Software Testing in Context

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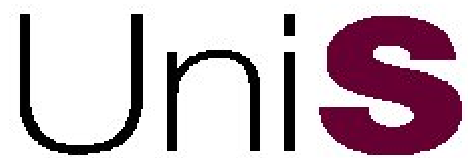
Appendix to the Thesis “The Design and Construction of a State Machine System that Handles Nondeterminism”



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Summary

This paper presents a broad approach to testing – an approach that theoretically could be adapted and applied to a typical software project. It is a condensation of what appear to be the best state-of-the-art practical testing techniques. We cover module testing, integration testing, and system testing; white-box testing and black-box testing; automated test execution and automated test generation.

The purpose of the paper is to situate state-based-testing in a broad testing context.

A word of caution is in place. Owing to the variety of techniques presented, one would be unwise to attempt them all on any one project, as this could easily lead to an overload of tooling and lack of focus on key testing issues for the particular project in hand.

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1. A general testing approach

The V-model for the software development life-cycle is well-known. The testing phases of this model are shown in Figure 1.

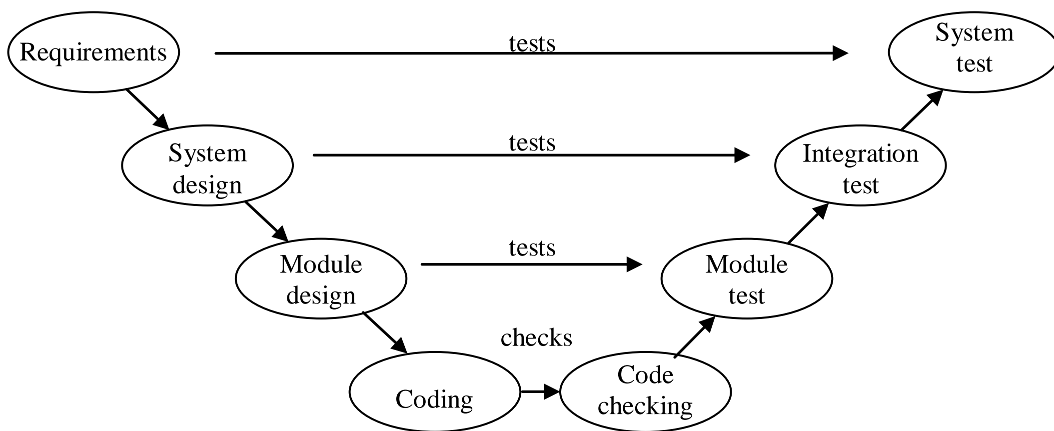

Figure 1. V-model and testing

The V model identifies various kinds of testing activity, and each has its own emphasis. We consider the aims of and techniques for each form of testing, starting at the bottom of the V model and working up the right-hand side:

- ***Code checking in general***: Static analysis can reveal bad coding style and possible pitfalls. Dynamic techniques can check for memory leaks and can provide code coverage, such as statement coverage, described in more detail later.
- ***Module testing***: The question to be answered is: Does the implementation correspond to the design? Modules are usually single functions, or a small number of tightly coupled functions designed against a single specification. Exercise code statements and branches. Use code instrumentation to check for coverage of these. Also include a memory leak check in the tests. Module testing is typically ***white-box testing*** - we have a knowledge of the code structure and use it to guide us in designing test cases, and we have detailed *controllability* and *observability* of the module.
- ***Integration testing***: The question to be answered is: Is the design internally consistent? Exercise interfaces between modules. Measure call-pair coverage (i.e. every call and every return from it). Integration testing is typically ***black-box testing*** - some modules may even be only available as object code, and the only way we can test the integrated system is via the published interfaces.
- ***System testing***. The question to be answered is: Does the system satisfy the project requirements? This will typically be a ***black-box testing*** activity, since the requirements do not normally specify internal controllability and observability, but

rather the operations and their outputs which to which the end-user has access. For some kinds of system, a part of system testing will be ***volume testing***. For example, a set-top box will need to be tested with large quantities of MPEG streams, and a Global Positioning System will need to be tested with large quantities of sampled radio-front-end (intermediate frequency) satellite data.

Tests suites are best structured, where possible, as a set of individually self-sufficient test cases, defining their own *pass/fail* criterion (rather than e.g. comparing output with that of previous runs). Some tests will address robustness under error situations.

For each form of testing, it may be advantageous not to test against the specification directly, but to produce a test specification, and test against that. In this way, we admit that we are not testing everything (or every combination of things), but we do make explicit what combinations of things we *are* testing.

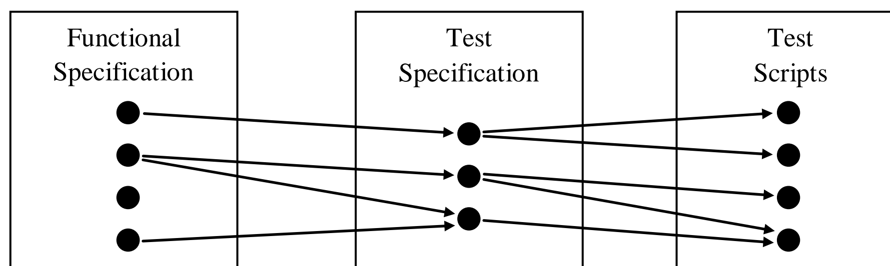

Figure 2. The Principle of a Test Specification

In addition to functional testing, there is non-functional testing, which is largely a form of system testing. This is considered in chapter 2. Further chapters address test automation.

We now consider the *aims* of each form of testing in a little more detail.

1.1 Code checking

At the bottom of the V model is coding. As code is produced (or perhaps upgraded from prototype to production status), it should be subjected to some ***static analysis***. This could be:

- Automated static analysis, e.g. for C and C++, by the [QAC] product. This analysis will reveal poor coding style and many potential bugs. It also provides code complexity metrics. Experience shows that complex code in terms of its branching and looping structure (having a high *cyclomatic complexity* metric) is much more liable to have bugs than one which is less complex.
- Code reviews by peers. This is often regarded as being as valuable as testing.

Code may also be subject to ***dynamic analysis***. The following can be used when testing:

- Memory leak and array bounds checking (using e.g. [Purify]).
- Code instrumentation for statement or branch coverage checking.
- Data flow testing. A tool tracks the use of variables, and reports on suspect use.

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We discuss code instrumentation and data flow testing in little more detail in section 1.2.

1.2 Module testing

Modules are tested against a module specification, and we aim to cover all statements or all branches in our tests. There is a saying that if in your tests you haven't executed any lines of code, you might as well rip them out of the product, because they are a good as defective. Statement coverage is essential, branch coverage is desirable, but there are various levels of detail of branch coverage, which we briefly discuss. Then we give some advice on how module tests could be designed.

Code coverage is obtained by *instrumenting* the code, so that when it is executed, apart from executing its own function, it also produces a log or trace of what code was executed.

Example (from [McCabe])
The program is regarded as segments (between potential branches or function calls), which are numbered by a node number. The node numbers are recorded on execution.

Uninstrumented

```
if (Getstate() > 0) {return Fred(); }
```

Instrumented

```
if ( (_mcrepco2(1662,1663,(GetState() > 0) != 0) ) )
    {return Fred();}
```

The call to `_mcrepco2` contains the evaluated condition in the third argument, so that the relevant node number (the first or second argument) can be logged according to whether it is true or false, *and* so the resultant boolean value can be returned into the `if` statement.

A table is then produced with coverage results, e.g.

Module Name	# Branch	# Covered	% Covered
LsdSyncDec::GetResource	8	5	62.5
LsdSyncDec::OpenSession	11	5	45.5

Table 1. Example of a coverage table

Before we discuss forms of statement and branch coverage, we must discuss a factor that interferes with measurement of some of them. C and many other languages use *short-circuit evaluation* of boolean expressions. Short-circuit evaluation skips evaluating operands where they do not contribute to the expression result. The problem that arises is

- Not all combinations of boolean terms are relevant - but in the context of short-circuit evaluation we know that, and do not count them against us in terms of the coverage percentage.
- Boolean operands could be function calls that may have side effects. So they cannot safely be evaluated in instrumented code if they would not be evaluated under normal uninstrumented circumstances. So we cannot measure some forms of coverage.

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In the examples below, our typical condition is

```
if (x==0 || y==0 ||z==0) ...
```

(For simplicity we do not call functions here).

The naming for code coverage is not universally standardised; we take frequently used names. The most commonly met forms of coverage that one could attempt to cover are:

1. ***Statement coverage***. This is achieved if the `if` statement is executed at all.

2. ***BDC: Branch decision coverage***
   Full coverage is obtained by any expressions that make the entire boolean expression true and false.

3. ***BCC: Branch condition coverage***. The individual *terms* (not the variables) in the boolean expression must be made true and false at some time. So `x==0` must be true and must be false on occasions, as must `y==0` and `z==0`. But we are not concerned about combinations, or even whether the branch is taken.

4. ***BDC/BCC***: The union of BDC and BCC.

5. ***MC/DC: Modified condition decision coverage***. Each boolean operand must individually affect the outcome of the decision. Four combinations would suffice for values of x, y, and z (using t=true, f=false, x=don't care): (f,f,f), (t,f,f), (f,t,f), (f,f,t). In general this requires n+1 tests for n boolean operands. Under *short-circuit evaluation*, this form of coverage can be measured on the understanding that it really is done in the context of short circuit evaluation. So (f,f,f), (t,x,x), (f,t,x), (f,f,t) gives full coverage. However, with all x=t in practice, say, it would not necessarily give full coverage if the terms in the expression were re-ordered, though with all x=f it would. MC/DC coverage in the short-circuit context is called ***masking-MC/DC*** and in the long-circuit context it is called ***unique cause MC/DC***.

