Intro to Model-Checking

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System Design Steps

- Establish *requirements*.
- Create *specification* for a system that meets the requirements.
- Design and implement ("code") the system.
- Establish that the implementation correctly obeys the specification.

Software Errors can be Expensive

- European Ariane 5 spacecraft
  ($.5 Billion loss)

- NASA Mars Climate Orbiter
  ($165 Million loss)

- Canadian Therac 25
  (5 deaths)

Relevance to HMC?

- It can't happen here?

- How many Clinic projects have we done with
  - Electus Technology?
  - Medtronic/MiniMed?
  - the FAA?

Who cares about this?

- Intel
- NASA
- IBM
- Rockwell
- TPC
- DOE
- Voters

Systems in all areas are increasingly software-centric.


The application PowerPoint quit unexpectedly.
Mac OS X and other applications are not affected.
Click Reopen to open the application again. Click Report to see more details or send a report to Apple.
Close
Report...
Reopen

Approaches to System Correctness

- Testing/Simulation
- Formal verification
- Model-checking

Testing/Simulation

- Can only establish existence, *not absence*, of errors, *unless* system can be tested exhaustively.

- Laborious and time-consuming.

Formal Verification

- Requires sophisticated axiomatic framework.
- Requires powerful theorem-proving system.
- Users writing specifications must be well-versed in *logic*.
- Requires creativity, in the form of intermediate correctness specifications.

Model Checking

+ More thorough than simulation.

+ Does not require axiomatic framework.

+ Doesn't require as much logic as verification.

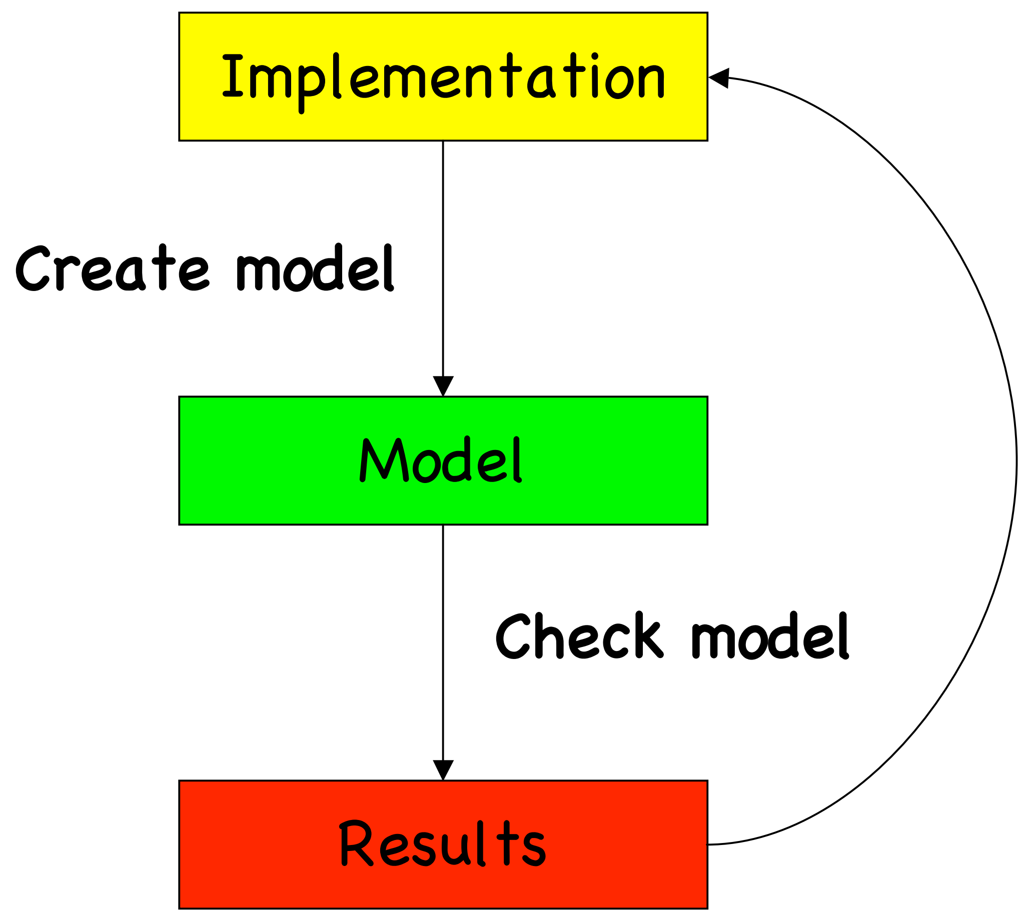
- System must be *finite-state*, however
+ certain types of errors can be detected even in infinite-state systems.

+ Software tools keep getting better.

Finite-state systems of interest

- Communication protocols
- Telephones
- Alarm systems
- File-opening protocols in software
- GUI protocols
- Business protocols

Model-Checking Steps



Automation Possibilities

- Create Model:
  - Sometimes manual
  - Can be automated, depending on implementation language (NASA Ames: Java Pathfinder)
  - Semi-automated via appropriate tools
- Check Model:
  - Usually automated

Modeling Language

- A language of some kind is needed as input for *any* automated task.
- Various modeling languages and companion checkers exist:
  - SPIN (Holzmann: Bell Labs, now JPL)
  - Uppaal (Uppsala, Sweden + Aalborg, Norway)
  - Murϕ (Stanford)

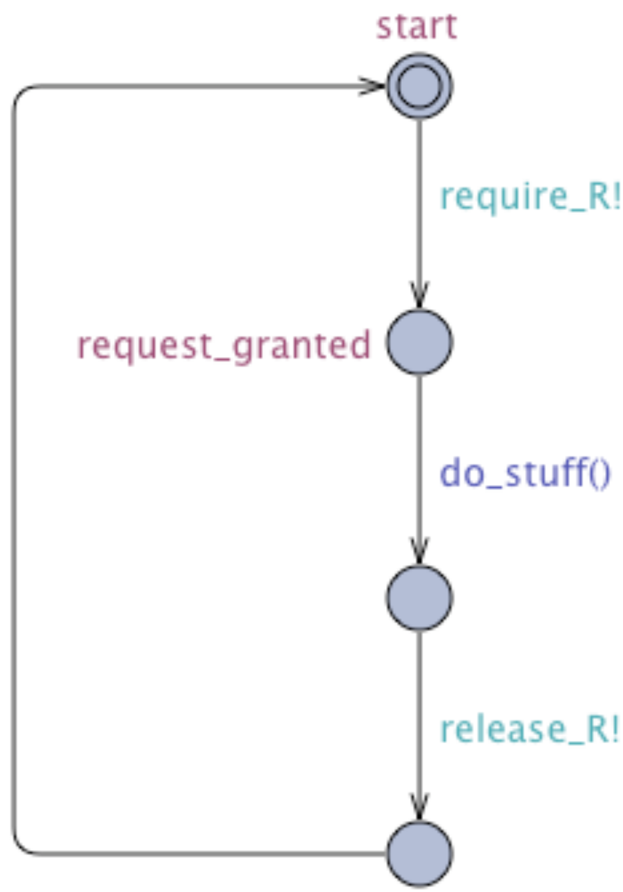
Uppaal Modeling Language

- Based on “timed automata” (finite-state automata + timing info)
- Model representations:
  - Graphical
  - Textual
  - XML

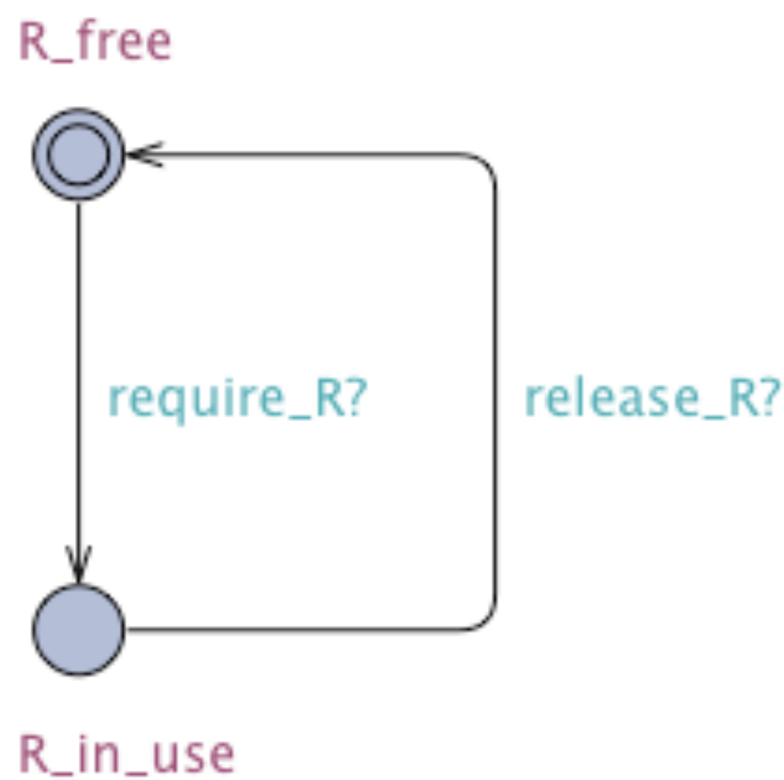
Basic Single-Resource Example

- Users make use of a single shared resource, call it R.
- Only one user can use R at a time.
- Protocol:
  - Users must *request* the resource to use it.
  - Users must *release* the resource when done.

