and System Design

In HCI research and development, we remain faced by the long-standing problem (see Barnard 1991; Newell and Card 1985) that the development of a theoretical science base has lagged behind more intuitive systems design. Cognitive psychology had an important early influence on HCI, providing a strong theoretical base on which to draw. In recent years, HCI has expanded its focus on groups of users using computers to support collaborative work. This more recent research has drawn more widely on social and cognitive psychology and on disciplines such as anthropology. However, the relationship between the theoretical models of these disciplines and the practice of HCI design is not straightforward. As the scope of HCI has expanded from its earlier areas of strength in the cognitive tradition, the development of a solid, unifying theoretical base has not kept pace.

Barnard (1991) adapted from Long (1989) a framework which portrays the relationships between a theoretical science base and 'real world' systems design. Barnard describes 'bridging representations' between the real world and the theoretical scientific representation of the way in which the real world behaves. Bridging representations are required in both directions between scientific theory and the world. More or less formal analysis of the world leads to a 'discovery representation' which simplifies the world according to the researcher's purposes. Scientific theory is then developed based on the discovery representations. Applied science then requires an 'application representation' to serve as a bridge between theory and the application domain.

The bridging representations always serve a particular purpose and their form depends upon this purpose. Representations used in developing basic theory differ from representations used in designing computer systems or other artefacts. The bridging representation in design is the product of a transformation of information in the science base. In turn, the information in the bridging representation must be synthesized into the problem space of the application domain. Thus, 'the direct theory-based product of an applied science paradigm operating in HCI is not an interface design. It is an application representation capable of providing principled support for reasoning about designs' (Barnard 1991, p.123).

Effective theory based design also depends on the adequacy of the underlying theory as a model of 'some aspect of the real world that is relevant to the specific artifact under development' (Barnard 1991, p.109). This too has been a problem for the development of theory driven design in HCI because of the lack of generalisability of many of the theoretical claims of its underlying disciplines.

Groupware, as software to support collaborative group working has come to be called, has been prolifically produced over the past decade without much in the way of theoretically based models of group activity to support design. There is nevertheless a tradition of designing systems, including collaborative systems, with direct bases in theory. Moreover, there have been examples in which the use of a theoretical model to guide system design has resulted in inflexible and ultimately unusable systems. For example, Winograd and Flores' (1986) design of Coordinator was heavily based upon speech act theory (Searle 1969) and had many criticisms for the way it constrained and forced group communication to occur.

In the case of Coordinator and speech act theory it would be wrong to conclude that theory based design does not work, or that the theory in question was a poor theory. The mistake that occurred was a failure to recognise that a theory of communication and language use is not an applied theory for the design or evaluation of computer systems. It fails to recognise that the problem domain of computer system design and evaluation is not the same as linguistics. Consequently, what may be a perfectly sound linguistic theory fails to be an applied linguistic theory for HCI. It fails because the scope of phenomena it was originally meant to explain is not the same as that to which it is being applied. Also, it fails because it does not take account of how to apply the constructs, assumptions and predictive base of the original theory in design and evaluation such that the designers and evaluators know how to interpret and make sense of the theory relative to human computer interaction and computer mediated group work.

In recent years, the work of Clark and colleagues (see Clark 1992) has begun to have an influence on research into the design of human-computer interaction and computer-mediated human interaction. Clark has presented an extensive body of theory on human communication and collaborative activities and its influence has ranged from use as a direct basis for design to a basis for bridging representations.

Barr and Keysar (1998), for example, claim that Clark's work provides one possible 'theory of the [computer] user'. It does not. Rather, Clark's work provides one possible theory of natural language use in human-human interaction. Barr and Keysar (1998) note that some claims of Clark's common ground model have weak empirical support. They argue that empirical testing of these claims 'might suggest a quite distinct "theory of the user" from that proposed by the collaborative model' of Clark and colleagues. However, as argued by Barnard (1991), basic theory construction and refinement is a separate issue from the derivation of bridging representations which allow basic theory to feed into design. The adequacy of Clark's model as an explanatory theory of language use is a separate problem from its suitability as a model for human-computer interaction.

Traum (1998) argues that Clark and Schaefer's (1987) model of contributions is inadequate as a model for the design of human-computer collaboration. He notes that this was never a task for which the model was intended by its authors and suggests that it can nevertheless be 'very useful in helping designers develop suitable design models'. Traum (1998) suggests that 'reasoning about the principles involved in Clark's work, such as the grounding criterion, degree of grounding and methods of increasing the degree of grounding will allow more natural and fluent interactions' between human and computer. Here, Traum (1998) seems to be proposing the development of bridging representations from common ground theory to the world of HCI design.

