SimCCSK: Simulation of the Reversible Process Calculi CCSK

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Abstract

Reversibility is becoming a more common trend in computer science research. This research ranges from programming languages through to process calculi. It is process calculi that we are interested in here. Reversibility of Milner's CCS has been studied by both Danos and Krivine with their process calculus RCCS as well as by Phillips and Ulidowski with theirs called CCSK.

We describe research in the simulation of Phillips and Ulidowski's CCSK. We primarily look at this from the standpoint of creating a tool for use within the academic sector, specifically the aiding of undergraduate students trying to learn process calculi. We will look into how we can represent the data associated with agents within the context of a computer simulator. We also look at how we can implement the operational semantics giving us the transitions between states within this system. Also we shall see how a Graphical User Interface that contains the relevant information in a clear and concise manner is an important part of making the tool more accessible to undergraduate students.

We will present both SimCCSK and WinSimCCS. SimCCSK is a prototype command line driven simulator for CCSK which includes the key operations and features of CCSK and allows for the user driven simulation of CCSK agents. WinSimCCSK is a graphical prototype version built on the same core engine from SimCCSK and contains all of the same features. WinSimCCSK also includes some additional features such as a built-in "Agent Editor" allowing easier creation and editing of agents and a dynamically generated graph based visualisation of the agent's transitions. It also includes an "Automatic Simulation" feature for the automatic generation of the visualisation for teaching examples. Finally, we will look at how this information can be presented and interacted with in order to make the whole system clear to students helping them reinforce the traditional learning process and present a few examples illustrating its action.

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Introduction

1.1 Context of Thesis

Process calculi have long been used as a method of modelling concurrent systems. In the 1970s Milner created the Calculus of Communicating Systems (CCS) (1). There is a long running trend to investigate the use of reversibility (2) (3). Process calculi are no exception. The reasoning is due to the wide number of possible uses for reversibility in computing. There are many well known examples, including biological system modelling and transactions in service oriented computing through to reversible debugging. Biological system modelling involves reversibility as biological systems by their very nature are reversible and so, therefore, the model should be able to cope with this natural reversibility. In the case of transactions in service oriented computing, reversibility comes into play when a series of events or transactions fail to complete midway through the process and therefore need to reverse back to a point where another sequence can be executed Alternative approaches to this transaction failure include compensation. Compensation is where instead of reversing back to a point, a sequence of events are triggered to reset the specific events or transactions which had been executed previously. Another example is reversible debugging, since the current issues with debugging revolve around a computer's inability to recover from an application crash. Reversibility would allow the debugger to reverse the steps leading up to the crash allowing for the creation of a more informative state of the

system leading up to the crash. Even more intriguing is something Landauer wrote back in 1961 on reversibility, in a paper he noted that it is not the computation but the deletion of information that generates an increase in entropy and thus dissipates heat (4), what this would mean is that if every action a computer made was reversible we would never need to erase it and therefore the heat generated would be far lower. This could then lead to higher clock speeds due to the increased space in temperature.

In the case of CCS we can now see two extensions to CCS that add reversibility, one by Danos and Krivine called Reversible CCS (*RCCS*) and another by Phillips and Ulidowski, CCS with Keys (*CCSK*). We are going to look into a sub-area to this, related to the computer simulation of process calculi; specifically the objective is to develop a simulator for CCSK to be possibly used in the reinforcement of learning by students studying about process calculi.

1.2 Challenges

Currently there is very little work concerning the design and construction of a simulator for reversible process calculi and particularly in the case of CCSK. Existing process calculi simulators deal only in non-reversible calculi. Two examples of these are Concurrency Workbench of New Century (CWB-NC), which is primarily CCS-based and FDR2 for CSP. Both tools have features that are useful, however, are not really suited to aiding student experimentation and learning. Whilst CWB-NC does have a graphical representation of a system, it is only trace based which means only the route taken is shown. Also due to it using CCS it has no real reversibility and, therefore, lacks the ability to show students how alternative choices alter the behaviour of a system. FDR2 on the other hand has no graphical representation, again has no real reversibility, and is therefore lacking the features required for students. What both tools have in common and really shows the main objective of these applications, is model checking. They are inherently designed to check systems as opposed to be interactive simulators; the interactive simulation is more of an add-on as opposed to the primary function.

So the challenges of this project are based around the creation of an interactive simulator that could be used in the teaching of students, allowing them to explore and interact with a system to gain a deeper understanding of process calculi. We feel that this gives us two key challenges:

- Implementation of the Operational Semantics
- Graphical User Interface Design

Of course being inherently a software oriented project, a key challenge is how we can represent and interact with agents (being a key construct in CCSK) within the realm of software. It has to be both well designed so that it is clear to the software what the agent is, as well as being flexible enough to cope with the variants of agents within CCSK. Once we have an internal representation, we need to be able to interact with it and make various transitions between the states of the agent. These transitions are defined by the operational semantics, it is a key challenge to design and implement these so that they operate in a consistent and intended way. As previously mentioned, our aim is that this simulator is accessible to students learning process calculi. This leads us to our second key challenge, the graphical user interface (GUI) design. We feel that for students learning process calculi, the simulator should help them with just that. We feel that it should not be a requirement to understand an intricate and overly complicated system to learn and experiment with process calculi. To this end, we feel that the GUI should present all of the relevant information in an easy to understand way, whilst maintain a simple to pick up and use piece of software.

1.3 Outline of Solution

In this thesis we will present our solution to the above challenges, culminating in a working prototype of a CCSK simulator called WinSimCCSK. We will also show a few examples with this tool highlighting its functionality; these examples include the classic CCS Jobshop, a biological system and the classic Dining Philosophers.

We will show how we internally represent agents (collectively known as a system). This is achieved using an almost static tree like structure, which we combine with keys and pointers to provide the current state of the system. The idea behind this approach to the solution is due to the almost static nature of the internal structure, that all previous states can be captured with this single structure. This also gives the added benefit that the amount of memory used for storage of the state of the system is restricted due to its limited size which is based on the size of the agent not on the transitions between them.

For the operational semantics, we show how through the uses of inheritance and polymorphism we can create a simple yet dynamic framework as a base for the operational semantics. This allows the various rules to be defined separately and yet be called dynamically at runtime from an agent. The agent does not need to know which rule to call, as this is all resolved dynamically through polymorphism aided by common data defined with the aid of inheritance.

The GUI is designed to be intuitive and easy to read. To this end we have created a GUI which not only contains the current state of the system, but also lists the possible forward and reverse moves in a clear and concise fashion. In order to aid student learning we felt a graphical representation was important, so we include a graph which is dynamically created as the user makes various moves showing the transitions between the various states of the system. In order to make the systems easy to pick up and use, we also include a simple “Agent Editor” which allows CCSK agents to be defined for use within the simulator and can be saved for future reuse, as well as an “Automatic Simulation” function which automatically generates the transition graph of the system up to a user specified depth.

1.4 Structure of Thesis

This thesis is organised as follows. In chapter 2 we shall look at the background of the project, specifically looking as CCS, RCCS and CCSK with a small comparison between RCCS and CCSK. Chapter 3 will look that the designs of the software, including the requirements, concept and how the data can be represented, as well as a brief look at related work. Chapter 4 will look at the implementation details of SimCCSK including the internal data structure and console based interface. Chapter 5 goes on to outline WinSimCCSK, the graphical version, looking at its extended features and user interface. We then go on to look at a few examples with the help of WinSimCCSK. Chapter 6 provides a concise user guide to WinSimCCSK, outlining how one can use the prototype. Chapter 7 looks what the project has achieved against its original aims. Finally, in Chapter 8 there is a review of the thesis with conclusions.

Chapter 2

Background

Over the course of this chapter we shall look at some of the background to the project including a brief look at CCS, RCCS and CCSK. Finally we shall end the chapter with a concise comparison between RCCS and CCSK, looking at our reasoning behind basing this project on CCSK.

2.1 Basics of CCS

Calculus of Communicating Systems (CCS) was created by Milner in the early 70's for modelling concurrent systems. In this section we will identify some of the ideas, concepts and constructs of CCS.

CCS is specified by the following BNF grammar:

$$P ::= 0 \mid a.P_1 \mid P_1 + P_2 \mid P_1|P_2 \mid P_1[b/a] \mid P_1\backslash a \mid A$$

where

0 is the zero agent
$a.P_1$ is the action a followed by the agent P_1
$P_1 + P_2$ is the choice of P_1 or P_2
$P_1|P_2$ is parallel composition and means both P_1 and P_2 can be used
$P_1[b/a]$ is relabeling and means all actions a in P_1 are renamed to b
$P_1\backslash a$ is restriction of the action a in P_1
A is an agent identifier. $A = P$ means A refers to the agent P

The simplest construct in CCS is that of the Zero agent (written simply as '0'). The Zero agent is simply a terminated agent. It can do nothing and it is often the terminating point in more complex CCS agents.

The second operator is the Prefix (denoted by a '.'). The Prefix operator specifies the transition between an agent $a.P$ and P by the execution of the action a. A simple example of this is if we take the action a and the Zero agent, the resulting Prefix agent would be $a.0$ which would specify the transition to 0 by the execution of action a. Equally, prefixing the action b to the resulting agent would result in $b.a.0$. This now gives us a route to 0 by the execution of b, resulting in the transition to $a.0$ and then a to 0.

The Choice operator (denoted by a '+') allows for two (or more) agents to be combined together to form a choice between them. A simple example of this is if we take the agents $a.0$ and $b.0$ and combine via the Choice resulting in the agent is $a.0 + b.0$. The Choice is destructive in the sense that once a path is chosen the other is no longer available. An example of this is if we take the agent $a.b.0 + c.d.0$. If we perform the action a, giving us the transition to $b.0$, we would have lost access to the agent $c.d.0$. The Choice agent is usually seen as a binary construct. However this is usually for the sake of convenience and is referred to as "Finite Summation" (1). It is formally defined in (1) as $\sum_{i \in I} E_i$, basically this states that for a set of indices I we can sum together the collection of agents E_i. Choice is also both commutative and associative, i.e. $P + Q = Q + P$ (commutative) and $P + (Q + R) = (P + Q) + R$ (associative).

In order to facilitate concurrency, CCS uses the Parallel operator (denoted by a '|'). The Parallel operator allows two (or more) agents to combine in a parallel and concurrent fashion. A simple example of this is if we take the agents $a.0$ and $b.0$ and combine via the Parallel, resulting in the agent is $a.0 \mid b.0$. Unlike Choice, Parallel is non-destructive in the sense that if we follow one path, the other is still open to us. An example of this is if we take the agent $a.b.0 \mid c.d.0$ and perform action a, we get a transition to $b.0 \mid c.d.0$, so we would still have access to the agent $c.d.0$. More often than not we will want to combine more than two agents in Parallel, this can be

done e.g. $a.0 \mid b.0 \mid c.0$. However like Choice, the Parallel agent is usually seen as a binary construct. Again this is more out of convenience as we can combine two together and then keep putting the resulting agent in parallel with another (E::= E|E). Parallel is also both commutative and associative, i.e. $P \mid Q = Q \mid P$ (commutative) and $P \mid (Q \mid R) = (P \mid Q) \mid R$ (associative).

CCS's second C stands for communication. Communication is available only between agents in parallel. It can only be performed by a pair of actions being the action and its counterpart, being the action overbar (denoted using a '¯'). An example of an agent where communication is possible is $a.b.0 \mid \overline{a}.c.0$, here we can perform the communication between a and $\overline{a}$ (denoted in the transition using a 'τ') resulting in the agent $b.0 \mid c.0$.

At times, we want to be able to restrict outside interactions with our agents so that they can only be triggered internally usually by communication. CCS has the concept of restriction (denoted using a '\') to facilitate just this. So if we take the example we previously used being $a.b.0 \mid \overline{a}.c.0$, however this time restricted the action a (which also includes the restriction of the overbarred counterpart as well), we get $(a.b.0 \mid \overline{a}.c.0)\backslash a$. Now we can only perform the communication move of a and $\overline{a}$ as the singular moves a and $\overline{a}$ are now blocked by the restriction. If we perform the communication, we get the agent $(b.0 \mid c.0)\backslash a$. The restriction remains because the agent it was bound to (in this case the parallel) is still active.

Occasionally it is useful to take two or more agents we have predefined and link them together into a larger agent, however if we are linking multiple copies of the same agent together we may get into the position whereby different actions share a common name which may lead to unnecessary confusion. In order to fix this, CCS also has the concept of relabeling (denoted using '[x/y]' where y is renamed x), whereby you can rename an action to something different and by extension the overbarred counterpart as well. If we take the agent $a.0$ and we wanted to put two together in parallel we would get $a.0 \mid a.0$. However, while this is perfectly valid, if we were to say we performed action a, it is not particularly clear which one. For added clarity, we

can change the second one from an a to a b thereby easily distinguishing between the two choices. This would give us a new agent $a.0 \mid (b.0)[b/a]$.

A more concrete example of this would be if we had a $Button$ agent defined as $press.Button$. Now we can put two buttons together, for example (in an example inspired by (1)) in a vending machine for chocolate (which can dispense a standard and large bars) with a button for each size. However currently we would have $press.Button \mid press.Button$ which makes it unclear which button relates to which size. Using renaming we can make this clearer by altering the names of the buttons, for example:

$$pressStd.Button\ [pressStd\ /\ press] \mid pressLrg.Button\ [pressLrg\ /\ press]$$

An alternative example is one where communication is possible. Taking our previous example, we want the button to trigger the dispensing of the chocolate. This time however we shall simplify the example by only having one type of chocolate bar. We will also update the $Button$ agent to include a out signal (showing the button has been pressed), which we shall define as $press.\overline{out}.Button$. We will also include $Dispense$ agent defined as $dispense.dropchoc.Dispense$. We want the two to communicate, so that when the button is pressed we trigger the dispense mechanism and the chocolate is dropped (as signified by the $dropchoc$ action). To do this we put them together in parallel, resulting in $press.\overline{out}.Button \mid dispense.dropchoc.Dispense$. The issue with this is that they cannot communicate because $\overline{out}$ and $dispense$ are not a matching pair. We solve this by renaming one of the actions to match the other, so if we rename the out to $dispense$ we would get $(press.\overline{out}.Button)[dispense/out] \mid dispense.dropchoc.Dispense$ which would now allow communication as we now have a matching pair, being $dispense$ and $\overline{out}$ which has been renamed $\overline{dispense}$.

2.1.1 SOS Rules of CCS

CCS's transitional rules can be expressed using Plotkin's Structural Operational Semantics (SOS) (5) (6). So for reference the SOS rules are included below.

$$Prefix\ \frac{}{a.X \xrightarrow{a} X}$$

$$Choice\ \frac{X \xrightarrow{a} X'}{X + Y \xrightarrow{a} X'} \qquad \frac{Y \xrightarrow{a} Y'}{X + Y \xrightarrow{a} Y'}$$

$$Parallel\ \frac{X \xrightarrow{a} X'}{X \mid Y \xrightarrow{a} X' \mid Y} \qquad \frac{Y \xrightarrow{a} Y'}{X \mid Y \xrightarrow{a} X \mid Y'}$$

$$Communication\ \frac{X \xrightarrow{a} X' \quad Y \xrightarrow{\overline{a}} Y'}{X \mid Y \xrightarrow{\tau} X' \mid Y'} \quad (a \neq \tau)$$

$$Restriction\ \frac{X \xrightarrow{a} X'}{X \setminus A \xrightarrow{a} X' \setminus A}\ a \notin A \cup \overline{A}$$

$$Relabelling\ \frac{X \xrightarrow{a} X'}{X[f] \xrightarrow{f(a)} X'[f]}$$

$$where\ X[f] = X\ renamed\ by\ function\ f$$

$$Recursion\ \frac{X \equiv Y \quad Y \xrightarrow{a} Y' \quad Y' \equiv X'}{X \xrightarrow{a} X'}$$

Figure 2.1-1: SOS Rules for CCS

2.1.2 Examples

We will now show a few simple examples illustrating CCS with the aid of the SOS rules.

Our first example is of prefix, taking $a.b.0$. From start to finish this agent has two transitions shown below.

$$a.b.0 \xrightarrow{a} b.0 \text{ and } b.0 \xrightarrow{b} 0$$

This example uses a single SOS rule (being prefix). The rule simply states that an agent with a prefixed action can make the transition to the agent by performing the action. So here $a.b.0$ is a prefixed on to $b.0$ can make the transition by performing the a. $b.0$ works similarly.

Our second example is one involving parallel, $a.b.0 \mid c.d.0$. From this state we have two transitions:

$$a.b.0 \mid c.d.0 \xrightarrow{a} b.0 \mid c.d.0 \text{ and } a.b.0 \mid c.d.0 \xrightarrow{c} a.b.0 \mid d.0$$

This time round in the first instance we look at the parallel rules. The rules state that we can make the transition if either side of the parallel can make a transition, so in our case $a.b.0$ or $c.d.0$ can make a transition. Clearly these can apply the prefix rule we saw earlier. The parallel also states the result of the transition is the result of the agent that made the transition in parallel with the unaltered other agent. In our example this gave us $b.0 \mid c.d.0$ if we performed the a (of $a.b.0$) and $a.b.0 \mid d.0$ if we performed the c (of $c.d.0$).

Our final example is a simple recursive one, being P with $P = a.P$. Here we have a single transition:

$$P \xrightarrow{a} P$$

This transition does look a little odd at first sight, the reason for this is that both sides of the transition are the same. This however does make a lot of sense in reality. If we

look at what is happening, we can see that the P is defined as $a.P$ so we really have the following transition:

$$a.P \xrightarrow{a} P$$

This transition is of course a simple prefix and shows that P does in fact have a transition to P with the action a. Of course what has really happened is that we have replaced the P agent with an actual instance of $a.P$. As such subsequent transitions would be different a's as opposed to repeatedly performing the same one.

2.2 Basics of RCCS

Danos and Krivine have created a way of adding reversibility to CCS (7) (8) (9), by utilising the concept of a memory stack using the notion of pushing previous data onto the stack so that it can be popped off in the event of a roll back. We shall now look at the ideas and constructs of RCCS.

Let us look at the Prefix agent in RCCS. Here we will use an example $a.b.0$ to help visualise and explain the process.

$$[a.b.0]_1 \xrightarrow{1,r,a} < r, a, 0 >.[b.0]_1$$

This one transition makes the forward move of a. As we can see this is slightly more complex than the CCS version due to the added information required in order to facilitate the reverse move. The label of the transition (being $1, r, a$) is made up of three parts, the first being the 1; this is the process label which identifies which process the transition is being actioned on. In this example with only one process it is of little relevance, however, with two or more processes it gains usefulness. Second is the r, which is just a label for ease of reference. Finally the a, which is the action performed.

The resulting agent is both the CCS equivalent (in this case $b.0$) and the created stack (notated using < >). In the stack there are three parts; the label (r), the action

performed (a) and any 'lost' agents. In our case because it is a simple Prefix agent and therefore with no other agents to lose, we use the Zero agent (0).

Now let us look at the reverse move, using the same example.

$$< r, a, 0 >. [b. 0]_1 \overset{1.r.a}{\longleftarrow} [a. b. 0]_1$$

Here we see that the label and action are both in the stack and the transition effectively links the two. The process label again matches the transition to a process. It is worth noting that the transition does in fact go from left to right; the transition arrow (going from right to left) just signifies that we are performing a reverse move. The resulting agent is constructed by adding the action to the front of the process and by then adding any lost agents. However in our case due to there being no lost agents (signified by the Zero agent), none are added.

Choice is also in RCCS, again we will use an example this being $a. b. 0 + c. d. 0$ to help visualise and explain the process.

$$[a. b. 0 + c. d. 0]_1 \overset{1,r,a}{\longrightarrow} < r, a, c. d. 0 >. [b. 0]_1$$

This single transition shows the execution of the forward action a. As in the previous example we still have the transition label (being $1, r, a$) which has the same meaning. The key difference here is that in our resulting agent we now have a 'lost' agent (being $c. d. 0$) so whereas in our previous example the third part of the stack was set to be empty (notated by the Zero agent), there is now something on it, this being the lost agent.

Look at how this affects the reverse move.

$$< r, a, c. d. 0 >. [b. 0]_1 \overset{1,r,a}{\longleftarrow} [a. b. 0 + c. d. 0]_1$$

Once again the transition label is the same as our previous example (as we are still performing action a); the key difference here is clearly the stack and more specifically the third part of it. This time around we have a 'lost' agent to re-attach to the resulting agent. This is created by adding the previous action to the front of the agent.

Like CCS, communication plays an important role. So with the help of a final example: $a.b.0 \mid \overline{a}.c.0 \mid \overline{d}.e.0$ we will look at the processes behind such an agent.

$$[a.b.0]_1 \mid [\overline{a}.c.0]_2 \mid [\overline{d}.e.0]_3$$
$$\xrightarrow{1,2,\tau} \ll (2,a); 0 \gg [b.0]_1 \mid \ll (1,\overline{a}); 0 \gg [c.0]_2 \mid [\overline{d}.e.0]_3$$

The transition shown here is of the communication between a and $\overline{a}$. For communication the transition label takes a slightly different form, the first two parts are the labels of the two processes involved in the communication, the third part is the action which being a communication transition is τ. The resulting agent is constructed by creating the resulting processes and reconstructing the parallel agent. Only the two processes involved in the communication are changed. If we look at the first processes resulting agent (being $\ll (2,a); 0 \gg [b.0]_1$) we can see that a slightly different stack notation is used to signify that the move was communication based (this is notated using << >>). The stack is made up of two parts, the first being the pair of the matching processes label (in this second process) and the action communication took place across. The second part of the stack is again for storing any 'lost' agents. In this example, since there are none, the agent that is used is Zero. Process two's resulting agent is constructed in a similar fashion; here the pair is the first process and the matching action, complete with overbar. Once again there is no 'lost' agent so the Zero agent is used.

$$\ll (2,a); 0 \gg [b.0]_1 \mid \ll (1,\overline{a}); 0 \gg [c.0]_2 \mid [\overline{d}.e.0]_3$$
$$\xleftarrow{1,2,\tau} [a.b.0]_1 \mid [\overline{a}.c.0]_2 \mid [\overline{d}.e.0]_3$$

The reverse transition works similarly, here however the reverse move can only take place if the stacks on both processes involved are matching counterparts. The reverse transition label is like its forward counterpart and is made up using both process id's and the τ. The resulting agent is constructed using the resulting processes in parallel. The two processes are constructed by taking the action from the pair, adding it to the front of the agent and then adding any 'lost' agents to the resulting agent. In this example, for clarity, there are no 'lost' agents.