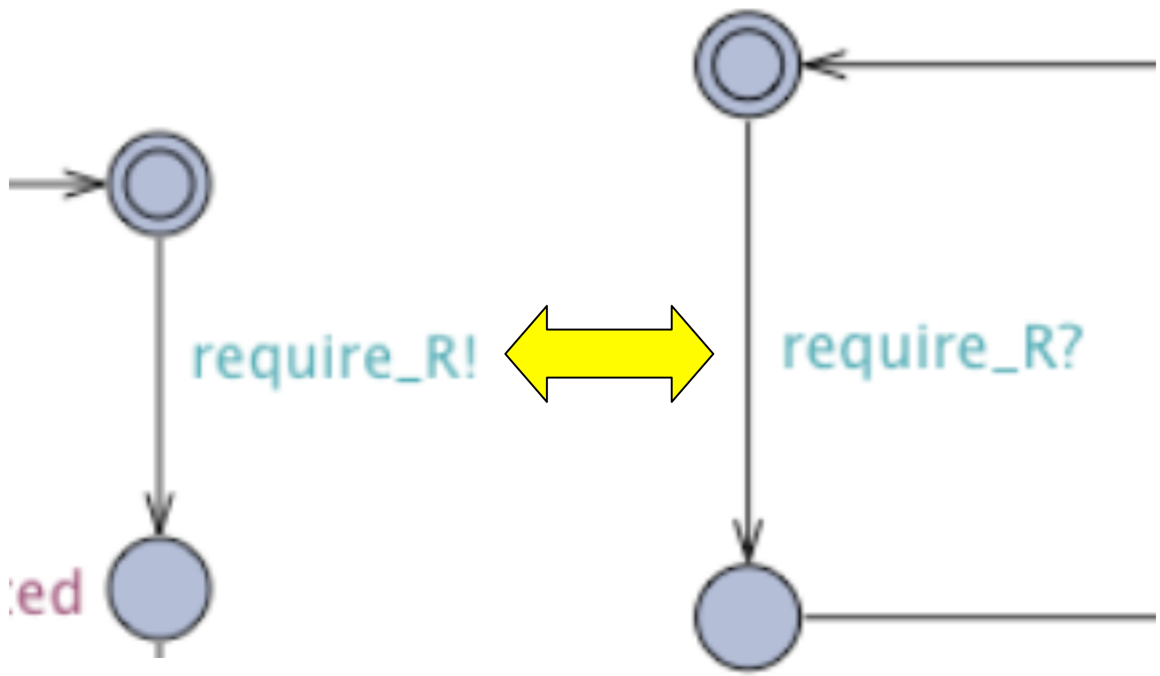
User Cycle



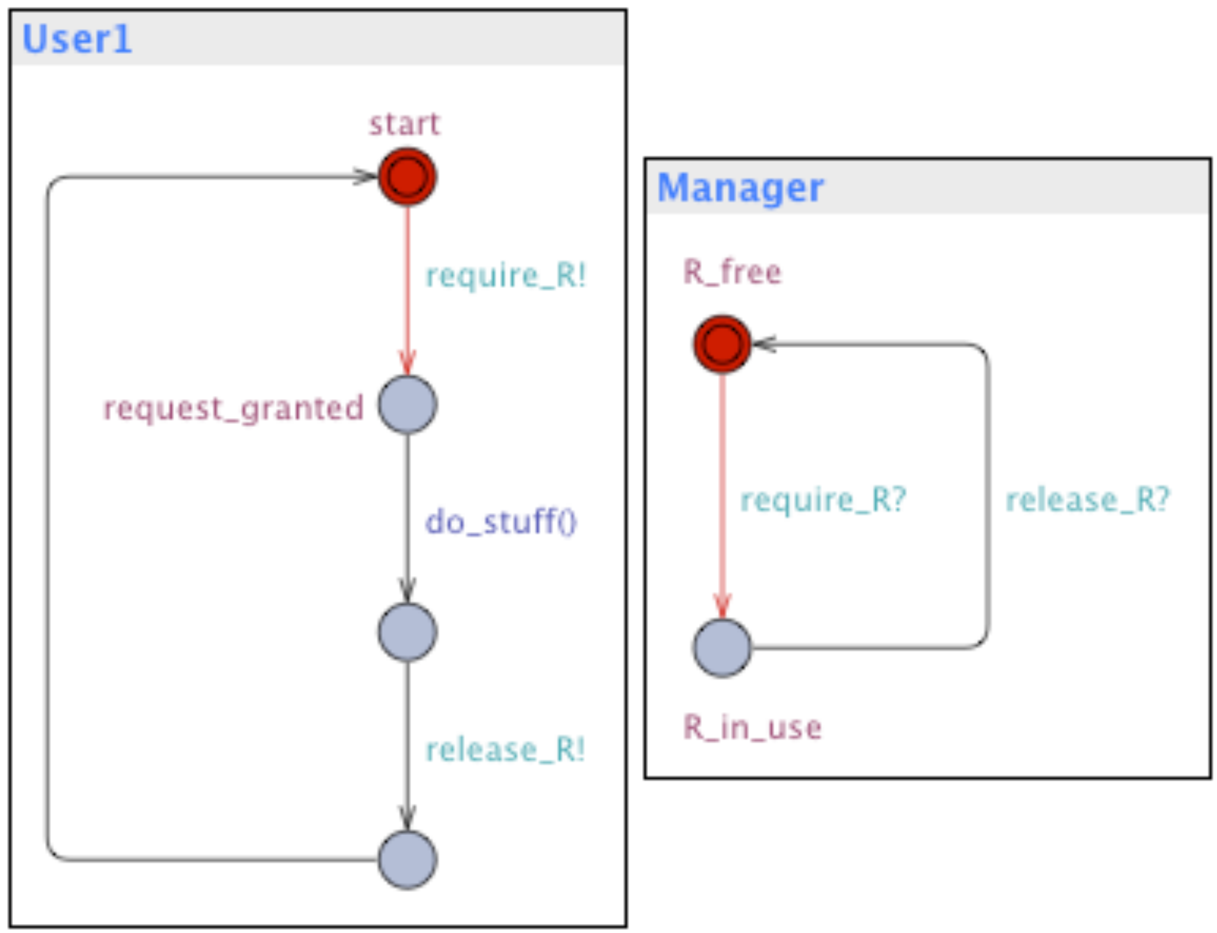
Resource-Manager Cycle



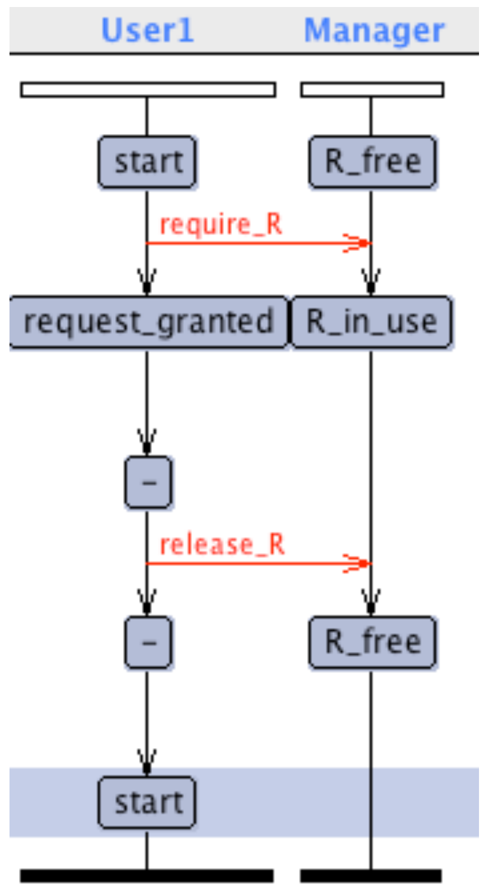
Rendezvous Paradigm



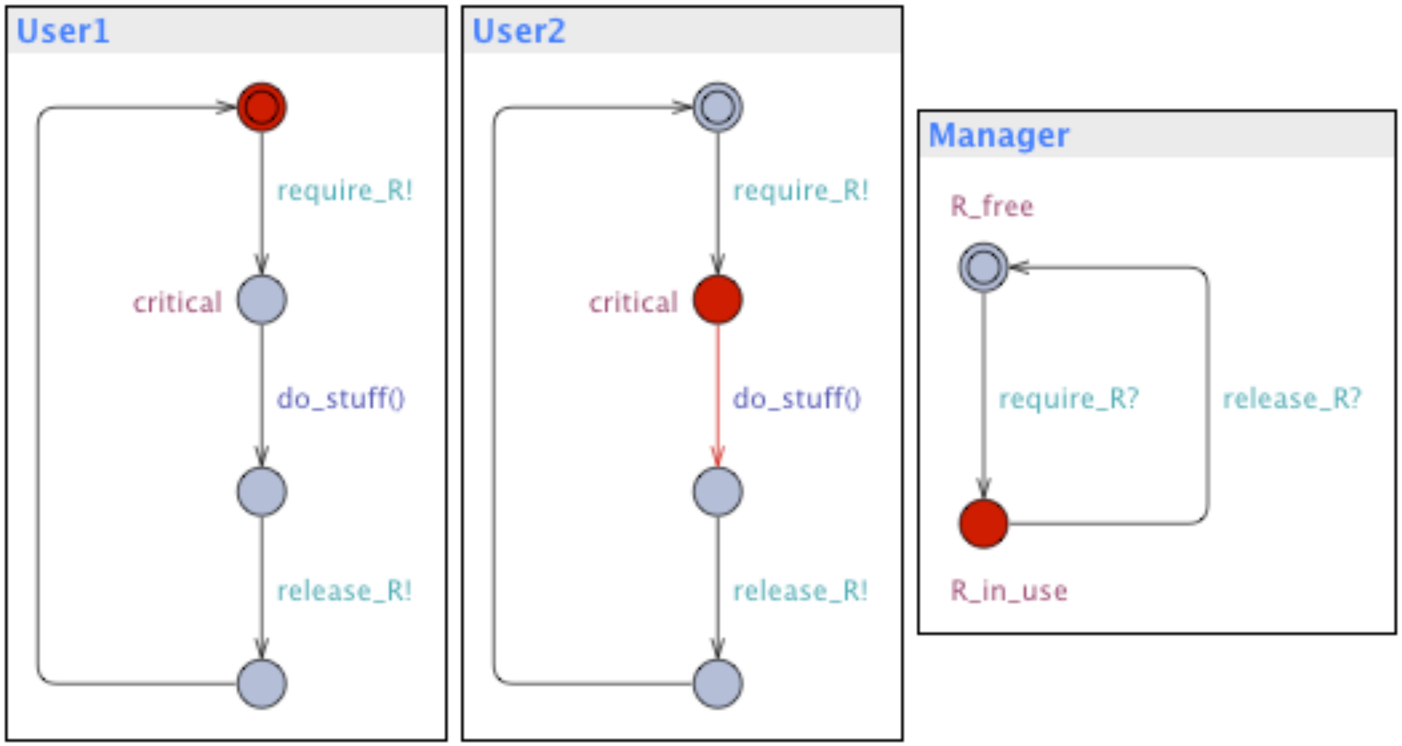
