Validating open and component based systems

Lars-Åke Fredlund

Formal methods for specifying components

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- Model oriented
  - Mathematical: Z, ...
  - Logics: temporal logic
  - Object oriented: Object-Z
- Algebraic process algebras for concurrency and distribution
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- **Today:** methods and tools for validating components

Design by Contract

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  - is expected of users of the component
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- For general software components we can think of a number of desirable component properties:
  - safety properties: what a component **does not do** – e.g., does not modify its parameters
  - liveness properties: what the component **must do** – e.g., return a value upon correct invocation
  - *security*: does not leak information about its parameters
  - *resource usage*: which resources will the component use – e..g, no more than X KB of stack
  - *timing characteristics*: response time

Design by Contract, part II

- Modern design by contract solutions popularized by the Eiffel language (Bertrand Meyer)
- But now available for many object-oriented and non-object oriented programming languages (Java, C++, C#, Erlang, . . .)
- Existing contract frameworks mostly address only functional behaviour, i.e., they cannot express claims about performance, or about resource usage
- Normally only input-output relations for methods are specified, i.e., not reactive behaviours (sequences of calls)

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- The language for specifying pre– and post–conditions is up to the method (normally English or first-order logic)

Contracts in OO languages, part II

- Possibly there is also a specification of an invariant *inv* of the object state, preserved by the pre-conditions such that:

  if the invariant holds and the pre-condition is satisfied (pre **and** *inv) then in the resulting state both the post-condition and the state invariant holds (post* **and** *inv)*

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- Such invariants help specify the ***internal consistency*** of a class/object:

```
class IntSet {
  int[] a;

  //@ invariant 0 <= size && size <= a.length;
  int size;
  ...
}
```

Checking Specifications and code

- Given a specification of your (component based) system
- What should be checked?
  - Are all contract specifications satisfied?
  - Are the pre– and post–conditions strong enough to guarantee that state invariants are kept?
- What methods are available for checking compliance?
- What tools are available?

Validation Techniques For Contracts

- Runtime Monitoring
- Static Analysis
- Systematic Testing
- Model checking
- Theorem proving
- And many combinations of these techniques. . .

Validation Quality

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A good analysis tool is one that generates few false positives and has good coverage with respect to the actual bugs in the code (has few false negatives)

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- **Example**: check all I/O operations by an applet and allow only writes and reads to and from certain locations

Runtime Monitoring: Difficulties

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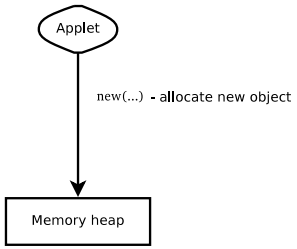
- Difficult to implement some contracts (e.g., efficiency concerns, conditions involving quantification, undefinedness)

Runtime Monitoring: Java example

- Ensure that a Java applet doesn't allocate too much memory



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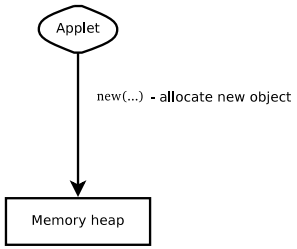
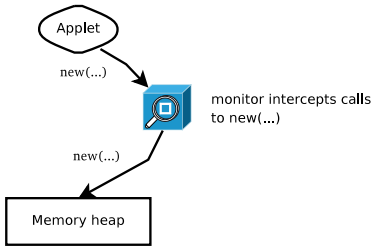


- Design a monitor which is invoked upon every call to `new`, and forbids a new allocation if too much memory has already been allocated



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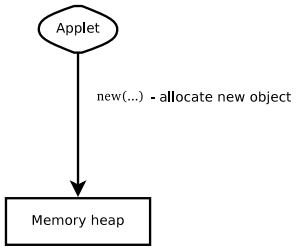

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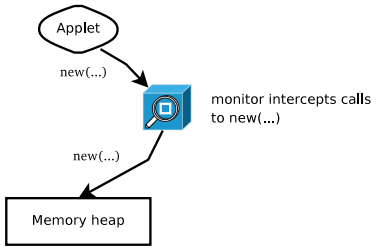

- **Implementation**: insert code to call the monitor before every instance of a `new` or `newarray` Java bytecode instruction in the Java applet object code

Static Analysis

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- Example: the **Java byte code verifier** ensures that no user program can crash the Java runtime system
- Programs can of course still generate exceptions (null pointer dereferenced) but never crash the host runtime system (caused by e.g. treating an integer as a pointer)
- **Implementation**: the byte code verifier *executes symbolically* the program to be checked but *replaces concrete values with domains* – their types (**abstract interpretation**)

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- Recursive behaviour is handled by noticing and stopping at recurring (abstract) states

Typical static analyses

Beyond the byte code verifier for Java:

- Can exceptions be raised at runtime?
- Can null pointers be dereferenced?
- Can any array operations reference an out-of-bound index?
- Calculation of the method call graph for a Java program
- Estimate memory usage of a Java applet
- Estimate time usage for a method call
- Checking pre and post conditions

C programs: static analysis

When you have a poor language – and a poor type system – use static analysis to improve error detection:

- Example in point: a severe X-Windows security bug was detected by the Coverity static analysis tool
- Code fragment to check permissions:

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- But was incorrectly written:

```
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```

- The bug (expression always true!) was not detected by the GCC compiler, and thus stayed as a security problem . . .
- Many static analysis tools attempts to detect security problems in C programs from buffer overruns etc

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- Microsoft has developed a range of tools for static analysis: Microsoft PREfix, PREfast and SDV (Static Driver Verifier)

  These tools check device driver specific rules: does a 3rd party device driver interact correctly with the Windows kernel?

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- **Advantages**: automatic method, scales to reasonably sized programs
- **Disadvantages**: often a rather coarse analysis (need to over-approximate, to over-abstract, results in many false positives)

Systematic Testing

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  - Or. . . how to write as few tests as possible
  - How to **automate** tests? For instance, in a GUI, how to measure that the visual presentation is correct?

Testing Experiences

- Many products are difficult to test because they are deployed in challenging environments that cannot be simulated before deployment (AXD-301 telephone switch) or simply have huge state spaces
- Example: around 10.000 tests are used for the AXD 301 telephony switch

Testing

What to test:

- **Unit testing** (a method, a function, . . .)
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Testing trends: **test-driven development (TDD)**

- Write tests early (before software is written)
- Write code to satisfy tests
- Refactor code

Testing with contracts

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  - For concurrent systems, test are expressed as properties over execution traces

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- Counterexamples are simplified

QuickCheck variants

QuickCheck is rather successful; note the number of tools developed for different languages:

- QuickCheck/Haskell (the original)
- QuickCheck/Erlang (the commercial variant)
- QuickCheck/Java
- QuickCheck/Scala
- QuickCheck/Perl, QuickCheck/Python, . . .

Hint: a good exercise is to use QuickCheck/XXX for working with an exercise. . .

QuickCheck example

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- In Quickcheck/Erlang:

```
commutes() ->
    ?FORALL(X,set(),?FORALL(Y,set(),
        sets:union(X,Y) == sets:union(Y,X))).
```

  - `set()` is a test data generator (with a probability distribution)
  - `?FORALL(X,set(),...)` expresses that the variable `X` should be bound to set values,
  - `sets:union(X,Y) == sets:union(Y,X)` uses normal Erlang term equality `==` for set equality

Test Results

- `quickcheck(commutes)` generates a set of test data (sets X, Y), and finds a counterexample: `X={-6,7,11,10,2}` and `Y={7,1,-4,11,-7}`

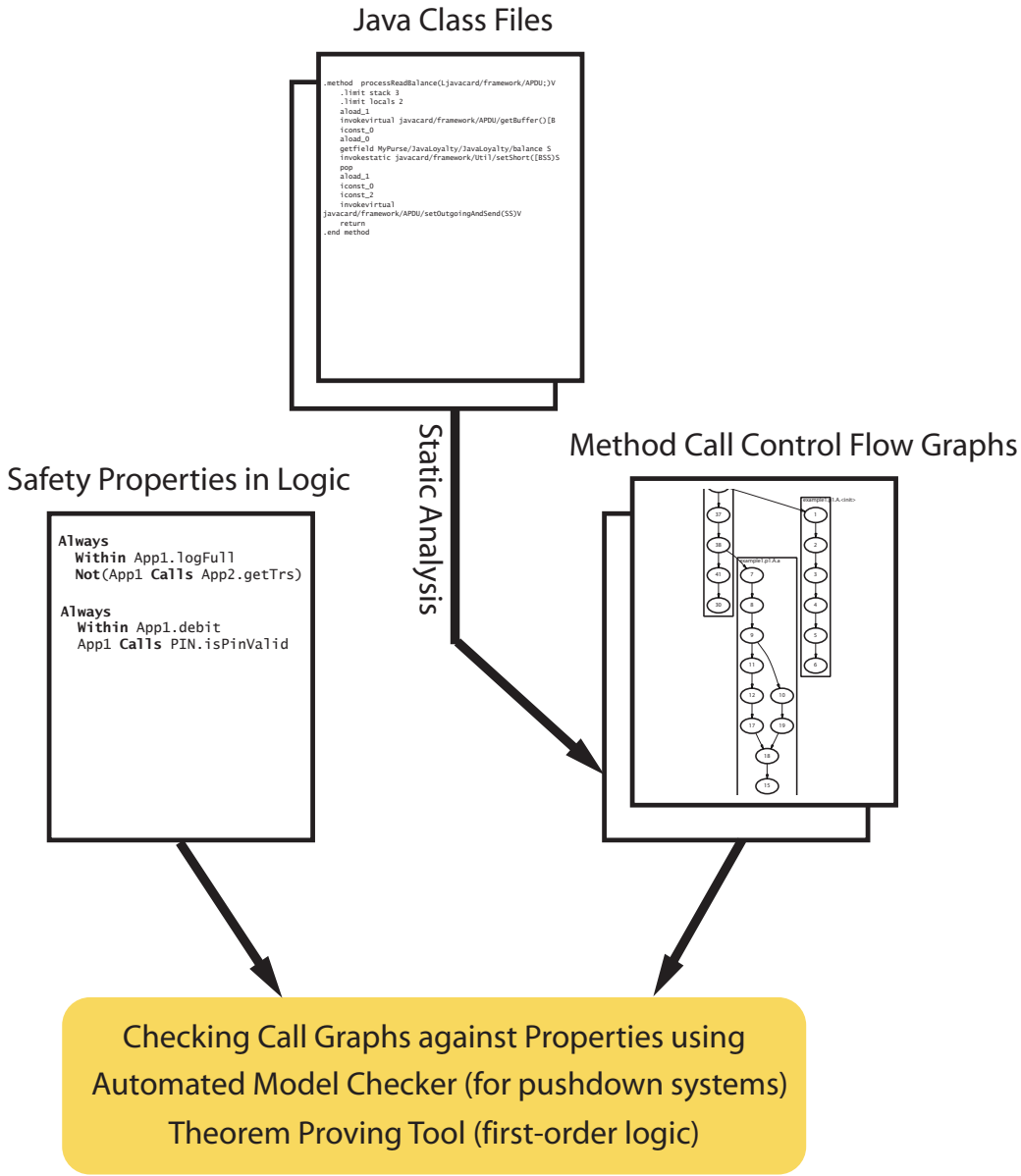
Test Results

- `quickcheck(commutes)` generates a set of test data (sets X, Y), and finds a counterexample: `X={-6,7,11,10,2}` and `Y={7,1,-4,11,-7}`
- Why? `sets:union` can represent sets in different ways: `[1,2]` and `[2,1]` may both be the internal representation of the Erlang set $\{1, 2\}$ but `[1,2] =/= [2,1]`
- Not a bug in the `sets` class but in our test. Happens often.
- How to fix? Use a different equality test.

Model Checking

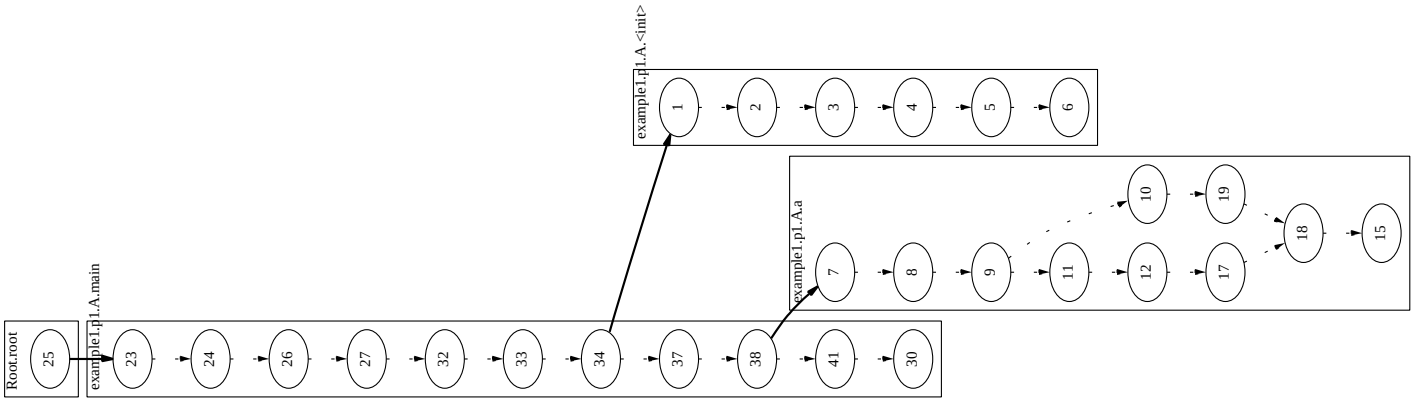
- Idea: **Construct** an abstract **model** of the behaviour of the program, usually a finite state transition graph
- **Check** the abstract model, against some description of desirable/undesirable model properties usually specified in a **temporal logic**
- Usually applied to **reactive systems** (systems that continously react to stimuli)
- Advantage: automatic push button technology
- Disadvantages:
  - Doesn't scale well to larger programs (the model of the behaviour of the program becomes too big)
  - How to construct a faithful model?

Model Checking: an example



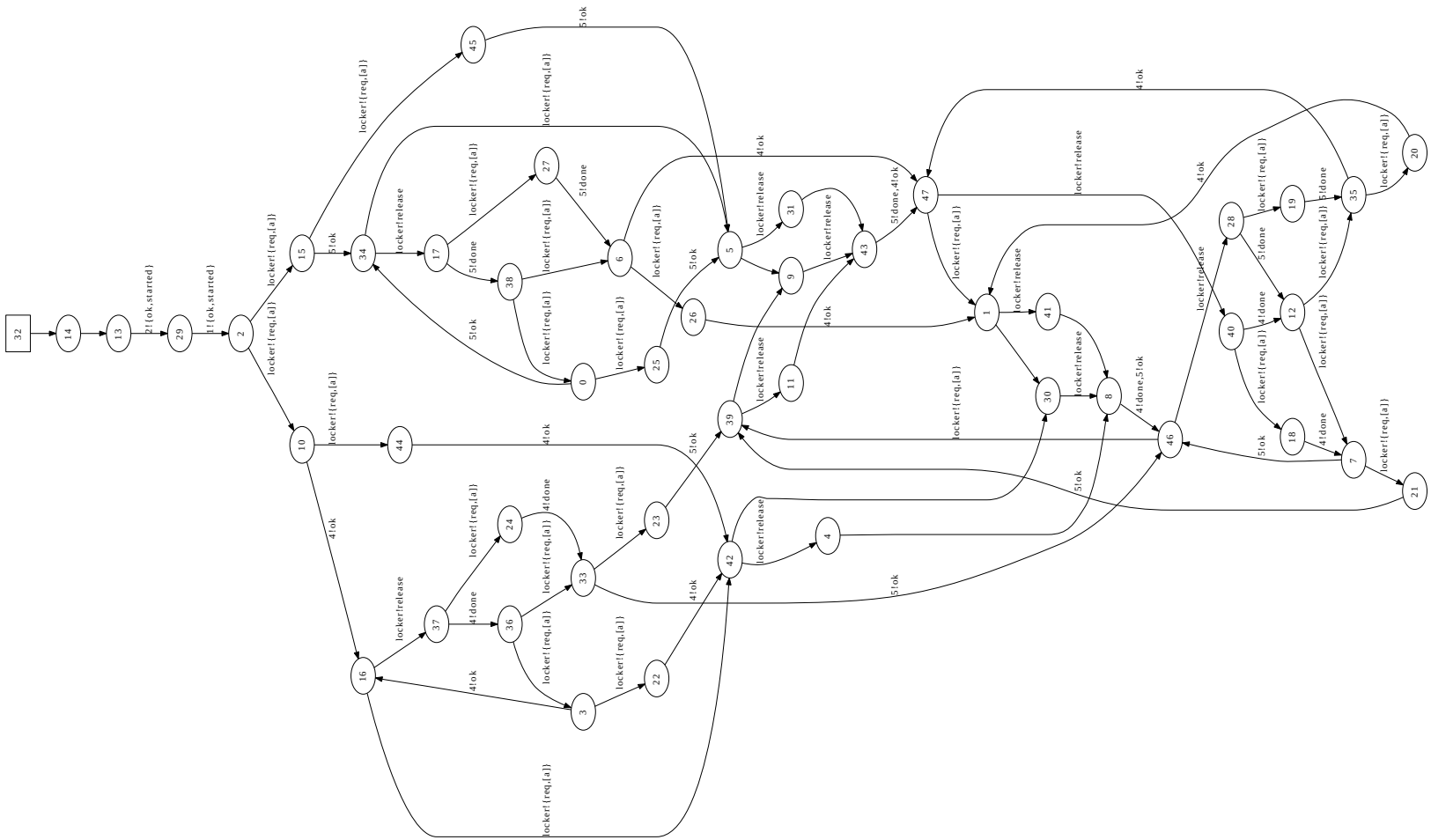
Abstract Model

- Model (method call-graph) extracted using static analysis
- Graph edges are method calls and in–method control flow
- Data is abstracted away – the result is a non-deterministic graph



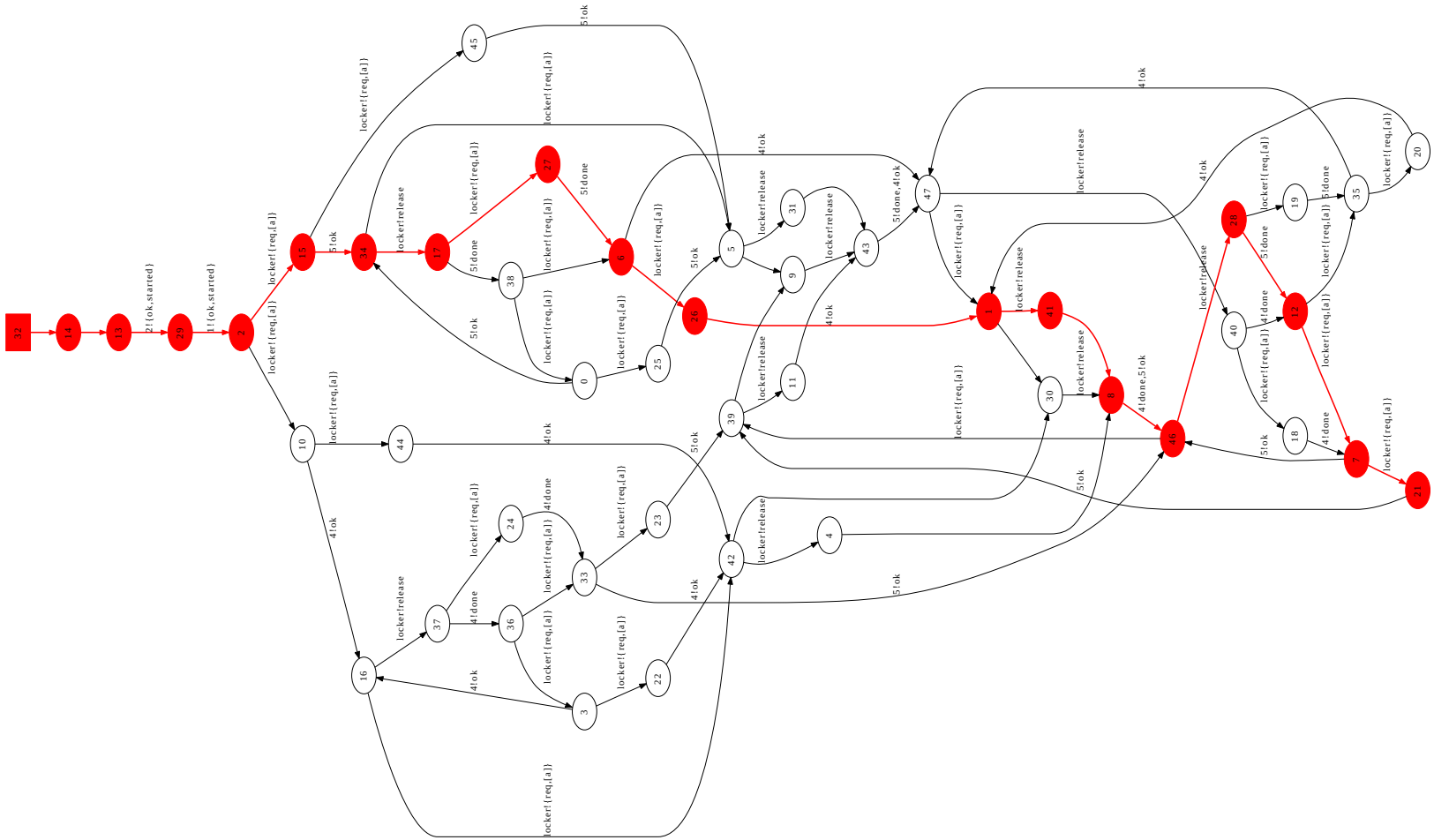
Comparison with Random Testing

The State Space of a small program:



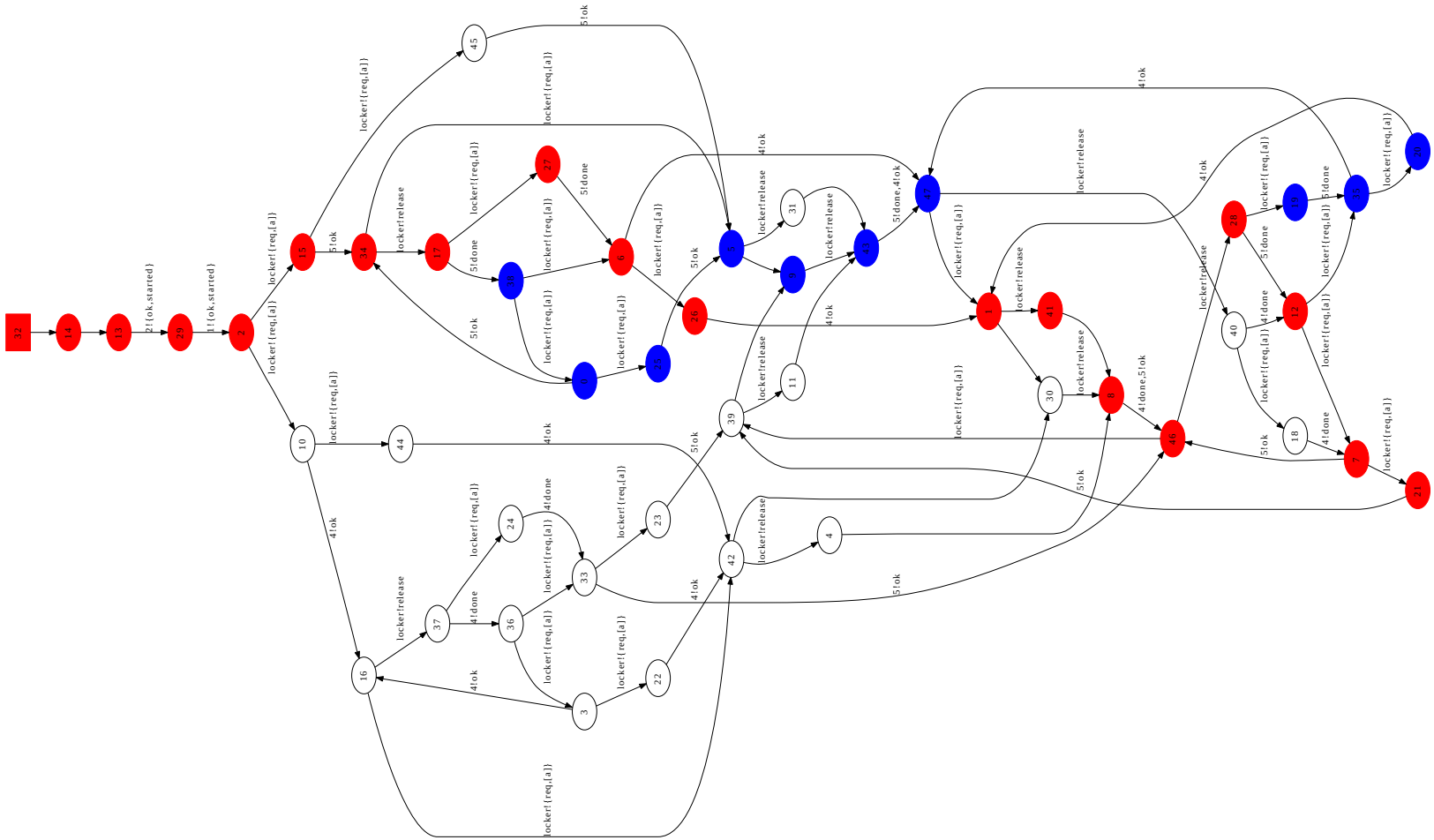
Testing, run 1:

Random testing explores one path through the program:



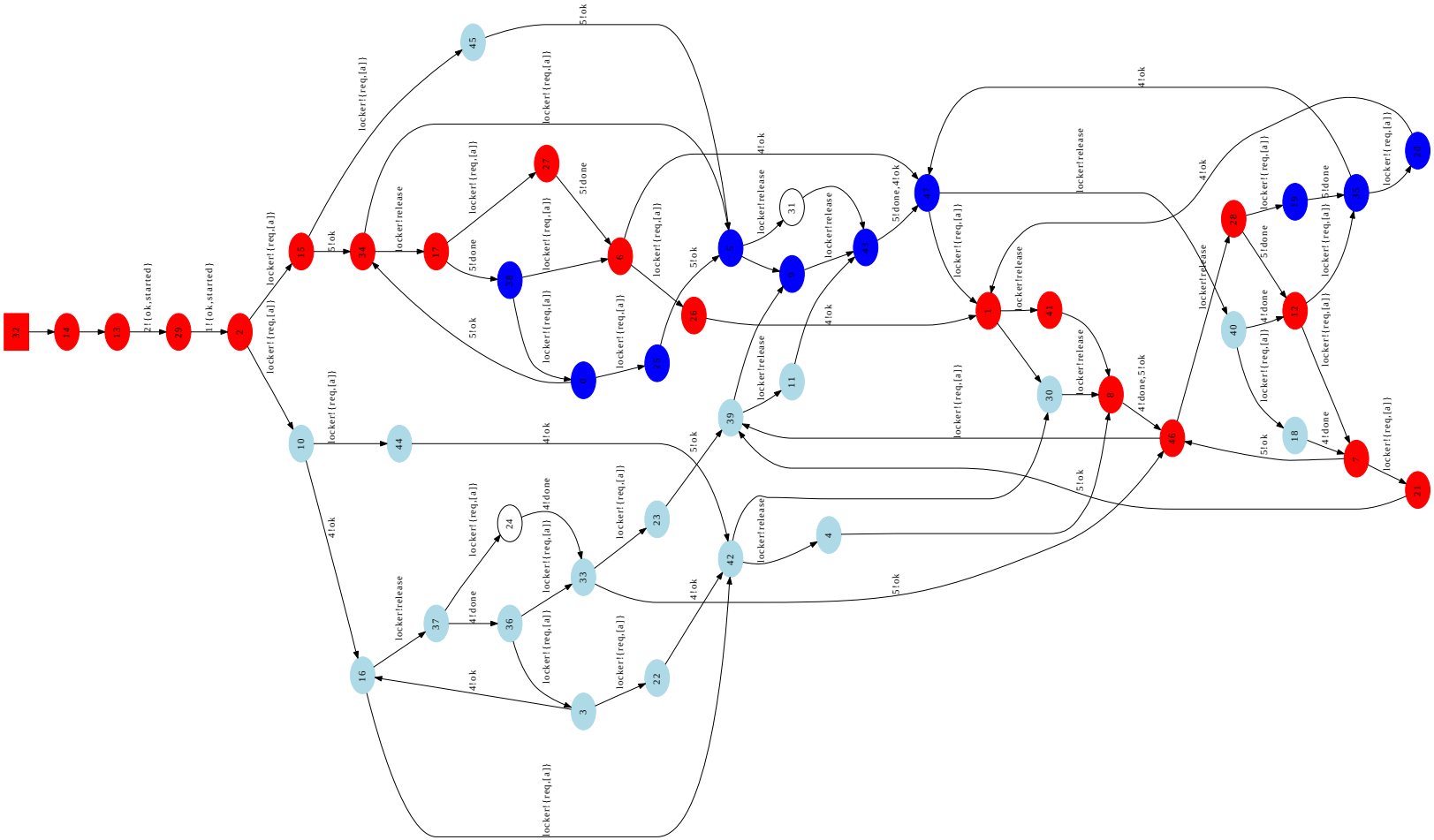
Testing, run 2:

With repeated tests the coverage improves:



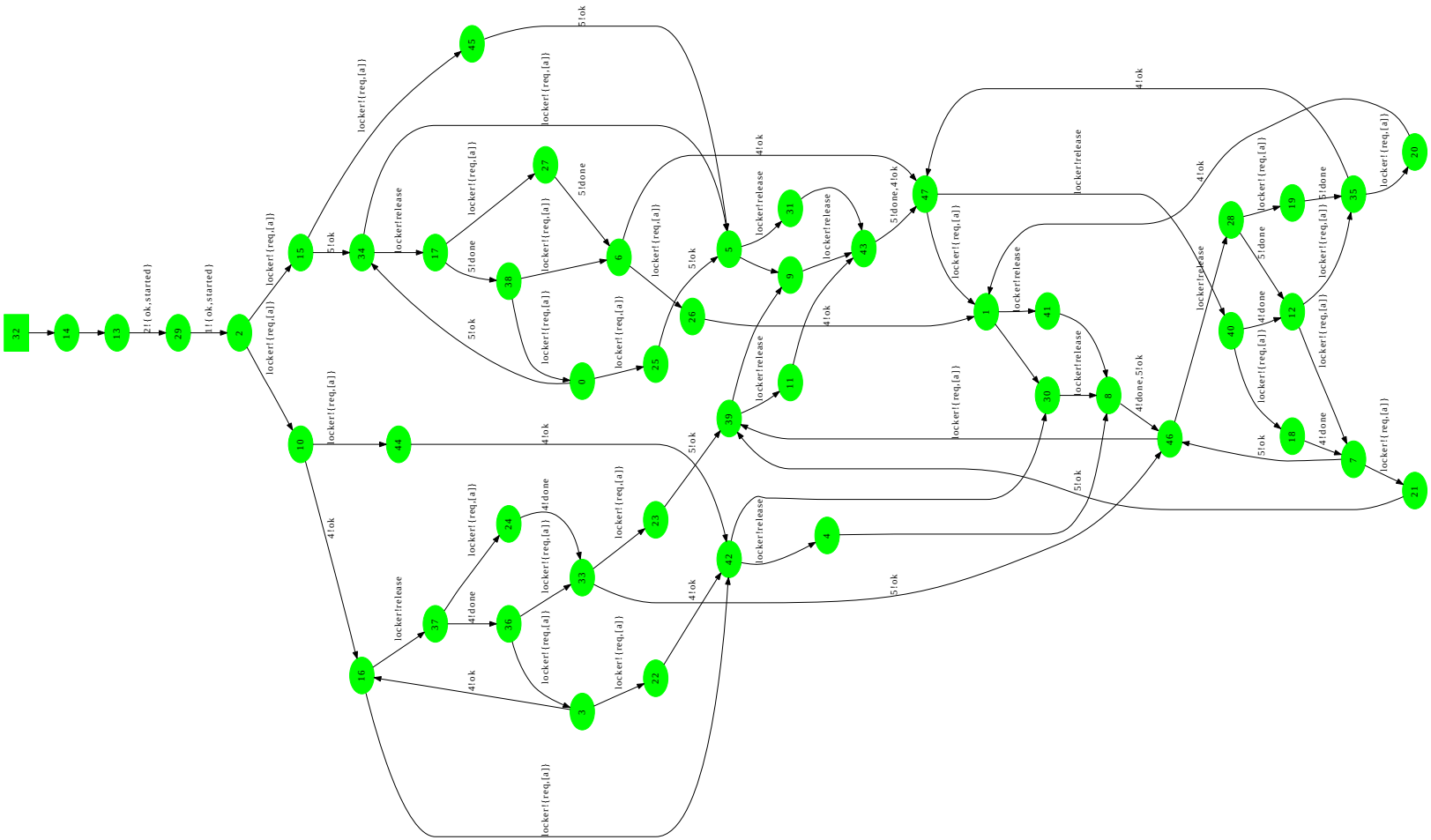
Testing, run n:

But even after a lot of testing some program states may not have been visited:



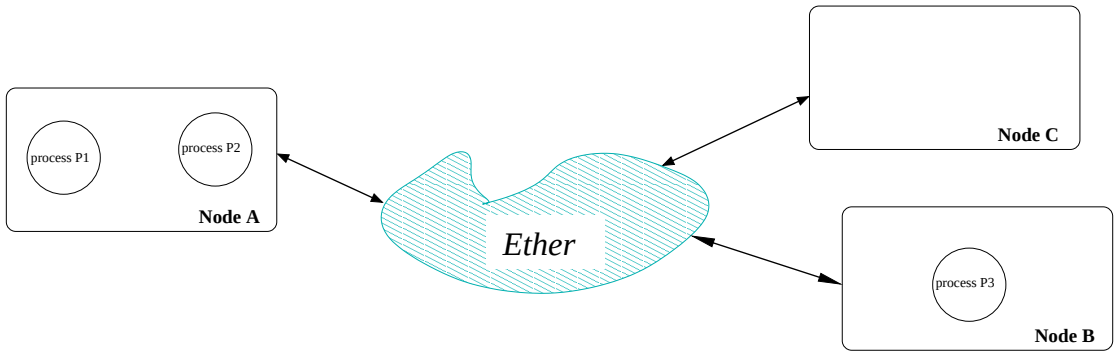
Model checking: 100% coverage

Model checking can guarantee that all states are visited, without revisiting states



What is the trick? How can we achieve 100% coverage

- Needed: the capability to take a **snapshot** of the model checked program (its program state)
  - A **program state** of an Erlang program is: the contents of all process mailboxes, the state of all running processes, messages in transit, . . .



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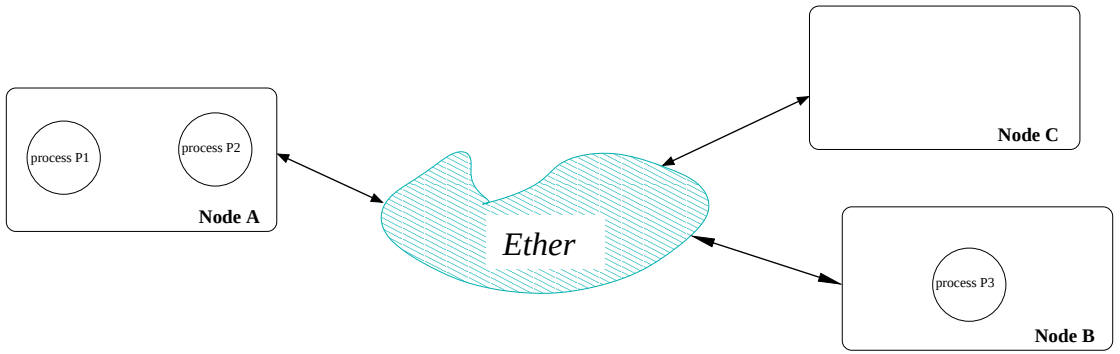
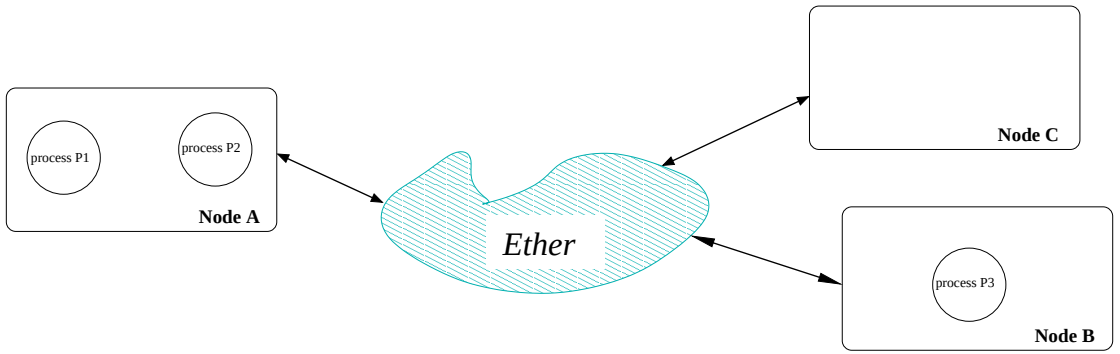


- Save the snapshot to memory and forget about it for a while
- Later continue the execution from the snapshot

What is the trick? How can we achieve 100% coverage

- Needed: the capability to take a **snapshot** of the model checked program (its program state)
  - A **program state** of an Erlang program is: the contents of all process mailboxes, the state of all running processes, messages in transit, . . .



- Save the snapshot to memory and forget about it for a while
- Later continue the execution from the snapshot
- **Difficulties**: too many states (not enough memory/time to save snapshots)

Examples of Model Checkers

- For Java: Java PathFinder
- For C: (SPIN), BLAST, CBMC, …
- For “abstract specifications”: NuSMV, …
- For multi-threaded Win32 programs: Chess

Theorem Proving

- In its pure form: develop a proof manually, have a computer **check the proof** steps
- For example checking our Hoare-style proofs:

$$\frac{A \supset I \qquad \{I \wedge E\}\ C\ \{I\} \qquad (I \wedge \neg E) \supset B}{\{A\}\ \texttt{while}\ E\ \texttt{do}\ C\ \{B\}}$$