6. ***BCCC: Branch condition combination coverage***. This requires that the boolean operands take on all values in all combinations, i.e. (f,f,f), (f,f,t), (f,t,f), (f,t,t), (t,f,f), (t,f,t), (t,t,f), (t,t,t). In general this involves 2^n tests for n boolean operands. Under *short-circuit evaluation*, this form of coverage can be sensitized for, but not all measured.

7. ***LCSAJ***: ***Linear Code Sequence And Jump*** coverage. This may appear to be like branch testing, but it differs in that it requires that loops are executed in ways that branches do not require.

8. ***Path coverage***. For full coverage, all paths through the program are taken. The enormous number of paths in a typical module makes this impracticable.

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In practice ***BDC*** is often chosen where testing time is very limited. ***BCC*** is very weak *on its own,* as it does not force branch decision. ***BDC/BCC*** appears to be offered by many inexpensive tools. ***MC/DC*** is potentially very powerful (it exposes the weakness of the above-mentioned coverage criteria) but takes quite some work (but so does BDC/BCC). MC/DC is required as part of the US Department of Defense standard DO-178B. ***BCCC*** is excessive in most cases, and impracticable with short-circuiting languages such as C. ***LCSAJ*** is powerful and should be feasible in many cases. Not all are supported by all tools.

Data flow coverage
This form of coverage is not based on statements, but on *data flow* as variables are ***D****efined* (created, initialized, or written to in an assignment), ***U****sed* (as a ***P****redicate* in a condition, or in a ***C****alculation* in the right hand side of an assignment), and ***K****illed* (e.g. by going out of scope). A coverage requirement might be that every path from ***D****efinition* to ***U****se* is exercised. Many more paths are useful. Anomalies are looked for such as ***DK*** (why define and kill without using?) or ***KU*** (definitely a bug - an undefined value is being used). Reference: [Beizer, ch.5].

There are many other forms of coverage - see for example [BCS Sigist].

How should module tests be designed?
The module under test will often be isolation tested, where all modules it calls are stubbed. Stubbing is replacing real modules by small modules with pre-cooked return values, preferably controllably by the test script. This gives more control over the module than when it is not stubbed.

Sometimes there is opportunity for *automatic test generation*, especially for state-based testing, decision table testing and cause-effect graphing (discussed later). But often module tests will be *hand crafted*. The tests will typically be matter of supplying various sets of parameter values in a function call. Global data may also play a role. Parameter values should be divided into *equivalence classes*, based on critical boundaries. Then 'grazing' values should be taken in and just out of each equivalence class. For example, if an equivalence class is the range -9..-4 (inclusive), test at least with values -10, -9, -4, -3. Correct error handling for out-of-range values should be checked.

Specific points of attention for numerical systems

Calculation-intensive applications have the potential for many numerical errors. Points of attention could be

- Finding all ***divisions*** in expressions and looking for possible sensitization of division by zero
- Looking for overflow / underflow / sign flip - perhaps in mid-expression - (perhaps detect it by assertion)
- Looking for int / unsigned / long int / unsigned long int / float / double / long double mixes in expressions and review them (maybe static analysis can help).
- Looking for all ***subtractions*** in expressions, and anticipate insufficient precision. The result of (large number)-(another similarly large number), e.g 123456789.12-

123456789.13, producing a very small number, is subject to great loss of precision, because much of the available precision was used up in storing the parts of the numbers that were subtracted away.

- Subjecting the module to massive feeds of data (volume testing) around critical expressions where it is claimed that dangerous values of variables cannot occur, with dense assertions in the codes; also continue to look for values indicative of overflow/underflow/sign flip (loss of precision due to subtraction might be hard to detect by assertion). The data might be:
  - random data
  - artificial data representing unusual circumstances.

After the tests have been designed, scripted and run the, the coverage figures can be analysed, and ways should be devised to sensitise for branches that were not taken. Occasionally, extra test software (such as special stubbing) is required to do this, because the error condition might be hard or impossible to sensitize from calling parameters alone.

Code coverage targets

What coverage targets should be set? Safety critical industries would require 100% MC/DC coverage. A paper claiming the experimental effectiveness of MC/DC is [Dupuy]. However, it does require considerably more effort than BDC/BCC, which are more commonly taken as norms. It is sometimes infeasible to sensitize for coverage certain parts of code, especially some error handing code, except by artificially forcing it.

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1.3 Integration testing

Integration testing is the testing of interfaces between modules. It is important, because if it is not done, errors will occur in system testing which will be hard to diagnose, because it will not be clear exactly what caused the failures. What may happen is that after the defective statement was executed, no failure was yet caught and more statements were executed, and memory blocks became overwritten, destroying evidence.

In integration tests, we do not attempt to reproduce the coverage of module testing. What we do concentrate on is module-to-module interfacing and interaction. Potential causes of integration errors in a system, and how to address them, are described in [Trew 99], covering:

- Incompatibilities between actual and formal parameter ranges.
  → Test with boundary values.
- Errors in large scale state behaviour
  → Reach all states. Make all transitions, perhaps all pairs of transitions
- Interpretation of parameter values, (e.g. in interpretation of units, of array offsets, in enumerated values, a defect caused by a *make* file bug)
  → Exercise all call pairs (tooling can give the call pair coverage)
- Parameter ordering. Parameters of the same type may be inadvertently exchanged
  → Exercise all call pairs (tooling can give the call pair coverage)
- Dependencies on shared global data. Is the data used consistently? Is it always initialised?
  → Structured data-flow tests
  or
  → Volume test with high levels of activity, and check for integrity of the data
- Re-entrancy (direct recursion, indirect recursion).
  → Visualisation tools will reveal it
- Race conditions
  → (State-based) test under all preconditions.
  → Ensure design (and code) employs a handshake
- Deadlock
  → Rigorous design inspections
  → Volume testing.

It is seen that exercising call pairs (client-server calls) and state-based testing can play an important role, as does design/code inspection.

1.4 System testing

System testing addresses the question of whether the system meets the customer's or project manager's requirements. Even perfect module and integration testing, with 100% coverage figures, will not protect against swathes of missing functionality. System testing is against requirements and system level analysis documents, and obviously the approach is very application specific. The use of a test specification (see Figure 2) is particularly useful here. Many tests of a fully integrated system should be centred around the user - i.e. they should be *use cases*.

Use cases

Use cases are part of UML. For the UML baseline, see [Catalysis, Ch. 4]. Use cases are important in system testing, because, if well chosen, they exercise the software in the way it is likely to be used in practice. Use cases are part of the [PHASST] approach in Philips, where they are described as follows:

> A use case describes the system's behaviour under various conditions as the system responds to a request from its users. The system user, primary actor in use case terminology, interacts with the system to achieve some goal. Each use case is a high level description of the group of scenarios which may be triggered when a particular set of conditions holds. It also includes a set of conditions that are valid when the sequence of events associated with any of the scenarios in the set is completed.

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2. Non-functional testing

According to [Evans], reporting for the BCS SIGiST, functional areas are concerned with *what* a product does, and non-functional areas are concerned with *how well* the product behaves, including whether a product is enjoyable to use and perceived as trustworthy.

The list of non-functional testing techniques from [Evans] and [TestingStds] is as follows:

- Memory Management
- Performance
- Stress Procedure
- Reliability
- Security
- Interoperability
- Usability
- Portability
- Compatibility
- Maintainability
- Recovery
- Installability
- Configuration
- Recovery
- Disaster Recovery
- Conversion

The SIGiST is currently (2003) in the process of elaborating on these concepts. Each project needs to review which of the above are applicable and how to address them in the light of its own context of use.

3. Automated test execution

The techniques described here apply across different levels of testing (module, integration, system testing).

Testing should normally be automated where possible. Humans become weary of e.g. repeatedly following written test instructions manually and checking output by eye. But even a collection of diverse test programs can be difficult to manage. The best kind of test suite is one in which

- All tests are called in a uniform way
- Every test calls the Implementation Under Test (IUT) and examines the IUT output directly in the script.
- Every test defines its own pass/fail criterion
- Every test logs the test name or number and a pass or fail indication.
- If possible, the test script supplies values to stubbed modules, so that all relevant data to a test comes from the test script, and is not distributed among special stub routines.

A basic way of automating test execution is illustrated in the following figure:

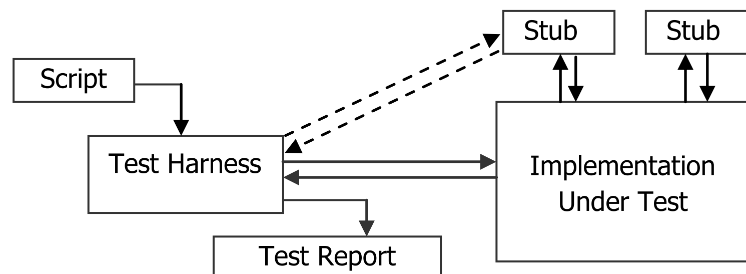

Figure 3. Automated test execution

There are two levels at which tests may be scripted:

- Hard-linking the test script to the IUT (Implementation Under Test). In this case, the tests are direct function calls and tests on return values or on global data. A tool that supports this kind of testing, and also gives coverage data, is **Cantata** [Cantata].
- Communicating with the IUT at the executable level. A good public domain tool for communicating via *Standard Input* and *Standard Output* is **DejaGnu**. [DejaGnu].

Examples of Cantata and DejaGnu in use are now given.

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Cantata

Cantata [Cantata] is a commercial test harness from IPL. It is suitable for C testing. There is a sister product called Cantata++ which is suitable for C or C++ testing, which is more actively promoted by the company. We show what is essentially involved in writing test cases in Cantata.

In the example below, we are testing some function `myfunc` which takes an integer parameter and returns an integer. This function calls another function, which is artificially called `stub`, since it will be stubbed. The figure below shows a Cantata test script, including stubs for the stubbed function, and instructions on how the stub is to be used on each call to it.