Uppaal Simulation View



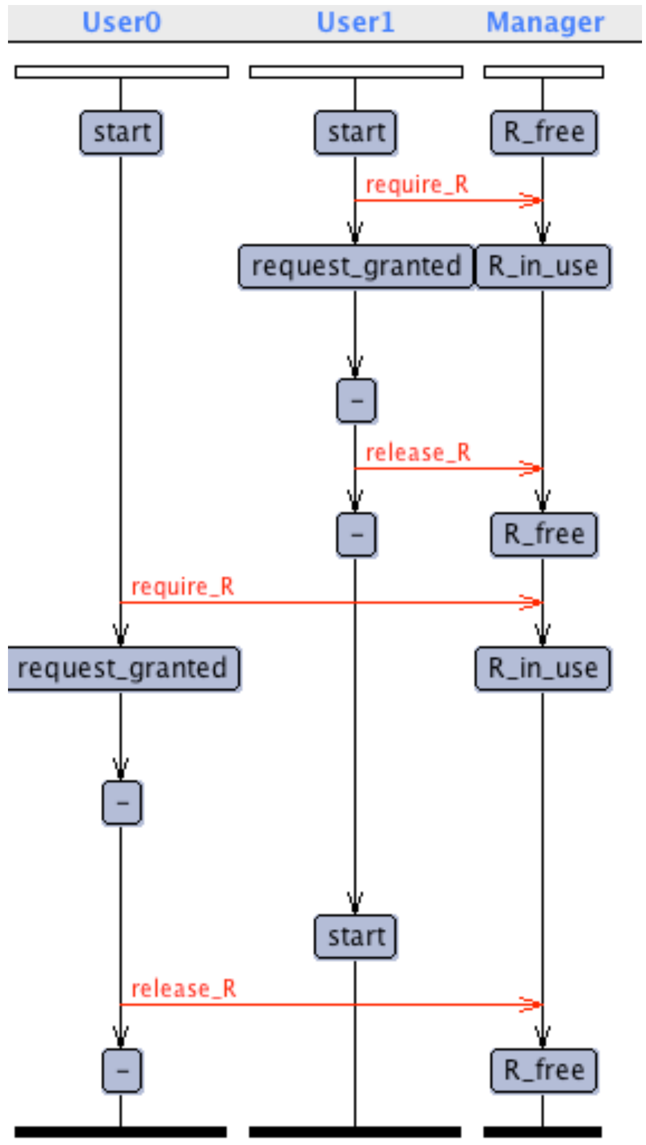
Uppaal Sequence Diagram View



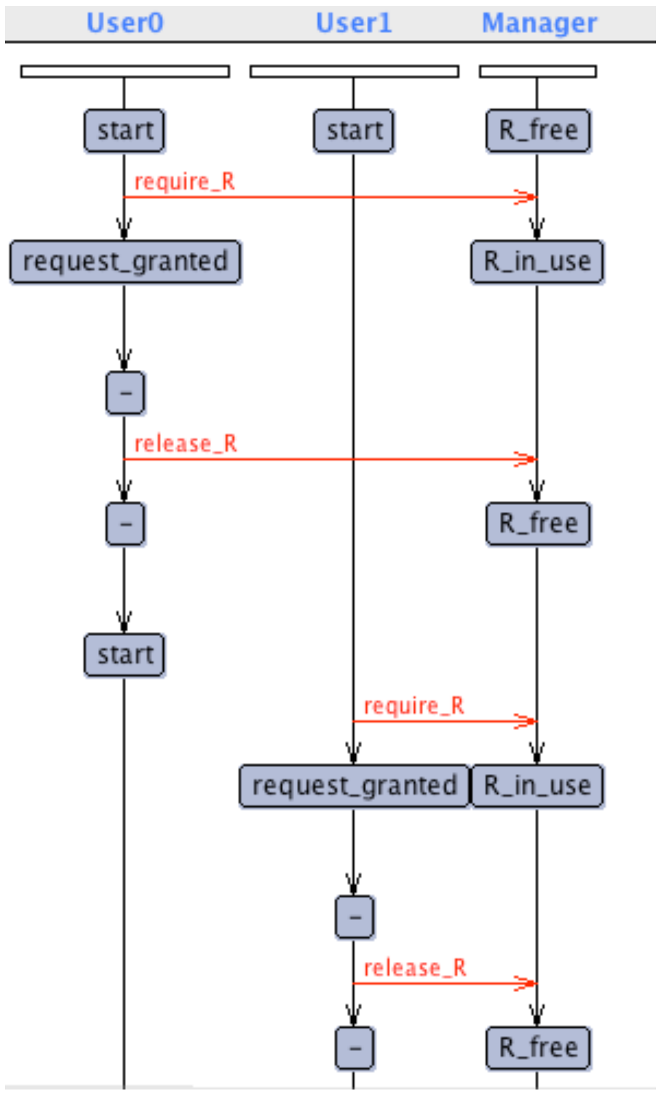
2 Users, 1 Resource

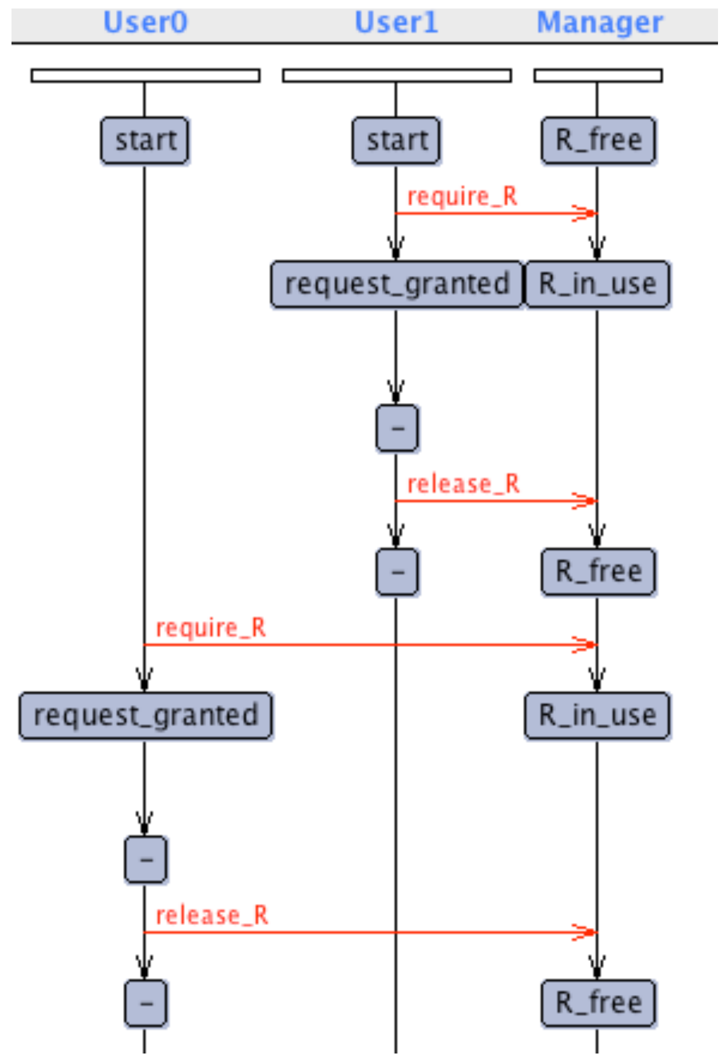


