STATECRUNCHER User Manual

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Report Relating to the Thesis “The Design and Construction of a State Machine System that Handles Nondeterminism”

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Summary

This document is a user manual and training course for users of STATECRUNCHER. STATECRUNCHER is a state transition language in which a dynamic model of a system (i.e. a statechart) can be written and exercised. Given a dynamic model of a system, STATECRUNCHER provides an ***oracle*** to state based tests. It specialises in its handling of nondeterminism. It has been integrated by Philips Research India - Bangalore into a tool chain to provide automated generation and execution of tests. This report assumes a basic knowledge of UML dynamic modelling, and shows how to implement them in STATECRUNCHER, describing both syntax and semantics.

Contents

1. Introduction

This document is a user manual for STATECRUNCHER . It covers the syntax and explains the semantics, mainly by example. Both the STATECRUNCHER modelling language and the main user commands that can be sent to it are treated.

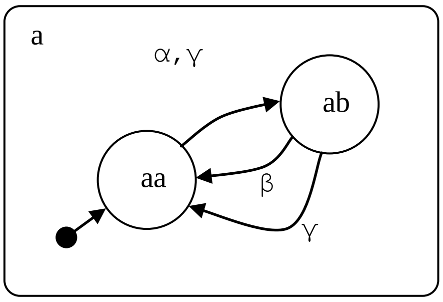
It does not cover advanced commands that would probably only be given under program control (by a primer), except in a reference section, nor at all the art of producing good models from a software specification, nor does it cover software component composition issues, except for a basic client-server paradigm. These are or will be the subjects of separate studies.

STATECRUNCHER and some proposals for extensions are the subject of a number of pending patents (PHGB-020195, PHGB-020196, PHGB-030116).

1.1 What STATECRUNCHER is and does

STATECRUNCHER is a state machine system that handles nondeterminism. As a language system, it provides a means to textually describe and compile UML dynamic models and produce an executable exhibiting the state behaviour of the model. This in turn provides an *oracle* to state based tests. A very simple deterministic model is shown below.

statechart sc



STATECRUNCHER source code

```
statechart sc(a)
event alpha,beta,gamma;
   cluster a(aa,ab)
      state aa {alpha,gamma->ab;}
      state ab {beta->aa; gamma->aa;}
```

Figure 1. A very simple deterministic model and its source code

This model is always in one of two states `aa` or `ab`. The initial, or default, state is `aa` (marked by the arrow). Transitioning between `aa` and `ab` occurs if the model is in state `aa` and is given event α or γ to process. Transitioning between `ab` and `aa` occurs if the model is in state `ab` and is given event β or γ to process. The fact that α and γ are on the same transition in one direction, but that β and γ are on separate transitions in the other direction, simply shows flexibility in how the model is written; the effect is the same in cases like this whether the events are put on the same transition or separate transitions. If the model is in state `aa` and it is given event β to process, there is no change in state. Similarly if it is in state `ab` and it is given event α to process. All this behaviour is assumed to be what we require and expect of a real system: the System Under Test (SUT), also referred to as an Implementation Under Test (IUT), especially when there may be several implementations of one specified system.

If we compile and run this model, and get the initial configuration (with the `gc` command), the output is :

```
SC:gc
2    statechart sc
2       cluster a [sc] = OCC []  **
2          leafstate aa [a, sc] = OCC []  **
2          leafstate ab [a, sc] = VAC []
2    TRACE =[]
2    TREV [[alpha, [sc]], 0, [], []]
2    TREV [[gamma, [sc]], 0, [], []]

outworlds=[2]
number of outworlds=1
```

The fact that leafstate `aa` is occupied, and `ab` is vacant can be seen. The double asterisks draw attention to occupied states. Cluster `a` is occupied is because it is the parent of `aa` and `ab`; this will be explained later. The output also shows transitionable events (the `TREV` lines), showing that events `alpha` and `gamma` will trigger a transition. The rest of the output will be explained in due course.

If we now give a command to process event gamma (`pe gamma`), and then get the new configuration (`gc`) , the new configuration is seen:

```
SC:pe gamma
SC:gc
3    statechart sc
3       cluster a [sc] = OCC []  **
3          leafstate aa [a, sc] = VAC []
3          leafstate ab [a, sc] = OCC []  **
3    TRACE =[]
3    TREV [[beta, [sc]], 0, [], []]
3    TREV [[gamma, [sc]], 0, [], []]

outworlds=[3]
number of outworlds=1
```

What we have is a tool giving the result of a test - a *test oracle*. But it is not a test *generator* because the user had to decide what event to give STATECRUNCHER to process. Now since STATECRUNCHER outputs what events it will transition on (and it can also give *all* its events on request), one can imagine STATECRUNCHER being connected to another program that decides on the events to be processed. Such a tool is called a *test generator* or *primer*. The primer will also pass the events to be tested, and their oracle, to a *test harness*. The test harness will (directly or indirectly) call the *Implementation Under Test* and obtain its new state, and compare this with the test oracle, and log a pass or fail. This is the basis of automated test execution.

A possible toolset working as described above to go with STATECRUNCHER is TorX [CdR].

A system to be tested may be a formal component. The following diagram shows the processes applied to a specification and then a model as it is compiled, validated and deployed in a testing tool chain such as TorX.

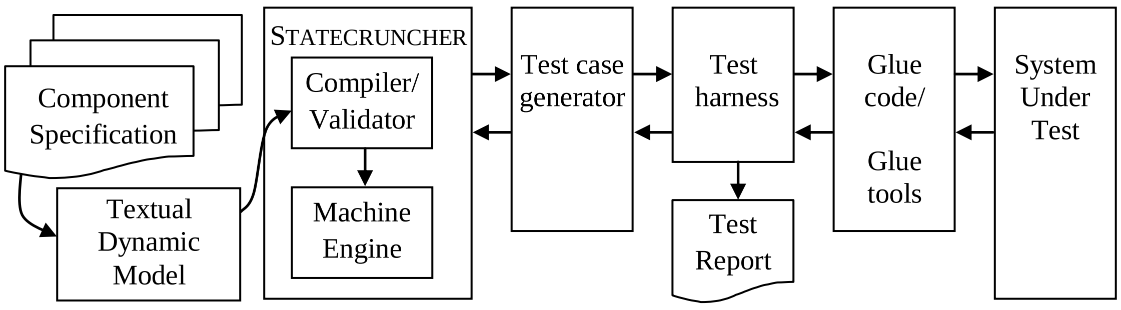


Figure 2. Compilation, Validation and Application to a Testing Tool Chain

1.2 STATECRUNCHER and Prolog

STATECRUNCHER is currently implemented in Prolog. STATECRUNCHER's own syntax is independent of Prolog, and STATECRUNCHER can be run in a mode that hides Prolog completely, but it is generally somewhat more convenient to develop a model using a Prolog environment. The ordinary user does not need to know Prolog as a language at all, however STATECRUNCHER is run.

STATECRUNCHER can be run:

- As an MS-DOS executable. Apart from a startup message, the user will not be aware of any connection with Prolog.
- Under SWI-Prolog - a public domain system, (but read the conditions), reference [SWI-Prolog].
- Under WinProlog - a commercial system, reference [WinProlog].

1.3 Notation

UML describes a detailed notation for diagrams, but for historical reasons, (and perhaps also compactness) this manual differs in respect of certain features:

- on entry to a state (UML “entry/”) is a solid triangle pointing in to the state, e.g. $\boxed{\blacktriangleleft\ \text{v=6}}$
- on exit from a state (UML “exit/”) is a solid triangle pointing out of the state, e.g. $\boxed{\blacktriangleright\ \text{v=6}}$
- events declared in a part of the hierarchy are denoted by the symbol ↯, e.g. $\boxed{\text{↯}\zeta 1}$
- variables are declared in a part of the hierarchy by the symbol ‖ , e.g. $\boxed{\|\ \text{v=6}}$
- PCOs (Points of Control and Observation) are declared by the symbol ℗, e.g. $\boxed{\text{℗}\texttt{pco1}}$

1.4 Related documentation by the present author

- For the underlying parsing technique: [StCrGP4]
- For detail of STATECRUNCHER parsing: [StCrParsing]
- For detail of STATECRUNCHER system and design: [StCrMain]
- For detail of the STATECRUNCHER-primer protocol: [StCrPrimer]
- For test models: [StCrTest]

This manual is self-sufficient as a basic tutorial without reference to other documentation, but references will be given for amplification on the material in many instances.

2. Installation

2.1 Hardware requirements

The supported platforms are Windows 98 and above. The disk usage is about 20MB (though this includes much test material and can be pruned away to about 1 MB).

STATECRUNCHER will run on older, slower machines, but the following will be noticed:

- run-time response for deterministic models will still be fast, by human standards at least.
- run-time response time when there are many worlds in existence will be slow.
- compile time for models with long statements will be noticeably slow.

STATECRUNCHER compilation of models runs rather slowly on a 120 MHz laptop, runs adequately on a 300 MHz machine (on which it was largely developed), and runs all the better on more modern machines. There will always be a performance bottleneck under highly nondeterministic situations, since there is potential for combinatorial explosion. If possible, keep the number of worlds that models generate to below, say, 100.

2.2 Installation overview

There are various implementations of STATECRUNCHER:

- As an MS-DOS executable, using an embedded WinProlog kernel. Apart from a startup message, the user will not be aware of any connection with Prolog.
- Under SWI-Prolog - a public domain system, (but read the conditions), reference [SWI-Prolog].
- Under WinProlog - a commercial system from Logic Programming Associates (LPA), reference [WinProlog].

There is also a special socket version under SWI-Prolog, (not relevant to a learner), described in section 5.

In order to run STATECRUNCHER under SWI-Prolog or WinProlog, you need the STATECRUNCHER source. The MS-DOS executable does not need a Prolog system or the STATECRUNCHER source.

All versions work with the same modelling language and the same command language though there are some alternative ways of working, e.g. *modelname mode*, which are not available in the MS-DOS executable version). The executable runs in an MS-DOS window, which has the disadvantage that is may not be scrollable. It is possible, however, under later versions of Windows, to set an MS-DOS window to more than the default 24 lines.

We consider installation of SWI-Prolog and of each STATECRUNCHER system, taking the process as far as starting up STATECRUNCHER and obtaining a STATECRUNCHER command prompt (`SC:`). After this stage, the difference between the systems becomes largely irrelevant. Follow a path in the tree below according to your way of working.

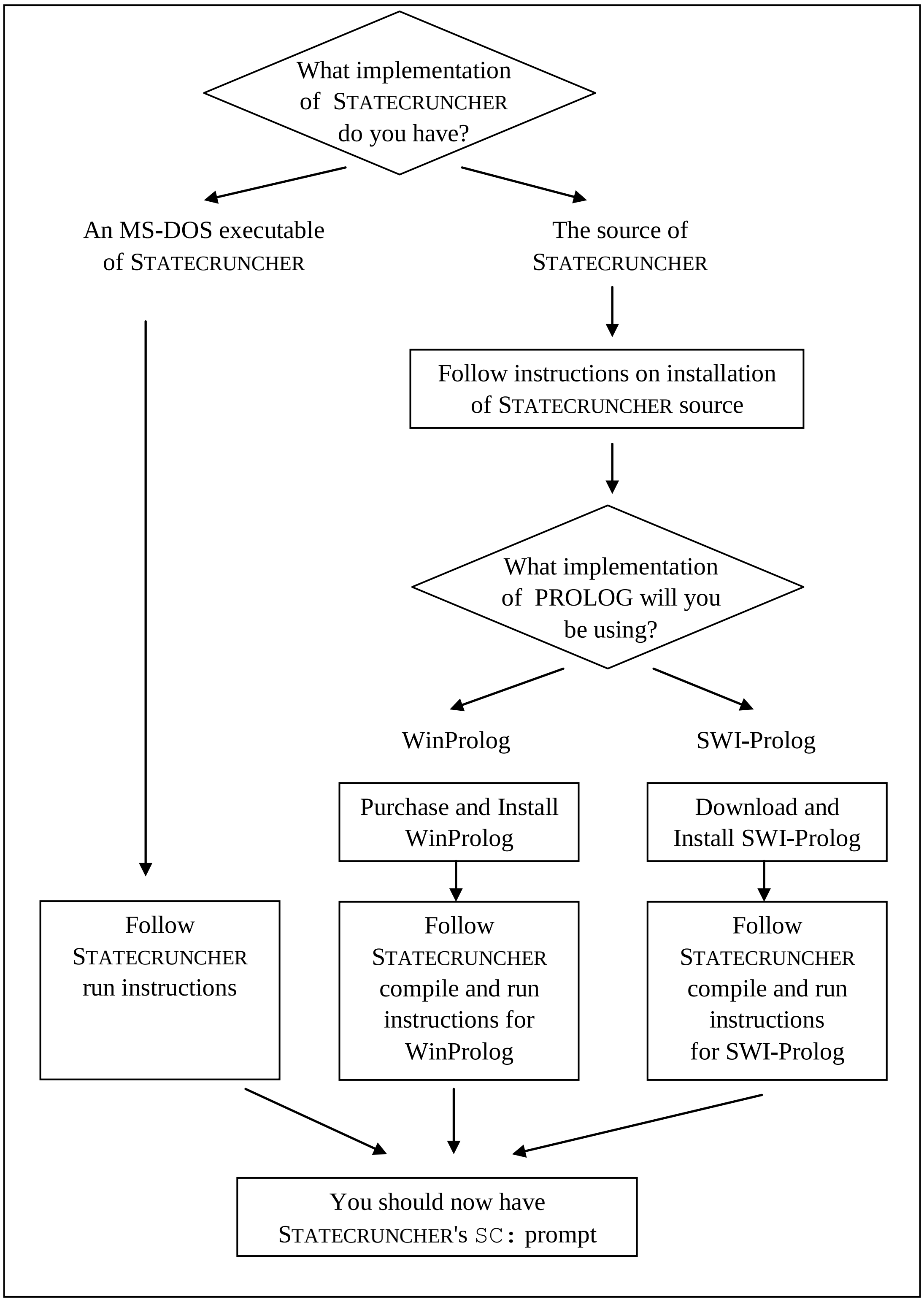

What implementation of STATECRUNCHER do you have?
An MS-DOS executable of STATECRUNCHER
The source of STATECRUNCHER
Follow instructions on installation of STATECRUNCHER source
What implementation of PROLOG will you be using?
WinProlog
SWI-Prolog
Purchase and Install WinProlog
Download and Install SWI-Prolog
Follow STATECRUNCHER run instructions
Follow STATECRUNCHER compile and run instructions for WinProlog
Follow STATECRUNCHER compile and run instructions for SWI-Prolog
You should now have STATECRUNCHER's SC: prompt

Figure 3. Diagram of installation routes

2.3 To install STATECRUNCHER source from the zip file

STATECRUNCHER is supplied in a zip file. Create a directory KWinPro. Extract STATECRUNCHER from the zip file into it; that should generate a directory structure at least as shown, (though there will be more subdirectories if supplied, e.g. containing documentation). The structure below KWinPro is best regarded as fixed. The path to and including KWinPro is not fixed and can be user defined (in a STATECRUNCHER loader file, **`aux_load_sc.pl`**).

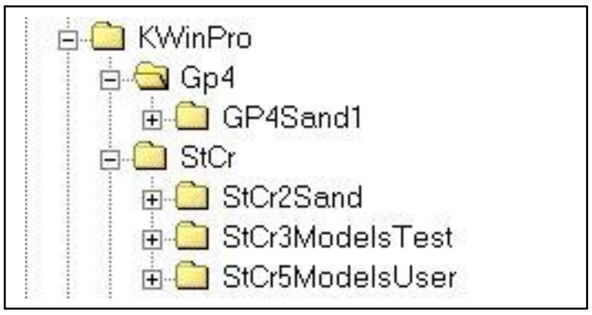

```
KWinPro
  Gp4
    GP4Sand1
  StCr
    StCr2Sand
    StCr3ModelsTest
    StCr5ModelsUser
```

Figure 4. Installation directory structure

Edit (the equivalent to) file

`P:\KWinPro\StCr\StCr2Sand\Boot_sc\`**`aux_load_sc.pl`**

Edit the `boot_root` lines to reflect the actual location in your directory hierarchy

```
boot_root(gp4,'P:\Kwinpro\GP4\GP4Sand1\').
boot_root(sc, 'P:\Kwinpro\StCr\StCr2Sand\').
```

(Ignore any `xxboot_root` lines - they are effectively disabled and have no effect).

2.4 Downloading and installing SWI-Prolog

The SWI Prolog site is:

http://www.swi-prolog.org/

Read and heed the license details. Do not distribute public domain and Philips proprietary software together without permission from Philips IP&S.

Versions at or above 5.0.3 should be suitable. Download SWI-Prolog for Windows:

SWI-Prolog/XPCE for MS-Windows

Install as instructed with standard options. This includes accepting `.pl` as the Prolog extension (sorry, Perl users).

Preferably, increase the capacity of the main window with *regedit*. Go to

HKEY_CURRENT_USER\Software\SWI\Plwin\Console\SaveLines

and change the value from 0xc8 (200 decimal) to, say, 0x1f4 (500 lines).

2.5 To compile and run STATECRUNCHER under SWI Prolog

It is assumed that STATECRUNCHER source has been installed as instructed, and that SWI-Prolog has been installed.

In the `StCr\StCr2Sand\boot` directory, double click on the file

`boot_sc_swipro_win.pl`

STATECRUNCHER is recompiled by SWI-Prolog every time it is started up. This only takes a few seconds on a modern machine.

First SWI Prolog should start up, then STATECRUNCHER will be boot loaded (many files will be loaded), and you should end up with the following (details may differ slightly):

```
%   F:\KWinPro\StCr\StCr2sand\va_sc\zva_sc.pl compiled 0.00 sec, 4,888 bytes
%   F:\KWinPro\StCr\StCr2sand\zt_sc\zt_sc_1.pl compiled 0.00 sec, 1,136 bytes

Boot load complete. Prolog system=swiprolog
%  aux_load_sc.pl compiled 3.89 sec, 3,638,548 bytes

STATECRUNCHER (Version 1.05)
Copyright (C) Philips Electronics N.V., 2000-2003
SC:
```

To exit:
- At the `SC:` prompt, enter **`quit`**
- Close the Window (or, in good Prolog tradition, type **`halt.`**).

2.6 To compile and run STATECRUNCHER under WinProlog

It is assumed that STATECRUNCHER source has been installed as instructed, and that WinProlog has been installed.

Start up WinProlog, e.g. using a short cut, with the following command and parameters (read as one line):

```
"D:\Program Files\WIN-PROLOG-4010\PRO386W.EXE" /B512
/L1024 /P50000 /H3000 /T1024
```

This is a considerable amount of memory, and the startup may be slow (a few minutes) on an older (say, 1998) computer, but once WinProlog has started up, it will perform well.

Open (under the *File* button)

`boot_sc_winpro_win.pl`

in the `StCr\StCr2Sand\boot` directory, and *Compile* it (under the *Run* button). Then minimize the **`boot_sc_winpro_win.pl`** window, and in the console window, type

?- cruncher.

This will give STATECRUNCHER's `SC:` prompt.
- To exit STATECRUNCHER, enter **`quit`** (without a full stop).
- To exit WinProlog, select *File*, *Exit*, or close the application window.

2.7 To run the STATECRUNCHER MS-DOS executable

Extract the Zip file into a directory of suggested name KWinPro.

If the full STATECRUNCHER development directory tree has been supplied, then the executable and related files are to be found in the directory equivalent to

```
    P:\KWinPro\StCr\StCr2Sand\BOOT_SC\StCrExe-Re105
```

Otherwise, they are in the top level directory.

The executable is

```
    statecruncher.exe
```

It must be collocated with

```
    statecruncher.ovl
```

Do not just double click on `statecruncher.exe`. It must be run with the parameters specifying memory usage as for WinProlog. The following should be sufficient for most purposes:

```
    statecruncher.exe /B512 /L1024 /P50000 /H3000 /T1024
```

Make a shortcut to wherever you put `statecruncher.exe` on your system. The suggested parameter settings are made in the shortcut file by right clicking it, selecting *properties*, and editing the *target* to e.g. (read as one line):

```
    F:\KWinPro\StCr\StCr2Sand\BOOT_SC\StCrExe-
    Re105\statecruncher.exe /B512 /L1024 /P50000 /H3000
    /T1024
```

The shortcut can best also be set to *start in* the current directory, which is set by clearing the shortcut *start in* edit box.

This file, when edited as just mentioned, can conveniently be copied to any directory in which the user is working on a model and used to start it up. (By working this way, the STATECRUNCHER `root` command will not be needed). No other files (except the user's models) are required to run the executable.

When STATECRUNCHER is started up, the prompt

```
    SC:
```

is given and commands can be entered as described in the report. The command to quit is

```
    SC:quit
```

3. Getting started

In this section, we assume that you are able to run STATECRUNCHER and obtain its prompt (`SC:`). It does not matter whether you are using the MS-DOS, SWI-Prolog or WinProlog variety of STATECRUNCHER.

We will make the following model from scratch. It is functionally the same as the model of section 1.1, but with slightly different naming. Remind yourself of the functionality of the model from that section. We will call the model

```
    get_started
```

and put it in directory (adapted for your path)

```
    F:\KWinPro\StCr\StCr5ModelsUser\u5110_get_started
```

The `u5110` naming relates the model to test model `t5110`, and gives us a convenient ordering for our models when alphanumerically sorted. The solutions to this manual/tutorial will be found in directory

```
    F:\KWinPro\StCr\StCr6ModelsTutorial
```

Here is the model we will implement:

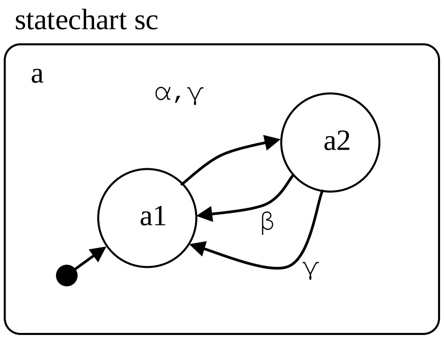


Figure 5. Model `u5110_get_started\get_started`

We will often use Greek letters for event names, for compactness on diagrams and to distinguish them from states and variables. In a STATECRUNCHER source file, they will need to be spelled out. The glossary (section 10) contains the names of the Greek letters.

We will first implement the state machine hierarchy, without events or transitions. This is always good practice. Create a file

```
      get_started.scs.txt
```

in directory (equivalent to)

```
      F:\KWinPro\StCr\StCr5ModelsUser\u5110_get_started
```

The ending `.scs.txt` stands for **S**TATE**C**RUNCHER **S**ource. Enter the following text:

```
statechart sc(a)
   cluster a(a1,a2)
      state a1;
      state a2;
```

The default state of a cluster is its first member - here `a1`.

Start STATECRUNCHER and enter (adapting to your path)

```
  SC:root F:\KWinPro\StCr\StCr5ModelsUser\u5110_get_started
  SC:cp get_started
```

Note: If you are using the MS-DOS version of STATECRUNCHER and put a shortcut in the same directory as the `get_started.scs.txt` file, you do not need the first command above.

As long as you are working in the same directory, correcting and refining your model, with the same invocation of STATECRUNCHER, you will not need to repeat the `root` command when you recompile.

The listing that appears on the screen is also available in two parts, in two files that are created in the same directory as the source file:

```
  get_started.scl.txt
  get_started.scv.txt
```

Observe in passing that two other files are created:

```
  get_started.sco.pl
  get_started.scd.pl
```

These are the compiled model, as PROLOG code, for use by the STATECRUNCHER engine. The first file contains a basic structural parse of the model, and the second file contains a symbol table, cross-reference table, and data store.

On compilation, there should be no errors, and one warning, that state `a2` is unreferenced. This can be ignored. If there are errors, check your source code carefully.

It is worth experimenting with a deliberate error, say calling state `a2` "`a3`", or omitting it altogether. You will get a *machine path error*. This means that there is a problem that the states `a1` and `a2`, declared in `cluster a(a1,a2)`, are not found in the expected place.

Now add the events and transitions. You can also add comments as shown, with // applying to the rest of the line, as in C++, and /*...*/ enclosing a comment as in C.

Statements of code can be split across more than one line by ending the line with `\` (as in Unix shell commands), but in our model the separate statements (event declarations, state declarations etc.) easily fit on one line. Do not put two statements on one line.

```
// My first model

statechart sc(a)
event alpha,beta,gamma;
   cluster a(a1,a2)
      state a1 {alpha,gamma->a2;}
      state a2 {beta->a1; gamma->a1;}
```

Compile this model. You only need the `root` command if you have a new invocation of STATECRUNCHER.

```
  SC:root F:\KWinPro\StCr\StCr5ModelsUser\u5110_get_started
  SC:cp get_started
```

The screen output (also written to the files mentioned) is a compiler listing, and a symbol and cross reference table. An entry such as

```
SYMB gamma      [sc]              eventdecl              []
     XREF leafstate    a1:[a,sc]
     XREF leafstate    a2:[a,sc]
```

identifies symbol `gamma` in statechart scope (`[sc]`), as an event (`eventdecl`) at an unnamed (`[]`) Point of Control and Observation, and is referenced (`XREF`) in leafstates `a1` and `a2`, both in *cluster a* scope (`[a,sc]`). Scopes and Points of Control and Observation will be described later.

We are now in a position to run the model, getting the configuration and processing events.

If you have previously compiled the model, but are in a new invocation of STATECRUNCHER, enter

```
  SC:root F:\KWinPro\StCr\StCr5ModelsUser\u5110_get_started
  SC:run get_started
```

If you have just compiled the model is ready for the next command.

To see the initial state of the machine, enter

```
SC:gc
```

This stands for ***g**et **c**onfiguration*. The output is

```
SC:gc
2    statechart sc
2       cluster a [sc] = OCC []  **
2          leafstate a1 [a, sc] = OCC []  **
2          leafstate a2 [a, sc] = VAC []
2    TRACE =[]
2    TREV [[alpha, [sc]], 0, [], []]
2    TREV [[gamma, [sc]], 0, [], []]

outworlds=[2]
number of outworlds=1
```

As explained in section 1.1, we see the state occupancies (occupied and vacant). The parent of states `a1` and `a2` is cluster `a`. Only one child state of a cluster can be occupied, and if it is, the cluster is occupied. If no child states are occupied, the cluster is not occupied. This explains why cluster `a` is also occupied. The current configuration has two transitionable events, `alpha` and `gamma`. Since they are in statechart scope (`[sc]`), they can be entered without scope in the next command we will give. The remaining items of output will be explained as the subject matter arises throughout this manual.

To ***p**rocess **e**vent* `alpha`, enter

```
SC:pe alpha
```

The command has completed when a new prompt is given. Follow it up with the *get configuration* command.

```
SC:gc
```

The output is

```
SC:gc
3    statechart sc
3       cluster a [sc] = OCC []  **
3          leafstate a1 [a, sc] = VAC []
3          leafstate a2 [a, sc] = OCC []  **
3    TRACE =[]
3    TREV [[beta, [sc]], 0, [], []]
3    TREV [[gamma, [sc]], 0, [], []]

outworlds=[3]
number of outworlds=1
```

State `a1` is now vacant, and state `a2` is occupied. The transitionable events have changed.

Experiment with more `pe` and `gc` commands, and see the machine transition (or not, as the case may be).

To quit, enter

```
   SC:quit
```

If this leaves a Prolog prompt, close the window, or type

```
   ?- halt.
```

For a guide to all STATECRUNCHER commands, see chapter Table 4 and [StCrPrimer].

4. Guide to operation

This section covers the functionality of STATECRUNCHER feature by feature. The reader is assumed to be familiar with the concept of a STATECRUNCHER statechart from the previous chapter. All statecharts in the following models are implicitly called "`sc`".

The model numbers as used in directory names in the following sections are of the type u*nnnn* (where *n* is a digit) and run in parallel to the test model numbers t*nnnn*, which are described in [StCrTest]. Where the numbers correspond, the subject matter is similar, but the tutorial model is not necessarily identical to the test model - it will often be simpler. The order of presentation in this manual is not completely sequential with respect to these numbers, since it is regarded as important to present the material in a the best order for learning, whilst retaining established model numbering.

The tutorial models are identified for short as a "u*nnnn*" model for convenience, but unlike the test models, they cannot be run under this name - all it means is that they are found in a directory u*nnnn_something* and they must be compiled and run using the *actual name of the source file*, which is what a user must always do when creating a new model.

4.1 Variables, and parameterised and conditional transitions

We will implement the following model:

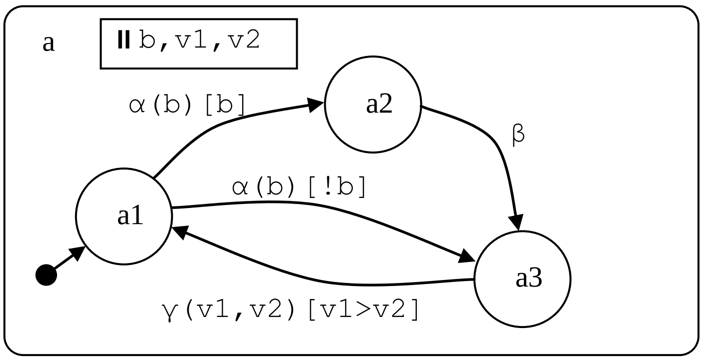


Figure 6. Variables, parameterised and transitional conditions

Features of the model are:

- Three variables are declared: `b` (which is a boolean), `v1` and `v2` (which are integers). The integers will be declared as belonging to a range. (Enumerated value integers and strings are also possible).
- Transitions are triggered by parameterised events. Trigger `α(b)` means event `α` with a parameter `b`. The parameter is not a formal parameter as in other languages, but a destination variable for the supplied parameter. When we give the transition this event and a parameter, that parameter will be stored in variable `b`.
- Two transitions in this model are conditional. The condition is put in square brackets. The trigger `α(b)[b]` means that the value of `b` must be true for the transition to be eligible. The term `[b]` could have been any other expression yielding a boolean. The condition expression need not refer to any parameters, but it often will, as here. There is also a transition on gamma if `v1` is greater than `v2`, where these variables happen to be locations of the transition parameters.

First implement the state machine hierarchy, without events or transitions. Create a file

```
param.scs.txt
```

in directory (equivalent to)

```
F:\KWinPro\StCr\StCr5ModelsUser\u5123_param
```

Enter the following text :

```
statechart sc(a)
   cluster a(a1,a2,a3)
      state a1;
      state a2;
      state a3;
```

Compile it (as in Chapter 3, Getting started).

```
SC:root F:\KWinPro\StCr\StCr5ModelsUser\u5123_param
SC:cp param
```

Then upgrade it to the following:

```
statechart sc(a)
event alpha,beta,gamma;
   cluster a(a1,a2,a3)
      enum int10 {0,..,10};
      int10 v1,v2;
      bool  b=false;

      state a1 {alpha(b)[b]->a2; alpha(b)[!b]->a3;}
      state a2 {beta->a3;}
      state a3 {gamma(v1,v2)[v1>v2]->a1;}
```

See how our integer type, `int10`, specifies a range. Having specified the type (`int10`), we declare integers v1 and v2. The boolean type `bool` is built-in, as are constants `true` and `false` (equivalent to 1 and 0 respectively).

We arbitrarily initialise `b`, but not `v1` or `v2`.

The type and integer declarations have been declared at *`cluster a`* scope. They could have been put after the `statechart` statement; then they would have been at statechart scope. We address these variables in a very local scope, in the scope of the source state of the transitions, i.e. in `a1`, `a2` and `a3` scopes. It does not matter that these variables were not defined in these scopes. Variables declared in ancestors of the place where they are used will always be found. An *outbound search* mechanism will find the nearest variable. But if we declare a variable deep in the hierarchy, we cannot address it from higher up in the hierarchy without using some scoping operators. There is more on scoping in section 4.12.

Run the model and get the initial configuration

```
SC:run param
SC:gc
```

This should be:

```
SC:gc
2    statechart sc
2       cluster a [sc] = OCC []  **
2          leafstate a1 [a, sc] = OCC []  **
2          leafstate a2 [a, sc] = VAC []
2          leafstate a3 [a, sc] = VAC []
2    VAR  INTEGER b [a, sc] =0
2    VAR  INTEGER v1 [a, sc] =unknown
2    VAR  INTEGER v2 [a, sc] =unknown
2    TRACE =[]
2    TREV [[alpha, [sc]], 1, [[r, 0, 1]], []]

outworlds=[2]
number of outworlds=1
```

The line

```
2    TREV [[alpha, [sc]], 1, [[r, 0, 1]], []]
```

tells us that there is a transitionable event `alpha` which takes `1` parameter, which takes values in a range 0 to 1 (`[r,0,1]`).

Transition to state `ac` as follows

```
SC:pe alpha p=0
SC:gc
```

This gives us:

```
SC:gc
3    statechart sc
3       cluster a [sc] = OCC []  **
3          leafstate a1 [a, sc] = VAC []
3          leafstate a2 [a, sc] = VAC []
3          leafstate a3 [a, sc] = OCC []  **
3    VAR  INTEGER b [a, sc] =0
3    VAR  INTEGER v1 [a, sc] =unknown
3    VAR  INTEGER v2 [a, sc] =unknown
3    TRACE =[]
3    TREV [[gamma, [sc]], 2, [[r, 0, 10], [r, 0, 10]], []]

outworlds=[3]
number of outworlds=1
```

Now transition to `a1` as follows

```
SC:pe gamma p=[3,2]
SC:gc
```

The output is:

```
SC:gc
4    statechart sc
4       cluster a [sc] = OCC []  **
4          leafstate a1 [a, sc] = OCC []  **
4          leafstate a2 [a, sc] = VAC []
4          leafstate a3 [a, sc] = VAC []
4    VAR  INTEGER b [a, sc] =0
4    VAR  INTEGER v1 [a, sc] =3
4    VAR  INTEGER v2 [a, sc] =2
4    TRACE =[]
4    TREV [[alpha, [sc]], 1, [[r, 0, 1]], []]

outworlds=[4]
number of outworlds=1
```

Note that `v1` and `v2` now have values.

Experiment by transitioning to state `ab` on event `alpha` by providing a parameter value of 1 (=true).

To quit, enter

```
SC:quit
```

If this leaves a Prolog prompt, close the window, or type

```
?- halt.
```

Remark on enumerated integers with tagnames:
Although not used in these examples, an integer type can be declared with *tagnames* as follows:

```
enum colour   {red,green=3,blue};
```

Actual integral values are assigned as in C. After the declaration, the symbols `red`, `green` and `blue` can be used in expressions.