Cantata test case example

```
extern int myfunc(int);   // IUT Declaration:
                          //    a function taking and returning an int

int myfunc_P1;            // Variable to hold the parameter value
int R_myfunc;             // Variable to hold the return value
int E_R_myfunc;           // Variable to hold the expected return value

/*** Test Case ***/
START_TEST(2);

myfunc_P1=10;             // Initialize input parameter to myfunc
E_R_myfunc=20;            // Set expected return value

EXECUTE_BY_REF("myfunc","stub#1;stub#1;stub#2");
R_myfunc=myfunc(myfunc_P1);

DONE();
CHECK_S_INT ("myfunc return", R_myfunc, E_R_myfunc);
END TEST();
```

IUT called here

Stub definition example

```
int stub (int p1)
{
  int ret_val;
  START STUB ("stub1");
  switch (ACTION)())
  {
   case 1:
      CHECK_U_INT("p1",p1,30);
             retval=TRUE;
         break;
   case 2:
      CHECK_U_INT("p1",p1,40);
             retval=FALSE;
         break;
  default:
      ILLEGAL_ACTION();
         break;
  }
END_STUB();
return (ret_val);
}
```

this part for stub#1

this part for stub#2

Figure 4. Cantata test case example

The above example shows how function `myfunc` is tested. The test calls it with a parameter value of 10, and expects a return value of 20. The function calls another function, `stub`, which takes an integer parameter and returns a boolean. We stub this function by defining pre-cooked return values (TRUE and FALSE) based on the calling parameter. The stub definition allows us to check that calling parameter is 30 or 40 depending on which occasion

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the stub was called. The test case itself specifies (by `"stub#1;stub#1;stub#2"`) that the stub is expected to be called 3 times, twice under case 1 conditions, then once under case 2 conditions. Under case 1 conditions we expect `stub` to be called with parameter value 30 and we return the pre-cooked value TRUE. Under case 2 conditions we expect `stub` to be called with parameter value 40 and we return the pre-cooked value FALSE.

Any deviations from the expected values in the stub or in the return value of `myfunc` will cause the test to report a failure.

The test report is of the following format:

```
=======================================================================
Test Script  Checks  Checks  Checks  Stubs   Paths   Assertions  Status
     Errors  Passed  Failed  Warning Failed  Failed  Failed
-----------------------------------------------------------------------
PTE     0       0       0       0       0       0       0          PASS
001     0       2       0       0       0       0       0          PASS
002     0       3       1       0       0       0       0        >>FAIL
ANS     0       2       0       1       0       0       0          PASS
------------------------------------------------------------------------
Total   0       7       1       1       0       0       0        >>FAIL
=======================================================================
```

PTE stands for Pre-Test Errors.
ANS stands for analysis check warning (the user can define a coverage measure as a check).

DejaGnu

DejaGnu [DejaGnu] is a layer on top of Expect [Expect-DL], which is a layer on top of TCL (Tool Command Language) [TCL].

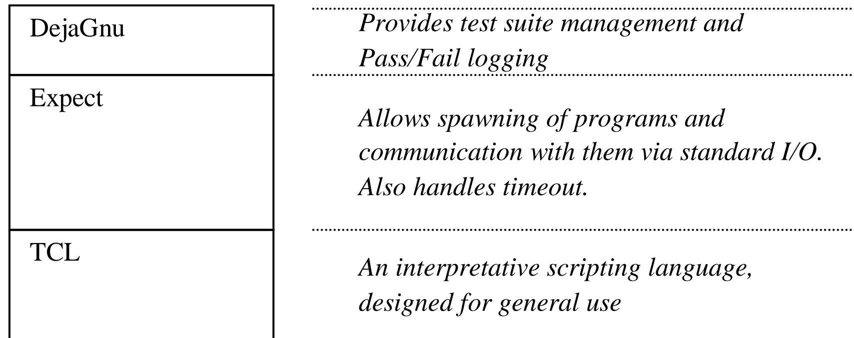

Figure 5. TCL, Expect and Deja Gnu

TCL and Expect can both be learnt from [Expect-DL]. There is also a detailed book on TCL, [TCL], by its creator, John Ousterhout.

DejaGnu is well established on Unix Systems, and has been ported to Windows for use under CYGWIN [CYGWIN]. A separate port of Expect to Windows (by Gordon Chaffee) also exists. Both versions are pointed to by [Expect-Nist]. DejaGnu was used on the Philips G+4 set-top box platform project.

The essence of DejaGnu testing is to spawn the IUT (Implementation Under Test) and talk to its via standard input and standard output. If the IUT does not respond within a certain time, a timeout can catch this in DejaGnu.

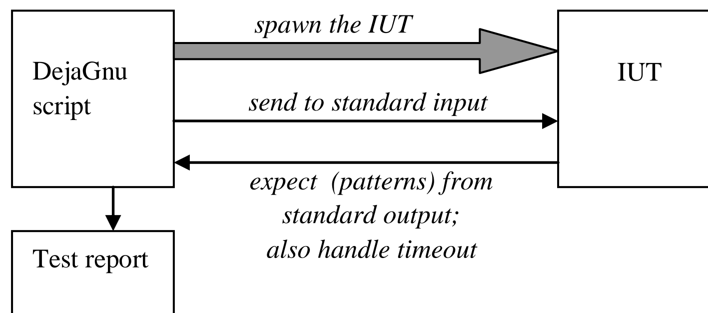

Figure 6. DejaGnu

DejaGnu communicates with an executable program, the IUT or a program relaying I/O to and from the IUT. So the IUT could be on the same computer as DejaGnu, or on another machine. In the latter case, DejaGnu would spawn e.g. a serial line program or a socket program communicating with the actual IUT. This scheme is suitable for testing the IUT on a target board, providing the necessary glue code is in place. DejaGnu (being in essence EXPECT) can spawn more than one program and control them independently if necessary.

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A *calc* demonstration program is supplied with DejaGnu. It would not be confused with the proper Unix *calc* program, because of its verbose commands, `add` and `multiply`. It has the following behaviour:

```
% calc
calc: add 2 3
5
calc: add 1 2 3
Usage: add #1 #2
calc: multiply 3 4
12
calc: multiply 2 4
12
calc: quit
%
```

Note that the program produces a prompt after any other output. *Notice its bug!*

Excerpts from a DejaGnu Test Script (as supplied - it could be improved)

```
spawn calc

expect_after {
   -re "\[^\n\r]*$prompt$" {
      fail "$test (bad match)"
   }
   timeout {
      fail "$test (timeout) "
   }
}

set test add1
send "add 3 4\n"
expect {
   -re "7+.*$prompt$"   {pass $test}

}
set test add2
send "add 1 2 3\n"
expect {
   -re "Usage: add #1 #2.*$prompt$"  {pass $test}
}

set test multiply2
send "multiply 2 4\n"
expect {
   -re "8.*$prompt$"   {pass $test}
}
```

The script first spawns the `calc` program. The `calc` program will then run internally, without a window, obtaining input from Expect and writing output to Expect. The

`expect_after` statements in the script are effectively extensions to `expect` statements discussed below. Each test consists of setting a test name and sending an ASCII string to the `calc` program. Then the script waits for *(expects)* output from `calc`, which may match the regular expression defined. If this happens, the test is passed by a call to the DejaGnu `pass` function. If the text from `calc` for any test does not match the `expect` regular expression, but does match the `expect_after` regular expression, then control is passed to the associated statements before returning to the next test. In this example, two possibilities for `expect_after` have been defined: one for when some text at least ending in the `calc` prompt has been obtained, and one for a timeout when all else fails. Both the `expect_after` situations are fails, but are logged with a different annotation.

The log after running these tests

```
=== calc tests ===

spawn calc

calc: Running
./testsuite/calc.test/calc.exp ...
--------------------------------------
add 3 4
7
calc: PASS: add1
--------------------------------------
add 1 2 3
Usage: add #1 #2
calc: PASS: add2
--------------------------------------
multiply 2 4
12
calc: FAIL multiply2 (bad match)
--------------------------------------

   === calc Summary ===

# of expected passes      2
# of unexpected failures  1
```


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4. Automated test generation

We have discussed how the test framework must support ***automated test execution*** (as far as possible) for all testing phases. Under some circumstances it may be possible to deploy ***automated test generation*** as well. The generated tests may be generated as a batch, in which case the same testing set-up can be used as for automated test execution. A more advanced form of automated test generation is ***on-the-fly automated test generation***, where what later tests are generated depends on the results earlier tests.

- Automatic generation of tests is possible where the specifications are in a formalism with which a test generator can work:
    - state-based tests (derived from a state-transition diagram)
    - decision tables
    - cause-effect graphing
    - syntax testing
- Another form of automated testing is
    - random testing

4.1 State-based testing

The state behaviour of a system is described by a statechart, as in the dynamic model of UML. The elements of the model are

- states (in a hierarchy)
- events
- transitions (these connect source state(s) to target state(s) on an event; we say an event *triggers* a transition).

