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## Definitive specification of concurrent systems

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### Abstract

A new approach to the modelling and simulation of concurrent systems, characterised by the use of sets of definitions to represent states and transitions, is described. The simulation of system behaviour is derived from a specification of possible agent actions by taking account of relative speeds of response and operation. A distinctive feature of the approach is that the perceptions and capabilities of agents are explicitly modelled.

### 1. Introduction

As distributed computing systems become ever more sophisticated, the complexity of their design continues to increase [12]. In response to this trend, many different methods for specifying and analysing concurrent systems have been proposed [9]. Broadly speaking, two perspectives can be adopted when modelling a concurrent system: the one "event-oriented" (in which the emphasis is upon describing the abstract behaviour of the system as a whole), the other "activity-oriented" (where the objective is to describe the interactions between component parts of the system) [15]. Both of these approaches are now well-developed [2,20] and can provide valuable support in important aspects of design. Neither, however, provides a complete picture.

In the systematic development of concurrent systems software, there is in general an important need to bring both views to bear. Ideally we would like to reason about the abstract behaviour of a system and at the same time describe precisely how system components relate to each other.

This paper considers how these views might be combined. The central principle behind our approach is that the behaviour of a complex system is typically first conceived by the designer in terms of the actions that agents can perform. To characterise the system behaviour, the designer must specify the privileges of agents in a framework that enables the consequences of actions to be faithfully represented. The relationship between an action and its consequences may be very complex. By way of illustration, entitling an agent to open a door may be an open-ended privilege to change the state of the system, depending upon the context in which the action is performed. It may be an entitlement to move - in a single atomic action that incorporates opening the door - any

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piece of furniture that is adjacent to the door. To maintain conceptual control over the design it is essential to avoid the need to specify each context-dependent entitlement separately. This motivates a computational model in which the transition associated with one and the same primitive action can depend upon the frame of reference.

Following [4], a definitive (definition-based) representation for state is adopted. The values of the characteristic variables in the designer's model of the concurrent system are specified implicitly, without cyclic definition, as functions of the values of other variables. The redefinition of a variable in the context of a system of interdependent definitions is an appropriate way to represent atomic actions in a concurrent system whose effect is to change several features of the current state simultaneously [5]. This is the essential principle underlying the spreadsheet. For example, through expressing the profit as a function of the price and number of sales of a product, it is possible to regard "changing the profit by side-effect when changing the price" as one indivisible action.

Within a definitive computational framework, agent privileges are specified in the **special-purpose** language LSD. A distinctive feature of LSD is that the perceptions and capabilities of agents are explicitly modelled [6]. This is important in at least two respects:

- it is possible to consider the implications of changing the perceptions of agents (e.g. when designing protocols for a blind user of a telephone system), or their capabilities (e.g. when assigning dialling privileges to users);
- it is possible to distinguish between synchronisation based upon an agent's perception (as in "inserting coins when the display is flashing"), and synchronisation based upon implicit assumptions about the speed with which protocols are executed (as in "assuming that all digits are registered no matter how rapidly the user dials").

This paper is a development of the ideas introduced in [4], in which the emphasis is upon illustrating the problems of characterising system behaviour using LSD alone. A constructive approach to the behavioural issues raised in [4] is adopted; the principles that have been developed to simulate the behaviour of concurrent systems specified in LSD are described and illustrated. These make use of a new computational model supplied by the Abstract Definitive Machine (ADM) [5]. There are four sections: an overview that supplies the context for the method of systems modelling we introduce, an example to illustrate how LSD can be used to model part of a telephone system, a description of the simulation framework and an appraisal of our present progress. Brief references to related research are also included; for more discussion, see [4].

## 2. Background to the method

In an event-oriented approach to modelling, a concurrent system is conceived in terms

of its possible behaviours, each of which is defined by a sequence of events that can occur in simulation. An appropriate model of the system is then e.g. a mathematical expression that represents all possible behaviours. Whatever approach to modelling is used, some kind of formal representation of the possible behaviours of the system is essential in order to attain intellectual control over a design. For example, such a representation is needed in order to determine the characteristic properties of the system e.g. in what circumstances a deadlock or a critical violation can occur.