4.2 Nested cluster and history

We will implement the following model:

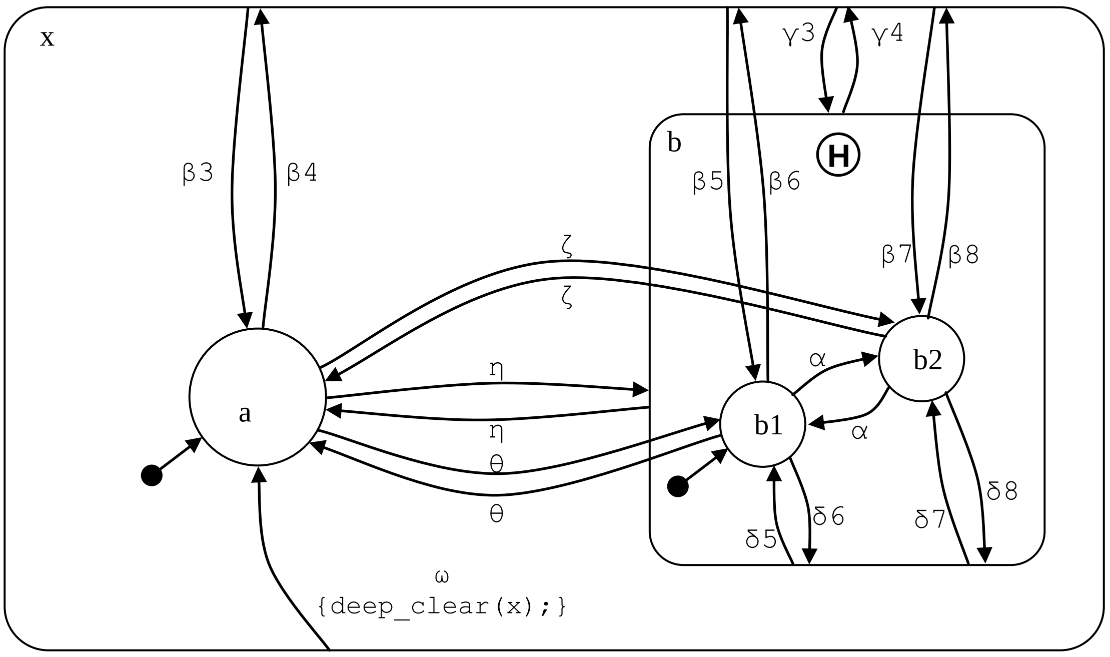


Figure 7. Nested cluster, self transitions, and history [model `u5130`]

The **(H)** symbol indicates that the cluster can on entry go into the historical state rather than the default state (though history can be cleared, as will be shown). This is not quite the same as a UML pseudo-state: STATECRUNCHER does not currently support these directly (they are on the wish-list), but the functionality of pseudo-states can be imitated with the combination of a history cluster and selective *clear history* actions.

Some transitions are *from* or *to* non-leaf states, i.e. their *source* states or *target* states are not leaf states. A transition *from* a non-leaf state counts as if it is from any occupied descendant state. A transition *to* a non-leaf state goes either to the historical state (i.e. to the state last occupied in the cluster) or to the default state, depending on whether history is marked and whether the historical state is available (the cluster may have never been entered, or the history may have been cleared).

Call the file `nested_cluster.scs.txt` in directory `u5130_nested_cluster`. Prepare the hierarchy first, but include the `history` keyword, and compile it (as already learned).

```
  SC:root F:\KWinPro\StCr\StCr5ModelsUser\u5130_nested_cluster
  SC:cp nested_cluster
```

The hierarchy is:

```
statechart sc(x)

cluster x(a,b)
   state a;
   cluster b(b1,b2) history
      state b1;
      state b2;
```

Now add the declarations and transitions:

```
statechart sc(x)
event alpha;
event beta3,beta4,beta5,beta6,beta7,beta8;
event gamma3,gamma4;
event delta5,delta6,delta7,delta8;
event zeta, eta, theta;
event omega;

cluster x(a,b) {beta3->x.a;                    \
                beta5->x.b.b1;                 \
                beta7->x.b.b2;                 \
                gamma3->x.b;                   \
                omega->x.a{deep_clear(x);};    }

   state a { beta4->$x;  zeta->b.b2;  eta->b;  theta->b.b1; }

   cluster b(b1,b2) history {gamma4->$x;       \
                             delta5->b.b1;     \
                             delta7->b.b2;     \
                             eta->a;           }

      state b1 {alpha->b2;  beta6->$$x;  delta6->$b;  theta->$a;}

      state b2 {alpha->b1;  beta8->$$x;  delta8->$b;  zeta->$a;}
```

Points to note

- A statement can be split over several lines using a backslash (with nothing following on the line, and not commented out by use of the // comment symbol).
- A *parent* state is targeted using a `$` operator, and a grandparent using `$$`.
- A *child* state is targeted using the dot operator, e.g. `x.a` and a *grandchild* by e.g. `x.b.b1`.

- This model does not have *cousin* states, but to target a cousin state, the construction is e.g. `$a.a1` - see test model `t5130`, depicted in [StCrTest], for an example.
- The fragment `{deep_clear(x);}`, which clears history in all clusters in and below cluster `a`, is called an *action* on the transition. A similar kind of action is an *assignment*, described in section 4.6.
- Instead of `history`, we could have marked the cluster with `deep history`. In models with deeper nesting, there would be a distinction, because deep history clusters would keep history of descendants, recursively, as well. See test model `t5200` for an example.

Run the model (as learned in previous sections). Process events `eta`, `alpha`, `eta`. This takes us through states `a`, `b1`, `b2`, and back to `a`. Then get the configuration. It is:

```
SC:gc
5    statechart sc
5       cluster x [sc] = OCC []  **
5          leafstate a [x, sc] = OCC []  **
5          cluster b [x, sc] = VAC b2
5             leafstate b1 [b, x, sc] = VAC []
5             leafstate b2 [b, x, sc] = VAC []
5    TRACE =[]
5    TREV [[beta4, [sc]], 0, [], []]
5    TREV [[zeta, [sc]], 0, [], []]
5    TREV [[eta, [sc]], 0, [], []]
5    TREV [[theta, [sc]], 0, [], []]
5    TREV [[beta3, [sc]], 0, [], []]
5    TREV [[beta5, [sc]], 0, [], []]
5    TREV [[beta7, [sc]], 0, [], []]
5    TREV [[gamma3, [sc]], 0, [], []]
5    TREV [[omega, [sc]], 0, [], []]

outworlds=[5]
number of outworlds=1
```

Observe the line formatted in bold print. Cluster `b` is vacant, but its historical state is **`b2`**. Now process event `eta`. Get the configuration and observe that state `b2` is entered, not `b1`.

```
6             leafstate b2 [b, x, sc] = OCC []  **
```

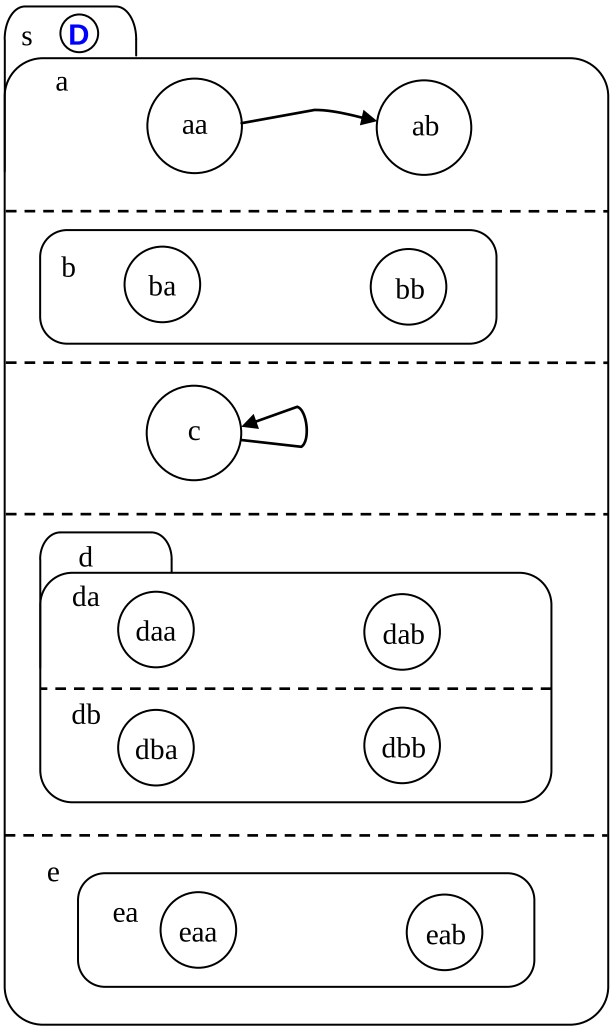
Now reset the machine to its default state
`SC:`**`rm`**

Process events `eta`, `alpha`, `eta`. as before. But now process `omega`, observing the configuration. The history of cluster `b` has been cleared, - instead of `b2` there is`[]`. Now process event `eta`. The *default* state `b1` is entered, not the historical state.

```
8             leafstate b1 [b, x, sc] = OCC []  **
```

4.3 Sets

Sets, like clusters, have members (which can be leafstates, clusters or sets). But if a set is occupied, *all* its members are occupied. The cluster rule applies to members: if one of the members is a cluster, and it is occupied, then only one member of the cluster will be occupied. Sets enable us to model parallelism, and we may speak of the set members as *parallel machines*. A set can have deep history. The symbol for a set is a rounded box with a tab on the top left for the set name. The following diagram shows how set members may be depicted.



Note deep history marker

member is a cluster
(containing two leafstates)
*note symbol **a** in the member area*

***alternative**: member is a cluster*
(containing two leafstates)
*note **no** symbol outside the cluster*

member is a leafstate
*note **no** symbol outside the leaf state*
(can be useful for self transition actions)

member is a set
(containing two clusters, each of which contains two leafstates)

member is a cluster
(containing a cluster (containing two leafstates))

Figure 8. Set members

Transitions to sets may specify several specific target states in different members, or they may omit some (in which case the default or historical state will be taken where appropriate), or they may simply target the set, in which case all the target states will be selected using default or historical considerations.

We will implement the following model:

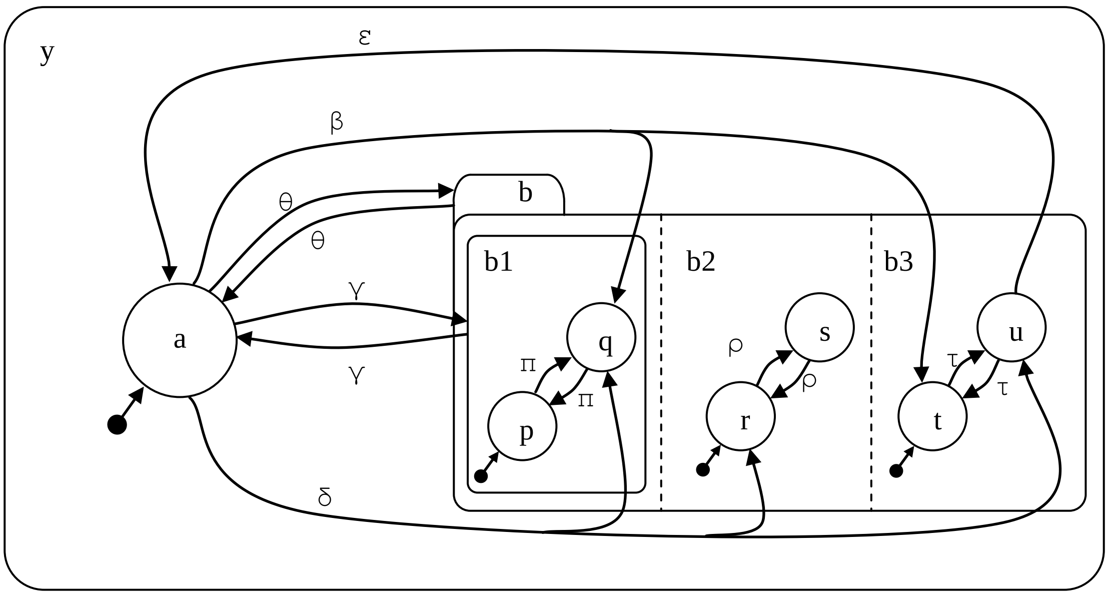


Figure 9. Set [model `u5140`]

Points to note

- There is no difference in structure between the members `b1`, `b2`, `b3`. The alternative notation is used for member `b1` so that it can be made clear that the transition on event γ targets member `b1`, and not just set `b`.
- The transition from `a` on β targets `b1.q` (a nondefault state), `b3.t` (a default state), but omits a target for member `b2`. The default state `b2.r` will be taken.
- The transition from `a` on θ targets the set only, not a member or anything in a member. Default states will be taken.
- The transition from `a` on γ targets member `b1` only. Default states will be taken in all members.
- The transition on ε exits from a child of set member `b3` explicitly. A transition on γ exits from a nonleaf member. A transition on θ exits from the set as such. In all these cases, all members of the set will be exited.

Call the file `set.scs.txt` in directory `u5140_set`. Prepare the hierarchy first and compile it (as already learned).

```
  SC:root F:\KWinPro\StCr\StCr5ModelsUser\u5140_set
  SC:cp set
```

The hierarchy is:

```
statechart sc(y)
      cluster y (a,b)
         state a;
         set b (b1,b2,b3)
            cluster b1(p,q)
               state p;
               state q;
            cluster b2(r,s)
               state r;
               state s;
            cluster b3(t,u)
               state t;
               state u;
```

Now add the declarations and transitions:

```
statechart sc(y)
event beta,gamma,delta,epsilon,theta,pi,rho,tau;
      cluster y (a,b)
         state a    {beta-> b.(b1.q/\b3.t);        \
                     delta->b.(b1.q/\b2.r/\b3.u); \
                     gamma->b.b1;                 \
                     theta->b;                    }
         set b (b1,b2,b3) {theta->a;}
            cluster b1(p,q) {gamma->$a;}
               state p {pi->q;}
               state q {pi->p;}
            cluster b2(r,s)
               state r {rho->s;}
               state s {rho->r;}
            cluster b3(t,u)
               state t {tau->u;}
               state u {tau->t; epsilon->$$a;}
```

Points to note

- Multiple targets are addressed using the split operator, `/\`.
- Set `b`, being a sibling of state `a`, is targeted from state `a` without scoping operators: `theta->b`. Members of the set require the child operator: `gamma->b.b1`. The leafstates in the set are all a level deeper still, e.g. `b.b1.q`.

Run the model (as learned in previous sections). Process event `beta`. Use the `gc` command to observe the leafstates in the set that are occupied:

```
SC:gc
3    statechart sc
3       cluster y [sc] = OCC []  **
3          leafstate a [y, sc] = VAC []
3          set b [y, sc] = OCC []  **
3             cluster b1 [b, y, sc] = OCC []  **
3                leafstate p [b1, b, y, sc] = VAC []
3                leafstate q [b1, b, y, sc] = OCC []  **
3             cluster b2 [b, y, sc] = OCC []  **
3                leafstate r [b2, b, y, sc] = OCC []  **
3                leafstate s [b2, b, y, sc] = VAC []
3             cluster b3 [b, y, sc] = OCC []  **
3                leafstate t [b3, b, y, sc] = OCC []  **
3                leafstate u [b3, b, y, sc] = VAC []
3    TRACE =[]
3    TREV [[pi, [sc]], 0, [], []]
3    TREV [[rho, [sc]], 0, [], []]
3    TREV [[tau, [sc]], 0, [], []]
3    TREV [[gamma, [sc]], 0, [], []]
3    TREV [[theta, [sc]], 0, [], []]

outworlds=[3]
number of outworlds=1
```

Process events `tau` and `epsilon` . Observe how the whole set has been exited:

```
5          set b [y, sc] = VAC []
5             cluster b1 [b, y, sc] = VAC q
5                leafstate p [b1, b, y, sc] = VAC []
5                leafstate q [b1, b, y, sc] = VAC []
5             cluster b2 [b, y, sc] = VAC r
5                leafstate r [b2, b, y, sc] = VAC []
5                leafstate s [b2, b, y, sc] = VAC []
5             cluster b3 [b, y, sc] = VAC u
5                leafstate t [b3, b, y, sc] = VAC []
5                leafstate u [b3, b, y, sc] = VAC []
```

Experiment with the other transitions.

Remark

- We have seen how to target several *target* states of a transition. The reader might ask about several *source* states. The question makes sense, because we might require that several states in a set be occupied before we allow a transition out of the set. This is achieved by making one of the source states the "master" and adding a condition that the other states are occupied using the `in()` function, described in section 4.9.

4.4 Fired events

Events may be supplied by the user, with the `pe` command, or they may be generated in the model, by an action which we call *firing* an event.

As with user-supplied events, fired events can take parameters.

We illustrate fired events in two contexts

- Where a transition in one part of a machine fires an event which will be responded to in a parallel part of the machine to cause a transition there.
- An engagement between two parallel parts of a machine representing STATECRUNCHER's ***client-server paradigm***. This is considered in the next section (4.5).

Other aspects to fired events, for which we refer the interested reader to test models, are:

- A simple knock-on effect in a machine with no parallelism (see test model `t5152`).
- Fired events can also be used to generate loops (see test model `t5240`).

The model we first implement is as follows:

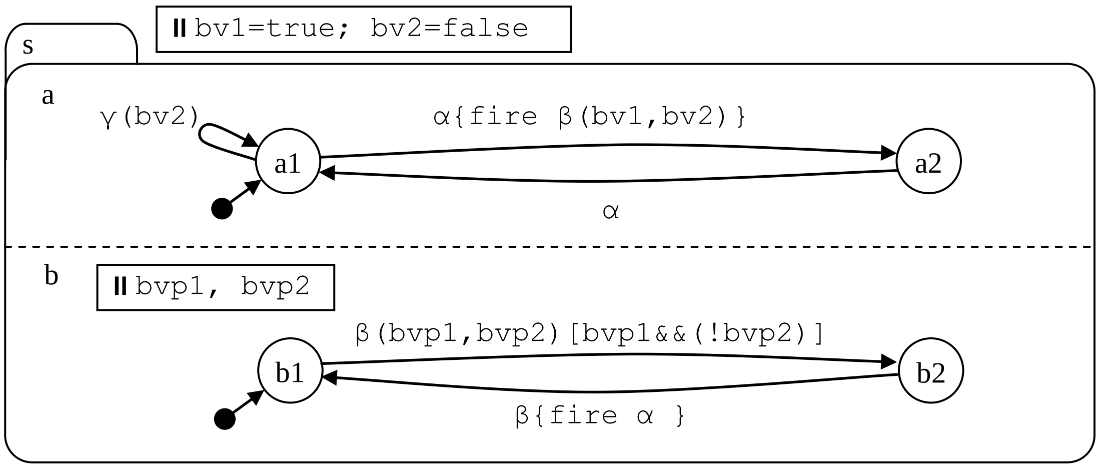


Figure 10. Fired event [model `u5150`]

Points to note

- The user will initially supply event α, and the system will fire event β. After this, when we are in states `a2` and `b2`, the user can supply event β, and the system will fire event α.
- We declare two boolean variables, `bv1` and `bv2`, and use them as parameters when we fire the event β.
- The transition labelled `β(bvp1,bvp2)[bvp1&&(!bvp2)]` receives the parameters and puts them in its own locations (`bvp1` and `bvp2`). The initial values of `bv1` and `bv2` (true and false respectively) will allow the transition on `β(bvp1,bvp2)` to take place, because the condition evaluates to true. However, `bv2` can be set to any value using the self-transition on γ, so we can arrange for the condition to evaluate to false.

- Although we will initially fire event β via event α, β can be supplied by the user from the start.

Call the file `fire.scs.txt` in directory `u5150_fire.` Prepare the hierarchy first and compile it (as already learned).

```
  SC:root F:\KWinPro\StCr\StCr5ModelsUser\u5150_fire
  SC:cp fire
```

The hierarchy is:

```
statechart sc(s)
   set s(a,b)
      cluster a(a1,a2)
         state a1;
         state a2;
      cluster b(b1,b2)
         state b1;
         state b2;
```

Then add the declarations and transitions:

```
statechart sc(s)
event alpha,beta,gamma;
bool bv1=true,bv2=false;
  set s(a,b)
     cluster a(a1,a2)
        state a1 {alpha->a2{fire beta(bv1,bv2);}; gamma(bv2);}
        state a2 {alpha->a1;}
     cluster b(b1,b2)
     bool bvp1,bvp2;
        state b1 {beta(bvp1,bvp2)[bvp1&&(!bvp2)]->b2;}
        state b2 {beta->b1 {fire alpha;};}
```

Run the model (as learned).

- Process event `alpha`, get the configuration, and observe that the transition on `beta` took place as well as the one on `alpha`.
- Reset the model (command **`rm`**). Process event `gamma` with a parameter of 1 (command `pe gamma p=1`). Now process event `alpha`. The condition on the receiving transition, `[bvp1&&(!bvp2)]`, is now false, and that transition does not take place.
- Experiment with other transitions. Apart from altering variable values, how many different state occupancy configurations does the model have? Finding the configurations is called *exploring* the model. The figure below shows the explored model.

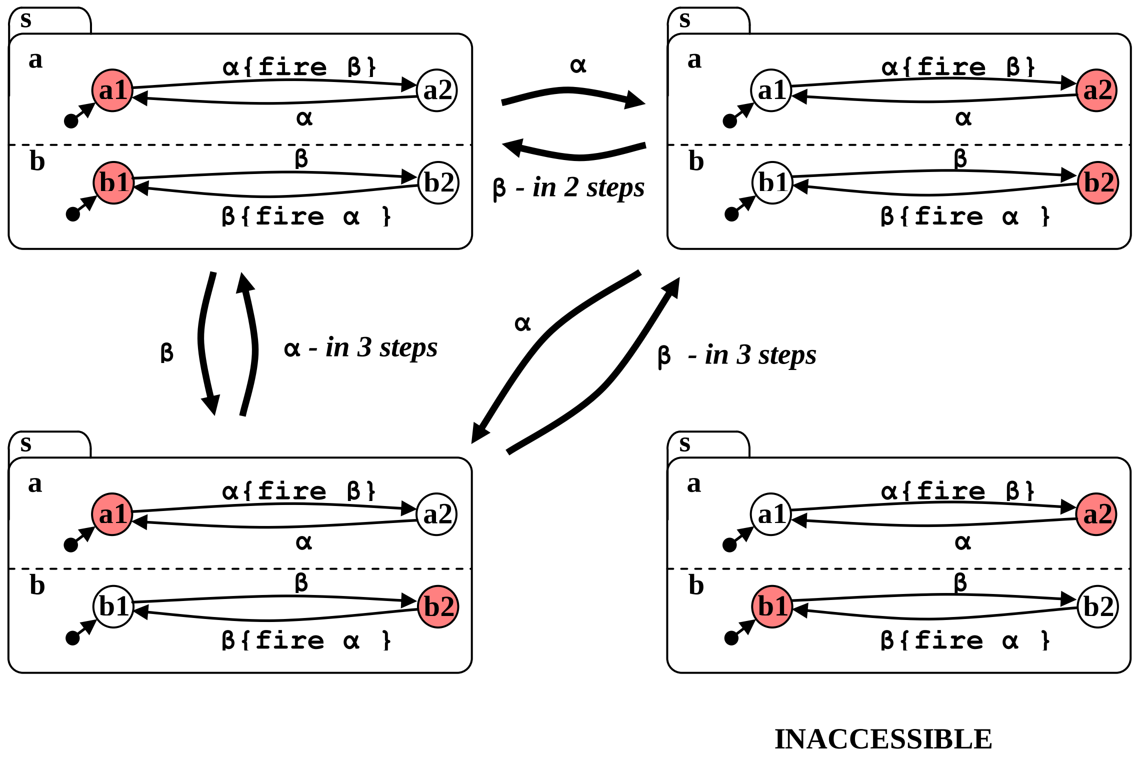


Figure 11. Fired event model explored

Occupied states are shown shaded, in red.

4.5 Client-server composition and PCOs

In this section, we see how to model one software component or function calling another, using fired events. We introduce the concept of PCOs: Points of Control and Observation. We will implement the following model:

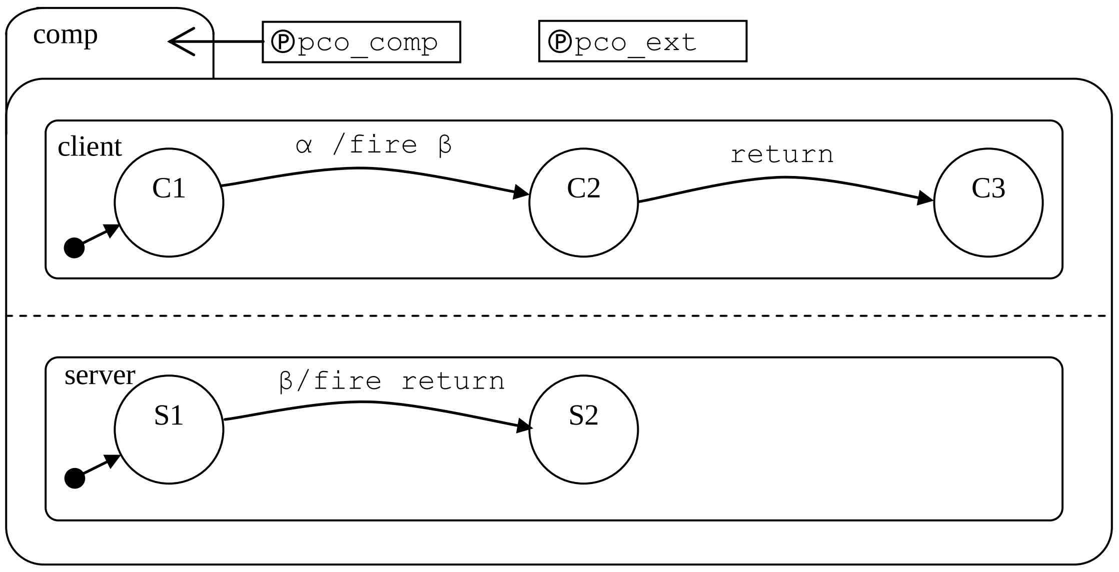


Figure 12. Component composition

Points to note

- STATECRUNCHER's composition paradigm is closely analogous to the function call and return of imperative languages such as 'C'.
  - The *making* of the function call is modeled by a fired event
  - The *response* to this is modeled by a transition on the event that was fired
  - The *return statement* is modeled by fired return event
  - The *response* to this is modeled by a transition on the return event that was fired.

  If there are many such calling sequences in a model, return names can be made unique to a server function by affixing the function name to the event (e.g. `return_max`) or by putting the return event in a sufficiently local scope (using STATECRUNCHER's scoping capabilities.

- The client can be seen as an independent state machine, which can be driven through its cycle with events alpha and return. It does not care who it is that responds to its firing of β, nor who it is that provides the `return` event. A different server to the one shown might be connected to the client, e.g. with more states and transitions between its initial and final states (S1 an S2). Similarly the server is independent of its client, except for the agreed interface of β and `return`.

- Event α is supplied externally to the client and server. Events β and `return` are part of the agreed interface between the client and server. We indicate this by putting the events on different PCOs. STATECRUNCHER's output will reveal the PCOs so that a test generator program can distinguish, and if required, restrict itself to certain PCOs only. We put α on `pco_ext` (for *external*) and β on `pco_cmp` (for *composition*). If we had more events local to the server only, say, we could put them on `pco_serv` and so on, but we have kept this model to the basics.

Call the file `client_server.scs.txt` in directory `u5154_client_server`. Prepare the hierarchy first and compile it (as already learned).

```
  SC:root F:\KWinPro\StCr\StCr5ModelsUser\u5154_client_server
  SC:cp client_server
```

The hierarchy is:

```
statechart sc(comp)
  set comp(client, server)
     cluster client(C1,C2,C3)
        state C1;
        state C2;
        state C3;
     cluster server(S1,S2)
        state S1;
        state S2;
```

Then supply the declarations and transitions:

```
statechart sc(comp)
PCO ext,cmp;
event alpha@ext;
event beta,return@cmp;

  set comp(client, server)
     cluster client(C1,C2,C3)
        state C1 {alpha->C2 {fire beta;}; }
        state C2 {return->C3;}
        state C3;
     cluster server(S1,S2)
        state S1 {beta->S2 {fire return;}; }
        state S2;
```

Points to note

- PCOs are declared in their own declaration statements, and are used in event declarations.
- We haven't used capital letters for identifiers so far, but they are allowed. Identifiers are as in 'C', so non-leading underscores are allowed too, but double underscores can have a special meaning in connection with arrays, discussed later.

Compile and run the model. The initial state is:

```
SC:gc
2    statechart sc
2       set comp [sc] = OCC []  **
2          cluster client [comp, sc] = OCC []  **
2             leafstate C1 [client, comp, sc] = OCC []  **
2             leafstate C2 [client, comp, sc] = VAC []
2             leafstate C3 [client, comp, sc] = VAC []
2          cluster server [comp, sc] = OCC []  **
2             leafstate S1 [server, comp, sc] = OCC []  **
2             leafstate S2 [server, comp, sc] = VAC []
2    TRACE =[]
2    TREV [[alpha, [sc]], 0, [], [ext, [sc]]]
2    TREV [[beta, [sc]], 0, [], [cmp, [sc]]]

outworlds=[2]
number of outworlds=1
```

Point to note

- The `TREV` lines show the PCO on which the event has been declared. PCOs can themselves be scoped; our PCOs are both in statechart scope, i.e. `[sc]`.

Process event `alpha` and obtain the configuration:

```
SC:pe alpha
SC:gc
5    statechart sc
5       set comp [sc] = OCC []  **
5          cluster client [comp, sc] = OCC []  **
5             leafstate C1 [client, comp, sc] = VAC []
5             leafstate C2 [client, comp, sc] = VAC []
5             leafstate C3 [client, comp, sc] = OCC []  **
5          cluster server [comp, sc] = OCC []  **
5             leafstate S1 [server, comp, sc] = VAC []
5             leafstate S2 [server, comp, sc] = OCC []  **
5    TRACE =[]

outworlds=[5]
number of outworlds=1
```

Points to note

- The complete transaction between the server and client has run its course.
- This particular model has no reset event and has reached a dead end. There are no transitionable events. This sort of situation could be an indication of deadlock in a real system. A server would typically return to its initial state on completion, but we have left this one in state S2 as we feel it more clearly expresses the client-server paradigm.

4.6 Assignments on transitions and inexact variable scoping

In this section we show how assignments can be made on transitions. We also show that variables of the same name can be declared in different scopes; they are then completely separate variables.

We will implement the following model:

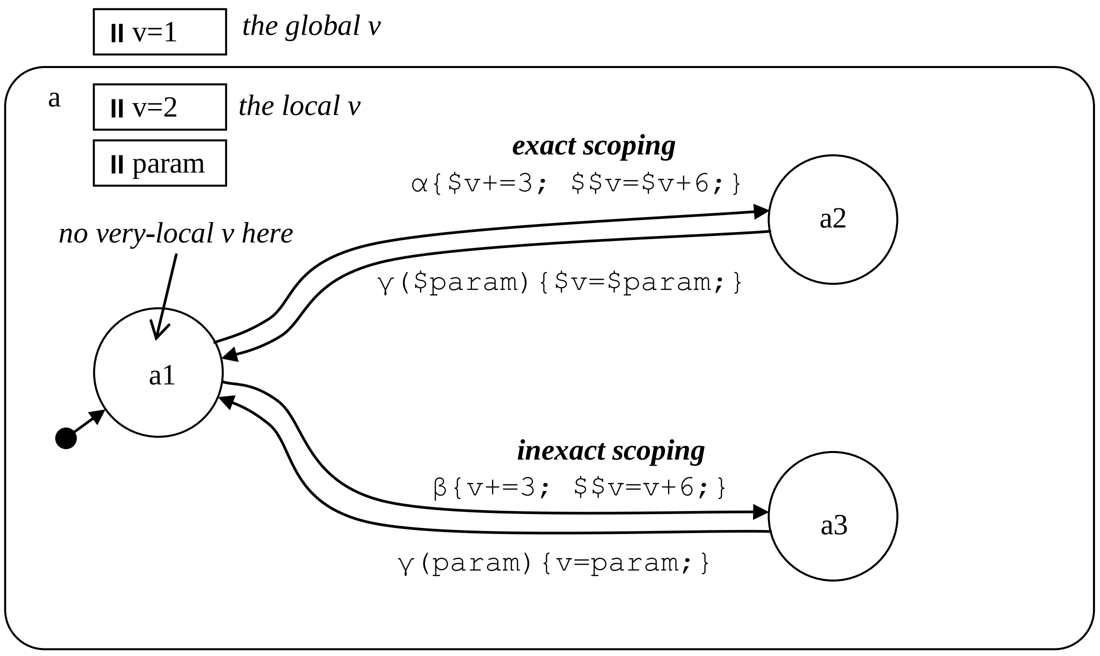


Figure 13. Assignment on transition with overloaded variable names [model `u5160`]

Points to note

- There can be several assignments (and other actions) on a transition.
- An arithmetic expression on a transition such as `v+=3` in principle refers to a `v` in the scope of the source state. So for a transition from state `a1`, it refers to a `v` declared in state `a1` scope. However, if there is no such variable in this scope, which is the situation here, the nearest `v` will be used; it is the `v` in cluster `a` scope.
- An expression such as `$v+=3` refers to a `v` in the parent scope. So for a transition from state `a1`, it refers to a `v` declared in cluster `a` scope. This `v` exists.
- An expression such as `$$v+=3` refers to a `v` in the grandparent scope. So for a transition from state `a1`, it refers to a `v` declared in statechart `sc` scope. This `v` exists, and is distinct from the `v` in cluster `a` scope.
- The rule about finding the nearest variable in scope, searching up the hierarchy, applies to variables on the left hand side or right hand side of expressions.

Call the file `assign.scs.txt` in directory `u5160_assign.` Prepare the hierarchy first and compile it (as already learned).

```
  SC:root F:\KWinPro\StCr\StCr5ModelsUser\u5160_assign
  SC:cp assign
```

The hierarchy is:

```
statechart sc(a)
  cluster a(a1,a2,a3)
    state a1;
    state a2;
    state a3;
```

Then supply the declarations and transitions:

```
statechart sc(a)
event alpha,beta,gamma;
enum int1 {0,..,1000};
int1 v=1;
  cluster a(a1,a2,a3)
  int1 v=2;
  int1 param;
    state a1 {alpha->a2 {$v+=3;$$v=$v+6;};   \
              beta->a3  {v+=3;$$v=v+6;};     }

    state a2 {gamma($param)->a1{$v=$param;}; }

    state a3 {gamma(param)->a1{v=param;};    }
```

Run the model and get the initial configuration:

```
SC:gc
2    statechart sc
2       cluster a [sc] = OCC []   **
2          leafstate a1 [a, sc] = OCC []   **
2          leafstate a2 [a, sc] = VAC []
2          leafstate a3 [a, sc] = VAC []
2    VAR  INTEGER param [a, sc] =unknown
2    VAR  INTEGER v [a, sc] =2
2    VAR  INTEGER v [sc] =1
2    TRACE =[]
2    TREV [[alpha, [sc]], 0, [], []]
2    TREV [[beta, [sc]], 0, [], []]

outworlds=[2]
number of outworlds=1
```

Points to note

- The two variables called `v` are shown with their scope. A scope of `[a,sc]` is read from right to left if we descend in the hierarchy: we get to this `v` by going to statechart `sc` and cluster `a`.
- *Variable* expressions are evaluated from the perspective of the source state of the transition. Note in passing that states are also listed with their scope. We have already seen how we target states using scoping operators. The issue of states and their scope can be a little confusing, because a scope is itself a state. Given a state, we say its scope is the parent state. This explains output such as

  ```
  leafstate a1 [a, sc] = VAC []
  ```

  State expressions such as `a.b` are evaluated from the perspective of the scope part, or *parent,* of the source state of a transition. This gives the most natural way to address states: siblings require no operators, parents require a `$`, and child states require a dot.

Process event `alpha`. This will cause the following evaluations to take place

- `$v+=3;`

  `$v` is the `v` in `[a,sc]` scope and was initialized to 2, so it gets the value 5.
- `$$v=$v+6;`

  `$$v` is the `v` in `[sc]` scope and was initialized to 1. `$v` is as above and has the value 5. So `$$v` gets the value 5+6=11.

```
SC:gc
5    statechart sc
5       cluster a [sc] = OCC []  **
5          leafstate a1 [a, sc] = VAC []
5          leafstate a2 [a, sc] = OCC []  **
5          leafstate a3 [a, sc] = VAC []
5    VAR  INTEGER param [a, sc] =unknown
5    VAR  INTEGER v [a, sc] =5
5    VAR  INTEGER v [sc] =11
5    TRACE =[]
5    TREV [[gamma, [sc]], 1, [[r, 0, 1000]], []]

outworlds=[5]
number of outworlds=1
```

There is now a transition on event `gamma`, taking a parameter, which is then assigned to an exactly specified local `v`. Process it with some parameter value, say, 88 (`pe gamma p=88`):

```
7    VAR  INTEGER param [a, sc] =88
7    VAR  INTEGER v [a, sc] =88
```

Reset the model (command `rm`) and process event `beta`. The effect on the variables is the same as when we processed event `alpha`, although one variable was addressed inexactly. There is also a transition on event `gamma`, taking a parameter, which is then assigned to an inexactly specified local `v`. The effect is as above, in the exactly specified case. Remember that we could have placed our parameter directly into variable `v`, specifying the transition with `γ($v)` rather than `γ($param)`, but here we make a copy of the parameter.