Design without theory and models is at best intuitive and experience based and does not result in a discipline of HCI that can pass on a reasoned and causal understanding of what leads to good design and good usability. On the other hand, the lack of applicable theoretical models to support the design and evaluation of groupware has not prevented systems being produced and some of these may well be highly usable, effective and efficient systems. That is not the point. The point is to know what makes a system good or bad, what causal explanation can be given as to why one design idea works and another one does not. Without such understanding, design knowledge and the discipline of HCI cannot be established, communicated or developed. Furthermore, designers will have a poor basis for predicting the usability and quality of their designs, and good HCI will be achieved only by *post hoc* evaluations of design ideas to find out if they are good or bad.

Task Knowledge Structures

In previous research (Johnson and Johnson 1991; Johnson, Johnson, and Wilson 1995; Hamilton, Johnson, and Johnson 1998), we have developed a theory of Task Knowledge Structures (TKS) for the purpose of understanding and explaining the structure of human task activity. From this applied theory of tasks we developed a model based approach to user interaction design (ADEPT) and demonstrated how the TKS models of human activity could be used to inform design.

In summary, TKS encompasses: roles (within and between tasks); task goal structures and task procedures (procedural dependencies); declarative knowledge (taxonomic substructures). TKS models actual and required knowledge and has been applied to complex and creative tasks. It includes a methodology for gathering, analysing and modelling tasks, and applying task knowledge to design (see Johnson 1992). TKS has fed into the ADEPT model based design environment to model existing task knowledge and user interface designs and has been used as a basis for formal modelling of interaction using LOTOS process algebra (Markopoulos, Johnson, and Rowson 1998).

More recently, following from the theoretical work, we have been able to formulate four principles of design that have a theoretical explanatory basis, provide predictive guidance to designers and have been empirically shown to produce increased usability. These principles represent a bridging structure between the psychological theory of TKS and HCI design practice. Again in summary form, these principles are:

- Taxonomic Structure. Objects that are the same or similar will be conceptually grouped together, and actions on the same or similar objects will be carried out together.
- Procedural Dependency. Actions which are causally related to each other through a task goal structure will be conceptually grouped together.
- Conformance. User interfaces which conform to the user's conceptual grouping will be easier to use.
- Transformation. Transforming a conceptual grouping to accommodate changes in the level or structure of concepts is cognitively expensive.

We do not propose to expound these principles here since our objective in this short paper is to begin to address the extension of TKS to collaborative work. However, it is worth noting that these four principles have direct implications for the design of all classes of systems.

The scope and form of the original TKS theory was limited to individual users carrying out tasks by themselves. While it accommodated a role perspective on work it did not consider how people work together to perform group tasks or how individual and group tasks interact. To extend this theoretical basis we must consider the nature of group tasks and of collaboration and the interaction between group tasks and individual tasks. Moreover, we approach this with the motivation and for the purpose of informing the design and evaluation of computer supported collaborative work.

Extending TKS Theory and Principles to Collaborative Group Work

In developing an HCI account of collaborative work that can contribute to the design and evaluation of collaborative systems we must be able to understand the structure of group work and how such human activity can be affected by computer technologies. In an attempt to model collaborative group work for HCI design, we have proposed the following group task modelling framework:

Group goals; purpose of group activity, responsibilities of group, focus of common ground.

Individual goals; purpose of individual activity, responsibilities of individuals, individuals' contributions to common ground.

Group objects; artefacts available to the group, properties, relations, states, content of common ground.

Individual objects; artefacts available to the individual, properties, relations, states, excluded from common ground.

Group processes; actions available to the group, procedural relations, effects, content of common ground.

Individual processes; actions available to the individual, procedural relations, effects, excluded from common ground.

In considering the nature of collaborative group work, three important activities need to be understood, not as separate activities but as synthesised acts. These activities can be thought of as tasks in so far as they require cognitive, social and external resources and are purposeful. The three forms of activity that are synthesised in collaborative group work are group tasks, individual tasks and the additional tasks required to achieve collaboration.

For example, consider what may go on when a team of doctors and nurses performs an operation in a neurosurgical operating theatre. Together, the group works at a common goal such as removing a tumour from a patient's brain. Each member of the team will carry out various acts, some in coordination with other members of the team and others on their own. Some of these acts will be part of the team activity and some not. For instance, the consultant surgeon may be accessing and removing the tumour. The anaesthetist may be involved in monitoring the patient's body state and life support system while the surgery is in progress. At times, the surgeon and the anaesthetist may be working completely independently on tasks that form part of the group activity but do not *per se* require any overt collaboration. At other times, the surgeon may, for example, require the anaesthetist to alter the body state of the patient (e.g. the oxygen level) in concert with a particular part of her removing the tumour. Thus, there are various forms of group and individual task structures involved and in addition there are collaboration tasks, as for example how the surgeon signals to the anaesthetist that she wants him to alter the oxygen level.

