Erlang and the McErlang Model Checker

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Talk Overview

- The Erlang programming language

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- McErlang: a tool for model checking Erlang programs (short intros to model checking and linear temporal logic)

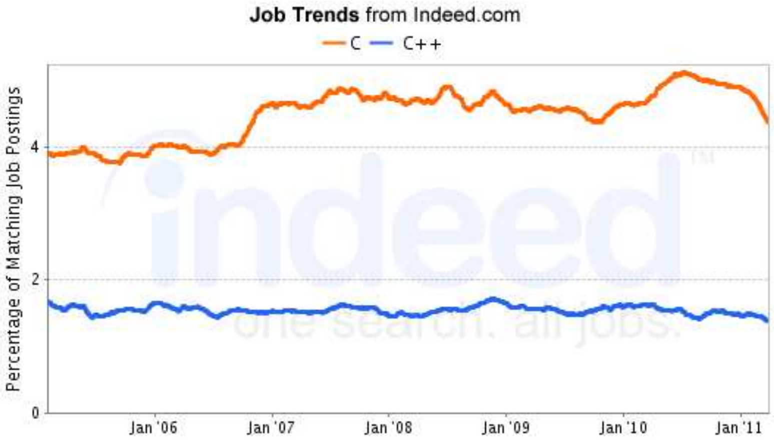
Part 1: Erlang

Erlang/OTP History

- Erlang language born in 1983 at Ericsson
- Used inside and outside Ericsson for implementing challenging concurrent and distributed applications
- Application example: High-speed ATM switch developed in Erlang (2 million lines of Erlang code), C code (350 000 lines of code), and 5 000 lines of Java code
- Other examples: parts of Facebook chat written in Erlang (70 million users), CouchDB (integrated in Ubuntu 9.10), users at Amazon, Yahoo, . . .
- In Spain: Tuenti, LambdaStream (A Coruña), . . .
- Open-source; install from `http://www.erlang.org/`

Erlang is becoming popular

C and C++ job offers over the last 5 years:



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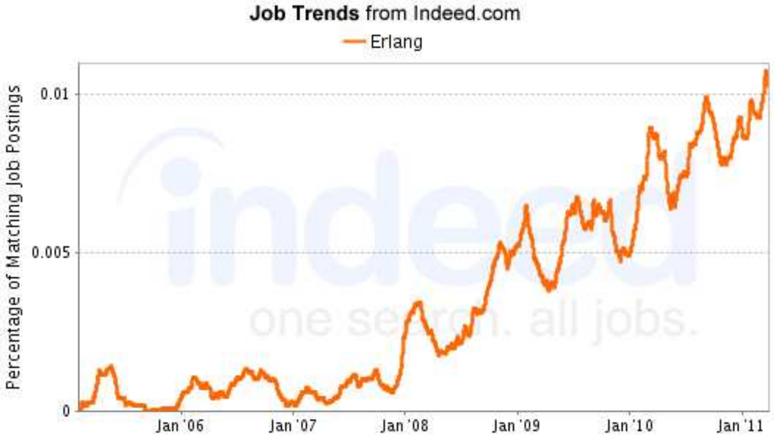

Erlang as a source of inspiration

- Ideas from Erlang are also influencing other programming languages and libraries like Scala, Node.js, Clojure, …
- So lets see the main features…

Erlang/OTP

- Basis: a general purpose functional programming language
- Automatic Garbage Collection
- With lightweight processes
  (in terms of creation time and memory requirements)
  Typical software can make use of many thousands of processes; **smp** supported on standard platforms
- Support for fault-tolerance and distributed computation in the programming language!
- Implemented using virtual machine technology
  Available on many OS:es (Windows, Linux, Solaris, . . .)
- Supported by extensive libraries:
  OTP – open telecom platform – provides design patterns, distributed database, web server, etc

Erlang basis

A simple functional programming language:

- Simple data constructors:
  integers (`2`), floats (`2.3`), atoms (`hola`), tuples (`{2,hola}`) and lists (`[2,hola]`,`[2|X]`), functions, records (`#process{label=hola}`), bit strings (`<<1:1,0:1>>`)
- Call-by-value
- Variables can be assigned once only (Prolog heritage)
- *No static type system!*
  That is, expect runtime errors and exceptions
- Similar to a scripting language (python, perl) – why popular?

Erlang basis, II

- Example:

```
fac(N) ->
  if
      N == 0 -> 1;
      true -> N*fac(N-1)
  end.
```

Variables begin with a capital (`N`)
Atoms (symbols) begin with a lowercase letter (`fac`, `true`)

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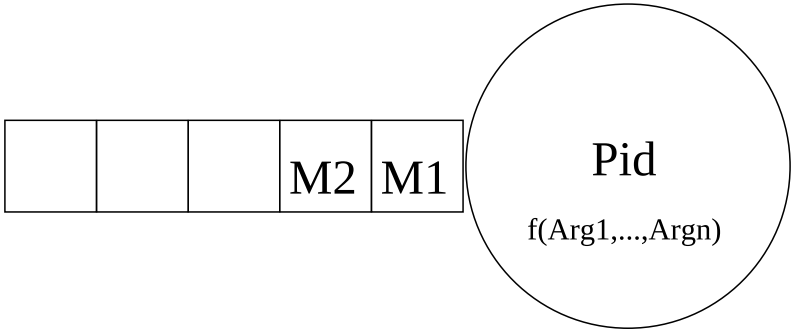
- And this call is permitted (what happens?): `fac(0.5)`

Concurrency and Communication

- Concurrency and Communication model inspired by the *Actor model* (and earlier Ericsson software/hardware products)
- Processes execute Erlang functions
- No implicit sharing of data (shared variables) between processes
- Two interprocess communication mechanisms exists:
    - processes can send asynchronous messages to each other (**message passing**)
    - processes get notified when a related process dies (**failure detectors**)

Erlang Processes



- Processes execute Erlang functions ($f(Arg1, \ldots, Argn)$)
- A process has a unique name, a **process identifier** (Pid)
- Messages sent to a process is stored in a **mailbox** ($M2$, $M1$)

Erlang Communication and Concurrency Primitives

- Sending a message to a process:

```
Pid!{request, self(), a}
```

- Retrieving messages from the process mailbox (queue):

```
receive
  {request, RequestPid, Resource} ->
      lock(Resource), RequestPid!ok
end
```

- Creating a new process:

```
spawn(fun () -> locker!{request,B} end)
```

- A name server assigns symbolic names to processes:

```
locker!{request,a}
```

Communication Primitives, receiving

Retrieving a message from the process mailbox:

```
receive
  $pat_1$ when $g_1$ -> $expr_1$ ;
  ...;
  $pat_n$ when $g_n$ -> $expr_n$
  after time -> expr'
end
```

- pat_1 is matched against the oldest message, and checked against the guard g_1. If a match, it is removed from the mailbox and $expr_1$ is executed
- If there is no match, pattern pat_2 is tried, and so on…
- If no pattern matches the first message, it is kept in the mailbox and the second oldest message is checked, etc
- `after` provides a timeout if no message matches any pattern

Receive Examples

- Given a receive statement:

```
receive
    {inc,X} -> X+1;
    Other -> error
end
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and the queue is $a \cdot \{inc, 5\}$ what happens?

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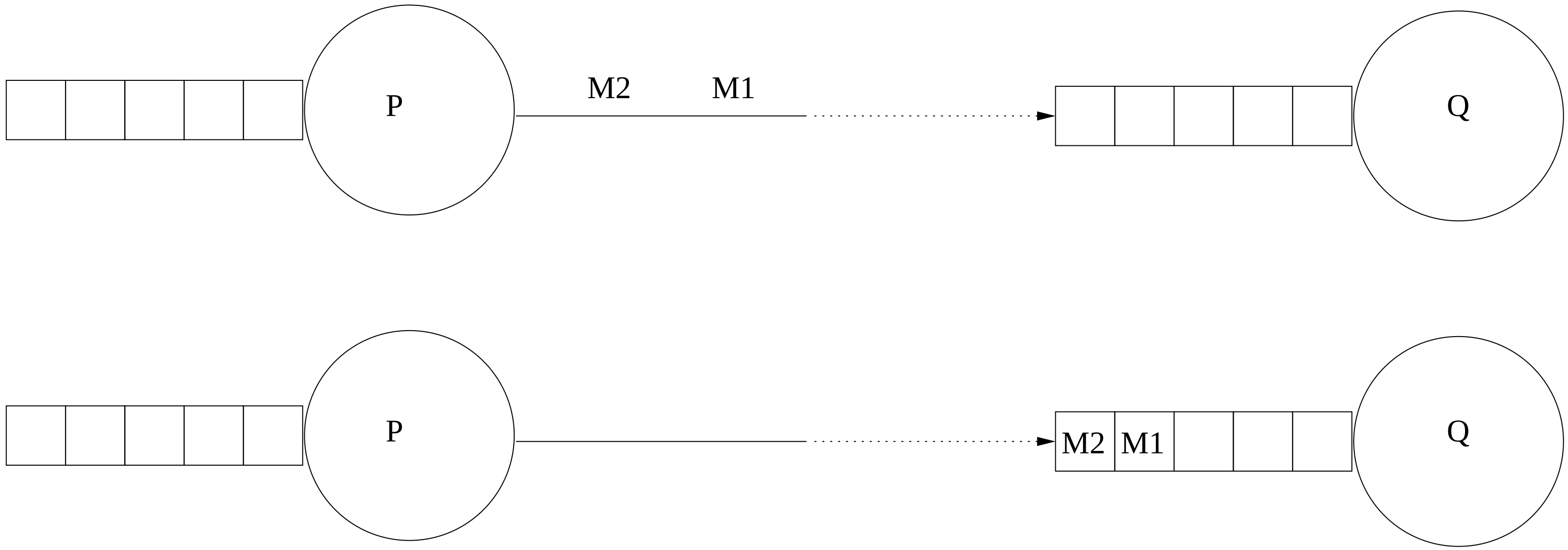
- And if the queue is $a \cdot b$?

Communication Guarantees

Messages sent from any process P to any process Q is delivered in order (or P or Q crashes)



A Simple Concurrent Program

```
facserver() ->
  receive
    {request, N, Pid}
    when is_integer(N), N>0, pid(Pid) ->
        spawn(fun () -> Pid!(fac(N)) end),
        facserver()
  end.
```

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2>  X = spawn(fun () -> facserver() end).
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3>  X!{request,2,self()}.
{request,2,<0.31.0>}
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3>  X!{request,2,self()}.
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4>  X!{request,4,self()}, receive Y -> Y end.
2
```

Erlang and Errors

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- The Erlang philosophy is to do error detection and recovery, but not everywhere in the code, only in certain places
- Higher-level Erlang components offer convenient handling of errors

Erlang and Errors, part II

- Error handling example:

```
g(Y) ->
  X = f(Y),
  case X of
    {ok, Result} -> Result;
    reallyBadError -> 0 % May crash because of ...
  end.
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- The local process will crash; another process is responsible from recovering (restaring the crashed process)
- Error detection and recovery is localised to special processes, to special parts of the code (*aspect oriented programming*)

Error Detection and Recovery: local level

- Exceptions are generated at runtime due to:
  - type mismatches ($10 * $ `"upm"`)
  - failed pattern matches, processes crashing, ...
- Exceptions caused by an expression e may be recovered inside a process using the construct **`try`** e **`catch`** m **`end`**
- Example:

```
try
  g(Y)
catch
  Error -> 0
end
```

Error Detection and Recovery: process level

- Within a set of processes, via bidirectional process links set up using the **`link`**`(pid)` function call
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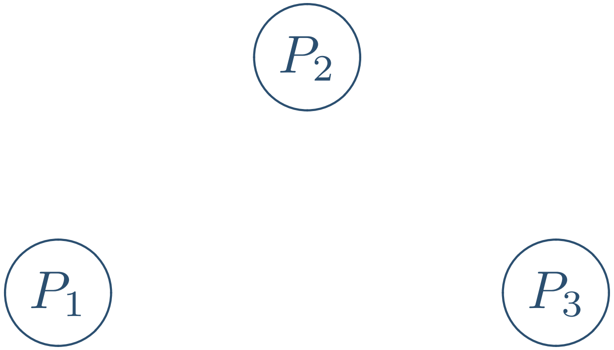
  Initially we have a system of 3 independent processes:



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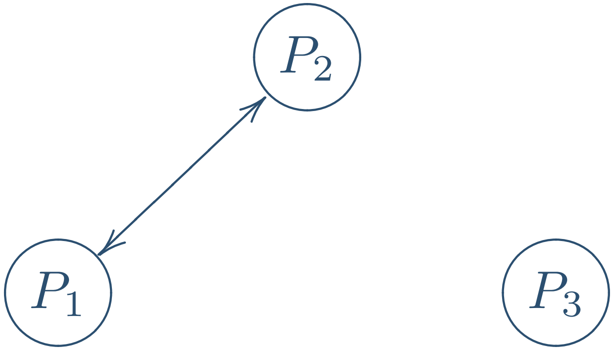

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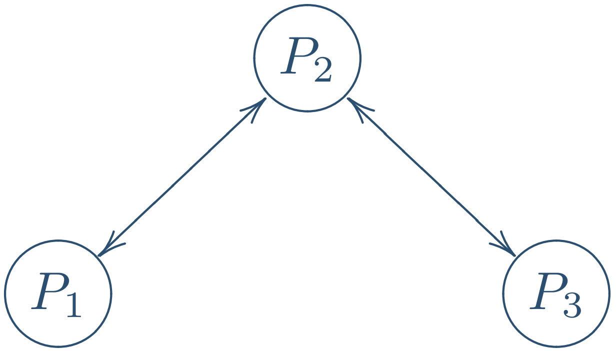

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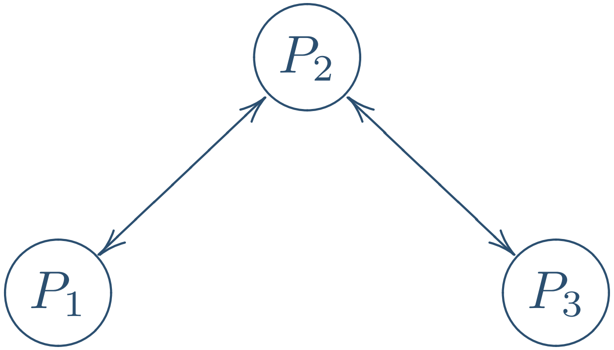

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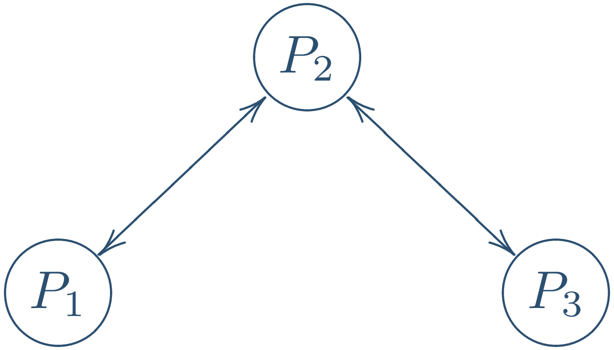


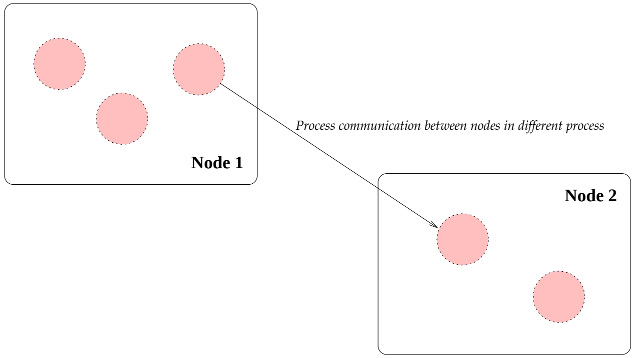
- If P_2 dies abnormally then P_1 and P_3 can *choose* to die
  If P_1 dies abnormally then P_2 can *choose* to die as well
- Alternatively when P_2 dies both P_1 and P_3 receives a message concerning the termination

What is Erlang suitable for?

- Generally intended for long-running programs
- Processes with state, that perform concurrent (and maybe distributed) activities
- Typical is to have a continously running system (24/7)
- Programs need to be fault-tolerant
- So hardware is typically replicated as well – because hardware invariably fail – and thus we have a need for distributed programming (addressing physically isolated processors)

Distributed Erlang

- Processes run on nodes (computers) in a network



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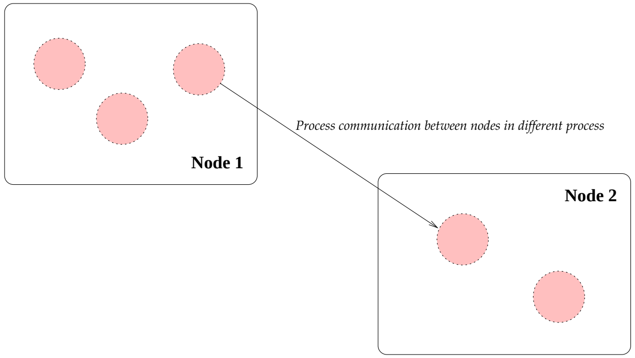

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  - No syntactic difference between inter-node or intra-node process communication
  - Communication link failure or node failures are interpreted as process failures (detected using linking)
  - Compare with Java: no references to objects which are difficult to communicate in messages (copy?)
  - The only references are process identifiers which have the same meaning at both sending and receiving process

Erlang Programming Styles

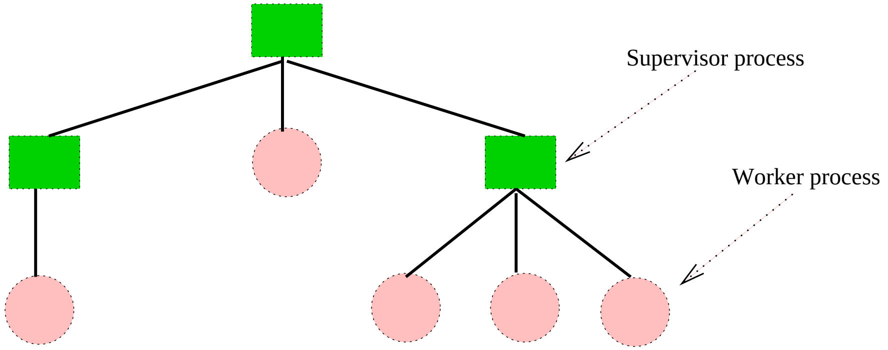
- Using only the basic communication primitives (send/receive) makes for messy code – everybody invents their own style and repeats lots of code for every program
- A standard way is needed to:
  - a standard way to handle process **start, termination and restarts**
  - to handle **code upgrading**
  - and maybe more structured communication patterns: *who* communicates with *whom*, in *what role*?…
- For Erlang one generally uses the design patterns and the framework of the **OTP library – Open Telecom Platform** – as an infrastructure

OTP components

- Application
  – provides bigger building blocks like a database (Mnesia), a web server, and interfaces to other languages and formats (Java, XML)
- Supervisor
  – used to start and bring down a set of processes, and to manage processes when errors occur
- Generic Server
  – provides a client–server communication facility
- Event Handling
  – for reporting system events to interested processes
- Finite State Machine
  – provides a component facilitating the programming of finite state machines in Erlang

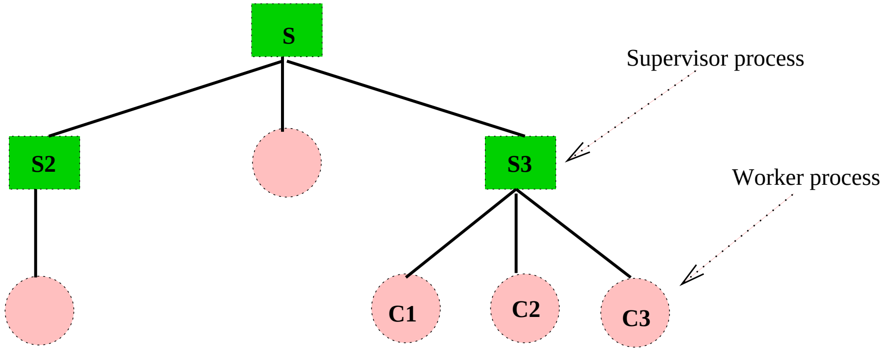
The Supervisor Component