2.3 Basics of CCSK

CCSK is another approach to adding reversibility to Milner's CCS, introduced by Phillips and Ulidowski (10) (11) (12) (13) and is based on the use of keys to both signify past actions and to lock communicating actions together. In this section we will look at the ideas and constructs of CCSK.

CCSK is specified by the following BNF grammar:

$$P ::= 0 \mid a.P_1 \mid a[k].P_1 \mid P_1 + P_2 \mid P_1|P_2 \mid P_1[b/a] \mid P_1\backslash a \mid A$$

where

0 is the zero agent
$a.P_1$ is the action a followed by the agent P_1
$a[k].P_1$ is the past action a with key k followed by the agent P_1
$P_1 + P_2$ is the choice of P_1 or P_2
$P_1|P_2$ is parallel composition and means both P_1 and P_2 can be used
$P_1[b/a]$ is relabeling and means all actions a in P_1 are renamed to b
$P_1\backslash a$ is restriction of the action a in P_1
A is an agent identifier. $A = P$ means A refers to the agent P

The Prefix agent in CCSK is very similar to its CCS counterpart. The key difference between the two is the introduction of a key which is used to signify past actions and, as described later, also binds two agents together in communication. In order to help illustrate the CCSK approach to Prefix we shall look at the simple example of $a.b.0$.

$$a.b.0 \xrightarrow{a[k]} a[k].b.0$$

The transition is labelled by the action and the key (in the example k is a unique key) being assigned to that action (denoted in [ ]). The result is the previous agent with the new key now associated to the action that has just been performed. This move can only be made however if the rest of the result, the part following the action performed (in this example $b.0$) is a 'standard' CCS agent, i.e. it does not contain any keys.

The reversed counterpart is similar.

$$a[k].b.0 \overset{a[k]}{\rightsquigarrow} a.b.0$$

Here we see the transition is labelled again with the action and the key, however to signify the reverse nature of the move a squiggled arrow $\rightsquigarrow$ is used. The resulting agent is the agent with the key removed from the action performed.

Like CCS and RCCS, CCSK also has the notion of choice; in fact like most of CCSK it is very similar to its CCS counterpart. An example of this is $a.b.0 + c.d.0$.

$$a.b.0 + c.d.0 \xrightarrow{a[k]} a[k].b.0 + c.d.0$$

The transition is again labelled with the action and a key. The resulting agent is the key added to the performed action. The other part of the choice is left infix, however the choice rule states that the other part of the choice is a 'standard' CCS agent (i.e. it contains no past actions). It would be impossible to perform an action from the other side i.e. $c.d.0$ as this would now be locked as $a[k].b.0$ is not a 'standard' CCS agent as it uses a key.

In reverse Choice works similarly; using the example above we get.

$$a[k].b.0 + c.d.0 \overset{a[k]}{\rightsquigarrow} a.b.0 + c.d.0$$

The transition is once again labelled with the action and the key. The resulting agent is simply generated by removing the key from the action that has just been performed. Again like its forward counterpart the rule for reverse choice again requires that the other part of the choice is a 'standard' CCS agent. In practice you should not really be in the position where both parts of the choice are non-standard, i.e. contain keys. If this was the case this would mean you had violated the forward transition rule, as somehow you would have actioned both sides of the choice (meaning you had effectively treated them as agents in parallel).

One of CCS's traits is the modelling of concurrent processes. CCSK carries this trait forward and as such there is also the concept of agents in parallel in CCSK as well. To illustrate its working we will use the example $a.b.0 \mid c.d.0$.

$$a.b.0 \mid c.d.0 \xrightarrow{a[k]} a[k].b.0 \mid c.d.0$$

The transition is labelled in the same way as most of CCSK's transitions with both the action and a key. The resulting agent is constructed simply by attaching the key to the action performed. However there is a key point yet to mention, back with Choice we looked at how the requirement of 'standard' CCS agents would prevent the Choice from acting more like a parallel agent. The parallel rule has a similar requirement that the key used must not appear in the other part of the parallel. On reflection this is a necessary move as without this restriction it would be possible to action two moves of a matching pair separately with the same key; this would then suggest that communication had occurred. We will look at communication shortly.

In reverse the process follows the similar patterns of prefix and choice giving you a transition such as the following (based on the previous example).

$$a[k].b.0 \mid c.d.0 \overset{a[k]}{\rightsquigarrow} a.b.0 \mid c.d.0$$

In a similar way to Choice, the reverse parallel move also enforces the unused key requirement. This means that the reverse move can only be made if the key is not present in the other part of the parallel, unlike Choice however this is far more important in practice as without this requirement, you would be able to reverse a move created by communication in two separate steps.

Communication is a key thread within CCSK; to demonstrate how communication works in CCSK we will look at the example $a.b.0 \mid \overline{a}.c.0 \mid \overline{d}.e.0$.

$$a.b.0 \mid \overline{a}.c.0 \mid \overline{d}.e.0 \xrightarrow{\tau[k]} a[k].b.0 \mid \overline{a}[k].c.0 \mid \overline{d}.e.0$$

Here the transition is now labelled with a τ as this is a communication move, again along with a key. The resulting agent is again constructed by attaching the key to both

of the matching pair of actions (i.e. action and action overbar, with action overbar being the same as in CCS) performed thus locking the two agents and actions together.

The reverse equivalent looks like this.

$$a[k].b.0 \mid \overline{a}[k].c.0 \mid \overline{d}.e.0 \overset{\tau[k]}{\rightsquigarrow} a.b.0 \mid \overline{a}.c.0 \mid \overline{d}.e.0$$

Again the transition is labelled with a τ along with a key. The resulting agent is constructed by removing the keys from both actions of the matching pair which make up the communication move. The important point here is that the key must be identical on both parts of the matching pair of actions.

Finally like CCS, CCSK also has the notions of restriction and relabeling and they operate in the same way as CCS for the forward moves. For the reverse moves they operate in exactly the same way as one would expect, however like the rest of CCSK reverse moves, the 'reverse' transitions for both relabeling and restriction are notated using the squiggled arrow $\rightsquigarrow$.

2.3.1 SOS Rules of CCSK

Like CCS, CCSK's transition rules can also be expressed using Plotkin's Structural Operational Semantics. So for reference and possible comparison we shall include the SOS rules below.

2.3.1.1 SOS Rules for the *std(X)* Relation

CCSK introduces a relation $std(X)$. We say that X is std if it can be defined by the following SOS rules:

$$\frac{}{a.X \xrightarrow{a} X} \qquad \frac{X \xrightarrow{a} X'}{X + Y \xrightarrow{a} X'} \qquad \frac{Y \xrightarrow{a} Y'}{X + Y \xrightarrow{a} Y'}$$

$$\frac{X \xrightarrow{a} X'}{X \mid Y \xrightarrow{a} X' \mid Y} \qquad \frac{Y \xrightarrow{a} Y'}{X \mid Y \xrightarrow{a} X \mid Y'} \qquad \frac{X \xrightarrow{a} X' \;\; Y \xrightarrow{\overline{a}} Y'}{X \mid Y \xrightarrow{\tau} X' \mid Y'} \;\; (a \neq \tau)$$

$$\frac{X \xrightarrow{a} X'}{X \setminus A \xrightarrow{a} X' \setminus A} \; a \notin A \cup \overline{A} \qquad \frac{X \xrightarrow{a} X'}{X[f] \xrightarrow{f(a)} X'[f]} \qquad \frac{X \equiv Y \;\; Y \xrightarrow{a} Y' \;\; Y' \equiv X'}{X \xrightarrow{a} X'}$$

$$where\ X[f] = X\ renamed\ by\ function\ f$$

Figure 2.3-1: SOS Rules for the *std(X)* Relation

As we can see these rules effectively specify CCS. This is the intention, as such $std(X)$ can be informally described as a standard CCS rule, i.e. one without any past actions.

2.3.1.2 Forward SOS Rules

$$Prefix\ \frac{std(X)}{a.X \xrightarrow{a[m]} a[m].X} \qquad \frac{X \xrightarrow{b[n]} X'}{a[m].X \xrightarrow{b[n]} a[m].X'}\ m \neq n$$

$$Choice\ \frac{X \xrightarrow{a[m]} X'\ \ std(Y)}{X + Y \xrightarrow{a[m]} X' + Y} \qquad \frac{Y \xrightarrow{a[m]} Y'\ \ std(X)}{X + Y \xrightarrow{a[m]} X + Y'}$$

$$Parallel\ \frac{X \xrightarrow{a[m]} X'\ \ fsh[m](Y)}{X \mid Y \xrightarrow{a[m]} X' \mid Y} \qquad \frac{Y \xrightarrow{a[m]} Y'\ \ fsh[m](X)}{X \mid Y \xrightarrow{a[m]} X \mid Y'}$$

$$Communication\ \frac{X \xrightarrow{a[m]} X'\ \ Y \xrightarrow{\overline{a}[m]} Y'}{X \mid Y \xrightarrow{\tau[m]} X' \mid Y'}\ (a \neq \tau)$$

$$Restriction\ \frac{X \xrightarrow{a[m]} X'}{X \setminus A \xrightarrow{a[m]} X' \setminus A}\ a \notin A \cup \overline{A} \qquad Relabelling\ \frac{X \xrightarrow{a[m]} X'}{X[f] \xrightarrow{f(a)[m]} X'[f]}$$

$$Recursion\ \frac{X \equiv Y\ \ Y \xrightarrow{a[m]} Y'\ \ Y' \equiv X'}{X \xrightarrow{a[m]} X'}$$

Figure 2.3-2: Forward SOS Rules for CCSK

$fsh[m](X)$ is defined such that it holds if m does not occur as a key in X, i.e. m is a fresh key.

2.3.1.3 Reverse SOS Rules

$$Prefix\ \frac{std(X)}{a[m].X \overset{a[m]}{\rightsquigarrow} a.X} \qquad \frac{X \overset{b[n]}{\rightsquigarrow} X'}{a[m].X \overset{b[n]}{\rightsquigarrow} a[m].X'}\ m \neq n$$

$$Choice\ \frac{X \overset{a[m]}{\rightsquigarrow} X' \quad std(Y)}{X + Y \overset{a[m]}{\rightsquigarrow} X' + Y} \qquad \frac{Y \overset{a[m]}{\rightsquigarrow} Y' \quad std(X)}{X + Y \overset{a[m]}{\rightsquigarrow} X + Y'}$$

$$Parallel\ \frac{X \overset{a[m]}{\rightsquigarrow} X' \quad fsh[m](Y)}{X \mid Y \overset{a[m]}{\rightsquigarrow} X' \mid Y} \qquad \frac{Y \overset{a[m]}{\rightsquigarrow} Y' \quad fsh[m](X)}{X \mid Y \overset{a[m]}{\rightsquigarrow} X \mid Y'}$$

$$Communication\ \frac{X \overset{a[m]}{\rightsquigarrow} X' \quad Y \overset{\overline{a}[m]}{\rightsquigarrow} Y'}{X \mid Y \overset{\tau[m]}{\rightsquigarrow} X' \mid Y'}\ (a \neq \tau)$$

$$Restriction\ \frac{X \overset{a[m]}{\rightsquigarrow} X'}{X \setminus A \overset{a[m]}{\rightsquigarrow} X' \setminus A}\ a \notin A \cup \overline{A} \qquad Relabelling\ \frac{X \overset{a[m]}{\rightsquigarrow} X'}{X[f] \overset{f(a)[m]}{\rightsquigarrow} X'[f]}$$

$$Recursion\ \frac{X \equiv Y \quad Y \overset{a[m]}{\rightsquigarrow} Y' \quad Y' \equiv X'}{X \overset{a[m]}{\rightsquigarrow} X'}$$

Figure 2.3-3: Reverse SOS Rules for CCSK

2.4 CCSK vs. RCCS: A Comparison

Given the title of this thesis, it would seem a reasonable guess that we will be looking at CCSK as opposed to RCCS, however why CCSK over RCCS? Over the course of this section we will look at some of the similarities and differences between them along with why the project had decided to be based around CCSK.

As we previously have seen, both CCSK and RCCS provide an approach to reversing CCS. Both take a somewhat different approach to achieve a similar goal. CCSK is based around the use of inline keys to signify past moves and to synchronise communicating actions together where as RCCS uses a stack based approach, whereby past moves are stored on a stack.

To aid with further discussion, we shall look at the agent $a.b.0$ in both RCCS and CCSK to compare the similarities and differences.

$$[a.b.0]_1 \xrightarrow{1,r,a} < r, a, 0 >. [b.0]_1$$

$$a.b.0 \xrightarrow{a[k]} a[k].b.0$$

If we compare the two, we can see that both can make the move a which leads to $b.0$ (under CCS), this is clearly the state we are trying to represent and as we have previously seen both handle the past move in different ways. RCCS, puts the action onto a stack, complete with a couple of other pieces of data, one being a label the other being the other half of a choice (in this example there is not one, hence it is represented by a 0). CCSK on the other hand, leaves the action in place, however attaches a key inline, signifying its past action status. As we can see, the CCSK approach is slightly shorter and cleaner to write in this simple example.

Taking this one step further, by adding choice we get the agent $a.b.0 + c.d.0$.

Forwards:

$$[a.b.0 + c.d.0]_1 \xrightarrow{1,r,a} < r, a, c.d.0 >. [b.0]_1$$

$$a.b.0 + c.d.0 \xrightarrow{a[k]} a[k].b.0 + c.d.0$$

Reverse:

$$< r, a, c.d.0 >. [b.0]_1 \xleftarrow{1,r,a} [a.b.0 + c.d.0]_1$$

$$a[k].b.0 + c.d.0 \overset{a[k]}{\rightsquigarrow} a.b.0 + c.d.0$$

This time around, we get a similar scenario, however under RCCS we see that the second half of the choice is now on the stack. The key point here is that if we compare the resulting state (going forward), we can see that under CCSK it is clear that it is a choice agent. This is not so clear under RCCS, in fact you would have to look into the stack to work this out. Whilst this is fairly trivial in this example however, imagine it

being a piece of a much larger agent then it clearly would become more difficult to glance at it and work out the structure of the agent.

Communication only adds to this argument, to illustrate this we shall look at the agent $a.b.0 \mid \overline{a}.c.0 \mid \overline{d}.e.0$.

Forwards:

$$[a.b.0]_1 \mid [\overline{a}.c.0]_2 \mid [\overline{d}.e.0]_3 \xrightarrow{1,2,\tau} \ll (2,a); 0 \gg [b.0]_1 \mid \ll (1,\overline{a}); 0 \gg [c.0]_2 \mid [\overline{d}.e.0]_3$$

$$a.b.0 \mid \overline{a}.c.0 \mid \overline{d}.e.0 \xrightarrow{\tau[k]} a[k].b.0 \mid \overline{a}[k].c.0 \mid \overline{d}.e.0$$

Reverse:

$$\ll (2,a); 0 \gg [b.0]_1 \mid \ll (1,\overline{a}); 0 \gg [c.0]_2 \mid [\overline{d}.e.0]_3 \xleftarrow{1,2,\tau} [a.b.0]_1 \mid [\overline{a}.c.0]_2 \mid [\overline{d}.e.0]_3$$

$$a[k].b.0 \mid \overline{a}[k].c.0 \mid \overline{d}.e.0 \overset{\tau[k]}{\rightsquigarrow} a.b.0 \mid \overline{a}.c.0 \mid \overline{d}.e.0$$

Again by looking at the resulting agents (going forward), this time around it is slightly clearer that we have a collection of agents in parallel. However it is not clear that communication has occurred. This requires looking in the stacks and finding the sub agent label, then matching it to the sub agent and finally, confirming that the matching sub agents stack contains the original sub agents label. Under CCSK this is much clearer as the matching keys signify communication are inline.

As can be seen from the approaches taken, while both RCCS and CCSK do similar jobs, CCSK provides a clearer syntax for the current state of the agent. It is for this reason that this project has decided to construct as simulator for CCSK as opposed to RCCS.

2.5 Conclusions

Over the course of this chapter, we looked at the concepts and constructs of CCS, RCCS and CCSK complete with the SOS rules for both CCS and CCSK. We then discussed the similarity and differences between RCCS and CCSK and while they both do similar jobs in facilitating a reversible version of CCS, we saw CCSK had a clearer syntax when compared with RCCS which allowed easier identification of the agents structure. It was due to this clear syntax that lead to the decision to design and construct a simulator based on CCSK as opposed to RCCS.

Chapter 3

Design

In this chapter, we shall look at some of the design requirements of the project as well as the concept behind our internal data structure before moving on to discuss implementation language choices. We finish this chapter with a brief feature comparison of SimCCSK with Concurrency Workbench of New Century and FDR2 and look at the concept design for the graphical user interface.

3.1 Requirements

We shall now look at the requirements of the system using WinSimCCSK as it is a superset of the SimCCSK requirements (SimCCSK does not have the graphical aspects, the Automatic Simulation feature nor the Agent Editor). We shall do this using a system based on a technique by Tom Gilb (14) and specify the requirements as either Functional (F) or Quality (Q). We explain the Quality requirements in further detail in Section 3.1.1.

WinSimCCSK (F)
- Agents (F) Simulation of agents.
  - FowardMove (F) Ability to make a forward move.
  - ReverseMove (F) Ability to make a reverse move.
  - AutomaticSim (F) Ability to automatically generate a graphical representation of the loaded agent, to a specified maximum depth.

Speed (Q) Speed of automatic simulation.
UI (F) User interface to interact with agent.
CurrentState (F) Shows current state of agent.
PreviousStates (F) Shows previous states, agent history.
GraphicalRepresentation (F) Show a graphical representation of movement through states of the agent.
EaseOfUse (Q) Ease of tool.
SuitabilityOfLayout (Q) Suitability of data layout.
Peformance (Q) Performance of tool.
AgentEditor (F) Simple built-in text editor for agent creation / editing.
Load (F) Ability to load a pre-created agent(s) from a file.
Save (F) Ability to save agent(s) to a file for future use.
LoadToSim (F) Load defined agent(s) to simulator.

3.1.1 Quality Requirement Details

WinSimCCSK.AutomaticSim.Speed

Speed of the Automatic Simulation feature is measured by the duration of time taken for it to complete. There is an obvious difficulty in measurement here as the duration of time taken is clearly linked to the complexity of the agent being simulated. As such we will base this on two measurements, one of relatively small examples which we aim to complete in a time frame of minutes (for use in a 'live' teaching scenario) and one of hours for slightly more complex ones (for use in one-off visualisations to be completed in advance, possibly overnight).

WinSimCCSK.UI.EaseOfUse

WinSimCCSK is designed as a teaching tool for students. Our aim is to keep the tool easy to use so that the focus is on the learning process calculi as opposed to learning a tool. As ease of use is difficult to quantify, we will measure this based on student feedback.

WinSimCCSK.UI.EaseOfUse.SuitabilityOfLayout

Following on from EaseOfUse, the suitability of the layout is clearly a key component in achieving this. We aim to provide the relevant information in a logical and well laid out fashion. Again as this is difficult to quantify, we will measure this based on student feedback.

WinSimCCSK.UI.Performance

Performance of WinSimCCSK in interactive mode. The performance of the tool is a key component of whether it succeeds in its aim, if the tool is too slow, it acts as an artificial barrier to learning. We aim that in the standard interactive mode of the simulator that all moves are completed almost instantaneously and certainly within a few seconds.

These requirements both functional and quality provide a conceptual snapshot of what the system should ideally achieve, look and feel like. Over the rest of this chapter we shall look into some of the design concepts and decisions involved in attempting to transform these requirements from a conceptual snapshot in to a working prototype like system.

3.2 Concept

The design of any piece of software is important as it will guide the entire development process. In this section we will look at the design concepts of SimCCSK and some of the motivation and reasoning behind them.

By looking at the rules structures and concepts of CCSK it is apparent that there are two key components: actions and agents. On further inspection one can observe that actions are always embedded in agents, however it does not follow that agents must have embedded actions. Neither does it follow that the action has or needs any knowledge of the agent it is embedded in. This gives the situation illustrated below.

Figure 3.2-1: Concept of Action and Agent

Due to the nature of the project, being to create a simulator for CCSK, a third component springs to mind, that being the simulator. The simulator itself of course would simulate CCSK agents. The agent itself does not really require any knowledge of the simulator. So we suggest that an agent can be fed into the simulator, so we can add this concept of a simulator component into our previous illustration to generate the following.

Figure 3.2-2: Concept of Action, Agent and Simulator

These three components represent the concept of a simulator for CCSK. However as we saw earlier CCSK (and indeed CCS as well) does not just have one type of agent; it has several ranging from the simple Zero agent through to the more complex Choice and Parallel agents which in themselves contain agents. While all these different agent types exist they all share a common sense of being. This can be observed for example with the Choice or Parallel agent, which connects two agents together; however it does not require a specific type of agent, it will quite happily accept any type. So this leads us to the following hierarchal concept of a CCSK agent.

