Beyond The Knowledge Level

Mark S. Fox

Intelligent Systems Laboratory
Robotics Institute
Carnegie Mellon University
Pittsburgh, Pennsylvania 15213

1. Introduction

This paper extends the stratification of computer systems introduced by Bell and Newell (1971) and Newell (1981) to include an additional level called the *Organization Level.* The organization level provides a means of describing the competence of a distributed system without reference to the underlying structures. In the following, the *Knowledge Level* is described, followed by a discussion of its limitations in modeling distributed systems. Finally, the organization level is proposed as an answer to these limitations.

2. The Knowledge Level

Allen Newell, in his presidential address to the American Association of Artificial Intelligence, proposed the existence of a *knowledge level* as being a distinct, separate, and above the *symbol level* (Newell, 1981). Part of the motivation for this proposal was the vagueness of the term knowledge coupled with its ubiquitous use.

> The term representation is used clearly (almost technically) in AI and computer science. In contrast, the term *knowledge* is used informally, despite its prevalence in such phrases as *knowledge engineering* and *knowledge sources.* It seems mostly a way of referring to whatever it is that a representation has. (Newell, 1981, p. 2)

In proposing this stratification, his intent was to answer the following questions:

- What is the nature of knowledge?
- How is it related to representation?
- What is it that a system has, when it has knowledge?

Central to the understanding of what knowledge is, is that knowledge has two components, an explicit part which can be tied directly to a representation and an implicit part which is derived using some method of inference.

An important property of this stratification was the separation of *what* from *how.* That is, the knowledge level is an investigation of competence rather than representational structure.

> The Knowledge Level permits predicting and understanding behavior without having an operational model of the processing that is actually being done by the agent. (Newell, 1981, p. 11)

A level is composed of a "*medium* that is to be processed, *components* that provide primitive processing, *laws of composition* that permit components to be assembled into *systems*, and *laws of behavior* that determine how system behavior depends on the component behavior and the structure of the system." (Newell, 1981, p. 5).

The components of the knowledge level are:

Expert Database Systems: Larry Kerschberg, Editor.

System: Agent
Components: Goals, Actions, Bodies
Medium: Knowledge
Composition Law: None
Behavioral Law: Principle of Rationality

The behavior of an agent is teleological; it constructs a plan which achieves one or more goals. The process of how to plan its actions is constrained by the Principle of Rationality:

> If an agent has knowledge that one of its actions will lead to one of its goals, then the agent will select that action. (Newell, 1981, P. 8)

Newell describes refinements to the principle, but the result is still somewhat vague.

The utility of the knowledge level is demonstrated by Brachman and Levesque's (1986) analysis of the relationship between a database and a knowledge base. It has been argued that there exists an intrinsic difference between knowledge and data (Wiederhold, 1984). But an analysis from the knowledge level perspective demonstrates that a database is a limited form of a knowledge base. The limitations being that database facts do not contain negation, disjunction, nor existential quantification. Consequently, "inference reduces to calculation" when the database is viewed as a closed world. Knowledge bases tend to incorporate fewer assumptions, at least not the closed world assumption, while provided a richer semantics for describing ambiguity (i.e., disjunction). This analysis is directly due to their use of logic to describe a database's competence at the knowledge level.

Dietterich (1986) explores the issues of knowledge acquisition by using the knowledge level to categorize learning into two types: symbol level learning which does not result in additional knowledge, and nondeductive knowledge level learning which does. In some cases the latter's behavior cannot be predicted at the knowledge level.

3. Limitations of the Knowledge Level

Three "real" knowledge based systems were examined to identify their database requirements (Fox & McDermott, 1986):

- R1: computer configuration (McDermott, 1982; Bachant & McDermott, 1984),
- ISIS: job-shop scheduling (Fox, 1983; Fox & Smith, 1984; Smith et al., 1986), and
- Callisto: engineering project management (Sathi et al., 1985; 1986).

The following capabilities were found to be necessary for their production use:

1. access to one or more databases by a single knowledge based system,
2. one or more knowledge based systems accessing the same database, and
3. multiple knowledge based systems cooperating to solve a single problem.