- Applications are often structured as *supervision trees*, consisting of *supervisors* and *workers*



- A supervisor starts child processes, monitors them, handles termination and stops them on request
- The actions of the supervisor are described in a declarative fashion (as a text description)
- A child process may itself be a supervisor

Supervision Dynamics



- When a child process C1 dies (due to an error condition), its supervisor S3 is notified and can elect to:
    - do nothing
    - itself die (in turn notifying its supervisor S)
    - restart the child process (and maybe its siblings)
    - kill all the sibling processes (C2,C3) of the dead process

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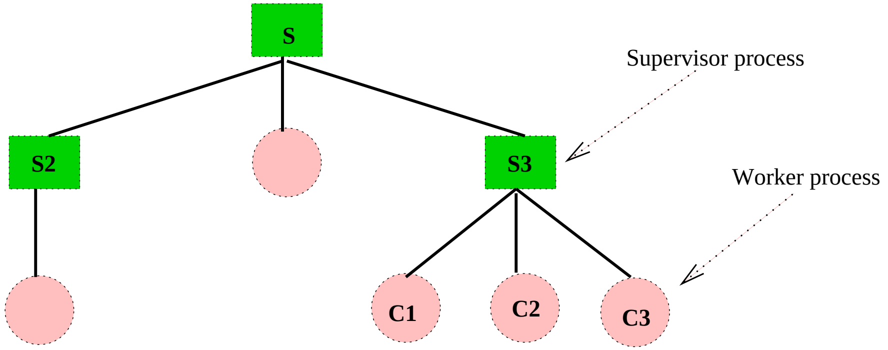

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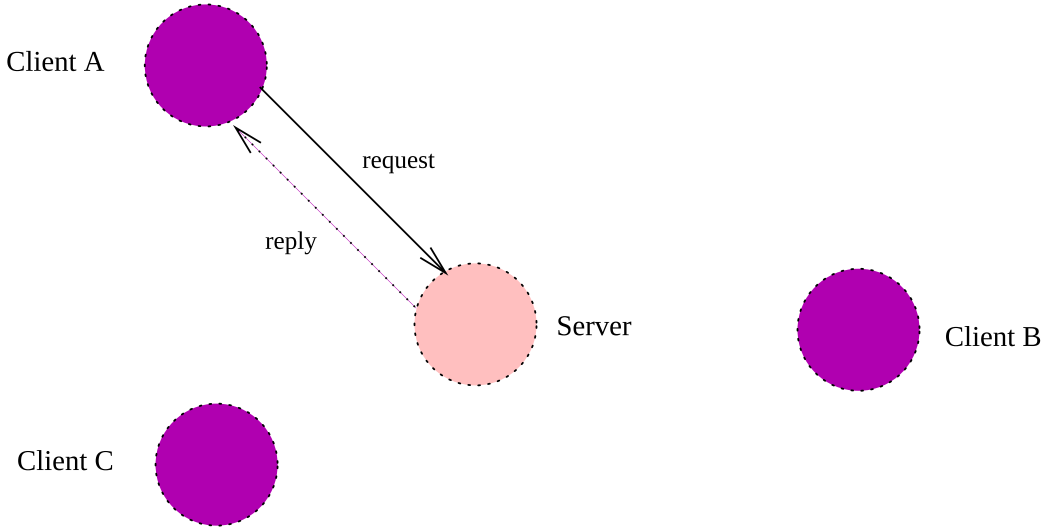
- One can control the frequency of restarts, and the maximum number of restarts to attempt – it is no good having a process continuing to restart and crash

The Generic Server Component

- `gen_server` is *the* most used component in Erlang systems
- Provides a standard way to implement a server process, and interface code for clients to access the server
- The client–server model has a central server, and an arbitrary number of clients:



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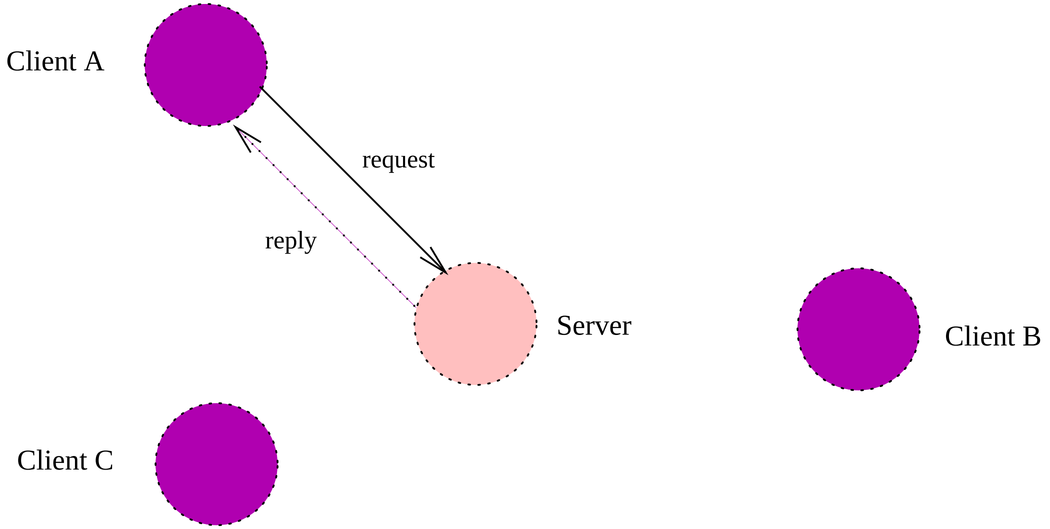


- Clients makes *requests* to the server, who optionally *replies*
- A server has a state, which is preserved between requests
- A generic server is implemented by providing a callback module specifying the concrete actions of the server (server state handling, and response to messages)

Part 2: Verifying Erlang Programs

Debugging/Verifying Erlang Programs: Tools

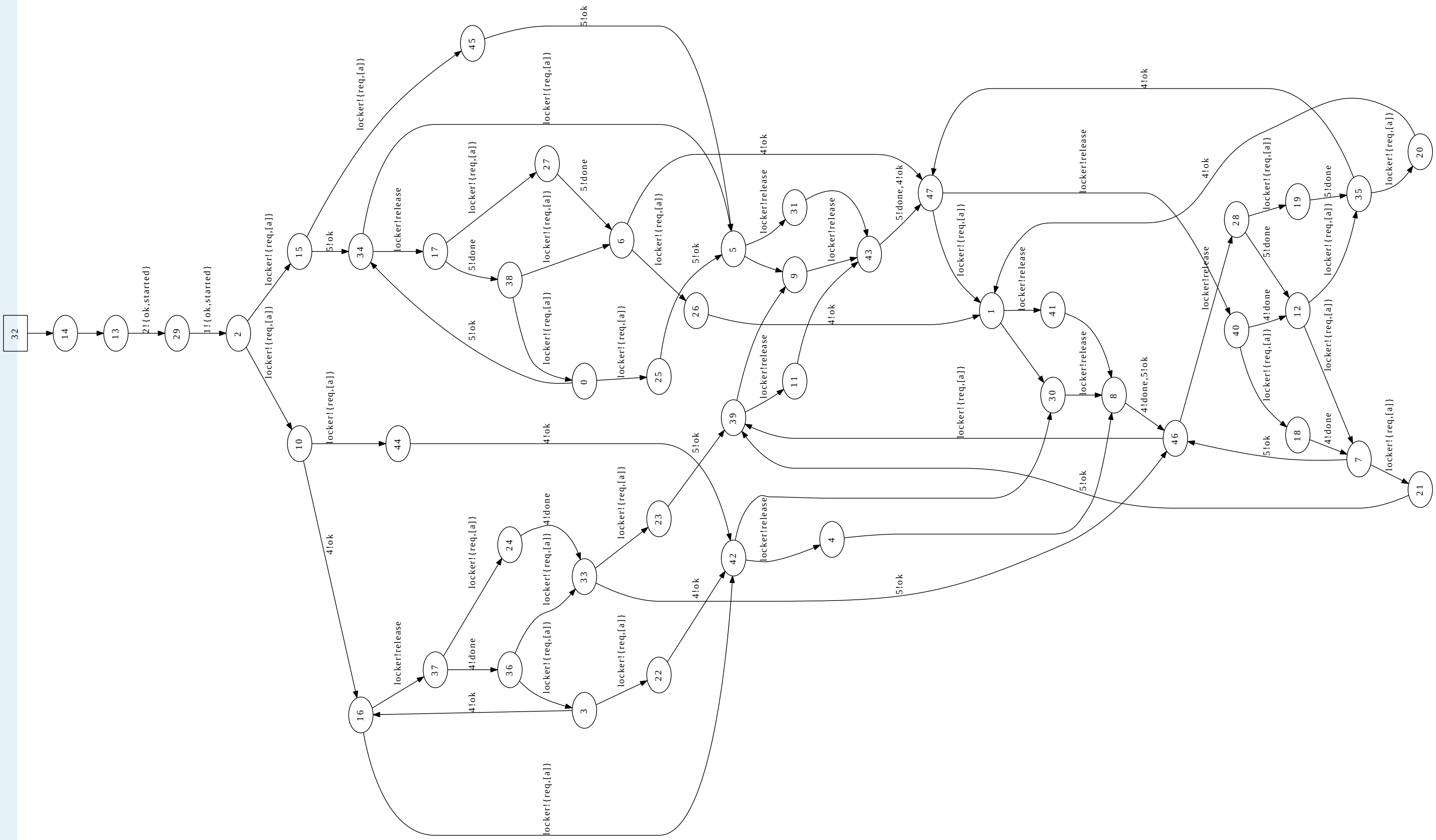
- Dialyzer – type checking by static analysis (necessary to minimize type errors at runtime)
- Testing: QuickCheck (`http://www.quiviq.com`) - a testing tool for Erlang
- Model checking – our tool McErlang (`https://babel.ls.fi.upm.es/trac/McErlang/`)

Testing Concurrent Programs

Why is (random) testing of concurrent programs difficult?

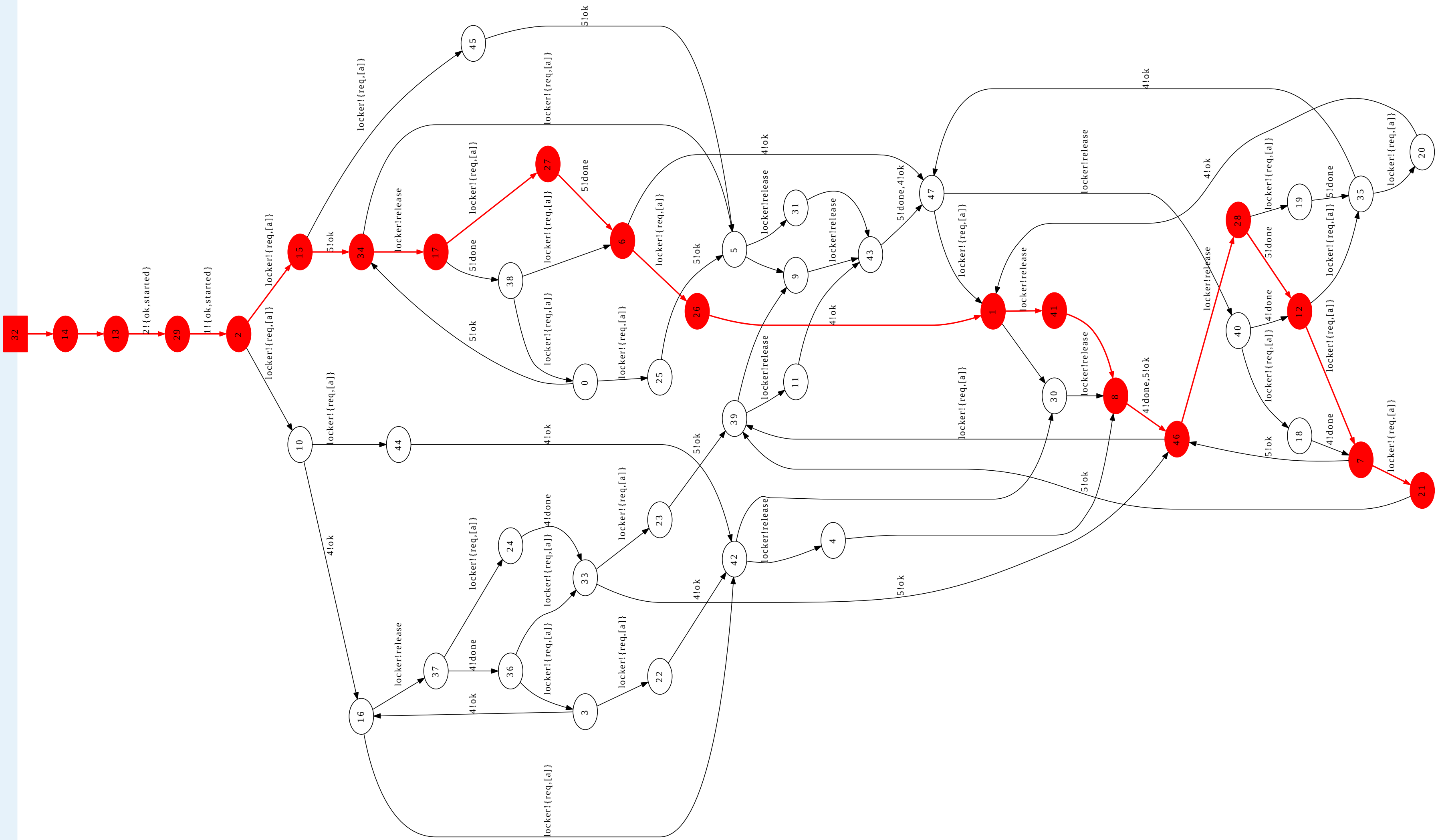
Testing Concurrent Programs

Consider the state space of a small program:



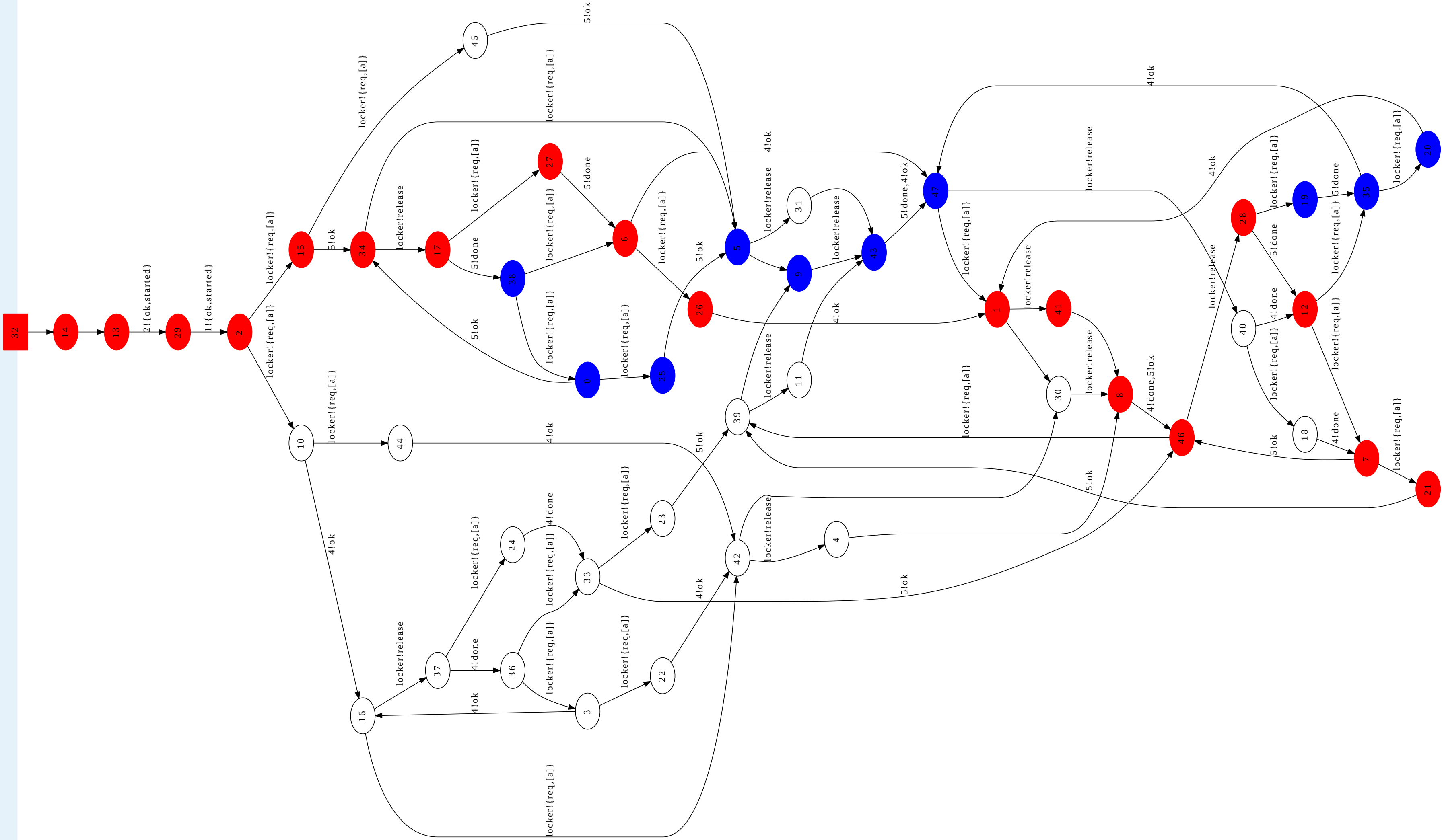
Testing Concurrent Programs

Random testing explores **one** path through the program:



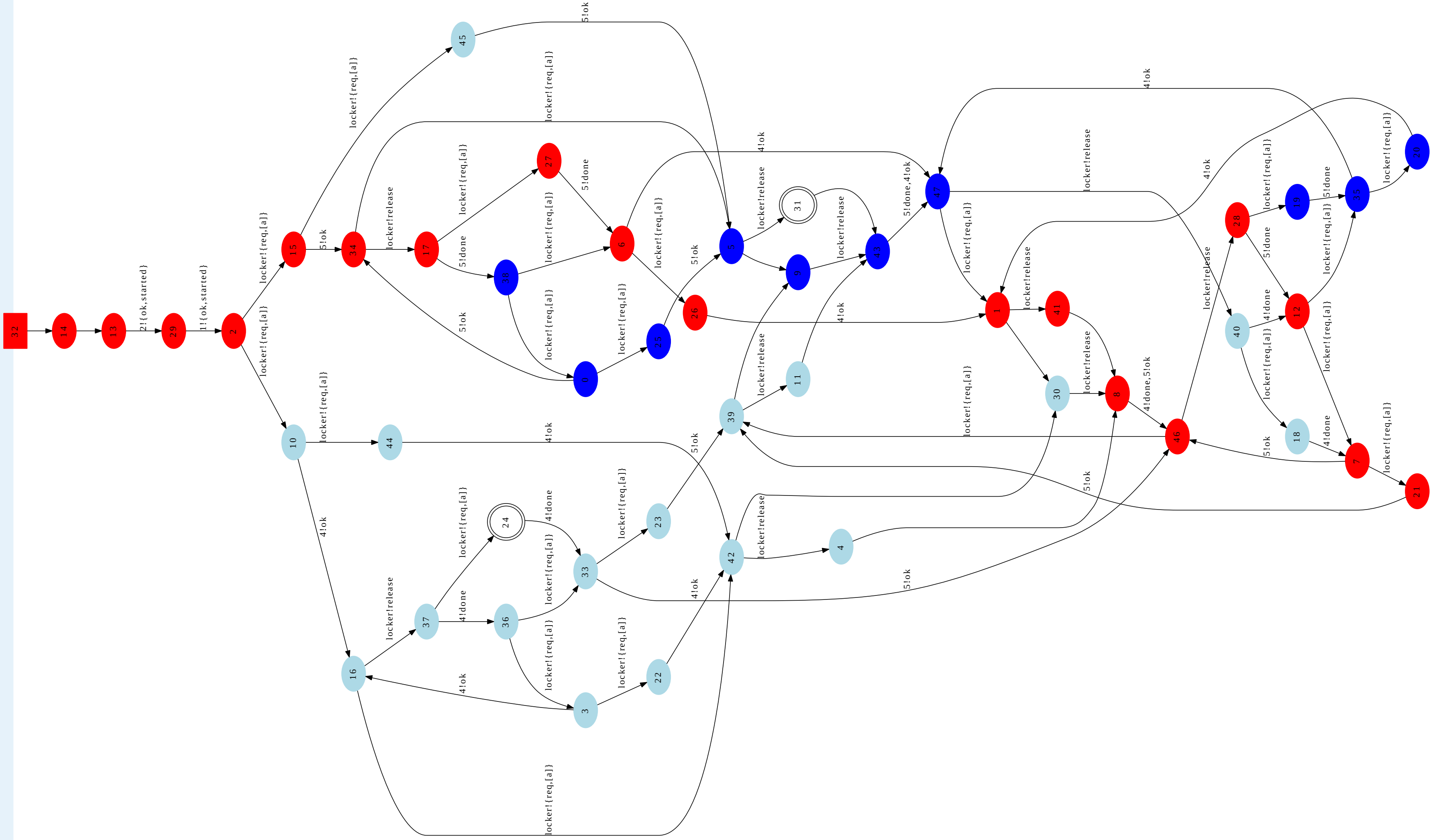
Testing Concurrent Programs

With repeated tests the coverage improves:



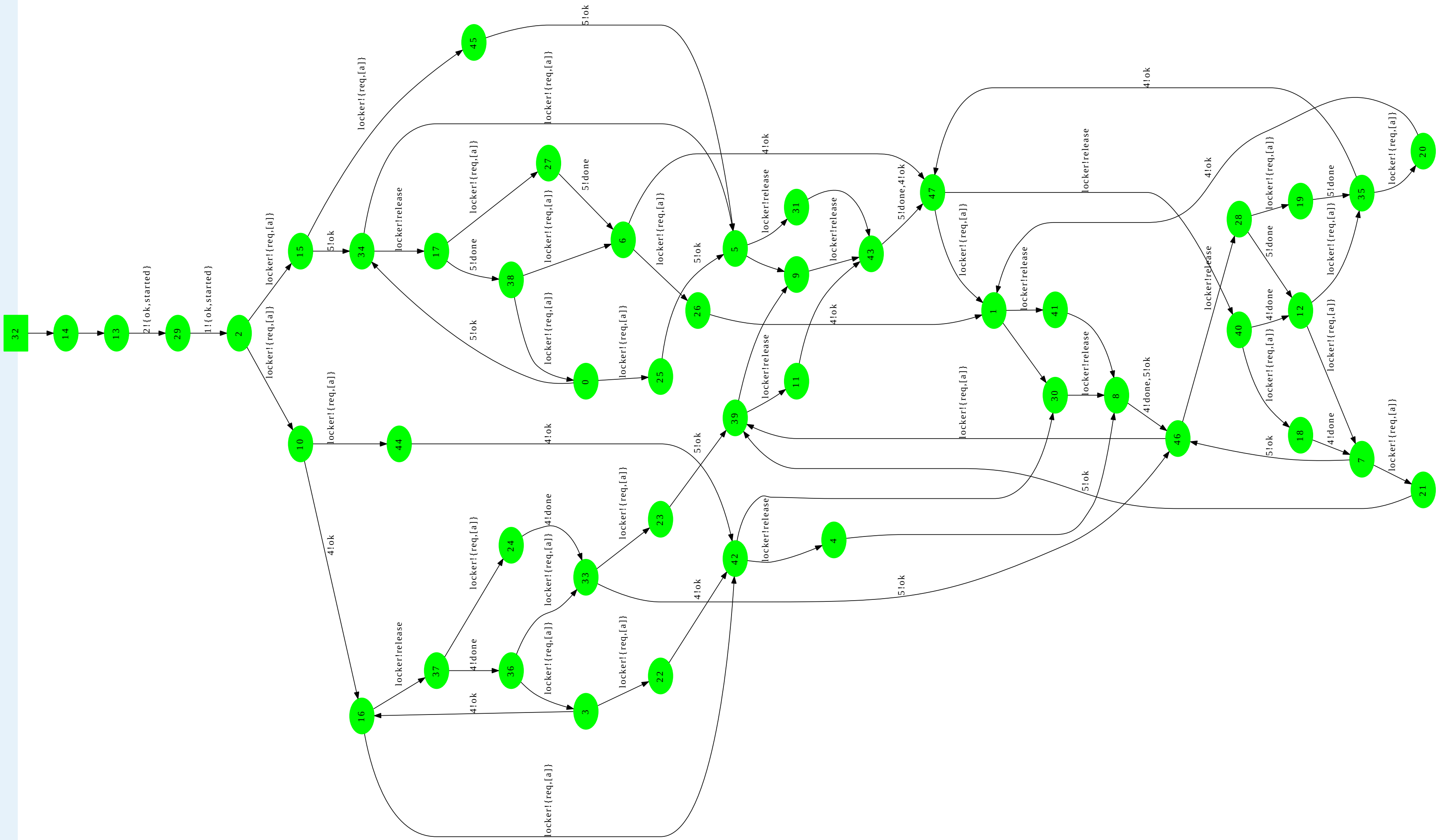
Testing Concurrent Programs

A lot of testing later (note the states not visited):



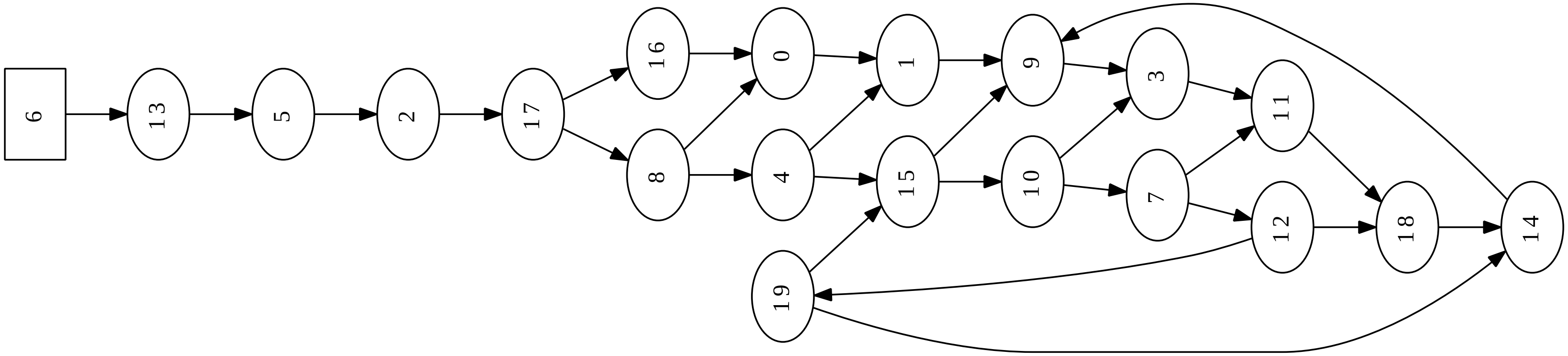
Testing Concurrent Programs

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



Model Checking: Basics

- **Construct** an abstract **model** of the behaviour of the program, usually a finite state transition graph



  - A node represents a **Program state** $(x = 0, y = 3)$
  - **Graph edges** represent computation steps from one program state to another

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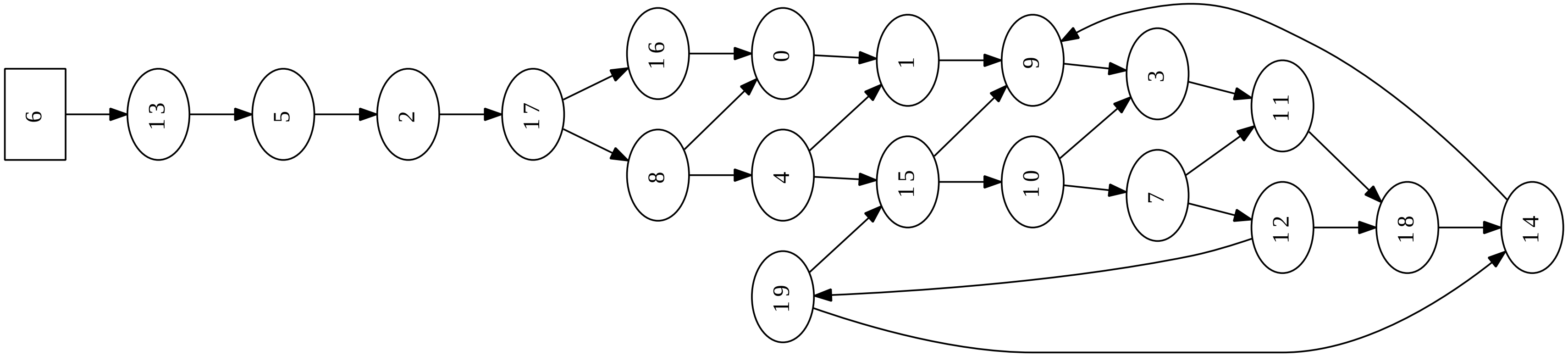

  - A node represents a **Program state** $(x = 0, y = 3)$
  - **Graph edges** represent computation steps from one program state to another