Below is an example from a smart-card manager:

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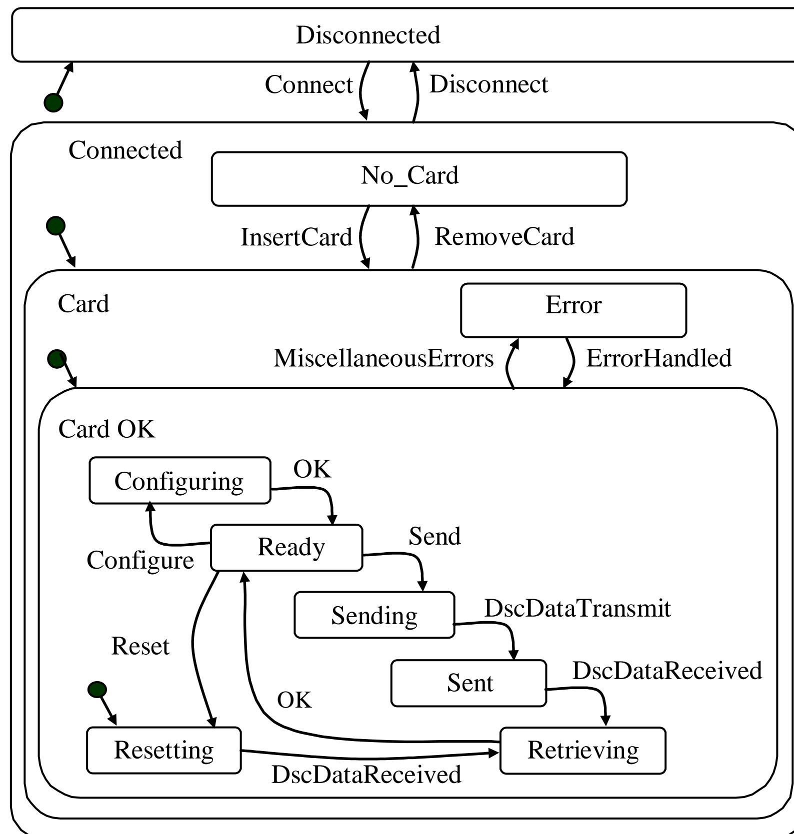

Figure 7. Statechart of a smart-card manager

Statecharts like this are valuable in pinning down the specifications and in providing a good handle for testing, whether by hand-crafted tests or by automatic test generation. To test against a statechart like this, we need to at least cover all transitions. Deeper coverage could be obtained by requiring transition pairs.

To automate the process, we need two key programs (best kept separate)

- A test *generator* that says what events are to be processed
- A test *oracle* to the tests that says what the new state is (or what outputs were expected). The oracle program may entail a language to describe the statechart, a compiler and a run-time machine engine for that language. STATECRUNCHER [StCrMain] is such an oracle.

For ***white-box testing***, we are able to examine the state of the IUT and test against states. For ***black box testing***, we test against outputs. The figure below illustrates white box state-based testing.

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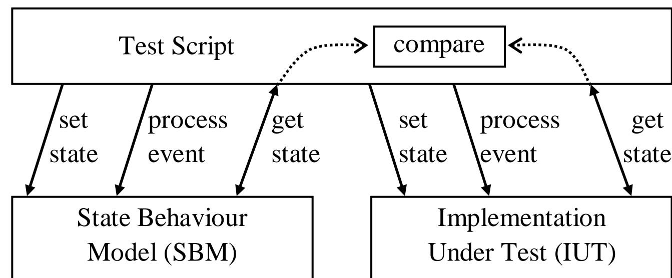

Figure 8. State based testing basics

The [TorX] architecture has a more explicit test case generator in a tool chain as follows (with TorX terminology at the top, and more conventional terminology below).

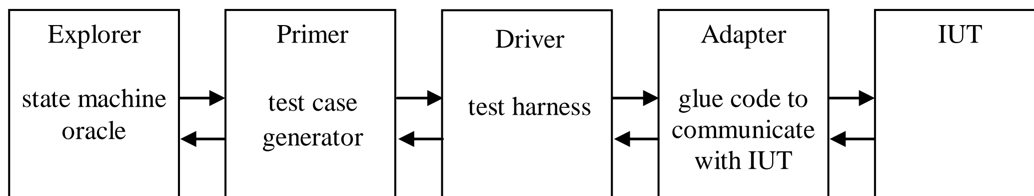

Figure 9. TorX architecture

The TorX tool chain forms the basis of investigations by Philips Research Bangalore in the use of the TorX toolchain using STATECRUNCHER [StCrMain] as the oracle.

Very large numbers of tests can be generated using state-based testing, though the nature of the tests is often very unlike that of hand-crafted ones. This is especially true where there is parallelism in the model. The technique has been effective in finding defects in a DVD system and in the G+4 set-top box platform.

4.2 Decision tables

Decision tables directly relate combinations of inputs to multiple outputs.

Inputs are called the *condition stub.*
Outputs are called the *action stub.*

Table 2. Decision table example

Rule (e.g. from Requirements Specification)	Condition stub			Action stub	
	C1	C2	C3	A1	A2
	true	true	true	true	true
	true	true	false	false	false
	true	false	x	false	true
	false	x	x	true	false

Use x for "don't care" in the condition stub.
The decision table represents a (usually pruned) tree:

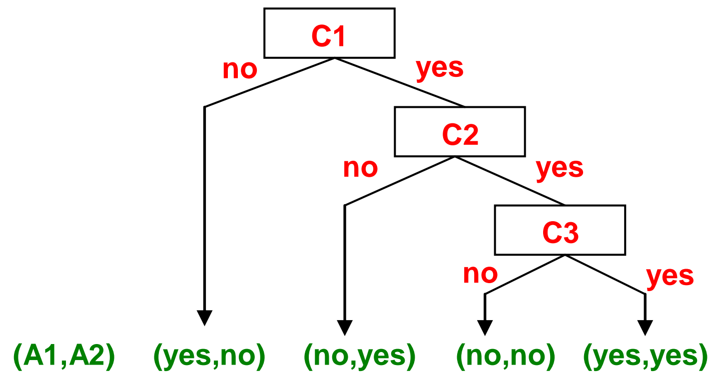

Figure 10. Decision table as a tree

Check the decision table for

- completeness (no undetermined outputs)
- consistency (no contradictions)
- good sense (review activity)

In principle generate ***all*** input combinations

Condition stub			Action stub	
C1	C2	C3	A1	A2
true	true	true	true	true
true	true	false	false	false
true	false	x→true	false	true
true	false	x→false	false	true
false	x→true	x→true	true	false
false	x→true	x→false	true	false
false	x→false	x→true	true	false
false	x→false	x→false	true	false

Table 3. Combinations in a decision table

An *x* does ***not*** mean “don't care” to the tester!! In principle generate ***all*** input combinations, (so whever an *x* occurs, generate the *true* and *false* value).

Use the decision table as an oracle to the tests. To *generate* the tests:

- For small decision tables, the test cases can be generated by hand.
- Decision tables are a simple case of CEG (Cause Effect Graphing), and a CEG tool can be used (see section 4.3).
- Rules from the requirements specification can be expressed in a rule or logic based program such as PROLOG.

The following example illustrates how PROLOG can be used to generate the tests.

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Robot Arm Example[1]

A robot has three kinds of gripper:

- magnet
- sucker
- parallel fingers

The following rules to determine how to pick up an object:

- A magnet can only be used on ferrous objects
- A magnet requires an accessible upper surface
- A sucker requires a smooth object
- A sucker requires an accessible upper surface
- Parallel fingers require a rough object
- Parallel fingers require accessible parallel faces

---

[1] This example was suggested to the author for an exercise with an expert system shell by an engineer at Agfa-Gevaert in Antwerp in 1985.

PROLOG program to derive test cases from rules

```
/*-------------------------------------------------------------------*/
/* Module:    robot1.pl                                              */
/* Author:    Graham Thomason, Philips Research Laboratories, Redhill */
/* Date:      10 Jun, 1999                                           */
/* Purpose:   Example of unpruned decision table generation          */
/*                                                                   */
/* Copyright (C) 1999 Philips Electronics N.V.                       */
/*-------------------------------------------------------------------*/


/*-------------------------------------------------------------------*/
/* Representation of an object                                       */
/* ===========================                                       */
/*   An object is of the format [AUS,APF,FERROUS,SMOOTH]             */
/*      AUS = Accessible Upper Surface                               */
/*      APF = Accessible Parallel faces                              */
/*      FERROUS= is ferrous                                          */
/*      SMOOTH = is smooth                                           */
/*   Each item in this list can be 't' (true) or 'f' (false)         */
/*   if SMOOTH=f, then we say the object is rough                    */
/*-------------------------------------------------------------------*/


/*-------------------------------------------------------------------*/
/* Rules for picking up by different robot arms                      */
/* Self explanatory predicate names                                  */
/*                                                                   */
/* Parameters                                                        */
/*   X   (In)  The object being examined for picking                 */
/*             For representation of the object, see comment above   */
/*   VAL (Out) ='y' (yes) or 'n' (no) according to the pickability   */
/*-------------------------------------------------------------------*/
pickByMagnet(X,y):-
  hasAccUpSurf(X),
  isFerrous(X),
  !.
pickByMagnet(X,n).

pickBySucker(X,y):-
  hasAccUpSurf(X),
  isSmooth(X),
  !.
pickBySucker(X,n).

pickByFingers(X,y):-
  hasAccParFaces(X),
  isRough(X),
  !.
pickByFingers(X,n).


/*-------------------------------------------------------------------*/
/* Testing for different properties in object                        */
/* ==========================================                        */
/* The predicates take an object as their parameter and succeed if:  */
/*   hasAccUpSurf(X):   if X has an accessible upper surface         */
/*   hasAccParFaces(X): if X has an accessible parallel faces        */
/*   isFerrous(X):      if X is ferrous                              */
/*   isSmooth(X):       if X is smooth                               */
/*   isRough(X):        if X is rough                                */
```

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```
/*-------------------------------------------------------------------*/
hasAccUpSurf(X):-
  X=[t,_,_,_].

hasAccParFaces(X):-
  X=[_,t,_,_].

isFerrous(X):-
  X=[_,_,t,_].

isSmooth(X):-
  X=[_,_,_,t].
isRough(X):-
  X=[_,_,_,f].


/*---------------------------------------------------------------*/
/* Generate all objects (on backtracking)                        */
/*   generates [f,f,f,f], [f,f,f,t], [f,f,t,f],  etc.            */
/*---------------------------------------------------------------*/
obj([AUS,APF,FERROUS,SMOOTH]):-
  ausVal(AUS),          /* accessible upper surface value  */
  apfVal(APF),          /* accessible parallel faces value */
  ferrousVal(FERROUS),  /* ferrous value                   */
  smoothVal(SMOOTH).    /* smooth value                    */

ausVal(X):-    tfVal(X).
apfVal(X):-    tfVal(X).
ferrousVal(X):-tfVal(X).
smoothVal(X):- tfVal(X).

tfVal(f).
tfVal(t).