4.7 Orbits, self-transitions, upon-enter and upon-exit actions

When a transition takes place, (apart from some self-transitions), various states are exited and various states are entered. In this section we show how an action can be attached to the internal event of a state being exited or entered, which we call ***upon enter actions*** and ***upon exit actions***.

We also show how a transition course can be taken to a higher level than normal. Normally, a transition course will be as low-flying as possible. A transition which causes more states to be exited and entered, in our notation, is given a loop in the arc and is called an ***orbital transition***.

Self transitions are transitions with the same source and target state. They may nevertheless cause a transition between states. They can be internal or external.

- ***Internal self-transitions*** are drawn on the inside of the state and never cause transitions between states. As with other transitions, they are valid for processing if the state to which they are attached is occupied; if not, they are totally discounted.
  - There is no difference between leafstate and non-leafstate internal self-transitions. If they are valid and there is an action attached to them, the action is performed.
  - Internal transitions cannot be orbital.

- ***External self-transitions*** are drawn outside the state.
  - If they are on a nonleaf state, they can cause transitions to default states, (but not in clusters with history, because the current state is counted as the historical state). This applies to the self-transition on `ε3` in Figure 14 when state `p2` is occupied.
  - If they are on a leafstate, nothing is exited or entered (unless the self-transition is orbital), but actions are executed, and they behave like internal transitions.
  - External self transitions can be orbital (to any height of orbit). In this case they always cause exiting and entering to the height of the orbit.

Self transitions can be parameterised, but we do not illustrate that here; an example was given in section 4.4.

If there are actions on a transition, the order of action execution is:

1. Do the exit actions, starting with the source state
2. Do the on-transition actions
3. Do the enter actions, ending with the target state.

If several parallel states are exited and entered, we are in the realm of set-transit nondeterminism, to be discussed later.

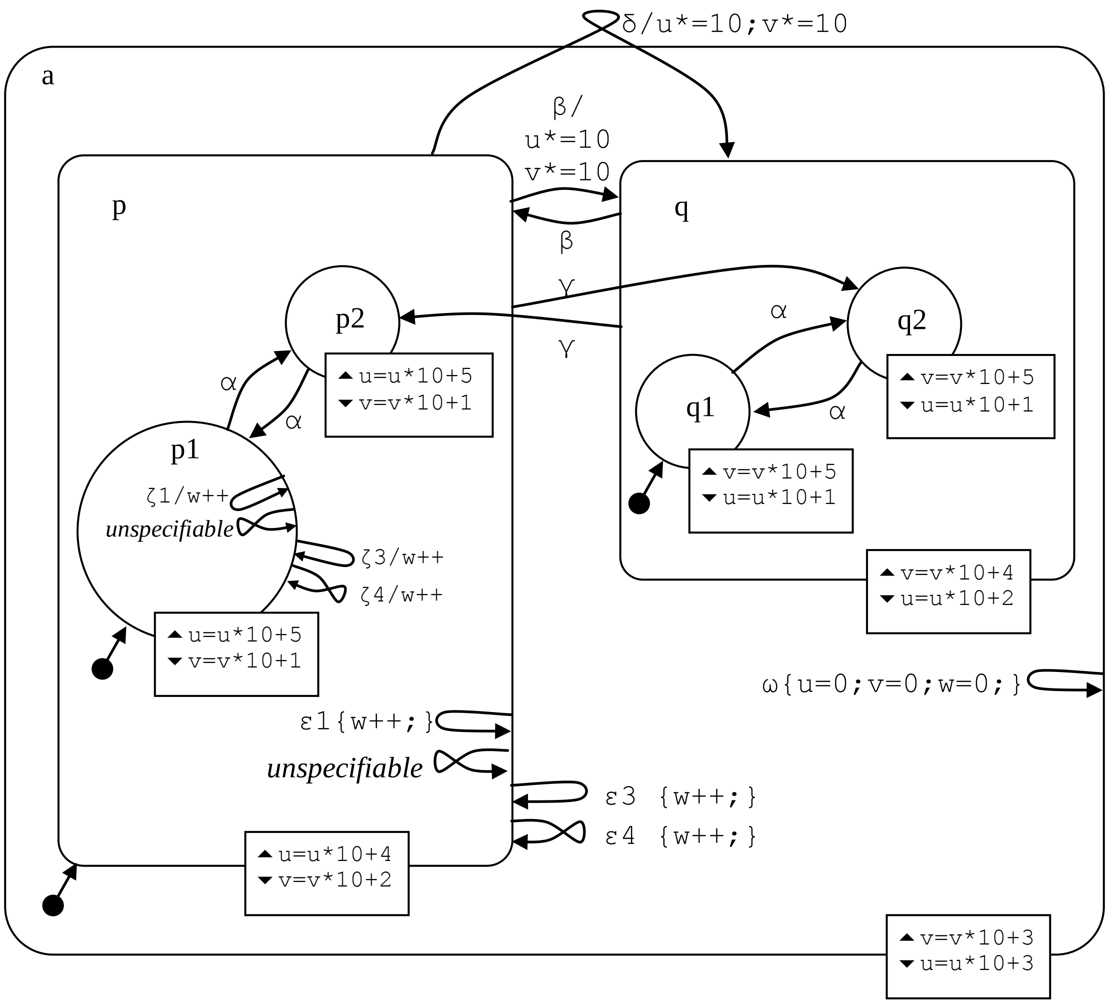


Figure 14. Orbits, self-transitions, upon-enter and upon-exit actions [model `u5170`]

Points to note

- We often for compactness will use a shorter notation for events and transition actions: *event/action* rather than *event*{*action*;}.
- The arrow symbols ▲ and ▼ indicate actions that take place when the state is exited or entered. Imagine a transition from say, `p1` to `q1` (which event β could occasion). The action on exiting `p1` is `v=v*10+1`. This adds a digit `1` to the current value of `v`. On exiting state `p`, we add the digit `2` to the value of `v`. Each exit or enter action is tracked in this way. Variable `v` tracks a transition from `p` to `q`. Variable `u` tracks a transition from `q` to `p`. The *on-transition actions* simply add digit `0` to `u` and `v` by multiplying by `10`. This gives us a complete record of the order of the actions that take place during a transition. The variables can be reset without any transitioning by executing event ω.
- In addition to assignment actions we can have any other actions, e.g. fired event actions (not used in this model, but see test model `t5170` for an example).
- For more examples of orbits, see test model `t6260`, which includes an orbit that exits members of a set without exiting the set itself.

Call the file `orbits.scs.txt` in directory `u5170_orbits`. Prepare the hierarchy first and compile it (as already learned).

```
  SC:root F:\KWinPro\StCr\StCr5ModelsUser\u5170_orbits
  SC:cp orbits
```

The hierarchy is:

```
statechart sc(a)
  cluster a(p,q)
    cluster p(p1,p2)
      state p1;
      state p2;
    cluster q(q1,q2)
      state q1;
      state q2;
```

Add the declarations and transitions, (perhaps compiling as individual transitions are added, to check for typing errors).

```
statechart sc(a)

event alpha,beta,gamma,delta;
event epsilon1,epsilon3,epsilon4;
event zeta1,zeta3,zeta4;
event omega;

enum int {0,..,10000};
int u=0,v=0,w=0;

  cluster a(p,q)      {upon enter{u=u*10+3;}   upon exit{v=v*10+3;}  \
                       omega{u=0;v=0;w=0;};                          }

    cluster p(p1,p2)  {upon enter{u=u*10+4;}   upon exit{v=v*10+2;}  \
                       delta->$$sc->q{u*=10;v*=10;};                 \
                       beta->q{u*=10;v*=10;};  gamma->q.q2;          \
                       epsilon1{w++;};         epsilon3->p{w++;};    \
                       epsilon4->$a->p{w++;};                        }

      state p1        {upon enter{u=u*10+5;}   upon exit{v=v*10+1;}  \
                       zeta1{w++;};            zeta3->p1{w++;};      \
                       zeta4->$p->p1{w++;};    alpha->p2;            }

      state p2        {upon enter{u=u*10+5;}   upon exit{v=v*10+1;}  \
                       alpha->p1;                                    }

    cluster q(q1,q2)  {upon enter{v=v*10+4;}   upon exit{u=u*10+2;}  \
                       beta->p;                gamma->p.p2;          }

      state q1        {upon enter{v=v*10+5;}   upon exit{u=u*10+1;}  \
                       alpha->q2;                                    }

      state q2        {upon enter{v=v*10+5;}   upon exit{u=u*10+1;}  \
                       alpha->q1;
```

Points to note

- If there are *upon enter* actions and *upon exit* actions, the *upon enter* actions must be specified first.
- An example of orbital notation is `delta->$$sc->q`.
  Useful rules on orbital states
  - If the transition arc to an *orbital* state crosses n hierarchical layers, use (n+1) `$` characters in specifying it.
  - If the transition arc to a *target* state crosses n hierarchical layers, use (n) `$` characters in specifying it.
  - The hierarchical layers can be counted by counting the number of boxes crossed (but *not* set member boundaries, i.e. the dotted line). Note, however, that a cluster member of a set can be specified without drawing a box round it, so when counting boxes exited, allow for an 'invisible' box in this case.

  An alternative to counting `$` operators is to use an absolute path. The `::` operator takes us to statechart scope, but it requires an argument, so statechart scope is a little inconvenient to specify, and we must go the statechart parent and re-specify the statechart. In our example, we could have used `delta->::$sc->q`.

  So far, we have been precise about the orbital state. Where states have unique names, the operators can be omitted and the correct state will be found by the outbound search for the nearest state in scope. So we can also specify the example as simply `delta->sc->q`.

Compile and run the model.

Process event `delta` and notice in particular the values of the variables

```
11   VAR  INTEGER u [sc] =3
11   VAR  INTEGER v [sc] =123045
11   VAR  INTEGER w [sc] =0
```

The value of `v` shows that actions took place as follows

`v=v*10+1`	on exiting `p1`
`v=v*10+2`	on exiting `p`
`v=v*10+3`	on exiting `a`
`v=v*10`	as the transition action
`v=v*10+4`	on entering `q`
`v=v*10+5`	on entering `q1`

Variable `u` gained its value when cluster `a` was entered from the highest point in the transition trajectory.

Reset the model (command `rm`) and process event `beta`. Observe and explain the new variable values.

```
9    VAR  INTEGER u [sc] =0
9    VAR  INTEGER v [sc] =12045
9    VAR  INTEGER w [sc] =0
```

Reset the model and process event `alpha`, followed by event `omega`. The state is `p2` and the variables have been reset. Process from this state, resetting as required, the self transitions `epsilon1`, `epsilon3`, `epsilon4`, observing at each stage the new state. Note that `epsilon3` and `epsilon4` cause a transition to `p1`.

In state `p1`, experiment with events `zeta1`, `zeta3`, `zeta4`. Note that `zeta4` causes `p1` to be exited and re-entered, as is seen by the values of `u` and `v`.

4.8 Meta-events

In the previous section, we saw how to attach actions to the internal event of a state being exited or entered. This section shows how that the internal events are like any others, and can be used to trigger transitions. They never take parameters. We call them meta-events.

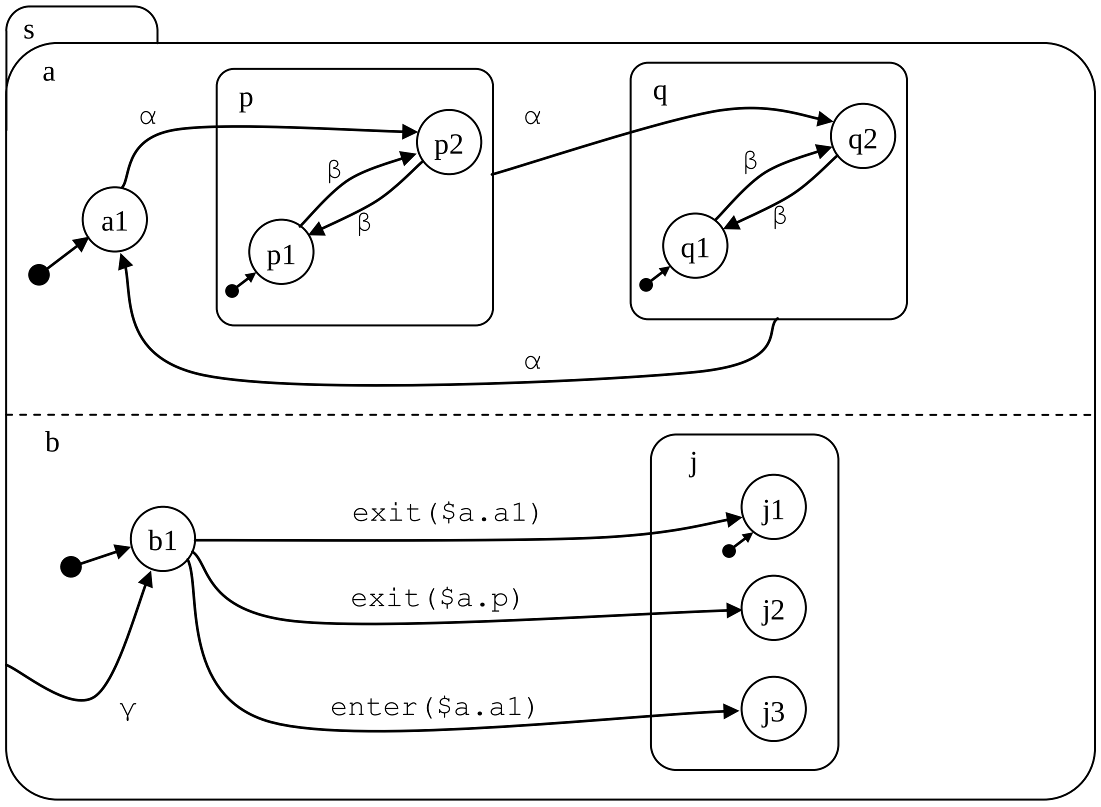


Figure 15. Meta event (state entry/exit) [model `u5180`]

Points to note

- We respond in set member `b` to meta events in set member `a`, and address the states with the usual scoping notation. The initiating event is in each case α.
- Event γ acts as a reset in member `b`. In state `b1` we respond to various meta events we might see. Having responded to one meta event, we can reset to state `b1` and wait for the next one.

Call the file `meta.scs.txt` in directory `u5180_meta`. Prepare the hierarchy first and compile it (as already learned).

```
  SC:root F:\KWinPro\StCr\StCr5ModelsUser\u5180_meta
  SC:cp meta
```

The hierarchy is:

```
statechart sc(s)
set s(a,b)
   cluster a(a1,p,q)
      state a1;

      cluster p(p1,p2)
         state p1;
         state p2;

      cluster q(q1,q2)
         state q1;
         state q2;

   cluster b(b1,j)
      state b1;
      cluster j(j1,j2,j3)
         state j1;
         state j2;
         state j3;
```

Add the declarations and transitions:

```
statechart sc(s)
event alpha,beta,gamma;
set s(a,b)
   cluster a(a1,p,q)
      state a1              {alpha->p.p2;}

      cluster p(p1,p2)      {alpha->q.q2;}
         state p1 {beta->p2;}
         state p2 {beta->p1;}

      cluster q(q1,q2)      {alpha->a1;}
         state q1 {beta->q2;}
         state q2 {beta->q1;}

   cluster b(b1,j) {gamma->b.b1;}
      state b1      {exit  ($a.a1)-> j.j1;   \
                     exit  ($a.p) -> j.j2;   \
                     enter ($a.a1)-> j.j3;   }
      cluster j(j1,j2,j3)
         state j1;
         state j2;
         state j3;
```

Compile and run the model. Process event `alpha`, and observe the configuration:

```
SC:gc
4    statechart sc
4       set s [sc] = OCC []  **
4          cluster a [s, sc] = OCC []  **
4             leafstate a1 [a, s, sc] = VAC []
4             cluster p [a, s, sc] = OCC []  **
4                leafstate p1 [p, a, s, sc] = VAC []
4                leafstate p2 [p, a, s, sc] = OCC []  **
4             cluster q [a, s, sc] = VAC []
4                leafstate q1 [q, a, s, sc] = VAC []
4                leafstate q2 [q, a, s, sc] = VAC []
4          cluster b [s, sc] = OCC []  **
4             leafstate b1 [b, s, sc] = VAC []
4             cluster j [b, s, sc] = OCC []  **
4                leafstate j1 [j, b, s, sc] = OCC []  **
4                leafstate j2 [j, b, s, sc] = VAC []
4                leafstate j3 [j, b, s, sc] = VAC []
4    TRACE =[]
4    TREV [[beta, [sc]], 0, [], []]
4    TREV [[alpha, [sc]], 0, [], []]
4    TREV [[gamma, [sc]], 0, [], []]

outworlds=[4]
number of outworlds=1
```

The fact that leafstate `j1` is occupied shows that the `exit($a.a1)` meta-event was responded to.

Process events `gamma` and `alpha`, and observe that the `exit($a.p)` meta event was responded to:

```
7                leafstate j1 [j, b, s, sc] = VAC []
7                leafstate j2 [j, b, s, sc] = OCC []  **
7                leafstate j3 [j, b, s, sc] = VAC []
```

Process events `gamma` and `alpha` again and observe that the `enter($a.a1)`meta event was responded to:

```
10               leafstate j1 [j, b, s, sc] = VAC []
10               leafstate j2 [j, b, s, sc] = VAC []
10               leafstate j3 [j, b, s, sc] = OCC []  **
```

4.9 Conditional actions and the in() function

We have already seen (section 4.1) how a transition can be conditional. In this section we will see how a *transition action* can be conditional, even if the transition is unconditional. In fact, any action can be conditional, so an *upon entry* action or *upon exit* action can be conditional too.

Conditions are expressions evaluating to a boolean value. The expression can make use of the function `in()`. This function takes a scoped state as an argument (in the same way a transition target state is expressed), and returns *true* (=1) if that state is occupied, *false* (=0) otherwise. It will normally be testing the occupancy of a state in a parallel part of the machine. It is evaluated during execution just before the transition is considered for taking place, and the value of the function at this time might not be the same as at the start of processing a user event (e.g. if various events have been fired in the meantime).

Conditions on *transitions* are written in square brackets. Conditional *actions* use the `if` keyword, and can have an `else` part. There is an *if* action and (optionally) an *else* action. These actions can be assignments, function calls, fired events, or nested `if` actions.

We will implement the model in the following figure:

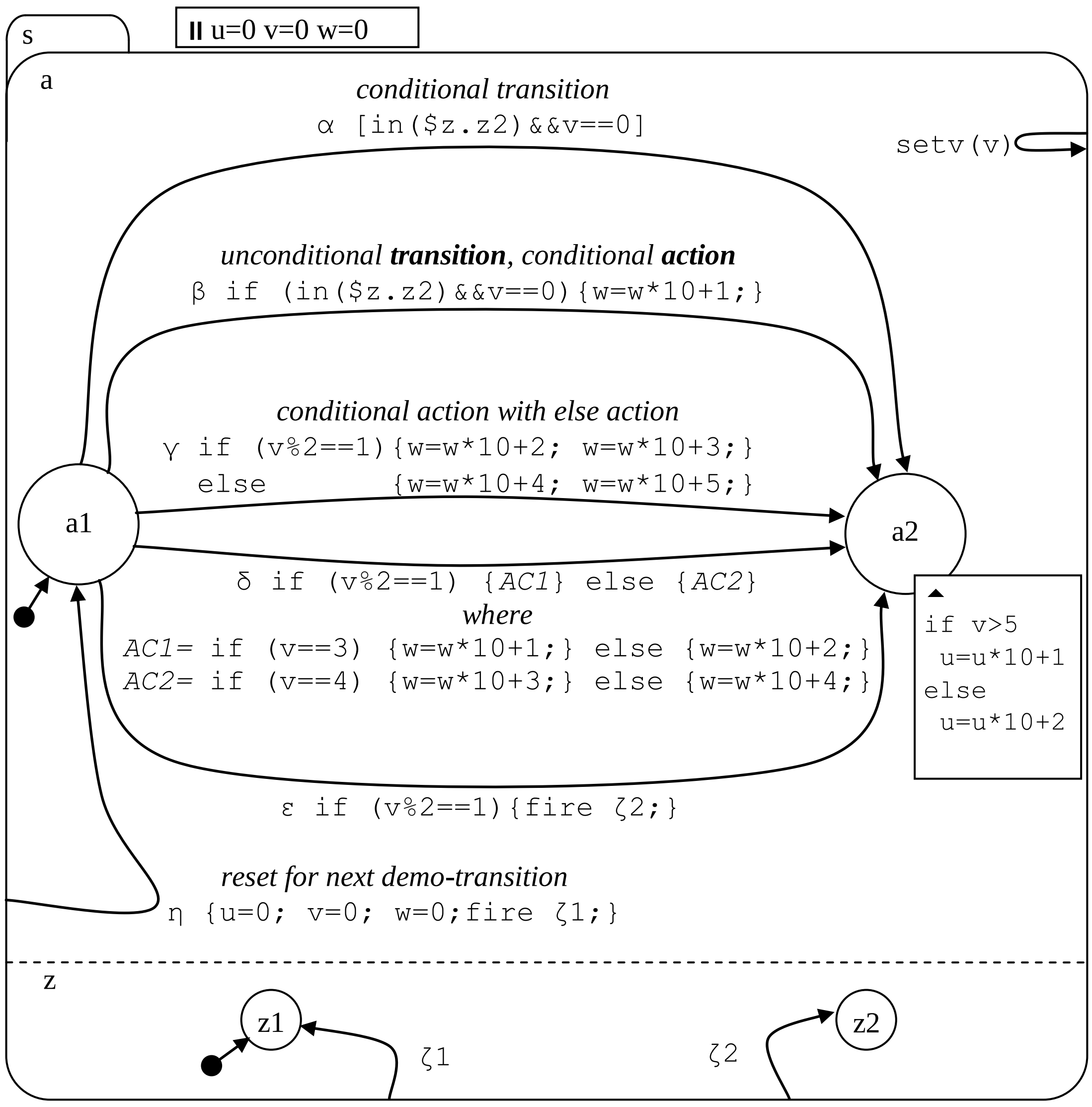

s
II u=0 v=0 w=0
a
conditional transition
α [in($z.z2)&&v==0]
setv(v)
unconditional transition, conditional action
β if (in($z.z2)&&v==0){w=w*10+1;}
conditional action with else action
γ if (v%2==1){w=w*10+2; w=w*10+3;}
else {w=w*10+4; w=w*10+5;}
a1
a2
δ if (v%2==1) {AC1} else {AC2}
where
AC1= if (v==3) {w=w*10+1;} else {w=w*10+2;}
AC2= if (v==4) {w=w*10+3;} else {w=w*10+4;}
if v>5
u=u*10+1
else
u=u*10+2
ε if (v%2==1){fire ζ2;}
reset for next demo-transition
η {u=0; v=0; w=0;fire ζ1;}
z
z1
ζ1
ζ2
z2

Figure 16. Conditional actions and `in()` function [model `u5190`]

Points to note

- There is a conditional transition on α.
- There is a conditional action on the transition on β, and also on entering state `a2`.
- The transition on γ has an *else* part.
- The transition on δ has nested conditional actions.
- The conditional action of the transition on ε fires an event, putting cluster `z` in state `z2`.
- We can set the value of `v` (use in the conditions) using the `setv` event.
- We can reset variables and states using the η event.

Call the file `cond_action.scs.txt` in directory `u5190_cond_action`. Prepare the hierarchy first and compile it (as already learned).

```
  SC:root F:\KWinPro\StCr\StCr5ModelsUser\u5190_cond_action
  SC:cp cond_action
```

The hierarchy is:

```
statechart sc(s)
set s(a,z)
  cluster a(a1,a2)
     state a1;
     state a2;
  cluster z(z1,z2)
     state z1;
     state z2;
```

Add the declarations and transitions:

```
statechart sc(s)
event alpha,beta,gamma,delta,epsilon,eta;
event setv;
event zeta1,zeta2;

enum int1 {0,..,10000};
int1 u=0,v=0,w=0;

set s(a,z)
  cluster a(a1,a2) {setv(v);  eta->a.a1 {u=v=w=0; fire zeta1;}; }

     state a1                                                   \
       {alpha [in($z.xxx.z2) && (v==0)]->a2;                    \
        beta->   a2 {if (in($z.z2) && (v==0)) {w=w*10+1;} };    \
        gamma->  a2 {if (v%2==1) {w=w*10+2;w=w*10+3;}           \
                     else        {w=w*10+4;w=w*10+5;} };        \
                                                                \
        delta->  a2 {if (v%2==1)                                \
                        {if (v==3) {w=w*10+1;} else {w=w*10+2;}}    \
                     else                                       \
                        {if (v==4) {w=w*10+3;} else {w=w*10+4;}} }; \
        epsilon->a2 {if (v%2==1) {fire zeta2;}};                }

     state a2 {upon enter { if(v>5) {u=u*10+1;} else {u=u*10+2;}}   }

  cluster z(z1,z2) {zeta2->z.z2; zeta1->z.z1;}
     state z1;
     state z2;
```

Compile and run the model.

Conditional transition (revision) and conditional upon enter action: Process event `alpha`, and note that no transition takes place. This is because we are not in state `z2`, which the condition requires. (In fact `alpha` is not even shown as transitionable, because the condition is known to be false). Process events `zeta2` and `alpha`. This time a transition does take place, and we are in state `a2`. When we entered state `a2`, the else part of a conditional action was executed, and `u` got the value 2. The important lines of output showing what has happened are:

```
5            leafstate a2 [a, s, sc] = OCC []  **
5            leafstate z2 [z, s, sc] = OCC []  **
5    VAR  INTEGER u [sc] =2
```

Unconditional transition, conditional action: Reset the model, (command `rm`) and process event `beta`. As we are not in state `z2`, the action does not take place (variable `w` remains at 0), but the transition goes ahead.

```
4            leafstate a2 [a, s, sc] = OCC []  **
4            leafstate z1 [z, s, sc] = OCC []  **
4    VAR  INTEGER w [sc] =0
```

Reset the model, process events `zeta2` and `beta`. Now the action does take place (variable `w` gets the value 1).

```
6            leafstate a2 [a, s, sc] = OCC []  **
6            leafstate z2 [z, s, sc] = OCC []  **
6    VAR  INTEGER w [sc] =1
```

Conditional transition action with else action: Reset the model and process event `gamma`. As `v2`=0, (so *v2 modulo 2* is also =0), the *else* action takes place (variable `w` becomes 45); the transition goes ahead anyway.

```
6            leafstate a2 [a, s, sc] = OCC []  **
6    VAR  INTEGER u [sc] =2
6    VAR  INTEGER v [sc] =0
6    VAR  INTEGER w [sc] =45
```

Reset the model, process event `setv` with parameter 7 (command `pe setv p=7`), and process event `gamma`. This time the *if* action takes place (`w` gets the value 23), and the transition goes ahead as usual. Since `v` is now >6, `u` gets the value 1 on entry to `a2` for a change.

```
7            leafstate a2 [a, s, sc] = OCC []  **
7    VAR  INTEGER u [sc] =1
7    VAR  INTEGER v [sc] =7
7    VAR  INTEGER w [sc] =23
```

Nested conditional transition action: Reset the model and process event `setv` with parameter 4 (syntax as given above). Now process event `delta`. We satisfy the *else* part of the outer condition and the *if* part of the associated inner condition, and `w` gets the value 3.

```
6            leafstate a2 [a, s, sc] = OCC []  **
6    VAR  INTEGER u [sc] =2
6    VAR  INTEGER v [sc] =4
6    VAR  INTEGER w [sc] =3
```

Experiment with other values of `v`.

Conditional transition action firing an event: Reset the model and process event `epsilon`, Since `v2` modulo 2 is not equal to 1, the action does not take place and we remain in state `z1`.

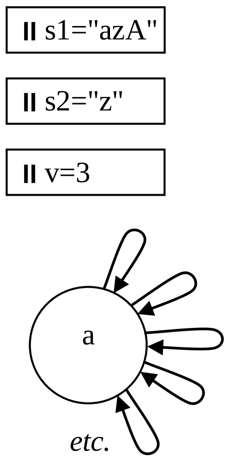
```
4            leafstate z1 [z, s, sc] = OCC []  **
4            leafstate z2 [z, s, sc] = VAC []
4    VAR  INTEGER u [sc] =2
4    VAR  INTEGER v [sc] =0
4    VAR  INTEGER w [sc] =0z2 [z, s, sc] = VAC []
```

Reset the model and process event `setv` with a parameter 1. Now process event `epsilon`; the action takes place and we are in state `z2`.

```
6            leafstate z1 [z, s, sc] = VAC []
6            leafstate z2 [z, s, sc] = OCC []  **
6    VAR  INTEGER u [sc] =2
6    VAR  INTEGER v [sc] =1
6    VAR  INTEGER w [sc] =0
```

4.10 Strings and string functions

Strings are a *type* of constant/variable like boolean and enumerated integer types. Certain operators can be used to make string expressions. Strings might be useful in producing annotated and formatted output. We will implement the following model to illustrate them:



all are self- transitions:

```
sets1(s1)     //direct parameter placement
sets2(s2)     //direct parameter placement
setv(v)       //direct parameter placement

α1 {s1="abcdef";}
α2 {s2="cd";}
α3 {s1=s1+s2;}
α4 {s1=s1-s2;}
α5 {s1=s1*v;}
α6 {s1=s1/3;} //illegal
α7 {s1="";}

β1 {if (s1==s2) {v++;}}
β2 {if (s1>s2) {v++;}}
β3 {if (s1>=s2) {v++;}}

γ1 {s1=upper_case(s1+"aA");}
γ2 {s1=lower_case(s1+"zZ");}
γ3 {v=length(s1);}

γ4 {s1=format(v,0);}
γ5 {s1=format(v,3);}
γ6 {s1=format(v,-3);}
```

Figure 17. Strings and String Functions [model `u5220`]

Points to note

- Strings are expressed in double quotes. The empty string is "".
- Strings can be compared. The comparison is on the ASCII values. String "ab" is less than string "bc". String "ab" is less than "abc".
- Although the above model does not illustrate it, string variables can be scoped, and might be addressed e.g. as `$$s2`. For an example of scoped strings, see test model `t5520`.
- We have drawn the transitions as external, but as they are on a leafstate, they are as good as internal, and will be implemented as such.

Call the file `strings.scs.txt` in directory `u5220_strings`. Prepare the hierarchy first and compile it (as already learned).

```
  SC:root F:\KWinPro\StCr\StCr5ModelsUser\u5220_strings
  SC:cp strings
```

The hierarchy is:

```
statechart sc(a)
  state a;
```

Add the declarations and transitions:

```
statechart sc(a)
event sets1,sets2,setv;
event alpha1, alpha2, alpha3, alpha4, alpha5, alpha6, alpha7;
event beta1,  beta2,  beta3;
event gamma1, gamma2, gamma3, gamma4, gamma5, gamma6;

enum int1 {0,..,1000};
int1 v=3;
string s1= "az" + "A";
string s2="z";

  state a {                                                    \
       sets1(s1);  sets2(s2);  setv(v);                        \
                                                               \
       alpha1 {s1="abcdef";};  alpha2 {s2="cd";};              \
       alpha3 {s1=s1+s2;};     alpha4 {s1=s1-s2;};             \
       alpha5 {s1=s1*v;};      alpha6 {s1=s1/3;}; /* illegal */  \
       alpha7 {s1="";};                                        \
                                                               \
       beta1 {if (s1==s2) {v++;}};                             \
       beta2 {if (s1> s2) {v++;}};                             \
       beta3 {if (s1>=s2) {v++;}};                             \
                                                               \
       gamma1 {s1=upper_case(s1+"aA");};                       \
       gamma2 {s1=lower_case(s1+"zZ");};                       \
       gamma3 {v=length(s1);};                                 \
       gamma4 {s1=format(v,0);};                               \
       gamma5 {s1=format(v,3);};                               \
       gamma6 {s1=format(v,-3);};                             }
```

Compile the model. Ignore the warning that state `a` is unreferenced. The warning would not appear if the leafstate were the first or only leafstate in a cluster or set, but here it is somewhat abnormally in the statechart directly. Run the model.

String values: Obtain the initial configuration and observe how strings are output. The ASCII values are printed in a list, and the printable characters follow.

```
2    VAR  STRING  s1 [sc] =[97, 122, 65] =azA
2    VAR  STRING  s2 [sc] =[122] =z
2    VAR  INTEGER v [sc] =3
```

Setting strings in event parameters: Transitionable events taking string parameters are shown by e.g.

```
2    TREV [[sets1, [sc]], 1, [[<string>]], []]
```

Process event `sets1` with a parameter of string "aAzZ". The formal way to do this is to give the following (try it):

```
  pe sets1 p=[[ex_str, [97, 65, 122, 90]]]
```

If there were several more parameters, they would be inserted at the ellipsis:

```
  pe sets1 p=[[ex_str, [97, 65, 122, 90]],...]
```

However, provided the string looks like an identifier, the following is accepted (reset the model and try it).

```
  pe sets1 p=aAzZ
```

```
3    VAR  STRING  s1 [sc] =[97, 65, 122, 90] =aAzZ
```

String assignment on transition: A simple assignment is illustrated by events `alpha1` and `alpha2`. Reset the model and process these two events, giving:

```
6    VAR  STRING  s1 [sc] =[97, 98, 99, 100, 101, 102] =abcdef
6    VAR  STRING  s2 [sc] =[99, 100] =cd
```

Strings can be added: Without resetting after the last events, process event `alpha3`. The strings are concatenated by the "+" operator:

```
8 VAR STRING  s1 [sc] =[97, 98, 99, 100, 101, 102, 99, 100] =abcdefcd
8 VAR STRING  s2 [sc] =[99, 100] =cd
```

Strings can be subtracted: Without resetting after the last events, process event `alpha4`. The "−" operator removes the first occurrence of the second operand in the first:

```
10   VAR  STRING  s1 [sc] =[97, 98, 101, 102, 99, 100] =abefcd
10   VAR  STRING  s2 [sc] =[99, 100] =cd
```

Strings can be multiplied by a constant: Without resetting after the last events, process event `alpha5`. The "`*`" operator causes the string to be repeated.

```
12   VAR  STRING  s1 [sc] =[97, 98, 101, 102, 99, 100, 97, 98, 101,
 102, 99, 100, 97, 98, 101, 102, 99, 100] =abefcdabefcdabefcd
```

String division is illegal: Without resetting after the last events, process event `alpha6`. The "`/`" operator is not supported and the string takes on a value of *unknown*.

```
14   VAR  STRING  s1 [sc] =unknown
```

String comparison: Reset the model (command `rm`) and process event `beta1`. Variable `v` remains =3, because `s1` and `s2` are not equal. Process command

```
  pe sets1 p=z
```

Now `s1` and `s2` are both "z". Process `beta1` again. This time `v` is incremented to 4:

```
6    VAR  STRING  s1 [sc] =[122] =z
6    VAR  STRING  s2 [sc] =[122] =z
6    VAR  INTEGER v [sc] =4
```

Experiment with other string values and with the other beta transitions. The comparison is on the ASCII values. String "ab" is less than "abc".