- **Check** the abstract model against some description of desirable/undesirable model properties usually specified in a **temporal logic**: *Always* $x \geq 0$

Model Checking

- Usually applied to **reactive systems**
  (systems that continously react to stimuli)

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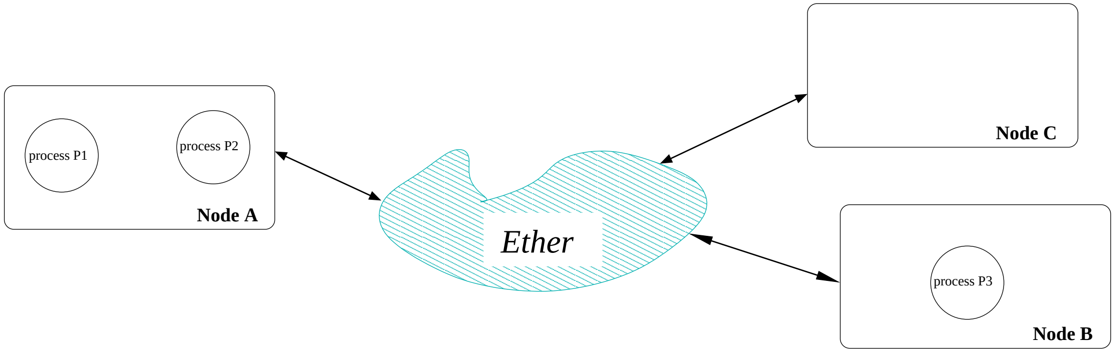
  (systems that continously react to stimuli)
- Advantages: automatic push button technology
  (algorithms can decide, with decent complexity, whether a model satisfies a property)
- Disadvantages:
  - Models can be difficult and time consuming to construct
  - Doesn't scale well to larger programs (the model of the behaviour of the program becomes too big – the well known **state explosion problem**)

The McErlang model checker: Design Goals

- Reduce the gap between program and verifiable model (the Erlang program *is* the model)
- Write correctness properties in Erlang (and linear temporal logic)
- Implement verification methods that permit partial checking when state spaces are too big – on-the-fly checking and using Holzmann's bitspace algorithms
- Implement the model checker in a parametric fashion (easy to plug-in new algorithms, new abstractions, . . .)

Step-by-step execution of Erlang Programs

- To be able to visit **all** the states of an Erlang program we need the capability to take a **snapshot** of the Erlang system
  - A **snapshot**/**program state** is: the contents of all process mailboxes, the state of all running processes, messages in transit (the ether), all nodes, monitors, . . .



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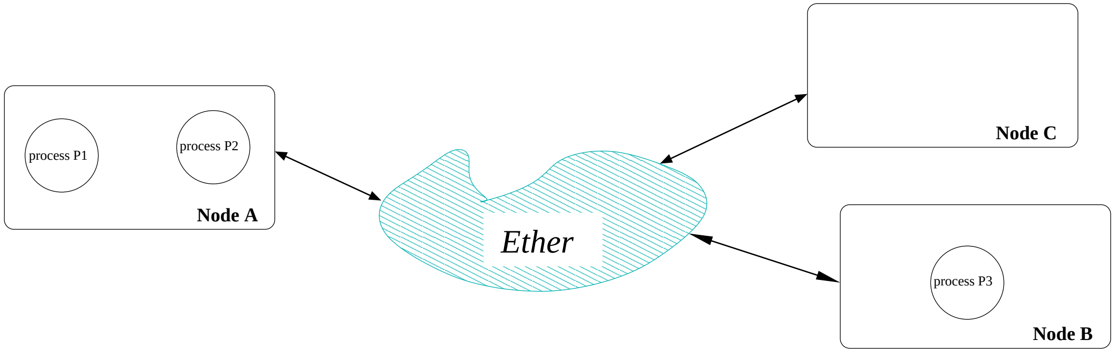

- Save the snapshot to memory and forget about it for a while
- Later continue the execution from the snapshot

The McErlang approach to model checking

- The lazy solution: just execute the Erlang program to verify in the normal Erlang interpreter
- And extract the system state (processes, queues, function contexts) from the Erlang runtime system

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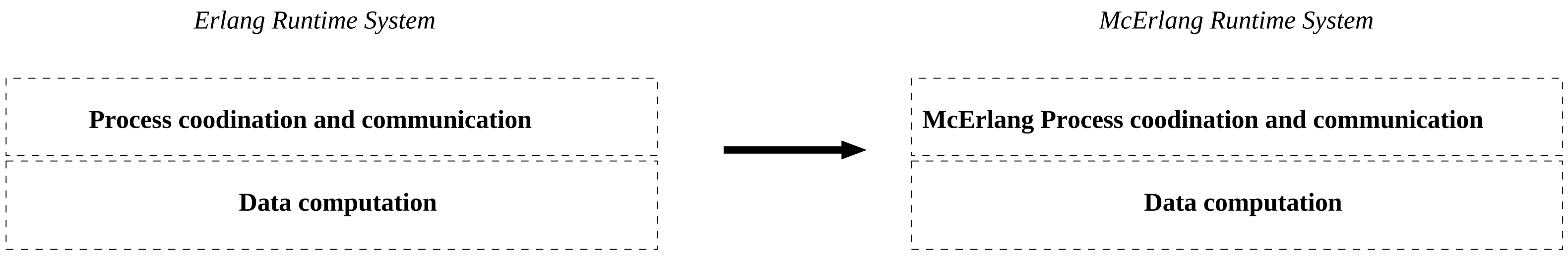
- The lazy solution: just execute the Erlang program to verify in the normal Erlang interpreter
- And extract the system state (processes, queues, function contexts) from the Erlang runtime system
- Too messy! We have developed a **new runtime system** for the process part, and still use the old runtime system to execute code with no side effects



Correctness Properties: Temporal logic

- Pneuli 1977: added discrete and linear time operators to propositional logic, to be able to specify properties of reactive systems
- Program meaning (semantics):
  - a *program state* s maps the program variables to values
  - a *run* of the program is an infinite sequence of program states $(s_0, s_1, s_2, \ldots)$ from an initial state s_0
  - for a terminating system simply add a self-loop in the terminating state to yield an infinite run
  - the *semantics* of a program p is its set of runs, $\|p\|$
  - If the program is **nondeterministic** (or accepts input) there will be more than one run of the program

Runs of concurrent programs: examples

Consider the following simple shared variable program:

```
if x>0 then x:=x-1 || if x<3 then x:=x+1
```

where `S1||S2` runs the atomic statements `S1` and `S2` in parallel

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Its runs starting from the state `x=0` is the **infinite** set:

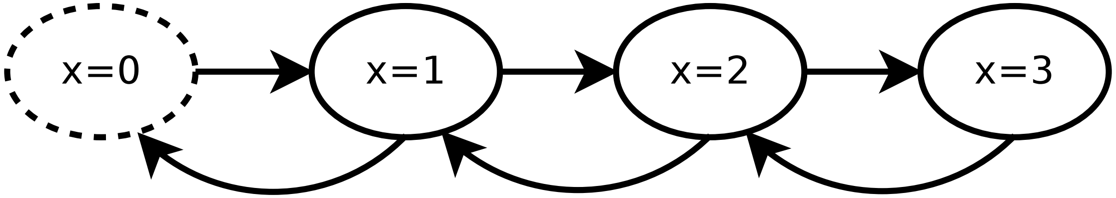
$$\left\{ \begin{array}{l} \langle x=0\rangle \cdot \langle x=1\rangle \cdot \langle x=0\rangle \cdot \ldots \\ \langle x=0\rangle \cdot \langle x=1\rangle \cdot \langle x=2\rangle \cdot \langle x=1\rangle \cdot \ldots \\ \langle x=0\rangle \cdot \langle x=1\rangle \cdot \langle x=2\rangle \cdot \langle x=3\rangle \cdot \langle x=2\rangle \ldots \\ \ldots \end{array} \right\}$$

Program runs

We can also depict the runs

$$\left\{\begin{array}{l}\langle x=0\rangle\cdot\langle x=1\rangle\cdot\langle x=0\rangle\cdot\ldots\\ \langle x=0\rangle\cdot\langle x=1\rangle\cdot\langle x=2\rangle\cdot\langle x=1\rangle\cdot\ldots\\ \langle x=0\rangle\cdot\langle x=1\rangle\cdot\langle x=2\rangle\cdot\langle x=3\rangle\cdot\langle x=2\rangle\ldots\\ \ldots\end{array}\right\}$$

as a state graph:



Temporal logic operators

Classical linear temporal operators (defined over runs):

- *Always* ϕ

  ϕ holds in all future states of the run

- *Eventually* ϕ

  ϕ holds in some future state of the run

- *Next* ϕ

  ϕ holds in the next state

- ϕ_1 *Until* ϕ_2

  ϕ_1 holds in all states until ϕ_2 holds

- And the normal ones: negation $\neg\, \phi$, implication $\phi_1 \supset \phi_2, \ldots$

Temporal logic state propositions

These provide basic statements about program states

- For Pneuli's shared variable language: $x > 0$, $x < y$, *even*(z), $\ldots$
- For Erlang: `Pid!{request,a}`
  (a request message is sent to some process)

Temporal logic – meaning

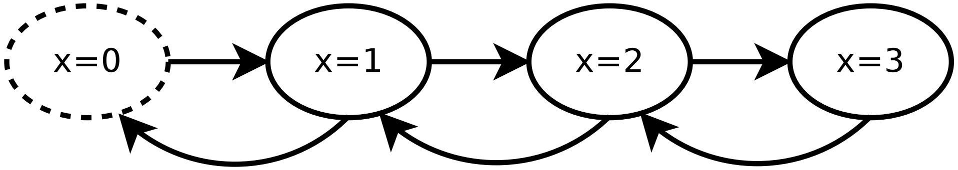
- A program p satisfies a formula ϕ when all the runs of the program are satisfied by the formula
- The logic is linear because it doesn't talk about the branching structure of the state graph of the program (*what is set of possible next states of the program*)
- So called *branching time* logics (CTL, μ-calculus) do consider the branching structure of the state graph of the program

Temporal logic – examples

Consider the atomic parallel program