2 Users, 1 Resource Sequence

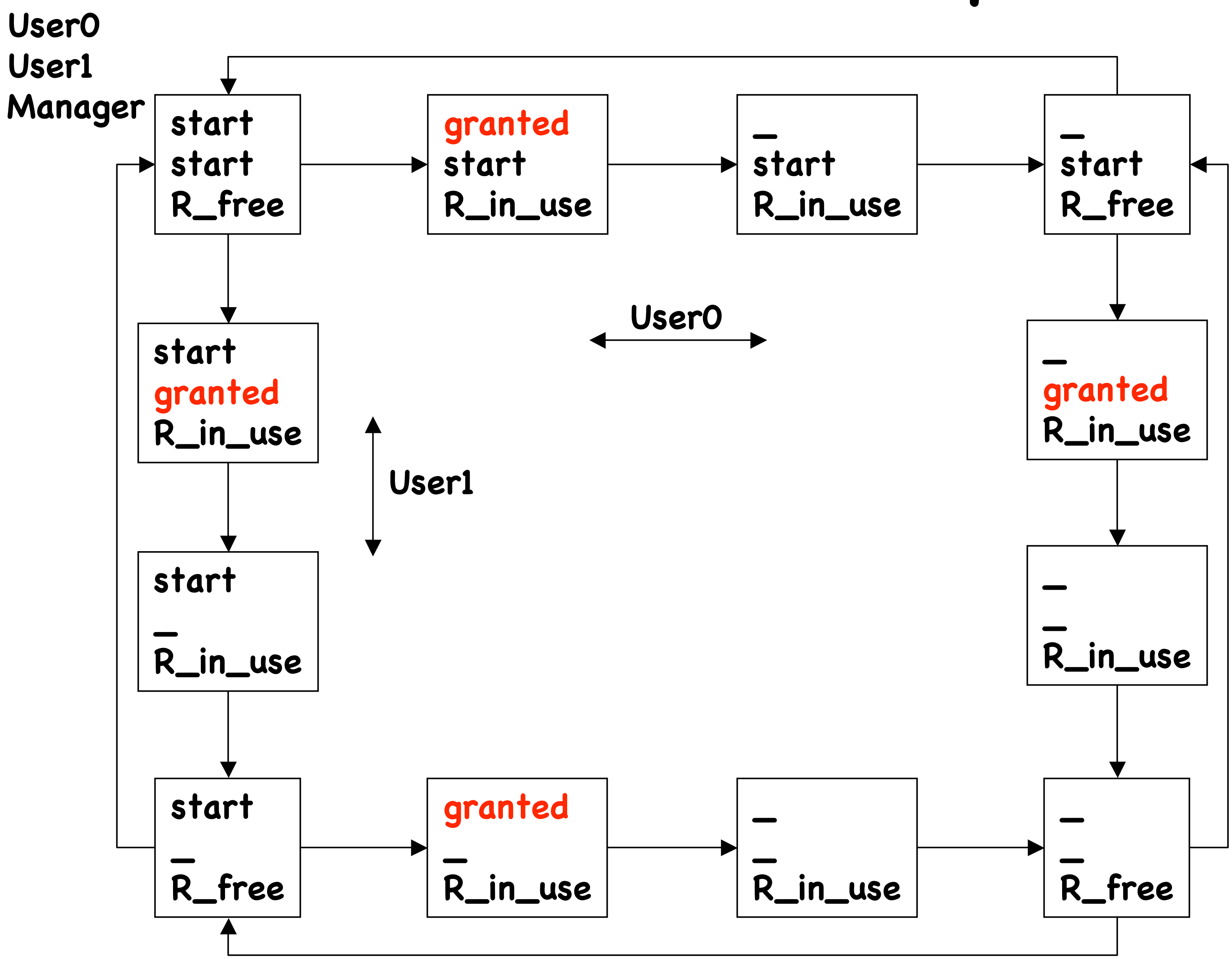


2 Users, 1 Resource
Different Sequences

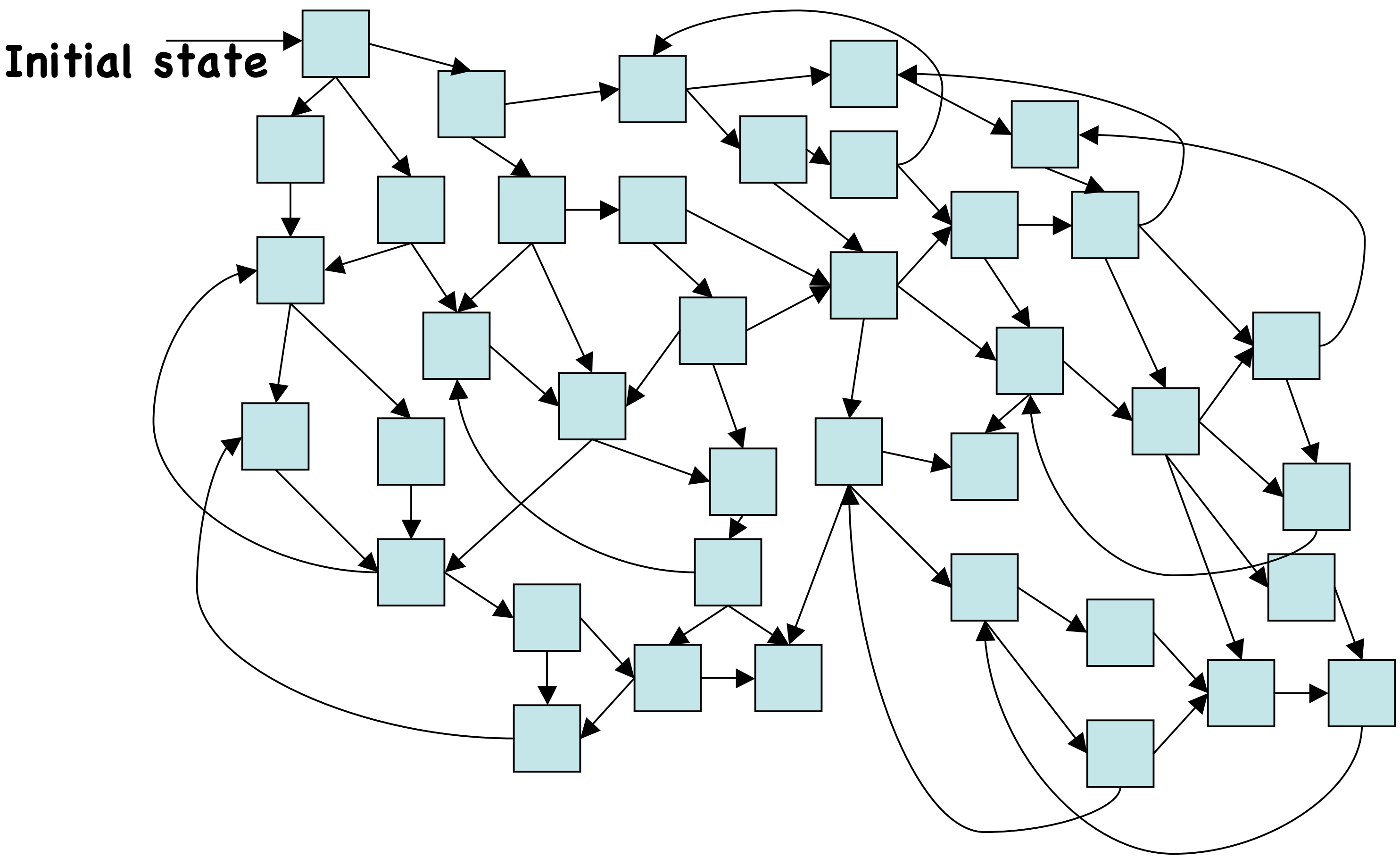




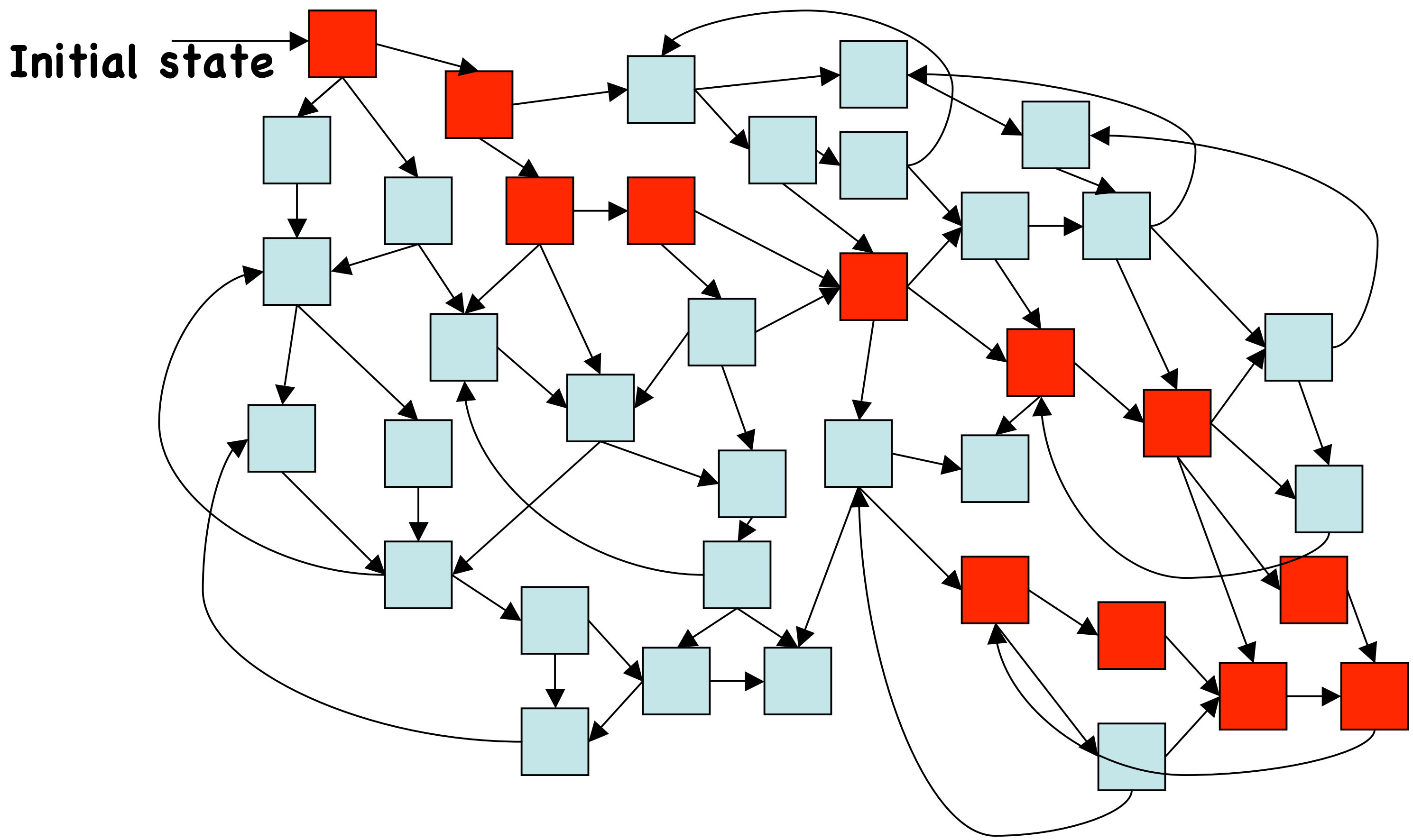
Global State View (conceptual)