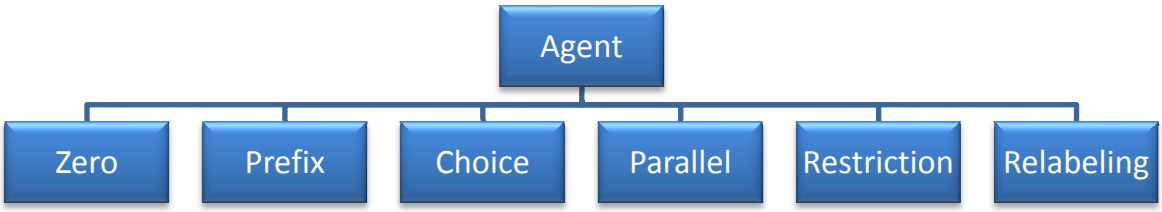


Figure 3.2-3: Concept of Agent Hierarchy

Given these two concepts (as illustrated in figures Figure 3.2-2 and Figure 3.2-3), we see that the project could lend itself to an Object-Oriented design mainly due to the possibly inherited nature of agents which could lead to polymorphism and the more general notion of objects that could be implied from the three key components.

Now that we have established that an Object-Oriented approach may be suitable, we shall now give it some more thought and look at whether or not it really would be a possible and suitable design approach.

We have suggested that inheritance could play a significant part of this design. We suggested a hierarchical approach to the agent type. Anyone familiar with a UML style class notation will already be familiar with the similarities. In fact it does of course translate into a class diagram quite easily and as such we include this concept class diagram below:

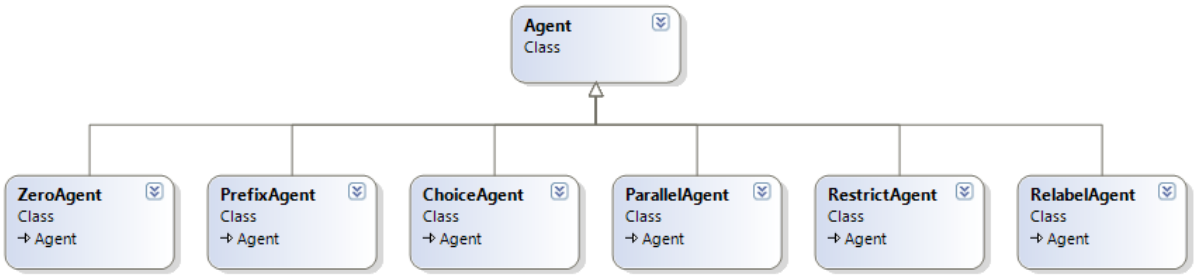


Figure 3.2-4: Inheritance Concept Class Diagram

If you look at the concept of SOS rules, you see that the rule is in a nutshell the concept behind making a move. Equally the SOS rules all apply to agents, not a single one applies to an action, although of course the actions are part of the rules themselves. This leads us down the route where by an agent can perform an action. However as we saw with the SOS rules, they are split into two sets, forward and reverse. Looking at the forward rules first we see that an agent can possibly make more than one move, Choice is a good example of this concept. In theory all agents can possibly make at least one forward move with the exception of the Zero agent. This makes sense as you would use the Zero agent as the terminating state in a agent. Earlier it was suggested that polymorphism could be used, this is a good candidate. So

we can add the default MakeMove() method to the base Agent class and subsequently override it in a derived class to take into account of the SOS rules for the agent's type. Adding the method to our diagram gives us Figure 3.2-5.

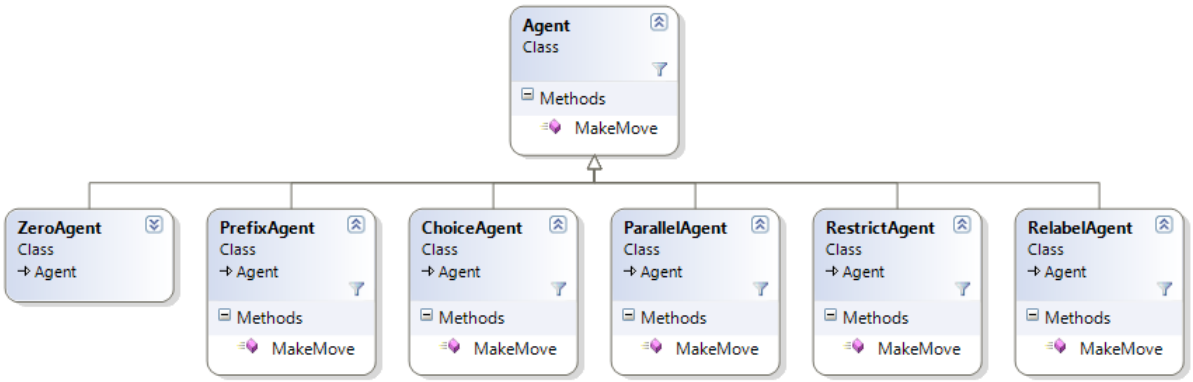


Figure 3.2-5: Inheritance Concept Class Diagram (Part 2)

Looking at the reverse moves, we clearly have something similar. Similar to forward generally we have at least one reverse move. The simple reason for this is that if you can get to a state going forwards there will always be a reverse move undoing the last forward one returning you to the previous agent. This obviously gives us the polymorphic method for reverse moves (called MakePrevMove() in WinSimCCSK). However this also gives us our first candidate for an inherited member, that being the one for the previous agent. There is of course an exception to this, that being the first agent which clearly would not have a previous agent. We can model this exception by using a null previous agent for the first, thus not impacting on the concept of the inherited member. By adding these two additions we get the following:

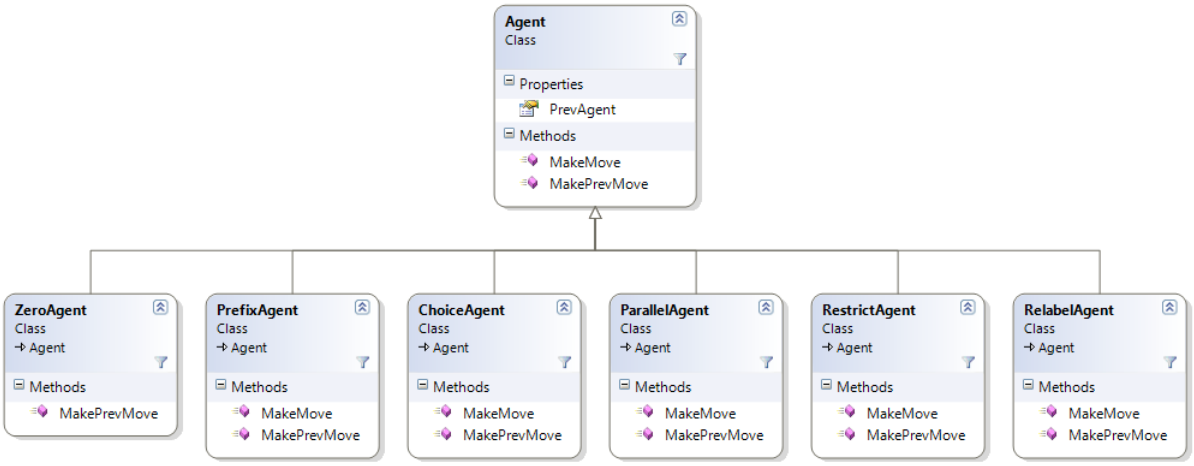


Figure 3.2-6: Inheritance Concept Class Diagram (Part 3)

We have seen that an Object-Oriented approach is both a distinct possibility along with being a highly suitable approach to take. This is due to the two key factors of the use of both polymorphism, for the shared and yet slightly different abilities of agents, along with the use of inheritance for the shared concept of a predecessor. We have shown this in a concept class diagram giving us already an idea about the layout and interaction of the software.

3.3 Internal Data Structures

In our initial concept, we came to the conclusion that agents are linked to other agents and that actions would somehow let us move between agents. A simple example is the agent $a.b.0$, this is linked to the agent $b.0$ by the action a. Now if we assume that $b.0$ links to the Zero agent, this would suggest a design looking something like this:

Figure 3.3-1: Constructing a.b.0 using a simple approach

This seems a perfectly reasonable and intuitive approach to take, however it would seem to be duplicating data, if we take a look at $a.b.0$, we can clearly see the data of $b.0$ and the Zero agent embedded in the original agent and therefore the subsequent copies are not ideal. Although we could probably get away with this when looking at such simple agents this clearly is not very scalable, if we consider agent $a.b.0 + c.d.0$, we would end up with something looking similar to this:

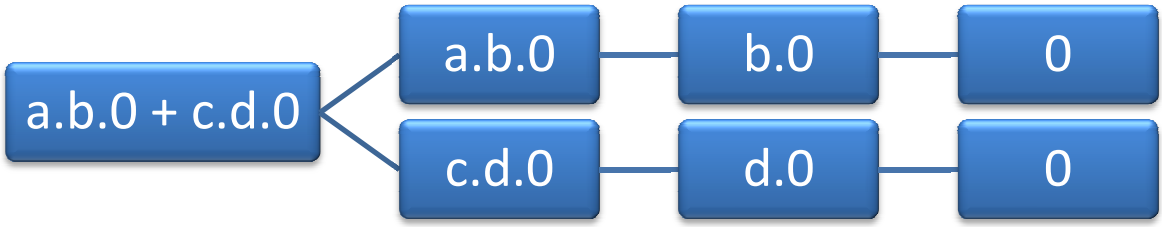


Figure 3.3-2: Constructing a.b.0 + c.d.0 using a simple approach

While it holds all the information, we still have the duplication, however we now have two branches of duplicated data, imagine what we would end up with if we had multiple choices.

It is clear that this is not going to be the most efficient way forward however parts of the concept do in fact have their uses. If we look at Figure 3.3-2 we can see the start of a tree like structure, similar derivations can be made for other constructs in CCSK. Given this we suggest that we can base the internal representation of agents using an abstract syntax tree.

If we now apply the concept of an abstract syntax tree (AST), we can break down our two examples above as follows:

- $a.b.0$ is Prefix(a, $b.0$) with action a and sub-tree $b.0$. $b.0$ can be derived similarly.
- $a.b.0 + c.d.0$ is Choice($a.b.0$, $c.d.0$) with sub-trees $a.b.0$ and $c.d.0$. These two sub-trees can be derived as above.

More generally, we can see this approach being applied to the constructs of CCSK as shown below.

$a.X$ is Prefix(a, X) with action a and sub-tree X.

$X + Y$ is Choice with sub-trees X and Y.

$X \mid Y$ is Parallel Composition with sub-trees X and Y.

$X\backslash A$ is Restriction with sub-tree X being restricted by the set of actions A.

$X[f]$ is Relabeling with sub-tree X being relabelled according to function f.

As we can see, these five definitions already give us a clear approach to a design for WinSimCCSK. They show how each agent can be defined using a combination of sub-trees and additional information to allow us to model the various aspects of CCSK. Earlier we suggested the possibly polymorphic methods of MakeMove() and MakePrevMove(). The AST approach supports this notion with a move being able to be made in a similar fashion to the SOS rules whereby the move is made if the move can be made by a component of the agent (or sub-tree of the AST in this case).

3.4 Implementation Language

Usually the process of deciding the implementation language is guided by three key technical factors. The three technical factors are:

1) the suitability of the language to the task in hand
2) the possible reuse of existing code either via existing libraries of functions which could either be custom written or more globally available APIs such as .NET or the Java API
3) the target platform(s) of the project.

Over this section we will look at these factors and how they can guide the choices of the SimCCSK project.

The suitability of a language to the task in hand is one of the most important factors which could make or break any software project. On the simplest level it is about choosing a language that matches the design concept. A programming language should always be chosen such that its coding paradigm (e.g. object oriented, functional, etc) matches that of the design paradigm. If we look at the SimCCSK project, we saw previously that the concept lent itself to an Object-Oriented approach. Of course there are several such languages, in fact Wikipedia lists over 100 different Object-Oriented languages or variants (15). It would be impractical to look at all of them here so for the rest of this discussion we shall look at C++, C#, Java and Visual Basic.

The target platform(s) of any project can often be crucial in guiding design choice. Depending on the project this could already be fixed or nearly fixed, for example a video game would be designed to work on a console of some sort, either a home based one such as the Xbox 360 or PlayStation 3 or a handheld one such as the Nintendo DS or PlayStation Portable. Most projects target platform however would be a desktop workstation PC, whilst this in itself is a decision, it raises a secondary decision. A PC by itself, whilst a platform, is not defined enough from a development perspective. Specifically a PC's platform is more usually described by either it's operating system such as Windows Vista or Mac OS X 10.5 "Leopard" or family of operating systems such as Win32 or Mac OS X. From this point, the project's platform can be chosen based on a target audience or a gap in the market. Examples of this are that most businesses use some variety of Windows so it is no surprise that a number of Office applications are designed for use on the Windows platform. Equally the world of the Mac is most often used by more creative people such as artists, musicians and film or sound editors, so equally such products are designed for the Mac platform, although a number also do have Windows counterparts. In the case of SimCCSK we do not really have either of these guiding our process as the project is more about a prototype than a commercial level software production. For this reason, along with the fact that most (if not all) universities will provide access to Windows PCs and the fact that all of the languages run on Windows, it would seem an appropriate decision to choose Windows as the platform as this does not limit our language options.

Choosing a non Windows platform would of course remove C# and Visual Basic as the .NET framework is not common place on other platforms and therefore could not be relied on.

The use of existing libraries is clearly becoming more common place. The simple reason that if everything was always written from the ground up, any software project would take far longer and be more expensive to produce. This is, of course, fairly obvious as for example at the beginning of any project the design team would spend time recreating code they had previously used for the new project. A library is a solution to this very issue. In the modern world APIs and standard libraries are more common due to the fact that a very large number of software projects are based around similar ideas at some point, whether it is that they use something as simple as a String or a slightly more complex structure such as a linked-list there are a number of key small components that make up these projects. As such most modern programming languages have some form of standard library or API to deal with this frequently used boilerplate type code. Our four languages are no exception to this, C++ has the Standard Library (16) and the Standard Template Library (17), also should the decision be made to write the software for a Win32 or Win64 platform the .NET Framework (18) (19) and associated libraries would also be an option. C# and Visual Basic both have access to the .NET Framework and Java has the Java API which is contained within the Java Platforms of which there are three, Java ME (Micro Edition) for environments with limited resources; Java SE (Standard Edition) for standard workstation environments and Java EE (Enterprise Edition) for distributed environments and the internet. For our purposes we are interested in Java SE (20) (21) and for the rest of the discussion we use Java and the Java SE platform interchangeably.

Apart from the very general language ‘standard’ APIs, other APIs or libraries can come in to play. One of our requirements for the GUI version was the ability to see a graphical representation. All four of the languages have some form of graphical drawing ability, .NET (so by extension C#, C++ and Visual Basic) and C++ (natively under Windows) have the ability to draw via GDI+ (22) (23), Java in order to maintain its cross platform nature uses Swing, however Swing results in Java based GUIs looking

different to their more native counterparts. An extension to graphical drawing is of course hardware accelerated graphics; again all four languages have some form of hardware accelerated graphics. C++ has DirectX (24) (25), which allows native based 2D and 3D hardware accelerated graphics. .NET languages have a couple of options, managed DirectX or XNA (26) (27) which is a superseding (and natural successor) of managed DirectX. XNA is officially only supported by C# currently however being .NET based it can technically be used by any .NET language. Java has the community based project of Java3D, which whilst is not quite hardware accelerated in the same sense as DirectX or XNA due to Java's cross platform nature, there is some hardware acceleration options available to it. Finally another option is a 'plug-in' style libraries for graph drawing, such as Microsoft Automatic Graph Layout (MSAGL) (28) (29) which is a project by Lev Nachmanson at Microsoft Research (Redmond) which allows graphs to be created and viewed using a .NET enabled language. Based on these observations and to allow the project to move in one of a number of directions, C# seems a suitable choice for the implementation language of SimCCSK as it allows the possible use of GDI+, DirectX, XNA or MSAGL.

3.5 Related Work

3.5.1 CWB-NC

Concurrency Workbench of the New Century (CWB-NC) (30) (31) (32) is one of the leading tools currently used for the simulation of CCS and similar process calculi created using SML of New Jersey by Rance Cleaveland, Steve Sims and Tan Li with its original release in 1996 through to its current version 1.2 released in 2000. CWB-NC is primarily text based although there is a GUI available which uses Expectk. The system allows for simulations of agents; however this is very much a unidirectional process, yet this does allow the production of a trace of an agent.

Concurrency Workbench has the capabilities to work with multiple process calculi mainly CCS and derivatives of it such as Prioritized CCS, Timed CCS and Synchronous CCS, along with Communicating Sequential Processes (CSP) and Basic LOTOS. Along with its simulation ability, it also has the ability to do bisimulation, model checking and equivalence checking.

3.5.2 FDR2

FDR2 (33) is refinement and model checker for CSP (34) (35). It is a commercial product created by Formal Systems (Europe) Ltd, which was formed in 1989 by some of the Oxford University Computing Laboratory and some of the founders of its sister company Formal Systems Design and Development Inc.

FDR2 functionality revolves around its two key functions of refinement and model checking for CSP; it is a GUI based application however it lacks any graphical representation of the system being looked at.

3.5.3 Comparison with SimCCSK

Given that there are these two simulation applications (amongst others), why use SimCCSK at all? Over this next section we shall look at some of the advantages that SimCCSK has over CWB-NC and FDR2.

	SimCCSK	CWB-NC	FDR2
Process Calculi Support			
CCSK Support	Yes	No	No
CCS Support	No[1]	Yes	No
CSP Support	No	Yes	Yes
Variations of CCS Support	No	Yes	No
Simulator Support			
Simulation of Agents	Yes	Yes[2]	Yes
Graphical Representation	Yes	Yes	No
True Reversibility	Yes	No	No
Easy to Use GUI	Yes	No	Yes
Easy to Install / Setup	Yes	No	Yes
Operating System Support			
Windows (x86)	Yes	Yes[3]	No
Linux (x86)	No	Yes	Yes
MacOSX (Intel)	No	No	Yes
MacOSX (PowerPC)	No	Yes[3]	Yes
Solaris (SPARC)	No	Yes	Yes

Figure 3.5-1: Comparison of SimCCSK, CWB-NC and FDR2

Notes:

1) Although CCS is not formally included due to the nature and similarities of CCSK converting between them is relatively simple.
2) Only trace simulation; user chooses transitions at each state.
3) Support is only available by self compilation.

Here we see that while SimCCSK does not have all the support of either Concurrency Workbench or FDR2, we can see that SimCCSK achieves its goals and is (out of the three) the only one to handle true reversibility, which means that it is the only one out of the three which can handle going backwards within the calculi. This is particularly prevalent in comparing Concurrency Workbench trace visualisation with WinSimCCSK's graph representation. In terms of language compatibility it is clear that Concurrency Workbench is the most appropriate in terms of the number of languages supported, however while FDR and SimCCSK only support the one language, SimCCSK is currently the only simulator to support CCSK. Equally while Concurrency Workbench and FDR2 have additional functionality such as model checking, it is worth remembering that the purpose of the SimCCSK project was to produce a simulator. Additionally both Concurrency Workbench and FDR2 have been around far longer and usually more functionality is added in later versions. Also it is worth noting that FDR2 does not have any form of graphical visualisation of the model (although does run in a GUI) which is something that SimCCSK has.

Finally a couple of the key points of the SimCCSK project is to create a simulator that is both simple to install along with being easy and intuitive to use. Out of the three, SimCCSK is the simplest to install as it is packaged in one file that just need to be unpacked (however it does require the .NET library to be installed, this is common place on most copies of Windows, so this has been discounted from this discussion). FDR2 comes a very close second, again being in packaged in one file that needs to be unpacked, it then requires a second small step of creating an environment variable for it before it can be run. Concurrency Workbench however is not the easiest by far, while the instructions are clear, usually it is often easiest to self compile (which requires SML of New Jersey) with whatever version of the libraries you happen to be using. This is of importance if you wish to use the GUI as Concurrency Workbence requires Expectk (version 5.20, current version 5.43), which in turn requires Tcl (version 7.5, current version 8.5) and Tk (version 4.1, current version 8.5). Based on personal experience Concurrency Workbench seems to have an issue working with the current versions, meaning that it is often easier to download and use the older versions its expecting, however this means you may end up with both the older

versions for Concurrency Workbench and a newer version for some other applications on you system.

The second point is one of usability; both WinSimCCSK and FDR2 use a GUI design similar to most modern applications. This to a certain extent makes it fairly intuitive from the start as it resembles other applications the user may be familiar with. Secondly in terms of file handling, both WinSimCCSK and FDR2 have the ability to browse file systems as part of the loading procedure (WinSimCCSK also has this for saving as well). This allows for a simple disjunction between the application and the users files. Concurrency Workbench on the other hand (probably due to its age) requires you to load the application from whatever directory you want to work in or to use absolute file paths to load the file.

So in conclusion the applications all have strengths and weaknesses. While Concurrency Workbench is probably the most feature loaded, handling multiple process calculi, allowing multiple functionality on them and coming complete with a graphical trace creating simulator this comes at a cost as it is probably the most complex to install and use. FDR2 excels at its job as a CSP model checker and, while it is relatively easy to setup and use, lacks any form of graphical visualisation of the model. Finally SimCCSK is probably the simplest to setup and use, this stems from the fact it has only one key function, the simulation of CCSK agents. It is however the only one of the three to feature true reversibility and a graph based visualisation.

3.6 Graphical User Interface Concept

The concept behind the graphical user interface is to provide a simple and relatively intuitive front end for any potential user. The key idea here is that the main form will be home to the current state of the agent along with a history of previously visited states and the possible forward and reverse moves together with a current graph of the system and its associated key. To illustrate this, a mock up of the main screen is included below.