```
if x>0 then x:=x-1 || if x<3 then x:=x+1
```

with the starting state $\langle x = 3 \rangle$ and the state graph



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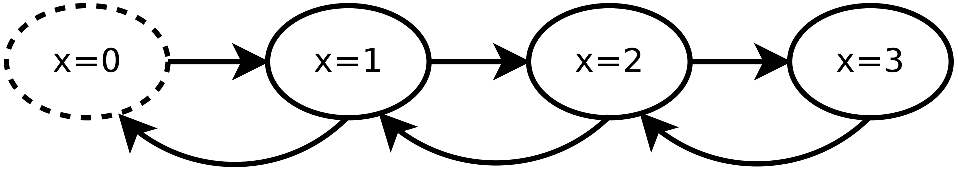

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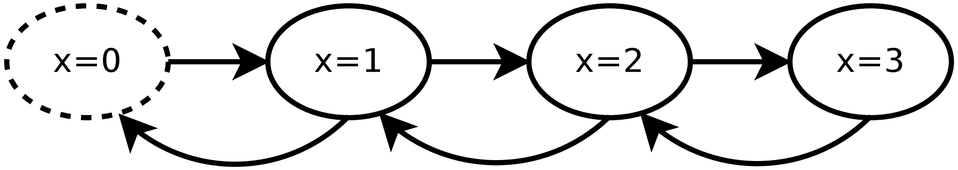

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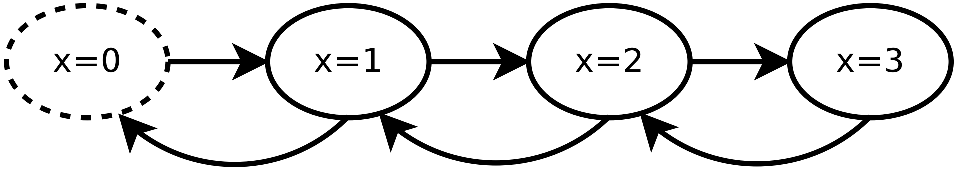

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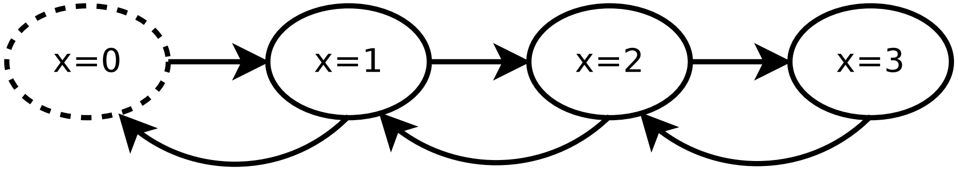

- Does *Always* $x \geq 0$ hold?
- **Yes**; if x=0 then the guard prevents further decrease
- Does *Always* $(x = 3 \supset$ *Eventually* $x = 0)$ hold?
- **No**; there is a run $\langle x = 3 \rangle \cdot \langle x = 2 \rangle \cdot \langle x = 3 \rangle \cdot \langle x = 2 \rangle \cdot \ldots$

General temporal logic patterns

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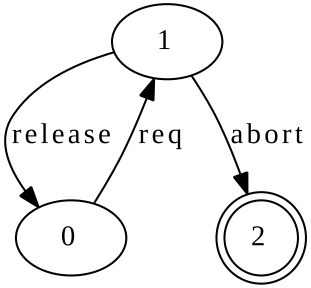
- *Fairness assumptions* are used to rule out abnormal program behaviours; ϕ eventually holds under the assumption that ψ doesn't always hold:

$$(\neg \mathit{Always}\ \psi)\ \supset\ (\mathit{Eventually}\ \phi)$$

How to check LTL properties on programs?

- LTL formulas are translated into Büchi automata

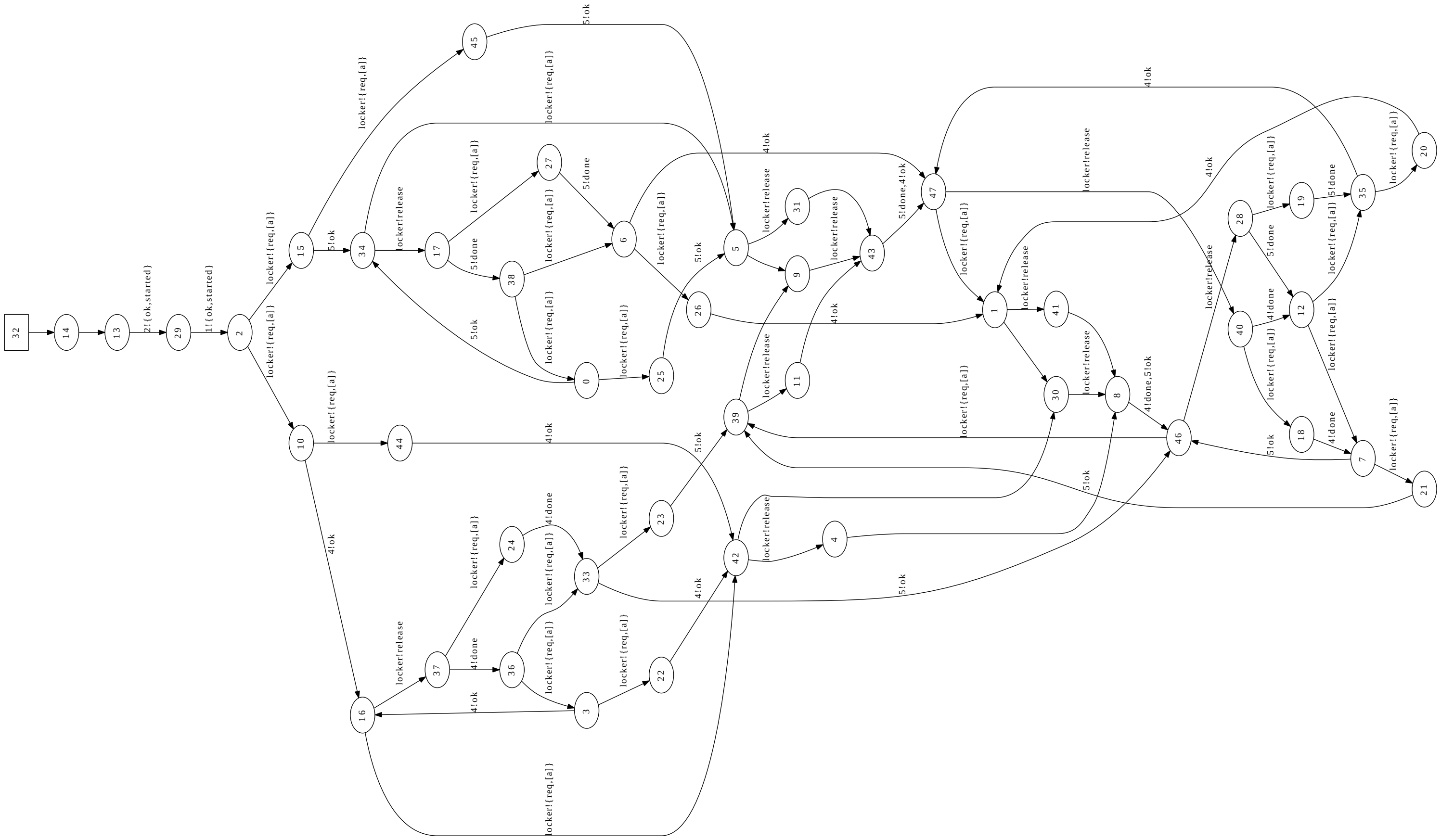
$$\mathit{Always}(\texttt{req} \supset \mathit{Next}(\neg\, \texttt{abort}\ \mathit{Until}\ \texttt{release}))$$