Conversion to upper case: Reset the model and process event `gamma1`.

```
4    VAR  STRING  s1 [sc] =[65, 90, 65, 65, 65] =AZAAA
```

Conversion to lower case: Reset the model and process event `gamma2`.

```
4    VAR  STRING  s1 [sc] =[97, 122, 97, 122, 122] =azazz
```

Length of a string: Reset the model, set `v` to 0 with `pe setv p=0`, (optionally set `s1` to some string of your choice), and process event `gamma3`. Variable `v` is assigned to the length of string `s1`.

```
5    VAR  INTEGER v [sc] =3
```

Formatting an integer: Events `gamma1`, `gamma2` and `gamma3` show a variable being formatted in various ways.

Event `gamma1` *just justifies* the variable `v` (which has a reset value 3)

```
4    VAR  STRING  s1 [sc] =[51] =3
```

Event `gamma2` *right justifies* `v` in a field width of 3. Note the leading spaces in the list (with ASCII value 32), and after the second equals sign.

```
6    VAR  STRING  s1 [sc] =[32, 32, 51] =  3
```

Event `gamma3` *left justifies* `v` in a field width of 3. Note the trailing spaces.

```
8    VAR  STRING  s1 [sc] =[51, 32, 32] =3
```

4.11 Traces

There are two well-known ways of testing: ***white box*** and ***black box*** testing. White box testing assumes access to the internals of the implementation under test (IUT), and so in our case the ability to observe its state, and perhaps its variables. But with black box testing, only certain outputs will be observable (typically return values of functions, or specific data that is written into a user buffer). Certain transitions may produce no observable output at all. Some transitions that might be distinguishable in a white box case, because the target states are different, might not be immediately distinguishable in the black box case, because the outputs are the same. We need a way to model observable outputs, and this is what ***traces*** are. By calling the trace function, a trace is stored indicating that an output should be given by the IUT. Traces are output as part of the get configuration command (`gc`). It is also possible to request traces only with the get traces command (`gt`).

Traces items can be integers or strings. Traces can be cleared using a function in the model (`trace_clear()`) or by a command (`ct`).

We will implement the following model:

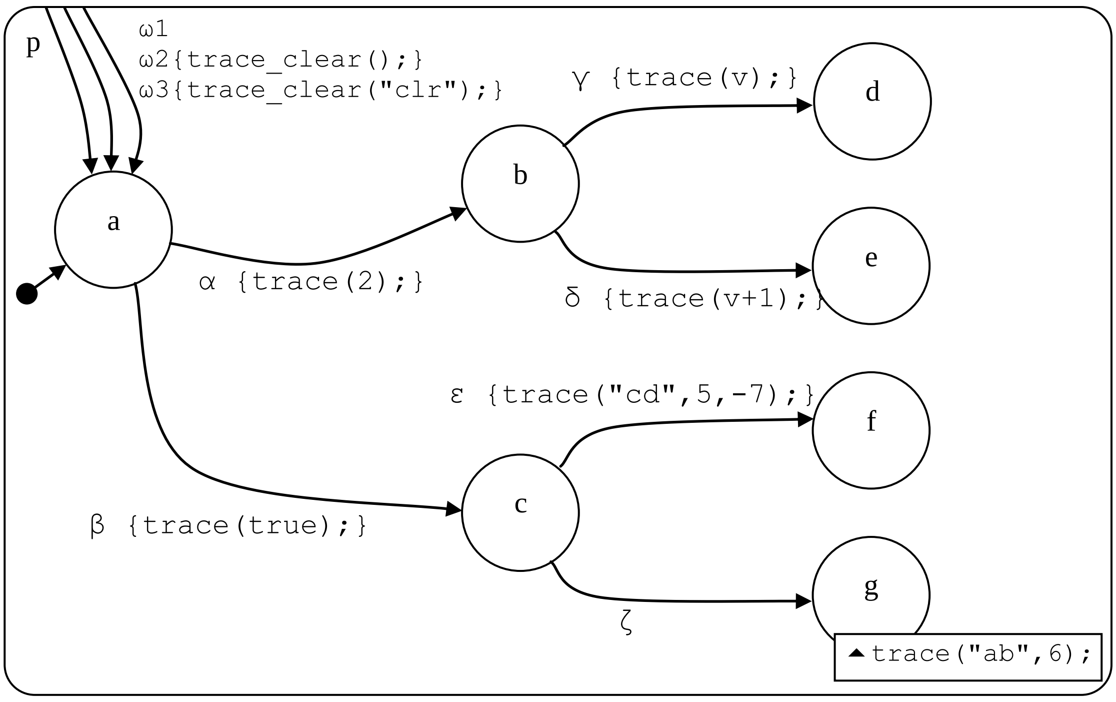


Figure 18. Traces [model `u5230`]

Call the file `traces.scs.txt` in directory `u5230_traces.` Prepare the hierarchy first and compile it (as already learned).

```
  SC:root F:\KWinPro\StCr\StCr5ModelsUser\u5230_traces
  SC:cp traces
```

The hierarchy is:

```
statechart sc(p)
   cluster p(a,b,c,d,e,f,g)
      state a;
      state b;
      state c;
      state d;
      state e;
      state f;
      state g;
```

Add the declarations and transitions:

```
statechart sc(p)

enum int1 {0,..,1000};
int1 v=8;

event alpha,beta,gamma,delta,epsilon,zeta,omega1,omega2,omega3;
   cluster p(a,b,c,d,e,f,g) {omega1->p.a;                        \
                             omega2->p.a {trace_clear();     };  \
                             omega3->p.a {trace_clear("clr");}; }
      state a { alpha->b {trace(2);};            beta->c
{trace(true);}; }
      state b { gamma->d {trace(v);};            delta->e
{trace(v+1);};  }
      state c { epsilon->f {trace("cd",5,-7);};  zeta->g; }
      state d;
      state e;
      state f;
      state g { upon enter {trace("ab",6); } }
```

Compile and run the model. Process event `alpha` and get the trace (command `gt`).

```
4    TRACE =[2]
```

Process event `gamma` and get the trace.

```
6    TRACE =[8, 2]
```

Note that traces are added to the list on the *left*.

Clear the trace with the `ct` command and get the trace again.

```
6    TRACE =[]
```

Reset the model (command `rm`) and process events `beta` and `epsilon`, and get the trace.

```
6    TRACE =[-7, 5, cd, 1]
```

On event epsilon, the trace call was `trace("cd",5,-7)`. This shows that the first parameter was added to the trace list (on the left) first, then the second and so on.

One of the traced items was a string. ***A string in the trace list is best kept to an identifier*** in connection with an advanced feature of the command language (the ability to feed traces back in to STATECRUNCHER).

Process event `omega3` and get the trace. This transitions to state `a` and causes `trace_clear` to be called, which clears the old trace and puts its own argument(s) into the trace.

```
8    TRACE =[clr]
```

Process event `omega2` which causes `trace_clear` to be called without arguments. The trace is cleared.

```
10   TRACE =[]
```

Process events `beta` and `zeta`. The second part of the trace is added as an *upon enter action*. Traces can be added wherever an action is allowed.

```
14   TRACE =[6, ab, 1]
```

4.12 Inexact state scoping

We have already seen inexact variable scoping (section 4.6), and mention has been made in passing of inexact state scoping. This section reinforces the concept of inexact state scoping.

Inexact state scoping applies when the reference state is below the addressed state in the hierarchy. A reference state is typically the parent of the source state of a transition. An addressed state is typically the target state of a transition, but may be an orbital state, the parameter of the `in`, `clear`, or `deep _clear` functions.

The `clear` and `deep_clear` and `in` functions also allow for inexact scoping, but since these functions are normally called outside (i.e. in a parallel part of the machine to) the cluster whose history is to be cleared, the case does not normally arise. History is set on cluster exit, and to clear history while in the same cluster, which could be done with inexact scoping, would be pointless. Therefore, we do not contrive a situation to illustrate inexact scoping with these functions.

Inexact scoping never searches deeper into the hierarchy; the real state is found by an *outbound search*. So references to parallel parts of a machine should be exact.

We will implement the following model:

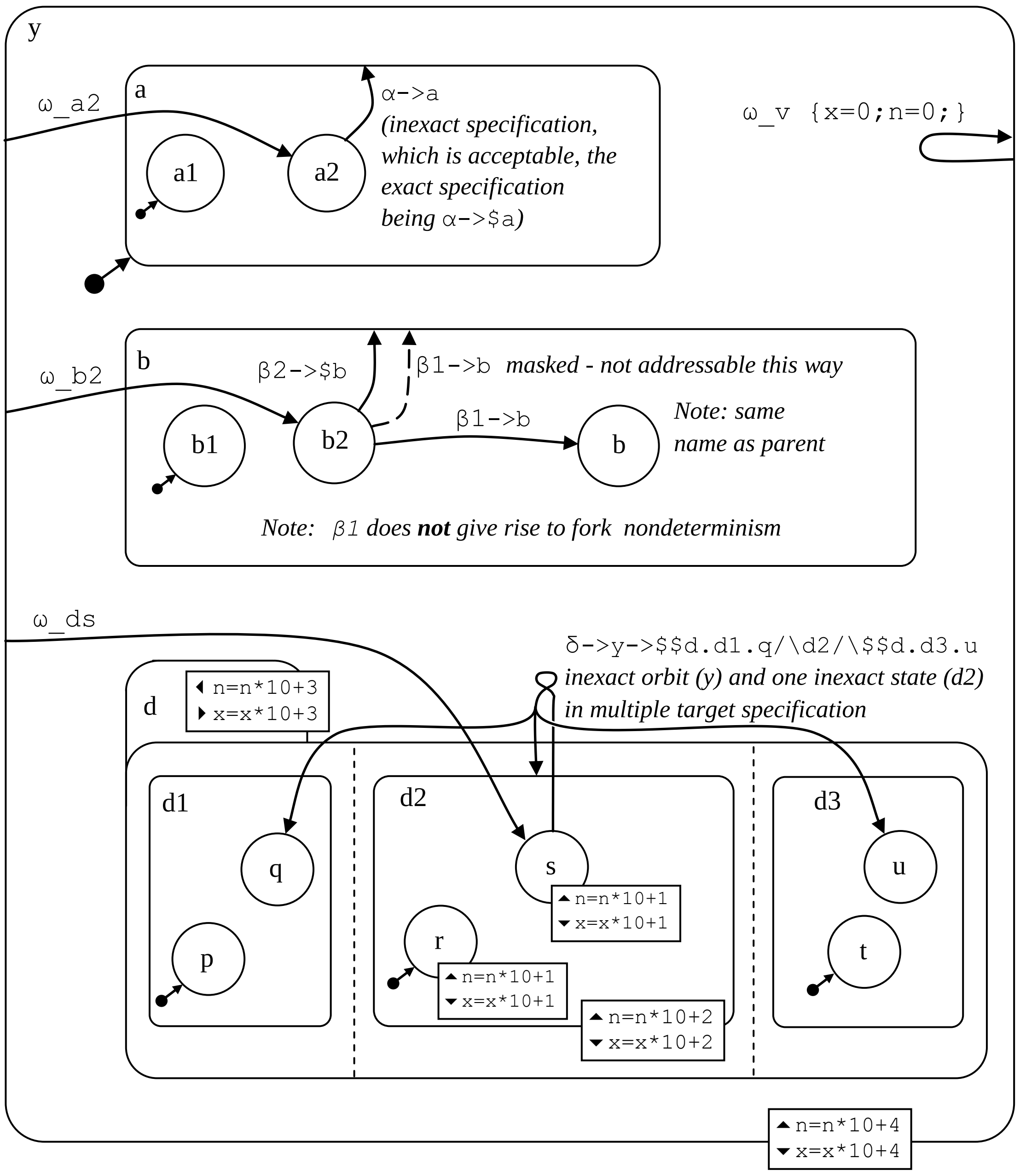


Figure 19. Inexact state scoping - [model u5250]

Call the file `state_scoping.scs.txt` in directory `u5250_state_scoping`. Prepare the hierarchy first and compile it (as already learned).

```
  SC:root F:\KWinPro\StCr\StCr5ModelsUser\u5250_state_scoping
  SC:cp state_scoping
```

The hierarchy is:

```
statechart sc(y)
  cluster y(a,b,d)
      cluster a (a1,a2)
         state a1;
         state a2;
      cluster b(b1,b2,b)
         state b1;
         state b2;
         state b;
     set d(d1,d2,d3)
         cluster d1(p,q)
            state p;
            state q;
         cluster d2(r,s)
            state r;
            state s;
         cluster d3(t,u)
            state t;
            state u;
```

Add the declarations and transitions:

```
statechart sc(y)
enum vint {0,..,100000};
vint x=0,n=0;
event omega_a2, omega_b2, omega_ds, omega_v;
event alpha,    beta1,    beta2,    delta;

  cluster y(a,b,d) {upon enter {n=n*10+4;}   upon exit  {x=x*10+4;} \
                    omega_a2 ->  y.a.a2;     omega_b2 ->  y.b.b2;   \
                    omega_ds ->  y.d.d2.s;   omega_v {x=0; n=0;};   }
      cluster a (a1,a2)
         state a1;
         state a2          {alpha->a;}
      cluster b(b1,b2,b)
         state b1;
         state b2          {beta1->b; beta2->$b;}
         state b;
     set d(d1,d2,d3)       {upon enter {n=n*10+3;} upon exit{x=x*10+3;} }
         cluster d1(p,q)
            state p;
            state q;
         cluster d2(r,s)   {upon enter {n=n*10+2;} upon exit{x=x*10+2;} }
            state r        {upon enter {n=n*10+1;} upon exit{x=x*10+1;} }
            state s        {upon enter {n=n*10+1;} upon exit{x=x*10+1;} \
                            delta -> y -> $$d.d1.q/\d2/\$$d.d3.u;       }
         cluster d3(t,u)
            state t;
            state u;
```

Compile the model. Process event `omega_a2` and check that state `a2` has been entered (with the `gc` command):

```
3             leafstate a2 [a, y, sc] = OCC []  **
```

Process event `alpha`. Observe that the transition is processed, and that state `a1` is entered, showing that the transition was accepted with the inexact target state scope:

```
4             leafstate a1 [a, y, sc] = OCC []  **
```

Process event `omega_b`, and check that state `b2` has been entered.

```
5             leafstate b2 [b, y, sc] = OCC []  **
```

Process event `beta1`, and observe that leafstate `b` has been entered (so the target was not the parent of the same name).

```
6             leafstate b [b, y, sc] = OCC []  **
```

Process events `omega_ds` and `omega_v`. Check that state `y.d.d2.s` is occupied, and that the variables have been set to zero.

```
28               leafstate s [d2, d, y, sc] = OCC []  **
28   VAR  INTEGER n [sc] =0
28   VAR  INTEGER x [sc] =0
```

Process event `delta`, and check the occupation of set `d` and the variable values, which show what has been entered and exited. The inexact orbit `y` was accepted, and inexact target state `d2` was accepted.

```
50         set d [y, sc] = OCC []  **
50            cluster d1 [d, y, sc] = OCC p  **
50               leafstate p [d1, d, y, sc] = VAC []
50               leafstate q [d1, d, y, sc] = OCC []  **
50            cluster d2 [d, y, sc] = OCC s  **
50               leafstate r [d2, d, y, sc] = OCC []  **
50               leafstate s [d2, d, y, sc] = VAC []
50            cluster d3 [d, y, sc] = OCC t  **
50               leafstate t [d3, d, y, sc] = VAC []
50               leafstate u [d3, d, y, sc] = OCC []  **
50   VAR  INTEGER n [sc] =321
50   VAR  INTEGER x [sc] =123
```

4.13 Introduction to nondeterminism

We have now introduced most of STATECRUNCHER's language features (but see arrays, a recent addition in section 4.27). All the models so far have been *deterministic*, i.e. on processing an event, they have produced one set of state occupancies, cluster histories, variable values and traces. We now introduce some models where this is no longer the case - they are *nondeterministic* models. Nondeterminism arises when not enough is known about an implementation under test to be able to predict exactly what it will do, so we must allow for some alternatives. For example, supposing a tuner produces notification messages while tuning, *tuning in progress*, until it finds a station. We may not be able to predict how many notifications will be generated, and if there are other possible events, their interleavings may not be exactly known. STATECRUNCHER allows for differing outcomes to be produced by its six forms of nondeterminism:

- fork nondeterminism, where an event triggers more than one transition form the same source state.
- race nondeterminism, where an event triggers more than one transition in parallel parts of a machine.
- set-transit nondeterminism, where the members of a set are entered and exited in various orderings.
- set-action nondeterminism, where actions take place within members of a set, and are carried out in various orderings.
- set-meta-event nondeterminism, where *meta-events* (internally generated exit and enter events) are broadcast in various orderings.
- fired event (or: broadcast event) nondeterminism, where any form of nondeterminism arises as a result of a fired event, so in mid-algorithm, rather than directly as a result of a user event.

STATECRUNCHER models the different outcomes as *worlds*. Each world maintains its own set of state occupancies, cluster histories, variable values, and traces. The get configuration (`gc`) command produces output for all worlds.

The different forms of nondeterminism will now each be described in turn.

4.14 Fork nondeterminism

Fork nondeterminism occurs where an event triggers more than one transition form the same source state. STATECRUNCHER handles this by generating a world for each prong of the fork. If any resultant worlds end up by being identical (in terms of state occupancies, cluster histories and variable values), duplicates will be removed.

We will implement the following model:

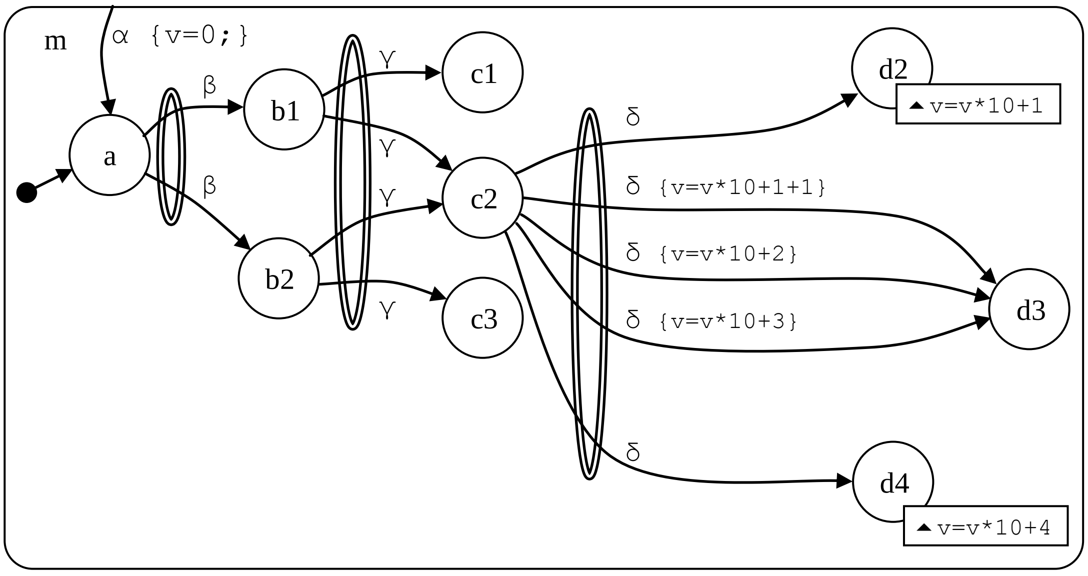


Figure 20. Fork nondeterminism [model `u5420`]

The forks are emphasised by the double ellipses. The first fork is on event β, where the fork leads to two different target states. Then on event γ there is another fork, but with two transitions from different source states (`b1` and `b2`) converging on the same target state. A duplicate world will be discarded, and there will be 3 resultant worlds. On event δ, two worlds do not respond (those in states `c1` and `c3`); these will be left intact. Departing from the world where `c2` is occupied, there are 5 transitions, but they only lead to 4 new worlds, because two transitions lead to an identical world. In all there are 6 worlds after event delta. The model can effectively be reset by event `alpha`, which will be processed in all worlds, but will take them to the same configuration, and duplicates will be removed, leaving one world.

World numbers are arbitrary. Internally, the numbers are allocated sequentially as more and more events, transitions and actions are processed, but some world numbers may never be seen by the user as they are only used temporarily during processing. Worlds are not presented in numerical order, and the order is not significant.

Call the file `fork.scs.txt` in directory `u5420_fork`. Prepare the hierarchy first and compile it (as already learned).

```
   SC:root F:\KWinPro\StCr\StCr5ModelsUser\u5420_fork
   SC:cp fork
```

The hierarchy is:

```
statechart sc(m)
   cluster m(a,b1,b2,c1,c2,c3,d2,d3,d4)
      state a;
      state b1;
      state b2;
      state c1;
      state c2;
      state c3;
      state d2;
      state d3;
      state d4;
```

Add the declarations and transitions:

```
statechart sc(m)
event alpha,beta,gamma,delta;
enum vint {0,..,100000};
vint v=0;
   cluster m(a,b1,b2,c1,c2,c3,d2,d3,d4) {alpha->m.a{v=0;};}
      state a  {beta->b1;  beta->b2;}
      state b1 {gamma->c1; gamma->c2;}
      state b2 {gamma->c2; gamma->c3;}
      state c1;
      state c2 {delta->d2;               \
                delta->d3{v=v*10+1+1;};  \
                delta->d3{v=v*10+2;};    \
                delta->d3{v=v*10+3;};    \
                delta->d4;}
      state c3;
      state d2 {upon enter {v=v*10+1;}}
      state d3;
      state d4 {upon enter {v=v*10+4;}}
```

Compile and run the model. Process event `beta`. There are two worlds, one in state `b1` and the other in `b2`:

```
SC:gc
3    statechart sc
3       cluster m [sc] = OCC []  **
3          leafstate a [m, sc] = VAC []
3          leafstate b1 [m, sc] = VAC []
3          leafstate b2 [m, sc] = OCC []  **
...

4    statechart sc
4       cluster m [sc] = OCC []  **
4          leafstate a [m, sc] = VAC []
4          leafstate b1 [m, sc] = OCC []  **
4          leafstate b2 [m, sc] = VAC []
...

outworlds=[3, 4]
number of outworlds=2
```

Process event `gamma`. There are 3 worlds, in states `c1`, `c2` and `c3` respectively.

```
5          leafstate c1 [m, sc] = VAC []
5          leafstate c2 [m, sc] = OCC []  **
5          leafstate c3 [m, sc] = VAC []
...
6          leafstate c1 [m, sc] = OCC []  **
6          leafstate c2 [m, sc] = VAC []
6          leafstate c3 [m, sc] = VAC []
...
7          leafstate c1 [m, sc] = VAC []
7          leafstate c2 [m, sc] = VAC []
7          leafstate c3 [m, sc] = OCC []  **
...
outworlds=[5, 6, 7]
number of outworlds=3
```

Process event delta. there are 6 worlds, in 5 states (`c1`, `c3`, `d1`, `d2`, `d3`), with 2 worlds of differing variable values in state `d3`.

```
7          leafstate c3 [m, sc] = OCC []  **
...

6          leafstate c1 [m, sc] = OCC []  **
...

10         leafstate d4 [m, sc] = OCC []  **
10   VAR  INTEGER v [sc] =4
...

12         leafstate d3 [m, sc] = OCC []  **
12   VAR  INTEGER v [sc] =3
...

14         leafstate d3 [m, sc] = OCC []  **
14   VAR  INTEGER v [sc] =2
...

18         leafstate d2 [m, sc] = OCC []  **
18   VAR  INTEGER v [sc] =1
```

Fork nondeterminism is relatively fast (compared to other forms of nondeterminism). The `gpt` command gets the elapsed processing time of the last event.

```
SC:gpt
exec time=00h 00m 00s 160ms
```

Process event `alpha`. This takes us to the initial state.

```
20         leafstate a [m, sc] = OCC []  **
20   VAR  INTEGER v [sc] =0
```

4.15 Fork nondeterminism differentiated by history and trace

In the preceding example, the *distinguishing aspects* of the worlds were state occupation and variable values. The other distinguishing aspects are cluster history and traces, illustrated in this section by fork nondeterminism (we could have chosen any other kind of nondeterminism).

We will construct the following model:

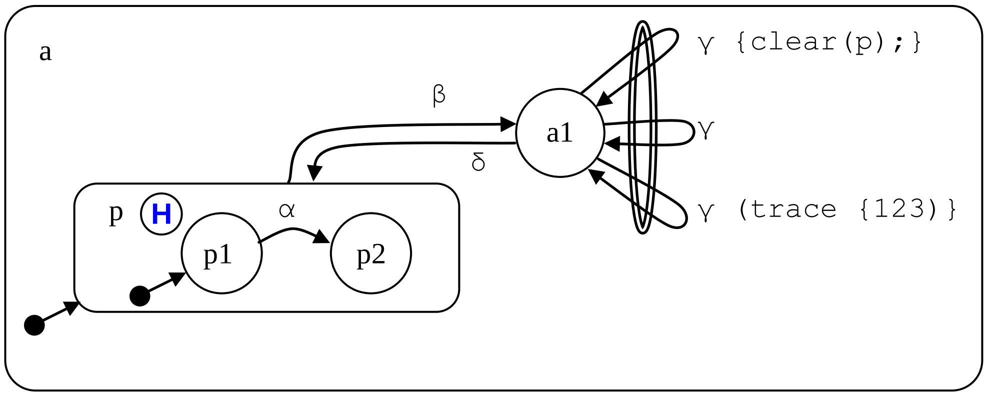


Figure 21. Fork nondeterminism differentiated by history and trace [model `u5422`]

On event α, cluster `p` enters a non-default state. Then on event β, cluster `p` is exited and its history is recorded (which is also the case even if we skip event α - the history is then state `p1`). On event `gamma` there are three prongs to fork nondeterminism. Although they all end up in the same state, one world has a different history to another, and one world has a different trace to another.

Call the file `fork_history.scs.txt` in directory `u5422_fork_history.` Prepare the hierarchy first and compile it (as already learned).

```
SC:root F:\KWinPro\StCr\StCr5ModelsUser\u5422_fork_history
SC:cp fork_history
```

The hierarchy is:

```
statechart sc(a)
  cluster a(p,a1)
     cluster p(p1,p2)
        state p1;
        state p2;
     state a1;
```

Add the declarations and transitions:

```
statechart sc(a)
event alpha,beta,gamma,delta;
  cluster a(p,a1)
     cluster p(p1,p2) history {beta->a1;}
        state p1 {alpha->p2;}
        state p2;
     state a1     {gamma{clear(p);};    \
                   gamma;               \
                   gamma{trace(123);}; \
                   delta->p;            }
```

Compile the model. Process events `alpha` and `beta` and get the configuration. Observe cluster `p`'s history.

```
4    statechart sc
4       cluster a [sc] = OCC []  **
4          cluster p [a, sc] = VAC p2
4             leafstate p1 [p, a, sc] = VAC []
4             leafstate p2 [p, a, sc] = VAC []
4          leafstate a1 [a, sc] = OCC []  **
4    TRACE =[]
4    TREV [[gamma, [sc]], 0, [], []]
4    TREV [[delta, [sc]], 0, [], []]
```

Process event `gamma`. This yields three worlds: one with a trace (6), one with history cleared (9) and one with neither of these things (7).

```
6          cluster p [a, sc] = VAC p2
6          leafstate a1 [a, sc] = OCC []  **
6    TRACE =[123]
...
7          cluster p [a, sc] = VAC p2
7          leafstate a1 [a, sc] = OCC []  **
7    TRACE =[]
...
9          cluster p [a, sc] = VAC []
9          leafstate a1 [a, sc] = OCC []  **
9    TRACE =[]
...
outworlds=[6, 7, 9]
number of outworlds=3
```

Give command to clear traces (`ct`). This causes duplicate worlds to be destroyed. World 7 is the victim.

```
6           cluster p [a, sc] = VAC p2
6           leafstate a1 [a, sc] = OCC []  **
6     TRACE =[]
...
9           cluster p [a, sc] = VAC []
9           leafstate a1 [a, sc] = OCC []  **
9     TRACE =[]
...
outworlds=[6, 9]
number of outworlds=2
```

Process event `delta`. Cluster `p` is then occupied in two different ways in two different worlds.

```
10    statechart sc
10       cluster a [sc] = OCC []  **
10          cluster p [a, sc] = OCC []  **
10             leafstate p1 [p, a, sc] = OCC []  **
10             leafstate p2 [p, a, sc] = VAC []
10          leafstate a1 [a, sc] = VAC []
10    TRACE =[]
10    TREV [[alpha, [sc]], 0, [], []]
10    TREV [[beta, [sc]], 0, [], []]

11    statechart sc
11       cluster a [sc] = OCC []  **
11          cluster p [a, sc] = OCC p2  **
11             leafstate p1 [p, a, sc] = VAC []
11             leafstate p2 [p, a, sc] = OCC []  **
11          leafstate a1 [a, sc] = VAC []
11    TRACE =[]
11    TREV [[beta, [sc]], 0, [], []]

outworlds=[10, 11]
number of outworlds=2
```

4.16 Scoped events illustrated by fork nondeterminism

This model shows how to distinguish between

- different ways of expressing the same event (or other item) at the same point in the hierarchy
- how an event or (other item) is automatically searched for in the hierarchy by the *outbound search* mechanism.

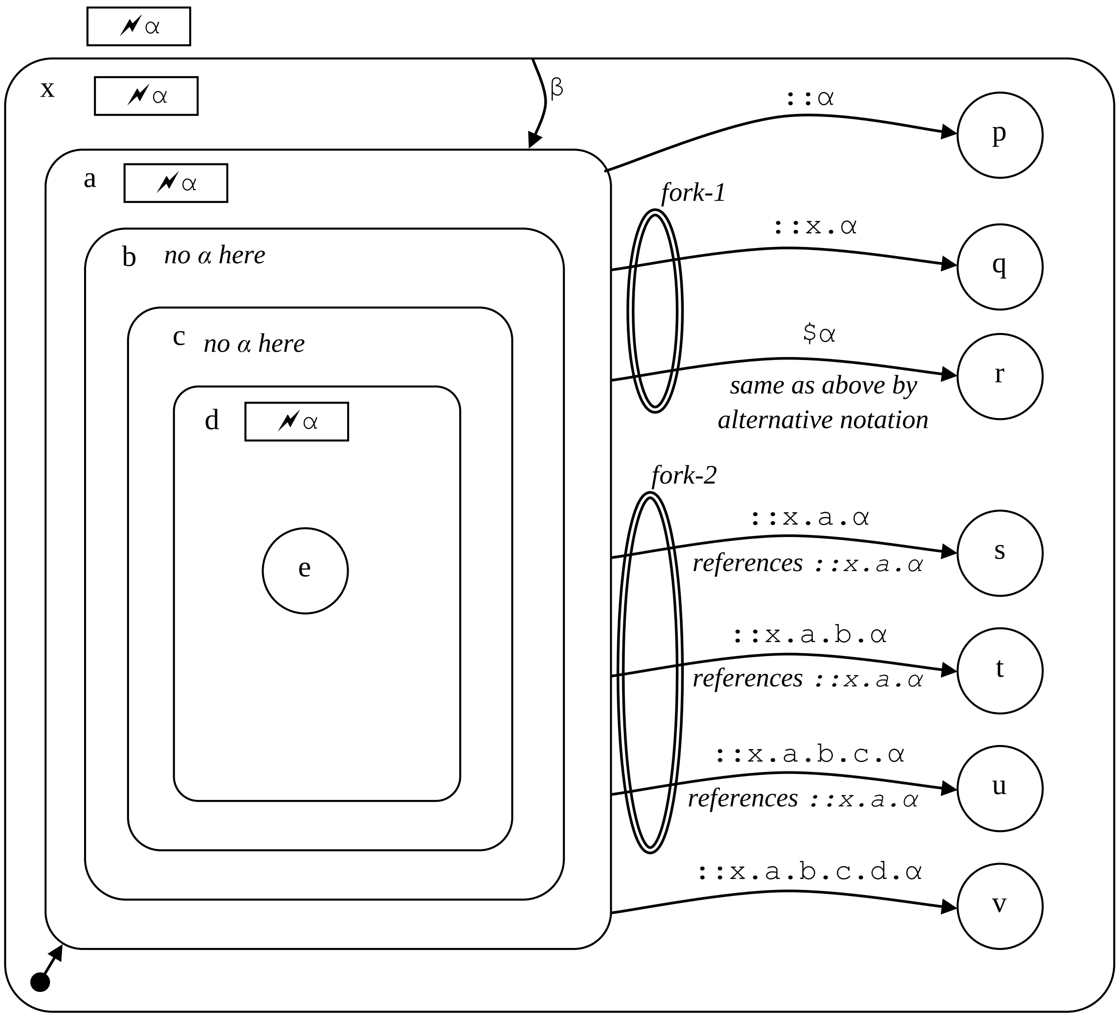


Figure 22. Scoped events illustrated by fork nondeterminism [model `t5510`]

There are 4 events called α but in different scopes, which we can denote in expression form with the corresponding scope in right-to-left list form as output:

`::α`	scope`[sc]`
`::x.α[x,sc]`	scope`[x,sc]`
`::x.a.α`	scope`[a,x,sc]`
`::x.a.b.c.d.α`	scope`[d,c,b,a,x,sc]`

The expressions beginning with `::` (statechart scope) can be used anywhere in the model. But these events can also be expressed by relative addressing, e.g. using the `$` operator. We have an instance where two expressions yield the same α at the same point in the hierarchy. We have arranged for this to cause fork nondeterminism.

This should be distinguished from addressing a point in the hierarchy (by an absolute or relative expression) where, strictly speaking, no α exists. This is the case when we address `::x.a.b.α`. But by an *outbound search*, the α at `::x.a.α` is found. Similarly `::x.a.b.c.α` is converted to `::x.a.α`. We have also arranged for transitions labeled with these expressions to cause fork nondeterminism.

We now construct and run the model.

Call the file `scoped_fork.scs.txt` in directory `u5510_scoped_fork.` Prepare the hierarchy first and compile it (as already learned).

```
SC:root F:\KWinPro\StCr\StCr5ModelsUser\u5510_scoped_fork
SC:cp scoped_fork
```

The hierarchy is:

```
statechart sc(x)
cluster x(a,p,q,r,s,t,u,v)
   cluster a(b)
      cluster b(c)
         cluster c(d)
            cluster d(e)
               state e;
   state p;
   state q;
   state r;
   state s;
   state t;
   state u;
   state v;
```

Add the declarations and transitions:

```
statechart sc(x)
event alpha,beta;                         // ::alpha

cluster x(a,p,q,r,s,t,u,v) {beta->x.a;}
event alpha;                              // ::x.alpha

   cluster a(b) {::alpha->p;             \
                 ::x.alpha->q;           \
                 $alpha->r;              \
                 ::x.a.alpha->s;         \
                 ::x.a.b.alpha->t;       \
                 ::x.a.b.c.alpha->u;     \
                 ::x.a.b.c.d.alpha->v; }
   event alpha;                           // ::x.a.alpha

      cluster b(c)
         cluster c(d)
            cluster d(e)
            event alpha;                  // ::x.a.b.c.d.alpha

               state e;
   state p;
   state q;
   state r;
   state s;
   state t;
   state u;
   state v;
```

Compile the model. Get the configuration and note the transitionable events:

```
2    TREV [[beta, [sc]], 0, [], []]
2    TREV [[alpha, [sc]], 0, [], []]
2    TREV [[alpha, [x, sc]], 0, [], []]
2    TREV [[alpha, [a, x, sc]], 0, [], []]
2    TREV [[alpha, [d, c, b, a, x, sc]], 0, [], []]
```

The first alpha can be processed by

`SC:`**`pe alpha`**

This results in one world where we are in state `p`.

```
3          leafstate p [x, sc] = OCC []  **
```

Process `beta` and then the second `alpha`, by the command

```
SC:pe [alpha,[x,sc]]
```

This gives rise to two worlds under fork nondeterminism, where states `r` and `q` are occupied:

```
5          leafstate r [x, sc] = OCC []  **
...
6          leafstate q [x, sc] = OCC []  **
```

Process `beta` and then the third `alpha`, by the command

```
SC:pe [alpha,[a,x,sc]]
```

This gives rise to three worlds under fork nondeterminism, where states `s`, `t` and `u` are occupied:

```
9          leafstate u [x, sc] = OCC []  **
...
10         leafstate t [x, sc] = OCC []  **
...
11         leafstate s [x, sc] = OCC []  **
```

Process `beta` and then the fourth `alpha`, by the command

```
SC:pe [alpha,[d,c,b,a,x,sc]]
```

This gives rise to one world, where state `v` is occupied:

```
15         leafstate v [x, sc] = OCC []  **
```

4.17 Race nondeterminism

In STATECRUNCHER, race nondeterminism occurs where an event triggers more than one transition in parallel parts of a machine. If the order in which these transitions is executed affects the outcome, then a world will be generated for each outcome. The worlds may be distinguished by state occupancy, cluster history, variable value or trace.

