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The Role of Games and Cognitive Models in the Understanding of Complex Dynamic Systems

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Computers are being applied to increasingly complex real time monitoring and control tasks. What is the best way to develop this type of computer application? This paper argues that the development of games can reveal a great deal about the complexity of the application, its users and the circumstances in which it will be operated. The development of a game plays a similar role to the development of a prototype or simulation in identifying the most critical factors pertinent to a design. However, developing a game often focuses more attention on the user, his tasks, strategies and learning. Cognitive modelling techniques are especially relevant to understanding the user and contribute to the development of games and to understanding the very nature of complexity.

1. INTRODUCTION

With generally increasing levels of technological sophistication, the world contains more and more real time monitoring and control tasks. Examples include the control of power stations, chemical and manufacturing processes, traffic control (air, ship, train and road) , dealing in financial markets, defence systems, resource management, crowd control, communications, and organisational management. These tasks are highly interactive requiring the human operative to make many small interventions to keep their systems in efficient, predictable and safe states. Inevitably, computers are now used in a wide variety of these applications to provide the human operator with information and to allow him/her to make interventions within tight constraints of time, economy and safety.

What are the appropriate methods for building computer systems for these challenging applications ? Clearly the range of techniques applicable to the development of traditional batch data processing applications are quite inadequate. For example, moving from requirements specification, to design specification and building, in a linear sequence of activities with little planned feedback, cannot hope to deal with the complexity of predicting how the design of a system may predispose the operator to making particular (perhaps inaccurate or unsafe) interpretations of what is going on in a highly complex and changing system. New techniques are required for developing appropriate systems for these applications.

This paper considers the role of games and cognitive modelling techniques as a contribution to new development methods for designing computer-based real time monitoring and control system. It is argued that games provide a useful way of understanding complex dynamic systems. The developer of the game, the player of the game and the analyst of game playing behaviour can all benefit.

In order to be useful a technique must also be cost effective. The paper argues that games are a cost effective method because they allow a high fidelity modelling of critical aspects of the real situation they are mimicking. This leads to games providing a higher quality end product than alternative methods. By carefully selecting which aspects of a situation to include in a game, and the degree of fidelity required, the costs can be minimised for a given level of quality of results.

Cognitive modelling techniques have a significant role to play in determining which factors are critical and what degree of fidelity is required. There are a wide range of techniques for modelling users of complex systems. These range from models of human sensory/motor performance, through cognitive to social and environmental models. Within this range different models focus on different aspects of human performance. Some provide general explanatory frameworks, some describe human processes while others focus on human error. The paper gives examples of some of these techniques.

Complexity itself can only be understood as a function of the mechanism of human cognition. Complexity is as much a function of the person perceiving it, as it is of the situation or system itself. The development of computer systems in relation to real time monitoring and control tasks must, therefore, include techniques which focus on the user in the entire human-computer system.

2. DEFINITIONS

A game is understood to be some more or less formally defined system with which a person interacts but where the consequences of their actions do not impact on the real world. Games can be abstract (e.g. Chess) or they can attempt to simulate some aspect of the real world. In the second case, the game plays the role of the real world while the player plays the role that he/she would normally play in relation to the real world situation that the game depicts. However, a game is more than a domain model. It includes a specification of the way in which players may interact with it and a specification of the state that the player is trying to achieve or maintain.

It is not the intention to distinguish in detail between the terms 'game', 'simulation' and 'prototype'. With prototypes the emphasis is on the design of the artifact with which a person will interact. With games the emphasis shifts to include the human element ; the player, his performance and skill development. The term 'simulation' seems relatively neutral in this respect. Much of what is said about games applies equally to simulations and prototypes so the definition can be taken quite broadly.

Complex dynamic systems are systems which comprise a number of inter-relating variables that change over time. They are complex if it is difficult for a person to understand the relationships between the variables or keep track of their progress over time. Complexity is a property of the interaction between the person, the task and the view that the system presents of itself, not just a property of the system.