/*-------------------------------------------------------------------*/
/* main loop                                                         */
/*   Writes abbreviated keywords vertically                          */
/*      AUS=Accessible Upper Surface (object has)                    */
/*      MAG=Magnet (object is pickable pickable by)                  */
/*      etc.                                                         */
/*-------------------------------------------------------------------*/
go:-
  write(' A A F S  M S F'),nl,
  write(' U P E M  A U I'),nl,
  write(' S F R O  G C N'),nl,
  fail.
go:-
  obj(X),           /* loop over all objects */
  pickByMagnet(X,PBM),
  pickBySucker(X,PBS),
  pickByFingers(X,PBF),
  write(X),tab(1),write(PBM),tab(1),write(PBS),tab(1),write(PBF),nl,
  fail.
go.
```

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Output (with minor reformatting to facilitate annotation)

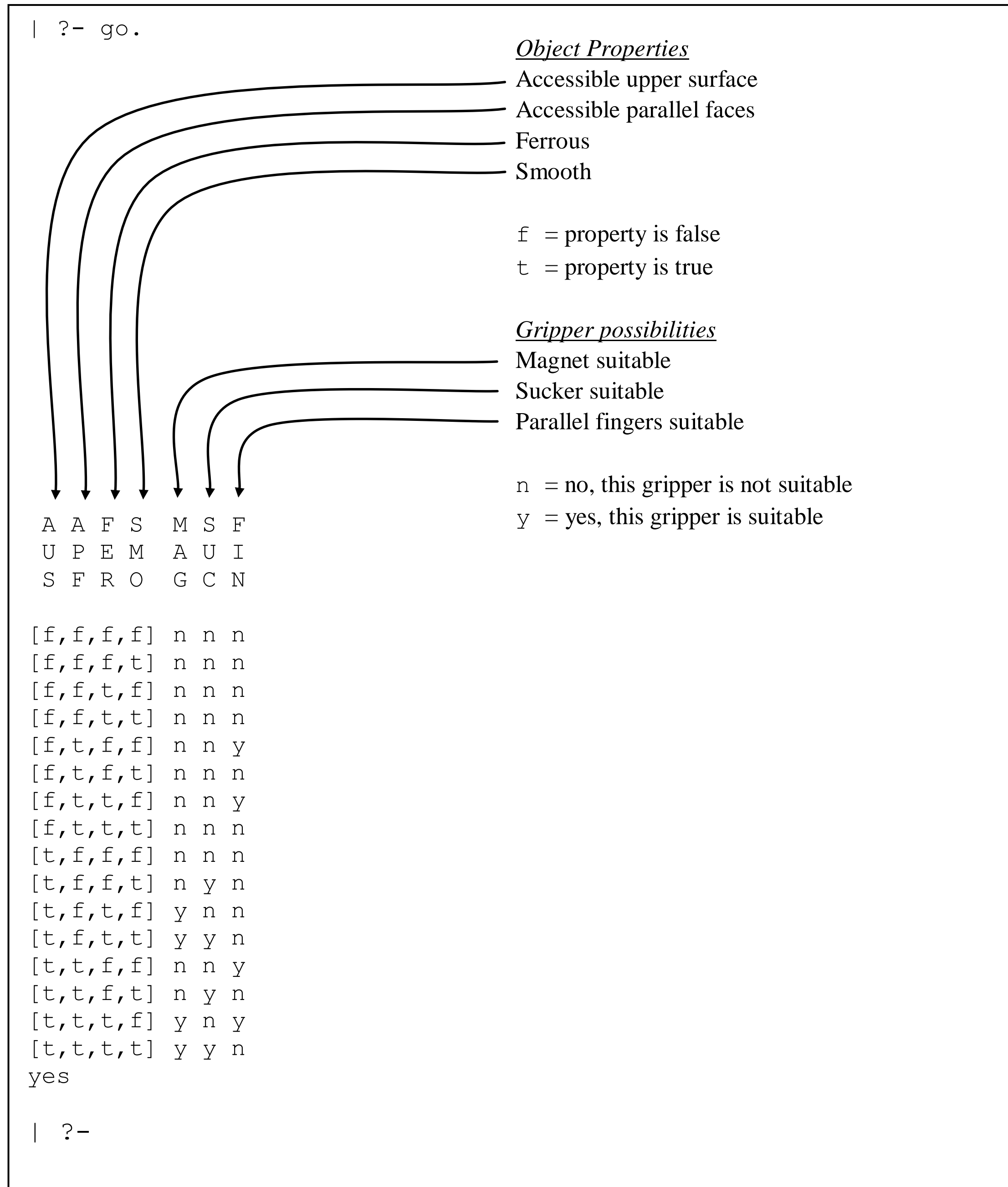

Figure 11. Robot arm output

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Karnaugh maps

Decision tables can also be represented as grids or spreadsheets (with 2 inputs) or as cubes (with 3 inputs - but then separate planes are drawn) or as hypercubes for more inputs. These diagrams are called Karnaugh maps. Adjacent cells with the same output value, but with at least one input value held constant, reveal where a *group of outputs* is not dependent on all inputs, and so showing where decision logic can be simplified. The figure below shows the Karnaugh map for the robot arm, with colour coding to show grouping.

INPUTS: 4 binary variables (values **t** and **f**)

- [AccUppSurf, ParFaces, Ferrous, Smooth]

OUTPUTS: 3 binary variables (values **y** and **n**)

- [CanUseMagnet, CanUseSucker, CanUseFingers]

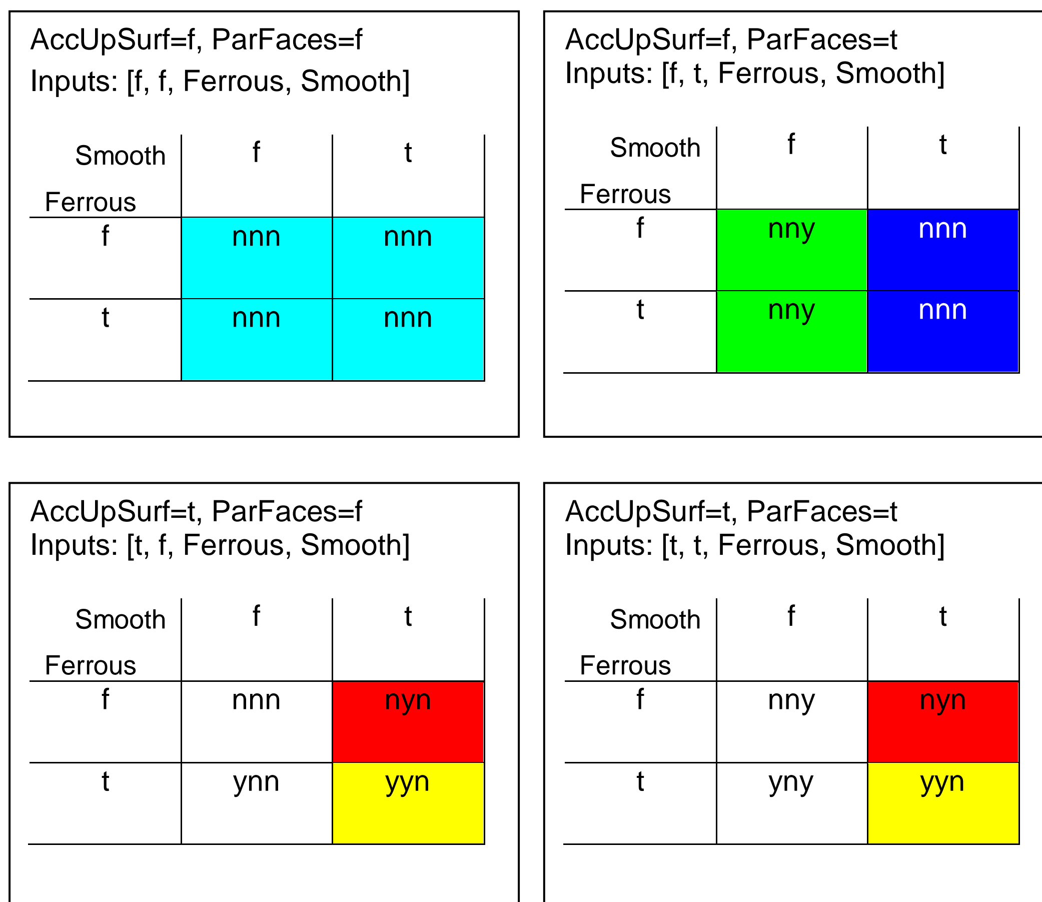

Figure 12. Karnaugh map

From the Karnaugh map a decision table with *don't cares* can be constructed. The same colour code as in the Karnaugh map is used below. Where 2 Karnaugh map cells form a group, there will be one *don't care*, and where 4 cells form a group, there will be 2 *don't cares*.

Condition				Action		
Upper Surface	Parallel Faces	Ferrous	Smooth	Magnet	Sucker	Parallel Fingers
f	f	x	x	n	n	n
f	**t**	**x**	**t**	**n**	**n**	**n**
f	t	x	f	n	n	y
t	x	t	t	y	y	n
t	x	f	t	n	y	n
t	f	f	f	n	n	n
t	f	t	f	y	n	n
t	t	f	f	n	n	y
t	t	t	f	y	n	y

Table 4. Robot gripper decision table

Decision tables are a *feed-forward* technique. They are applicable where there is no obvious memory in the logic, in contrast to state-based testing where states represent memory so that the same event can have a different effect at different times because of the state. However, it is possible to model simple state models as decision tables, where parallel states become condition stub items, the event becomes another condition stub item, and the action stub items are the new states.

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4.3 Cause-effect graphing (CEG)

Cause-effect graphing is described in detail in [Myers, p.56]. The technique consists establishing a relationship between inputs and outputs where the logic is more than a simple decision table. There is typically a network of logical gates (with their own CEG symbols), under constraints (shown by dotted lines below).

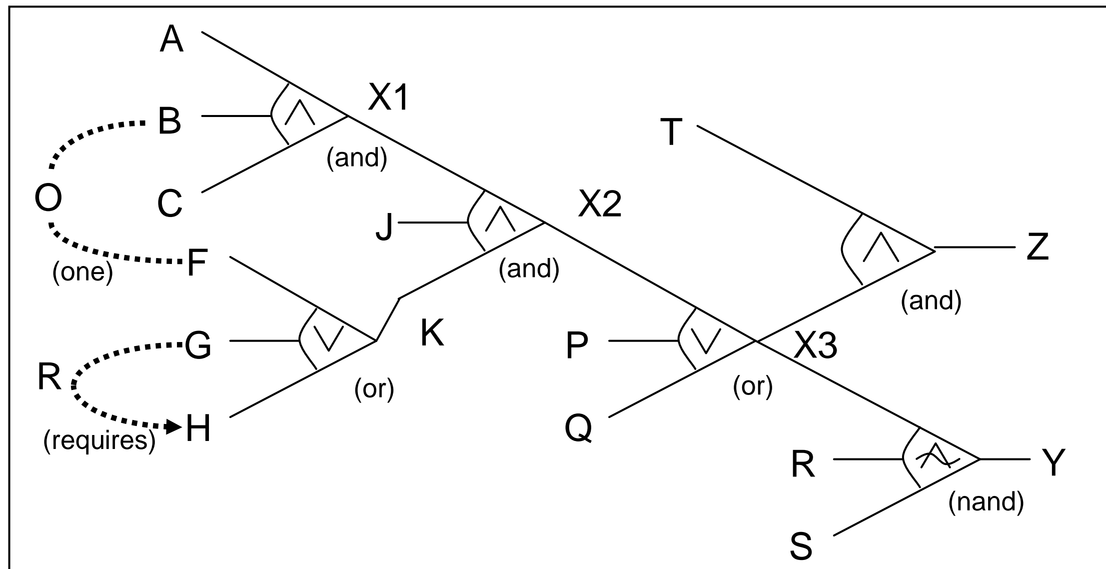

Figure 13. A CEG

The constraint *one* above indicates that exactly one of the inputs *B* and *F* must be true, and *G requires H* indicates that for *G* to be true, *H* must be true.

The idea is to test key input combinations of each gate. The complexities arise from:

- The need to avoid combinatorial explosion, so to combine tests efficiently.
- The presence of constraints, such as one input requiring a truth-value of another to make sense. For example if one input is (x>0) and another is (x>6), it is not possible to have the first true and the second false.
- Observability issues. If intermediate nodes are not observable, the output of a gate must be propagated through the network. This puts sensitization requirements on other gates. This is not always logically possible - leaving certain gate combinations untestable (unless extra observability/controllability measures are taken).

The output of test cases from a CEG tool is similar to that of decision tables.

There is a commercial tool for generating CEGs:

- A tool originally called SoftTest from Bender and Associates, then apparently under Borland called Caliber-RBT and now under Nohau called Caliber-RM.

The following pages show how CEGs can be used to test the colour of a teletext object[1]. Teletext objects are used to overwrite parts of a teletext page, but with quite complex rules to govern the colour of the new text.

We take specifications from the standard (ETS 300 706, May 1997), paragraph 13, page 98.

Example of an object overwriting underlying text:

	T	H	E		F	A	S	T		D	O	G		A	N	D	
					L	A	Z	Y									

	T	H	E		L	A	Z	Y		D	O	G		A	N	D	

One application of teletext objects is to place an advertisement in a certain place on a set of pages, without the need to re-code the pages individually.

There are 3 kinds of object, plus underlying text, with highest-to-lowest priority as follows:

- Passive
- Adaptive
- Active
- Underlying text

We consider the 3 kinds of object in turn.

[1] The test cases are for illustrative purposes. Absolute accuracy cannot be guaranteed, though care has been taken with them, as, due to changing testing priorities, these tests have not actually been deployed.

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Active Objects

- Colour change affects underlying text (“AND”)
- Until underlying text changes colour, (“CAT”)
- Colour change stays in effect to <u>end of row</u> (not end of object range)

Active object example

b	T	H	E		F	A	S	T		D	O	G		A	N	D	r	C	A	T	g	R	A	N		I	N
					L	A	Z	Y		C	O	W						F	O	X		S	A	T			
										p												y					
					--range of object cells addressed by object--																						
	T	H	E		L	A	Z	Y		C	O	W		A	N	D		F	O	X		S	A	T		I	N
blue					*blue*					*pink*				*pink*				*red*				*yellow*				*yellow*	

Object does not have an initial colour change ***-> Underlying colour***	Object sets a new colour	Colour change ***stays in effect***	***<u>Underlying</u>*** ***<u>text</u>*** sets new colour	Active object sets a new colour This stays in effect to ***end of row***

Figure 14. Active object example

Adaptive Objects

- Colour depends on
  - Colour set by adaptive object
  - Else as set by previous *active* object
  - Else colour of underlying text,
- Underlying col change gets overridden
- Colour changes end at <u>end of object</u>

Adaptive object example

b	T	H	E		F	A	S	T		D	O	G		A	N	D	r	C	A	T	g	R	A	N		I	N
					L	A	Z	Y		C	O	W						F	O	X		S	A	T			
										p												y					
					--range of object cells addressed by object--																						
	T	H	E		L	A	Z	Y		C	O	W		A	N	D		F	O	X		S	A	T		I	N
blue					*blue*					*pink*				*pink*				*pink*				*yellow*				*green*	

Object does not have an initial colour change ***-> Underlying colour***	Object sets a new colour	Colour change ***stays in effect*** on under-lying text	Object *overrides* underlying colour change	Object sets a new colour. Does ***not remain in force*** after end of object

Figure 15. Adaptive object example

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Passive objects

- If no object colour specified, displayed colour=WHITE (highest priority inherits nothing)
- Where no character defined in object, underlying text retains its colour.
- Colour changes end at end of object

Figure 16. Passive object example

b	T	H	E		F	A	S	T		D	O	G		A	N	D	r	C	A	T	g	R	A	N		I	N
					L	A	Z	Y		C	O	W						F	O	X		S	A	T			
										p												y					
					--range of object cells addressed by object--																						
	T	H	E		L	A	Z	Y		C	O	W		A	N	D		F	O	X		S	A	T		I	N
blue					*white*					*pink*				*blue*				*pink*				*yellow*				*green*	

Object does not have an initial colour change ***->WHITE***	Object sets a new colour	Under-lying colour ***back in force***	Object ***overrides underlying*** colour change	Object sets a new colour Does ***not remain in force*** after end of object

Figure 17. Passive object example

SoftTest Source of the Teletext Object CEG