We consider a race where the winner is determined by a variable value:

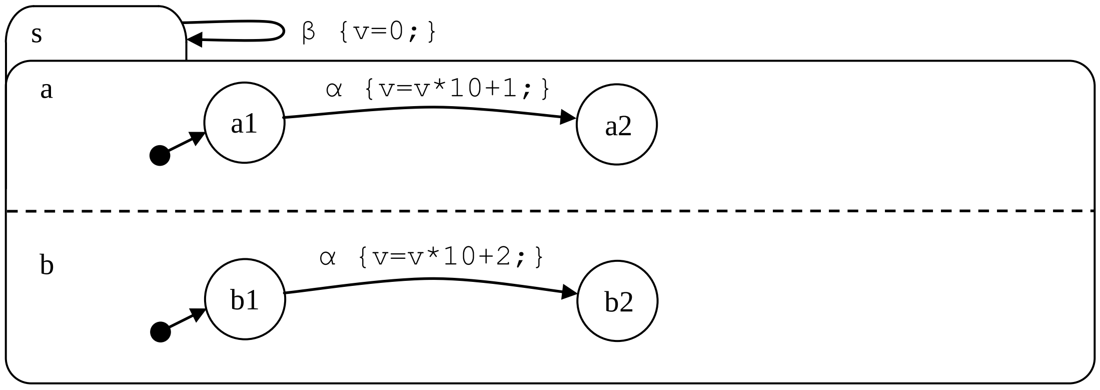


Figure 23. Race nondeterminism - winner detected by variable value [model `u5450`]

Call the file `race_var.scs.txt` in directory `u5450_race_var`. Prepare the hierarchy first and compile it (as already learned).

```
   SC:root F:\KWinPro\StCr\StCr5ModelsUser\u5450_race_var
   SC:cp race_var
```

The hierarchy is:

```
statechart sc(s)
   set s(a,b)
      cluster a(a1,a2)
         state a1;
         state a2;
      cluster b(b1,b2)
         state b1;
         state b2;
```

Add the declarations and transitions:

```
statechart sc(s)
event alpha,beta;
enum int1 {0,..,1000};
int1 v=0;
   set s(a,b)          {beta->s{v=0;};}
      cluster a(a1,a2)
         state a1      {alpha->a2{v=v*10+1;};}
         state a2;
      cluster b(b1,b2)
         state b1      {alpha->b2{v=v*10+2;};}
         state b2;
```

Compile the model. Process event `alpha`. The worlds are distinguished by the variable value, which reveals the order in which the transitions were executed. World 6 has `v`=12, which reveals that the upper transition was executed first. In world 10, `v`=21 showing that the lower transition was executed first.

```
6    statechart sc
6       set s [sc] = OCC []  **
6          cluster a [s, sc] = OCC []  **
6             leafstate a1 [a, s, sc] = VAC []
6             leafstate a2 [a, s, sc] = OCC []  **
6          cluster b [s, sc] = OCC []  **
6             leafstate b1 [b, s, sc] = VAC []
6             leafstate b2 [b, s, sc] = OCC []  **
6    VAR  INTEGER v [sc] =12
...

10   statechart sc
10      set s [sc] = OCC []  **
10         cluster a [s, sc] = OCC []  **
10            leafstate a1 [a, s, sc] = VAC []
10            leafstate a2 [a, s, sc] = OCC []  **
10         cluster b [s, sc] = OCC []  **
10            leafstate b1 [b, s, sc] = VAC []
10            leafstate b2 [b, s, sc] = OCC []  **
10   VAR  INTEGER v [sc] =21
...
```

Process event `beta` to effectively reset the model:

```
12   statechart sc
12      set s [sc] = OCC []  **
12         cluster a [s, sc] = OCC []  **
12            leafstate a1 [a, s, sc] = OCC []  **
12            leafstate a2 [a, s, sc] = VAC []
12         cluster b [s, sc] = OCC []  **
12            leafstate b1 [b, s, sc] = OCC []  **
12            leafstate b2 [b, s, sc] = VAC []
12   VAR  INTEGER v [sc] =0
...
```

We now give examples from the *test suite* of race nondeterminism where the winner is detected by meta event, fired event, and trace. We also show a race to a single target and a race to start. These need not be implemented as an integral part of the user training programme, but should be studied for the point being illustrated.

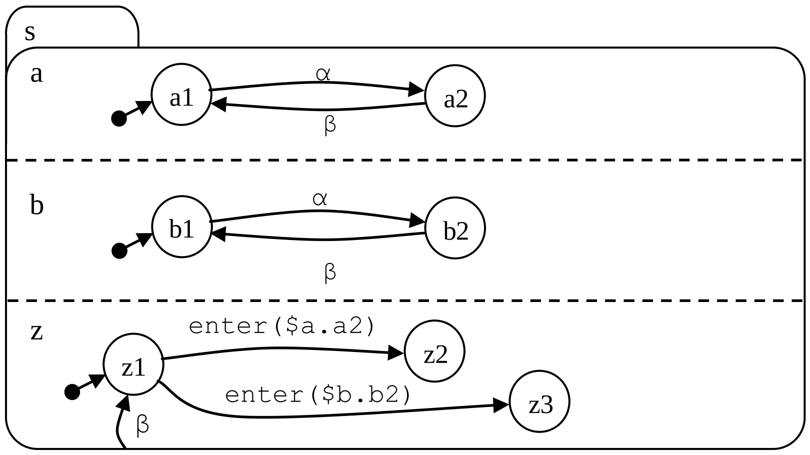


Figure 24. Race nondeterminism; winner detected by meta-event [model `t5430`]

In the above model, on event α, one ordering of the two transitions causes `a2` to be entered before `b2`, and the other ordering of the two transitions is the other way round. There will be two worlds as a result. In one world, `z2` will be occupied, and in the second world it will be `z3` that is occupied.

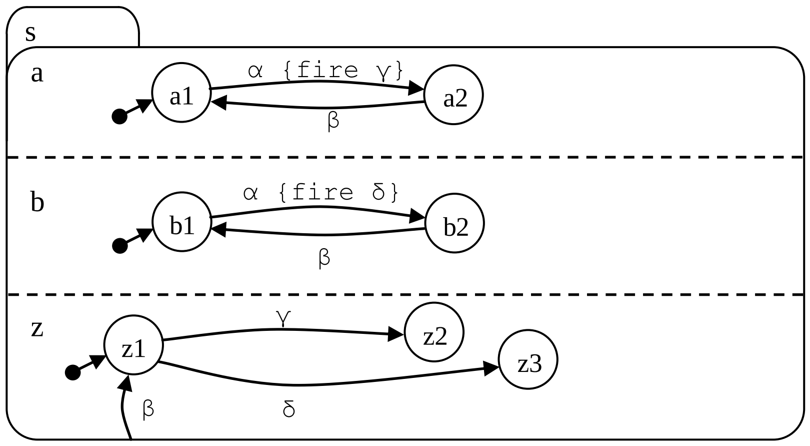


Figure 25. Race nondeterminism - winner detected by fired event [model `t5440`]

This model is very similar to the one above it. The difference is that instead of using the internally generated `enter()` meta-events to trigger transitions in member z, we fire events γ and δ manually (on the transition, not on entering `a2` and `b2`) to trigger transitions in member `z`.

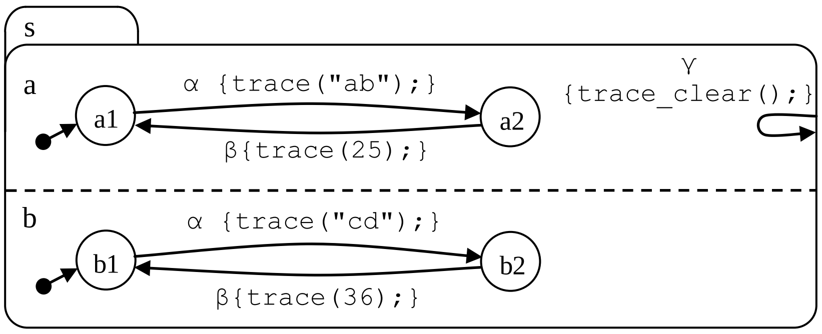


Figure 26. Race nondeterminism - winner detected by trace [model `t5470`]

In the above model the two transitions on event α generate different traces, so when both have transitions have taken place, the order of the traces will distinguish worlds with different orderings.

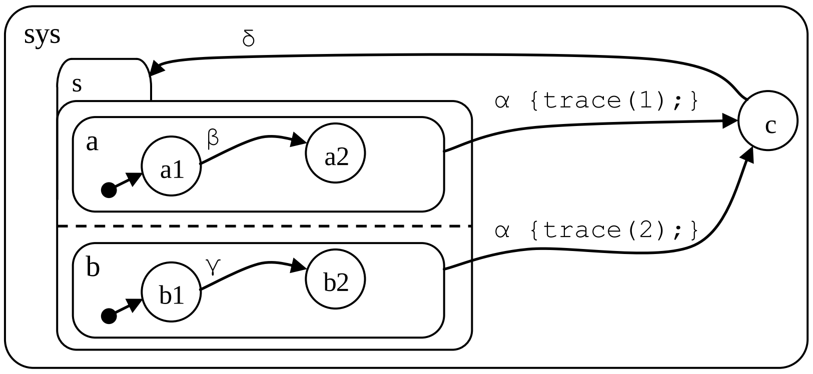


Figure 27. Race to a single target with traces [model `t5472`]

"

In this model there is a race distinguished by traces, but the race is to a single target. The first transition to be processed causes the whole set to be exited and invalidates the other transition at execution time. This illustrates an important principle: ***transitions are reconsidered for validity just before execution***, and do not run if they are in any way invalidated, which might be because the source state has become vacant, or because the condition now evaluates to false. The two worlds produced each have just the *one* trace produced by the only transition to actually run.

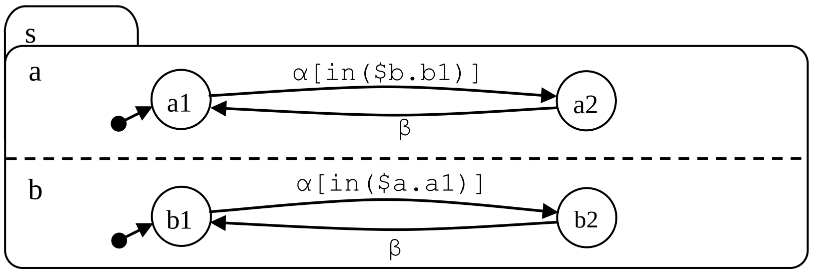


Figure 28. Race to start (mutually exclusive transitions) [model `t5474`]

In this model, two transitions on α each block the other, and only the first transition in the ordering will take place. Two worlds are produced: one in states `a1` and `b2`, and one in `a2` and `b1`.

4.18 Set-transit nondeterminism

When a set is entered, all it members are entered (similarly when it is exited, but we take entering as an example). The order in which the members are entered may be significant, because of *upon enter* actions. STATECRUNCHER offers the facility to generate different orderings of entering the members. The number of orderings can be controlled (see section 4.24); we will work with the default which generates all orderings of a set with three members, but not all orderings for larger sets.

We will implement the following model:

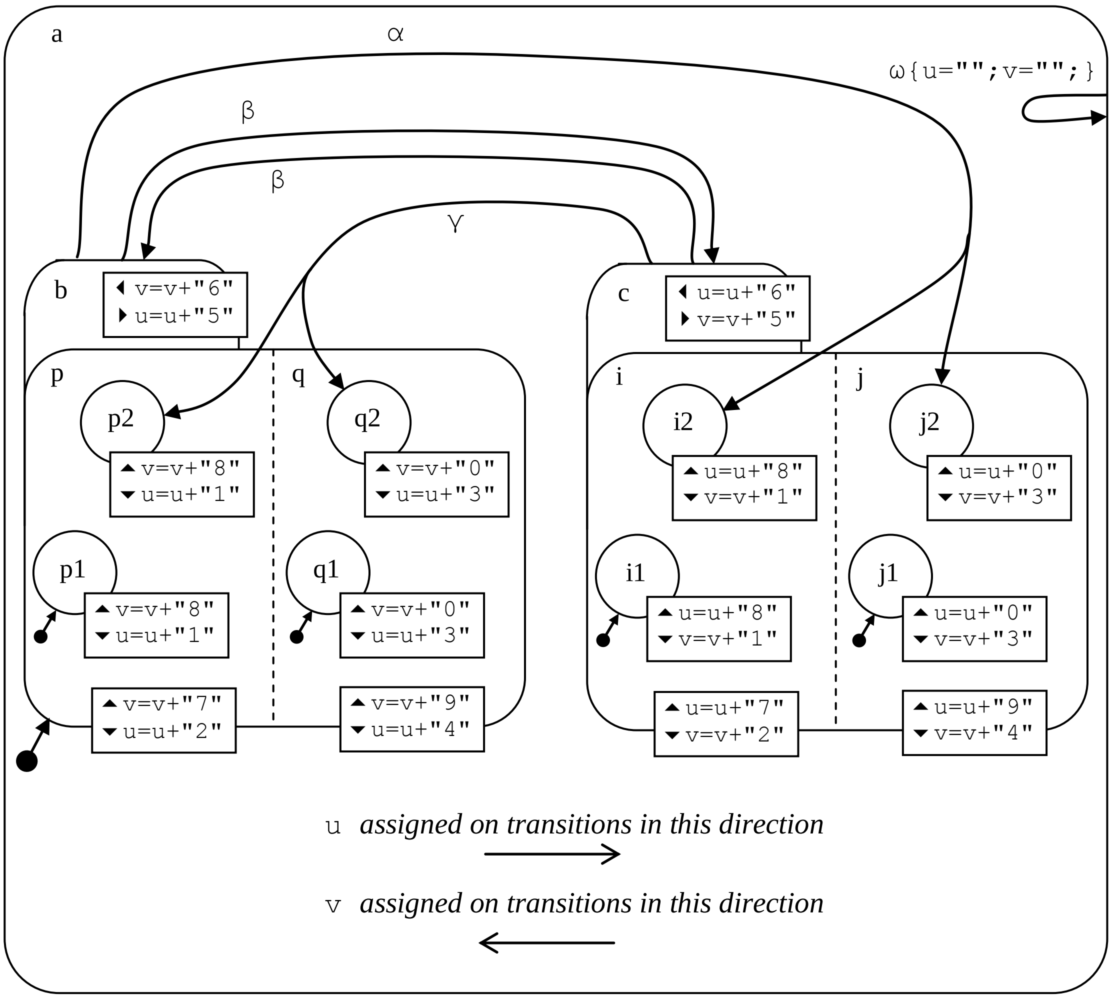


Figure 29. Set transit nondeterminism [model `u5410`]

Call the file `set_tran.scs.txt` in directory `u5410_set_tran`. Prepare the hierarchy first and compile it (as already learned).

```
  SC:root F:\KWinPro\StCr\StCr5ModelsUser\u5410_set_tran
  SC:cp set_tran
```

The hierarchy is:

```
statechart sc(a)
  cluster a(b,c)
    set b(p,q)
      cluster p(p1,p2)
        state p1;
        state p2;
      cluster q(q1,q2)
        state q1;
        state q2;
    set c(i,j)
      cluster i(i1,i2)
        state i1;
        state i2;
      cluster j(j1,j2)
        state j1;
        state j2;
```

Add the declarations and transitions etc.

```
statechart sc(a)
event alpha,beta,gamma,omega;
string u="", v="";
  cluster a(b,c) {omega {u=""; v="";};}
    set b(p,q)        {upon enter {v=v+"6";} upon exit {u=u+"5";} \
                                beta->c; alpha-> c.i.i2/\c.j.j2;}
      cluster p(p1,p2){upon enter {v=v+"7";} upon exit {u=u+"2";}}
        state p1      {upon enter {v=v+"8";} upon exit {u=u+"1";}}
        state p2      {upon enter {v=v+"8";} upon exit {u=u+"1";}}
      cluster q(q1,q2){upon enter {v=v+"9";} upon exit {u=u+"4";}}
        state q1      {upon enter {v=v+"0";} upon exit {u=u+"3";}}
        state q2      {upon enter {v=v+"0";} upon exit {u=u+"3";}}

    set c(i,j)        {upon enter {u=u+"6";} upon exit {v=v+"5";} \
                                 beta->b; gamma-> b.(p.p2/\q.q2);}
      cluster i(i1,i2){upon enter {u=u+"7";} upon exit {v=v+"2";}}
        state i1      {upon enter {u=u+"8";} upon exit {v=v+"1";}}
        state i2      {upon enter {u=u+"8";} upon exit {v=v+"1";}}
      cluster j(j1,j2){upon enter {u=u+"9";} upon exit {v=v+"4";}}
        state j1      {upon enter {u=u+"0";} upon exit {v=v+"3";}}
        state j2      {upon enter {u=u+"0";} upon exit {v=v+"3";}}
```

We use strings rather than integers, because the integers would become large, and may be output in exponential form, depending on the Prolog system.

Compile and run the model. Process event `alpha`. This causes set `b` to be exited in two orderings, then for each of those orderings, for set `c` to be entered in two different orderings. There are 4 different orderings of the set transit, and the values of `u` will register them:

```
  exit (p2,p),(q2,q),b;  enter c,(i,i2),(j,j2); u=1234567890
  exit (p2,p),(q2,q),b;  enter c,(j,j2),(i,i2); u=1234569078
  exit (q2,q),(p2,p),b;  enter c,(i,i2),(j,j2); u=3412567890
  exit (q2,q),(p2,p),b;  enter c,(j,j2),(i,i2); u=3412569078
```

These orderings are produced in different *worlds*. When the get configuration command (`gc`) is given, four blocks of output are given, one for each world. The integer at the start of each line of output is the world number. From the user's perspective, the numbers are arbitrary, but distinct.

```
22   VAR  STRING  u [sc] =[49, ...] =1234569078
23   VAR  STRING  u [sc] =[51, ...] =3412569078
32   VAR  STRING  u [sc] =[49, ...] =1234567890
33   VAR  STRING  u [sc] =[51, ...] =3412567890
```

If we transition back to set a with event `gamma`, say, then variable `v` will track another 4 orderings. And these will be done in the 4 existing worlds. That will produce 16 worlds. On a slow machine (300 MHz), this may take a few seconds to process. The last lines of output are:

```
157  VAR  STRING  u [sc] =[49, ...] =1234569078
157  VAR  STRING  v [sc] =[51, ...] =3412567890
157  TRACE =[]
157  TREV [[omega, [sc]], 0, [], []]
157  TREV [[beta, [sc]], 0, [], []]
157  TREV [[alpha, [sc]], 0, [], []]

outworlds=[53, 54, 63, ... 156, 157]
number of outworlds=16
```

The order of transit in this last world was:

```
  exit (j2,j), (i2,i), c;  enter: b, (p,p2), (q,q2).
```

Note that when a set member is exited, we exit the leafstate then always immediately follow this by the set member, before moving on to the other member. So we never have an ordering such as exit j2, exit i2, exit j, exit i. This would be too fine an interleaving, and would exacerbate combinatorial explosion. We have bracketed tied orderings such as `(j2,j)` in the above descriptions.

If event `beta` is now given, then there will be 64 worlds. The execution time for the last event can be obtained with the command `gpt` (get processing time). On a 300 MHz machine, running under SWI-Prolog, this gives

```
SC:gpt
exec time=00h 00m 26s 530ms
```

If we process event `omega`, the variables are reset, and the number of worlds goes down from 64 to 1. This is an internal event and takes place rather faster:

```
SC:pe omega
SC:gpt
exec time=00h 00m 05s 210ms
```

Although our model does not show it, set transit nondeterminism is applied at several levels in the hierarchy if necessary. Test model `t6311` illustrates this, but it suffers to some extent from combinatorial explosion, although event `beta1` can be processed in under 15 minutes (at 300MHz, SWI Prolog) producing 128 worlds.

4.19 Set-action nondeterminism

In the last section, we saw *set-transit* nondeterminism. But what about when the transitions are within the sets, and there is no transit in and out of the set? We still have to consider orderings. We consider the following model, which has *nested sets*, and we warn in advance for the beginnings of combinatorial explosion and poor performance. However, some more efficient ways to obtain similar behaviour are also discussed.

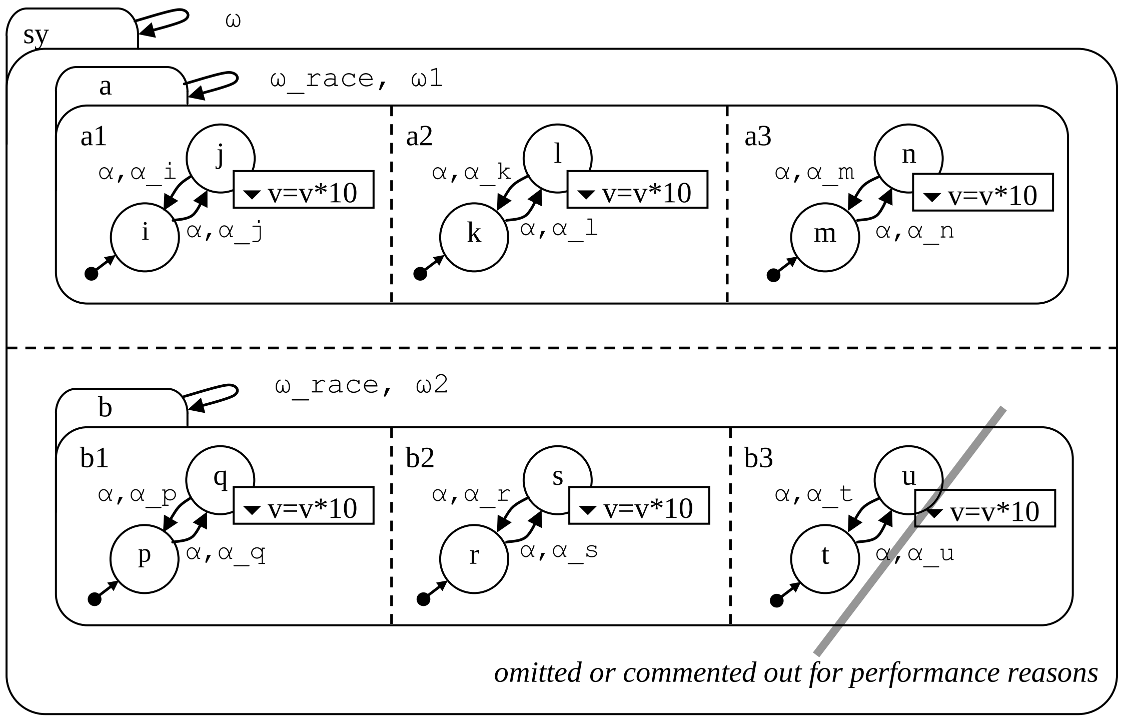


Figure 30. Set action nondeterminism [model `u5412`]

When event α is given, all the set members undergo a local transition. (There is actually a race between them, but there is no difference in outcome whatever the race order, and we ignore the race. Race nondeterminism of this kind was considered in section 4.17).

We could make all these set members transition back with another request to process event α. As the set members transition back, they generate values of v that record the order in which it happened. Each order generates a different value of v. There are 5! = 120 orderings, although this can be restricted, to be explained later (section 4.23).

Now event ω will do a similar thing in principle, although it is only attached to one transition. But there is one difference in what happens: orderings will be hierarchically generated as follows: the 3! =6 orderings within set a will be generated, and the 2! = 2 orderings within set b will be generated. Then these 6 and 2 orderings will be regarded as single entities and ordered in 2! =2 different ways. So the total number of orderings will be 3!.2!.2! =24. We call this set-action nondeterminism.

As it happens, on a 300MHz machine under SWI-Prolog, the 120 worlds of the *race* are generated in $2^1/_2$ minutes, and the 24 worlds of the *set-action* are generated in $5^1/_2$ minutes. But if there were to be further processing with nondeterminism of any kind, it would be better to depart from 24 worlds than 120, if the 24 cover the needs of the user.

We will prepare the model and see this in action.

Call the file `set_action.scs.txt` in directory `u5412_set_action`. Prepare the hierarchy first and compile it (as already learned).

```
SC:root F:\KWinPro\StCr\StCr5ModelsUser\u5412_set_action
SC:cp set_action
```

The hierarchy is:

```
statechart sc(sy)
set sy(a,b)
   set a(a1,a2,a3)
      cluster a1(i,j)
         state i;
         state j;
      cluster a2(k,l)
         state k;
         state l;
      cluster a3(m,n)
         state m;
         state n;
   set b(b1,b2)
      cluster b1(p,q)
         state p;
         state q;
      cluster b2(r,s)
         state r;
         state s;
```

Add the declarations and transitions:

```
statechart sc(sy)
event alpha;
event alpha_i, alpha_j, alpha_k, alpha_l, alpha_m, alpha_n;
event alpha_p, alpha_q, alpha_r, alpha_s;
event omega, omega_vreset, omega_race, omega1, omega2;

enum vint {0,..,1000000};
vint v=0;

set sy(a,b)  {omega->sy; omega_vreset {v=0;};}

   set a(a1,a2,a3) {omega_race->a; omega1->a;}

      cluster a1(i,j)
         state i   {                      alpha, alpha_j->j;}
         state j   {upon exit {v=v*10+1;} alpha, alpha_i->i;}

      cluster a2(k,l)
         state k   {                      alpha, alpha_l->l;}
         state l   {upon exit {v=v*10+2;} alpha, alpha_k->k;}

      cluster a3(m,n)
         state m   {                      alpha, alpha_n->n;}
         state n   {upon exit {v=v*10+3;} alpha, alpha_m->m;}

   set b(b1,b2)    {omega_race->b; omega2->b;}

      cluster b1(p,q)
         state p   {                      alpha, alpha_q->q;}
         state q   {upon exit {v=v*10+4;} alpha, alpha_p->p;}

      cluster b2(r,s)
         state r   {                      alpha, alpha_s->s;}
         state s   {upon exit {v=v*10+5;} alpha, alpha_r->r;}
```

Compile the model. Process event `alpha`. (This should be quick - a few seconds at most - assuming the default race setting, medium race, is in place. This will be explained later). All the local transitions will take place, and there will be one world:

```
7    statechart sc
7       set sy [sc] = OCC []  **
7          set a [sy, sc] = OCC []  **
7             cluster a1 [a, sy, sc] = OCC []  **
7                leafstate i [a1, a, sy, sc] = VAC []
7                leafstate j [a1, a, sy, sc] = OCC []  **
7             cluster a2 [a, sy, sc] = OCC []  **
7                leafstate k [a2, a, sy, sc] = VAC []
7                leafstate l [a2, a, sy, sc] = OCC []  **
7             cluster a3 [a, sy, sc] = OCC []  **
7                leafstate m [a3, a, sy, sc] = VAC []
7                leafstate n [a3, a, sy, sc] = OCC []  **
7          set b [sy, sc] = OCC []  **
7             cluster b1 [b, sy, sc] = OCC []  **
7                leafstate p [b1, b, sy, sc] = VAC []
7                leafstate q [b1, b, sy, sc] = OCC []  **
7             cluster b2 [b, sy, sc] = OCC []  **
7                leafstate r [b2, b, sy, sc] = VAC []
7                leafstate s [b2, b, sy, sc] = OCC []  **
7    VAR  INTEGER v [sc] =0
...
```

Now process event `omega` (and if your machine is not too new, take a coffee). Then get the configuration (command `gc`). There are 24 worlds. The last one is as follows:

```
173  statechart sc
173     set sy [sc] = OCC []  **
173        set a [sy, sc] = OCC []  **
173           cluster a1 [a, sy, sc] = OCC []  **
173              leafstate i [a1, a, sy, sc] = OCC []  **
173              leafstate j [a1, a, sy, sc] = VAC []
173           cluster a2 [a, sy, sc] = OCC []  **
173              leafstate k [a2, a, sy, sc] = OCC []  **
173              leafstate l [a2, a, sy, sc] = VAC []
173           cluster a3 [a, sy, sc] = OCC []  **
173              leafstate m [a3, a, sy, sc] = OCC []  **
173              leafstate n [a3, a, sy, sc] = VAC []
173        set b [sy, sc] = OCC []  **
173           cluster b1 [b, sy, sc] = OCC []  **
173              leafstate p [b1, b, sy, sc] = OCC []  **
173              leafstate q [b1, b, sy, sc] = VAC []
173           cluster b2 [b, sy, sc] = OCC []  **
173              leafstate r [b2, b, sy, sc] = OCC []  **
173              leafstate s [b2, b, sy, sc] = VAC []
173  VAR  INTEGER v [sc] =54321
173  TRACE =[]
...
outworlds=[58, 63, 68, ... 168, 173]
number of outworlds=24
SC:gpt
exec time=00h 05m 38s 120ms
```

This world, with `v`=54321, shows that the exit order was `b2`, `b1`, `a3`, `a2`, `a1`. Examine other worlds and deduce the exit order. You will see orderings of (`a3`, `a2`, `a1`) but always next to each other, and orderings of (`b2`, `b1`), but always next to each other, and sometimes the `a`'s will be before the `b`'s. But you will never see an ordering such as `a1`, `b1`, `a2`, `b2`, `b3`.

The following are optional extras.

As a first optional extra, the reader can experiment with resetting the machine (command `rm`) and the following sequence of events: `alpha`, `omega1`, `omega2`. On `omega1`, 6 worlds are generated (quite fast), and on `omega2` this is increased to 12 worlds (and again is quite fast). If this kind of approach, ***where set action nondeterminism applies to one set at a time***, is adequate to model the Implementation Under Test, ***it is recommended, being quicker in execution***.

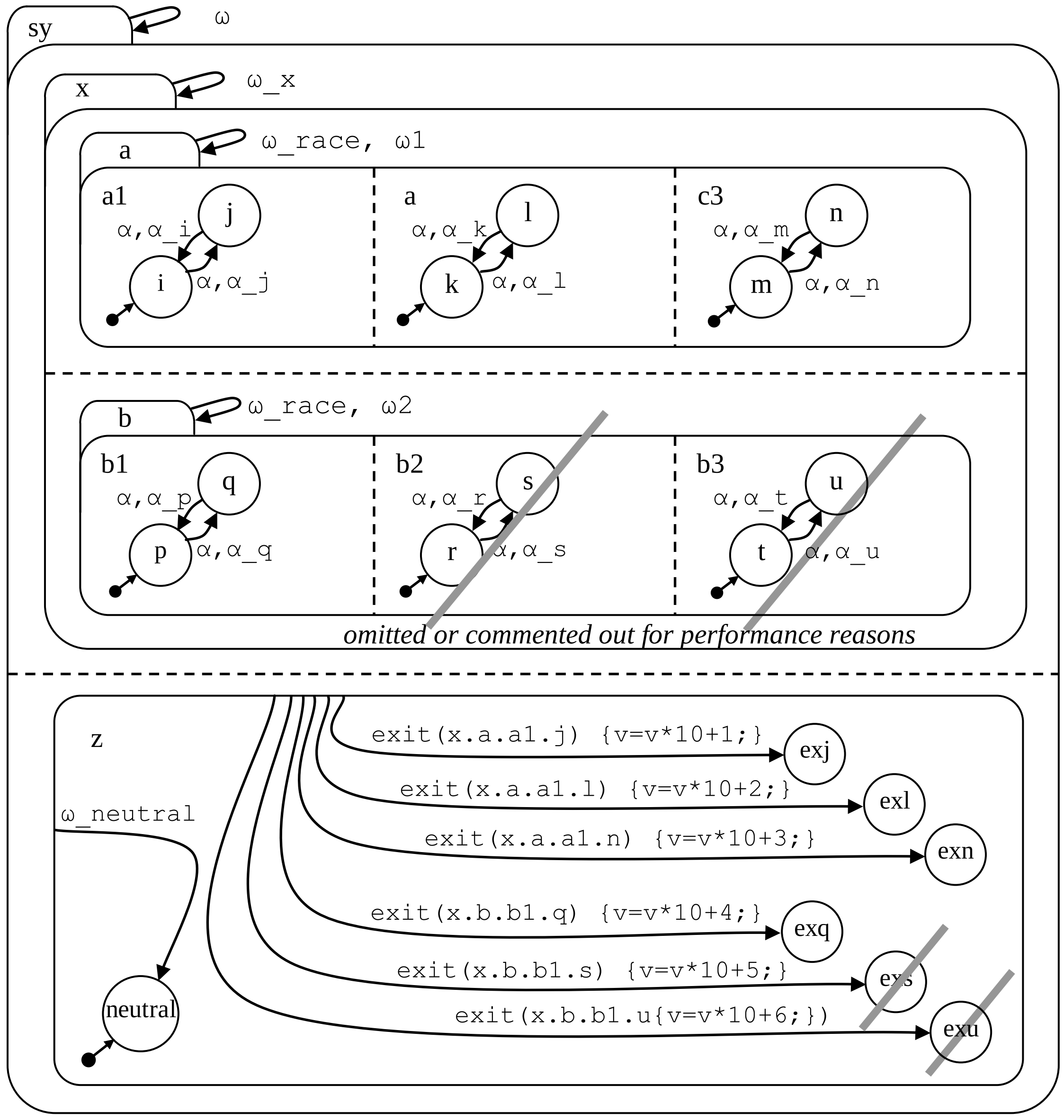
Another optional extra is to reset the machine and process the following sequence of events: `alpha`, `omega_race`. In about 14 seconds (300MHz, SWI Prolog) 24 worlds are generated just as in the `omega` case. Sets `a` and set `b` undergo their own internal set actions in various orderings, and a race is run between the sets as single entities, in two ways, giving the same effect as the `omega` case but via a different approach, which happens to be considerably faster (in the implementation mentioned).

4.20 Set meta-event nondeterminism

Another form of set nondeterminism arises from the internally generated exit and enter events, which we call *meta-events*, that can occur in sets as the result of transitions on the whole set. Meta-events were introduced in section 4.8.

Meta-event nondeterminism is very similar to set-action nondeterminism just considered. In the figure below, on event sequence `alpha`, `omega`, many leaf-states in sets are exited, and the associated meta-events are responded to in the lower part of the model.

Performance is particularly poor on event `omega`, as it affects *nested sets*, and the outer one (`sy`) is bigger than in the previous set-action model. This is however, not a cause for alarm, but rather for understanding of when performance is poor and when it is good. It should also be noted that performance with nondeterminism switched off is always good, and by controlling nondeterminism judiciously, good performance can generally be attained.



sy
ω
x
ω_x
a
ω_race, ω1
a1
α,α_i
α,α_j
a
α,α_k
α,α_l
c3
α,α_m
α,α_n
b
ω_race, ω2
b1
α,α_p
α,α_q
b2
α,α_r
α,α_s
b3
α,α_t
α,α_u
omitted or commented out for performance reasons
z
ω_neutral
neutral
exit(x.a.a1.j) {v=v*10+1;}
exj
exit(x.a.a1.l) {v=v*10+2;}
exl
exit(x.a.a1.n) {v=v*10+3;}
exn
exit(x.b.b1.q) {v=v*10+4;}
exq
exit(x.b.b1.s) {v=v*10+5;}
exs
exit(x.b.b1.u{v=v*10+6;})
exu

Figure 31. Set meta-event nondeterminism [model `u5414`]

All meta-events associated with the transitions on event `alpha` are responded to in member `z`, with variable `v` recording the sequence.