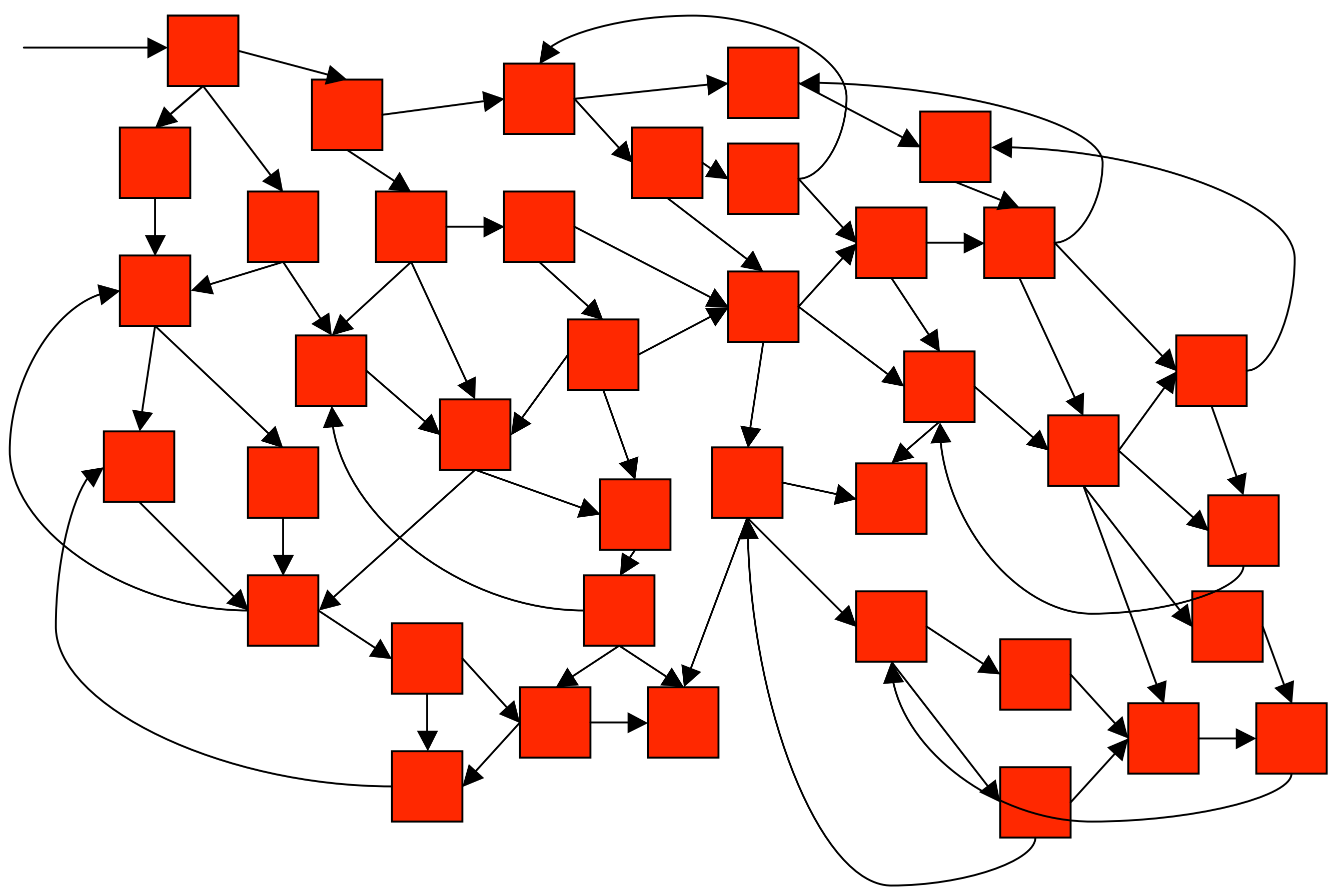
General Global State View



Path Analyzed by *One Simulation*



Paths Analyzed by One Model-Check



e.g. Steiner, et al., 2004

"The resulting models have billions or even trillions of reachable states, yet the symbolic model checker of SAL is able to examine these in a few tens of minutes (for billions of states) or hours (for trillions)."

Expressing Checkable Properties

- **Temporal Logic** (TL) is an extension of predicate logic (PL) expressing properties of behavioral sequences.

- PL concerned with logical properties of a *single state*:

  "x > y + 5"

- TL concerned with properties of a *sequence* of states:

  "after y > 0, x > y + 5 is possible"