In constructing an adequate behavioural model there are many issues to be addressed. To specify such a model, the designer has first to acquire a comprehensive understanding of the system. The designer's informal initial knowledge of the system is typically expressed in terms that are less abstract and more activity-oriented. The designer may know for instance what actions particular agents can perform in specific states. Extrapolating from such knowledge to global system behaviour is a difficult process. It involves developing an abstract event-oriented model for the system behaviour that can be understood in its relation to the perceived activity-oriented requirement. Only in this way is the designer able to relate the behavioural limitations of a partial design to the perceived role of the participating agents, so that an iterative process of validation and refinement of the model becomes feasible [2].

The skeletal picture of a concurrent system that the designer can construct from consideration of particular agents, states and actions can be viewed as part of a state-transition model of almost inconceivable complexity. Such a model is defined by all valid statements of the form "when the system is in this state, the following actions can be performed concurrently leading to transition to the following new state".

The **comprehensive** state-transition model of a complex system is the abstraction that links the event-oriented and activity-oriented frameworks. Because of its complexity, the model defies explicit description and both event-oriented and activity-oriented approaches employ characteristic methods of simplification. It is the behaviour of this state-transition model that has to be analysed and adapted by the system designer through modifying the components of the system, whether by reprogramming an electronic device, prescribing protocols for human users or identifying appropriate assumptions about the system environment. In effective modelling of concurrent systems, the challenge is to establish a close relationship between an event-oriented behavioural perspective and the activity-oriented issues that underlie component redesign.

The above discussion supplies the context for the method of systems modelling, based upon new principles to support the design process, that is proposed in this paper. A fundamental innovation is the use of a new computational model in which states are represented by sets of interdependent definitions of variables and transitions by sets of redefinitions to be executed in parallel. Exceedingly complex state-transition models can

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be succinctly described using such *definitive* ("definition-based") representations, so that they are potentially good candidates for behavioural models of systems. Of equal significance is the fact that definitive representations appear to be well-suited to expressing the effects of agent actions as conceived by the system designer.

A strategy that exploits such representations in the initial phases of concurrent system design will first be described in outline with reference to the specification of a rudimentary telephone system. A fuller account, illustrating technical details of the tools used, will be given in sections 3 and 4.

When first conceiving a concurrent system, a designer typically develops an informal activity-oriented model based upon knowledge of how specific agents can act in specific states. The representation of state depends upon the use of sets of variables whose values represent features of the system being modelled. In modelling a telephone system, for example, the state will be determined e.g. by whether the receiver is lifted and/or the telephone is ringing. In one transition, two actions might be performed concurrently, as when a user lifts the receiver to answer a call at the same instant that the caller puts the phone down. To investigate the behaviour of the model, the designer has to consider possible scenarios for agent action and confirm that these are consistent with observed or intended patterns of behaviour within the system being modelled.

The concept of a **comprehensive** state-transition model for a concurrent system is too elusive for explicit definition. To characterise all possible state-transitions from an activity-oriented perspective presumes precise knowledge of what agents can act, when and how. This observation is of seminal importance in our design method, in which the first objective is the identification of the participating agents in a concurrent system and the privileges they conditionally have to change the system state. Of particular interest is the role that definitive representations play in enabling information about agent privileges to be effectively interpreted in state-transition terms.

When modelling the constraints upon transitions from a particular state of a concurrent system, the most obvious consideration is which variables can be redefined by each agent. In the telephone system, the status of the telephone receiver can be recorded by the boolean variable *onhook* whose value is explicitly defined as TRUE or FALSE according to the system state. When a call is in progress, the tone that the telephone emits is a function of the state of the line; it can be represented by a variable *tone* defined in terms of call-status variables under the control of the exchange. The telephone user agent can pick up the phone and so redefine *onhook*, but has no control - for instance - over what tone the telephone emits when the caller engaged signal is received and so cannot redefine *tone*.