```
/*-----------------------------------------------------------------------*/
/* Module: TutTxtObj.ceg - Teletext objects                              */
/* Author: Graham Thomason, Philips Research Laboratories, Redhill      */
/* Date:   28 May, 1999                                                  */
/*-----------------------------------------------------------------------*/

TITLE 'Teletext Objects'.

NODES

/*-----------------------------------------------------------------------*/
/* CAUSES                                                                */
/*-----------------------------------------------------------------------*/
CharBeforeObj = 'Char is before any object'.
CharAfterPAS =  'Char is after a  PASSIVE  object'.
CharAfterADP =  'Char is after an ADAPTIVE object'.
CharAfterACT =  'Char is after an ACTIVE   object'.
CharInPAS =     'Char is in a  PASSIVE  object'.
CharInADP =     'Char is in an ADAPTIVE object'.
CharInACT =     'Char is in an ACTIVE   object'.

ExplicitObjChar =       'Char is explicitly overwritten in the object'.
UnderlyingColChange =   'Underlying text changes colour under the object'.
ObjColSet =             'Object has set colour'.

/*----------------------------------------------------------------------*/
/* Intermediate Nodes                                                   */
/*----------------------------------------------------------------------*/
AfterObjDispColUnder = 'Char after object- Display in underlying col'.
AfterObjDispColObj =   'Char after object- Display in object colour'.
InObjDispColUnder = 'Char in object- Display in underlying col'.
InObjDispColObj =   'Char in object- Display in object colour'.
InObjDispColWhite = 'Char in object- Display in white'.

/*----------------------------------------------------------------------*/
/* Effects                                                              */
/*----------------------------------------------------------------------*/
DispColUnder = 'Display the char in the underlying colour'.
DispColObj   = 'Display the char in the last colour set by the object'.
DispColWhite = 'Display the char White'.

/*----------------------------------------------------------------------*/
/* Constraints                                                          */
/*----------------------------------------------------------------------*/
CONSTRAINTS
ONE (CharBeforeObj,
    CharAfterPAS,CharAfterADP,CharAfterACT,
    CharInPAS,CharInADP,CharInACT).

MASK (CharBeforeObj,ExplicitObjChar,UnderlyingColChange,ObjColSet).
MASK (CharAfterPAS,ExplicitObjChar).
MASK (CharAfterADP,ExplicitObjChar).
MASK (CharAfterACT,ExplicitObjChar).

/*----------------------------------------------------------------------*/
/* Relations                                                            */
/*----------------------------------------------------------------------*/
RELATIONS
AfterObjDispColUnder:-
     CharAfterPAS
```


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```
  OR CharAfterADP
  OR (CharAfterACT AND NOT ObjColSet)
  OR (CharAfterACT AND     ObjColSet AND UnderlyingColChange).

AfterObjDispColObj:-
     CharAfterACT AND ObjColSet AND NOT UnderlyingColChange.

InObjDispColUnder:-
     (CharInACT AND     ObjColSet  AND     UnderlyingColChange)
  OR (CharInACT AND NOT ObjColSet)
  OR (CharInADP AND NOT ObjColSet)
  OR (CharInPAS AND     ObjColSet  AND NOT ExplicitObjChar)
  OR (CharInPAS AND NOT ObjColSet  AND NOT ExplicitObjChar).

InObjDispColObj:-
     (CharInACT AND ObjColSet AND NOT UnderlyingColChange)
  OR (CharInADP AND ObjColSet)
  OR (CharInPAS AND ObjColSet AND ExplicitObjChar).

InObjDispColWhite:-
     CharInPAS AND NOT ObjColSet AND ExplicitObjChar.

DispColUnder:-CharBeforeObj OR AfterObjDispColUnder OR InObjDispColUnder.
DispColObj:-                   AfterObjDispColObj   OR InObjDispColObj.
DispColWhite:-InObjDispColWhite.

/* -----[End of script] ----*/
```

SoftTest "definition matrix"

The parameter settings for each of 15 tests are seen from the table produced, below. The first test, TEST#01, says that a character after the *end* of a passive object (and so not *before* or *in* any object), where no colour was set in the object, but where the colour of the underlying text in the range of the object did change, is displayed in the underlying colour. The three observable output properties are marked `{obs}`.