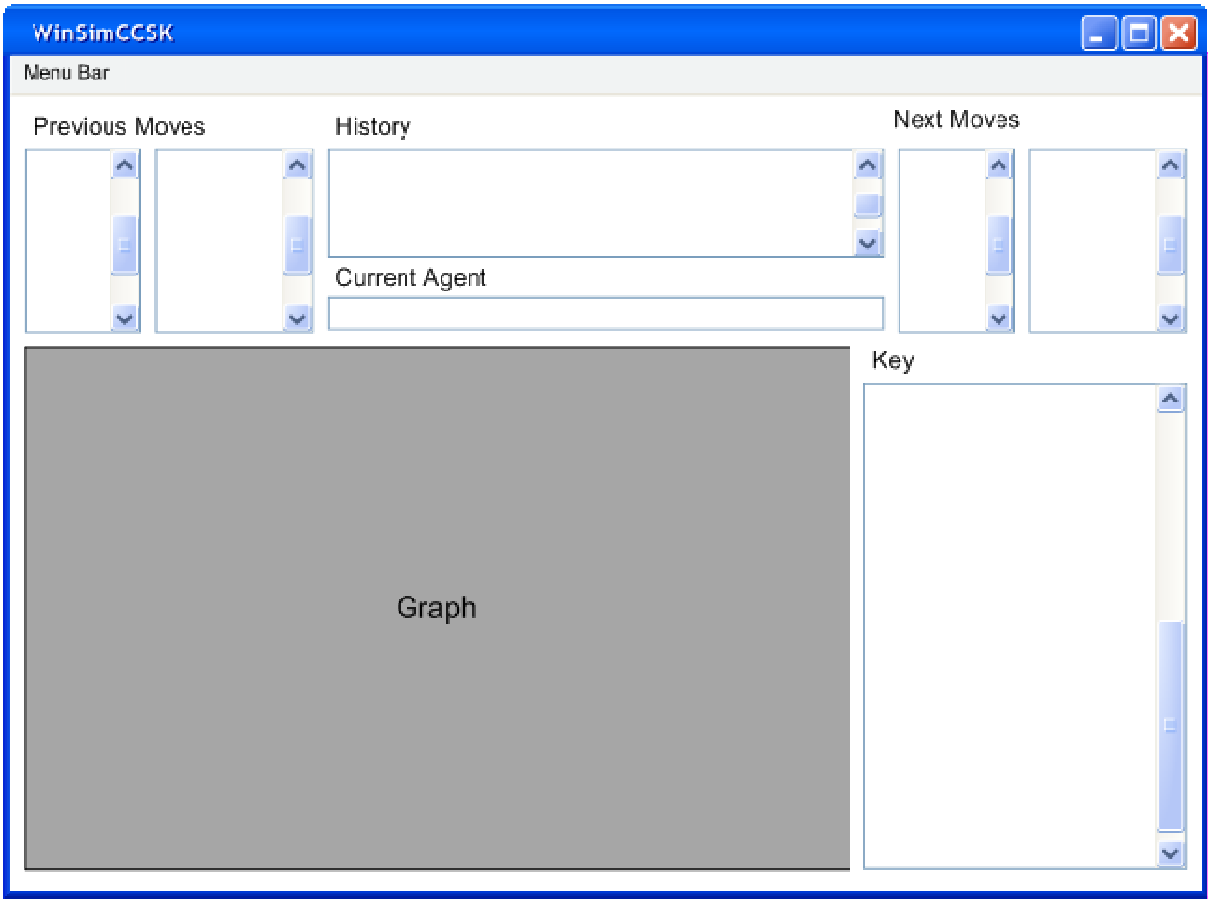


Figure 3.6-1: Mock up of WinSimCCSK Main Form

Along with the main form, WinSimCCSK will also provide an additional form for the creation of agents via a simple text editor (with save and load functionality). We can represent the movement through the functionality of the GUI using a state diagram as shown below.

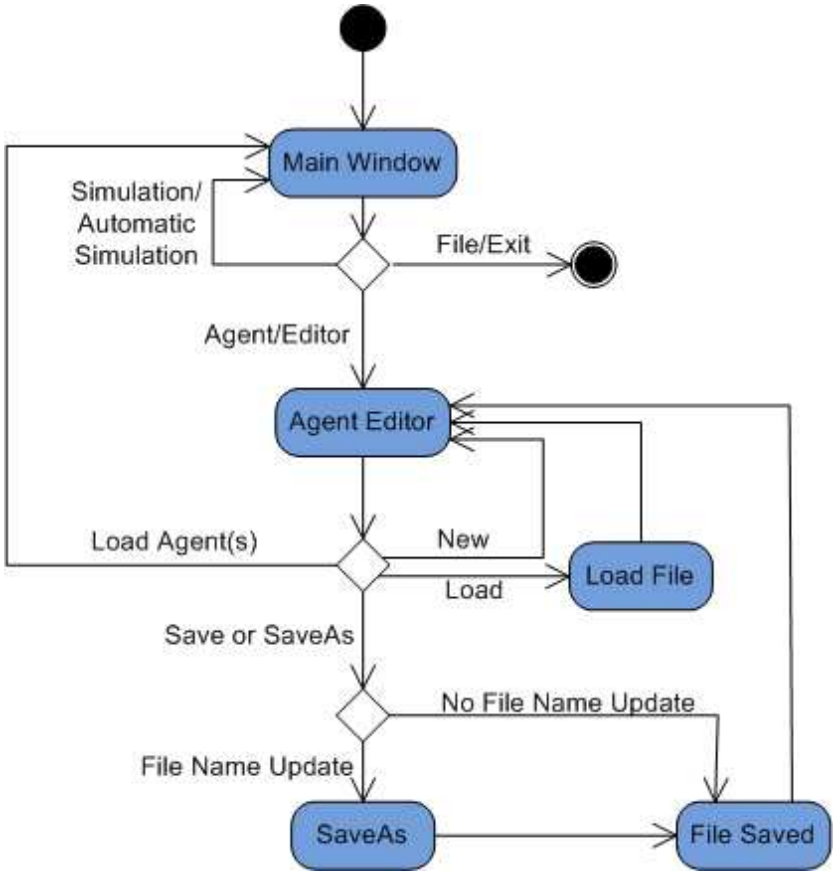


Figure 3.6-2: GUI State Diagram

3.7 Conclusions

Over the course of the chapter, we have looked at the concepts behind a CCSK simulator and its required components along with the theoretical links between them and how this would seem to suit an Object-Oriented approach. We have seen how we can take these concepts and derive a concept of a possible and feasible internal data structure. Finally we discussed an approach to choosing an implementation language and then used this approach to look at SimCCSK and chose C# as the implementation language based on the different factors involved with this project.

Chapter 4

Implementation

In this chapter we shall look into some of the implementation details of the project including the construction of the internal data structure before moving on to look at the construction and workings of SimCCSK, the console based simulator.

4.1 Laying the Ground Work

As discussed in Chapter 3, SimCCSK is designed to use an Object-Oriented approach due to the possibility of inherited attributes and polymorphism for the agent components. We then went on to show a concept class diagram for the inheritance of agents (Figure 3.2-6). From this concept diagram, we can easily add the two additional components we have identified, being the Action and the Simulator. This is shown in Figure 4.1-1 below.

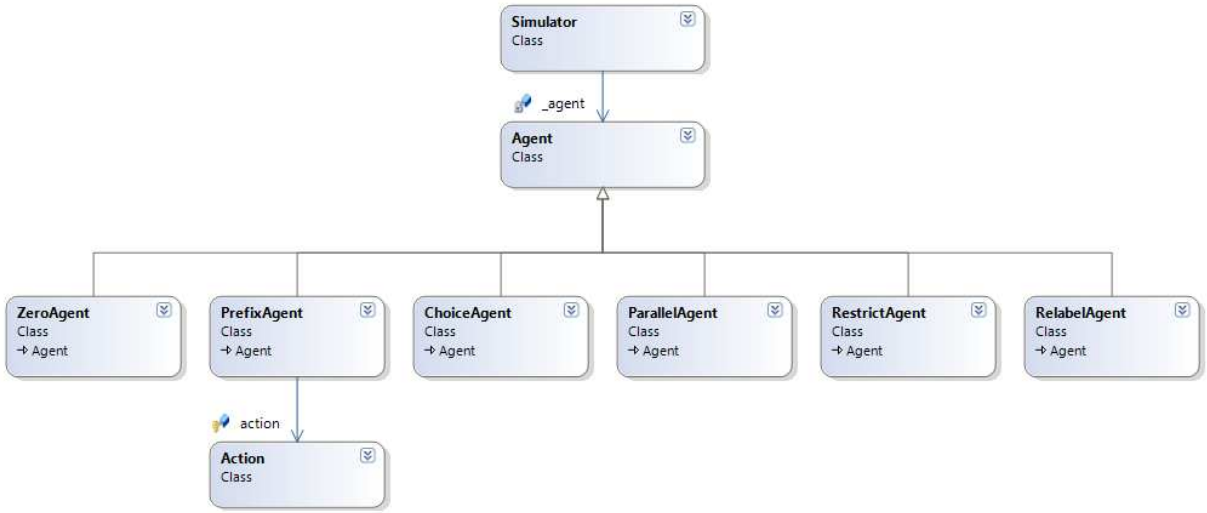


Figure 4.1-1: Class Structure of SimCCSK Core (part 1)

Figure 4.1-1 effectively shows at an overview level the class diagram of the core of SimCCSK. In practice this is not strictly true. Although it was a point along the development process, the final version of the core includes two additional 'Agent' classes, BracketAgent and LabelAgent. Whilst these two are not strictly agents in the CCSK sense, we implement them as such in order to take advantage of the polymorphic nature that comes with inherited objects, allowing the agents to be linked to any other type. These additional classes give us the core class diagram as shown below.

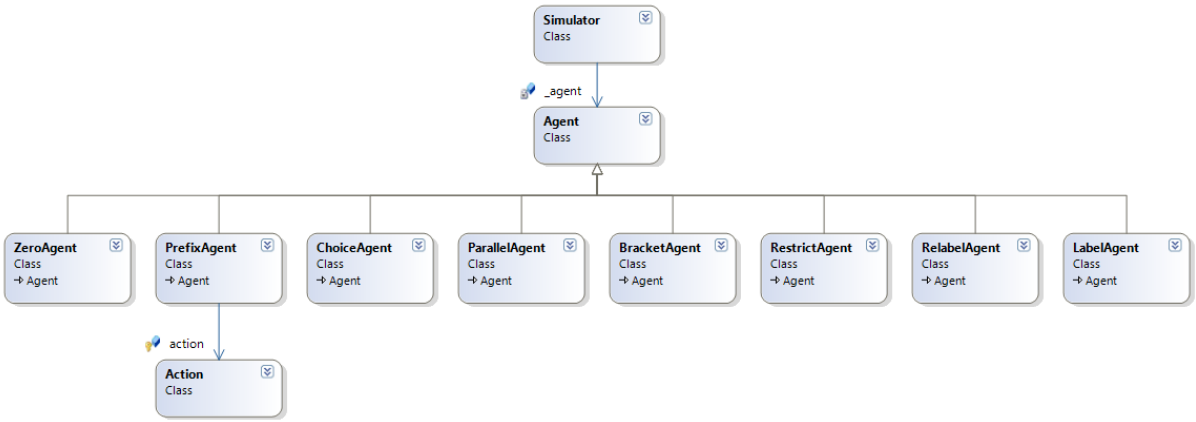


Figure 4.1-2: Class Structure of SimCCSK Core

4.2 Construction of the Internal Data Structure

It is by using the structure in Figure 4.1-2 and the polymorphic nature exposed with it that we can implement the AST described in section 3.3. For the forward moves described by the AST we use a single inherited and polymorphic method MakeMove(). MakeMove() is effectively an abstract method in the base Agent class, strictly speaking though it is not actually abstract as it does maintain some simple error generating code. It is the derived classes that actually implement the code behind the AST. Like the rules of the AST, each derived class implements the rule for its type, e.g. the Prefix class implements the AST rule for Prefix. The rules maintain next agent type independence by relating the rules to the Agent class as opposed to one of the derived types. This can be shown graphically as demonstrated by the class diagram below, which for the simplicity of the diagram we show both a single route derived class (Prefix) and a multi route derived class (Choice).

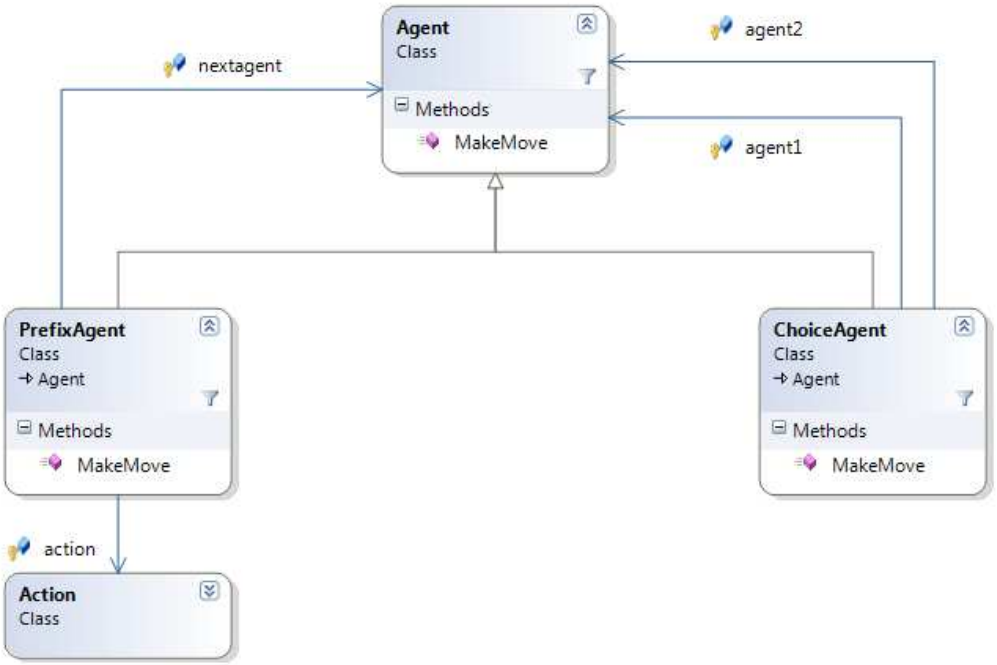


Figure 4.2-1: AST Implementation Example Class Diagram

This class diagram in essence shows the looping nature of the AST and how it is implemented internally. Basically when MakeMove() is called on the current agent, it

calls the relevant classes version e.g. Prefix, Choice, etc. From there the move is attempted to be made through the use of the next agent's MakeMove() method. This is achieved using polymorphism as each specific agent type always links to the next agent via the Agent base class, thus ensuring the relevant MakeMove() method is called. A simple example of this would be $a.b.0 + c.d.0$. Here if we call MakeMove(), the MakeMove() method of the ChoiceAgent class is called via polymorphism. We outline this method below (with error handling code removed).

```
Agent ret = null;

//Agent 1
ret = agent1.MakeMove(move);

//Agent 2
if (ret == null)
{
      ret = agent2.MakeMove(move);
}

return ret;
```

Figure 4.2-2: Code for ChoiceAgent.MakeMove()

This method represents the AST rule. Basically the code attempts to make the move on both sides of the Choice by attempting "agent1" first and if this fails then "agent2", then having successfully completed the move it returns the new agent. It is worth noting that like the "ret", "agent1" and "agent2" are both of the base class Agent type.

In our example, if we attempt to make the move a, this calls the MakeMove() method of the ChoiceAgent class. Following the code above we see this calls the MakeMove() of agent1, this by polymorphism translates to the MakeMove() of the PrefixAgent class (as the agent is $a.b.0$). This successfully returns the agent $b.0$, so back in the ChoiceAgent class we do not execute MakeMove() for agent2 and return the correct resulting agent of $b.0$. Had we chosen to make the move c, MakeMove() for agent1 would have failed and returned a null pointer, thereby triggering MakeMove() for agent2.

We use the approach of mirroring the AST rules for the agent types, as such most call their sub agents in an attempt for the move to be completed successfully. Just like in

the AST rules, it stops at one of two points, the first is when we hit the Zero agent and as such have been unsuccessful and null is returned. The second is when we hit a Prefix agent, the agent checks the move against the action it is related too. If the Prefix's action and the Move's action match, it makes to move (by updating the Prefix's action with a key) and returns the resulting agent, if not it returns a null pointer. We can encapsulate this idea in the following bit of pseudo code:

```
if (action == move.action)
{
      UpdateAction();

      return nextagent;
}

return null;
```

Figure 4.2-3: Pseudo code for Prefix.MakeMove()

In order to maintain the agent's structure throughout any simulation it is important that any move made is effectively non-destructive and all of the information remains. To achieve this in SimCCSK a pointer based system is used, whereby a pointer points to the "current" working agent in a fashion similar to a destructive CCS equivalent where a pointer would point to the agent. This allows us to make moves which only make alterations to some internal data, specifically the keys associated with past moves and then moving the pointer to the new "current" agent. If we consider the agent $a.b.0$ after we have made the move a we have the agent $a[0].b.0$, now this means that our "current" agent is $b.0$ as it would be in CCS. However we still retain the information about the past action a, so we are able to reverse it.

We achieve this in the simulator by using the approach intrinsically built for the AST. In fact we actually glossed over it earlier. We pointed out that MakeMove() returned an agent if it was successful. It is this very agent that we define to be the "current" agent when it is returned to the simulator class (by the original MakeMove() call). Inside the Simulator class we update the "current" pointer to be the result of that call. The call itself originates from the "current" pointer, thereby the "current" agent

returns the next "current" agent on a successful return of MakeMove(), as shown by the line of code below.

```
current = current.MakeMove(move);
```

Figure 4.2-4: Calling MakeMove() and Updating "current" Agent

In order to maintain access to the entire agent (and by extension its current state) we also maintain a second pointer in the Simulator class, the head of the AST, which allows access to the current state of the agent for outputting to the user.

These two concepts combined encapsulate the functionality of MakeMove() for all agent types. We can represent the simulator MakeMove() sequence graphical as shown below.

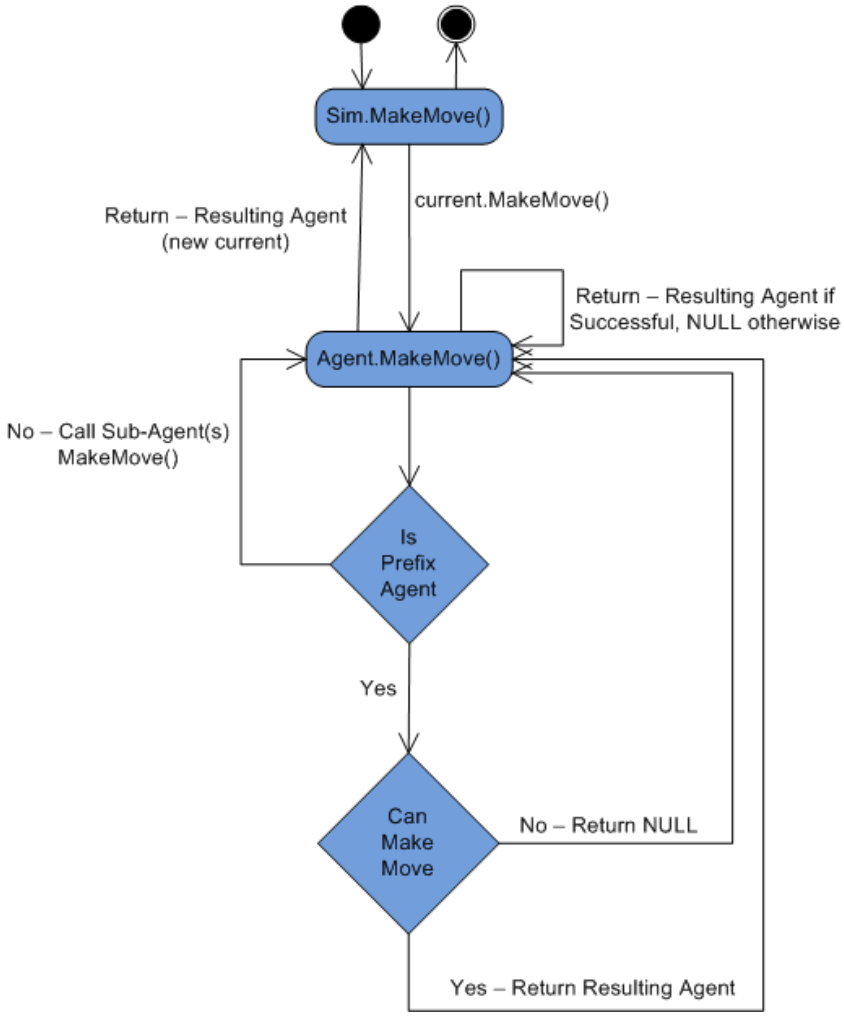


Figure 4.2-5: State Diagram for MakeMove()

As previously stated the functionality of the AST rules are encapsulated in each derived agents MakeMove() method. All work in a similar way, attempting to make the move and if successful returning the new "current" agent. However there is a subtle difference with the Parallel agent. The key reason for this is the maintaining of its structure in a non-destructive fashion whilst retaining its parallel functionality. In SimCCSK we achieve this by deploying a local pointer system (within the scope of the parallel agent), on top of the global "current" agent pointer system as described earlier.

If we look at the other agent types, they all share a destructive nature in that once the agent has been executed it has no influence on its sub agents. Parallel is different in that the parallel composition lives on between the sub agents. For the Parallel agent, in order to preserve the history of the agent, we duplicate the concept of the "current" agent at a local level. Instead of MakeMove() returning the next agent in the sequence to become the current agent, Parallel agents return themselves in order to continue the parallel composition across the sub agents. This however only tells half of the story, clearly if an agent just returns itself, nothing has changed and we would be able to make the move indefinitely without achieving anything. To solve this problem, Parallel agents act based on their local "current" sub agents. As such MakeMove() in a Parallel agent updates the "current" sub agents using exactly the same approach we took for agents in general.