To appreciate the significance of choosing a state representation based upon definitions

rather than explicit values, two points should be noted. The use of an implicit definition for the variable tone makes it possible to express the semantically significant fact that the telephone tone is a characteristic of the device fixed by design, from which we can infer that the tone emitted by the telephone stands in the same relationship to the signal received in every simulation state. In this manner, definitions together with knowledge of the agent privileges for redefinition can express important relationships between the global states and transitions in a concurrent system. Even more significantly, where a state representation based upon definitions is used, the implications of the same redefinition depend upon the context supplied by the other definitions. So it is that e.g. changing the price of an article affects the profit in relation to the number of articles sold. This power to express the context-dependent nature of action using inter-related sets of definitions that can be introduced independently is of primary importance.

The key concept underlying definitive representations of state is that of *data dependency*. By exploiting data dependency it becomes possible to express the fact that authorisation to press a button may entail **disproportionate** privileges to change the system state in a conceptually indivisible fashion. What is more, in a definitive framework for specification the user's entitlement to press a button can be recorded quite independently of what the consequences are intended to be. In this respect, the introduction of new definitions into a particular definitive representation of state resembles the introduction of a system of levers into a mechanical device, allowing indivisible propagation of state change from one component of the system to another. This is the crucial technical role that a definitive representation of state can serve: mediating between an activity-oriented model based upon the identification of agent privileges that is developed incrementally during the design process and a behavioural model that is implicitly specified by the effects of potential agent actions.

The technical development of the above ideas will be described and illustrated in later sections. The representation of agent privileges makes use of a special-purpose language - LSD - in which to specify the interface through which an agent acts in a concurrent system. The LSD specification provides a preliminary approximation to a behavioural model for the system that is expressible in definitive state-transition terms. The status of this model and its relationship to the required behavioural model have been discussed at length in a companion paper [4]. There are many aspects of concurrent system behaviour that cannot be faithfully captured by considering agents' privileges for action in isolation. This paper develops a constructive approach to this problem, demonstrating how in principle it is possible to impose additional constraints upon the execution of agent protocols to reflect environmental assumptions e.g. about the speed at which agents act, in order to simulate the behaviour of the system. Such simulations are described in terms of a new parallel machine model that is specially designed for describing computation in definitive state-transition terms.

### 3. Specifying the agent protocols in LSD

The function of an LSD specification is to describe the roles of the agents that participate in a concurrent system. The interface between each agent and the system is specified using techniques originally applied to modelling the user-computer interface [8]. This interface is determined by the user's knowledge of the current state of the system and by their privileges to change this state. The user's view can be modelled by a set of definitions of variables in which the variables that are explicitly defined serve as parameters in the defining expressions for implicitly defined variables. In general, the user can change only certain parameters. By inspecting the set of definitions, the user can infer the current status of the interaction and see the effect of changing a parameter. This mode of interaction is most simply illustrated by the spreadsheet: the user may know (for instance) the profit as a function of the price at which the final product is to be sold, the number of sales, and the cost of components and services.

Developing the idea a little further, different classes of variables in the user's view can be distinguished. There are those variables - such as the profit - that are implicitly defined and are subject only to indirect changes of value; these will be called **derivates**. Other variables, such as the cost of components, are subject to change beyond the user's direct control; these will be called **oracles**. Finally, there are variables that are conditionally under user control (such as the price at which the final product is sold); these will be called the **state** variables.

The framework for specification in LSD is derived by regarding the user as an archetypal **agent** i.e. as one participant in a concurrent system, having a particular view of the system, and certain privileges to interact with the system. In LSD, a concurrent system is modelled by a family of agents, each having its characteristic oracle, state and derivate variables. A template for the specification of an LSD agent takes the form:

```
agent agent_name ( parameter_list )
{
    oracle    list_of_oracle_variables
    state     list_of_state_variables
    derivate  list_of_derivates
    protocol  list_of_guarded_commands
}
```

As in the Specification and Description Language SDL [23], such a specification may correspond to one or more active instances within the concurrent system model, and agent instances can be dynamically created and destroyed. In an agent specification, the variables referenced by an agent are not necessarily, nor typically, bound to the agent. Each derivate of an agent has a non-cyclic definition, and each *guarded\_command* takes the form of a guard together with an associated sequence of actions, each of

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which either redefines a state variable, or invokes another agent instance. The guards and definitions are expressed in terms of variables referenced by the agent.