We will prepare the model and see this in action.

Call the file `set_mev.scs.txt` in directory `u5414_set_mev`. Prepare the hierarchy first and compile it (as already learned).

```
SC:root F:\KWinPro\StCr\StCr5ModelsUser\u5414_set_mev
SC:cp set_mev
```

The hierarchy is:

```
statechart sc(sy)
set sy(a,b)
   set a(a1,a2,a3)
      cluster a1(i,j)
         state i;
         state j;
      cluster a2(k,l)
         state k;
         state l;
      cluster a3(m,n)
         state m;
         state n;
   set b(b1)
      cluster b1(p,q)
         state p;
         state q;
```

Add the declarations and transitions:

```
statechart sc(sy)

event alpha;
event alpha_i, alpha_j, alpha_k, alpha_l, alpha_m, alpha_n;
event alpha_p, alpha_q;
event omega, omega_x, omega_race, omega1, omega2;
event omega_neutral, omega_vreset;

enum vint {0,..,1000000};
vint v=0;

set sy(x,z)                 {omega->sy; omega_vreset {v=0;};}

  set x(a,b)                {omega_x->x;}

      set a(a1,a2,a3)       {omega_race->a; omega1->a;}

         cluster a1(i,j)
            state i         {alpha, alpha_j->j;}
            state j         {alpha, alpha_i->i;}

         cluster a2(k,l)
            state k         {alpha, alpha_l->l;}
            state l         {alpha, alpha_k->k;}

         cluster a3(m,n)
            state m         {alpha, alpha_n->n;}
            state n         {alpha, alpha_m->m;}

      set b(b1) {omega_race->b; omega2->b;}

         cluster b1(p,q)
            state p         {alpha, alpha_q->q;}
            state q         {alpha, alpha_p->p;}

   cluster z(neutral, exj,exl,exn, exq)                      \
                     {omega_neutral  -> z.neutral;           \
                      exit(x.a.a1.j) -> z.exj {v=v*10+1;}; \
                      exit(x.a.a2.l) -> z.exl {v=v*10+2;}; \
                      exit(x.a.a3.n) -> z.exn {v=v*10+3;}; \
                      exit(x.b.b1.q) -> z.exq {v=v*10+4;}; }
      state neutral;
      state exj;
      state exl;
      state exn;
      state exq;
```

Compile the model. Process event `alpha`. (This should be quick - a few seconds at most - assuming the default race setting, medium race, is in place. This will be explained later).

```
6    statechart sc
6       set sy [sc] = OCC []  **
6          set x [sy, sc] = OCC []  **
6             set a [x, sy, sc] = OCC []  **
6                cluster a1 [a, x, sy, sc] = OCC []  **
6                   leafstate i [a1, a, x, sy, sc] = VAC []
6                   leafstate j [a1, a, x, sy, sc] = OCC []  **
6                cluster a2 [a, x, sy, sc] = OCC []  **
6                   leafstate k [a2, a, x, sy, sc] = VAC []
6                   leafstate l [a2, a, x, sy, sc] = OCC []  **
6                cluster a3 [a, x, sy, sc] = OCC []  **
6                   leafstate m [a3, a, x, sy, sc] = VAC []
6                   leafstate n [a3, a, x, sy, sc] = OCC []  **
6             set b [x, sy, sc] = OCC []  **
6                cluster b1 [b, x, sy, sc] = OCC []  **
6                   leafstate p [b1, b, x, sy, sc] = VAC []
6                   leafstate q [b1, b, x, sy, sc] = OCC []  **
6          cluster z [sy, sc] = OCC []  **
6             leafstate neutral [z, sy, sc] = OCC []  **
6             leafstate exj [z, sy, sc] = VAC []
6             leafstate exl [z, sy, sc] = VAC []
6             leafstate exn [z, sy, sc] = VAC []
6             leafstate exq [z, sy, sc] = VAC []
6    VAR  INTEGER v [sc] =0
...
```

All the local transitions have taken place, and there is one world. Cluster `z` is in its neutral state. Variable `v` is zero.

Now process event `omega.` This takes 1m40s (300MHz, SWI-Prolog). Then get the configuration (command `gc`). There are 12 worlds. The last one is as follows:

```
131  statechart sc
131     set sy [sc] = OCC []  **
131        set x [sy, sc] = OCC []  **
131           set a [x, sy, sc] = OCC []  **
131              cluster a1 [a, x, sy, sc] = OCC []  **
131                 leafstate i [a1, a, x, sy, sc] = OCC []  **
131                 leafstate j [a1, a, x, sy, sc] = VAC []
131              cluster a2 [a, x, sy, sc] = OCC []  **
131                 leafstate k [a2, a, x, sy, sc] = OCC []  **
131                 leafstate l [a2, a, x, sy, sc] = VAC []
131              cluster a3 [a, x, sy, sc] = OCC []  **
131                 leafstate m [a3, a, x, sy, sc] = OCC []  **
131                 leafstate n [a3, a, x, sy, sc] = VAC []
131           set b [x, sy, sc] = OCC []  **
131              cluster b1 [b, x, sy, sc] = OCC []  **
131                 leafstate p [b1, b, x, sy, sc] = OCC []  **
131                 leafstate q [b1, b, x, sy, sc] = VAC []
131        cluster z [sy, sc] = OCC []  **
131           leafstate neutral [z, sy, sc] = VAC []
131           leafstate exj [z, sy, sc] = OCC []  **
131           leafstate exl [z, sy, sc] = VAC []
131           leafstate exn [z, sy, sc] = VAC []
131           leafstate exq [z, sy, sc] = VAC []
131  VAR  INTEGER v [sc] =4321
...
outworlds=[43, 51, 59, 67, 75, 83, 91, 99, 107, 115, 123, 131]
number of outworlds=12
SC:gpt
exec time=00h 01m 39s 750ms
```

This world has `v`=4321, which shows the order of meta-event response was from the exiting of states `b1,a3,a2,a1` in that order. Examine other worlds and deduce the order of exiting of states. As in the set-action case, you will see orderings of `a3,a2,a1,` and you would see additional orderings of `b` states if there were any, and you will also see the `a`'s before the `b`, but you will never see an ordering such as `a1,b1,a2,a3`.

As in the previous section, some optional extras are offered.

As a first optional extra, the reader can experiment with resetting the machine (command `rm`) and the following sequence of events: `alpha`, `omega1`, `omega2`. On `omega1`, 6 worlds are generated (in 11 seconds, 300MHz, SWI Prolog). On `omega2` (which is fast) set `b` is reset, without increasing the number of worlds, because it only has one member. If this kind of approach, ***where set meta-event nondeterminism applies to one set at a time***, is adequate to model the Implementation Under Test, ***it is recommended, being quicker in execution***.

Another optional extra is to reset the machine and process the following sequence of events: `alpha`, `omega_race`. In about 24 seconds (300MHz, SWI Prolog) 12 worlds are generated just as in the `omega` case. Sets `a` and set `b` undergo their own internal set actions in various orderings, and a race is run between the sets as single entities, in two ways, giving the same effect as the `omega` case but via a different approach, which happens to be considerably faster (in the implementation mentioned).

4.21 Fired event and multiple nondeterminism

So far, the kinds of nondeterminism we have seen have all been illustrated separately. But they can all take place in the same model as a result of processing one event. The initiating event may not obviously be the cause of nondeterminism - it may be that nondeterminism arises as a result of other events fired during transition processing. In that case we speak of *fired event* (or: *broadcast event*) *nondeterminism*. We will implement the following model:

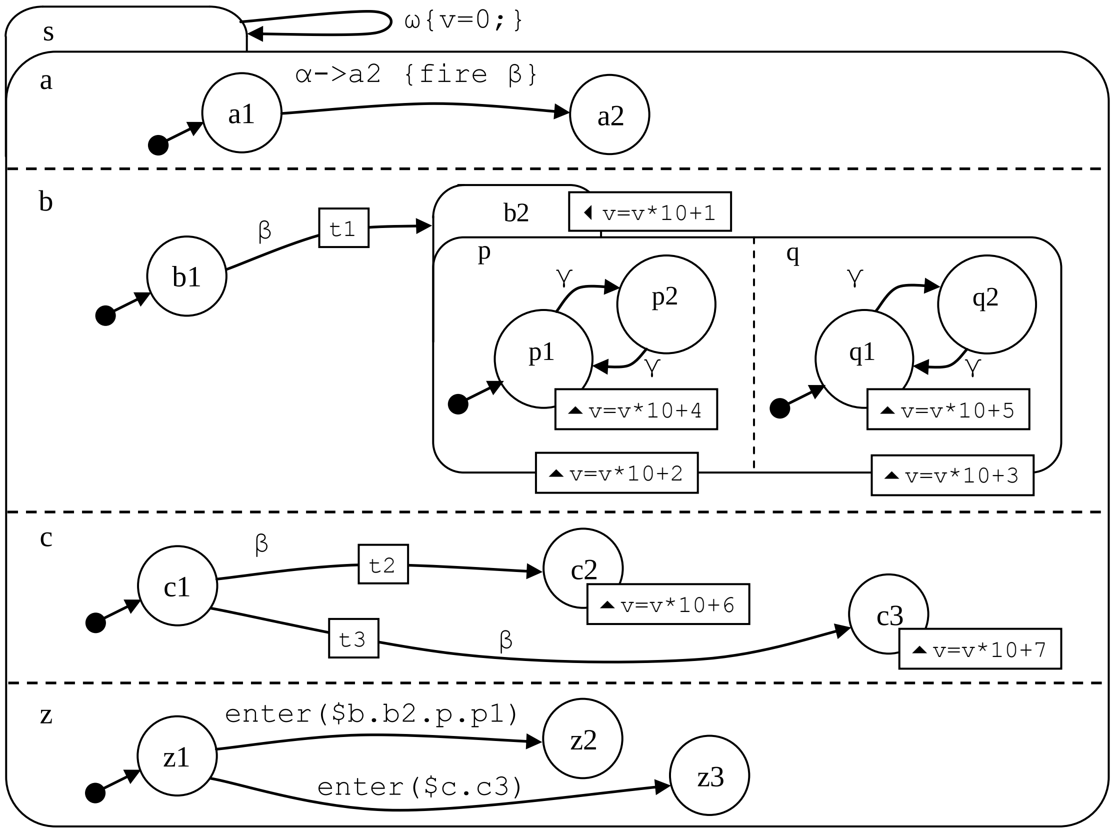


Figure 32. Multiple nondeterminism [model `u5480`]

This model can be used with event β to illustrate set-transit, fork, and race-condition nondeterminism. But we can include fired event nondeterminism by starting with event α, which causes β to be fired. To help with the explanation, we have named the transitions on β: `t1`, `t2` and `t3`. On event β there is a fork with prongs `t2` and `t3`. One of these will be chosen for one line of processing and one for another. But whichever is chosen, it must race against `t1`, and so different orderings will be generated. STATECRUNCHER will start by generating 4 sequences of transitions: <`t1`,`t2`>, <`t2`,`t1`>, <`t1`,`t3`> and <`t3`,`t1`>. Now when `t1` is processed in any of these sequences, set `b2` is entered. This occasions set-transit nondeterminism. The two members of the set will be entered in two different orderings. The net effect is that starting from the initial configuration, 8 worlds are produced. Variable `v` records the order in which key states are entered. Partially corroborating this are the resultant states in set members `c` and `z`.

Call the file `multi_nd.scs.txt` in directory `u5480_multi_nd`. Prepare the hierarchy first and compile it (as already learned).

```
  SC:root F:\KWinPro\StCr\StCr5ModelsUser\u5480_multi_nd
  SC:cp multi_nd
```

The hierarchy is:

```
statechart sc(s)
   set s(a,b,c,z)
      cluster a(a1,a2)
         state a1;
         state a2;
      cluster b(b1,b2)
         state b1;
         set b2(p,q)
            cluster p(p1,p2)
               state p1;
               state p2;
            cluster q(q1,q2)
               state q1;
               state q2;
      cluster c(c1,c2,c3)
         state c1;
         state c2;
         state c3;
     cluster z(z1,z2,z3)
         state z1;
         state z2;
         state z3;
```

Add the declarations and transitions:

```
statechart sc(s)
event alpha,beta,gamma,omega;
enum int1 {0,..,1000};
int1 v=0;
   set s(a,b,c,z) {omega->s {v=0;};}  // reset
      cluster a(a1,a2)
         state a1          {alpha->a2 {fire beta;};}
         state a2;
      cluster b(b1,b2)
         state b1          {beta->b2;}
         set b2(p,q)            {upon enter {v=v*10+1;}}
            cluster p(p1,p2)    {upon enter {v=v*10+2;}}
               state p1         {upon enter {v=v*10+4;} gamma->p2; }
               state p2         {upon enter {v=v*10+4;} gamma->p1; }
            cluster q(q1,q2)    {upon enter {v=v*10+3;}}
               state q1         {upon enter {v=v*10+5;} gamma->q2; }
               state q2         {upon enter {v=v*10+5;} gamma->q1; }
      cluster c(c1,c2,c3)
         state c1          {beta->c2; beta->c3;}
         state c2               {upon enter {v=v*10+6;}}
         state c3               {upon enter {v=v*10+7;}}
     cluster z(z1,z2,z3)
         state z1 { enter($b.b2.p.p1)->z2;  enter($c.c3)->z3; }
         state z2;
         state z3;
```

Compile the model. Process event `alpha`. The eight worlds will be generated fairly quickly (1.5 sec on a 300MHz machine running SWI-Prolog). Get the configuration (command `gc`). The key configuration lines are:

```
18           leafstate c3 [c, s, sc] = OCC []  **
18           leafstate z2 [z, s, sc] = OCC []  **
18   VAR  INTEGER v [sc] =124357

20           leafstate c3 [c, s, sc] = OCC []  **
20           leafstate z2 [z, s, sc] = OCC []  **
20   VAR  INTEGER v [sc] =135247

29           leafstate c3 [c, s, sc] = OCC []  **
29           leafstate z3 [z, s, sc] = OCC []  **
29   VAR  INTEGER v [sc] =713524

34           leafstate c3 [c, s, sc] = OCC []  **
34           leafstate z3 [z, s, sc] = OCC []  **
34   VAR  INTEGER v [sc] =712435

49           leafstate c2 [c, s, sc] = OCC []  **
49           leafstate z2 [z, s, sc] = OCC []  **
49   VAR  INTEGER v [sc] =124356

51           leafstate c2 [c, s, sc] = OCC []  **
51           leafstate z2 [z, s, sc] = OCC []  **
51   VAR  INTEGER v [sc] =135246

61           leafstate c2 [c, s, sc] = OCC []  **
61           leafstate z2 [z, s, sc] = OCC []  **
61   VAR  INTEGER v [sc] =613524

66           leafstate c2 [c, s, sc] = OCC []  **
66           leafstate z2 [z, s, sc] = OCC []  **
66   VAR  INTEGER v [sc] =612435
```

We take world 66 as an example. Variable `v` indicates that the order in which states were entered was `c2,b2,p,p1,q,q1`. This means that in this world transition `t2` was taken in the `t2`-`t3` fork, and that in the `t1`-`t2` race, `t2` ran before `t1`. This is corroborated by the fact that `c2` is occupied rather than `c3`, and that `z2` was entered rather than `z3`. The user should examine some other worlds in the same way.

Process event `omega` to take the model back to its initial configuration. It yields one world.

4.22 Transition prioritisation

We have seen fork nondeterminism where the transitions have the identical source state:

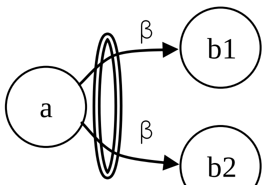


Figure 33. Fork nondeterminism with same source state

But how is the following situation to be handled? The transitions are named `t1` and `t2`.

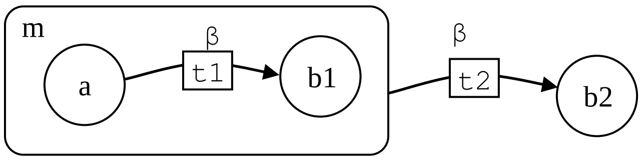


Figure 34. Hierarchical issue

There are three ways this could be handled:

(1) We could say it is fork nondeterminism, with one world ending up in state `m.b2` and the other in state `b2`.

(2) We could say that we prioritise and override by specialisation, saying that `t1` takes precedence and masks `t2`. In this case the model is deterministic. This is the approach taken by UML, and is in line with overriding member methods in C++ derived classes.

(3) We could say that we prioritise and override by the more external transition, saying that `t2` takes precedence and masks `t1`. In this case the model is again deterministic. This approach has the advantage that an external transition cannot be affected be perhaps poorly understood internals of a deeply embedded machine. This is the approach taken by [CHSM].

As pointed out by Lucas in [CHSM], under this scheme we can alter the precedence as follows:

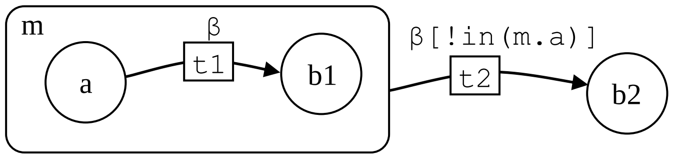


Figure 35. Forced prioritisation reversal giving specialisation

STATECRUNCHER implements option (2) and conforms with UML, since that is the standard with which many designs comply. We will build the following model to illustrate the details of this, including how transition conditions affect the transitions taken.

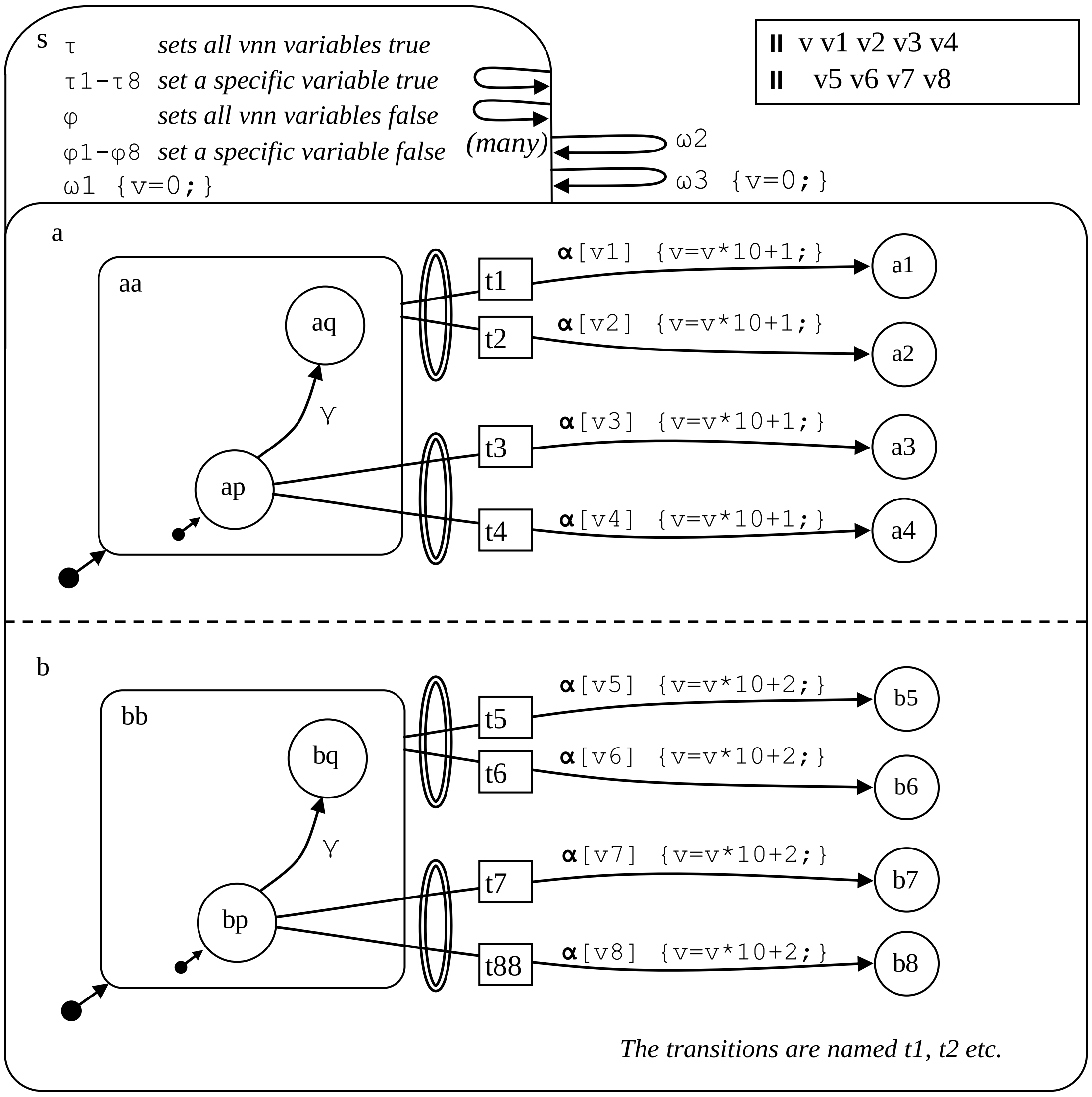


Figure 36. Transition prioritisation [model `u5500`]

This model also runs a race, to show that races are not affected by transition prioritisation. All transitions `t1`-`t8` are conditional on their own variable `v1`-`v8`, which can be set to true or false by internal event `τ1`-`τ8` and `φ1`-`φ8` respectively. We can also set all these variables to true or false in one go by events `τ` and `φ`, and then adjust selected ones specifically. This gives us the ability to invalidate specific transitions, so as to see the prioritisation algorithm under various circumstances. The value of `v` tells us about race ordering. We will see this in practice.

Call the file `trans_prio.scs.txt` in directory `u5500_trans_prio`. Prepare the hierarchy first and compile it (as already learned).

```
  SC:root F:\KWinPro\StCr\StCr5ModelsUser\u5500_trans_prio
  SC:cp trans_prio
```

The hierarchy is:

```
statechart sc(s)
set s (a,b)
  cluster a(aa,a1,a2,a3,a4)
     cluster aa(ap,aq)
        state ap;
        state aq;
     state a1;
     state a2;
     state a3;
     state a4;
  cluster b(bb,b5,b6,b7,b8)
     cluster bb(bp,bq)
        state bp;
        state bq;
     state b5;
     state b6;
     state b7;
     state b8;
```

Add the declarations and transitions:

```
statechart sc(s)

event alpha,gamma,delta,omega1,omega2,omega3;
event tau, phi;
event tau1,  tau2,  tau3,  tau4,  tau5,  tau6,  tau7,  tau8;
event phi1,  phi2,  phi3,  phi4,  phi5,  phi6,  phi7,  phi8;

enum int1 {0,..,100};
int1 v=0;
bool v1=true,  v2=true,  v3=true,  v4=true;
bool v5=true,  v6=true,  v7=true,  v8=true;

set s (a,b)                                                         \
  {tau {v1=true;         v2=true;         v3=true;         v4=true;   \
        v5=true;         v6=true;         v7=true;         v8=true;}; \
                                                                      \
   tau1{v1=true;};  tau2{v2=true;};  tau3{v3=true;};  tau4{v4=true;}; \
   tau5{v5=true;};  tau6{v6=true;};  tau7{v7=true;};  tau8{v8=true;}; \
                                                                      \
   phi {v1=false;        v2=false;        v3=false;        v4=false;  \
        v5=false;        v6=false;        v7=false;        v8=false;};\
                                                                      \
   phi1{v1=false;}; phi2{v2=false;}; phi3{v3=false;}; phi4{v4=false;};\
   phi5{v5=false;}; phi6{v6=false;}; phi7{v7=false;}; phi8{v8=false;};\
                                                                      \
   omega1{v=0;}; omega2->s; omega3->s{v=0;};                          }

  cluster a(aa,a1,a2,a3,a4)

     cluster aa(ap,aq)  {alpha[v1]-> a1{v=v*10+1;};  \
                         alpha[v2]-> a2{v=v*10+1;};  }

        state ap        {alpha[v3]->$a3{v=v*10+1;};  \
                         alpha[v4]->$a4{v=v*10+1;};  \
                         gamma->aq;                  }
        state aq;
     state a1;
     state a2;
     state a3;
     state a4;

  cluster b(bb,b5,b6,b7,b8)

     cluster bb(bp,bq)  {alpha[v5]->b5{v=v*10+2;};   \
                         alpha[v6]->b6{v=v*10+2;};   }

        state bp        {alpha[v7]->$b7{v=v*10+2;};  \
                         alpha[v8]->$b8{v=v*10+2;};  \
                         delta->bq;                  }
        state bq;
     state b5;
     state b6;
     state b7;
     state b8;
```

Process event α and get the configuration. The number of worlds produced is 8. The key lines of these worlds are shown below. We see that all the transitions are to `a3`, `a4`, `b7`, or `b8`, i.e. they are the inner, specialised ones. In all cases two transitions were executed, as is seen by the value of `v`, which is always 12 or 21, indicating whether a in set member `a` ran before or after a transition in set member `b`. The 8 worlds come from 3 multiplicative factors: choose a transition from `t3` or `t4`, choose a transition from `t7` or `t7`, and choose an ordering for these two transitions.

```
6           leafstate a4 [a, s, sc] = OCC []  **
6           leafstate b8 [b, s, sc] = OCC []  **
6    VAR  INTEGER v [sc] =12

10          leafstate a4 [a, s, sc] = OCC []  **
10          leafstate b8 [b, s, sc] = OCC []  **
10   VAR  INTEGER v [sc] =21

14          leafstate a4 [a, s, sc] = OCC []  **
14          leafstate b7 [b, s, sc] = OCC []  **
14   VAR  INTEGER v [sc] =12

18          leafstate a4 [a, s, sc] = OCC []  **
18          leafstate b7 [b, s, sc] = OCC []  **
18   VAR  INTEGER v [sc] =21

22          leafstate a3 [a, s, sc] = OCC []  **
22          leafstate b8 [b, s, sc] = OCC []  **
22   VAR  INTEGER v [sc] =12

26          leafstate a3 [a, s, sc] = OCC []  **
26          leafstate b8 [b, s, sc] = OCC []  **
26   VAR  INTEGER v [sc] =21

30          leafstate a3 [a, s, sc] = OCC []  **
30          leafstate b7 [b, s, sc] = OCC []  **
30   VAR  INTEGER v [sc] =12

34          leafstate a3 [a, s, sc] = OCC []  **
34          leafstate b7 [b, s, sc] = OCC []  **
34   VAR  INTEGER v [sc] =21
```

Process event `omega3` to effectively reset the machine (in this case). Then process event `phi7`, to set `v7` to `false`, and so invalidate transition `t7`. Then process event `alpha` and get the configuration. Four worlds are produced. They are like the ones above, but with worlds in `b7` removed. The last world listed, for example, has the following details:

```
68          leafstate a3 [a, s, sc] = OCC []  **
68          leafstate b8 [b, s, sc] = OCC []  **
68   VAR  INTEGER v [sc] =21
```

Process event omega3 to effectively reset the machine, except that the value of v7 is not reset. Process event phi8 so that v8 becomes false, and t8 is also invalidated. Process event alpha and get the configuration. There are 8 worlds. We see that all the transitions are to a3, a4, b5, or b6. The specialization rule that would normally say that transitions t7 and t8 mask transitions t5 and t6 does not have any force when both t7 and t8 are invalidated by their condition. So t5 and t6 come into view, and cause a fork and a race a transition from set member a.

```
82            leafstate a4 [a, s, sc] = OCC []  **
82            leafstate b6 [b, s, sc] = OCC []  **
82   VAR  INTEGER v [sc] =12

86            leafstate a4 [a, s, sc] = OCC []  **
86            leafstate b6 [b, s, sc] = OCC []  **
86   VAR  INTEGER v [sc] =21

90            leafstate a4 [a, s, sc] = OCC []  **
90            leafstate b5 [b, s, sc] = OCC []  **
90   VAR  INTEGER v [sc] =12

94            leafstate a4 [a, s, sc] = OCC []  **
94            leafstate b5 [b, s, sc] = OCC []  **
94   VAR  INTEGER v [sc] =2

98            leafstate a3 [a, s, sc] = OCC []  **
98            leafstate b6 [b, s, sc] = OCC []  **
98   VAR  INTEGER v [sc] =12

102           leafstate a3 [a, s, sc] = OCC []  **
102           leafstate b6 [b, s, sc] = OCC []  **
102  VAR  INTEGER v [sc] =21

106           leafstate a3 [a, s, sc] = OCC []  **
106           leafstate b5 [b, s, sc] = OCC []  **
106  VAR  INTEGER v [sc] =12

110           leafstate a3 [a, s, sc] = OCC []  **
110           leafstate b5 [b, s, sc] = OCC []  **
110  VAR  INTEGER v [sc] =21
```

The reader can experiment with this model by resetting it, then setting other combinations of values to variables v1-v8, and then processing event alpha. For a more extensive model on the same theme, see *test* model t5500.

4.23 Limited race nondeterminism

We have already seen that race (and set-transit) nondeterminism can hit performance. In this section we learn how to limit race nondeterminism - even to switch it off if desired. We will implement the following model:

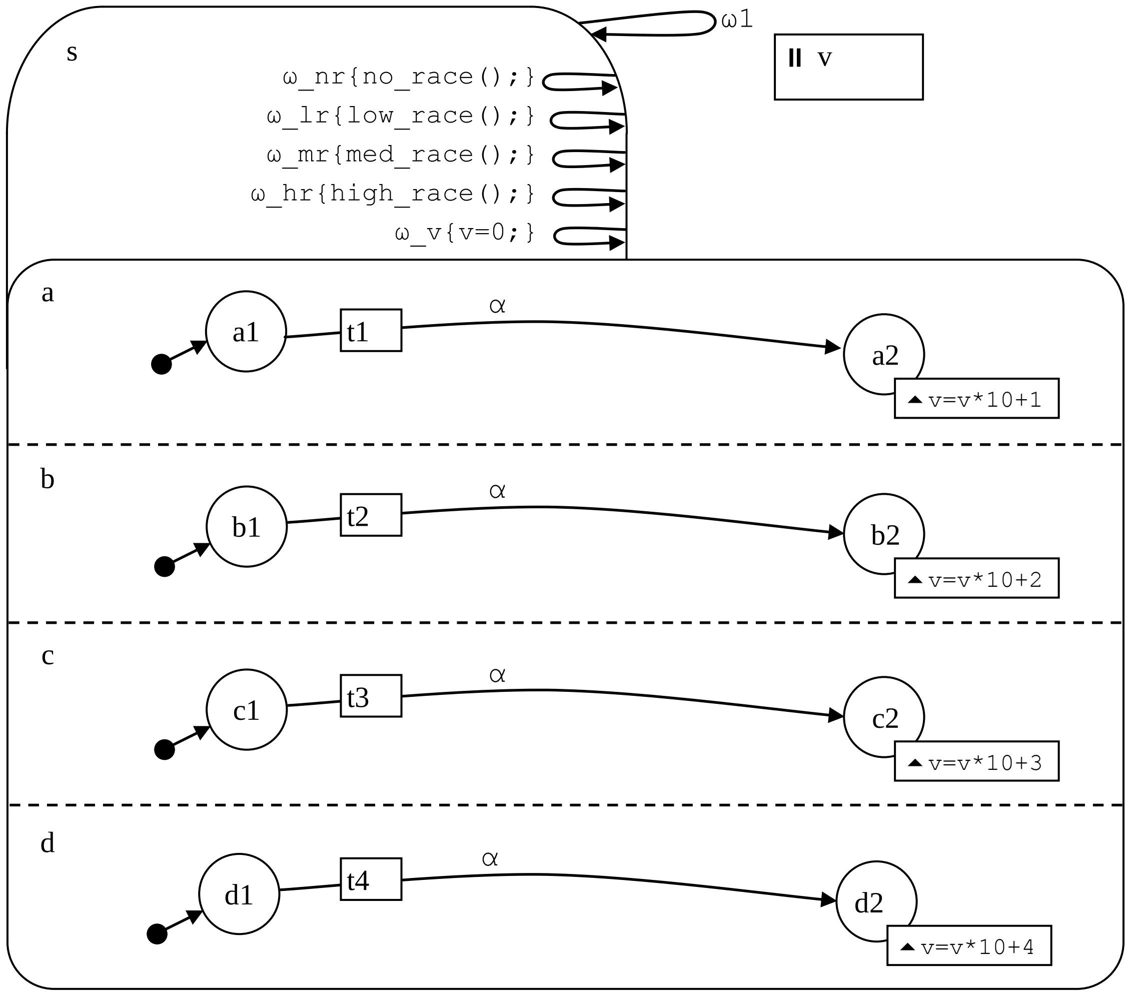


Figure 37. Limited race nondeterminism [model `t5520`]

The transitions are named, and the order of the raced transitions on event α is registered in variable `v` in the usual way. But before we run the race, we can either issue commands to control the race, or execute internal `ω_...` events to control the race. The options are

- ***No race:*** Use command `SC:`**`nr`** or event **`ω_nr`**. Only one ordering will be generated. The transition in the first set member will be executed first, then the one in the second set member etc. The transition order is `t1,t2,t3,t4`.

- ***Low race:*** Use command `SC:`**`lr`** or event **`ω_lr`**. Only two ordering will be generated. One is as above, and the other is the reverse of that order. The orderings are `t1,t2,t3,t4` and `t4,t3,t2,t1`.

- ***Medium race (default):*** Use command `SC:`**`mr`** or event **`ω_mr`**. The number of orderings generated is 2n. These orderings are all the cyclic and anticyclic rotation operations on the no-race ordering. The orderings are (cyclic):
  (t1,t2,t3,t4), (t2,t3,t4,t1), (t3,t4,t1,t2), (t4,t1,t2,t3),
  and (anticyclic):
  (t4,t3,t2,t1), (t3,t2,t1,t4), (t2,t1,t4,t3), (t1,t4,t3,t2).

- ***High race:*** Use command `SC:`**`hr`** or event **`ω_hr`**. All n! orderings are generated, i.e. 4! = 24 orderings in this case.