- Contemporary theorem provers help in **developing** and **finding proofs** as well
- Many first-order logic theorem provers are **completely automated today!**
- Integrates well with certain formal methods: Z, B–method where proof obligations are generated automatically and theorem provers are used to prove each proof obligation

Theorem proving

Example: checking whether the Z operation schema

$$
\begin{array}{|l}
\hline
\mathit{BadOp} \\
\Delta \mathit{Queue} \\
\mathit{insert}? : \mathbb{N} \\
\mathit{result}! : \mathit{Result} \\
\hline
\mathit{queue}' = \mathit{queue} \frown \langle \mathit{insert}? \rangle \\
\mathit{result}! = \mathit{ok} \\
\hline
\end{array}
$$

violates the state invariant

$$
\begin{array}{|l}
\hline
\mathit{Queue} \\
\mathit{queue} : \mathit{seq}\ \mathbb{N} \\
\hline
\# \mathit{queue} < 10 \\
\hline
\end{array}
$$

is a typical theorem proving task

Theorem Proving

Conclusions:

- **Positive**: very powerful technique, everything we know how to prove can be checked carefully
- **Negative**: generally not very cost effective in time and qualified manpower needed

Java and the Java Modelling Language

- To illustrate some of these validation techniques (design-by-contract, static analysis) we will be using Java and the Java Modelling Language (JML)
- But there are many other tools too. . .
- **Microsoft Research** are very active; tools
  - **Spec#** for C#: uses automatic theorem proving similar to ESC/Java2 below
  - **Code Contracts** for .NET based applications:
    Enables the user to write pre and post conditions
    Implemented using abstract interpretation
    For (C#, Visual Basic, . . .)
  - **Chess** for checking concurrent programs

Hint: a good exercise is to use Spec# or Code Contracts for working with an exercise. . .

The Java Modelling Language – JML

- Annotates Java methods and class descriptions with contract information as comments
- Example:

```
/*@ requires x >= 0.0;
  @ ensures JMLDouble.approxEqualTo
  @           (x,\result * \result);
  @*/
public static double sqrt(double x) {
  ...
}
```

- `requires` specifies the callers obligation
- `ensures` specifies the method guarantee
- `ensures` speaks about normal termination of the method; exceptional termination can be specified as well

The Java Modelling Language – JML, part II

- Universal and existential quantifiers are supported:

```
/*@ requires a != null
  @ && (\forall int i;
        0 < i && i < a.length;
        a[i-1] <= a[i]);
  @*/
  int binarySearch(int[] a, int x) { ... }
```

- *Pure* methods can be used in contracts; suppose the *pure* method *sorted* checks whether an array is sorted:

```
//@ requires a != null && sorted(a);
int binarySearch(int[] a, int x) { ... }
```

- Object invariants characterise object state properties (both caller visible and object internal state)

```
//@ public invariant weight>0;
public class person { public int weight; ... }
```

The Java Modelling Language – JML, part III

- `\result` describes the return value of the method
- `assignable` lists the state variables that may be modified by the method
- `old(variable)` references the old (before the method call) value of `variable`

A Class Example

An example class:

```
public class Purse {
 int balance;

int debit(int amount) throws PurseException {
  if (amount <= balance) {
    int saved_balance = balance;
    balance -= amount;
    return saved_balance;
  }
  else throw new PurseException();
} }
```

A Specified Class Example

The same class extended with contract specification information:

```
public class Purse {
 //@ invariant 0 <= balance;
 int balance;

/*@ requires amount >= 0;
  @ assignable balance;
  @ ensures balance == \old(balance)-amount
  @         && \result == \old(balance); @*/

int debit(int amount) throws PurseException {
  if (amount <= balance) {
    int saved_balance = balance;
    balance -= amount;
    return saved_balance;
  }
  else throw new PurseException();
} }
```

Tool Support for JML: Runtime Checking

After lots of API specification. . .

- The JML compiler compiles Java programs with embedded preconditions, postconditions and invariants
- These conditions and invariants are embedded with the code and checked at runtime

JML Testing

- The **jmlunit** tool is used for testing JML annoted Java programs
- Testing errors are reported only for methods called with correct pre–conditions that fail their post–conditions
- Test data (method parameters) is *not* automatically generated; a user must supply such data
- In comparison the testing tool QuickCheck for Haskell and Erlang seem more convenient to use

Tool Support for JML

- The ESC/Java2 tool permits to do limited static checking of Java programs annotated with JML specifications, *at compile-time*, before *runtime*
- Can check simple conditions such as dereferencing the `null` pointer (`person.name` when `person==null`)
- and whether array accesses can be out-of-bounds
- and precondition violation checking (but not fully)
- Checking is done internally using a first-order automatic theorem prover
- Works best for checking against a simple or restricted API:s, e.g., JavaCard (Java on a SmartCard)
- The prover needs domain specific help

A simple ESC/Java2 example

- Lets design a simple Bag class that stores elements in an array `a`, and has a constructor which initialises the array from a parameter:

```
class Bag {
  /*@ non_null */ int[] a;
  int n;
  //@ invariant 0 <= n && n <= a.length;

  public Bag(int[] input) {
    n = input.length;
    a = new int[n];
    System.arraycopy(input, 0, a, 0, n);
  }
  ...
}
```

- Note that the class variable `a` must be non-null always, and that `n` is bounded by the length of the array `a`

A simple ESC/Java2 example, part II

- What happens when we run the ESC/Java2 static checker?

A simple ESC/Java2 example, part II

- What happens when we run the ESC/Java2 static checker?