In using LSD to model a concurrent system, the first step is the specification of an appropriate set of abstract agents. For simulation purposes, certain agents must then be instantiated. The principles will be illustrated with reference to the portion of an LSD specification for a rudimentary telephone system in Figure 1.

The permanently instantiated agents in the system are specified by the exchange(), user() and telephone() agents. The parameters for the user are used for **disambiguation**: they specify the identity of the user and the telephone and distinguish references to different instances of the variables with the same name. In simulation, there is one instance of the exchange() agent, but there are many users and telephones. The specification in Figure 1 has been used to simulate a two user system, using telephones identified by their numbers S and T. For simplicity, only the variables of interest when simulating a call from S to T are explicitly represented in the specification of the exchange (). In the process of making simulating such a call, telephone(S) invokes a new agent dial(S) that in turn invokes the agent connect(S,T).

The oracles for the user are variables bound to the telephone: a boolean to indicate whether the telephone is ringing, and a variable with values to represent the various tones emitted by the earpiece. The user can determine whether or not the telephone is onhook, and can also enter a number into the dial register of the telephone. In the specification, this is viewed as an atomic action.

The oracles for the telephone represent information about its current state: whether or not it is onhook, the content of the dialling register, and other variables that record the status of a call that is in process. A definition such as

**oracle #dialling[S] = false**

specifies re-initialisation of the variable dialling[S]: it indicates that the value of the variable is from time to time conditionally under the control of a transient agent (in this case dial(S)) and will revert to **false** when this agent is no longer extant.

The protocols of the agent are readily interpreted in cognitive and informal operational terms. For instance, when the phone is onhook the user can lift the receiver. If the phone is not ringing, this results in an invocation of the dial() agent. Whilst the phone is offhook and the timeout for dialling has not lapsed, the status of the variable dialling[S] is specified by the derivate in dial() and the dialling tone is emitted by the phone. This entitles the user to enter a number into the dialling register. If this number is valid, the dial() agent invokes the connect() agent, and so on.

In an agent specification the special variable LIVE indicates when the agent is extant. The connect(S,T) agent is deleted when the condition engaged[S,T] is encountered; it is

otherwise extant whilst the connection between S and T is being established, whilst T is ringing and whilst the connection has been made and telephone T has not yet been answered or is offhook. The special variable "time" is used as a universal oracle associated with an unspecified clock() agent that increments a variable time. The protocol for this agent simply consists of a single guarded command:

$$\text{time} = \text{time} + 1$$

where time denotes the value of the variable time in the current context.

The detailed interpretation of the specification in Figure 1 is left to the reader. It should be emphasised that any idea that the LSD specification has an authentic behavioural interpretation is an illusion arising from the fact that additional cognitive input is unconsciously introduced by the intelligent reader. In interpreting the user protocol, we do not assume that the user necessarily answers a ringing phone promptly - if at all. In contrast, for appropriate behaviour of the system, the dial() and connect() agents must be assumed to have a relatively fast and consistent speed of execution and response. The specification of Figure 1 has many pathological behaviours associated with scenarios such as the user frenetically lifting and replacing the receiver whilst dialling numbers at the speed of light, but these are not typically conceived by the designer (cf [4]). Methods of deriving cognitively appropriate simulations are the subject of the next section.

#### 4. Simulating behaviour in the ADM

The primary role of an LSD specification is to describe the interaction between agents in a concurrent system in terms of their privileges to perform actions. As explained in section 1, the fact that these are to be interpreted in the context of definitive state-transition models is crucial, since it enables the same action to have different effects upon the state of the system in different contexts. This is the first step towards relating the behaviour of the system to the concurrent execution of atomic actions by agents in a **comprehensible** manner.

In practice, the relationship between an LSD specification and the simulation of system behaviour is nonetheless very complex. Determining agent privileges is not enough to characterise possible agent interactions, for a variety of reasons. In general, an LSD specification can be given many behavioural interpretations, most of which are inappropriate. The relevant issues are discussed at length in [4] and will be briefly reviewed here with reference to a framework within which an LSD specification can be given an appropriate behavioural interpretation.