Call the file `race_control.scs.txt` in directory `u5520_race_control.` Prepare the hierarchy first and compile it (as already learned).

```
SC:root F:\KWinPro\StCr\StCr5ModelsUser\u5520_race_control
SC:cp race_control
```

The hierarchy is:

```
statechart sc(s)
   set s(a,b,c,d)
      cluster a(a1,a2)
         state a1;
         state a2;
      cluster b(b1,b2)
         state b1;
         state b2;
      cluster c(c1,c2)
         state c1;
         state c2;
      cluster d(d1,d2)
         state d1;
         state d2;
```

Add the declarations and transitions:

```
statechart sc(s)
event alpha;
event omega1, omega_v;
event omega_nr;
event omega_lr;
event omega_mr;
event omega_hr;

enum int1{0,..,10000};
int1 v=0;

   set s(a,b,c,d)         {omega1->s;                    \
                           omega_v  {v=0;};              \
                           omega_nr      {no_race();};   \
                           omega_lr      {low_race();};  \
                           omega_mr      {med_race();};  \
                           omega_hr      {high_race();}; }

      cluster a(a1,a2)
         state a1         {alpha->a2;}
         state a2         {upon enter {v=v*10+1;} }
      cluster b(b1,b2)
         state b1         {alpha->b2;}
         state b2         {upon enter {v=v*10+2;} }
      cluster c(c1,c2)
         state c1         {alpha->c2;}
         state c2         {upon enter {v=v*10+3;} }
      cluster d(d1,d2)
         state d1         {alpha->d2;}
         state d2         {upon enter {v=v*10+4;} }
```

Compile and run the model. The default setting is ***medium race***. Process event `alpha` and get the configuration. There are 8 worlds, distinguished by variable `v`, which reveals the transition ordering. For example, the last world has `v`=4321, which tells us that the transition ordering was t4, t3, t2, t1.

```
10   VAR  INTEGER v [sc] =2341
18   VAR  INTEGER v [sc] =3412
26   VAR  INTEGER v [sc] =4123
34   VAR  INTEGER v [sc] =1234
42   VAR  INTEGER v [sc] =3214
50   VAR  INTEGER v [sc] =2143
58   VAR  INTEGER v [sc] =1432
66   VAR  INTEGER v [sc] =4321
```

Reset the model (command **rm**) [or process events omega_v and omega1] and process event omega_lr. This is the ***low race*** option, and it gives 2 worlds. The transition orders are revealed by the values of variable v:

```
12   VAR  INTEGER v [sc] =1234
20   VAR  INTEGER v [sc] =4321
```

Reset the model and process event omega_nr. This is the ***no race*** option, and it gives 1 world. The transition orders are revealed by the value of variable v:

```
10   VAR  INTEGER v [sc] =1234
```

Reset the model and process event omega_hr. This is the ***high race*** option, and it gives 24 worlds. The transition orders are revealed by the values of variable v:

```
10   VAR  INTEGER v [sc] =1234
18   VAR  INTEGER v [sc] =2134
26   VAR  INTEGER v [sc] =1324
34   VAR  INTEGER v [sc] =3124
42   VAR  INTEGER v [sc] =2314
50   VAR  INTEGER v [sc] =3214
58   VAR  INTEGER v [sc] =1243
66   VAR  INTEGER v [sc] =2143
74   VAR  INTEGER v [sc] =1423
82   VAR  INTEGER v [sc] =4123
90   VAR  INTEGER v [sc] =2413
98   VAR  INTEGER v [sc] =4213
106  VAR  INTEGER v [sc] =1342
114  VAR  INTEGER v [sc] =3142
122  VAR  INTEGER v [sc] =1432
130  VAR  INTEGER v [sc] =4132
138  VAR  INTEGER v [sc] =3412
146  VAR  INTEGER v [sc] =4312
154  VAR  INTEGER v [sc] =2341
162  VAR  INTEGER v [sc] =3241
170  VAR  INTEGER v [sc] =2431
178  VAR  INTEGER v [sc] =4231
186  VAR  INTEGER v [sc] =3421
194  VAR  INTEGER v [sc] =4321
```

Reset the model and control the race nondeterminism on event alpha by STATECRUNCHER commands at the prompt:
SC:**nr**, SC:**lr**, SC:**mr**, SC:**hr**.

4.24 Limited set nondeterminism

We illustrate controlling *set-transit* nondeterminism, but the settings we will introduce will control *set-meta-event* and *set action* nondeterminism as well, since all these orderings are derived from the same source.

We will implement the following model:

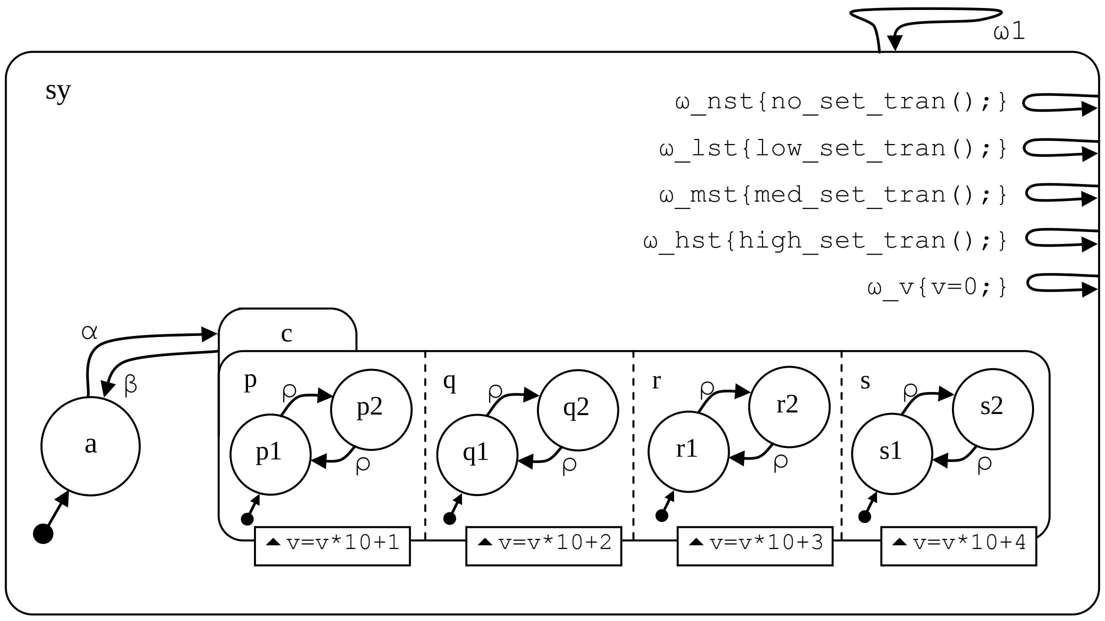


Figure 38. Limited set-transit nondeterminism [model `u5530`]

On entry into set `c`, four set members are entered, and the order in which this happens is recorded by variable `v` in the usual way. But before the set is entered, we can either issue commands to control the nondeterminism, or execute internal `ω_...` events to the same effect. The options are:

- ***No set transit nondeterminism:*** Use command `SC:`**`nst`** or event **`ω_nst`**. Only one ordering will be generated. The first-defined set member will be entered first, then the second set member etc. The entry order is `c1,c2,c3,c4`.

- ***Low set transit nondeterminism:*** Use command `SC:`**`lst`** or event **`ω_lst`**. Only two orderings will be generated. One is as above, and the other is the reverse of that order. The orderings are `c1,c2,c3,c4` and `c4,c3,c2,c1`.

- ***Medium transit set nondeterminism (default):*** Use command SC:**mst** or event **ω_mst**. The number of orderings generated is 2n. These orderings are all the cyclic and anticyclic rotation operations on the basic ordering. The orderings are (cyclic):
  (c1,c2,c3,c4), (c2,c3,c4,c1), (c3,c4,c1,c2), (c4,c1,c2,c3),
  and (anticyclic):
  (c4,c3,c2,c1), (c3,c2,c1,c4), (c2,c1,c4,c3), (c1,c4,c3,c2).

- ***High set transit nondeterminism:*** Use command SC:**hst** or event **ω_hst**. All n! orderings are generated, i.e. 4! = 24 orderings in this case.

Call the file `set_control.scs.txt` in directory `u5530_set_control`. Prepare the hierarchy first and compile it (as already learned).

```
SC:root F:\KWinPro\StCr\StCr5ModelsUser\u5530_set_control
SC:cp set_control
```

The hierarchy is:

```
statechart sc(sy)
   cluster sy(a,c)
      state a;
      set c(c1,c2,c3,c4)
         cluster c1(p1,p2)
             state p1;
             state p2;
         cluster c2(q1,q2)
             state q1;
             state q2;
         cluster c3(r1,r2)
             state r1;
             state r2;
         cluster c4(s1,s2)
             state s1;
             state s2;
```

Add the declarations and transitions:

```
statechart sc(sy)
enum int {0,..,100000};
int v=0;

event alpha, beta, rho, omega1, omega_v;
event omega_nst, omega_lst, omega_mst, omega_hst;

   cluster sy(a,c)        {omega1->sy;                    \
                           omega_v     {v=0;};            \
                           omega_nst   {no_set_tran();};   \
                           omega_lst   {low_set_tran();};  \
                           omega_mst   {med_set_tran();};  \
                           omega_hst   {high_set_tran();}; }

      state a              {alpha->c;  }

      set c(c1,c2,c3,c4)   {beta->a; }
         cluster c1(p1,p2) {upon enter {v=v*10+1;} }
             state p1      {rho->p2; }
             state p2      {rho->p1; }
         cluster c2(q1,q2) {upon enter {v=v*10+2;} }
             state q1      {rho->q2; }
             state q2      {rho->q1; }
         cluster c3(r1,r2) {upon enter {v=v*10+3;} }
             state r1      {rho->r2; }
             state r2      {rho->r1; }
         cluster c4(s1,s2) {upon enter {v=v*10+4;} }
             state s1      {rho->s2; }
             state s2      {rho->s1; }
```

Compile the model. The default setting is ***medium set tran***. Process event `alpha` and get the configuration. There are 8 worlds, distinguished by variable `v`, which reveals the ordering of set member entry. For example, the last world has v=1234, which tells us that the ordering of set member entry was c1, c2, c3, c4.

```
7    VAR  INTEGER v [sc] =1432
11   VAR  INTEGER v [sc] =2143
15   VAR  INTEGER v [sc] =3214
19   VAR  INTEGER v [sc] =4321
23   VAR  INTEGER v [sc] =4123
27   VAR  INTEGER v [sc] =3412
31   VAR  INTEGER v [sc] =2341
35   VAR  INTEGER v [sc] =1234
```

Reset the model (command **`rm`**) [or process events `omega_v` and `omega1`] and process event `omega_lst`. This is the ***low set transit*** option, and it gives 2 worlds. The set member entry orderings are revealed by the values of variable `v`:

```
7    VAR  INTEGER v [sc] =4321
11   VAR  INTEGER v [sc] =1234
```

Reset the model and process event `omega_nr`. This is the ***no set transit*** option, and it gives 1 world. The set member entry ordering is revealed by the value of variable `v`:

```
7    VAR  INTEGER v [sc] =1234
```

Reset the model and process event `omega_hst`. This is the ***high set transit*** option, and it gives 24 worlds. The set member entry orderings are revealed by the values of variable `v`:

```
7    VAR  INTEGER v [sc] =4321
11   VAR  INTEGER v [sc] =4312
15   VAR  INTEGER v [sc] =4231
19   VAR  INTEGER v [sc] =4213
23   VAR  INTEGER v [sc] =4132
27   VAR  INTEGER v [sc] =4123
31   VAR  INTEGER v [sc] =3421
35   VAR  INTEGER v [sc] =3412
39   VAR  INTEGER v [sc] =3241
43   VAR  INTEGER v [sc] =3214
47   VAR  INTEGER v [sc] =3142
51   VAR  INTEGER v [sc] =3124
55   VAR  INTEGER v [sc] =2431
59   VAR  INTEGER v [sc] =2413
63   VAR  INTEGER v [sc] =2341
67   VAR  INTEGER v [sc] =2314
71   VAR  INTEGER v [sc] =2143
75   VAR  INTEGER v [sc] =2134
79   VAR  INTEGER v [sc] =1432
83   VAR  INTEGER v [sc] =1423
87   VAR  INTEGER v [sc] =1342
91   VAR  INTEGER v [sc] =1324
95   VAR  INTEGER v [sc] =1243
99   VAR  INTEGER v [sc] =1234
```

Reset the model and control the set transit nondeterminism on event `alpha` by STATECRUNCHER commands at the prompt:
`SC:`**`nst`**, `SC:`**`lst`**, `SC:`**`mst`**, `SC:`**`hst`**.

4.25 Independence of race and set-transit control

Go back to section 4.21 on multiple nondeterminism and run the model there:

- with default settings, which will give (medium) race and set nondeterminism (8 worlds produced)
- with set nondeterminism but no race (4 worlds produced)
- with race nondeterminism but no set-transit (4 worlds produced)
- with neither (2 world produced, due to fork nondeterminism).

Fork nondeterminism can only be “switched off” by removing or invalidating the forks that are to be ignored in the model source code itself.

4.26 Pruning on the basis of traces

We have seen how traces work (section 4.11). The reader can imagine how after a test, there might be several worlds in existence, of which only a few correspond to the behaviour of an IUT (Implementation Under Test). The test control program would accept the test a pass as long as there was at least one world that did match the IUT. It would kill the other worlds with the kill command, e.g.

```
  SC:kill 6
```

would kill world 6.

But there is a more efficient way, first suggested by Tim Trew. An event is sent to the IUT first and the actual traces are obtained. Then STATECRUNCHER is asked to process an event, and is at the same time given the expected trace. The high-level syntax of the *process event* command is as follows (a question mark introduces an optional parameter):

```
pe EVENT  ?p=PARAMETERS  ?t=EXPECTEDTRACE
```

STATECRUNCHER will automatically, on the fly, kill worlds in direct violation of *EXPECTEDTRACE*. As an initial conservative approach, *overtrace* and *undertrace* are tolerated. Overtrace is where too much trace is produced by STATECRUNCHER, but where the IUT trace matches the leading part of it. Undertrace is where not enough trace is produced by STATECRUNCHER, but it matches the leading part of the IUT trace. This will be seen in the following model, which we will implement.

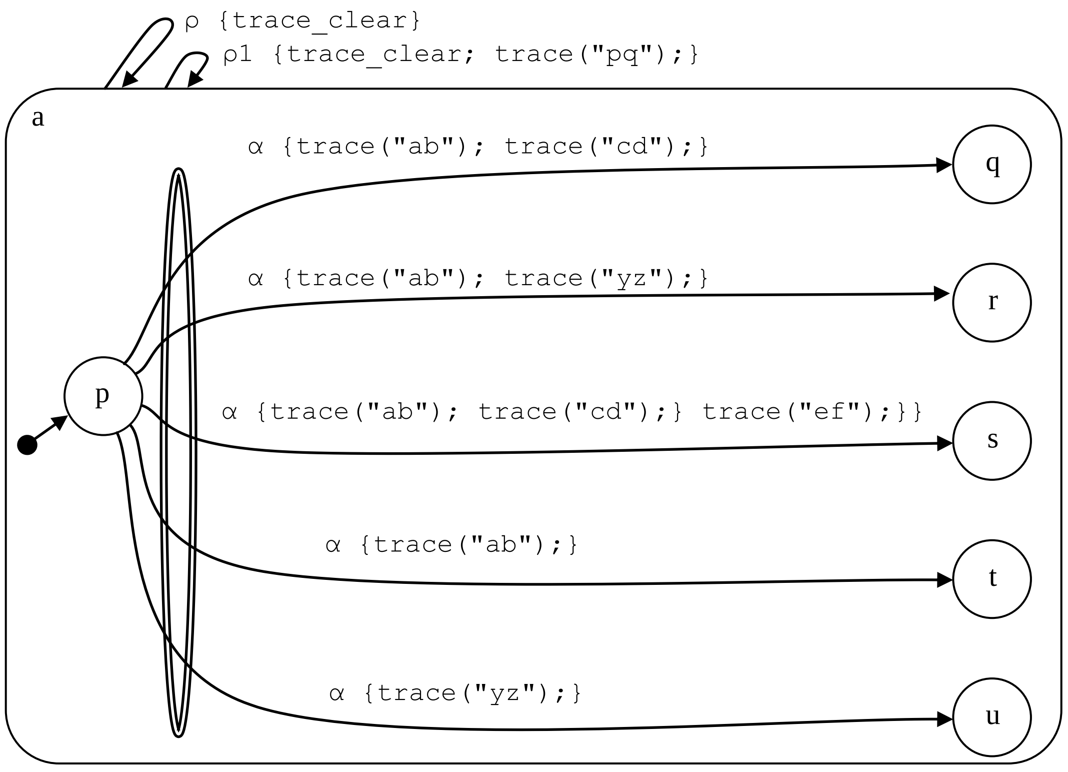

ρ {trace_clear}
ρ1 {trace_clear; trace("pq");}
a
α {trace("ab"); trace("cd");}
q
α {trace("ab"); trace("yz");}
r
p
α {trace("ab"); trace("cd");} trace("ef");}}
s
α {trace("ab");}
t
α {trace("yz");}
u

Figure 39. Pruning on the basis of traces [model u5550]

Call the file `prune_traces.scs.txt` in directory `u5550_prune_traces`. Prepare the hierarchy first and compile it (as already learned).

```
   SC:root F:\KWinPro\StCr\StCr5ModelsUser\u5550_prune_traces
   SC:cp prune_traces
```

The hierarchy is:

```
statechart sc(a)
cluster a(p,q,r,s,t,u)
   state p;
   state q;
   state r;
   state s;
   state t;
   state u;
```

Add the declarations and transitions:

```
statechart sc(a)
event alpha, rho, rho1;

cluster a(p,q,r,s,t,u){rho->a{trace_clear();};                  \
                       rho1->a{trace_clear(); trace("pq");  };  }

   state p {alpha->q {trace("ab"); trace("cd");              }; \
            alpha->r {trace("ab"); trace("yz");              }; \
            alpha->s {trace("ab"); trace("cd"); trace("ef"); }; \
            alpha->t {trace("ab");                           }; \
            alpha->u {trace("yz");                           }; }
   state q;
   state r;
   state s;
   state t;
   state u;
```

Compile the model and process event `alpha`. The different worlds are distinguished by trace and state, but the traces will determine our course of action.

```
4    TRACE =[yz]
6    TRACE =[ab]
10   TRACE =[ef, cd, ab]
13   TRACE =[yz, ab]
16   TRACE =[cd, ab]
```

Remember that traces are read from right to left when read from oldest to newest item. Suppose the IUT gives a trace of `[cd,ab]`. One trace above matches this, one has overtrace `[ef,cd,ab]`, and one has undertrace `[ab]`. Two directly violate the trace: `[yz]` and `[yz,ab]`.

Reset the model and give command

```
SC:pe alpha t=[cd,ab]
```

Then get the configuration. There are 3 worlds, with traces as shown

```
6    TRACE =[ab]
10   TRACE =[ef, cd, ab]
16   TRACE =[cd, ab]
```

The worlds with a trace match, or overtrace, or undertrace, are kept. Normally, only the world with an exact match would be kept, but one could imagine an IUT capable of spontaneously producing more trace, so justifying keeping STATECRUNCHER'S worlds with overtrace. Some creative use of a model might reverse the situation, requiring undertrace to be kept. We can in any case kill worlds 6 and 10 if we wish, as follows:

```
kill [6,10]
```

That leaves one world, which we show in full:

```
16   statechart sc
16      cluster a [sc] = OCC []  **
16         leafstate p [a, sc] = VAC []
16         leafstate q [a, sc] = OCC []  **
16         leafstate r [a, sc] = VAC []
16         leafstate s [a, sc] = VAC []
16         leafstate t [a, sc] = VAC []
16         leafstate u [a, sc] = VAC []
16   TRACE =[cd, ab]
16   TREV [[rho, [sc]], 0, [], []]
16   TREV [[rho1, [sc]], 0, [], []]

outworlds=[16]
number of outworlds=1
```

If we kill this world

```
kill 16
```

then we are left with no worlds at all, and the model is dead. It can be reset by the `rm` command, but this is not equivalent to processing an event. In testing, this situation will almost certainly represent detecting a defect, perhaps a design defect, and might represent deadlock.

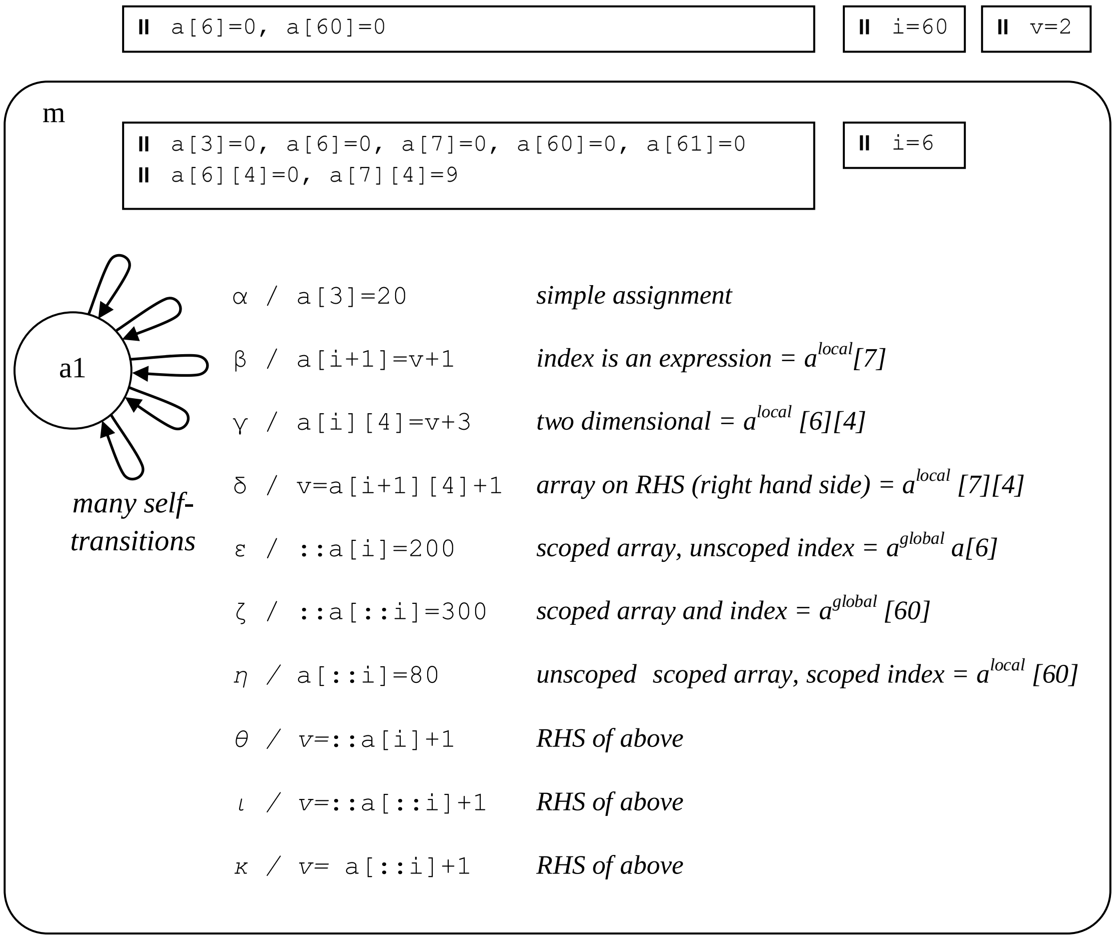
```
SC:gc
outworlds=[]
number of outworlds=0
SC:
```

4.27 Arrays

A provisional implementation of arrays is available (unscoped in Release 1.04, allowing scoping in Release 1.05). Array *indices* must be nonnegative integers. *Arrays* can be of type boolean, declared integer type, or string. Internally, and in output, array elements are given a constructed double underscore name, as will be seen, and the user should avoid declaring any other variables that would clash with this.

IMPORTANT: The user is required to declare the array name as a scalar (i.e. without square brackets), and any elements (with square brackets) that might be used in the model.

We will implement the following model:



ll a[6]=0, a[60]=0
ll i=60
ll v=2
m
ll a[3]=0, a[6]=0, a[7]=0, a[60]=0, a[61]=0
ll a[6][4]=0, a[7][4]=9
ll i=6
a1
many self-transitions
α / a[3]=20 simple assignment
β / a[i+1]=v+1 index is an expression = a^local[7]
γ / a[i][4]=v+3 two dimensional = a^local [6][4]
δ / v=a[i+1][4]+1 array on RHS (right hand side) = a^local [7][4]
ε / ::a[i]=200 scoped array, unscoped index = a^global a[6]
ζ / ::a[::i]=300 scoped array and index = a^global [60]
η / a[::i]=80 unscoped scoped array, scoped index = a^local [60]
θ / v=::a[i]+1 RHS of above
ι / v=::a[::i]+1 RHS of above
κ / v= a[::i]+1 RHS of above

Figure 40. Arrays [model `u5581`]

There are two arrays called `a` in this model in different scopes, a global one in scope, `[sc]`, and a local one in scope `[m,sc]`. There are also two variables called `i` in these two scopes, which will be used to index the arrays.

Call the file `arrays.scs.txt` in directory `u5581_arrays.` Prepare the hierarchy first and compile it (as already learned).

```
  SC:root F:\KWinPro\StCr\StCr5ModelsUser\u5581_arrays
  SC:cp arrays
```

The hierarchy is:

```
statechart sc(m)
  cluster m(a1)
    state a1;
```

Add the declarations and transitions:

```
statechart sc(m)
event alpha, beta, gamma, delta, epsilon, zeta;
event eta, theta, iota, kappa;
enum int {0,..,1000};

// ARRAY BASES MUST BE DECLARED
int    a, a[6]=0, a[60]=0, i=60, v=2;             // GLOBAL

  cluster m(a1)
    int a, a[3]=0, a[6]=0,    a[7]=0,    a[60]=0; // LOCAL
    int a[61]=0,   a[6][4]=0, a[7][4]=9, i=6;     // LOCAL
    state a1 {alpha   {a[3]=20;};          \
              beta    {a[i+1]=v+1;};       \
              gamma   {a[i][4]=v+3;};      \
              delta   {v=a[i+1][4];};      \
              epsilon {::a[i]=200;};       \
              zeta    {::a[::i]=300;};     \
              eta     {a[::i]=80;};        \
              theta   {v=::a[i]+1;};       \
              iota    {v=::a[::i]+1;};     \
              kappa   {v=a[::i]+1;};       }
```

Compile the model. Process event `alpha` and get the configuration. Element 3 of the local array `a`, i.e. in scope `[m,sc]`, is assigned the value 20.

```
4    VAR  INTEGER a__3 [m, sc] =20
```

Process event `beta`. Element `[i+1]`, referring to the local `i`, of the local array `a` is assigned the value `v+1`. Since `i=6` and `v=2`, we effectively have `a[7]=3`.

```
6    VAR  INTEGER a__7 [m, sc] =3
```

Process event `gamma`. The effective assignment is `a[6][4]=5` to the local array `a`.

```
8    VAR  INTEGER a__6__4 [m, sc] =5
```

Process event `delta`. We now have the array on the right hand side of an assignment. The effective assignment is `v=a[7][4]`. We initialised this element to 9.

```
10   VAR  INTEGER v [sc] =9
```

Process event `epsilon`. The scoping operator causes the global a, with scope `[sc]`, to be addressed. But the index is the local `i`, which has the value 6.

```
12   VAR  INTEGER a__6 [sc] =200
```

Process event `zeta`. Both array and index are the global ones. The global `i` has value 60.

```
14   VAR  INTEGER a__60 [sc] =300
```

Process event `eta`. The array is local but the index is global. The global `i` has value 60.

```
16   VAR  INTEGER a__60 [m, sc] =80
```

Process event `theta`. Here we assign to `v` with an array term as in event `epsilon` above.

```
18   VAR  INTEGER v [sc] =201
```

Process event `iota`. Here we assign to `v` with an array term as in event `zeta` above.

```
20   VAR  INTEGER v [sc] =301
```

Process event `kappa`. Here we assign to `v` with an array term as in event `eta` above.

```
22   VAR  INTEGER v [sc] =81
```

4.28 What else is there to STATECRUNCHER?

We have covered all the important features used in models. There are reference pages on the syntax, on expression operators, and on functions in section 8. There are reports covering STATECRUNCHER's algorithms, listed in section 11.

We have kept this manual to what is needed for normal model design. An advanced user may wish to add a function for use in expressions in a model. This requires a knowledge of Prolog, and of how functions are handled in STATECRUNCHER, described in [StCrGP4].

Another area of STATECRUNCHER is its command language. We have mentioned the commands needed for ordinary model usage: compiling, processing events, getting the configuration etc. In fact the commands provided make much more possible, e.g. efficiently flattening a state space, and providing for intelligent transition tours, but this would normally be done under control of a powerful separate program connected to STATECRUNCHER, and we do not discuss such possibilities here. Section Table 4 contains a summary of all STATECRUNCHER's commands, and [StCrPrimer] discusses them in more detail.

Another discipline that needs to be mastered is how to use STATECRUNCHER on real software components. This is the subject of investigation at Philips Research as STATECRUNCHER is trialled. It is often not trivial produce a good dynamic model of a software component - it requires skill and experience. Once a model has been obtained, it is not generally such a difficult task to represent it in STATECRUNCHER, though certain aspects of software behaviour may present a challenge, and may suggest that extensions to STATECRUNCHER would be desirable in the future.

5. Modelname mode

This is a mode of working that is convenient when giving demonstrations of many models, since the models can be referenced by a short model name, which is attached via a table in STATECRUNCHER to the full path and file name of the model.

Modelname mode is not applicable to the MS-DOS executable version of STATECRUNCHER, although pre-included demonstration models can be run this way using STATECRUNCHER's `root` command to set the equivalent of the boot directory.

5.1 To prepare your file and an index to it

Create your file and give it the "STATECRUNCHER source" extension `.scs.txt` – e.g. `DualWindow.scs.txt` or `hier.scs.txt`

Locate the file somewhere below the `StCr4ModelsCE` subdirectory, or in a same-level subdirectory with your own name.

Edit (the equivalent to) file
`P:\KWinPro\StCr2Sand\ci_sc\`**`ci_sc_2.pl`**.
This is a user file; the **`ci_sc_1.pl`** file is now reserved for STATECRUNCHER test/demo models (and for the `ci_current` setting, concerning which see below).

You will see some existing file references such as

```
  ci_file(c710, '..\StCr4ModelsCe\Ce700\c710_CoreTV\CoreTVexample').
```

Choose an index to your file. Do not use indices of the form `t`*nnnn*, such as `t`*`5230`*, as the `t` series is reserved for STATECRUNCHER tests. Avoid a clash with existing indices.

Create an index entry in an analogous way to the existing ones. The path is with respect to the root defined in the boot file, and starts by going up a level and then down into the set of models we are concerned with. ***Exclude the*** **`.scs.txt`** ***extension*** (as is the case for the existing references).

Edit the file **`ci_sc_1.pl`** which is in the same directory as the **`ci_sc_2.pl`** file. Make your file current by canceling or deleting any existing `ci_current` predicate and enabling your setting. You can cancel by prefixing `xx` or by deleting the line. Example:

```
xxci_current(t5410).
  ci_current(c770).
```

The full stops are important.

Unused `ci_file`... lines do not need to be cancelled.

5.2 Using modelname mode

Having modified the ci_sc files as instructed, run STATECRUNCHER in the normal way. At the STATECRUNCHER prompt, enter

```
  SC: mm
```

Now models can be compiled and run using commands such as

```
  SC: cp t5110          a test/demo model
  SC: run t5110
  SC: cp c710           a user model
  SC: run c710
```

To reset the mode to filenames, enter

```
  SC: mf
```

6. The STATECRUNCHER Release 1.02 loop

The Release 1.02 command loop has been superseded by a richer command language to STATECRUNCHER, but is still available in later releases to date.

6.1 To prepare a model

Models are prepared as described in Ch. 5, Modelname mode.

6.2 To compile and validate your file

<u>Step 0. Boot-load.</u>
Boot-load Prolog and STATECRUNCHER. The boot-loading will include loading the new `ci_sc_1.pl` and `ci_sc_2.pl` files. Scroll across all output and check there are no Prolog error messages. Then scroll back to the Prolog prompt (`?-`) or STATECRUNCHER prompt (`SC:`). If you have a STATECRUNCHER prompt, exit it with command `quit` to get to a Prolog prompt.

<u>Step 1. Compile the model source</u>
Against the Prolog prompt, type **`scb.`** (Think of this as "**S**tate**C**runcher **B**uild"). Note that all Prolog "queries" end with a full stop. You can also compile a non *ci_current* model by entering `scb(`*`modelindex`*`).`

If the file cannot be found, fix the file reference in the `ci_sc_2.pl` file and start again. If there are compilation or validation errors, correct them before proceeding. There is no need to re-boot STATECRUNCHER as you correct errors - just edit and "`scb.`" as necessary.

Compilation produces a Prolog-readable "object" file with extension `.sco.pl` and a listing file with extension `.scl.txt` in the same directory as the model source file. This is loaded, and if there are no errors, the validation phase is started, which produces a Prolog-readable data file with extension `.scd.pl` and a listing file with extension `.scv.txt`.

6.3 Exercising models

When you have compiled and validated a model, you can type

- `craft(`*`modelnumber`*`).`
  e.g. `craft(t5420).`   Remember the full stop.

- `craftnp(`*`modelnumber`*`).`
  e.g. `craftnp(t5420).`   Remember the full stop.

- `craft.`
  This is equivalent to running `craft` with the `ci_current` number.

- `craftnp.`
  This is equivalent to running `craftnp` with the `ci_current` number.

The `craft` command loads a (compiled and validated) model, enters the machine, and shows the state and what events can be processed. It requires two items of input per top-level event processing cycle:
- an event
- parameters to the event

The `craftnp` command assumes that no parameters are required, and only requires an event.

Note that the input must consist of Prolog-readable terms and so must end with a full-stop. There are various options.

For an event:
- Enter the full form, including the scope in right-to-left form, e.g. `[alpha,[aa,sc]].` This event has a local scope to a set or cluster `aa` in statechart `sc`.
- Enter the event name only, e.g. `alpha.` The scope is assumed to be `[sc]` - so this is a good option if you call your statecharts "`sc`".
- The input `quit.` is reserved to stop the processing cycle. So try to avoid using an event `quit` in your models, otherwise you must enter `[quit,[sc]].`

For parameters:
- Enter `[].` if you do not require parameters to this event
- You can enter the integers in a list (followed by a dot), (0=for false, 1 for true), e.g. `[0,2].`
- For one parameter, you can just enter the integer (followed by a dot), e.g. `2.`
- You can enter the full form: a list of STATECRUNCHER-wrapped constants or strings, (followed by a dot), e.g.
  `[[ex_co,int,1],[ex_co,int,0],[ex_str,[41,42]].`

7. The socket version of STATECRUNCHER

The socket version is a special version used by Philips Research India - Bangalore to enable STATECRUNCHER to communicate with a Linux machine on which TorX runs.

The socket version is currently only available with the Release 1.02 command loop, running under SWI-Prolog. The Release 1.02 loop is available as a legacy facility in later releases to date.

To load the socket version, change the `aux_load_sc.pl` file to load

```
cs_sc_8_socket.pl
```

rather than

```
cs_sc_8.pl
```

Then run under SWI-Prolog by double clicking on

```
boot_sc_swipro_win.pl
```

To exit STATECRUNCHER's command loop and run as in Release 1.02, exit as follows:

```
SC:mm
SC:quit
```

The `mm` command is needed, because without it, STATECRUNCHER will interpret model arguments as filenames, not model names.