In the Callisto system, the need for a group problem solving type of organization was most apparent. Issues of synchronization of access, security of information, incompleteness of knowledge, and inconsistency in knowledge among agents became an important consideration. At the knowledge level each member of the group could be modeled as an agent. But in Newell's description of the knowledge level, a system is composed of a *single* agent. Problems which require distribution, i.e., more than one

agent, cannot be modeled[1].

It is precisely these issues raised by the distribution of problem solving that have been addressed in the database literature. Multiple access to a single database has led techniques for handling synchronization and security at the symbol level. In the case of distributed databases, updating techniques, including version management[2], are being explored which maintain some level of *consistency* and *completeness.*

The knowledge level does not provide an adequate foundation on which to study the competence of distributed systems because its focus is on the single agent.

4. The Organizational Level

The intent of the organization level is to enable the study of the problem-solving competence of multi-agent systems, without reference to the underlying implementation. Issues concerning the problem solving competence of multi-agent systems include:

- The impact of knowledge partitioning.
- The impact of incomplete and inconsistent knowledge.
- The relationship between the number of agents and problem solving competence.
- The impact of conflicting goals.
- The impact of resource contention.

The study of such systems is not unique to AI but has been the focus of a number of fields, including: Organization theory, Organization behavior, Economics, and Sociology. Some of this literature is also concerned with competence independent of equivalent knowledge and symbol level models, providing a fertile ground from which to draw concepts. The following draws upon this literature to provide a basis for defining the organization level.

What is competence at the organization level? Perhaps it is the efficiency with which goals are accomplished. This is highlighted in the premises of Contingency Theory (Galbraith, 1973):

1. There is no best way to organize.
2. All ways of organizing are not equally effective

These premises recognize that it is not just "whether" a goal can be satisfied, but how efficient the process of satisfaction is.

Organizational research has focused on the determinants of organizational competence. Early research focused on two parts: 1) the structure which determines communication paths and, 2) the control regime which defines authority hierarchies and rules of behavior. A variety of structures have been investigated, including:

- Groups,
- Simple and uniform hierarchies,
- Multi-divisional hierarchies, and

[1]One could use a single agent to simulate multiple agents, but this would defeat the purpose.

[2]The issue of version management has also been a concern in AI (Katz et al., 1986; Sathi et al., 1986)

- Markets.

Structures are defined by *contracts* between an agent and an organization, or between organizations. In the former, they are also called *employment relations.* Part of an employment relation is the specification of behavior under varying conditions, in essence, stimulus-response pairs or rules.

Within these structures various behaviors are found. For example, groups are very good at adapting to changing market conditions. In hierarchies, *trained incapacity* (Merton, 1949) describes the rigid behavior which may arise when responses successfully applied in earlier situations are no longer valid, but still applied. The rigidity of contracts in the market place limit the ease with which an organization may adapt to changing market demands. Small numbers is a market condition where the number of market participants is small, circumventing the marginal pricing behavior of competition. Contracting under a small number condition may result in opportunistic behavior due to participant's lack of competitive pressure. The importance of these classifications is to identify both structure and information related conditions which will result in sub-optimal performance of the components and the system.

Organizations are dynamic, continualy moving from one structure to another. Two broad measures have evolved as a way of explaining why certain organization structures are required. *Uncertainty* is defined as the difference between information available and the information necessary to make the best decision. Different organization structures result from diverse attempts in reducing uncertainty. In addition to uncertainty in information, uncertainty may arise in predicting the behavior the environment and the behavior of organization participants.

Complexity is the second measure. It is defined as excessive demands on rationality. That is, task requirements exceed current bounds on the processing capabilities of the individual or organization.

Both of these measures are general, supporting a descriptive, almost anecdotal theory of organization structure. The evolution of organization structure based on changes of uncertainty and complexity is summarized in figure ORGSTRUC[3].

A more detailed analysis of organizational competence can be found in the transactional analysis of the firm (Williamson, 1975). Transactions take on a rather broad definition. They encompass normal contractual agreements, communication of information, monitoring, delegation and control, and most other activities that require interaction among agents within an organization or market. The handling of transactions requires the consumption of resources. Hence transactions are too complex when they require more resources than are available; complexity reduction becomes the problem of minimizing resource consumption.