Every behavioural interpretation of an LSD specification is based upon the behaviour of individual agents, as specified by the agent protocols. Informally, agent behaviour can be conceived in anthropomorphic terms. Each agent acts sequentially, and at any point in a



simulation is either "in transition" – in the process of sequentially executing the actions in one of the guarded commands specified in its protocol, or in a "waiting" state pending commitment to the execution of any particular guard whose guard is presently true. In guard evaluation, an agent refers to the values of referenced variables "as they are perceived". The choice between guarded commands whose guard is presently true is non-deterministic, and the rate of execution of the associated sequence of actions is unspecified. The motivating idea is that an LSD specification identifies the characteristics of the system behaviour that depend upon the inter-related capabilities and perceptions of its participating agents, but that a precise description of system behaviour requires additional assumptions.

Behavioural interpretations of an LSD specification can also be described in more precise - if more prosaic - computational terms. For this purpose, a state-transition model is used. The current state of a simulation is represented by a set of definitions in which each agent has a private copy of the variables it references, and the derivatives supply implicitly defined variables. The private copies of variables are used to record the perceived values of variables; the redefinition of a state variable during the execution of a protocol assigns a new definition to the authentic occurrence of the variable, viz. that associated with the agent to which it is bound. The computational interpretation is rendered complete by introducing appropriate mechanisms to model the communication of the authentic value of a variable to the other agents that reference it.

The definitive state-transition model described above provides a generic framework for simulating the behaviour of a system in which the agents act according to specified protocols under appropriate assumptions about speeds of operation and the nature of communication. Consideration of the telephone specification in Figure 1 readily demonstrates that devising a simulation from an LSD specification necessarily entails application-specific input from the designer that is based upon cognitive considerations. It is reasonable for instance to suppose that *dialled\_number* serves as a shared variable for the *telephone()* and *dial()* agents, so that the perceived value can be defined to be equal to the authentic value. It would not be so reasonable to suppose that the lifting of the receiver was instantaneously detected by the exchange. An appropriate simulation must take account of unpredictable behaviour on the part of the user, such as picking up or replacing the receiver at any time. The *dial()* agent on the other hand should respond promptly and consistently when the user lifts the receiver.

The computational framework in which the designer must operate in developing an activity-oriented specification can be conveniently described in terms of an appropriate machine model for context-sensitive parallel redefinition – the *abstract definitive machine* (ADM) [5,7]. In the ADM, the computational state is represented by a set of definitions *D* that is dynamically modified through redefinition of variables and the creation or deletion of definitions. The transitions to be performed in executing an ADM program are specified by a set of guarded actions *A* to be executed in parallel as and

when the guards allow. Each action is a sequence of instructions that either redefines a variable, or leads to the instantiation or deletion of an entity comprising a set of definitions and actions. The ADM gives output by redefining variables whose values model the state of an output device.

An ADM program consists of a set of abstractly specified entities. Execution is initiated by instantiating appropriate entities. On each machine cycle the guards associated with actions in  $A$  are evaluated in the context specified by the definitions in  $D$ . If there is no interference, those actions that are associated with true guards are then executed in parallel. Evaluation required in a redefinition – as in interpreting an action such as:

$$\text{time} = \text{time} + 1$$

– is performed in the same context as guard evaluation. Autonomous computation terminates when no action in  $A$  has a true guard.

An LSD specification can be transformed into several ADM programs, each associated with a different scenario for agent action. The parameters used in the transformation process reflect assumptions about the relative speeds at which agents operate and how closely the perceived value of a variable is linked to its authentic value. In practical implementation of a system, these assumptions in turn reflect physical and engineering considerations, such as "How fast can the user dial a number?".

Each LSD agent specification is transformed into an ADM entity description in which the actions are annotated to take account of the speed of an agent's response and execution. These annotations take the form of control parameters for the ADM simulation program to be chosen by the designer. In the present prototype, these parameters serve to assign a probability of selection to each guarded command and to introduce an element of random delay into its execution. The propagation of values from one agent to another is controlled by a similar technique. The result is a faithful computational image of a family of agents executing asynchronously, as informally described in anthropomorphic terms above.