For reverse moves we use the method MakePrevMove() to go back up, utilising a common inherited member "PrevAgent". PrevAgent as stated earlier always links back to its parent agent (with the exception of the root agent, in which case it is null). For the majority of agent types MakePrevMove() calls up the tree to check for the reverse move and if found is returned as the new "current" agent to pass back to the simulator, in a similar approach to MakeMove(). Parallel of course is an exception to this, due to the introduction of the local "current" sub agents. In the case of Parallel, MakePrevMove() utilises a similar approach on the "current" sub agents, reversing them back up towards their initial states. Should the Parallel agent be in its original state (i.e. all sub agents are in their original state), then Parallel calls up the tree using the same approach as the other agent types.

For both forward and reverse moves, the Parallel agent type is further expanded in order to deal with communicating moves. In the case of communicating moves, the Parallel agent attempts to perform (or reverse) the action and its counterpart on two distinct sub agents and only if it can achieve both does it update the two relevant "current" sub agents. Communicating moves are distinguished from non communicating moves by an addition prefix of "t->" for the communicating ones. Equally communicating moves a denoted using their action as opposed to its counterpart (overbar version).

4.3 Putting it Together

Now with the ground work and internal structure laid out, it is time to put these together to create SimCCSK. SimCCSK is a console based, command line driven application (although as hinted at, a graphical counterpart WinSimCCSK also exists which will discussed in Chapter 5), based around a core setup. This core revolves around the design of a Simulator object which processes an agent which itself is a combination of actions and agents constructed as previously discussed. On top of this sits the command line interface which is designed with the notion of informing the user what state they are in and then providing the options for moves in both a forward and reverse direction.

This is in fact the core loop of the application after loading an agent. Provided that the execution is not halted, the simulator will continuously calculate the possible forward and reverse moves (using a similar method to MakeMove()). Once the move lists have been generated it provides the current state of the agent, lists the possible forward and reverse moves to the user and then the simulator will make a move from the list based on user input (using MakeMove()). After successful completion of the move it updates the state of the agent and starts the loop again.

The state itself is represented using the standard CCSK representation which has been used throughout this document. The single exception to this is that due to the

limitations of a console terminal, in particular creating an overbar, the overbar is represented using a prefixed ‘ (single quote). The moves themselves are represented in two parts, the action associated with that move and the resulting agent of that move strand. This is represented using the following notation <*identifier*> -- <*action*> -> <*resulting agent*>. The *identifier* is simply a positive integer used to identify the move to allow easy selection of that move, the *action* clearly gives us the move and the *resulting agent* is included to provide clarity when two or more agents have identical names and are yet distinct and separate. An example of the would be $a.b.0 + a.c.0$ which has two a moves one leading to b the other c. All this put together produces something similar to the following example (based on $a.b.0 + c.d.0$):

```
Simulator Status:
Current Agent: a.b.0 + c.d.0

Possible Next Moves:
-- a --> b.0
-- c --> d.0

Next Move:
```

Figure 4.3-1: Example of SimCCSK interface (a.b.0 + c.d.0)

This example shows the output produced on each trip around the loop, the loop of course makes a single transition (either forward or reverse) during each trip. There is one minor exception to this which is in the event of user error in selection of a move i.e. selecting a move that does not exist or typing some other random thing. For added clarity the output is generated again, however it is worth noting that the moves are not recalculated, only the text is output again. Further to this, in the event we have a communication move, this too is displayed in the move list. However it uses a special syntax to identify it as a communication move. The *action* part of the move list is altered by prefixing "`t->`" to the action label. It is worth noting that this notation is also used in WinSimCCSK which we shall look at later. An example of this would be $a.b.0 \mid {'a}.c.0$:

```
Simulator Status:
Current Agent: a.b.0 | 'a.c.0

Possible Next Moves:
-- a --> b.0
-- 'a --> c.0
-- t->a --> b.0 | c.0

Next Move:
```

Figure 4.3-2: Example of SimCCSK interface (a.b.0 + 'a.c.0)

Other than the move list, there currently exists only one other command which is 'quit', its effect being to halt execution of the agent. At this point you would have the option to load another agent and start the process again.

4.4 Conclusions

Over the course of this chapter, we have looked at the basic constructs of SimCCSK. We have also looked at how a pointer-based system is deployed to maintain the current state of the agent in a non-destructive manner along with how the pointer-based system operates on the slightly more complex agents of Choice and Parallel. Finally we looked at how this was implemented in a console-based, command-line driven application and how this application provided a simple and easy to understand user interface.

Chapter 5

WinSimCCSK

Over the course of this chapter we shall see how SimCCSK was adapted and extended for a graphical world, resulting in WinSimCCSK. We then demonstrate WinSimCCSK's functionality by way of three examples.

5.1 SimCCSK for a More Colourful World

Had this project been undertaken 20 years ago, to a certain extent it would have been console based as command line driven programs were fairly common place. However fast forward 20 years and this is not the case, we now live in a more colourful world. Graphical user interfaces are now common place with very few console based applications. GUIs are on most users wish lists, since console based applications are just a little alien now. This is of particular importance from a teaching standpoint as the large majority of students grew up in a world populated with GUIs and that raises the question of whether we are teaching them how to use a specific application or whether we are trying to teach them a calculus. Clearly most students are likely to feel more comfortable using a GUI based application. This is due to the reason that GUI based applications will seem at least vaguely familiar and this of course would, to a certain extent, get around the issue of trying to teach them the aspects and use of the tool and allow the tool to aid them in their learning of process calculi. Based on this idea WinSimCCSK was born.

WinSimCCSK is at its core the same application as SimCCSK, in fact the entire core program is the same. The key difference is instead of a console based user interface that sits on top of the core simulation system, this time around we have a GUI that sits on top of it. The GUI links with the Simulator object in a similar way to its console based counterpart. The GUI itself is built using .NET based around the design proposed earlier, it features a collection of list boxes showing forward and reverse moves and resulting agent expressions, in a similar way to the console based version. It also includes the expression of the current agent again like in SimCCSK. In addition it also includes a state history, showing in sequence every state visited thus providing the route navigated through the agent. In order to assist with reference, the state history also includes the key to the state on the graph (which will be discussed later in this section). Finally, as has already been hinted at, there is the graph visualization and key, linking the nodes on the graph to a state of the agent. It is also worth noting that the window is resizable and that the components resize sensibly with it. For reference we now include a screen shot of the main window on loading (with default agent 0).

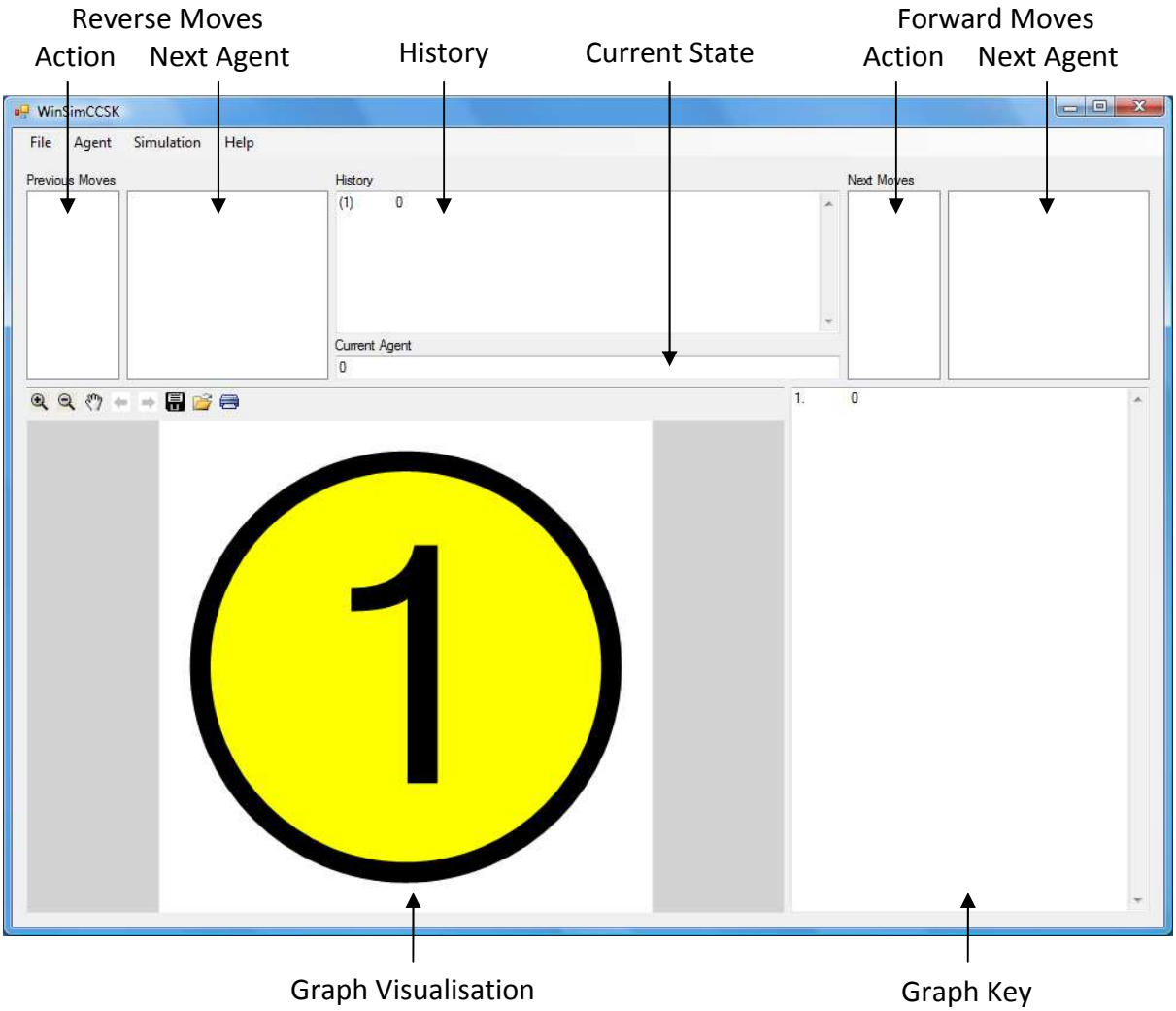


Figure 5.1-1: WinSimCCSK Main Form

WinSimCCSK also provides an agent editor, which is a simple text editor to edit agent expressions from within the program removing the need for an additional editor and comes complete with saving and loading functionality for future reuse. The saving and loading system links in with the operating system therefore allowing easier navigation through the file system. This in turn allows the user files to be stored anywhere, thereby separating the program from user files which is a key benefit from a teaching perspective as this allows the program to be stored either locally or in a network location whilst allowing students to store their files in their own user area. WinSimCCSK also provides one additional functionality not found in its console based equivalent, which is automatic simulation, whereby the program automatically (up to

a certain depth), generates the graph of the agents' possible movement, allowing a quick way of seeing the behaviour of an agent.

The graph visualisation is a key component of WinSimCCSK and is generated using the Microsoft Automatic Graph Layout (MSAGL) tool from Microsoft Research (Redmond). It is currently being used in this project under an academic license. The MSAGL tool provides two key advantages to the project. The first advantage is the integration of a graph into the project. The graph component itself has two parts of interest. The first is the graph itself which allows the construction of nodes and edges. The second is a graph viewer, which comes with the added benefits of being able to save (and subsequently load) the graph visualisation in two formats. The first format is to be viewed from the graph viewer and as such within WinSimCCSK at a later date. Although this graph would now be independent of the WinSimCCSK system, meaning that you would only be able to view the graph as opposed to interactively navigate through it. This would mean that the states of the system would not be reloaded in to WinSimCCSK simulation engine. The alternative (and probably more useful in this case) is the ability to export the graph as an image, thus allowing completed graphs to be saved in a multi application and multi platform use.

The second advantage stems from the fact that given a graph MSAGL will always draw the graph in a similar way, such that the overall structure of the graph will always look the same although certain parts may be flipped around. This means that two or more independent simulations of an agent, will result in a graph that structurally looks identical with the exception that some of the parts and labels are moved around (depending on execution order). This results in a positive benefit from a teaching tool standpoint as this allows the students to easily reproduce the graphs regardless of the execution order.

WinSimCCSK uses MSAGL to construct the graph using a combination of built in methods and some additional custom ones, that aid in the navigation of previously existing and visited nodes along with a couple that aid with the construction of edges within previously existing nodes. Due to the nature of keys within CCSK, the only rule being that they must be unique (or have only one matching in the case of

communication), means that the text based version of a state is slightly different dependent on the keys.

An example of this is if we take the agent $a.b.0$ and perform the action a. We would have $a.b.0 \xrightarrow{a[k]} a[k].b.0$ for all k but for the purposes of this example we shall just use only keys 1 and 2 giving us $a[1].b.0$ and $a[2].b.0$ respectively. Clearly these are equivalent from a theoretical standpoint as all we are really interested in is the fact we have performed the action a. Equally these should give rise to the "same" graph as well. However imagine we make the move with key 1 first, reverse it then make the same move with key 2, clearly we would expect to be in the same state, so how do you convince a computer of that? The solution used in WinSimCCSK is construction of an "absolute" agent (which is explained in the next paragraph). Given any agent with any key combination, it always produces the same result, thus giving two agents as before we would end up with the same "absolute" agent for both, thus if we base the graph around the "absolute" agent as opposed to the current agents text equivalent, we would end up in the same state, thus producing the same graph no matter what the key values are.

We define the "absolute" agent as the agent as if created with keys in sequential order starting with zero from left to right, e.g. $a[0].b[1]$. In the event of a communicating key, both would be substituted with the same key. So an example of this would be that both the following agents $a[3].b[4]$ and $a[57].b[58]$ would generate an "absolute" agent of $a[0].b[1]$. Effectively we can achieve this by some simple text post-process manipulation, whereby we go through the string and substitute the keys from left to right, starting with zero, making an exception for the communication keys. We outline the algorithm we use below using pseudo code.

```
currentkey = 0;

foreach (token t in AgentString)
{
	if(t is a Key)
	{
		if(t is in keylist)
		{
			AbsoluteString += keylist.newkey(t);
		}
		else
		{
			AbsoluteString += currentkey;
			keylist.Add(t, currentkey);
			currentkey++;
		}
	}
	else
	{
		AbsoluteString += t;
	}
}
```

Figure 5.1-2: Pseudo code for "absolute" Agent Generation

Now from a strict CCSK standpoint the first two agents are different and therefore would produce different graphs, which would look identical just with different key values. However for WinSimCCSK we take the idea of a visualisation as opposed to a completely accurate graph. This is useful from a teaching standpoint as we are more interested in the general layout of a graph for an agent than a specific graph and as such are more interested in whether or not an action is keyed as opposed to the key value. We can do this as the two graphs are similar. Using some thought out selection of keys the same graph layout could be generated by hand. It is also worth noting that we take this approach as currently WinSimCCSK allocates the keys automatically (again sequentially from 0). Without this abstraction based on the concept of the fact that an action is keyed as opposed to the value of the key being important, we avoid what would be an infinitely branching graph. Every time we reversed a move we would be unable to return to the previous state we were in as the key would be different, using this abstract visually we return to the same state.

We then use the “absolute” agent as the value of any given node, thus creating a visualisation based on the actions performed as opposed to the values of keys used. However this clearly would make the graphs completely unreadable if we were to label each node with the “absolute” agent. As such instead, as suggested earlier, we

use a key based system instead. Each time we visit a new node, we create a key for it and add it to the key list, the keys are sequentially generated starting with one. After every move, we generate the "absolute" agent and check for its presence in the key list, if it already exists, we move to that node. If not we generate a new node and add it to the graph.

5.2 Examples

Over the course of this section we shall look at several examples, illustrating WinSimCCSK and some of its functionality.

5.2.1 The DNA System

Our first example is a simple one from molecular biology based around gene expression (as taken and adapted from (7)). In this example, we have a complex protein machinery (denoted by A) which has to bind to the DNA strand. However in our example we have two inhibitors I1 and I2. I2 is trying to bind to the same site on the DNA as A and I1, which if it binds to the DNA prevents the DNA from folding correctly, which results in the gene not being expressed. The situation can be summarized graphically as shown in Figure 5.2-1 (as taken and adapted from (7)).

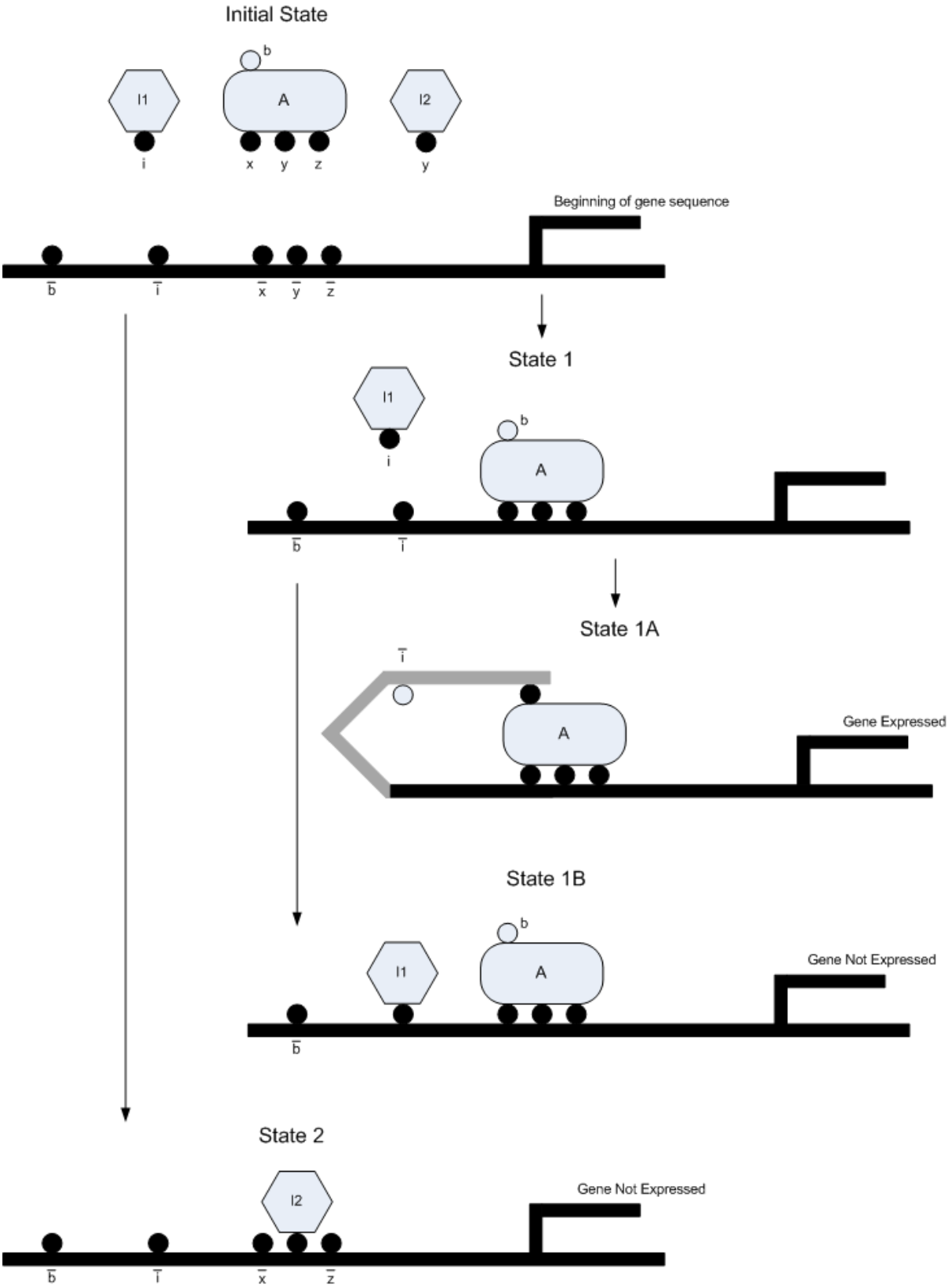


Figure 5.2-1: Illustration of Gene Expression

In our example because A has to bind on x, y and z prior to binding on b, it would seem natural to write $A = (x \mid y \mid z).b.exp.0$, however clearly we cannot write it like this as this is not valid under CCSK (or CCS either) as we are not allowed to prefix an agent to another agent. In order to construct this effectively we have to use the expansion law from CCS, whereby we expand $(x \mid y \mid z)$ and then attach $b.exp.0$ to the end of each of the expanded terms. This would give you the following:

$$A = x.(y.z.b.exp.0 + z.y.b.exp.0) + y.(x.z.b.exp.0 + z.x.b.exp.0) + z.(x.y.b.exp.0 + y.x.b.exp.0)$$

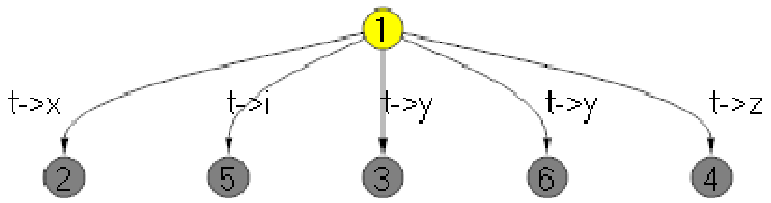
From this we can generate and use the following model in CCSK:

$$DNA = \overline{x}.0 \mid \overline{y}.0 \mid \overline{z}.0 \mid (\overline{b}.\overline{exp}.0 + \overline{i}.0)$$

$$I1 = i.0$$
$$I2 = y.0$$

$$Gene = (A \mid DNA \mid I1 \mid I2) \backslash \{x, y, z, b, i, exp\}$$

Once loaded into WinSimCCSK, we are presented with the five possible moves, three being binding of A to the DNA strand and one move from each of the inhibitors. At this point it is worth noting that WinSimCCSk uses the same notation of "t->" followed by the action label for symbolising communication over that channel. Visualizing this as a graph (created using the Automatic Simulation feature in WinSimCCSK[1]), we generate the following:



Already at this point we have two of the five routes that result in the gene not being expressed due to the activation of the inhibitors (namely t->i and one t->y, the other being the binding of connector y between A and the DNA strand). This already highlights a need for reversibility which is possible in CCSK and WinSimCCSK as

[1] Note: Due to the way the Automatic Simulation feature in WinSimCCSK generates the graphs, the numbering of the nodes is not consistent between the graphs of different depths and this is purely cosmetic and does not affect the structure of the graph.

although it is possible to continue making moves from these two states, no combination of forward moves will result in the gene being expressed. If we were using a trace based approach with no backtracking, as is common in CCS (as the agents defined above, are valid in CCS as well), if we wanted the gene to be expressed we would be required to start again from the beginning choosing a different route.