Transactions can also be characterized by the assumed differences in information, motivation, and behavior amongst the parties of the transaction. *Information impactedness* is a differential of information between parties of a transaction. Impactedness may be due to bounded rationality considerations because of the amount of information, unavailability of information due to one party's inability to communicate, or an agents deliberate hiding of information. Impactedness would be of little concern if the

[3]Fox (1979; 1981) provides a more detailed review of organization structures and how uncertainty and complexity affect movement between them.

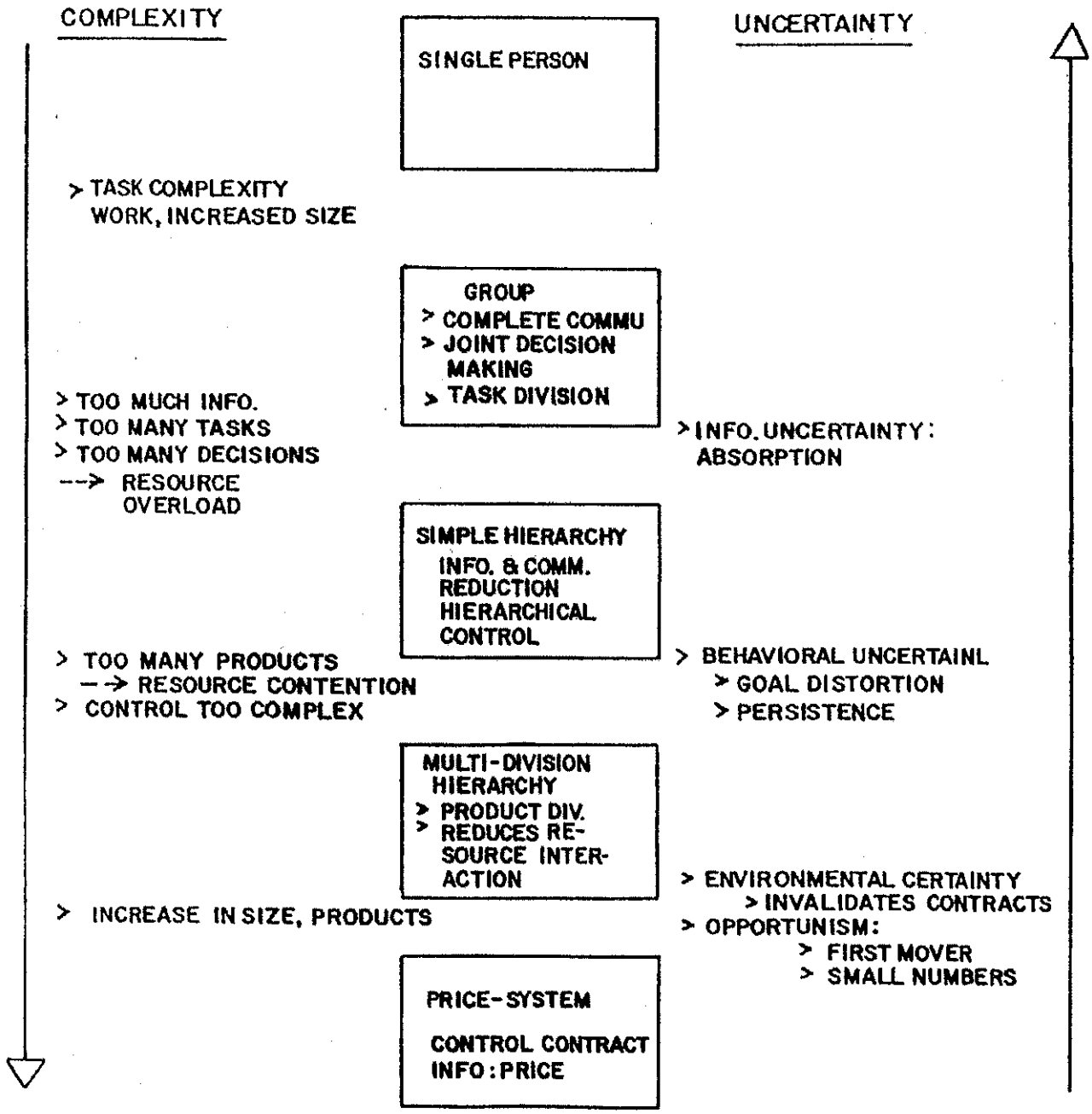

Figure 4-1: Organization Structure Continuum

cost of achieving parity was not prohibitive in most cases. Information impactedness is a recurring condition for opportunistic behavior. To the extent that this is important for the systems we wish to study at the organization level, the semantics of these assumptions would have to be elaborated and used in the measurement of alternative organizational structures.