The ADM computational model has several unusual features [5]. It allows the designer to interact fully with a simulation. In execution, an ADM program resembles an environment with an autonomous behaviour in which the designer is in principle privileged to intervene in an arbitrary fashion. Such intervention is feasible because the current state of the execution is recorded by stored definitions and pending actions that can be readily be interpreted by the designer. The parameters supplied for the transformation of LSD specification can be dynamically changed during simulation. It is also possible for the designer to take the part of the user agent, or indeed of any participating agent.

The precise representation of data dependency in the ADM has important implications

for the detection of interference [7]. This is particularly significant in a modelling context, where the designer may not wish to interpret potential conflicts such as two users fighting over the onhook status of a telephone receiver. Actions can interfere in several ways. The same variable may be redefined independently in concurrent actions, or the set of parallel redefinitions may introduce cyclic dependency. Such interference is detected during computation and the execution is suspended. In one possible mode of execution of the ADM, the designer can act as an auxiliary agent to resolve conflicts as they arise. By exploiting the graceful treatment of undefined values in the ADM, a similar technique can be used to handle user input.. The value of a variable is only required when it is encountered in a guard or an evaluated sub-expression in a defining formula. The ADM can either be programmed for default action in these circumstances, or request input from the user.

## 5. Evaluation and comparison

The approach described in this paper has been successfully applied to obtain simulations of the LSD specification of the telephone in Figure 1. At this stage of development, our methods serve best as an informal design aid, helping the designer to clarify the roles that agents play in influencing system behaviour. It is possible to show the implications of changing the user profile to increase the average length of calls for instance. For our approach to be fully effective, it is essential to move beyond simulation to methods of proving properties of the system behaviour subject to assumptions about the activity of agents. Without such methods, there can be no guarantee that the behaviour of the system meets the requirements of the designer.

Our approach nonetheless has several attractive features. The virtues of definitive representations for specifying transitions in a concurrent programming system have been discussed in detail elsewhere [7]. They include explicit representations of data dependency that can assist the identification of interference and expressive techniques for representing the synchronised propagation of state-changes through a system. As is in part illustrated by the telephone example, these techniques may be used as a means to replace a complex component of a system (such as the telephone exchange) by a simpler model with invisible internal behaviour. This can mean that a conceptually complex process of actions is represented as an atomic action at a higher level of abstraction, so that, for instance: "the telephone starts to ring at the moment that the connection is made". In the design context, this is an important method of enabling the decomposition of the system into component parts.

The use of definitive representations in conjunction with LSD is interesting in cognitive terms. Existing software systems supply empirical evidence that sets of interrelated definitions are well-suited both for representing data relationships in business applications and for modelling the movement of objects [14]. Knowledge that provides the basis for "commonsense reasoning" about the consequences of actions in our

environment has to be conveniently represented in terms that take account of the context-dependent nature of action (the frame problem) and admit universal statements about possible states and transitions [10]: the ideas explored in this paper are clearly directly relevant. The use of LSD to represent a user protocol – when the concept of modelling perceptions and capabilities is quite legitimate – makes it possible to interpret cognitive considerations in computational terms, as advocated by Pylyshyn in [17].

Future research will be aimed at extending our present prototype system, essentially based upon an interpreter for the ADM, into a **computer-aided** system for concurrent systems modelling and simulation. Within such a framework, the designer will be able to specify the privileges for action of individual agents, then construct scenarios in which to simulate concurrent action of the entire system. Whether or not it proves possible to perform formal analyses of behaviour on our models, some significant advantages can be expected. The relationship between the behaviour of the system and the components of the specification can be readily interpreted by the designer. Synchronisation based upon interaction between agents and on timing considerations can be treated as separate concerns. The ADM model potentially supports exceptionally rich interaction in a design environment, effectively giving the designer the privileges to act as an omniscient omnipotent agent within a simulation. The techniques for animation of the simulation within a definitive computational paradigm are also already well-developed [8].