If we follow the graph to the next level of depth, we generate Figure 5.2-3. We now have 12 possible states at depth 2, of which only 6 have the possibility of expressing the gene (this compares with 3 of five at depth 1). This indicates that the chance of success is reducing, therefore if the route taken was based on non-deterministic choices of transition, even just at a depth two; it is likely that we will need at least two attempts to have the possibility to get the gene expressed if we have no concept of reversibility. This is due to only 6 out of 12 states having this possibility which leads us to the chance of being in such a state as 1 out of 2.

By the time we complete the graph (as shown in Figure 5.2-2 to give an idea of structure as the graph has 54 different states with a maximum depth of only 5 and the image is over 2000 pixels wide), we only have 6 out of 14 final states that express the gene. The number of routes that lead to the gene not being expressed is far greater while only six routes lead to the six nodes that express the gene.

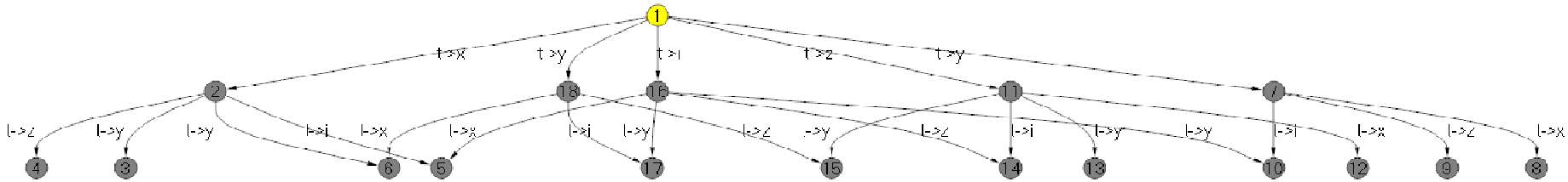


Figure 5.2-3: DNA Graph at depth of 2

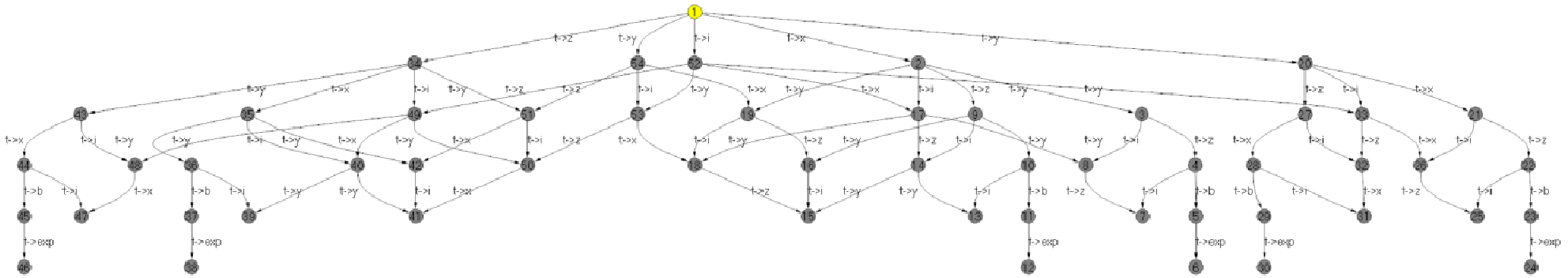


Figure 5.2-2: Complete DNA Graph

Now that we have seen the need for reversibility at a somewhat conceptual level, we shall take a concrete example illustrating the advantage of reversibility as opposed to a non-back tracking approach. Starting from the initial state we now present a possible computation trace:

$$(A \mid DNA \mid I1 \mid I2) \backslash \{x, y, z, b, i, exp\}$$

$$\xrightarrow{\tau[1]}$$

$$\begin{aligned}&(x[1].(y.z.b.exp.0 + z.y.b.exp.0) + y.(x.z.b.exp.0 + z.x.b.exp.0) + z.(x.y.b.exp.0 \\ &\qquad + y.x.b.exp.0) \\ &\mid \overline{x}[1].0 \mid \overline{y}.0 \mid \overline{z}.0 \mid \left(\overline{b}.\overline{exp}.0 + \overline{i}.0 \right) \\ &\mid I1 \mid I2) \backslash \{x, y, z, b, i, exp\}\end{aligned}$$

$$\xrightarrow{\tau[2]}$$

$$\begin{aligned}&(x[1].(y[2].z.b.exp.0 + z.y.b.exp.0) + y.(x.z.b.exp.0 + z.x.b.exp.0) + z.(x.y.b.exp.0 \\ &\qquad + y.x.b.exp.0) \\ &\mid \overline{x}[1].0 \mid \overline{y}[2].0 \mid \overline{z}.0 \mid \left(\overline{b}.\overline{exp}.0 + \overline{i}.0 \right) \\ &\mid I1 \mid I2) \backslash \{x, y, z, b, i, exp\}\end{aligned}$$

$$\xrightarrow{\tau[3]}$$

$$\begin{aligned}&(x[1].(y[2].z[3].b.exp.0 + z.y.b.exp.0) + y.(x.z.b.exp.0 + z.x.b.exp.0) + z.(x.y.b.exp.0 \\ &\qquad + y.x.b.exp.0) \\ &\mid \overline{x}[1].0 \mid \overline{y}[2].0 \mid \overline{z}[3].0 \mid \left(\overline{b}.\overline{exp}.0 + \overline{i}.0 \right) \\ &\mid I1 \mid I2) \backslash \{x, y, z, b, i, exp\}\end{aligned}$$

$$\xrightarrow{\tau[4]}$$

$$\begin{aligned}&(x[1].(y[2].z[3].b.exp.0 + z.y.b.exp.0) + y.(x.z.b.exp.0 + z.x.b.exp.0) + z.(x.y.b.exp.0 \\ &\qquad + y.x.b.exp.0) \\ &\mid \overline{x}[1].0 \mid \overline{y}[2].0 \mid \overline{z}[3].0 \mid \left(\overline{b}.\overline{exp}.0 + \overline{i}[4].0 \right) \\ &\mid i[4].0 \mid I2) \backslash \{x, y, z, b, i, exp\}\end{aligned}$$

At this point we are in the position whereby both the DNA and inhibitor I1 have successfully bound to the DNA strand (as illustrated in Stage 1B in Figure 5.2-1). Due to the inhibitor the DNA strand cannot fold properly to allow the binding of connector b and therefore the gene cannot be expressed.

We now have the following trace:

Figure 5.2-4: Trace of A and I1 binding on DNA

Under a non-reversible trace approach, we would have to go back to the start and repeat the process up to the last transition (where the inhibitor bound) to select the alternative route, which in our example is the folding of the DNA and binding on connector b. However due to the reversible capabilities (which in fact models what would happen in the bio system itself) we can reverse the inhibitors binding and then again move forward with the binding on connector b.

This leads to a successful expression of the gene, which can be observed in the following computation:

[From Above]

$\overset{\tau[4]}{\twoheadrightarrow}$

$(x[1].(y[2].z[3].b.exp.0 + z.y.b.exp.0) + y.(x.z.b.exp.0 + z.x.b.exp.0) + z.(x.y.b.exp.0 + y.x.b.exp.0)$
$| \overline{x}[1].0 | \overline{y}[2].0 | \overline{z}[3].0 | (\overline{b}.\overline{exp}.0 + \overline{i}.0)$
$| I1 | I2) \backslash \{x, y, z, b, i, exp\}$

$\overset{\tau[5]}{\longrightarrow}$

$(x[1].(y[2].z[3].b[5].exp.0 + z.y.b.exp.0) + y.(x.z.b.exp.0 + z.x.b.exp.0)$
$+ z.(x.y.b.exp.0 + y.x.b.exp.0)$
$| \overline{x}[1].0 | \overline{y}[2].0 | \overline{z}[3].0 | (\overline{b}[5].\overline{exp}.0 + \overline{i}.0)$
$| I1 | I2) \backslash \{x, y, z, b, i, exp\}$

$\overset{\tau[6]}{\longrightarrow}$

$(x[1].(y[2].z[3].b[5].\exp[6].0 + z.y.b.exp.0) + y.(x.z.b.exp.0 + z.x.b.exp.0)$
$+ z.(x.y.b.exp.0 + y.x.b.exp.0)$
$| \overline{x}[1].0 | \overline{y}[2].0 | \overline{z}[3].0 | (\overline{b}[5].\overline{exp}[6].0 + \overline{i}.0)$
$| I1 | I2) \backslash \{x, y, z, b, i, exp\}$

The above trace which contains reverse moves can be drawn as a graph (shown below in Figure 5.2-5) with the successful expression of the gene. However it is worth noting that the graph still shows that we visited the state in which the inhibitor had bound, and indicates that we went back and took an alternative route.

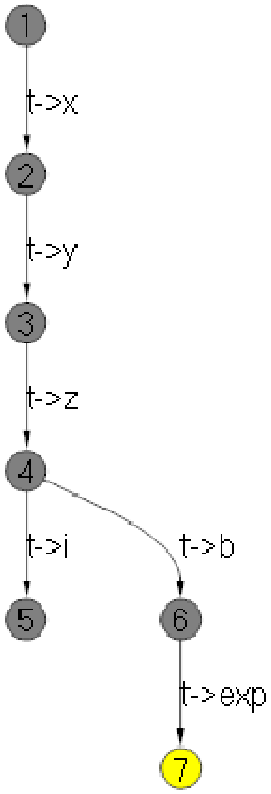


Figure 5.2-5: Trace back tracking binding of I1 to allow expression of gene

Over the course of the relatively simple example we have seen how CCSK and in turn WinSimCCSK can allow for the easier modelling of systems prone to deadlocking such as this biological system, it has also shown how the additional functionality of backtracking in a process calculi helps better represent system's behaviour.

5.2.2 The Jobshop

The second example we shall look at is the Jobshop (as taken and adapted from (1)), which models a fairly simple production line; the pieces (a base and a peg, together called a job) come in to the system, are constructed into an object called done(job) and then output. The production line features two workers (which we shall call Jobbers) and two tools, a hammer and a mallet. The construction is completed either by hand (for simple jobs), using a hammer (for hard jobs) or by using a tool (for all other jobs). We shall assume that the distribution of easy, hard and all other jobs is

even and that we shall simulate this very simply by just using a non-deterministic choice. This translates to the following CCSK agents:

$$Hammer = geth.puth.Hammer$$
$$Mallet = getm.putm.Mallet$$

$$Jobber = in.Start$$

$$Start = Finish + Usehammer + Usetool$$

$$Usetool = Usehammer + Usemallet$$
$$Usehammer = \overline{geth}.\overline{puth}.Finish$$
$$Usemallet = \overline{getm}.\overline{putm}.Finish$$

$$Finish = out.Jobber$$

$$Sys = (Jobber \mid Jobber \mid Hammer \mid Mallet)\backslash\{geth, puth, getm, putm\}$$

These agents can be loaded in to WinSimCCSK and then we can explore the various states of the system Sys. A key point to note here is that Sys is a recursive agent so any simulation of Sys via WinSimCCSK will not lead to a terminating state.

We shall follow this example with the aid of WinSimCCSK and the graphs it generates; once again the numbering of the nodes is not consistent between the graphs of different depths. Once loaded into WinSimCCSK (note for ease of reading the graphics, some action names have been shortened) we can see that two moves are possible, being in and in respectively. Note that they are the two different in moves, one for each Jobber.

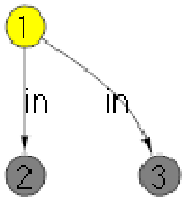


Figure 5.2-6: Jobshop graph at depth 1

Performing the in move would open up four new moves for that Jobber (being communication over $geth$ and $getm$ from Usetool, communication over $geth$ from Usehammer) and out from Finish. This would mean there are nine distinct states you could be in after just two moves, the four new moves per Jobber (depending which

made the first move as described above) along with the remaining possibility of both Jobbers just making their first move only.

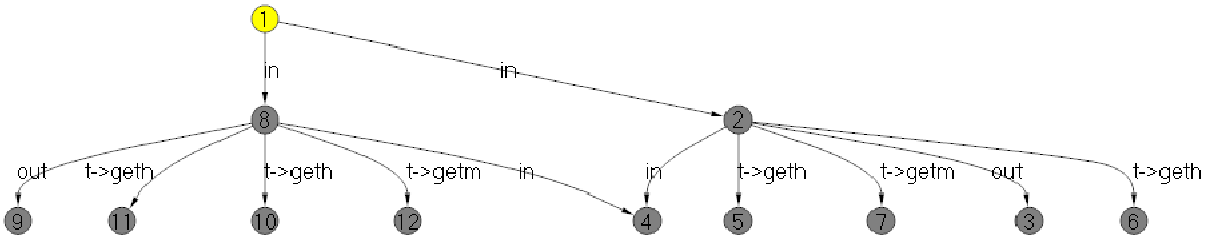


Figure 5.2-7: Jobshop graph at depth 2

From here each state which saw a single Jobber make two moves then has possibilities coming from it; one being the next move of that Jobber, either putting the tool down or getting a new job in, along with the other Jobber getting a new job in, giving us sixteen new states. The remaining state (from the previous group) being where both Jobbers have taken a job in, leads to one of eight states (four being for Jobber one, four for Jobber two). Of course these eight states overlap the previously stated sixteen as these would cover the same positions as one Jobber having picked up a job and either picked up a tool or finished it, and the other Jobber having just picked up a job.

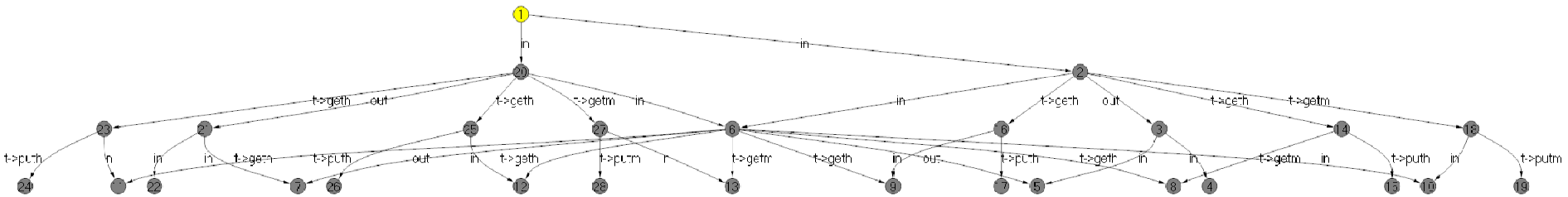


Figure 5.2-8: Jobshop Graph at depth 3

Already at this point the graph (Figure 5.2-8) is becoming quite large (the above images are scaled to fit the page up to actual size), the above image for example has been shrunk to just 45% of its original size, the bitmap version of the above graph measures over 2000 pixels wide.

Over the course of depths four and five we add 33 and 60 new nodes respectively, meaning at depth five we now have 121 nodes and a graph 8,500 pixels wide which is over four times the pixel width of depth three.

At this point we can start to see a pattern emerging in the progression of this agent, for each level of depth the new number of nodes added are roughly double the number the previous depth added. This results in our graph's width matching this growth again roughly doubling at each level of depth. By depths nine and ten we have reached a total of 1425 and 2536 nodes in total respectively with graph widths of 140,000 and 260,000 pixels respectively, these show that the system is able to cope with agents and graphs of reasonable size and complexity.

Using the Jobshop as our test agent, we collected data based on the automatic simulation of the agent to varying depths (ranging from 0 – 10) in order to test the system's functionality at handling ever larger agent information and ever growing graphs. As part of the test we measured the number of nodes created in the graph (which in turn gives us the number of new nodes) and the time taken to perform the automatic simulation on our test PC. The time taken is calculated using an internal timer within the program as it is part of the automatic simulation functionality. The test PC uses an Intel Core2 Quad processor running at 2.4GHz with 2GB of RAM running Windows Vista (32-bit) and .NET 3.5. A key point is that despite running the tests on a quad core machine, it is worth noting that WinSimCCSK is currently a non-threaded application and therefore only utilizes one of the four cores during testing. Hence the only benefit from running the tests on a multi core machine is that system tasks can be executed on a different core, which should give WinSimCCSK near enough uninterrupted use of one core.

	Nodes		
Depth	Total	New	Time
0	1	1	00:00:00
1	3	2	00:00:01
2	12	9	00:00:06
3	28	16	00:00:23
4	61	33	00:01:06
5	121	60	00:03:07
6	240	119	00:11:14
7	438	198	00:30:41
8	793	355	01:45:19
9	1425	632	06:04:52
10	2536	1111	22:33:22

Figure 5.2-9: Data Collected from Jobshop

As suggested previously we can see that the number of nodes roughly doubles at each depth. The time on the other hand expands using a much larger factor being roughly 3.5. This means that while WinSimCCSK is able to handle the larger graphs it is often going to be time that is the major constraint on it. At depths nine and ten, we are looking at 6 and 22 hours respectively, which are both relatively long times, however one would have to compare that to the time it would take to draw such graphs by hand. WinSimCCSK is clearly going to be both much quicker and more accurate due to the sheer scale of it, at a depth of 8, the graph has nearly 800 states and took under two hours to generate. It is worth noting that the depth of 8 is an important one, as only after eight moves are we guaranteed to have a particular job completed. This is of course based on both jobbers using a tool (which is four moves) and the second jobber completing their job before the first jobber, hence eight. This shows one of the major advantages of using a tool such as WinSimCCSK. However clearly the current prototype still has a few shortcomings in performance. In this example it is fairly clear that the depth of ten would really be a limit in practical terms, as nearly taking a day to generate a graph is a long time.

Of course it is fairly obvious that the Jobshop example does not require any reversibility, as in the event the tool required is in use, the other jobber clearly just needs to wait for the first to finish before carrying on. However, that does not mean

that the Jobshop is a poor example to use. Previously we have mentioned how WinSimCCSK could be used to aid the teaching of process calculi to students, this is one such example. The Jobshop is a fairly classic example from the world of CCS and as such it would not be out of place in a course teaching CCS to students. The added benefit of reversibility allows the students to effectively undo their choices and allow them to see the effect of a different choice, whilst still being able to see their previous choices (including the undone ones) in the graph. It is also worth noting that both Concurrency Workbench and FDR2 do not have anything similar to this visual exploration (that maintains previous choices) as well as any form of automatic generation of such a visualisation.

5.2.3 The Dining Philosophers

The third example we shall look at is the classic example of the dining philosophers (36). For completeness, we will briefly outline the problem here. Five philosophers sit around a table and do one of two things, thinking or eating. They do not do both at the same time and as such do either one or the other. In the middle of the table is a bowl of rice, on each side of each philosopher is a chopstick, which they share with their neighbour. In order to eat they need to pick up both chopsticks. They also do not talk to one another and therefore cannot ask their neighbour about the chopstick. We will simplify this problem slightly by dictating that each philosopher must pick up their right chopstick first. We can model this in CCSK using the following agents:

$$Stick1 = u1.d1.Stick1$$
$$Stick2 = u2.d2.Stick2$$
$$Stick3 = u3.d3.Stick3$$
$$Stick4 = u4.d4.Stick4$$
$$Stick5 = u5.d5.Stick5$$

$$Table = Stick1 \mid Stick2 \mid Stick3 \mid Stick4 \mid Stick5$$

$$Eat1 = 'u1.'u2.eat1.'d1.'d2.Phil1$$
$$Eat2 = 'u2.'u3.eat2.'d2.'d3.Phil2$$
$$Eat3 = 'u3.'u4.eat3.'d3.'d4.Phil3$$
$$Eat4 = 'u4.'u5.eat4.'d5.'d5.Phil4$$
$$Eat5 = 'u5.'u1.eat5.'d5.'d1.Phil5$$

$$Think1 = think1.Phil1$$
$$Think2 = think2.Phil2$$
$$Think3 = think3.Phil3$$
$$Think4 = think4.Phil4$$
$$Think5 = think5.Phil5$$

$$Phil1 = Think1 + Eat1$$
$$Phil2 = Think2 + Eat2$$
$$Phil3 = Think3 + Eat3$$
$$Phil4 = Think4 + Eat4$$
$$Phil5 = Think5 + Eat5$$

$$Room = (Phil1 \mid Phil2 \mid Phil3 \mid Phil4 \mid Phil5 \mid Table) \backslash \{u1, u2, u3, u4, u5, d1, d2, d3, d4, d5\}$$

We have specified the number of the chopstick being equal to the number of the philosopher to which it is directly to the right of. We have also shortened the names of the actions for picking up and putting down the chopstick to *u* and *d* respectively. The philosophers are numbered in a clockwise fashion.