Examples of Temporal Operators

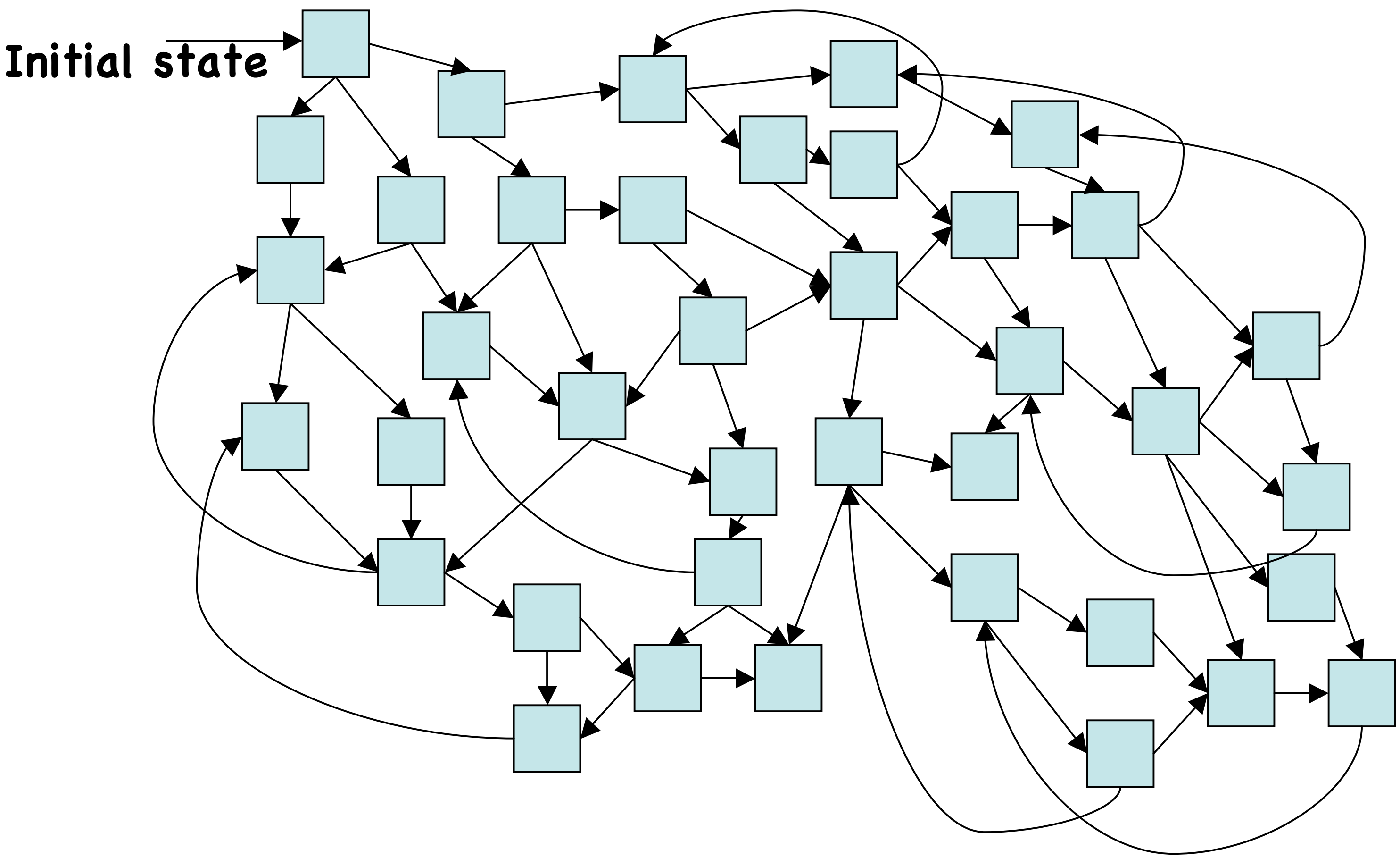
■ P "Henceforth" P
◆ P "Eventually" P

◆ ■ P Eventually henceforth P

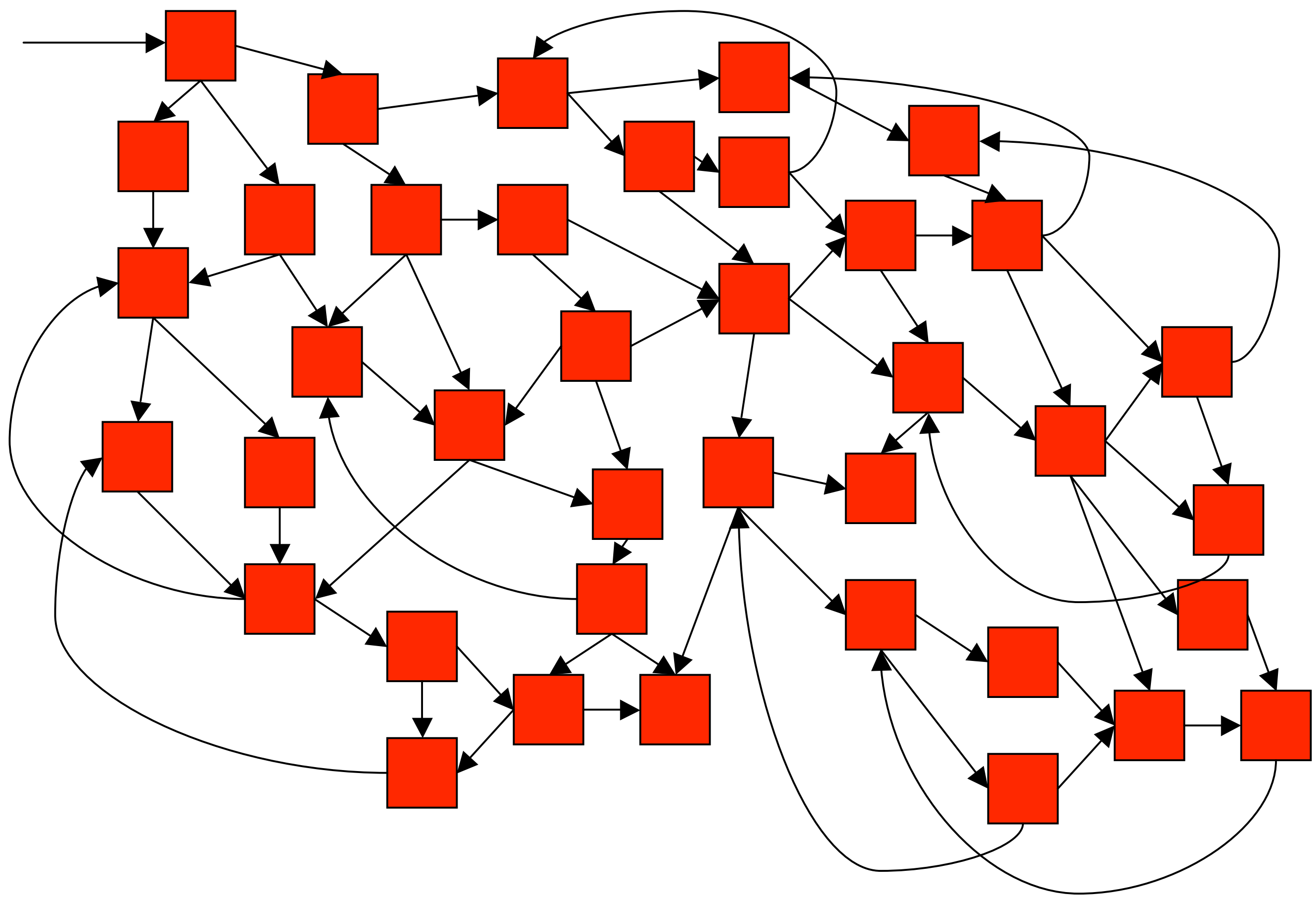
■ ◆ P Henceforth eventually P

◆ ■ ◆ P Eventually henceforth eventually P
etc.