Our limited experience with present tools so far confirms these expectations. When analysing the output from a simulation, inappropriate behaviour can be linked either to a flaw in the LSD specification, or to an unsatisfactory choice of parameters for its transformation into an ADM program. Both types of defect can be interpreted in cognitive terms. In the telephone specification, for example, we are led to consider issues such as: "is there any purpose in not replacing the receiver when the engaged signal is obtained?" – an issue for clarification in the LSD specification, or "when making a connection does it matter if the fact that the line is engaged is not immediately detected?" – an issue concerning the speed at which values are communicated to and from the exchange.

Because of the cognitive input required when interpreting an LSD specification in operational terms, its conversion to an ADM program can never be fully automated. It is realistic to generate a skeletal model automatically, however, so that the process of introducing assumptions about speeds of execution and communication can be reduced to substitution of parameters. Alternative approaches to prescribing the behavioural interpretation of an LSD specification are mentioned in [4]. The introduction of flags to constrain the interaction between agents, as in Numerical Petri Nets [21] involves no essential operational extension of LSD, but does disrupt the cognitive framework. The introduction of an environment variable *time* can be **accommodated** within the ADM in

a restricted sense (see for example the ADM simulation of a systolic array in [5]), but true real-time concerns raise many difficult issues beyond the scope of our present methods.

Our approach can be contrasted with an event-oriented approach such as CSP [11,13], and an activity-oriented approach based on an object-oriented programming paradigm (OOPP) [16,18].

CSP typifies the abstract behavioural perspective on concurrent systems. The philosophy behind the notation is that, where the behavioural view of a system is concerned ([11] p24): "... there is no need to make a distinction between events which are initiated by the object and those which are initiated by some agent outside the object. The avoidance of the concept of causality leads to considerable simplification in the theory and its application." Our approach is consistent with this point of view in that the abstract computational model used for simulation has no agent concept. From our perspective, the role of the agent abstraction in system design and modelling is on the other hand essential.

CSP permits the representation of system behaviour as a family of traces, each comprising a sequence of interleaved events. Our behavioural interpretations of an LSD specification are expressed in terms of a non-interleaving concurrency model resembling asynchronous transition systems. Much work on the semantics of the ADM will be required before there can be any prospect of developing concurrent programs from an abstract specification of behaviour in our framework.

It is perhaps more appropriate to compare LSD with the archetypal activity-oriented approach to simulation, viz that based upon an OOPP [16]. The basic concepts of the OOPP - that the internal structure of an object is hidden from other objects, and that the only way in which one object can act to change the state of another object is by sending it a message - are clearly well-adapted for programming in a totally distributed system. It does not seem that an OOPP serves the function of modelling real-world interactions as effectively as LSD however. It is surely appropriate to assert that the telephone user acts directly to take the telephone offhook for instance, rather than that they send a message to the telephone telling it to pick up its receiver. The concept of specifying the side-effects of actions through derivatives also has some advantages - cf [19], where the limitations of the OOPP as a medium for abstractly specifying geometrical relationships between the components of a robot arm are exposed.

It can be argued that most concurrent systems are abstractly "totally distributed" at a sufficiently low level of abstraction. That is to say, most systems are built up from digital components that communicate across channels that are physically short but nevertheless introduce problems of **synchronisation**. An LSD specification for such a system must closely resemble a specification based upon the OOPP: the only way in

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which one agent can change the state of another is by first changing the value of a variable known as an oracle to that agent, causing it to respond according to its private protocol. The synchronisation issues involved in transforming an LSD specification into an ADM program are similar to those that arise in studying the semantics of the parallel OOPP [1].

It may appear superficially that definitive specification methods are inappropriate when definitive state representations are absent from the final computational model. In fact, our design method seems well-suited to the incremental development of a complex specification by a process of refinement. For this purpose, we first construct a model in which some components and **communication** in a system are abstractly represented by derivative and state-oracle pairs, as in the specification of the exchange() agent in Figure 1. In the refinement process, these derivatives and state-oracle pairs can then be replaced by **communication** channels and protocols to derive a specification at a lower level of abstraction. Such a use of functional abstraction as a simplifying device is a common informal design technique.