For the most part the Room agent runs well and reversibility is not needed. However there is one particular case when reversibility is needed to overcome a deadlock situation. This situation is when all five philosophers decided to eat at the same time and as such they will all pick up their right chopstick. However because they have all picked up their right chopsticks, all chopsticks are now in use. This means that none of the philosophers can pick up their left chopstick and eat. We are now in situation similar to the following:

$$(think1.Phil1 + 'u1[0].'u2.eat1.'d1.'d2.Phil1) \mid$$
$$(think2.Phil2 + 'u2[1].'u3.eat2.'d2.'d3.Phil2) \mid$$
$$(think3.Phil3 + 'u3[2].'u4.eat3.'d3.'d4.Phil3) \mid$$
$$(think4.Phil4 + 'u4[3].'u5.eat4.'d5.'d5.Phil4) \mid$$
$$(think5.Phil5 + 'u5[4].'u1.eat5.'d5.'d1.Phil5) \mid$$
$$(u1[0].d1.Stick1 \mid u2[1].d2.Stick2 \mid u3[2].d3.Stick3 \mid u4[3].d4.Stick4 \mid u5[4].d5.Stick5) \backslash \{u1, u2, u3, u4, u5, d1, d2, d3, d4, d5\}$$

To solve this problem, one philosopher needs to put down their chopstick. In a forward move only world this is not possible as they can only put down their chopsticks after eating, which is currently not possible. What really needs to happen is for one philosopher to undo the decision they made to pick up the chopstick and put it down. This of course requires a reverse move. If we assume philosopher one makes this move, from our previous state we arrive here:

$(think1.Phil1 + \,'u1.'u2.eat1.'d1.'d2.Phil1)$ |
$(think2.Phil2 + \,'u2[1].'u3.eat2.'d2.'d3.Phil2)$ |
$(think3.Phil3 + \,'u3[2].'u4.eat3.'d3.'d4.Phil3)$ |
$(think4.Phil4 + \,'u4[3].'u5.eat4.'d5.'d5.Phil4)$ |
$(think5.Phil5 + \,'u5[4].'u1.eat5.'d5.'d1.Phil5)$ |
$(u1.d1.Stick1 \mid u2[1].d2.Stick2 \mid u3[2].d3.Stick3 \mid u4[3].d4.Stick4 \mid u5[4].d5.Stick5)$
$\backslash\{u1, u2, u3, u4, u5, d1, d2, d3, d4, d5\}$

From this point we can see that chopstick one is now free again and so philosopher five (the one being to philosopher one's right) can now continue. When finished, philosopher four can continue and so on until philosopher two finishes and all chopsticks are down. At this point both chopsticks would be available to philosopher one and the deadlock has been resolved. Of course under this scenario we could have quite easily reversed any of the philosophers not just number one, equally we could have reversed more than one too, although after the first, the deadlock would have already been lifted. Graphically this entire process would have generated this graph (Figure 5.2-10).

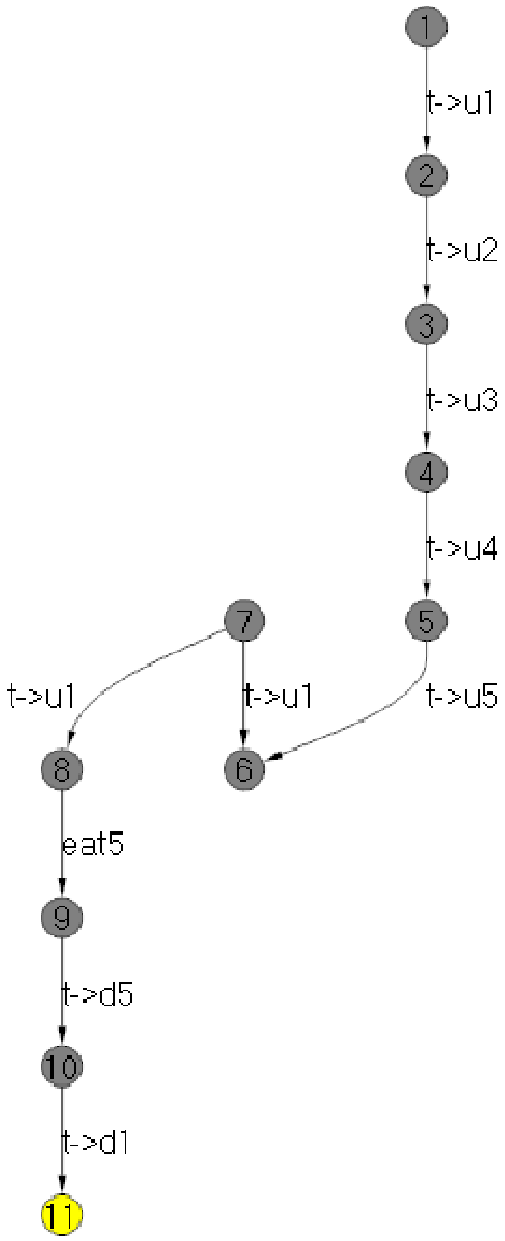


Figure 5.2-10: Dining Philosophers Deadlock Resolve graph

As we can see, all five philosophers pick up their right chopstick which leads us to a deadlocked state (number 6), at this point philosopher one undoes his picking up of the chopstick, which leads us to a new state (number 7), from here philosopher five is free to pick up chopstick one (state 8) from where philosopher five can eat, once finished philosopher five puts down both chopsticks (states 10 and 11). From here philosopher four can pick up chopstick five and eat and philosopher one can pick up chopstick one in preparation to eat when philosopher two has finished. A key point

highlighted here is that the reverse move which makes this possible leads to a new state and WinSimCCSK handles this scenario as expected. If we return to the beginning (state 1) and then follow the scenario where philosophers two to five pick up their right chopstick this would then correctly lead us to state 7, which was created when philosopher one undid their move. This is illustrated graphically below[2]:

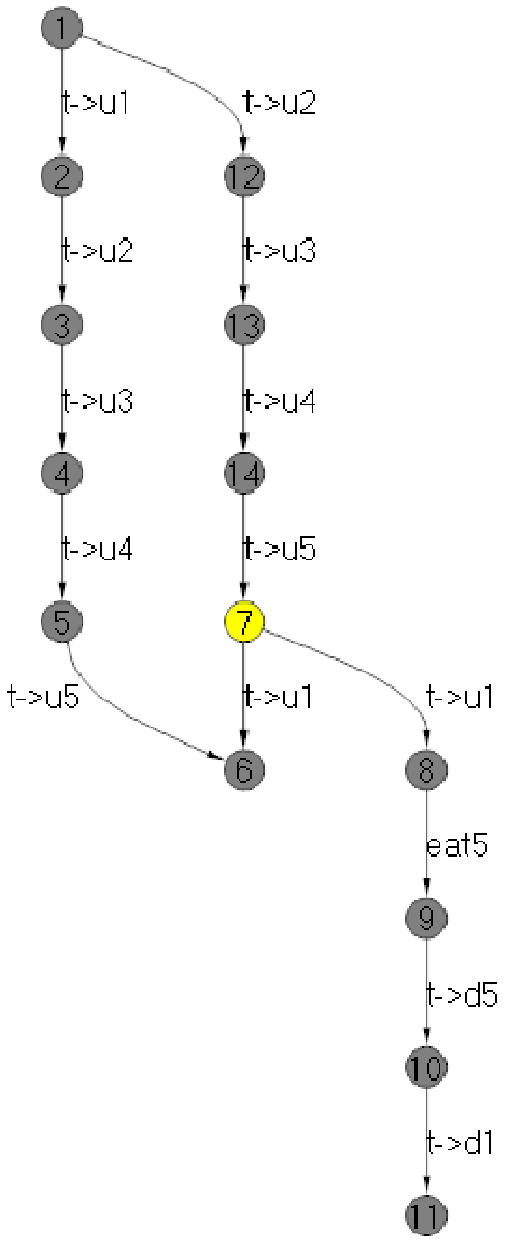


Figure 5.2-11: Dining Philosophers Deadlock Resolve graph with additional route

[2] Note: The graph has just been flipped around the vertical axis; if you look at the actual structure you will see the deadlock scenarios of both graphs are identical.

Over the course of this classic example, we have again seen the benefit of reversibility along with WinSimCCSK's handling of scenarios when a reverse move may not necessarily be the last. This is often the case when dealing with multiple agents in parallel and using some form of a shared resource. We have then seen how this state can then be linked up via another route if the sequence of events was different and yet led to the same scenario, in our case philosophers two to five have one chopstick each.

5.3 Conclusions

In this chapter we have looked at the alterations and extensions for putting SimCCSK into a graphical world, resulting in WinSimCCSK. We looked at how a graph was included and how the required us to generate an "absolute" agent, which we explained the process of genrating. We went on to look at three examples which we used to illustrate the functionality of WinSimCCSK, in particular the graph generation and highlighting its handling of certain scenarios.

Chapter 6

User Guide

Over this relatively short chapter, we present a simple user guide for WinSimCCSK, explaining its usage and finishing with a simple step by step tutorial example.

6.1 Requirements

The system requirements for SimCCSK and WinSimCCSK are as follows:

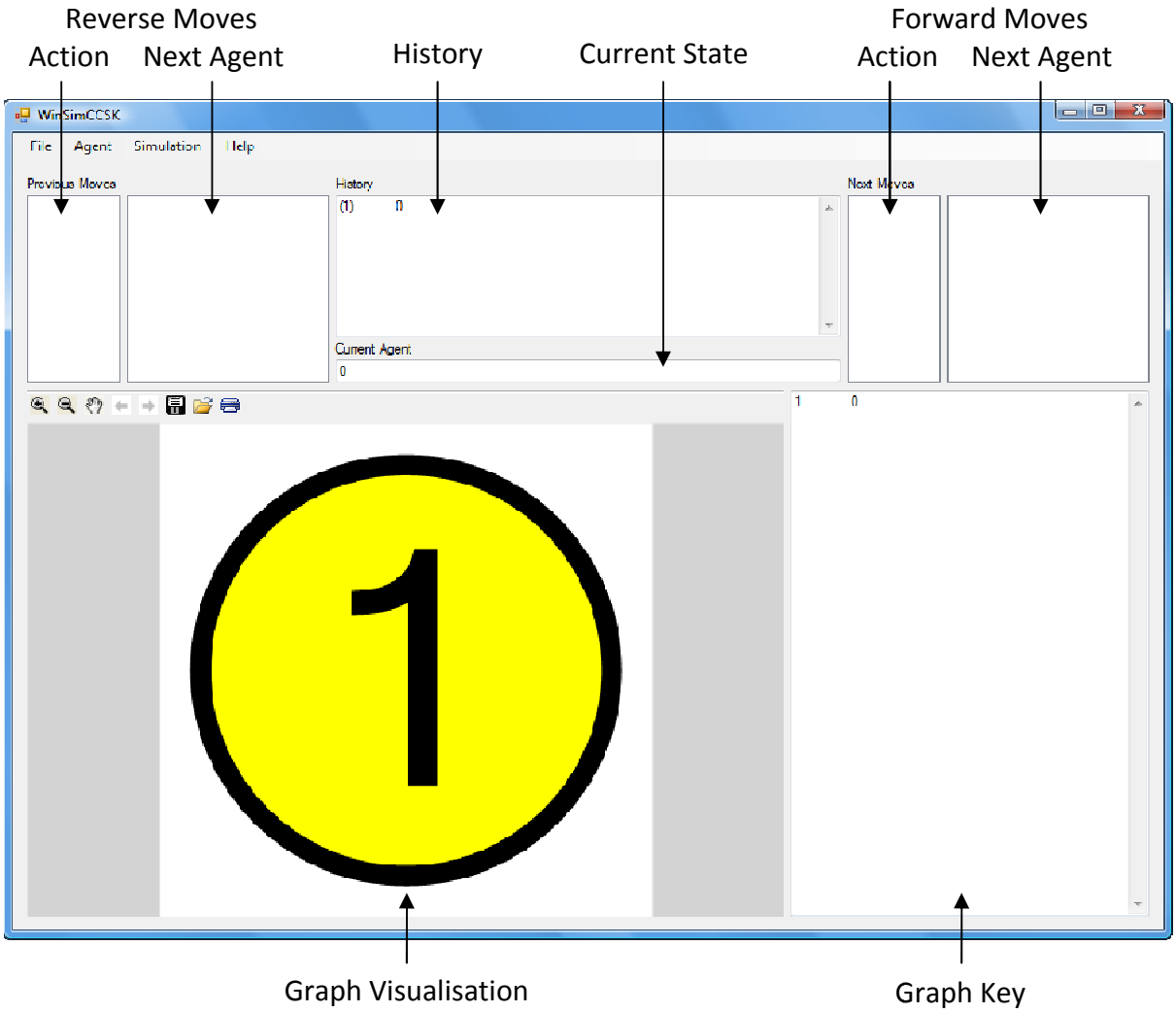
- .NET Framework 2.0 runtime
- Windows 98 (or higher)

6.2 Setting up WinSimCCSK

WinSimCCSK comes packaged in a self-extracting installer. To install the package, run 'setup.exe' and follow the onscreen instructions. Once installed you can start WinSimCCSK by either running WinSimCCSK from the Start menu or alternatively by running the WinSimCCSK.exe file from the WinSimCCSK folder within your file system.

6.2.1 WinSimCCSK Main Screen

On loading up WinSimCCSK you are presented with the main screen as shown below.



On the main screen there is:

- Current State – Indicates the current state of the agent.
- History – Shows (in order) the previously visited states, with graph key (in brackets) for additional cross reference.
- Forward Moves – In two columns, shows the possible next move and the resulting agents.

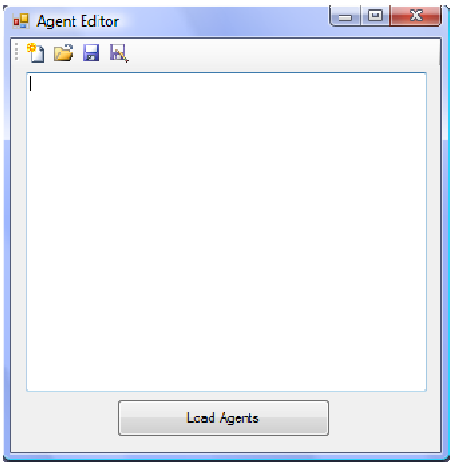
- Reverse Moves – In two columns, shows the possible reverse moves and the resulting agents.
- Graph Visualisation – Shows a graph of visited nodes and which moves link them, current node is highlighted in yellow.
- Graph Key – Shows a key, matching the nodes of the graph to states of the agent.

WinSimCCSK also includes four additional menus:

- File – Provides Exit functionality.
- Agent – Provides access to the Agent Editor.
- Simulation – Provides access to the Automatic Simulation feature.
- Help – Provides access to the About information including version number.

6.2.2 Agent Editor

The Agent Editor provides a simple text based entry system for the loading of agents into WinSimCCSK. Once the required text has been entered for the agents, they are loaded in to the simulator using the 'Load Agents' button.



The Agent Editor also includes four additional buttons for saving and loading the text for future use or reference, these are:

- New – This will create a new file.
- Open – Load an existing file.
- Save – Saves the text to the current file and will overwrite the file if it already exists. Will prompt for name if no current file is specified.
- SaveAs – Saves the text to a specified file and will overwrite the file if it already exists.

Agents are typed using CCSK syntax, just as one would on paper. We shall quickly go over the various components and how they can be entered in to WinSimCCSK.

Actions – Actions are specified using a text label, however, the following conditions must be observed. Actions must start with a lower case letter and cannot include spaces or any other reserved character, e.g. “a” . Overbar actions can be specified by prefixing a single quote “ ‘ “ in front of the label, e.g. “ ‘a”.

Zero Agent – The Zero agent is specified using the Zero character ‘0’.

Prefixing – Prefixing is specified using a period ‘.’, e.g. “a.b.0”

Choice – Choice is specified using the plus symbol ‘+’, e.g. “a.b.0 + c.d.0”

Parallel – Parallel is specified using a vertical bar ‘|’, e.g. “a.b.0 | c.d.0”

Brackets – Brackets can be used to change the order of binding of operators, specified using ‘(‘ and ‘)’, e.g. “(a.b.0)”

Restriction – Restriction is used to restrict actions from being executed independently, thus allowing for communication only. It is specified using a backslash ‘\’ followed by either a single action or by multiple actions which can be specified using curly brackets ‘{‘ and ‘}’ surrounding a list of actions by commas ‘,’. Examples “(a.b.0)\b” or “(a.b.0)\{b,c}”

Relabelling – Relabeling allows one or more actions to be symbolically relabelled to other actions. This is specified using square brackets ‘[‘ and ‘]’ which contain the new label followed by a forward slash ‘/’ then the existing label. Multiple re-labels can be

specified with the one set of square brackets using a comma ',' to separate them. Examples "(a.b.0)[d/a]" or "(a.b.0)[d/a,e/c]"

Named Agents – It is possible to name agents for future use (within the one file). The name must start with an upper case letter and cannot include spaces or any other reserved character, it must then be followed by the equals symbol '=', this must then be followed by an agent, e.g. "P=a.b.0". This can then be reused later by using the label associated with the agent, e.g. "P" in "P + c.d.0"

Note: The WinSimCCSK agent loader ignores additional whitespace, as such you can for example (using the above example), load "P = a.b.0" to the exact same effect (as "P=a.b.0").

6.2.2.1 Agent Loader Examples

Below are some examples of text that can be loaded into WinSimCCSK to load the respective agents, notes are specified by //.

```
a.b.c.0
a .b .c .0          //As above but with additional whitespace
a.b.c.0 + d.e.f.0
a.b.c.0+d.e.f.0+g.h.i.0
a.b.c.0 + (d.e.f.0 + g.h.i.0) + j.k.l.0
a.b.0 | c.d.0
a.b.c.0 | 'a.d.e.0 | 'd.f.0
( a.b.c.0 | 'c.d.e.0 ) \c
(a.b.c.0 | d.e.f.0)\{b,e,f}
(a.b.c.0)[x/a] + d.e.f.0
P= a.b.P
P | P               //Assumes P is defined e.g.  like above
```

6.2.3 Making a Move

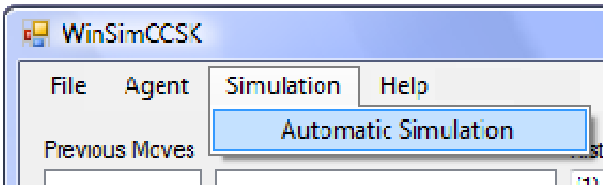
To make a move in WinSimCCSK, you simply choose the action you want to make from either the forward or reverse moves list and double click on it. Additionally, a single click will highlight any move in the list, which in turn highlights the corresponding

resulting agent. Conversely, it is possible to select the move by selecting the resulting agent.

After selecting a move, the screen is updated with the new state of the agent, the possible move lists are updated too and the graph is updated either with a new node or edge, or simply the currently selected node is changed.

6.3 Automatic Simulation

From within the 'Simulation' menu, there is the option of 'Automatic Simulation'.



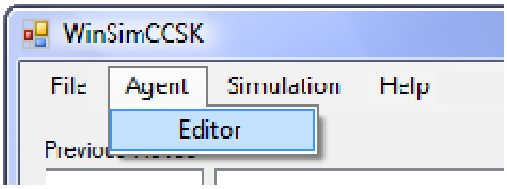
This option allows the automatic simulation of an agent in order to generate a complete graph of the movements within the agent up to a specified depth (the depth being the number of forward moves made from the start and reverse moves reduce the depth). This depth is specified by the user; however there is also a preset default value of 10. Please note that depending on the complexity of the agent and the depth used, the automatic simulation can take a long time (up to several hours or even longer) and due to the non-responsiveness can give the impression that WinSimCCSK has crashed.

After generation you will be in the initial state and can move through the agent freely (even adding additional nodes if you progress past the depth used in the automatic simulation) and have access to the rest of the functionality in WinSimCCSK including the ability to save the graph.

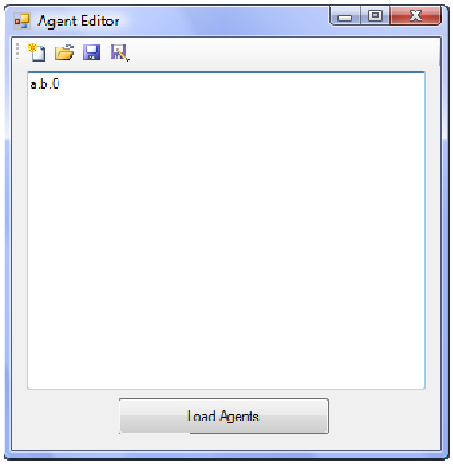
6.4 Tutorial Example – a.b.0

We now have a simple tutorial illustrating how the simple example of $a.b.0$ is loaded and then executed within WinSimCCSK.