```
> ../escjava2 Bag.java

Bag: Bag(int[]) ...
-----------------------------------------------
BadBag.java:7: Warning: Possible null dereference (Nu
    n = input.length;
```

- Aha. Maybe there is a bug. . . ?
  Yes! What if the input parameter is null!

Fixing the example

- Lets stipulate a contract that the caller has to provide a non-null parameter:

```
class Bag {
  /*@ non_null */ int[] a;
  int n;
  //@ invariant 0 <= n && n <= a.length;

  //@ requires input != null;
  public Bag(int[] input) {
  ...
  }
}
```

- Lets try:

```
> ../escjava2 Bag.java
```

- No warnings generated!

A simple ESC/Java2 example, part III

- Lets add a user of the Bag class:

```
class User {
  Bag bag;
  User() { bag = new Bag(null); }
}
```

- and run the analysis again. What happens?

A simple ESC/Java2 example, part III

- Lets add a user of the Bag class:

```
class User {
  Bag bag;
  User() { bag = new Bag(null); }
}
```

- and run the analysis again. What happens?

```
> ../escjava2 Bag.java User.java

User: User() ...
-----------------------------------------------------
BadBag.java:16: Warning: Precondition possibly not es
    User() { bag = new Bag(null); }
                       ^
Associated declaration is "BadBag.java", line 6, col
  //@ requires input != null;
      ^
```

A simple ESC/Java2 example, part IV

- Clearly User didn’t fulfil the precondition for creating a Bag

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A simple ESC/Java2 example, part IV

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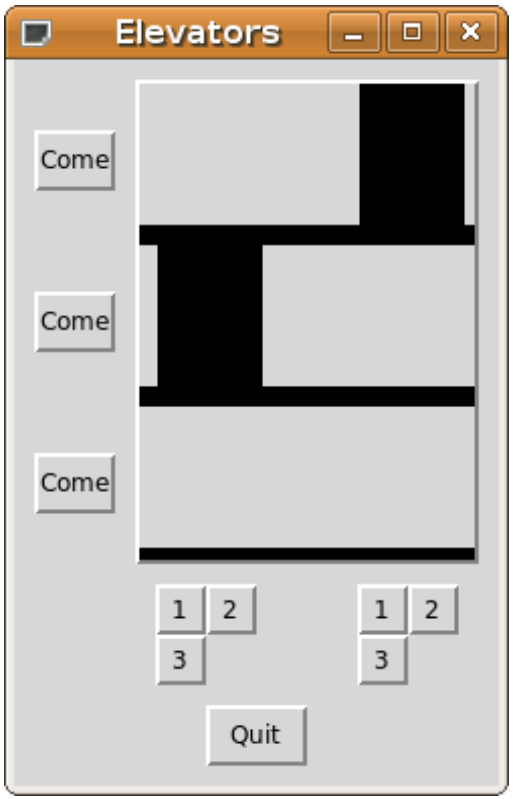
Model Checking – and building models

To illustrate model checking of components, and building models, lets us consider a reactive system: **the control software for a set of elevators**



Elevator Control Software

- Control software written in Erlang

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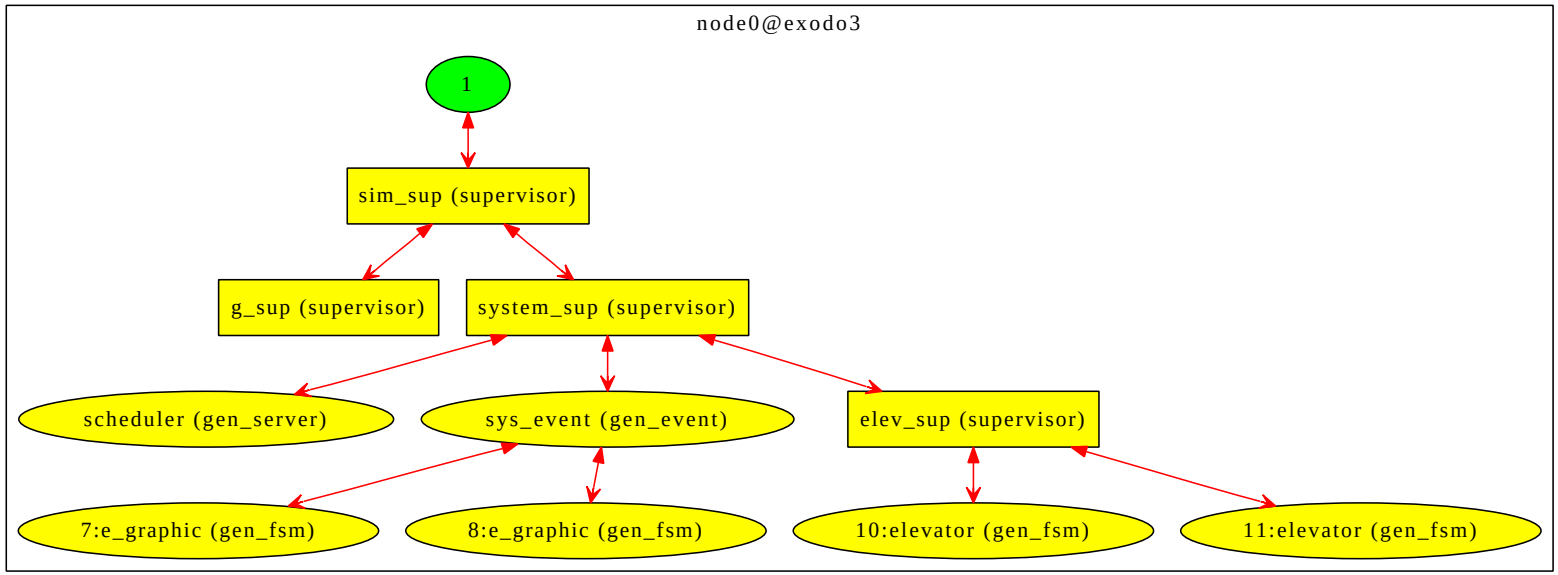
- Control software written in Erlang
- Static code complexity: around 1670 lines of code
- Dynamic complexity: around 10 processes (for two elevators)



Correctness Properties for the Elevator System

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Formulating Correctness Properties

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Formulating Correctness Properties

- How to formulate a property like: “an elevator only stops at a floor after receiving an order to go to that floor”?