Transaction analysis also focuses on uncertainty in transactions as a cause of organizational change. Uncertainty may arise in both information and behavior. As uncertainty increases, the transition from a heterarchy to a hierarchy becomes preferable.

The study of organizations provides insights which further distinguish the organization level from the knowledge level:

- At the knowledge level, the structure of the system is unimportant, whereas at the organization level, structure has been found to be a major factor in problem solving competence.
- At the knowledge level, functional performance is the concern, relegating time and space based performance to the symbol level. At the organization level, time based performance, at least, is an issue because it becomes a major determinant of organization structure.
- At the knowledge level, an agent must conform to the principle of rationality. At the organization level, though an agent may internally follow the principle of rationality, the class of behavior it exhibits (e.g., opportunism) is important.
- At the knowledge level there does not exist a law of composition. At the organization level, the relationships between agents (i.e., contracts) and protocols of communication and negotiation are important.

Based upon the above discussion, the aspects of the organization level are defined to be:

System: Organization
Components: Agents
Medium: Transactions
Laws of Composition: Contracts
Laws of Behavior: *Many*
Competence Measures: Cost: Time to achieve a goal, Number of Agents, Number of Transactions

The system at the organization level is defined to be an *organization.* The components of a system are either agents or other organizations. Hence, abstraction is basic to the definition. While it would appear that an organization composed of a single agent is reducible to an agent at the knowledge level, they differ in the attributes to be measured. Agents could also be specialized. For example, one could distinguish between agents which provide retrieval of information only (i.e., a simple database), versus agents which make decisions[4] The selection of types will depend on the performance measures.

The medium to be processed is a *transaction.* A transaction is a quantization of knowledge which can be studied independently or in relation to other transactions.

The law of composition is defined to be a *contract.* Any agent or organization may enter into a contract with another. A contract guarantees the response behavior of an agent to a defined set of stimuli. The

[4]In the Organization Design Language (ODL) such a distinction was made (Fox, 1979).

resulting behavior is more efficient. An agent's contractual relationship with an organization could be in the form of an employment relation or a consulting relation. Rules of behavior for an agent may differ accordingly.

At the organization level there may exist more than one law of behavior. For example, computer systems may display a law similar to that of a team rationality. On the other hand, it has been posed that a market style of interaction may arise given the intent of each agent to maximize their own goals.

Lastly, we introduce possible measures of competence. As mentioned earlier, goals may be accomplished with more than one organization structure. What distinguishes between them are the costs involved. Indirect measures of these costs include: time to achieve a goal, number of transactions to achieve it, and the number of agents involved.

These aspects of the organization level provide a model for multi-agent systems. As such, the model is incomplete. Progress in organizational research has depended upon the development of richer models, similarily progress in the study of the competence of multi-agent systems will depend upon the development of a richer semantics and set of measures.

5. Conclusion

An examination of database requirements for knowledge based systems has given rise to the need for a richer model of knowledge based systems not provided by the Knowledge Level. In particular, the need to study competence of distributed systems has given rise to the organization level. The definition of the organization level has been descriptive, being based on classical work in organization theory and economics. It is clear that while at the knowledge level the efficiency and structure of an agent is unimportant, the efficiency and structure of an organization is very important. Never the less, at this level of description, many questions have been left unanswered:

- What types of contracts, transactions, and goals are there?
- Are there other measures of competence and structure?
- What is the direct relationship between structure and competence?
- What is the relationship between contracts at the organization level and goals at the knowledge level?

Ultimately, one would hope that the organization level would support a normative analysis. Examples in this direction include the application of economic theory of teams (Marschak & Radner, 1972) to the analysis of group problem solving. In particular, the network model of organizations which is an outgrowth of team decision theory has been used to measure the increased certainty of results in a multi-agent systems (Fox, 1979, Chapter 4).

Computational models have been developed to described multi-agent systems: Actors (Yonezawa & Hewitt), ODL (Fox, 1979), and PCL (Lesser et al., 1979), and their modes of interaction: (Davis & Smith, 1983), (Georgeff, 1983), (Corkill & Lesser, 1983) and (Rosenschein & Genesereth, 1985). As with the knowledge level, logic may be the appropriate tool for analysis at the organization level.