- A combined program and automaton state graph is generated by executing the program in **lock-step** with the automaton
- When a new program state is generated, the automaton computes a new automaton state (by inspecting the program state)

LTL checking: correctness condition

For checking safety properties – *Always* $\neg \phi$ – *every* program state should be inspected once



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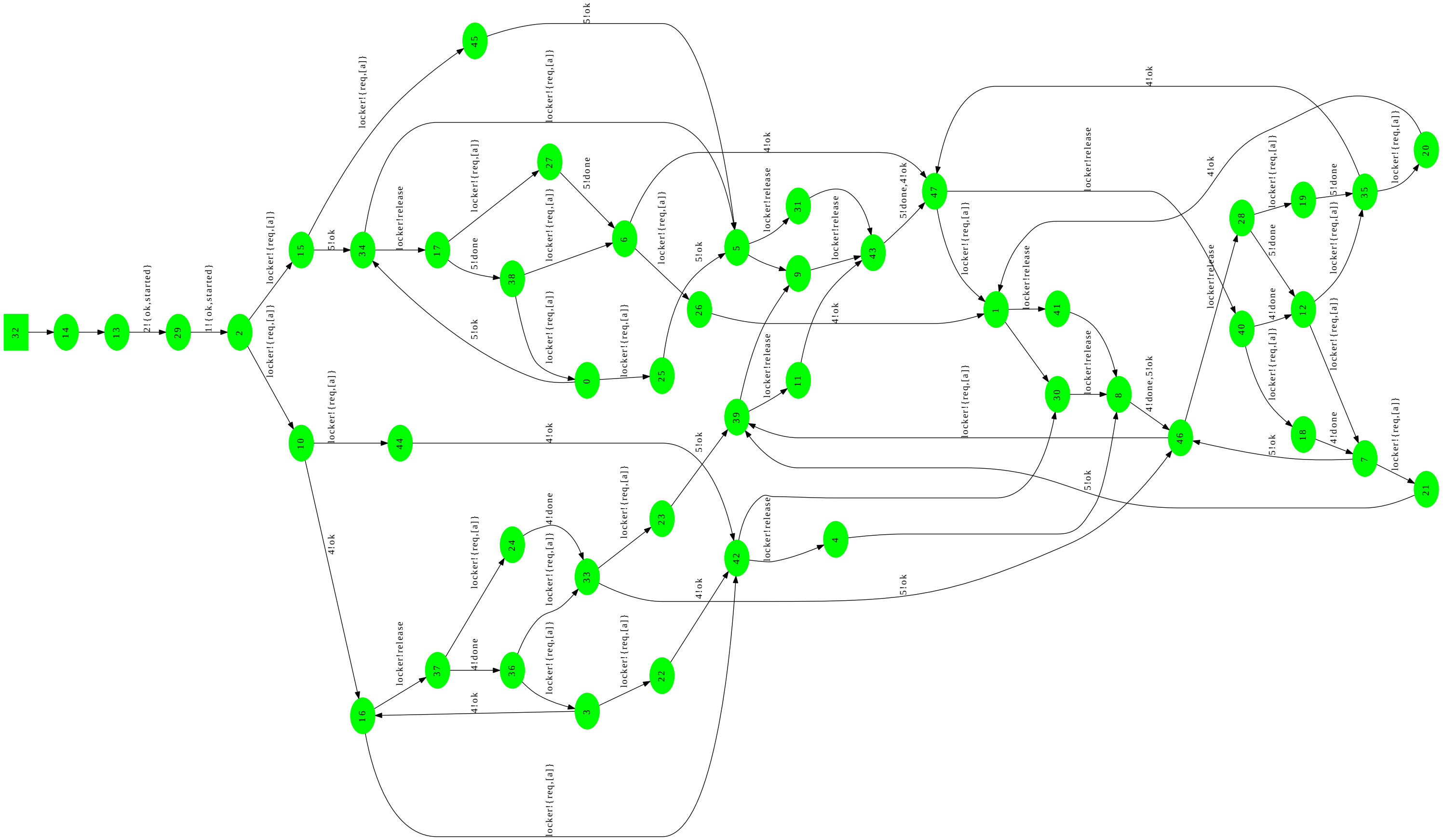

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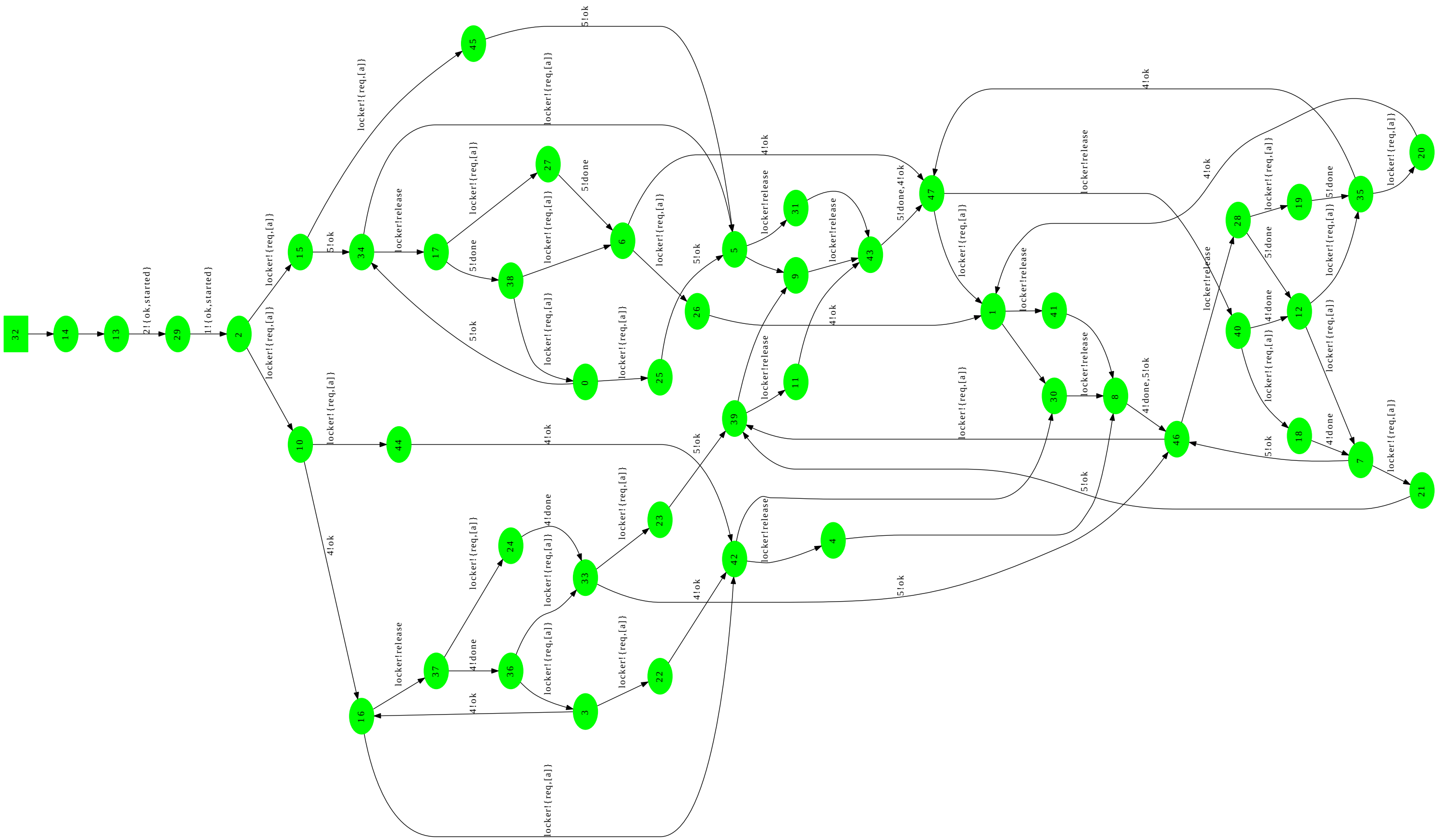

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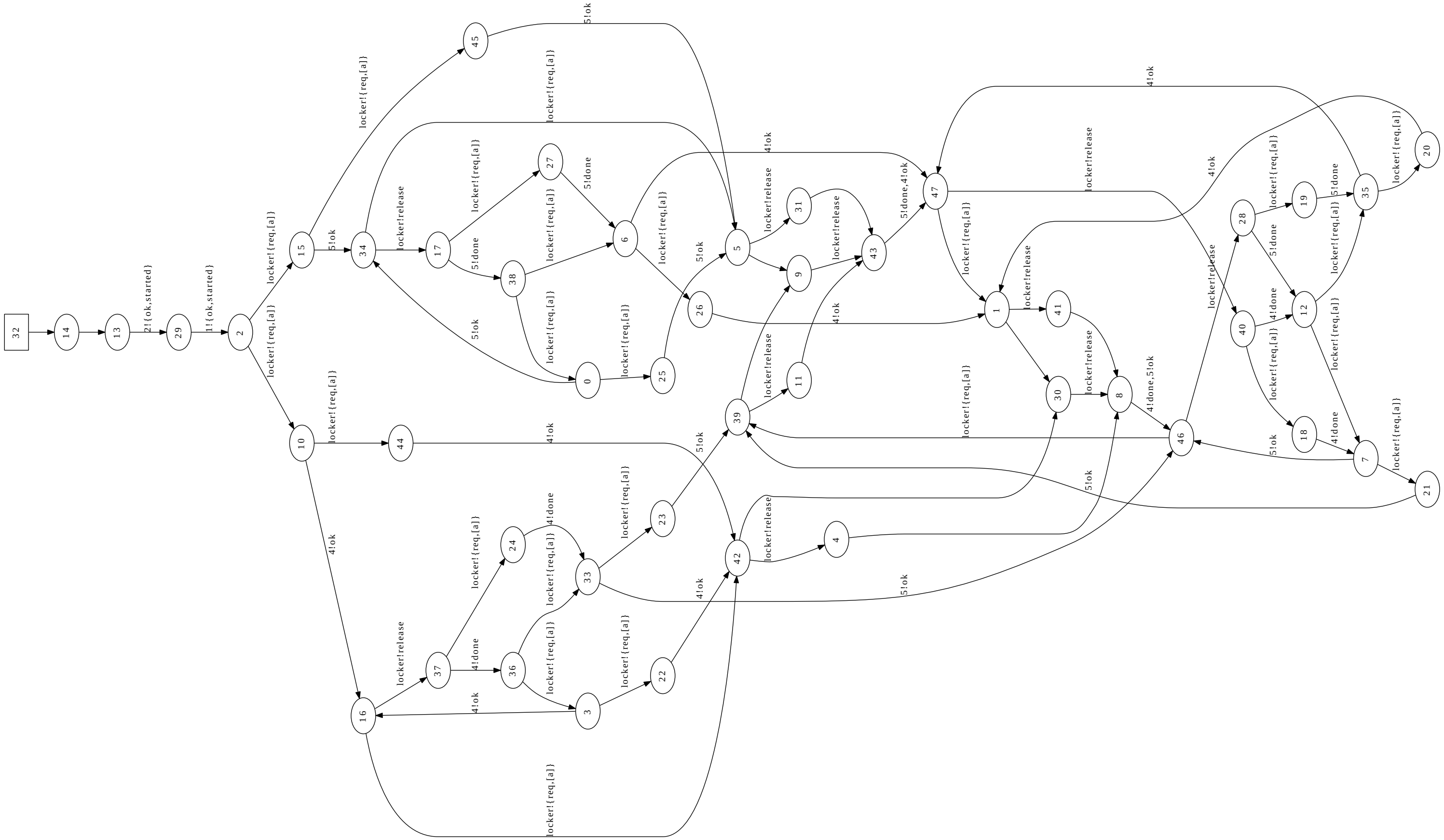
LTL checking: intuition

For a liveness property – *Eventually* ϕ – to hold, there can be no loop in the combined state graph where something bad happens



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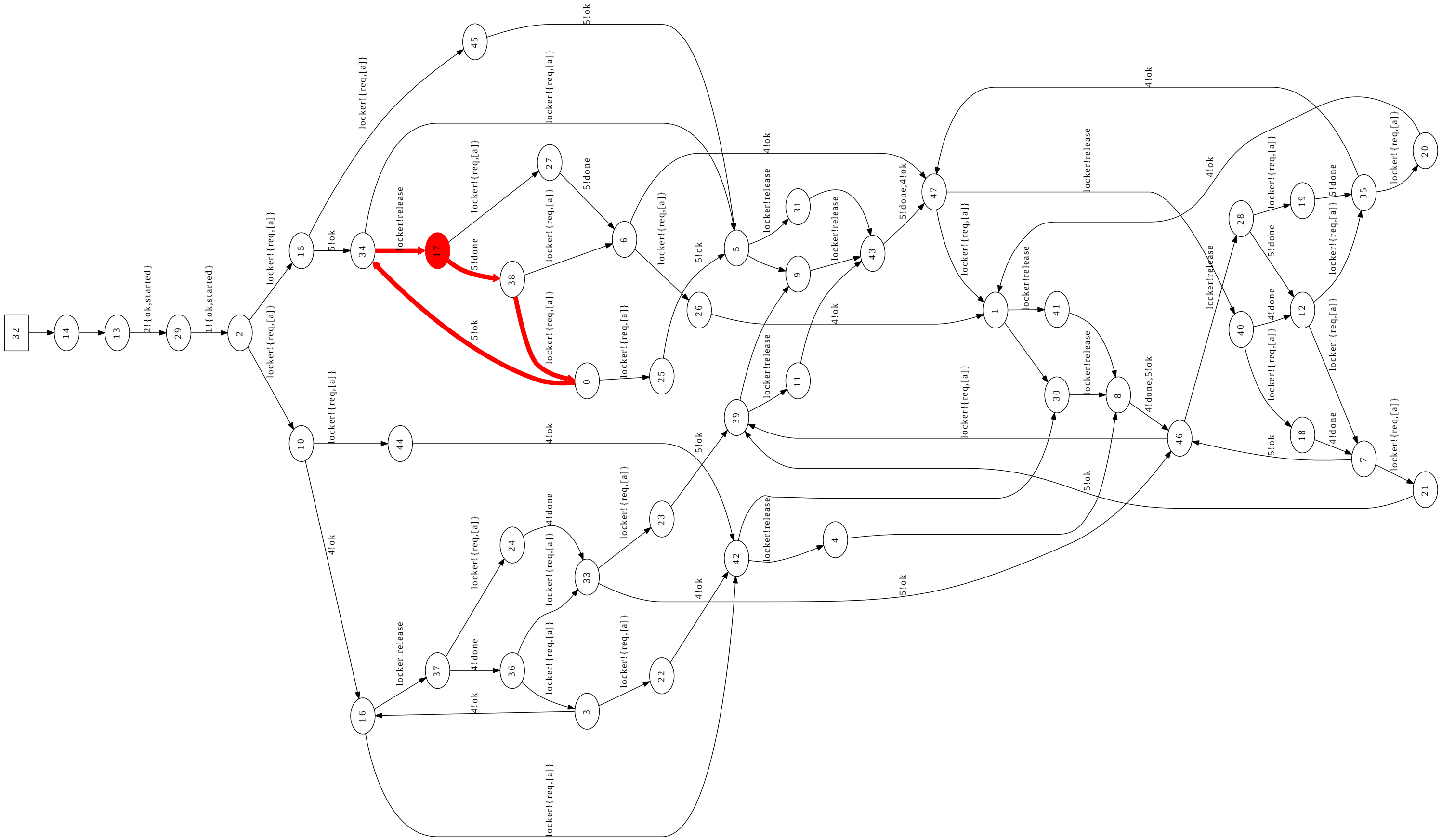

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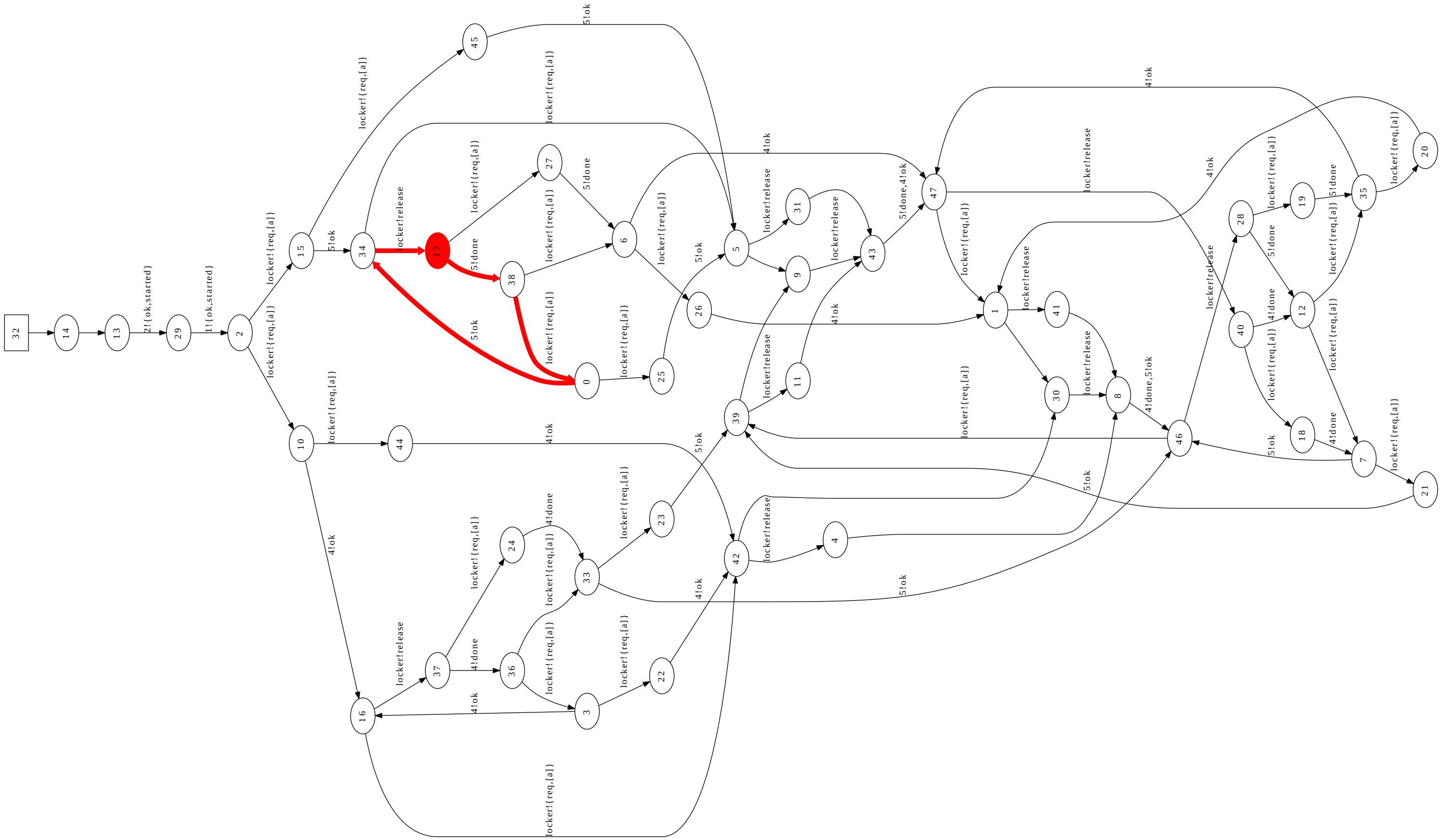

To prove a program *incorrect*, it may not be necessary to explore the whole state space of the program

McErlang in Practice

- Install Erlang first
- Then download McErlang from
  `https://babel.ls.fi.upm.es/trac/McErlang/`
- Runs on Linux, Windows, …

McErlang In Practice: A Really Small Example

Two processes are spawned, the first starts an “echo” server that echoes received messages, and the second invokes the echo server:

```
-module(example).
-export([start/0]).

start() ->
  spawn(fun() -> register(echo,self()), echo() end),
  spawn(fun() ->
             echo!{msg,self(),'hello␣world'},
             receive
               {echo,Msg} -> Msg
             end
           end).

echo() ->
  receive
    {msg,Client,Msg} ->
      Client!{echo,Msg}, echo()
  end.
```

Example under normal Erlang

Let’s run the example under the standard Erlang runtime system:

```
> erlc example.erl
> erl
Erlang (BEAM) emulator version 5.6.5 [source] [smp:2] ...

Eshell V5.6.5  (abort with ^G)
1> example:start().
<0.34.0>
2>
```

That worked fine. Let’s try it under McErlang instead.

Example under McErlang

First have to recompile the module using the McErlang compiler:

```
> mcerl_compiler -sources example.erl -output_dir .
```

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Then we run it:

```
> erl
Erlang (BEAM) emulator version 5.6.5 [source] [smp:2] ...

Eshell V5.6.5  (abort with ^G)
1> mce:apply(example,start,[]).
Starting McErlang model checker environment version 1.0 .
...

Process ... exited because of error: badarg

Stack trace:
  mcerlang:resolvePid/2
  mcerlang:send/2
  ...
```

Investigating the Error

An error! Let's find out more using the McErlang debugger:

```
2> mce_erl_debugger:start(get(result)).
Starting debugger with a stack trace; execution terminate
  user program raised an uncaught exception.

stack(@2)> where().
2:

1: process <node0,3>:
 run #Fun<example.2.125>([])
 process <node0,3> died due to reason badarg

0: process <node0,1>:
 run function example:start([])
 spawn({#Fun<example.1.278>,[]},[]) --> <node0,2>
 spawn({#Fun<example.2.125>,[]},[]) --> <node0,3>
 process <node0,1> was terminated
 process <node0,1> died due to reason normal
```

Error Cause

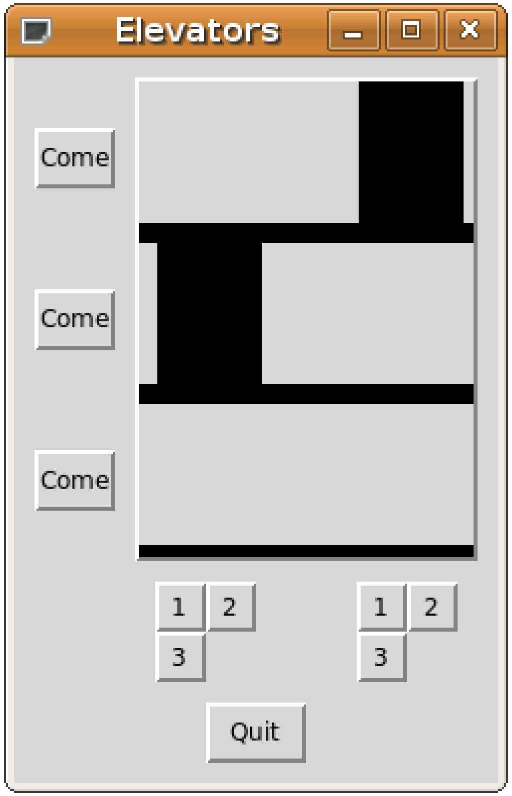
- Apparently in one program run the second process spawned (the one calling the echo server) was run before the echo server itself.
- Then upon trying to send a message

  ```
  echo!{msg,self(),'hello␣world'}
  ```

  the `echo` name was obviously not registered, so the program crashed.

McErlang in practise: The Elevator Example

- We study the control software for a set of elevators



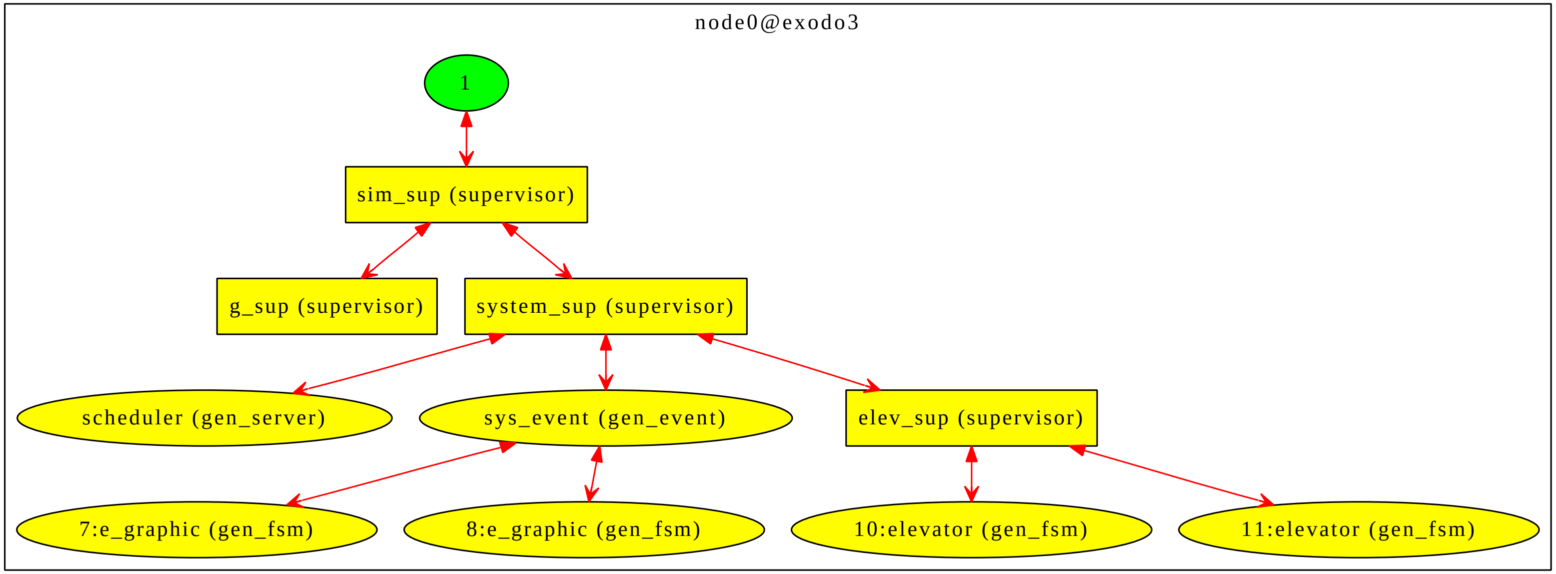
- Used to be part of an Erlang/OTP training course from Ericsson

Elevator Control Software

- Static code complexity: around 1670 lines of code (uses several OTP behaviours: supervisor, gen_fsm, . . .)

Elevator Control Software

- Static code complexity: around 1670 lines of code (uses several OTP behaviours: supervisor, gen_fsm, . . .)
- Dynamic complexity: around 10 processes (for two elevators)



We had to modify around 10 lines to model check this example

Correctness Properties for the Elevator System

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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/safety automaton 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 – fine, it is what models are supposed to do
- So we have to write more monitors and properties. . .

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- It runs in parallel (lock-step) with the program
- 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

Significant Events

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- Button presses in the elevator
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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

Safety Automata

- Safety automata is a subclass of automata which users can program directly in Erlang
- Concretely, to implement a safety automaton a McErlang user should provide a function

  ```
  stateChange(ProgramState, AutomatonState, Action) ->
    ...
    {ok, NewAutomatonState}.
  ```

  which is automatically called by McErlang when a program changes its state
- The automaton can inspect the current program state, its own state, and the side effects (actions) in the last computation step
- The automaton either returns a new automaton state (success), or signals an error

What can automata observe?

- Program actions such as e.g. sending or receiving a message
- Program state such as e.g. contents of process mailboxes, name of registered processes
- Indirectly the values of some program variables (can be somewhat difficult to access)
- Programs can be instrumented with special **“probe actions”**, that are easy to detect in monitors
- Programs can be instrumented too with special **“probe states”**, which are persistent (actions are transient)

Model Checking the Lift Example

- 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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- Instead of specifying one big scenario with a really big state space, we generate a number of smaller scenarios, similar to test cases:
  - Floor button 1 pressed
  - Floor button 2 pressed, Elevator button 1 pressed
  - Elevator button 2 pressed, Floor button 2 pressed, Floor button 2 pressed, . . .

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  - Floor button 2 pressed, Elevator button 1 pressed
  - Elevator button 2 pressed, Floor button 2 pressed, Floor button 2 pressed, . . .
- But since we are model checking every scenario is fully explored

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 elevator has already met the request

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

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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

A Pragmatic Testing-Like Approach to Model Checking

- We strive to reduce the effort in creating a model from a program (we support almost full Erlang)
- When programs are too complex to fully verify, model checking becomes a form of controlled testing:
    - The amount of memory and time available to verify a program can be control (a verification attempt can be *inconclusive*)
    - Randomized (wrt. state space exploration order) verification algorithms are available (thus repeating a verification run can explore new parts of the state space)
    - Randomized state storage data structures are available (Holzmann’s bitspace algorithms)
- Instead of building complex program environments a program is checked under a **set of** much simpler program environments

Self Study

- Install McErlang
  `https://babel.ls.fi.upm.es/trac/McErlang/`
- The file

  `https://babel.ls.fi.upm.es/trac/McErlang/attachment/wiki/midTermWorkshop/exercises.txt`

  contains instructions
- See the directory `examples` in the McErlang distribution for the lift example source code