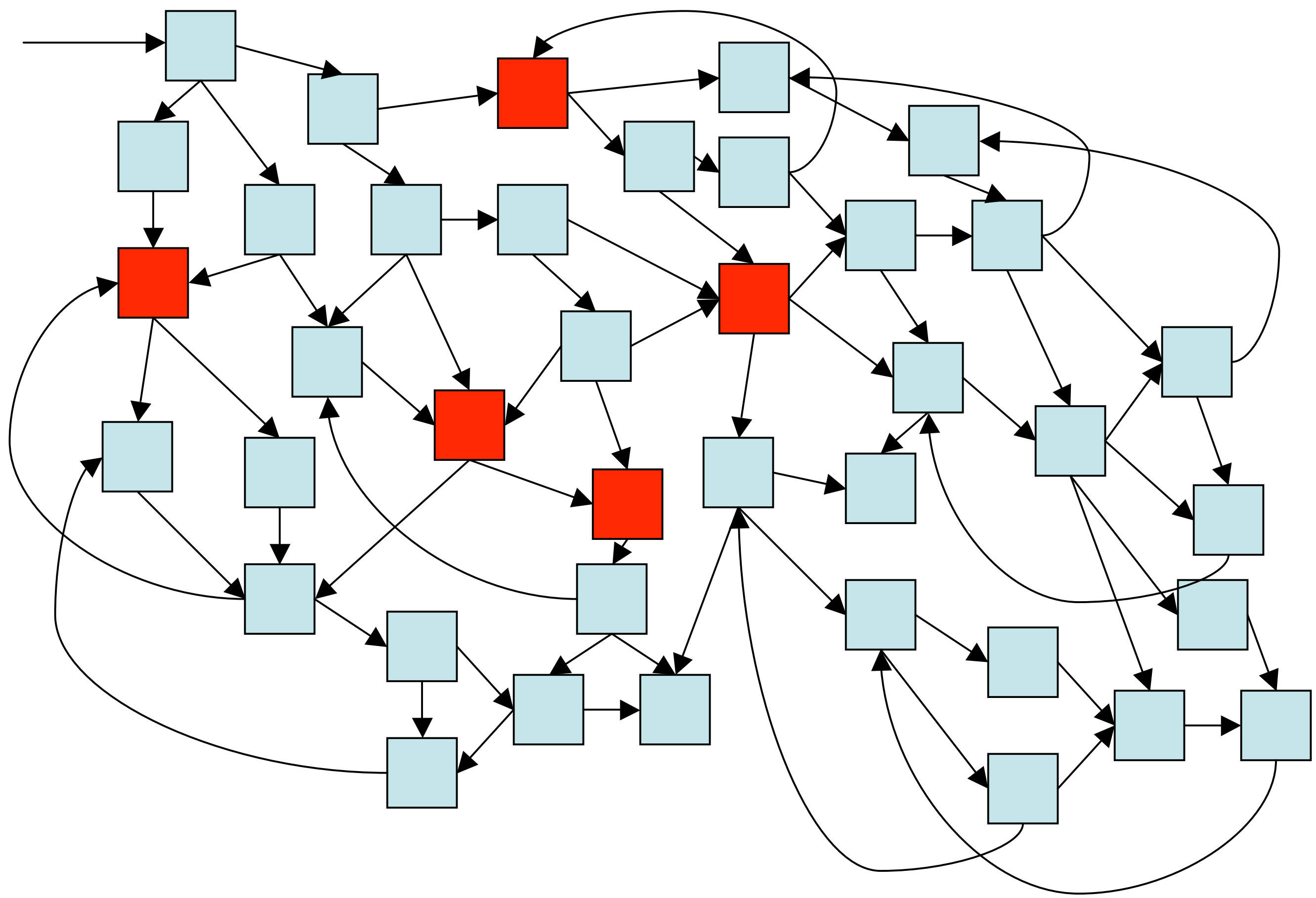
General Global State View



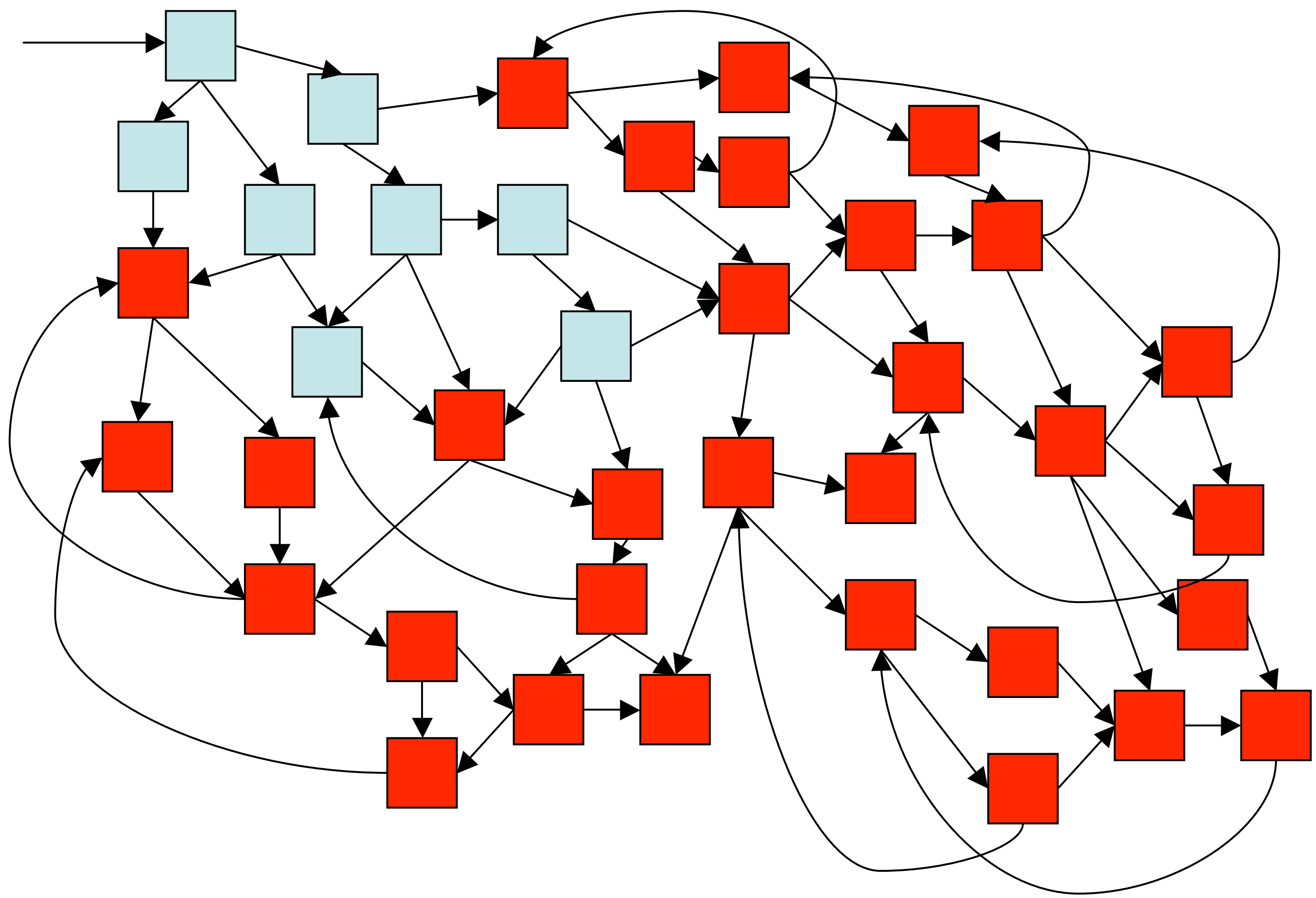
- Red (Henceforth Red)



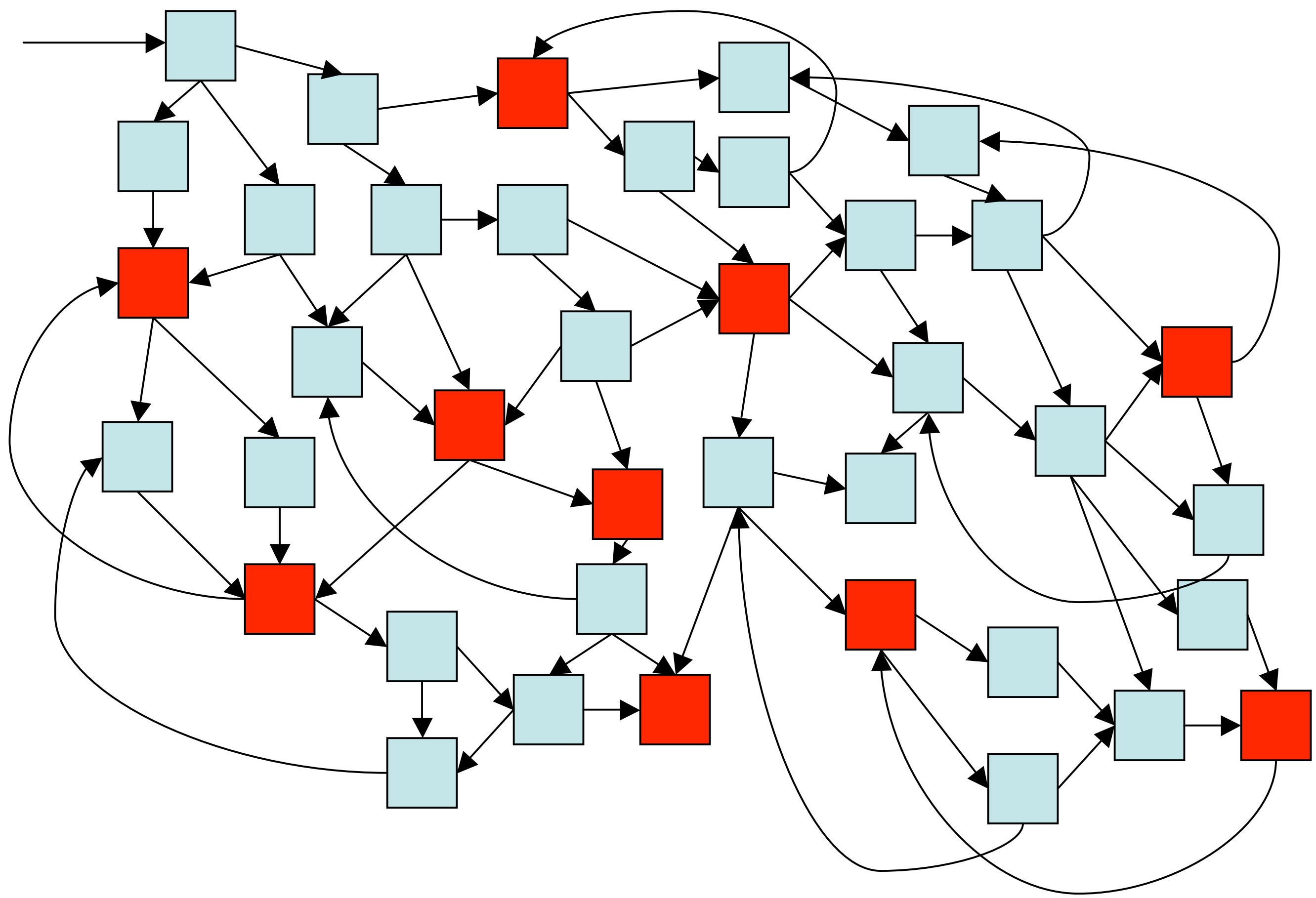
- Red (Eventually Red)



◆ ■ Red



■◆ Red



Temporal Operators in Uppaal

- Two levels of nesting only
- A[ ] *P* means *P* is true in all reachable states

Correctness Property 1

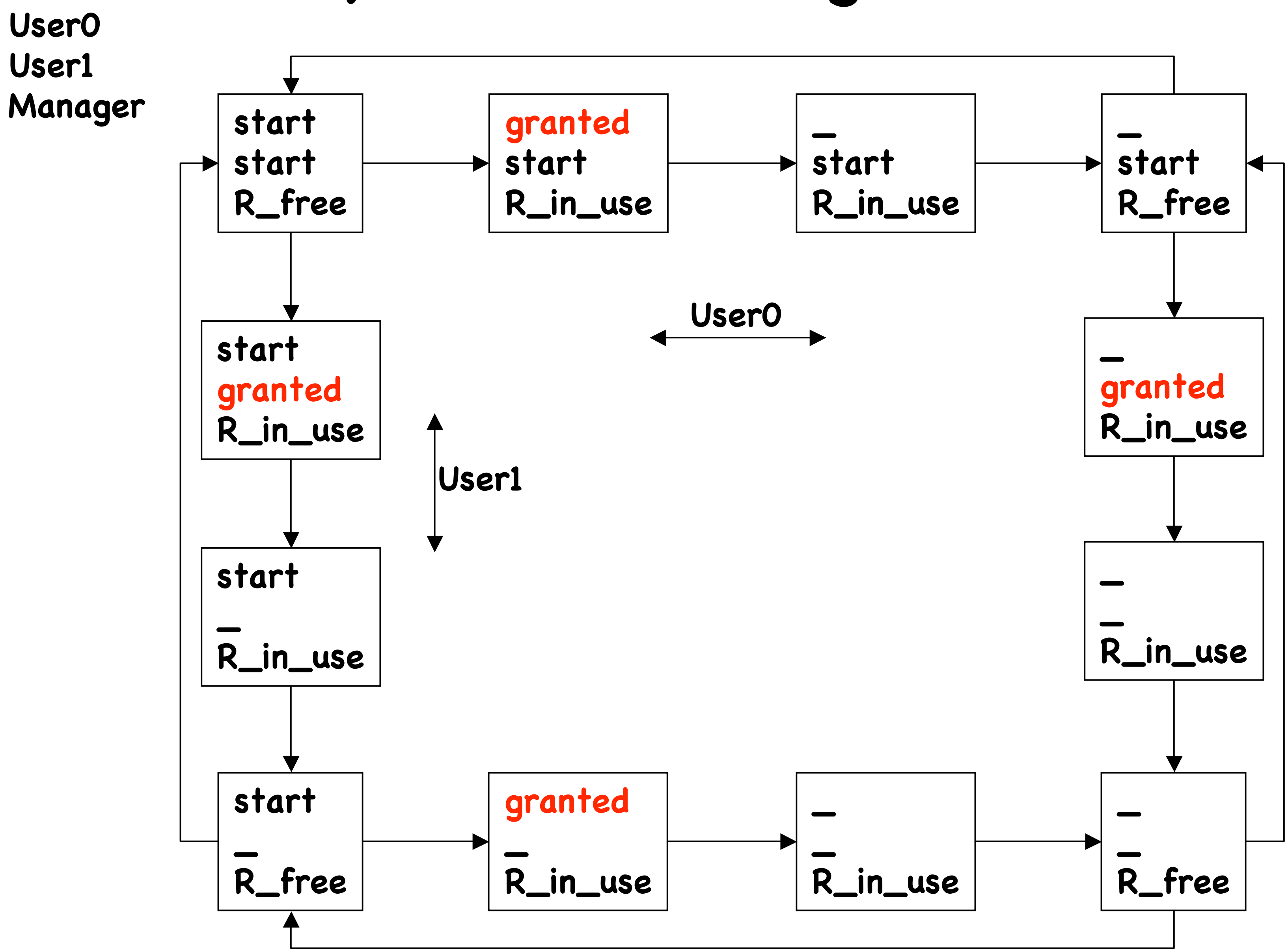
- Only one user should use the resource at a time.