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7. References

Bachant, J. and J. McDermott, (1984). "R1 revisited: four years in the trenches". *AI Magazine*, Vol. 5, No. 3.

Bell C.G., and A. Newell, (1971), *Computer Structures: Readings and Examples*, New York: McGraw-Hill Book Co.

Brachman R.J., and H.J. Levesque, (1986), "What Makes Knowledge Base Knowledgeable? A View of Databases from the Knowledge Level", *Expert Database Systems: Proceedings From the First International Workshop*, pp. 69-78, Menlo Park, CA: The Benjamin/Cummings Pub. Co. Inc.

Corkill D.D., and V.R. Lesser, (1983), "The Use of Meta-Level Control for Coordination in a Distributed Problem-Solving Network", *Proceedings of the International Joint Conference on Artificial Intelligence*, Karlsruhe, West Germany, pp. 748-756.

Davis R., and R.G. Smith, (1983), "Negotiation as a Metaphor for Distributed Problem Solving", *Artificial Intelligence*, Vol. 20, pp. 63-109.

Dietterich T.G., (1986), "Learning at the Knowledge Level", *Machine Learning*, Vol 1., pp. 287-316.

Fox M., and S. Smith, (1984), "ISIS: A Knowledge-Based System for Factory Scheduling", *International Journal of Expert Systems*, Vol. 1, No. 1.

Fox M.S. and J. McDermott, (1986), "The Role of Databases in Knowledge Based Systems", *On Knowledge Base Management Systems: Integrating Artificial Intelligence and Database Technologies*, M.L. Brodie & J. Mylopoulos (Eds), New York: Spring-Verlag.

Galbraith Jay, (1973), *Designing Complex Organizations*, Addison-Wesley.

Georgeff M., (1983), "Communication and Interaction in Multi-Agent Planning", *Proceedings of the American Association For Aritificial Intelligence.*

Katz R.H., M. Anwarrudin, and E. Chang, (1986), "Organizing a Design Database Across Time", *On Knowledge Base Management Systems: Integrating Artificial Intelligence and Database Technologies*, M.L. Brodie & J. Mylopoulos (Eds), New York: Spring-Verlag.

Lesser et al., (1979) "PCL", in Working Papers in Distributed Computation I, Computer and Information Science Dept., University of Massachusetts, Amherst MA.

March J.G., and H.A. Simon, with H. Guetzkow, (1958), *Organizations*, New York: John Wiley and Sons.

Marschak J. and R. Radner, (1972), *Economic Theory of Teams*, Yale University Press.

McDermott, J. (1982), "R1: A Rule-based Configurer of Computer Systems", Artificial Intelligence, Vol. 19, No. 1.

Merton R.K., (1949), *Social Theory and Social Structure*, Glencoe, Ill: The Free Press.

Newell A., (1981), "The Knowledge Level", *AI Magazine*, Vol. 2, No. 2.

Sathi A., M.S. Fox, M. Greenberg, (1985), "Representation of Activity Knowledge for Project Management", *IEEE Transactions on Pattern Analysis and Machine Intelligence*, Vol. PAMI-7, No. 5, September, 1985, pp. 531- 552. Also appeared as Technical Report CMU-RI-TR-85-17, Robotics Institute, Carnegie-Mellon University.

Sathi, A., T.E. Morton, and S. Roth, (1986), "Callisto: An Intelligent Project Management System", *AI*

Magazine, Winter 1986, pp. 34-52.

Smith S., M.S. Fox, and P.S. Ow, (1986), "Constructing and Maintaining Detailed Production Plans: Investigations into the Development of Knowledge-Based Factory Scheduling Systems", *AI Magazine*, Fall 1986, pp. 45-61.

Wiederhold G., (1984), "Knowledge and Database Management", *IEEE Software*, January 1984, pp. 63-73.

Williamson O.E, (1975), *Markets and Hiearchies: A Transactional and Antitrust Analysis of the Firm*, New York NY: The Free Press.

Yonezawa A., and C. Hewitt, (1977), "Modelling Distributed Systems", AI Memo 428, Massechusetts Institute of Technology, Cambridge MA.