Cognitive modelling techniques are more or less formal theories about how people learn and make decisions. They are usually descriptive or predictive techniques rather than normative techniques designed to guide how people should learn or decide.

3. DEVELOPING GAMES

Several requirement must be met in order to model a complex dynamic system. The method used must be sufficiently precise that the model is not open to interpretation. It must be able to deal with change over time. It must be testable and it must model those characteristics of the system that are essential in being able to predict its behaviour. The last of these implies that, where appropriate, it must take into account the whole system including the human element. Games provide the driving force for the development of models that meet these requirements in a way that other methods do not.

A narrative description of a complex system (such as a written specification), for example, will often fail because it lacks sufficient formality. The meanings of the terms used in the descriptions are not tightly defined and can shift in response to challenges about the accuracy of the model. Although narrative descriptions can provide coverage of a wide range of potentially important variables their lack of precise semantics means that they are essentially untestable. Also, much of the complexity of systems arises from the way in which variables interact over time. Once again, the informality of narrative descriptions leaves the precise nature of these interactions largely undefined.

Given these deficiencies it is tempting to jump to the other extreme of using very rigourous and precise mathematical or logical descriptions. However, many formal approaches to modelling cannot be used for all aspects of the description because they lack expressive power. For example, they may not be able to cope adequately with the description of change over time. Systems with very few variables often display dynamic behaviour of such complexity that they defy description using currently available formalisms. The effects of variables feeding back on each other may results in sudden changes to the global state of a system which look chaotic from the perspective of many formal techniques. Also, although formal models may be useful in describing deterministic aspects of the behaviour of complex systems, they provide little help in the description of the relatively unpredictable components, such as the human element.

The requirement is for some half way house between free form narrative descriptions which provide breadth but little precision, and rigourous formal approaches which provide precision but lack expressive power. Developing a game may provide that half-way house.

Even a simple game can involve variables which interact over time in a combinatorially explosive fashion such that it is not possible to describe all possible legal paths through it. While the dynamic behaviour of the game may defy complete formal description the rules by which the complexity unfolds can be described sufficiently formally to provide a model which is both executable and testable. When more formal techniques fail, a games approach encourages the development of an executable model which can be studied in a more empirical manner in order to reveal its behavioural characteristics.

Games are just one type of executable model offering the benefits of formality and testability. Any executable simulation of a complex dynamic system has these features. However, in contrast with other approaches the notion of developing a game also encourages the modelling of the interaction between players and the essential domain variables. It is necessary to distinguish between these essential domain variables and the view that a player has of them at any particular time. The rules of a game normally include a reasonably precise and explicit statement of the ways in which players may interact with and influence the essential variables.

Developing a game requires modelling the complexity of real world systems such that a player of the game believes it to be an accurate depiction of the essential features of the world. For this to happen the game must respond to the players interactions with it in a way that is either expected or can be justified as the way in which the world would actually behave. The player acts as a test of the fidelity of the model. If the player cannot be convinced the fidelity of the model is in question.

Stammers [1] lists several dimensions of fidelity. These include display / control relationships and feedback, task complexity, temporal aspects, environmental factors, and situational payoffs. In the main these dimensions are not concerned with the underlying complexity of the systems that are being modelled. Rather they are to do with the way in which the systems are represented to the player, and social / environmental factors.

The domain model represents the complex interactions of variables in the real world but does not pre-suppose a particular view. There may be many possible and partial views that a person may have of the domain model. Building one deep model of the domain facilitates the development of several partial views which are consistent even though they may not immediately appear to be when comparing then. The game developer must not only achieve fidelity in the domain model but must also achieve it in the view of the model that a player sees. He must consider exactly how the player will interact with the domain. In the real world information may arrive through a variety of communication channels (electronically, on paper, over the

phone, from conversation with someone in the same room etc.) and over different sensory channels (e.g. visual and auditory). Similarly, actions resulting from decision making may be executed over a variety of channels. The player's conceptual model of the overall state of the system may be critically dependent on his partial view of particular system states. Designing systems to ensure fidelity in this area is difficult. Work on the integration of formal techniques for system modelling and techniques for cognitive modelling in the design of interactive systems is working towards improved methods (Barnard and Harrison [2]).