Definition Matrix P:\KSoftTest\mg99\TxtObj.ceg

		TEST#01	TEST#02	TEST#03	TEST#04	TEST#05	TEST#06	TEST#07	TEST#08	TEST#09	TEST#10	TEST#11	TEST#12	TEST#13	TEST#14	TEST#15
Causes:																
CharAfterPAS		T	F	F	F	F	F	F	F	F	F	F	F	F	F	F
CharAfterADP		F	T	F	F	F	F	F	F	F	F	F	F	F	F	F
CharAfterACT		F	F	T	T	F	F	F	F	F	F	F	F	T	F	F
ObjColSet		F	F	F	T	T	F	F	T	F	M	T	F	T	T	T
UnderlyingColChange		T	T	F	T	T	F	T	F	T	M	T	T	F	F	T
CharInACT		F	F	F	F	T	T	F	F	F	F	F	F	F	T	F
CharInADP		F	F	F	F	F	F	T	F	F	F	T	F	F	F	F
CharInPAS		F	F	F	F	F	F	F	T	T	F	F	T	F	F	T
ExplicitObjChar		M	M	M	M	F	F	F	F	F	M	F	T	M	F	T
CharBeforeObj		F	F	F	F	F	F	F	F	F	T	F	F	F	F	F
Effects:																
AfterObjDispColUnder		T	T	T	T	F	F	F	F	F	F	F	F	F	F	F
AfterObjDispColObj		F	F	F	F	F	F	F	F	F	F	F	F	T	F	F
InObjDispColUnder		F	F	F	F	T	T	T	T	T	F	F	F	F	F	F
InObjDispColObj		F	F	F	F	F	F	F	F	F	F	T	F	F	T	T
InObjDispColWhite		F	F	F	F	F	F	F	F	F	F	F	T	F	F	F
DispColUnder	{obs}	T	T	T	T	T	T	T	T	T	T	F	F	F	F	F
DispColObj	{obs}	F	F	F	F	F	F	F	F	F	F	T	F	T	T	T
DispColWhite	{obs}	F	F	F	F	F	F	F	F	F	F	F	T	F	F	F

Figure 18. SoftTest definition matrix

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Limitations of SoftTest & CEGs

- SoftTest is not a test harness
  - It does not claim to be.
  - The tests are also output as an ASCII file and can be converted to a scripting language for use with a test harness.

- In SoftTest, the number of tests is so highly optimized that it may fail to generate tests that distinguish two inputs. For example if there is an input A to one gate, and B to another, we may find that A and B are always set to true and false together.

- CEGs are just one approach to systematic testing. They are not likely to be sufficient on their own, and should be supplemented by other forms of testing.

4.4 Syntax testing

Reference: [Beizer, ch 9] explains how syntax testing is not only applicable to formal computer languages, because software systems often have hidden languages. These may be

- a user input language
- a data format with many (perhaps nested) options (e.g. bmp files, avi files, mpeg files)
- an inter-process communication convention
- an API calling sequence convention
- communication protocols

Our example below is for C, but many systems that are not languages like C exhibit hidden languages that can be tested by syntax testing. The syntax may be represented diagrammatically as a railroad diagram, which defines the grammar, e.g.

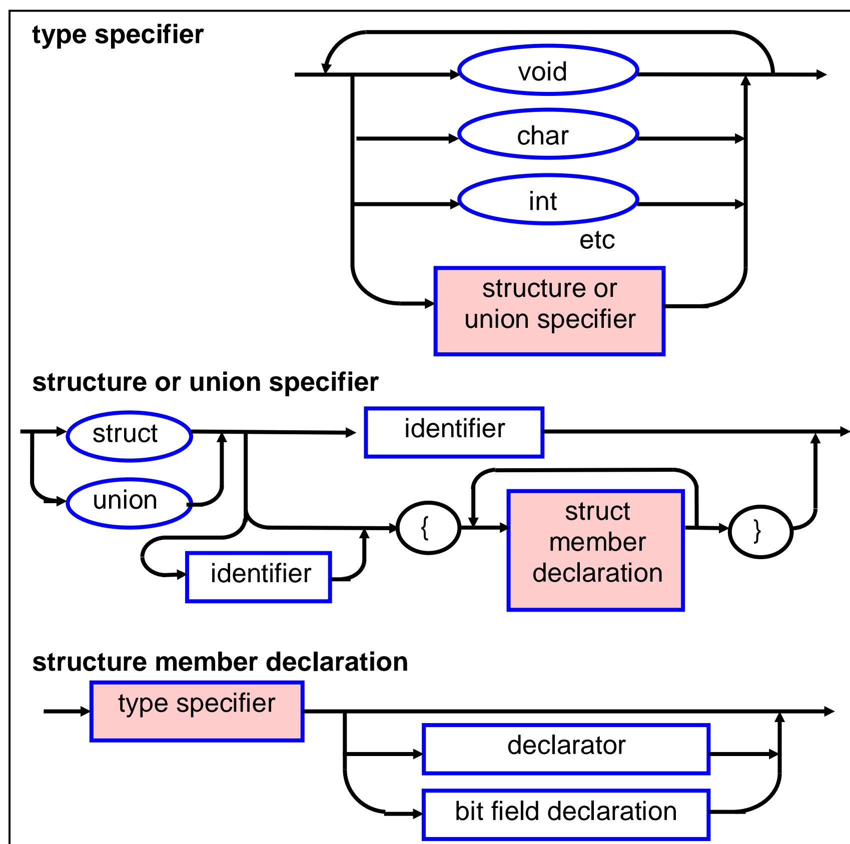

Figure 19. Syntax graph - a bit of C

Test generation possibilities

- Generate legal productions of the grammar and feed them to the IUT.
- Mutate the grammar, generate productions of that, filtering them out if they happen to also be parsable by the original grammar, feed these to the IUT and check that they are recognized as error situations.

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The oracle, if any, must come from some additional information, perhaps manually supplied, or embedded in the grammar. Even if no oracle to the tests is supplied, the tests have value in testing the robustness of the system. Value can be added by putting assertions in the code.

We now show how syntax coverage can be obtained using a Prolog program. The example illustrates how Prolog Definite Clause Grammars can serve two purposes:

- Obtaining a parse of input
- Generating productions from the grammar

The example generates sentences where several simple sentences can also be conjoined to make one long sentence of the kind:
the boy likes the girl and the girl eats a pear and ...

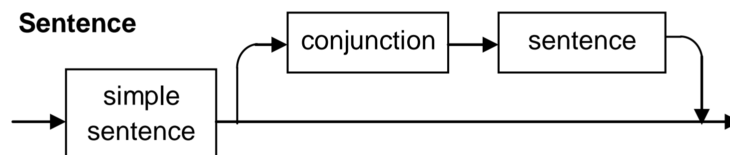

Figure 20. Syntax - a sentence

There is additional code to prevent sentences of the type

- the A likes the A
- the A likes the B and the A likes the B

Listing

```
/*-------------------------------------------------------------------*/
/* Module:    sentence.pl                                            */
/* Author:    Graham Thomason, Philips Research Laboratories, Redhill */
/* Date:      10 Jun, 1999                                           */
/* Project:   S/W Testing:                                           */
/* Purpose:   Example of syntax-based test generation                */
/*                                                                   */
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/*-------------------------------------------------------------------*/

/*-------------------------------------------------------------------*/
/* EXTERNALS used by this module                                     */
/*   ggtlib:io_pp                                                    */
/*-------------------------------------------------------------------*/

/*-------------------------------------------------------------------*/
/* NonTerminals                                                      */
/* ============                                                      */
/*-------------------------------------------------------------------*/

/*-------------------------------------------------------------------*/
/* sentence                                                          */
/*   recursive!!                                                     */
/*   we prevent sentences of the type                                */
/*     [A likes B ... and A likes B]                                 */
/*-------------------------------------------------------------------*/

sentence(Y,Z):-       /* non DCG goal supplies default parameters */
  sentence(1,Y,Z,[]).

sentence(DEPTH,[sentence,S1])-->
  simple_sentence(S1).

sentence(DEPTH,[sentence,S1,C|RESTLIST])-->
  simple_sentence(S1),
  conjunction(C),
  {(NEWDEPTH is DEPTH+1)},
  {( (NEWDEPTH =< 3 ) ; (NEWDEPTH > 3,!,fail) )},
  sentence(NEWDEPTH,S2),
  {(S2=[_|RESTLIST])},
  {(gn_not(gn_member(S1,RESTLIST)))}.

/*-----------------------------------------------------*/
/* simple_sentence                                     */
/*   we prevent [a Z likes a Z] type of sentence       */
/*-----------------------------------------------------*/
simple_sentence([simple_sentence,NP,VP])-->
  noun_phrase(NP),
  verb_phrase(VP),
  {(NP=[_,_,N],N=[_,NW],
    VP=[_,_,NP2],NP2=[_,_,N2],N2=[_,NW2],
    NW\=NW2)}. /* not the same noun in both places */

/*----------------------------*/
/* noun_phrase                */
/*----------------------------*/
noun_phrase([noun_phrase,A,N])-->
  article(A),
  noun(N).

/*----------------------------*/
/* verb_phrase                */
/*----------------------------*/
verb_phrase([verb_phrase,V,NP])-->
```


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```
  verb(V),
  noun_phrase(NP).