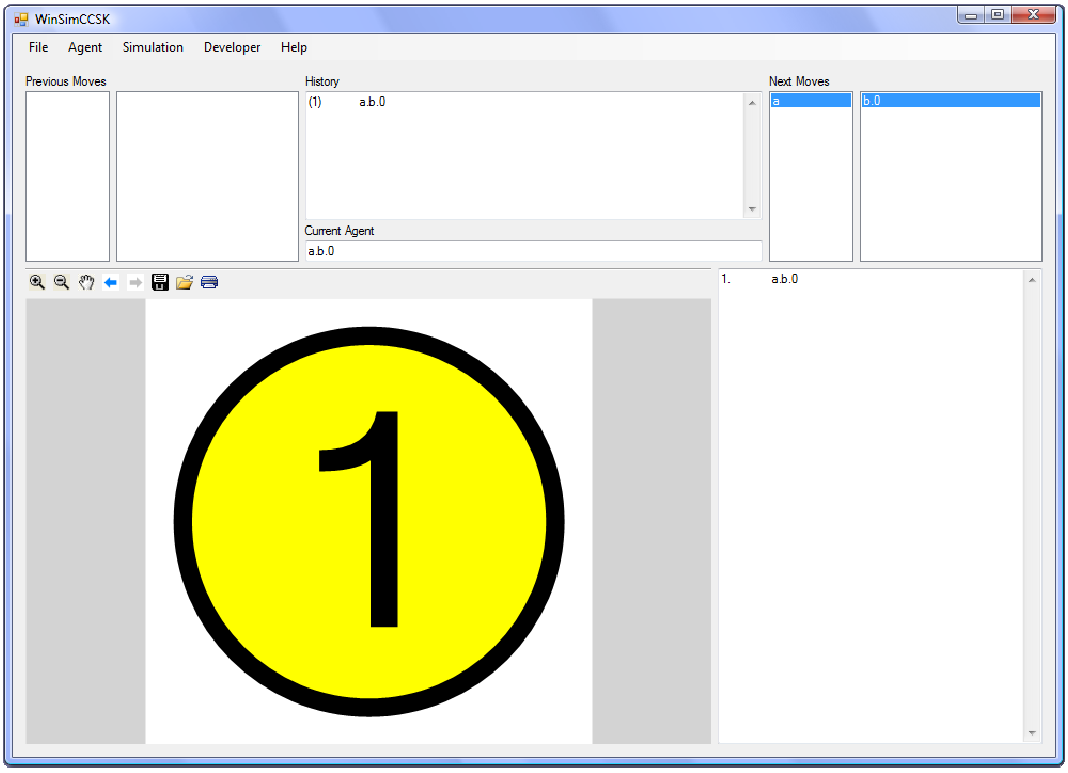
From the initial screen, select the 'Editor' from the 'Agent' menu.



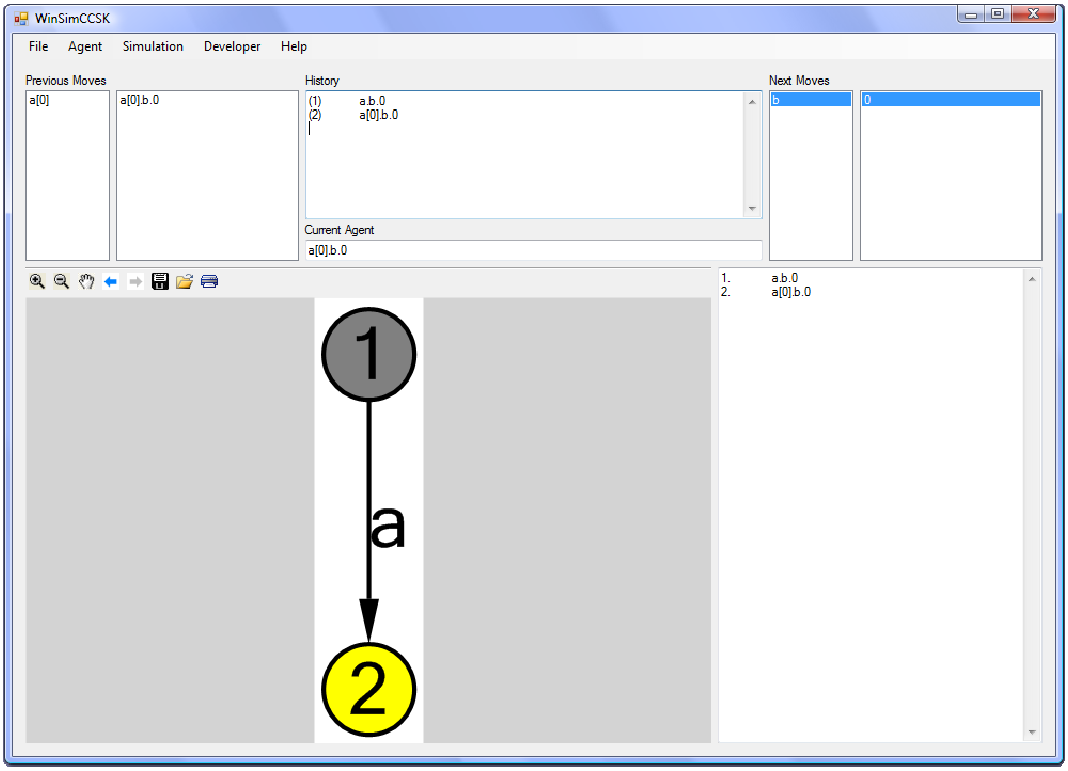
In the Agent Editor you load an agent by typing the text based version of it (whilst observing WinSimCCSK requirements, see section 6.2.2 for more information); in this example we simply type 'a.b.0', then click 'Load Agents' to load the agent into the simulator.



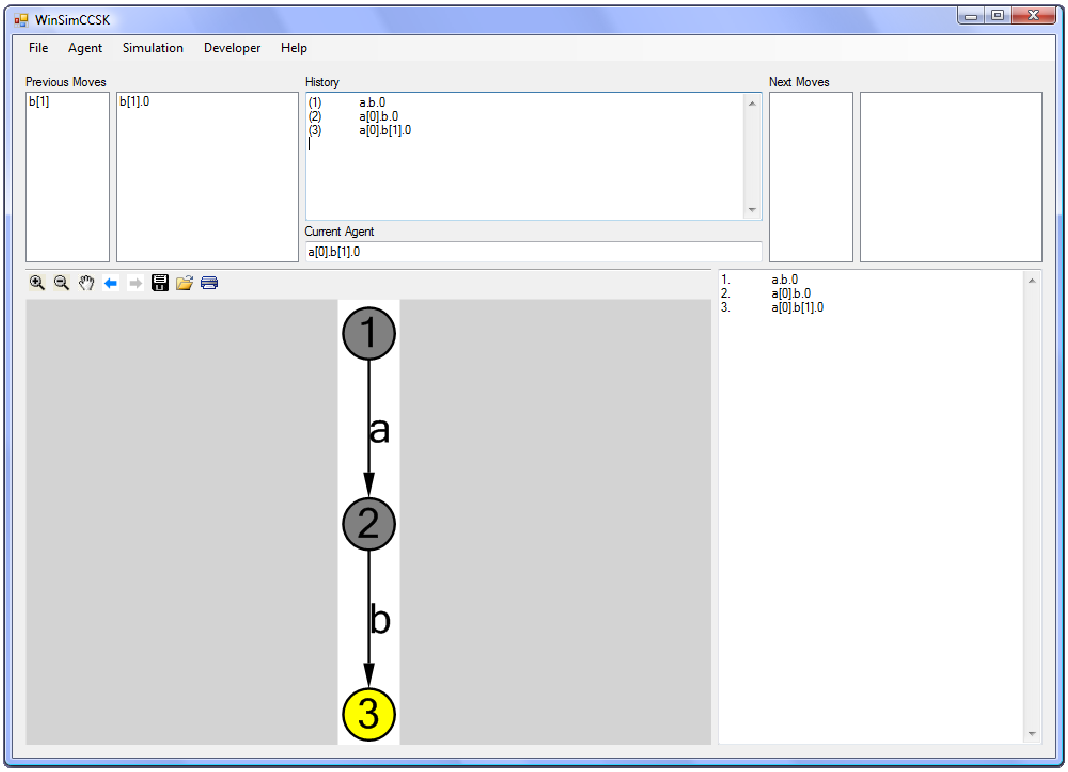
Now we have the agent $a.b.0$ loaded and have a single move available to us, the forward action a. To make the move, double click on the action (or resulting agent).



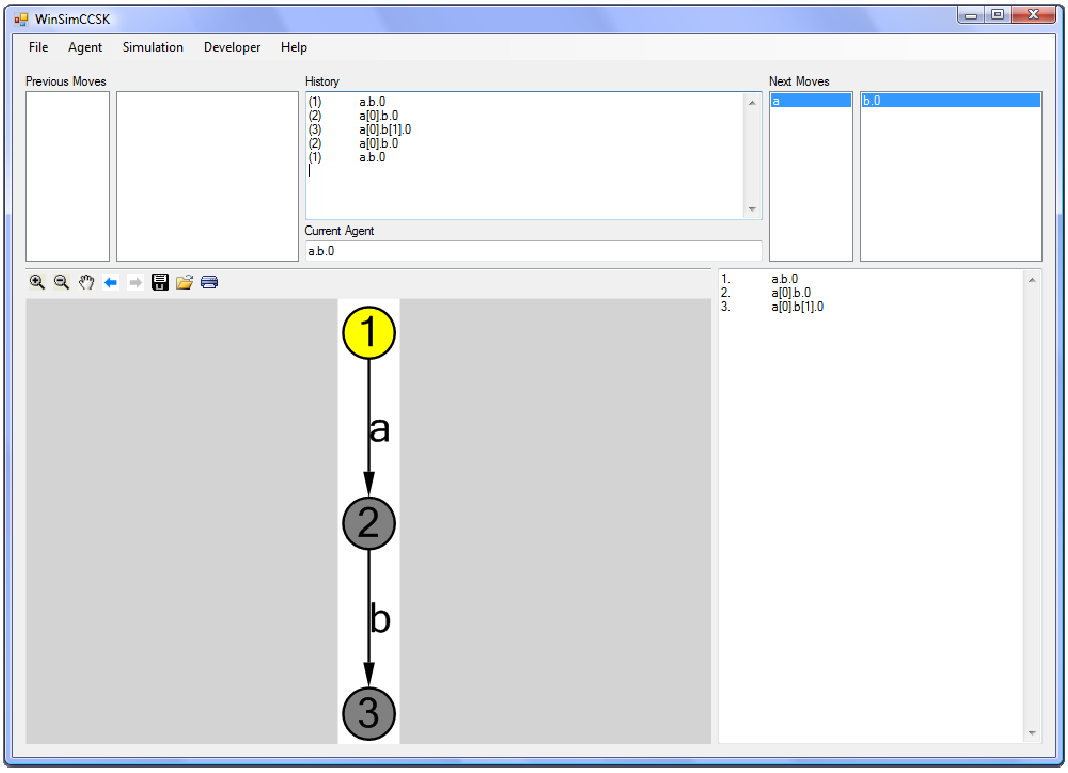
Now we are in the state $a[0].b.0$, notice the updated history and graph (the yellow node is the current one). We now have two moves available to us, going forward we have the action b and backwards we have the action a. Again to make a move, double click on the action (or resulting agent). For the purposes of this example we choose b.



We have now made it to the state $a[0].b[1].0$, which is the terminal state of this agent. Now we can only make a reverse move b. If we reverse the b and then the a afterwards we return to the initial state.



Having made the two reverse moves we return to the initial state, notice that the history has noted all points along the route (both forward and back) and that the graph still shows us the route with the yellow current node being '1'.



Through this simple tutorial we have seen how to load an agent and then move forwards and backwards through it.

Chapter 7

Critical Appraisal

Over the course of this chapter we shall look at what this project has achieved and how this compares to our original goals and requirements. We then go on to suggest some possible extensions to this project.

7.1 SimCCSK – A Simulator for CCSK?

A key question of this project has to be "Is SimCCSK a simulator for CCSK?". The reasoning behind this is of course fairly simple, the project started life to look into the design and construction of such a simulator, SimCCSK hopefully achieves this. We are not claiming that SimCCSK in its current form is going to revolutionise the world like the invention of the car or electricity. This is for two reasons: one the project only ever set out to create a working prototype of such a system to see if it was practical and feasible to do. Secondly of course, the world of process calculi (and even CCSK which is a much smaller within that world) will never have the far reaching and more general accessibility and use by a wider world. Cars and electricity are of far more general use, process calculi on the other hand are for modelling processes, which general the wider world does not do.

If we compare SimCCSK against our list of requirements we laid out in Chapter 3, we should see that a key list of requirements encompass this general notion of "Is

SimCCSK a simulator for CCSK?". These requirements were of course the simulation of the various agent types within CCSK along with the naming of agents, key generation and forward and reverse movement. We believe that we achieved all of these goals; the system does simulate the various agent types of CCSK. We also have a way of naming agents for reuse and recursive purposes. We have a system for generating and applying keys as well as forward and reverse transitions between the states of an agent.

Additional functional requirements for SimCCSK were the relaying of the current agent state to the user and showing all possible forward and reverse moves. For SimCCSK, due to its console based nature, these are output using text prior to the selection of a move, thus the relevant information is visible at the correct time. We also had two non-functional requirements of usability and performance. If we first look at performance, we have successfully created an application that performs the move very quickly giving an almost instant completion of a move to the user. This results in the user being unaware of any "wait" period for a move to be completed. We feel that this results in a successful completion of this requirement.

Moving on to usability, we feel that SimCCSK is fairly usable for a simple command line application. However from a teaching standpoint we felt that it was not an application that was easy enough to just pick up and use, it did require some form of explanation, to explain both its use and way of presenting the information. We identified that this could be an issue very early on, which was one of the reasons we extended the project to include and culminate in a graphical user interfaced based version. Interestingly enough what we did discover though is that although the majority of the project focused on the core of SimCCSK and was tested using SimCCSK, the project showed how much easier it is to relay data to a user via a graphical user interface. Whilst the console driven approach used in SimCCSK works and is understandable, you do need to understand the layout and notation first and for more general everyday use by students the graphical version is a much better interpretation.

7.2 WinSimCCSK – SimCCSK for All?

As previously said WinSimCCSK was always a planned part of the project. We always knew that a graphical user interfaced version of SimCCSK would be a positive and help us from the perspective of creating a tool to aid student learning of process calculi. Very few people now rely purely on a console based terminal style operating system and whilst all major operating systems still carry a command terminal, the majority of users will either never or rarely ever use it. In a world of ever increasing monitor sizes, graphics are king. Due to WinSimCCSK having been built on the core of SimCCSK, it obviously inherits its successful completion of the requirements related to the simulation of CCSK.

We have taken SimCCSK and made it better visually. This actually allowed us to present the information in a far better and more natural way, with distinct separations for forward and reverse moves as well as a separate section for the history of states of the agent which completes one of our additional requirements for WinSimCCSK. We had also always had the concept of a graphical representation of the agent. This led to our visualisation "graph" that is dynamically generated as the user makes moves, traversing through the various states. The automatic simulation is only possible in a graphical world as the whole purpose of the automatic simulation is to generate a complete "graph", or in the case of it being depth limited, a complete "graph" up to a particular depth. Under the original console based version, this would seem redundant as there is no graphical representation to show it. Finally we also added a simple text editor to WinSimCCSK, complete with saving and loading functionality for reuse on a later occasion.

As for our non-functional requirements when it comes to WinSimCCSK, we still have usability and performance. Performance wise, like SimCCSK for user driven simulation WinSimCCSK performs within our requirement, providing almost instantaneous, delay free moves. However WinSimCCSK has an additional feature, "Automatic Simulation". For the automatic simulation feature, the performance is reasonable within the context it is designed for. For the small and relatively simple examples used within

teaching, completion can take a few minutes. As we saw in Chapter 5 though, this can range up to a day and beyond, however at that point the resulting graph becomes far harder to read and use. Whilst WinSimCCSK's automatic simulation feature runs at speeds nowhere near that of a model checker, it is doing a different job. For the examples where the feature would be useful, that is those resulting in a relatively small graph; the times are reasonable and well within the bounds of use within a teaching context.

As for usability, we feel that the graphical layout makes the information far clearer and the separation and intuitive positioning of forward and reverse moves make the application easy enough to pick up and use for students learning process calculi, thereby allowing them to focus on the process calculi as opposed to the tool. Whilst we have not tested the tool on any students learning process calculi, we have run the tool past some of students who are part of a games and graphics group here at Leicester. Now bearing in mind that most of these have never learnt about or were in the process of learning process calculi, we did get some interesting responses. The key point here is that whilst they did not quite understand what was going on at the process calculi level, they did understand the tool and quickly grasped the concept of forward and reverse moves purely by the visualisation. The text representation meant little to them, however they understood the concept of a move leading to a path on the visualisation and how the reverse moves allowed them to go back. We feel that this small example shows that the tool is relatively useable as we have seen from a group not understanding process calculi that they are still able to pick it up and use it, if only on a visual level. They did however alter the final look of the GUI. In the first version shown to them, the forward and reverse moves were next to each other on the right (i.e. the previous moves and history were swapped). They felt that it was more natural and balance to have the history in the centre and the list of previous move on the left. This is of course analogous to moving forward and back across a horizontal line (with right being forward) as is often used for progress bars and other such monitoring concepts.

WinSimCCSK provides an easier and more informative interface, which should make SimCCSK available to all that want to use it. In this sense it does make SimCCSK

available to all, it just depends how you define all. From our point of view, this was really all about making it suitable for student use as an aid in the teaching of process calculi. We would like to think that WinSimCCSK is accessible to all students who would be learning process calculi. We would also like to think that it is a useful tool in illustrating how concurrent processes can perform actions in different orders and yet end up at the same state, no matter the sequence taken.

7.3 Possible Extensions to the Project

We feel that there are three key areas in which to take this project. Firstly the project could be extended to see how our approach could be applied to other similar process calculi. The whole static structure and pointer based approach used in SimCCSK could well be translated to another or multiple process calculi as this is not something necessarily unique to CCSK. Of course with multiple approaches to reversibility this may well not be quite as straight forward as it seems. If we consider RCCS for example, we would have to somehow add the concept of a stack to the approach we use for CCSK in SimCCSK.

Secondly, the project could be taken and investigated to see how it could be made more robust for more general simulation and analysis for use by both the academic and commercial sectors. This could include added additional functionality of the simulator such as checking for bisimulation of agents for example.

Finally, when we added the visualisation, we noted that whilst we generalise the graph pattern based on keys, there is an interesting discussion on recursion. Of course under CCSK recursion in some sense exists as we generate infinite paths as we keep extending agents using a recursive definition such as $P = a.b.P$. This of course gives use the infinite pattern of $a.b.a.b.a.b$ …… . Graphically though this translates to a long line, without the use of keys (as under CCS) we could represent this as a loop. We feel that this could well be an interesting area of research as we feel that this could somehow be represented using the third dimension, utilising a spiral or something

similar, then the loop could be created using effectively a visual trick when viewed from the right angle whilst maintain the ability to view that the spiral exists using either a layered approach to visualisation or even a free roaming 3 dimensional space.

Over this short section we have highlighted some areas which we feel may be worth further investigation in the future; however we by no means claim that this is an exhaustive list of areas that could be looked in to, with regards to furthering this area.

Chapter 8

Conclusions

Over the course of this thesis we have looked at how we could design and construct SimCCSK as a simulator for CCSK.

8.1 SimCCSK as a Simulator for CCSK

Firstly in Chapter 2 we looked at what CCS is, how it is constructed and how it works. From there we went on to look at two reversible derivations of CCS, namely RCCS and CCSK. We looked at how both of these are constructed and work and went on to compare the two and illustrate our reasoning for using CCSK for our project.

In Chapter 3 we came up with a concept design and showed how we derived this. We presented our approach to this which was to use a static structure built up using "agents" as blocks, building a larger agent by adding an action to a smaller one or combining agents together as in Choice or Parallel. We also presented a comparison between SimCCSK/WinSimCCSK and Concurrency Workbench of New Century and FDR2. Illustrating the gap that WinSimCCSK attempts to fill albeit in prototype form.

We then went on to show in Chapter 4 how we use a system of pointers to control the current state of the system. For the transitions, we showed how we probe around from the current state to generate possible moves, using the abilities of polymorphism within object oriented languages. We then went on to explain how we constructed a

console based prototype using C# and in doing so generated the core of the simulator on which the console based user interface sits on top of. We then illustrated how it was possible to interact with this tool.

8.2 WinSimCCSK as a Tool for Teaching

Whilst the SimCCSK prototype worked, due to its console based nature it was not a great tool to aid teaching. So by taking SimCCSK, stripping off the console based user interface and replacing it with a graphical one, WinSimCCSK was born. We presented WinSimCCSK in Chapter 5 which benefited from being easier to use due to a better and more natural layout of the information. We then showed how we extended the core functionality of SimCCSK by adding a simple to use built in agent editor (which is separate from the main form) and a dynamically generated graph and key to the main form of WinSimCCSK. Then using the added functionality that the graph brought to the project, we added an automatic generation feature, that when used would automatically generate the complete graph (up to a user specified depth) of the agent. We continue Chapter 5 by explaining three examples, a DNA example, the classic CCS Jobshop example and the classic Dining Philosophers example.

Chapter 6 provides a simple user guide to WinSimCCSK and in doing so highlights it usage. In Chapter 7 we reflect on the project, comparing the achievements with our requirements. We showed that the project successfully created a prototype simulation with the key functionality of CCSK. This included all agent types, key generation and the transitions between agents along with providing the ability to name agents for reuse. We also saw that we achieved the visualisation goal for WinSimCCSK. For the non-functional requirements, we saw that both SimCCSK and WinSimCCSK were reasonably easy applications to use however WinSimCCSK was probably more suited to teaching due to its easier and more intuitive pick up and use approach. Performance wise we saw that both run at reasonable speed whilst in a user driven context and that whilst performance could be better for the automatic

generation feature of WinSimCCSK, it still runs in a suitable time given its goal and target audience.

Given all of this we feel that WinSimCCSK in its current form could be a useful aid to teaching process calculi as it provides both user driven choices with the added benefit of reversibility to allow the exploration of the choice not made initially by reversing to a point and choosing a different route. We feel the graph that is dynamically produced is also a valuable tool as this allows the students to visualise the diverging and converging of states based on the different ordering of choices.

8.3 Final Thoughts

Did SimCCSK and its graphical counterpart WinSimCCSK complete its original goals? We would like to think so. We did indeed design and construct a prototype simulator for CCSK. The simulator manages to handle all the key parts of CCSK. It now provides both user interactive navigation of an agent, as well as an automatic complete generation of an agent's graph of transitions. We believe that this could be a very useful tool in illustrating the functionality and nature of process calculi. Add to this WinSimCCSK's relatively simple and fairly standard system requirements of a Windows PC running .NET 2.0, it makes WinSimCCSK easy to deploy to a student lab as it does not require any additional hardware or software libraries. We feel that this makes WinSimCCSK a serious contender in the aid of teaching students the fundamentals of process calculi.

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