There are many complex dynamic systems that evolve in ways that people do not anticipate, and this is more likely if the player has only a partial view of the domain model. It is possible that a player will question the underlying model rather than question his/her own ability to make sensible decisions and anticipate their outcomes. The evaluation of a game by players is not, therefore, a sufficient basis on which to make changes to the underlying domain model. In addition it may be necessary to test the game against reality. A game depicting a historical incident can be tested to see whether it is possible, within the rules, to reconstruct the way in which the real situation did unfold over time.

The use of the most effective development techniques involves borrowing from the experience of other game developers and avoiding the pitfalls they have already encountered. Huxham et al [3], for example, emphasize the need to base game development on an understanding of the processes of human decision making and being sure to include subjective accounts of decision making when collecting data for analysis. However, there are dangers in placing too much emphasis of verbal accounts (Berry and Broadbent [4]). Bainbridge [5] warns against the dangers of extrapolating about performance from one task to another and proposes a set of dimensions for the definition of complex dynamic tasks. Klein [6] examines the dimensions along which reality can be abstracted in a game and notes that anything more than trivial abstraction in the dimension concerned with the player's subjective model will alter the meaning of the model to the extent that it will not be understood.

In summary, games constitute testable theories about complex situations. Developing a game helps the understanding of a complex dynamic system because it encourages the design of a formal and testable model of the essential characteristics of the system including its human elements. The model is formal because it is necessary to specify precisely how the game will operate under the envisaged circumstances that may arise. It is testable because playing the game or comparing its operation against real situations will reveal ways in which the model is incorrect or needs refinement. Testing will tend to weed out the non-essential aspects in favour of only those important variables and relationships that give the game appropriate fidelity.

4. PLAYING GAMES

While developing games enables the developer to understand complex dynamic systems, playing games enables the player in a similar way. Through contact with the game the player is expected to become aware of the variables involves, their interactions and the way in which their own behaviour effects how the games develops.

Another possible method of instruction would be to present the variables, their interactions and the underlying essential model in the manner of a textbook or lecture. There are two broad arguments as to why actually interacting with the model in a game is better that simply studying it in abstract form. These are :

1. Textbooks and lectures miss out many of the essential aspects of the model
2. Transfer of learning / training is poorer from textbook / lecture material to the real situation than it is from game playing to the real situation.

Both these arguments concern the relationship between the learning / training situation and execution of the real task. The elements missing from the abstract model presented in a textbook or lecture include a failure to represent the dynamic aspects of the essential model in detail, a failure to represent the way in which the user of the model (the trainee) can influence the state of the variables, a failure to provide an environment in which the model can be explored by the trainee experimentally (for example, to test the sensitivity of variable values to other model parameters), a failure to convey information about frequency (of events and situations), and a failure to involve the trainee in the learning process adequately. These arguments also apply to much of the learning material presented in traditional computer based training and hypertext systems.

Whether or not transfer of learning / training is better as a result of interacting with a game than being presented with an abstract textbook account is a question open to empirical investigation. However, there are also a priori theoretical arguments which suggest that game playing may be more effective. The 'Encoding Specificity Principle' (Tulving [7]), for example, predicts that a memory is more likely to be retrieved the closer the match between the context of retrieval and the context of learning.

In summary, it is argued that playing games is a training method that leads more readily to improved performance in the real situation than other training methods. This is because games have closer fidelity to the real task than do other methods, and there are a priori theoretical grounds in the form of psychological models of learning and memory, to suggest that increased fidelity should lead to better transfer.

5. ANALYSING GAME PLAYING BEHAVIOUR

The analysis of game playing behaviour can help in understanding both aspects to do with modelling the real world and aspects to do with the player or human operative engaged in the real world task.