### Conclusion

This paper has described substantial progress towards understanding the problems of relating the activity-oriented and event-oriented perspectives on concurrent systems modelling, as they are identified in the context of a definitive approach to programming in [4]. The solutions proposed here are not yet sufficiently **well-developed** to meet the ultimate objective of relating the abstract behaviour of a system to the roles played by the participating agents as perceived by the designer. They have nevertheless already provided the basis for prototype systems that can assist the designer in the analysis of requirements and the development of a formal specification.

More research into abstract programming within the ADM and practical experience of the proposed design method is required to inform future work on tools. Parallel investigation into the semantics of LSD and the scope for generic methods of deriving ADM behavioural interpretations of an LSD specification is also essential before more practically useful design environments can be developed.

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```

agent dial(S) {
  oracle   (int) dialled[S],
           (time) Tdial, time,
           (bool) onhook[S],
           (bool) calling[S,dialled[S]] = false
  state    (time) #tstart = |time|
  derivate (bool) dialling[S] = ¬onhook[S] ∧ (time - tstart < Tdial),
           (bool) LIVE = dialling[S] ∧ ¬calling[S, dialled[S]]
  protocol dialling[S] and valid(dialled[S]) → connect(S, dialled[S])
}

agent connect(S,T) {
  oracle   (bool) onhook[S], onhook[T], ringing[D], engaged[S,T],
           (time) Tcall, time
  state    (time) #tcall = |time|,
           (bool) #answered[T] = false,
           (bool) connected[S,T] = false
  derivate (bool) calling[S,T] = ¬connected[S,T],
           (bool) LIVE = ¬onhook[S] ∧ (
               (calling[S,T] ∧ (time - tcall < Tcall)) ∨
               ringing[T] ∨
               (connected[S,T] ∧ (¬answered[T] ∨ ¬onhook[T]))
           )
  protocol
    ¬engaged[S,T] ∧ ¬connected[S,T] → connected[S,T] = true,
    ¬onhook[T] ∧ ¬answered[S,T] ∧ connected[S,T] → answered[T] = true,
    engaged[S,T] → LIVE = false
}

```

Figure 1b: Transient agents in the telephone system specification



```

agent user(U,S) {
  oracle (int) tone[S], (bool) ringing[S]
  state (bool) onhook[S], (int) dialled[S]
  protocol
    ¬onhook[S] → onhook[S] = true; dialled[S] = @,
    ¬onhook[S] ∧ (tone[S] == D) → dialled[S]=T,
    ¬onhook[S] ∧ (tone[S] == C) → speak,
    onhook[S] ∧ ¬ringing[S] → onhook[S] = false; dial(S),
    onhook[S] ∧ ringing[S] → onhook[S] = false; speak
}

agent telephone(S) {
  oracle   (bool) #onhook[S] = true,
           (int)  #dialled[S],
           (bool) #dialling[S] = false,
           (bool) #calling[S, dialled[S]] = false,
           (bool) engaged[S, dialled[S]],
           (bool) isringing[S],
           (bool) active[S]
  derivate (char) #tone[S] = D if dialling[S]:
            E if calling[S, dialled[S]] ∧ engaged[S, dialled[S]]:
            R if calling[S, dialled[S]] ∧ ¬engaged[S, dialled[S]]:
            C if active[S]:
            @ otherwise,
           (bool) #ringing[S] = onhook[S] and isringing[S]
}

agent exchange() {
  oracle   (bool) onhook[T], ...
           (bool) calling[S, T], ...
           (bool) #connected[S,T], ...
           (bool) #answered[T], ...
  derivate (bool) #isringing[T] = calling[?,T] ∧ onhook[T] ∧ ¬answered[T], ...
           (bool) #engaged[S,T] = calling[S,T] ∧ (ringing[T] ∧ ¬onhook[T]), ...
           (bool) #active[S] = connected[?,S] ∨ connected[S,?], ...
           (time) #Tdial = timeout_for_dialling,
           (time) #Tcall = timeout_for_calling
}

```

Figure 1a: Permanently instantiated agents in the telephone system specification