/*----------------------------------------------------------------------*/
/* Terminals                                                            */
/* =========                                                            */
/*----------------------------------------------------------------------*/
article([article,A])-->
  {(article(A))},
  [A].
article(the).
/* article(a). */

noun([noun,N])-->      /* noun/3 */
  {(noun(N))},         /* noun/1 */
  [N].
noun(boy).
noun(girl).
/* noun(cherry). */
/* noun(pear). */

verb([verb,V])-->
  {(verb(V))},
  [V].
verb(knows).
verb(likes).

conjunction([conjunction,C])-->
  {(conjunction(C))},
  [C].
conjunction(and).
/* conjunction(but). */

/*---------------*/
/* simple  tests */
/*---------------*/

tterm:-tarti,tnoun,tverb,tconj.

tarti:-article(P,[X],[]),write(P),tab(1),write(X),nl,fail.
tarti.

tnoun:-noun(P,[X],[]),write(P),tab(1),write(X),nl,fail.
tnoun.

tverb:-verb(P,[X],[]),write(P),tab(1),write(X),nl,fail.
tverb.

tconj:-conjunction(P,[X],[]),write(P),tab(1),write(X),nl,fail.
tconj.

tnp1:-noun_phrase(P,X,[]),io_pp(P),tab(1),write(X),nl,nl,fail.
tnp1.

tnp2:-noun_phrase(P,X,[]),         tab(1),write(X),nl,   fail.
tnp2.

tvp1:-verb_phrase(P,X,[]),io_pp(P),tab(1),write(X),nl,nl,fail.
tvp1.

tvp2:-verb_phrase(P,X,[]),         tab(1),write(X),nl,   fail.
tvp2.

tss1:-simple_sentence(P,X,[]),io_pp(P),tab(1),write(X),nl,nl,fail.
tss1.
```

```
tss2:-simple_sentence(P,X,[]),         tab(1),write(X),nl,nl,fail.
tss2.

tsen1:-
  sentence(1,P,X,[]),write(P),nl,io_pp(P),tab(1),write(X),nl,nl,fail.
tsen1.

tsen2:-
  sentence(1,P,X,[]),tab(1),write(X),nl,fail.
tsen2.

/*----------------[end of module sentence.pl]---------------------*/
```

Coverage Output

```
| ?- tsen2.
 [the,boy,knows,the,girl]
 [the,boy,likes,the,girl]
 [the,girl,knows,the,boy]
 [the,girl,likes,the,boy]
 [the,boy,knows,the,girl,and,the,boy,likes,the,girl]
 [the,boy,knows,the,girl,and,the,girl,knows,the,boy]
 [the,boy,knows,the,girl,and,the,girl,likes,the,boy]
 [the,boy,knows,the,girl,and,the,boy,likes,the,girl,and,the,girl,knows,the,boy]
 [the,boy,knows,the,girl,and,the,boy,likes,the,girl,and,the,girl,likes,the,boy]
 [the,boy,knows,the,girl,and,the,girl,knows,the,boy,and,the,boy,likes,the,girl]
 [the,boy,knows,the,girl,and,the,girl,knows,the,boy,and,the,girl,likes,the,boy]
 [the,boy,knows,the,girl,and,the,girl,likes,the,boy,and,the,boy,likes,the,girl]
 [the,boy,knows,the,girl,and,the,girl,likes,the,boy,and,the,girl,knows,the,boy]
 [the,boy,likes,the,girl,and,the,boy,knows,the,girl]
 [the,boy,likes,the,girl,and,the,girl,knows,the,boy]
 [the,boy,likes,the,girl,and,the,girl,likes,the,boy]
 [the,boy,likes,the,girl,and,the,boy,knows,the,girl,and,the,girl,knows,the,boy]
 [the,boy,likes,the,girl,and,the,boy,knows,the,girl,and,the,girl,likes,the,boy]
 [the,boy,likes,the,girl,and,the,girl,knows,the,boy,and,the,boy,knows,the,girl]
 [the,boy,likes,the,girl,and,the,girl,knows,the,boy,and,the,girl,likes,the,boy]
 [the,boy,likes,the,girl,and,the,girl,likes,the,boy,and,the,boy,knows,the,girl]
 [the,boy,likes,the,girl,and,the,girl,likes,the,boy,and,the,girl,knows,the,boy]
 [the,girl,knows,the,boy,and,the,boy,knows,the,girl]
 [the,girl,knows,the,boy,and,the,boy,likes,the,girl]
 [the,girl,knows,the,boy,and,the,girl,likes,the,boy]
 [the,girl,knows,the,boy,and,the,boy,knows,the,girl,and,the,boy,likes,the,girl]
 [the,girl,knows,the,boy,and,the,boy,knows,the,girl,and,the,girl,likes,the,boy]
 [the,girl,knows,the,boy,and,the,boy,likes,the,girl,and,the,boy,knows,the,girl]
 [the,girl,knows,the,boy,and,the,boy,likes,the,girl,and,the,girl,likes,the,boy]
 [the,girl,knows,the,boy,and,the,girl,likes,the,boy,and,the,boy,knows,the,girl]
 [the,girl,knows,the,boy,and,the,girl,likes,the,boy,and,the,boy,likes,the,girl]
 [the,girl,likes,the,boy,and,the,boy,knows,the,girl]
 [the,girl,likes,the,boy,and,the,boy,likes,the,girl]
 [the,girl,likes,the,boy,and,the,girl,knows,the,boy]
 [the,girl,likes,the,boy,and,the,boy,knows,the,girl,and,the,boy,likes,the,girl]
 [the,girl,likes,the,boy,and,the,boy,knows,the,girl,and,the,girl,knows,the,boy]
 [the,girl,likes,the,boy,and,the,boy,likes,the,girl,and,the,boy,knows,the,girl]
 [the,girl,likes,the,boy,and,the,boy,likes,the,girl,and,the,girl,knows,the,boy]
 [the,girl,likes,the,boy,and,the,girl,knows,the,boy,and,the,boy,knows,the,girl]
 [the,girl,likes,the,boy,and,the,girl,knows,the,boy,and,the,boy,likes,the,girl]
yes
| ?-
```

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Example of a parse

```
| ?-
sentence(P,[the,boy,likes,the,girl,and,the,girl,knows,the,boy]),io_pp(P).
   sentence
      simple_sentence
         noun_phrase
            article
            the
            noun
            boy
         verb_phrase
            verb
            likes
            noun_phrase
               article
               the
               noun
               girl
      conjunction
      and
      simple_sentence
         noun_phrase
            article
            the
            noun
            girl
         verb_phrase
            verb
            knows
            noun_phrase
               article
               the
               noun
               boy
P =
[sentence,[simple_sentence,[noun_phrase,[article,the],[noun,boy]],[verb_phra
se,[verb,likes],[noun_phrase,[article,the],[noun,girl]]]],[conjunction,and],
[simple_sentence,[noun_phrase,[article,the],[noun,girl]],[verb_phrase,[verb,
knows],[noun_phrase,[article,the],[noun,boy]]]]]

| ?-
```

Code for the above *pretty print* formatter is as in [Clocksin, p.81].

4.5 Orthogonal arrays

Suppose a routine needs testing with 4 parameters, (A, B, C, and D), each of which can take 3 values (1, 2, and 3). Exhaustive testing would require running 3^4=81 tests. But suppose we find it adequate that all *pairwise combinations* of parameter values are taken. A table can be found satisfying this with 9 entries of values of the 4 parameters as follows:

```
ABCD
1111
1223
1332
2122
2231
2313
3133
3212
3321
```

For pairwise coverage as above we speak of orthogonal arrays of strength 2. If we had required that all *triples* of parameters should be covered for all combinations of values, the strength would be 3 and so on. See also [Sloane]; the above array is equivalent to the one at

http://www.research.att.com/~njas/oadir/oa.9.4.3.2.txt.

4.6 Other model-based testing

Of the UML models, the dynamic model (state-based testing) is probably the most amenable to automated testing. But *use cases*, *message sequence diagrams*, *collaboration diagrams* etc. are also being used to derive tests. The [Agedis] project addresses model based testing including such models. There is also a very rich website on model-based testing maintained by Harry Robinson, with UML-based testing featuring prominently, [Robinson].

4.7 Random testing

Random testing can also be useful. In this case there is no precise oracle to the tests. However, by densely larding the code with assertions (which act as oracles in a way), the tests have value in testing the robustness of the system.

4.8 Summary of automated test generation

Automated test generation requires formal specifications such as a UML model, a decision table, a cause effect graph, or the grammar rules of a language. Large numbers of tests can be generated. State based testing has proved to be particularly effective in finding defects in practice. Sometimes the techniques, which could be used for automated test generation, can be applied by hand (e.g. for a small statechart or decision table).

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5. Abbreviations

5.1 Testing-related abbreviations

BCC	Branch Condition Coverage
BCS	British Computer Society
BDC	Branch Decision Coverage
BCCC	Branch Condition Combination Coverage
CEG	Cause Effect Graphing
IUT	Implementation Under Test
LCSAJ	Linear Code Sequence and Jump (coverage)
MC/DC	Modified Condition / Decision Coverage
PHASST	Philips Approach to Structured System Testing. See [PHASST]
QAC	*Probably*: Quality Assessment for C. See [QAC]
SIGiST	Special Interest Group in Software Testing
TCL	Tool Command Language

5.2 Other abbreviations used

API	Application Programmer Interface
GNU	Gnu's Not Unix - see http://www.gnu.org
GUI	Graphical User Interface
MPEG	Moving Picture Experts Group
UML	Unified Modelling Language

6. 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

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References

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[BCS Sigist] Standard for Software Component Testing
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- *A collection of tools, which provide Linux look and feel.*

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