The first of these concerns how analysis can lead to greater insights about the essential domain model that underlies the game and the way in which the player is given a view of the model. Simply logging information about the way in which particular runs of the game progress can give an indication

about the validity of the domain model. This can lead to changes in the game's design at the level of the domain model or at the level of the way information about states of the domain model are presented to the player(s). Many analytic techniques can be used including formal mathematical or logical analysis of information logged during runs of the game and semi-formal / informal gathering and analysis of data about the users subjective reactions to the game. All such data can contribute to improving the fidelity with which the game represents the real world situation.

Better understanding of the domain model is not only relevant to improving the game. It may actually lead to better performance in the real world. The analysis of the game may reveal misconceptions about the operation of the domain model which lead to a revised understanding about how the world operates. For example, it may be revealed that in an apparently complex situation there are, in fact, only two variables that matter at all. Analysis of games data allows these types of hypotheses to emerge so that they can be investigated in greater depth.

The player or human operative adds to the complexity of dynamic situations and needs to be studied both as part of the whole system and separately from any particular system so that the results can be generalized. Much of the benefit of analysis concerns gaining a better understanding of the human element and it is expected that understanding the player of the game will help in understanding the human operator in the real situation. There are several questions that need to be addressed. These include :

1. How do people generally make decisions and cope with complexity ?
2. How does the surface representation of the underlying dynamics of a situation effect peoples understanding of it ?
3. How do people generally learn to behave in relation to complex dynamic systems ?
4. What is the variability between individuals on these dimensions ?
5. To what extent are outcomes (in a game or in a real situation) influenced by the properties of the situation itself and to what extent can it be influenced by the human participant ?
6. To what extent is it possible to predict performance in the real situation from performance in a game (what is the validity and reliability of games as an approach to understanding real complex dynamic systems) ?

These are some of the research questions which the analysis of games playing data should aim to address. They are also some of the most important questions because the human element can have a large impact in the way a complex dynamic system develops and other techniques of analysis do not touch on them.

For the detailed analysis of the player of a game there are more sophisticated techniques than arbitrary data logging. For example, it is possible to incorporate within a game an Embedded User Model (EUM - Rivers [8]). An EUM is a description of a user of a computer application. The description takes the form of computer code and can be maintained by a computer program during the course of a users interaction with a computer based application. The EUM is the computer's model of the user. This model may be generic (of users in general), stereotypical (relating to particular classes of users) or individual (relating to one particular user). An individualized user model can be updated in real time during the course of a game playing session. It can be inspected at various points in time in order to monitor changes in the user's behaviour or the system's beliefs about the user's changing state of knowledge. The method by which the computer updates its model of the user is crucial because it is not neutral (as exhaustive data logging might be). It constitutes a theory about how the user is changing and needs to be developed and guided by an advanced understanding of cognitive modelling techniques. EUMs are not restricted to monitoring. A computer program may change its output depending upon the state of the user model and thereby adapt to changes in the user. In a game playing situation, for example, an EUM could keep track of an individuals skill development and adapt the difficulty of the game accordingly.

6. COGNITIVE MODELLING TECHNIQUES

The human element in a complex dynamic system can have a great effect on the way in which it develops over time. People differ in their ability to interpret and control complex dynamic systems and within an individual this ability changes over time. The same underlying system is easy or difficult to interpret and control largely as a function of the way it is represented, and the same underlying system represented in the same way may be interpreted and controlled differently as a result of various social and environmental circumstances.

Dixon [9] presents anecdotal evidence about how errors due to factors like boredom and stress have lead to a whole catalogue of train, plane and other transport disasters. He has also looked at the way these same factors have lead to a series of military disasters through-out history (Dixon [10]). In addition, there is experimental evidence. It has been known for some time that the way in which information is presented can be critical to task performance. A task presented as an abstract problem cannot be solved but becomes tractable when presented in a concrete situation (Wason and Johnson-Laird [11]).