With this model of group work, we can begin to evaluate collaborative work systems in terms of the resource costs. The amount of effort expended and resources required to perform the individual and group tasks may vary. In addition, the collaboration tasks require effort and resources above and beyond those of the individual and group tasks.

A primary goal of collaboration tasks is grounding, i.e. the maintenance of common ground (Clark 1996). Clark and Brennan (1991) argue that the techniques used for grounding vary with the purpose of the interaction and with the communication medium. The differing constraints imposed by different media incur different costs of grounding. Clark and Brennan (1991) describe formulation and production costs paid by the speaker, reception and understanding costs paid by the addressee and several other costs paid by both. Clark and Brennan (1991) claim that preferences for different communicative media may be explained in terms of the grounding costs imposed by the media for the communicants' particular purpose.

In recent work involving the application of computer technologies to support group work (as part of the EPSRC-funded MUSHROOM project) we have been studying how nurses, general practitioners (GPs) and consultants work together in the management of diabetes. Interaction and group work amongst the medics and patient are extended over space and time and occur through meetings, postal communcation, phone calls and through sharing common data and information.

Diabetes Patient Scenario. Cath is a chronic diabetes patient with recently developed eye problems. She visits her local diabetes clinic for a regular check-up, data are collected, checks made and notes taken. Cath is referred to a GP. Cath visits the GP with her friend, data are collected, checks made, notes consulted and taken. Cath is referred to a consultant. She visits the consultant, notes are consulted, checks made, Cath is referred to an eye specialist, notes are made, the GP is informed.

We can begin to think of the task costs involved in these activities, such as:

- the effort involved in co-ordination of the group processes; for example, the effort involved in the nurse flagging significant items to the GP and consultant;
- the effort involved in individual processes; for example, the effort involved in transformation of data from the patient's home-kept record to the nurses' clinic-kept record sheet;
- the effort involved in maintaining common ground between the GP and the nurse and between the GP and the consultant; for example, the GP reading through the notes to build up an understanding of the current situation.

We have found that there are problems in performing the collaborative group work that can be attributed to the collaboration tasks and the resources they require at a given time either being too great, not available or inadequately supported. Here are some examples of those problems found.

The GP may miss flagged items from the shared patient record. For example, on one occasion the GP missed important flagged eye information and consequently had to re-establish this from the patient. This resulted in a duplication of effort.

The information may be incomplete. For example, the notes did not contain details of a letter. This resulted in extra effort on the part of the GP to find out that the nurse had issued a letter.

The shared information can require effort on the part of the consultant to interpret and explain current results in the context of the patient's medical history. For example, finding trends in the patient's weight control was difficult because of the format of the data presentation.

The costs of the various tasks (group, individual and collaboration) are all incurred in performing the activity and most be borne by the members of the team. In developing the collaborative task modelling framework in terms of costs and resources in computer supported group work, we must consider both task resources and group-computer interaction resources. Task resources include the knowledge, both procedural and declarative, that the individual and the group as a whole need to carry out the tasks in which they are engaged.

In contrast, the group-computer interaction resources can be thought of in terms of the above plus the declarative and procedural resources that the computer system needs in order to support the group activity. Hence, we have a basis for designing and evaluating collaborative systems supporting collaborative group work in terms of resource costs. These resource costs are incurred in the efforts required to achieve group and individual goals through the interactions which constitute group procedures, individual procedures, group computational processes and individual computational processes, and in the consumption and use of group objects, individual objects, group data and individual data in those processes.

In order to account for collaborative work, the theoretical basis of TKS needs to be extended to consider group, individual and collaboration tasks. In addition, if the underlying theory is to have a use in HCI design, we must also extend the bridging structures represented by the HCI principles derived from TKS theory. Bridging representations need to be developed which reflect that (i) collaborative work requires grounding as a necessary overhead, (ii) common ground is derived from taxonomic and procedural knowledge of individuals in the group and from the context in which the collaboration occurs, and (iii) resources are expended in establishing the required levels of common ground amongst the group members relative to the tasks they are performing jointly, and in performing transformations of individual knowledge and information to shared knowledge. The work outlined above has begun these twin processes of extending both theory and design principles.

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