- We can borrow an idea from runtime monitoring: we write a monitor that *detects* when the above property is violated
- Seen from another viewpoint we have created a *model* for the elevator system
- The model only describes a *small subset* of the behaviour of the elevator – but that is fine, it is what models are supposed to do

  So we have to write more monitors and properties. . .

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- Has an internal state, which can be updated when the program does a *significant* action (or something happens – *a button press*)
- The monitor should signal an error if an action happens in an incorrect state

A Correctness Monitor

Which elevator actions do the monitor need to react to?

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A Correctness Monitor

Which elevator actions do the monitor need to react to?

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- The arrival of the elevator at a floor

State and Correctness Check

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State and Correctness Check

- What is the state of the monitor?

  A data structure that remembers orders to go to a certain floor

- What is the correctness check?

  When the elevator arrives at a floor, the order to do so is in the monitor state

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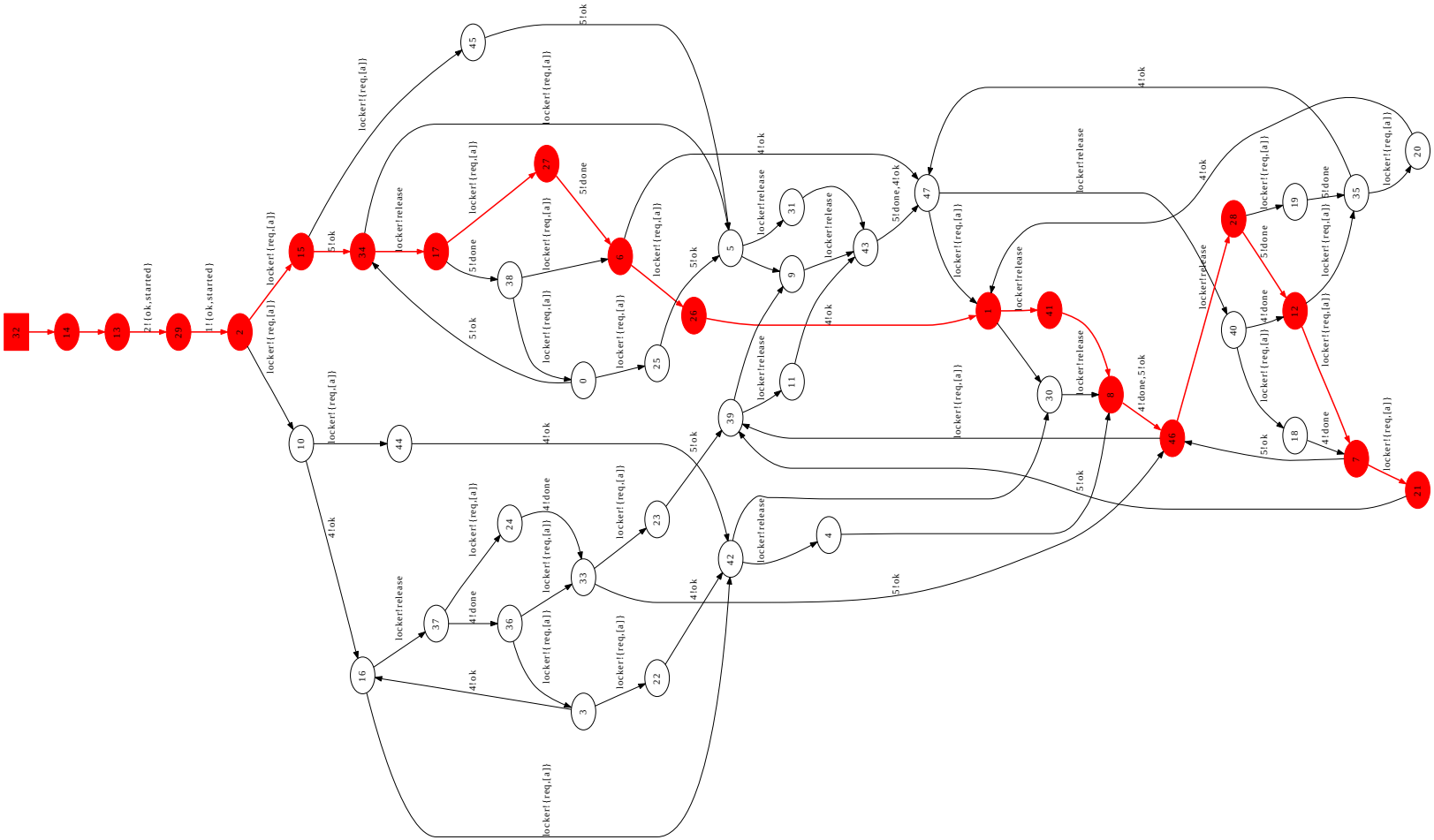
Checking Monitors

How to **Check** a Monitor?

- Well we can use runtime monitoring = testing
- **Note:** since the elevator control system is a nondeterministic reactive system we have to rerun the same test many times! (not so for sequential software)
- Using model checking is a viable alternative

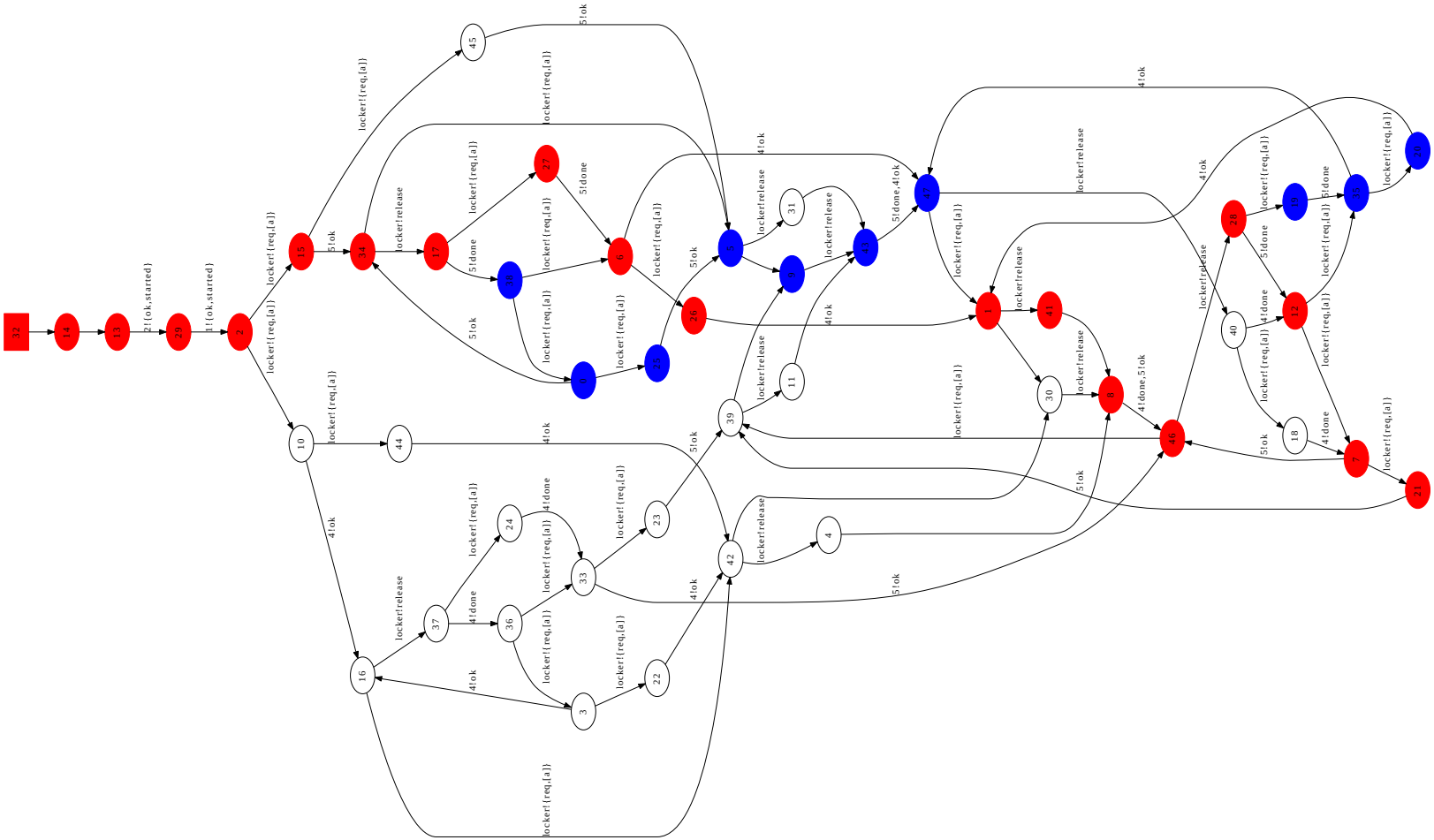
Model Checking vs Random Testing

Random testing explores one path through the program:



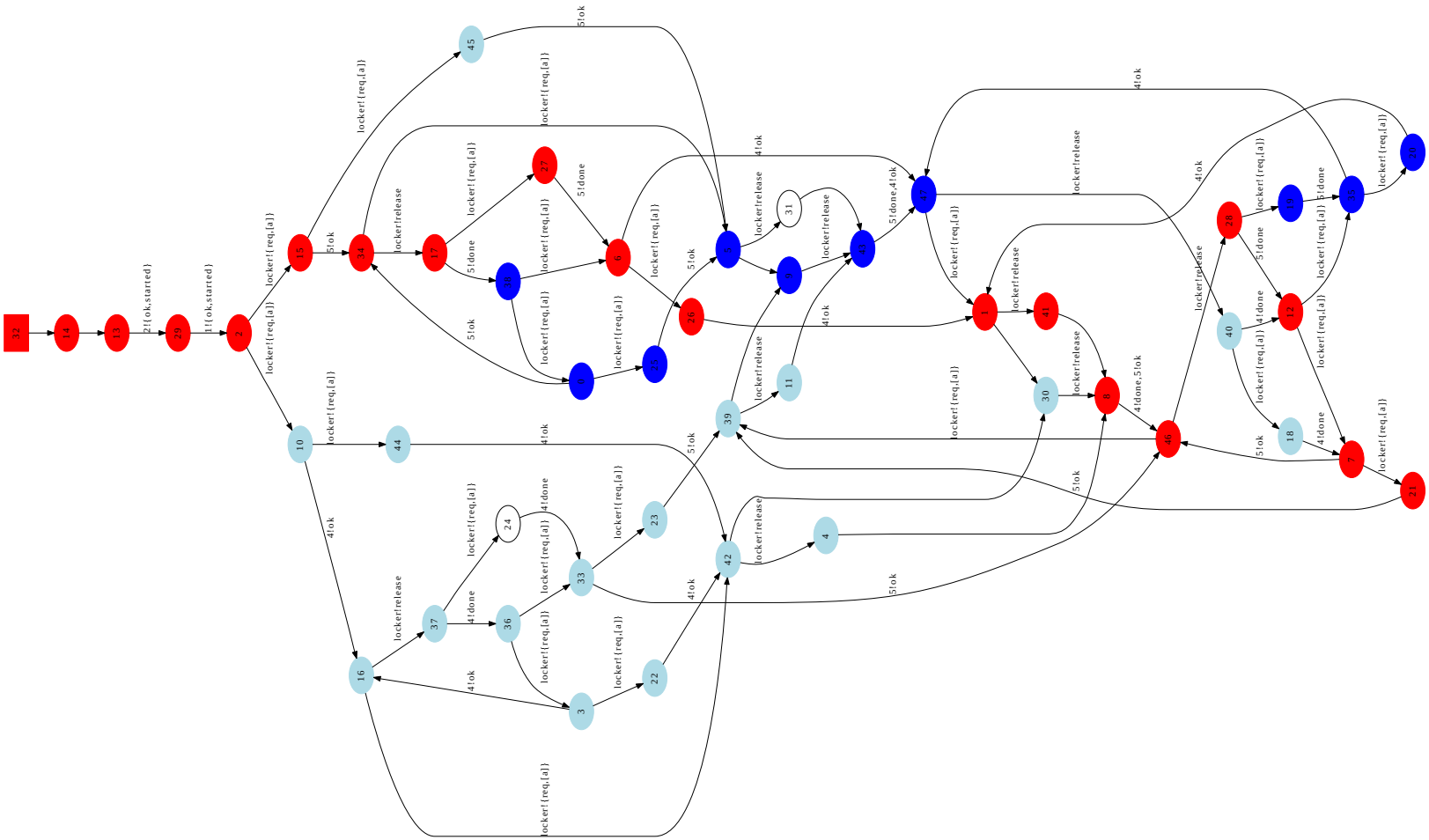
Model Checking vs Random Testing

With repeated tests the coverage improves:



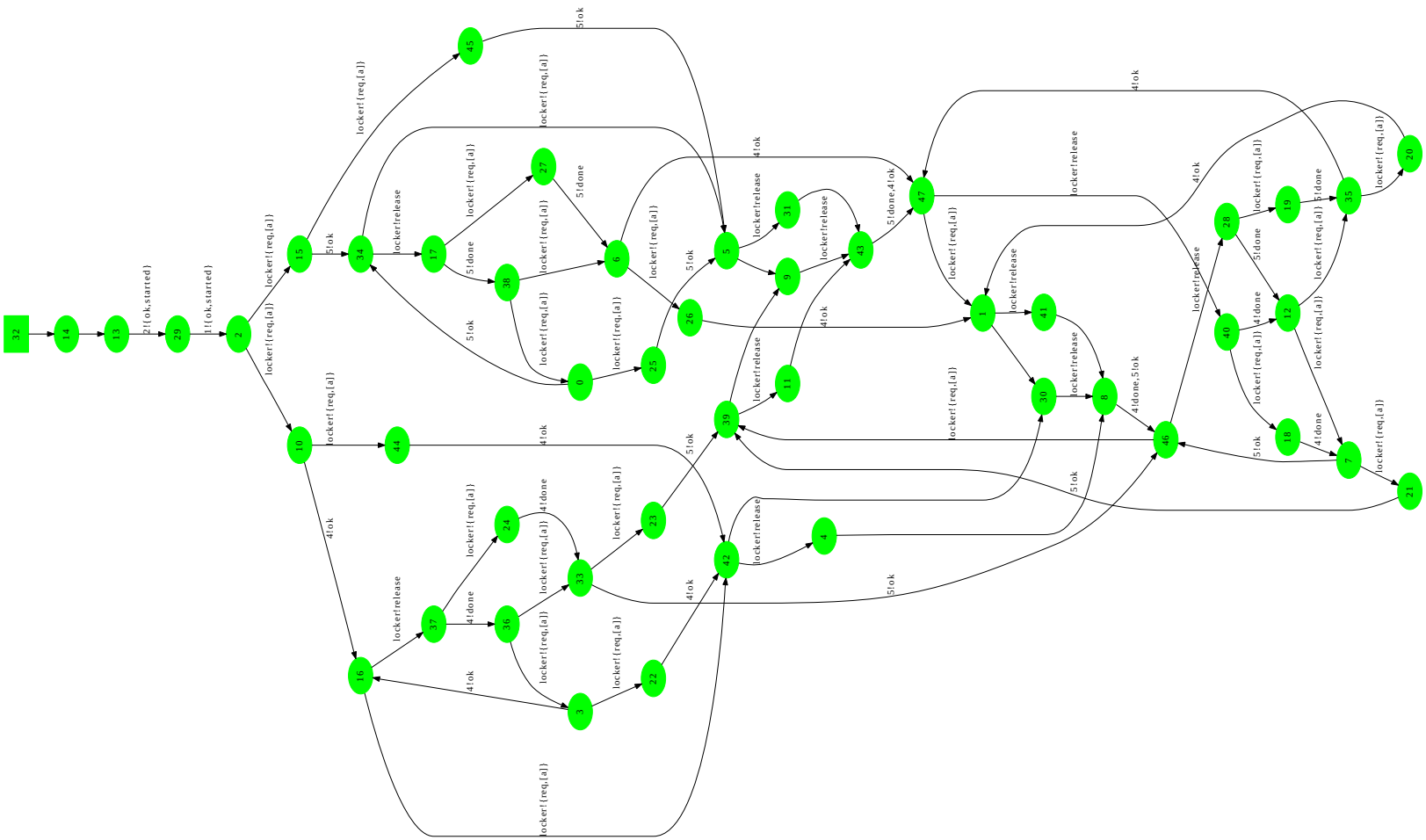
Model Checking vs Random Testing

But even after a lot of testing some program states may not have been visited:



Model Checking vs Random Testing

Model checking can guarantee that all states are visited, without revisiting states



Model Checking the Lift Example

- We use the **McErlang** model checker

Model Checking the Lift Example

- We use the **McErlang** model checker
- Correctness property spec:

```
stateChange(_,FloorReqs,Action) ->
  case Action of
    {f_button,Floor} ->
      ordsets:add_element(Floor,FloorReqs);
    {e_button,Elevator,Floor} ->
      ordsets:add_element(Floor,FloorReqs);
    {stopped_at,Elevator,Floor} ->
      case ordsets:is_element(Floor,FloorReqs) of
        true -> FloorReqs;
        false -> throw({bad_stop,Elevator,Floor})
      end;
    _ -> FloorReqs
  end.
```

- Uses ordered sets (`ordsets`) to store the set of floor orders (the state of the monitor)

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  - Elevator button 2 pressed, Floor button 2 pressed, Floor button 2 pressed
  - …
- But because we are using model checking we explore every scenario fully

More Correctness Properties

- Refining the floor correctness property:

  An elevator only stops at a floor after receiving an order to go to that floor, if no other elevator has met the request

  (implemented as a monitor that keeps a set of floor requests; visited floors are removed from the set)

Other Correctness Properties

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- The floor correctness property is a safety property (*nothing bad ever happens*)
- A Liveness property:
  If there is a request to go to some floor, eventually some elevator will stop there
- In temporal logic:

```
always
   (fun go_to_floor/3) =>
      next(eventually (fun stopped_at_floor/3))
```

- The state predicate `fun go_to_floor/3` is satisfied when an elevator has received an order to go to a floor
- The state predicate `fun stopped_at_floor/3` is satisfied when an elevator stops at a floor

Model Checking

Conclusions:

- **Positive**: automatic technique, can prove difficult (concurrent) programs correct
- **Negative**:
  - model construction is far from automatic, great care needed in constructing a verifiable model
  - how to make sure the right properties are checked?