There are a large number of models of human error. Kahneman et al. [12] identify many different biases that creep into human judgement and decision making. One specific example is the anchoring bias which may lead two decision makers who have been presented with exactly the same information but in different orders, to assess the same situation completely differently. There are also some process models of human error that have been implemented as computer programs. Sleeman [13] describes a computational model of error in terms of 'perturbations' to decision making rules which result in 'mal-rules'.

There are theories concerned with describing human understanding and decision making, with respect to complex systems, in terms of mental models (Johnson-

Laird [14], Gentner and Stevens [15]). These are important because they view the individual decision maker as an active agent who is trying to make sense of the environment or some system in terms of his own mental representation. Norman [16] gives a useful common sense accounts of how psychological theory can be applied to design and describes how many very ordinary designs are totally unusable because human factors issues are neglected.

How can cognitive models and theories be of use in building better games? The requirement is that they should give the game designer an orientation to the type of factors to consider and the type of systems that will meet the requirement. Specific theories should help in the detailed design of features in the system. Cognitive models should help answer questions such as : what is appropriate fidelity?, how do people learn to deal with complex dynamic situations?, and what should be studied in order to understand more about the complex dynamic systems and the people using them?

However, there are problems with the application of science to design. Scientific accounts are often too restricted to apply to the real issues. Theories often only account for some small aspect of human behaviour and, at worst, this behaviour may only exhibit itself within some restricted laboratory setting. Theories may not, therefore, have scope or relevance. Even when they do, it may be difficult to trace how a good theory should or can be translated into a specific design. An account of some of the problems of applying cognitive theories to the design of systems and artifacts is given by Barnard [17].

General theories of cognition not only help to understand design but also implicitly influence design (Carroll and Campbell [18]) and an inadequate cognitive theory may influence design for the worse. For example, early theories of human decision making were based on the theory of subjective utility. This theory assumed that a decision maker knew all his options in advance and could accurately evaluate the implications of selecting each one. Several decision support systems have been built based on this normative model. However, it is inappropriate for many decision making tasks and totally inadequate for real time monitoring and control tasks where decisions have to be made with limited information and under time and cognitive resource constraints (what Simon [19] calls 'bounded rationality').

There are now more sophisticated general models of human cognition which imply quite different designs for learning and decision support systems, and computer interfaces to real time monitoring and control tasks. Two leading candidates which have resulted in implemented computer models are SOAR (Laird et al [20]) and ACT (Anderson [21]). SOAR gives insight into how decisions are made with limited cognitive constraints and also provides a theory for explaining how many small learned tasks are chunked into higher level units. ACT attempts to account for how appropriate information is available to a decision maker within limited working memory, in terms of a theory of spreading activation around a network of related concepts. Both SOAR and ACT can be considered as both process and architectural theories. Their computer implementations aid the formulation of precise predications about what is going on in cognition and the resulting performance on some task. At the same time they both propose quite general mechanisms for cognitive processes that might operate across a wide range of cognitive tasks.

What is a complex system and how can complexity be measured? The world would be a much more straightforward place if it were possible to assess the complexity of a system independently of the way in which people perceive and understand it. A naive view is that it is possible to measure complexity by performing objective counts of such matters as the number of variables involved in a system and the extent of interactions between variables. However, it is clear from the large amount of psychological evidence available that such a method will not work. Quite independently of whether a game is being developed, played or analysed cognitive modelling has a fundamental role to play in the understanding of complexity. Some theories of cognitive complexity are now sufficiently well developed that they have resulted in computational approaches to the measurement of complexity (e.g. Kieras and Polson [22]).

These examples illustrate how theories of cognition tend to shape the way artifacts, including games, are designed. Different theories have different implications for design and using the best and most appropriate theories can make significant differences to the design and the way in which studies of human learning and behaviour should be analysed and interpreted. These theories provide some support along the spectrum from cold analytic decision making through to 'hot cognition' in complex dynamic real time tasks. Without these theories of cognition to guide design at an early stage the developer risks making many expensive mistakes.

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