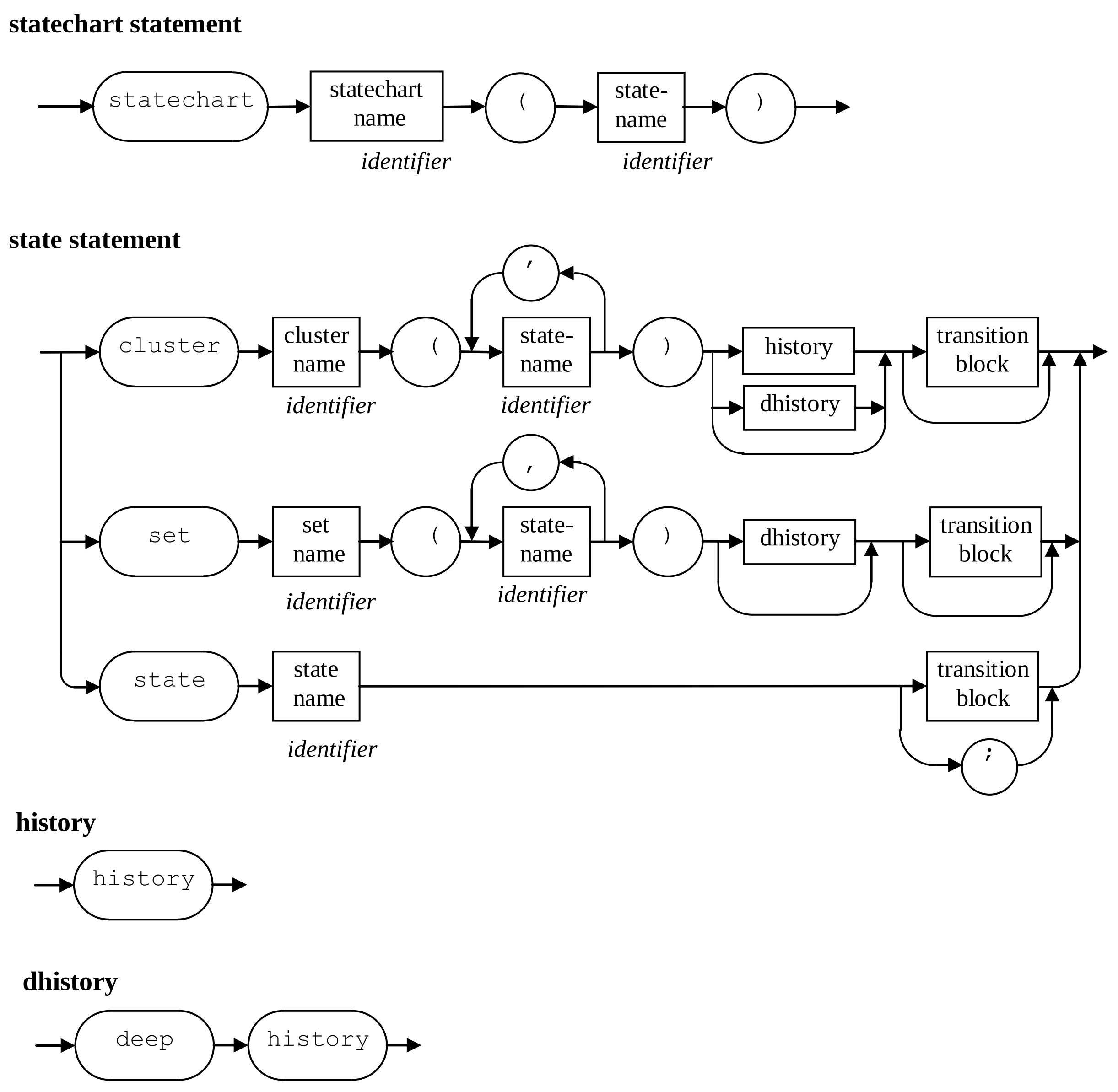
Then you can execute Prolog goals `craft` or `craftnp` as in release 1.02.

The socket functionality is not available under the executable version, or WinProlog.

8. Reference for STATECRUNCHER syntax

The following reference grammar is given in railroad form.

8.1 Declarations and an overview of *state* statements



<u>Note</u>

The **transition block** will be described later; note that it is optional.

Figure 41. Basic syntax of statechart / cluster / set and (leaf-)states

8.2 Transitions

The following figures give a functional overview and then the syntax of the transition block. The syntax is given in railroad diagram form where iterations are represented where convenient by feed-backward constructions. This representation has been converted into a purely feed-forward representation (not shown here) so that Prolog Definite Clause Grammar (DCG) rules can be used as a parser.

A transition block is defined in the context of the source state of the transition. The ***enter block*** and ***exit block*** pertain to that source state rather than the transition proper; they contain actions to be executed whenever that state is entered or exited respectively. Transitions are triggered by ***meta-events***, i.e. ordinary declared events or internal events generated whenever a state is entered or exited. Transitions can be ***conditional*** on the value of an expression yielding a boolean. The ***action block*** per transition contains actions that accompany the transition whenever it takes place; the actions can be conditional too.

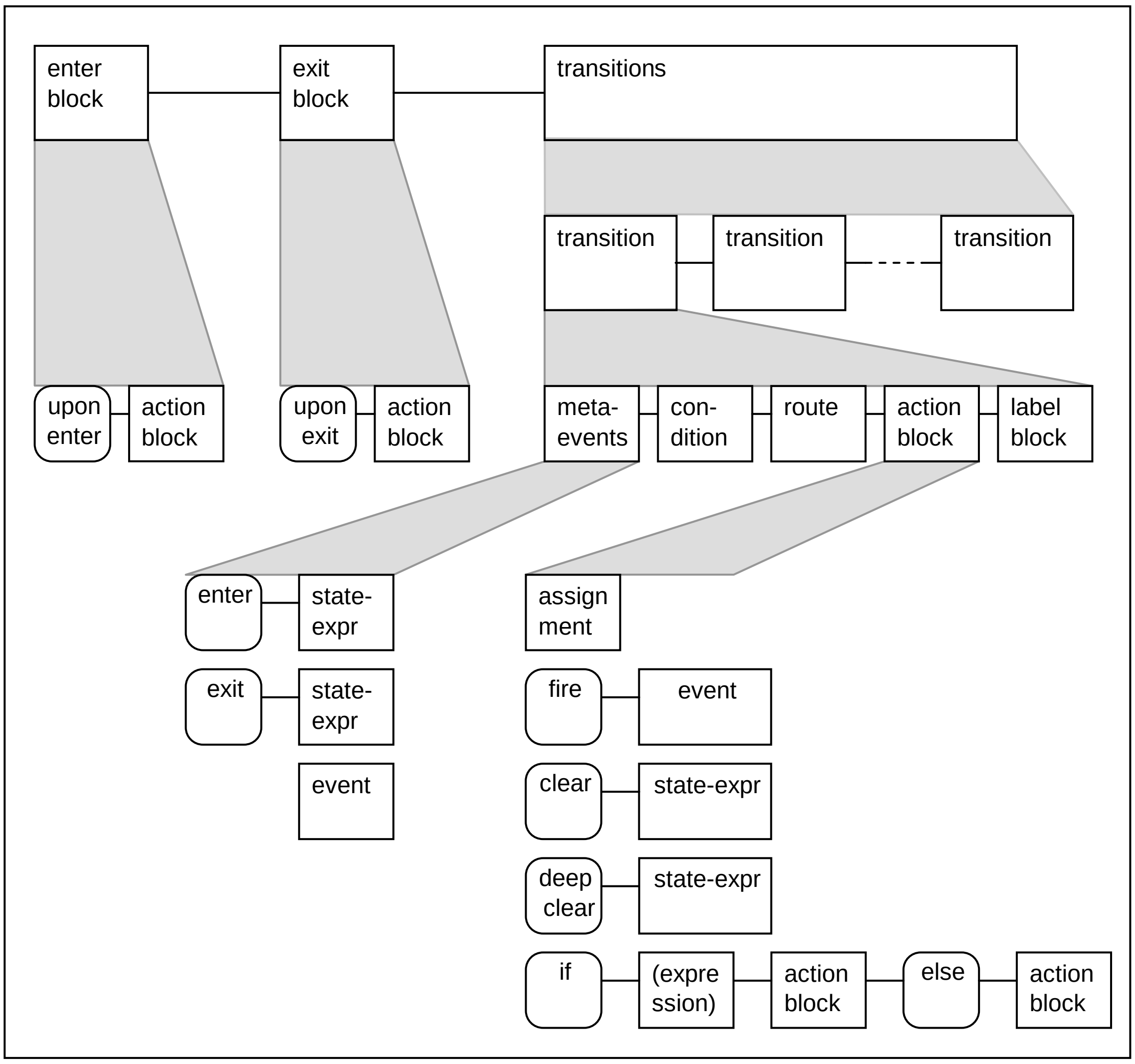


Figure 42. Overview of transition block (functional blocks rather than syntax)

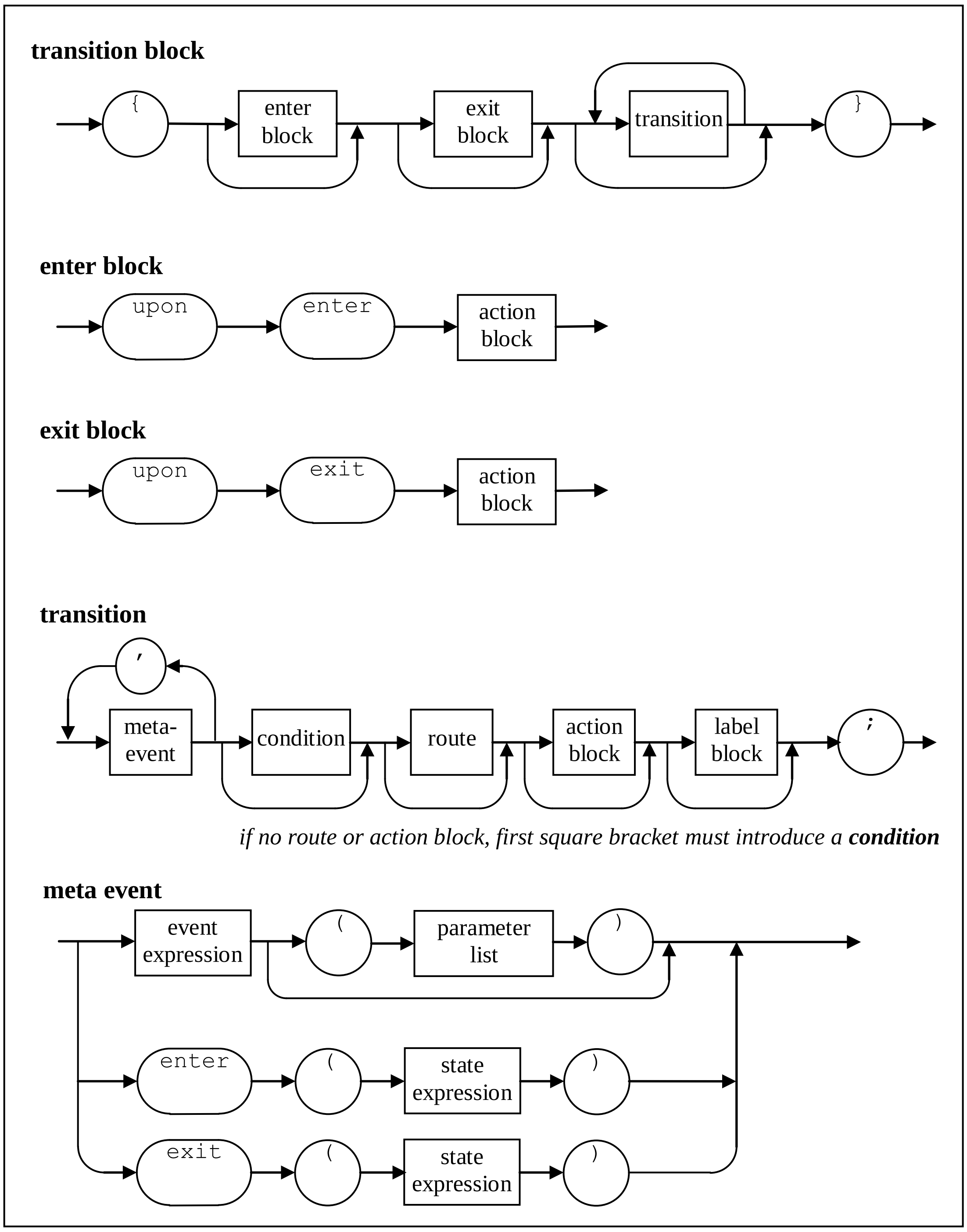


Figure 43. Overview of transition block syntax (1)

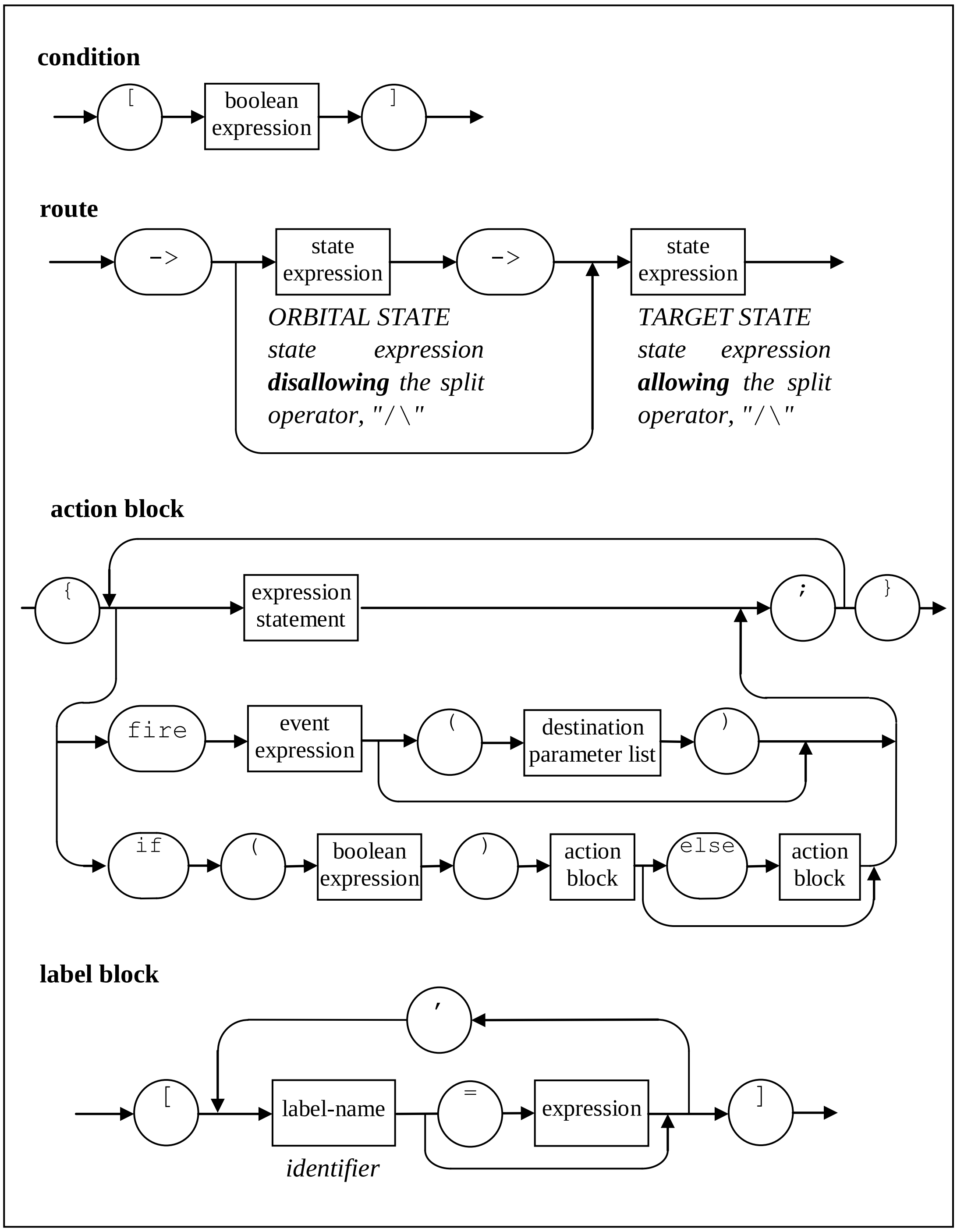


Figure 44. Overview of transition block syntax (2)

8.3 Arithmetic operators

Operation	Symbol	Arity	Precedence	Associativity	Position
Primary Suffixes					
Array indexing	[]	dyadic	18	none	circumfix
Function call	()	dyadic	17	none	circumfix
Various monadic					
plus	+	monadic	16	right	prefix
minus	−	monadic	16	right	prefix
logical not	!	monadic	16	right	prefix
post increment		monadic	16	left	postfix
post decrement		monadic	16	left	postfix
pre increment		monadic	16	left	postfix
pre decrement		monadic	16	left	postfix
Multiplicative					
multiplication	*	dyadic	15	left	infix
division	/	dyadic	15	left	infix
modulo	%	dyadic	15	left	infix
Additive					
addition	+	dyadic	14	left	infix
subtraction	−	dyadic	14	left	infix
Relational					
less than or equal	<=	dyadic	12	left	infix
greater than or equal	>=	dyadic	12	left	infix
less than	<	dyadic	12	left	infix
greater than	>	dyadic	12	left	infix
equal	==	dyadic	12	left	infix
not equal	!=	dyadic	12	left	infix
Logical					
short-circuit and	&&	dyadic	7	left	infix
xor	^^	dyadic	6	left	infix
equivalence	!^^	dyadic	6	left	infix
short-circuit or	||	dyadic	5	left	infix
Assignment					
assign	=	dyadic	2	right	infix

multiply-assign	`*=`	dyadic	2	right	infix
divide-assign	`/=`	dyadic	2	right	infix
modulo-assign	`%=`	dyadic	2	right	infix
add-assign	`+=`	dyadic	2	right	infix
subtract-assign	`-=`	dyadic	2	right	infix

Table 1. Arithmetic operators

8.4 Scoping operators

General design

Various items in STATECRUNCHER can be declared or accessed outside their natural scope by means of scoping operators. These operators can be used to form scoping expressions.
The operators (with their implementation names) are:

- `$` (parent) back out one level from the current scope
- `%%` (ancestor) back out to a named parent
- `::` (statechart scope) back out to the outermost level
- `.` (child) enter one named level deeper

The parent operator "$"

This is a monadic operator. The term "`$a`" means: "`a`" as it would be accessed if addressed in the hierarchical state one level more global than the current one. This operator is right associative, so "`$$$a`" takes us back three levels.

The ancestor operator "%%"

This is a dyadic operator. The term "`a%%b`" means: back out of the current level until a hierarchical machine named "`a`" is found. At least one level is always backed out. Then address "`b`" in that level. The operator is right associative, so that the expression "`a%%b%%c`" reads: back out to level "`a`", then back out from there to level "`b`", and evaluate "`c`" in that scope.

The statechart scope operator "::"

This is a monadic operator. The term "`::a`" means: address "`a`" at the statechart level.

The child operator "."

This is a dyadic operator. The term "`a.b`" means: enter the immediately deeper hierarchical level "`a`" and address "`b`" in that scope. The operator is right associative, which means that the expression "`a.b.c`" reads: enter "`a`", then "`b`" and address "`c`" in that scope.

Combining scoping operators

The monadic and dyadic operators combine with dyadic operations binding tighter.

Effect of scoping operators on declarations
Scoping operators can be used when *accessing* (rather than *declaring*) any item, i.e. PCO's, events, tagnames and variables and states.

Scoping operators can be used in *declarations* of PCO's, events, tagnames and variables (but not states). They have the effect of declaring the item as if it were an ordinary declaration in another part of the hierarchy. For example, to declare various items as if they all belonged one level up in the hierarchy:

```
PCO $pco1;
event $alpha;
enum $colour {red=1,green=3,blue=4};
$colour $mycolour;
```

In the variable declaration

```
$colour $mycolour;
```

the variable has a scope determined by its own scoping expression, and a type affected by the scoping expression on its tagname.

Operation	Symbol	Arity	Precedence	Associativity	Position
parent scope	`$`	monadic	19	right	prefix
statechart scope	`::`	monadic	19	right	prefix
named child scope *(evaluate arg2 in child arg1 scope).*	`.`	dyadic	20	right	infix
named ancestor scope *(evaluate arg2 in ancestor arg1 scope, backing out one level anyway, and then as far as the first occurrence of arg1).*	`%%`	dyadic	20	right	infix

Table 2. Scoping operators

8.5 The split operator

This operator is used to define multiple target states.

Operation	Symbol	Arity	Precedence	Associativity	Position
split	`/\`	dyadic	14	left	infix

Table 3. The split operator

8.6 Functions

Arguments are a comma separated list of expressions. P1, P2 refer to the first and second parameter respectively. The return value is an integer (which may represent a boolean), or string value.

Basic arithmetic	
abs(P1)	absolute value of a number
maximum(list)	maximum of several numbers, e.g. i=maximum(v1,v2+1,v3)
minimum(list)	minimum of several numbers, e.g. i=minimum(v1,v2+1,v3)
String related	
format(P1,P2)	Format integer expression P1 as text. P2 is the field width: -ve for left justify, 0 for just fit, +ve for right justify.
length(P1)	length of string
lower_case(P1)	convert string to lower case
upper_case(P1)	convert string to upper case
Casting	
cast(P1)	i=cast(j) allows an assignment that would otherwise be a type mismatch
Tracing	
trace(list)	add parameter(s) to the trace list
trace_clear()	clear the trace list
System information	
get_nworlds(P1)	get_nworlds() or get_nworlds(1) gets the number of worlds at the start of event processing. get_nworlds(2) gets the dynamic number of worlds.
Nondeterminism control	
no_race()	turn race nondeterminism off
low_race()	allows only two race permutations, forwards and backwards.
med_race()	allows 2N race permutations. Allows distinction of all triplet orderings
high_race()	allows all N! race permutations
no_set_tran()	turn set (e.g. set-transit) nondeterminism off
low_set_tran()	allows only two set permutations, forwards and backwards.
med_set_tran()	allows 2N set permutations. Allows distinction of all triplet orderings
high_set_tran()	allows all N! set permutations
Special functions taking a state-expression argument	
in(P1)	returns true (=1) if the state specified is occupied, else false (=0)
clear(P1)	clear history of the state specified
deep_clear(P1)	clear history of the state specified and its descendants

Table 4. Functions

9. Reference for STATECRUNCHER commands

The table below shows abbreviated commands as well as unabbreviated ones. Where abbreviated ones are not available, the arrow (→) refers the reader to the unabbreviated one.

Meta-syntax: An optional argument to a command is preceded by a question mark, (*?*). Normal `courier` indicates a literal item; *italics* indicate a non-literal or explanation. A choice is indicated by a vertical bar (|).

The important commands that were not possible in previous releases of STATECRUNCHER are those that allow setting of state occupancies and variables and traces. These make a state-space exploration algorithm possible. These are

- *WORLD STATEKIND STATENAME MPATH = OCCUPANCY HISTORY*
- *WORLD* `VAR` *VARKIND VARIABLENAME MPATH = VALUE*
- *WORLD* `TRACE` = *TRACE*

These commands are in STATECRUNCHER's own output format.

Abbrev. Command	Command *showing typical example and/or typical output*

Main processing: high priority black box testing commands

`pe ...`	**`process event`** *EVENT ?***`p=`***PARAMETERS ?***`t=`***EXPECTEDTRACE***
	 `pe gamma         p=[4,xy]` *(statechart scope assumed)*
	 `pe [alpha,[sc]] p=1`
	 `pe [alpha,[sc]]`
	 Parameters can also be supplied in STATECRUNCHER internal form, e.g.
	 `p=[[ex_co,int,4],[ex_str,[120,121]]]`
	 Worlds in direct violation of EXPECTEDTRACE will be killed, but overtrace and undertrace are tolerated.

`gt`	**`get trace`**
	 `7   TRACE =[1,2]`

`ct`	**`clear trace`** *(this also causes a world merge)*

Main processing: medium priority commands

`gae`	**`get all events`** *(whether transitionable or not; not world-related)* `EVENT [theta2, [z3,z,s,sc]] [pco1,[z,s,sc]]`
`gate`	**`get all transitionable events`** *(union from all worlds; no worlds shown)* `TREV [[delta,[sc]],0,[],[]]` `TREV [[gamma,[sc]],3, [[r,0,100000],[r,0,100000],[r,0,100000]],[]]` `TREV [[gamma,[sc]],1,[[r,0,100000]],[]]` `TREV [[gamma,[sc]],2, [[r,0,100000],[r,0,100000]],[]]` `TREV [[alpha,[sc]],0,[],[]]`
`gav`	**`get all variables`** *Gets the value-ranges, not the current value per world* `VAR INTEGER bool1 [sc] RANGE=[0, 1]` `VAR INTEGER col1 [sc] ENUM=[0, 7, 8, 4, 8]` `VAR INTEGER p1 [b2, b, s, sc] RANGE=[0, 9]` `VAR STRING  str [sc]`
`gaw`	**`get all worlds`** *Gets the current worlds* `[2,7,8]`
`gc`	**`get config`** `2   statechart sc` `2      cluster a [s, sc] =OCC []   **` `2         leafstate a1 [a, s, sc] =OCC []   **` `2         cluster a2 [a, s, sc] =VAC []` `2   VAR  INTEGER bool1 [sc] =1` `2   VAR  INTEGER col1 [sc] =8` `2   VAR  INTEGER p1 [b2, b, s, sc] =unknown` `2   VAR  STRING  p5 [b2, b, s, sc] =unknown` `2   VAR  STRING  str [sc] =[98] =b` `2   TRACE =[]` `2   TREV [[zeta,[s,sc]], 4,[[r,0,9],[e,0,7,8,4,8],[r,0,1],[<string>]], [pco1,[z3,z,s,sc]]]` `outworlds=[2,4]` `number of outworlds=2`
`gst`	**`get symbol table`** `SYMB delta      [sc]      eventdecl     []` `XREF leafstate    b1:[b, s, sc]` `XREF leafstate    z1:[z, s, sc]`
`kill` **...**	**`kill`** ***WORLD* | *WORLDS*** `kill 2` `kill [2,7,10]`

→	***WORLD* `TRACE` *= TRACE*** *input is as the output of* `get config` *this does **not** cause a world merge* *(we will probably issue this kind of command several times before requiring a world merge)*
→	***WORLD STATEKIND STATENAME MPATH = OCCUPANCY HISTORY*** *input is as the output of* `get config` *this does **not** cause a world merge (we will probably change more)*
→	***WORLD* `VAR` *VARKIND VARIABLENAME MPATH = VALUE*** *input is as the output of* `get config` *this does **not** cause a world merge (c.f. WORLD* `TRACE` *= TRACE)*
`cnw`	**`create new world`** *Creates a new world in its default state* *- needed before writing variable/state/trace values to a new world* `34` *(the new world number is returned)*
`mw`	**`merge worlds`** *(useful when all trace/state/variable changes have been made)*

`gpt`	**`get processing time`**
	(timing data is set on processing an event)
	`exec time=00h 00m 00s 210ms`

`gd`	**`get date`**
	(get date and time)
	`DATE:   24 Apr 2003 16:01:40/649`

Containment of combinatorial explosion: low priority commands

These commands limit the number of permutations used in set transit nondeterminism and race nondeterminism. See [StCrMain] for more explanation.

`nst`	**`no set tran`**
`lst`	**`low set tran`**
`mst`	**`medium set tran`**
`hst`	**`high set tran`**
`nr`	**`no race`**
`lr`	**`low race`**
`mr`	**`medium race`**
`hr`	**`high race`**

Compilation, loading, start-up, and finish: very low priority

`root ...`	**`root`** ***ROOTDIRECTORY*** *Sets the root directory to be used with FILENAMEs*
`mm`	**`mode modelnames`** *Sets compilation etc. to work with model names. The directory structure must be set up correctly.*

`mf`	**`mode filenames`** *(Default). Sets compilation etc. to work with file names. Use the root command to set the directory (can be null, then give a full path here).*
`cp …`	**`compile`** ***FILENAME | MODELNAME*** *(also loads machine, and enters it (as of Rel 1.05))*
`ld …`	**`load`** ***FILENAME | MODELNAME*** *(does not enter machine)*
`run …`	**`run`** ***FILENAME | MODELNAME*** *=Load and enter machine*
`nm`	**`enter machine`** *Machine enters default state*
`xm`	**`exit machine`** *Leaves a pristine machine ready to be entered*
`um`	**`unload machine`** *Removes data and object code*
`rm`	**`reset machine`** *=exit and enter*
`quit`	**`quit`**

System/diagnostic: very low priority

`help`	**`help`**
`prolog`	**`prolog`** *Gives a Prolog prompt; enter a Prolog goal*

Table 5. STATECRUNCHER commands

Notes.

- By priority, we mean the priority given through the parse-attempt order, which will affect the response time.
- If anything is to be set in nonexistent world, it is created (but a model must have been loaded)

A typical sequence of commands

1.	`mm`	*set model mode*
2.	`run t5110`	*load model and enter machine*
3.	`pe alpha`	*process event alpha (in statechart scope)*
4.	`gc`	*get configuration*
5.	`pe gamma`	*process event gamma (in statechart scope)*
6.	`gc`	*get configuration*
7.	`rm`	*reset machine*

8. `pe gamma`	*process event gamma (in statechart scope)*
9. `quit`	*quit STATECRUNCHER*

The following error and warning messages may be given:

Command parsing

PR-E-020	COMMAND SYNTAX ERROR

Preliminary checks

PR-E-040	NO MODEL LOADED (compiler-produced part)
PR-E-041	NO MODEL LOADED (validator-produced part)
PR-E-042	MULTIPLE COMPILED FILES LOADED
PR-E-043	MULTIPLE VALIDATED FILES LOADED
PR-E-044	THERE WAS A COMPILATION ERROR
PR-E-045	THERE WAS A VALIDATION ERROR
PR-E-046	VERSION INCOMPATIBILITY

Command execution

PR-E-060	COMMAND EXECUTION ERROR
PR-E-061	WORLD IS NEITHER EXTANT NOR EXTINCT

Internal errors

PR-E-900	INTERNAL ERROR - NO COMMAND HANDLER

Table 6. Error and warning messages

10. Glossary and abbreviations

α, Alpha: We have used the Greek alphabet for many event names. The English names of the letters are as follows:

α alpha	β beta	γ gamma	δ delta
ε epsilon	ζ zeta	η eta	θ theta
ι iota	κ kappa	λ lambda	μ mu
ν nu	ξ xi	ο omicron	π pi
ρ rho	σ sigma	τ tau	υ upsilon
φ phi	χ chi	ψ psi	ω omega

Action: A STATECRUNCHER term for processing that is associated with a transition (or the entering/exiting of a state). An action can be e.g.

- a "C"-like assignment to a variable
- the firing of an event
- the generation of output (a trace)

Black-box testing: Testing where system outputs can be observed, but not system internals. In the case of state-based testing, the state (more precisely, *configuration*) of the system will not be directly observable, and must be deduced from *traces* (outputs generated when events are processed).

Broadcast-event: An event that is generated within a statechart which can be responded to by the model (transitions can be triggered by it). The STATECRUNCHER keyword to generate a broadcast event is **`fire`** *`event`*.

Broadcast-event nondeterminism: Also known as fired-event nondeterminism, this is the form of nondeterminism that arises when an action associated with a transition fires an event, which in turn gives rise (directly or indirectly) to one of the other forms of nondeterminism (e.g. fork, race-condition, set-transit).

CHSM: Concurrent Hierarchical finite State Machine. A language implemented by Paul J Lucas [CHSM].

Cluster:	A hierarchical state and component of a statechart with the understanding that if the cluster is occupied, exactly one of its members must be occupied.
Configuration:	The dynamic state of a statechart in a broad sense, comprising: occupancy (occupied/vacant) of the states in the statechart, variable values, cluster history, and trace values.
DCG:	Definite Clause Grammar. This is the standard Prolog grammar notation, which enables grammar rules to be written in Backus-Naur form.
Event:	A signal (that has no time duration) which may be responded to in a statechart model by the triggering of transitions.
Fire:	The act of generating an event in an action associated with a transition: “the action fires the event”. [Compare “triggering a transition”, which may take place when the fired event is processed].
Fired-event nondeterminism:	Also known as broadcast-event nondeterminism, this is the form of nondeterminism that arises when an action associated with a transition fires an event, which in turn gives rise (directly or indirectly) to one of the other forms of nondeterminism (e.g. fork, race-condition, set-transit).
Fork nondeterminism:	The form of nondeterminism that arises when an event triggers mutually exclusive transitions in the statechart, and which produce a different outcome.
GP4:	Generic Prolog Parsing and Prototyping Package. An underlying layer of Prolog programs to provide parsing support (especially tokenization and expression parsing).
Harness:	A test harness is a tool that contains or accesses a test script so as to obtain tests and their oracle, and communicates with an implementation under test to run the tests. It compares actual with expected output, and logging the results as pass or fail.
IUT:	Implementation Under Test.
Leafstate:	A state and a component of a statechart at the lowest hierarchical level.

Machine engine:	A program that holds a representation of a statechart and a configuration of that statechart, and which can process an event and in so doing calculate and assume the new configuration.
Meta-event:	An event that is internally generated when a state is exited or entered, and which can be used to trigger transitions in other parts of the statechart.
Nondeterminism:	Dynamic behaviour of a system whereby there is more than one outcome of processing an event. Distinguishing aspects of an outcome are: state occupancy, cluster history, variable values, and traces.
Oracle:	The pre-determined output of the system on a successful test, for comparison purposes with the actual output.
PCO:	Point of Control and Observation. These are used for systems such as networked and client-server systems where inputs and outputs must be partitioned according to which separate testing point can provide and observe them.
Primer:	The TorX terminology for the part of the tool chain that decides what events (or transitions) are to be given to the explorer and indirectly to the implementation under test to be processed.
Race-condition nondeterminism:	The form of nondeterminism that arises when an event triggers transitions in parallel parts of the statechart, and when the order in which these events are processed will affect the outcome.
Set:	A state and a component of a statechart with the understanding that if the set is occupied, all its members must be occupied. This represents the parallelism of a model.
Set-action nondeterminism:	The form of nondeterminism that arises when actions (such as variable assignments) in different members of a set are executed, when the order in which this happens affects the outcome.
Set-transit nondeterminism:	The form of nondeterminism that arises when a *set* is exited or entered, when the order in which the members are exited or entered affects the outcome.

Set-meta-event nondeterminism: The form of nondeterminism that arises when elements of a set are exited or entered, (generating enter and exit meta-events), when the order in which this happens affects the outcome.

State: This word is used in two senses according to the context

- a statechart consists of a hierarchy of states, which may be sets, clusters, or leaf-states
- a state is the occupancy (occupied/vacant) of a state in the above sense

Statechart: A concurrent, hierarchical representation of a dynamic behaviour model consisting of states, events, transitions, and optionally variables and statements for processing them.

STATECRUNCHER: A provisional name for a program that compiles statecharts, process events, and provide state or trace information.

SUT: System Under Test. Modern literature generally employs the more precise term "Implementation Under Test" (IUT).

Trace: The output generated on processing an event (or transition), corresponding to the expected observable output of the Implementation Under Test.

Transition: The relation between the state of a system before and after that system has processed any event that triggers that transition.

Trigger: The act of responding to an event by processing an associated transition: “the event triggers the transition”. [Compare “firing an event”, which may take place as an action on the transition].

UML: Universal Modelling Language, as set out by the Object Modelling Group. UML is the industry standard for various modelling views on a system. The dynamic modelling view uses statecharts.

White-box testing: Testing where system internals can be observed. In the case of state-based testing, the state (more precisely, *configuration*) of the system can be observed directly.

11. References

STATECRUNCHER documentation and papers by the present author

Main Thesis	[StCrMain]	The Design and Construction of a State Machine System that Handles Nondeterminism

Appendices

Appendix 1	[StCrContext]	Software Testing in Context
Appendix 2	[StCrSemComp]	A Semantic Comparison of STATECRUNCHER and Process Algebras
Appendix 3	[StCrOutput]	A Quick Reference of STATECRUNCHER's Output Format
Appendix 4	[StCrDistArb]	Distributed Arbiter Modelling in CCS and STATECRUNCHER - A Comparison
Appendix 5	[StCrNim]	The Game of Nim in Z and STATECRUNCHER
Appendix 6	[StCrBiblRef]	Bibliography and References

Related reports

Related report 1	[StCrPrimer]	STATECRUNCHER-to-Primer Protocol
Related report 2	[StCrManual]	STATECRUNCHER User Manual
Related report 3	[StCrGP4]	GP4 - The Generic Prolog Parsing and Prototyping Package *(underlies the STATECRUNCHER compiler)*
Related report 4	[StCrParsing]	STATECRUNCHER Parsing
Related report 5	[StCrTest]	STATECRUNCHER Test Models
Related report 6	[StCrFunMod]	State-based Modelling of Functions and Pump Engines

References

[CdR]	Côte de Résyste http://fmt.cs.utwente.nl/CdR Côte de Resyste (COnformance TEsting of REactive SYSTEms) is a research and development project (1998-2002) funded by the Dutch Technology Foundation STW (http://www.stw.nl/), and is a collaboration between: - the University of Eindhoven (http://www.tue.nl) - the University of Twente (http://www.utwente.nl/) - Philips (http://www.philips.com)
[CHSM]	P.J. Lucas An Object-Oriented System for Implementing Concurrent, Hierarchical, Finite State Machines. MSc. Thesis, University of Illinois at Urbana-Champaign, 1993
[SWI-Prolog]	http://www.swi-prolog.org
[WinProlog]	http://www.lpa.co.uk/win.htm