- In Uppaal's TL specification language:

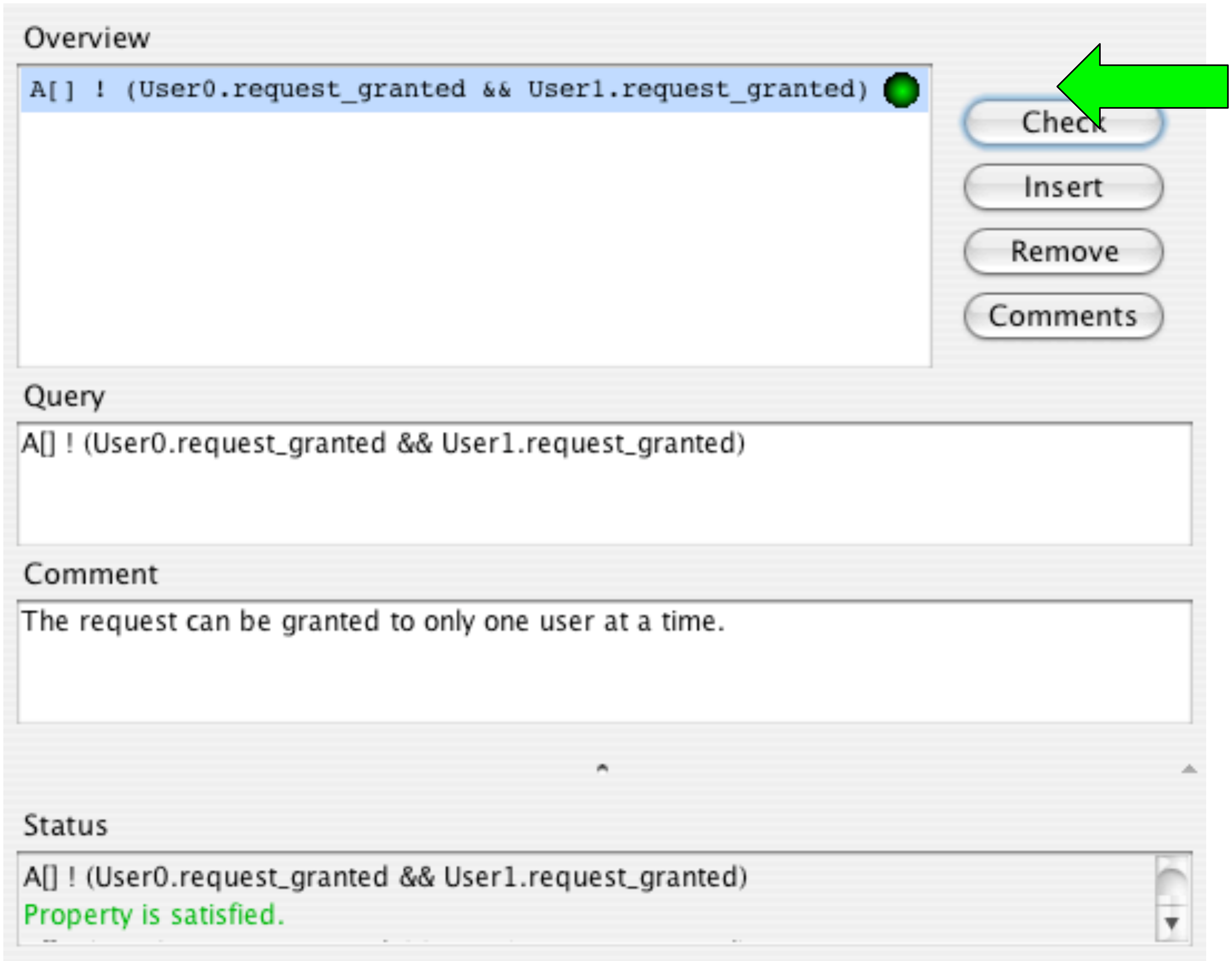
```
A[] !(User0.request_granted && User1.request_granted)
```

! is "not"   && is "and"

Only one user using at a time



Uppaal Verifying Property 1



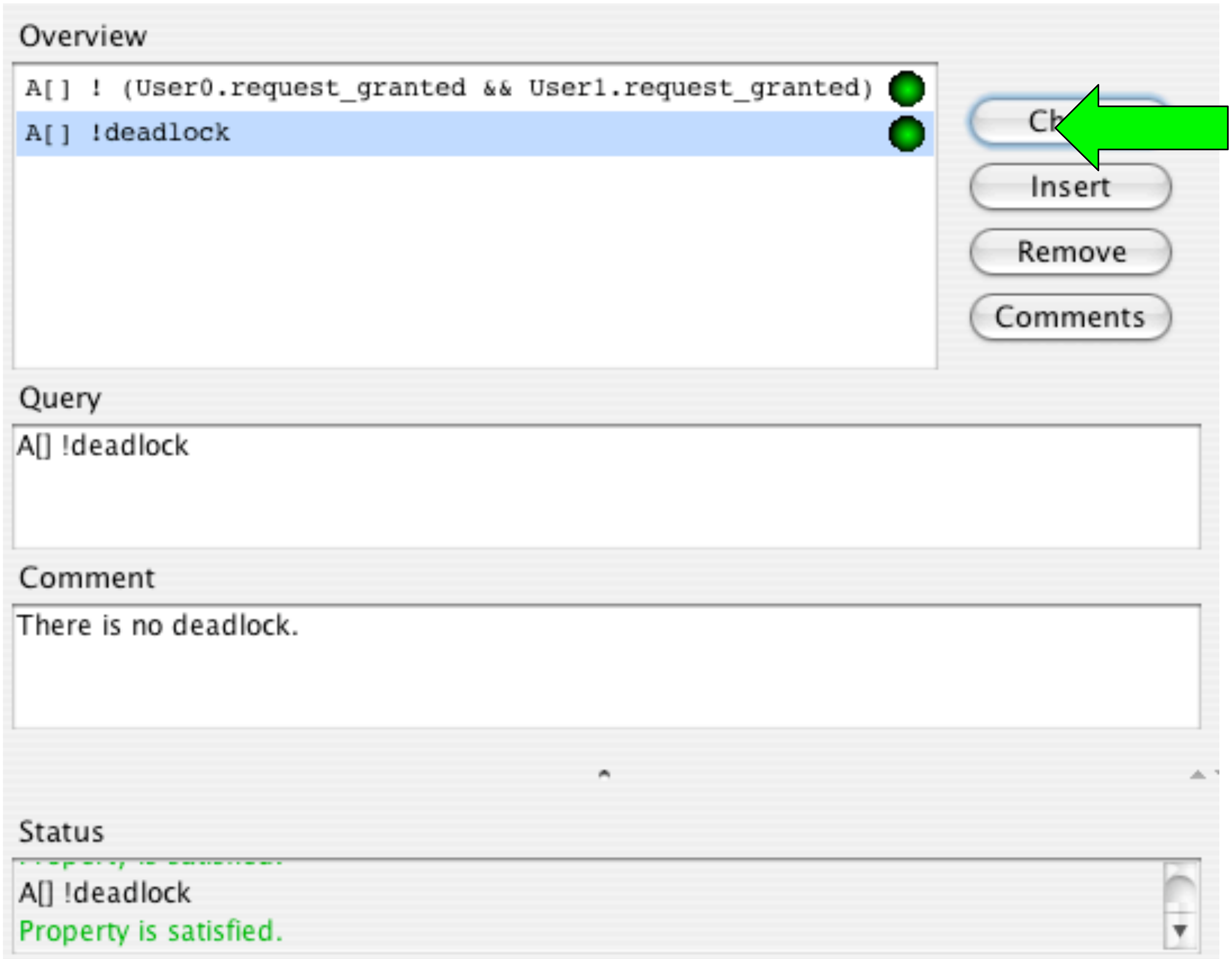
Correctness Property 2

- No deadlock
- In Uppaal's TL specification language:

```
A[] !deadlock
```

Here deadlock means "there is no way of leaving the state".

Uppaal Verifying Property 2



More on Uppaal Specification

- E<> *P* means there exists a path in which *P* becomes true.

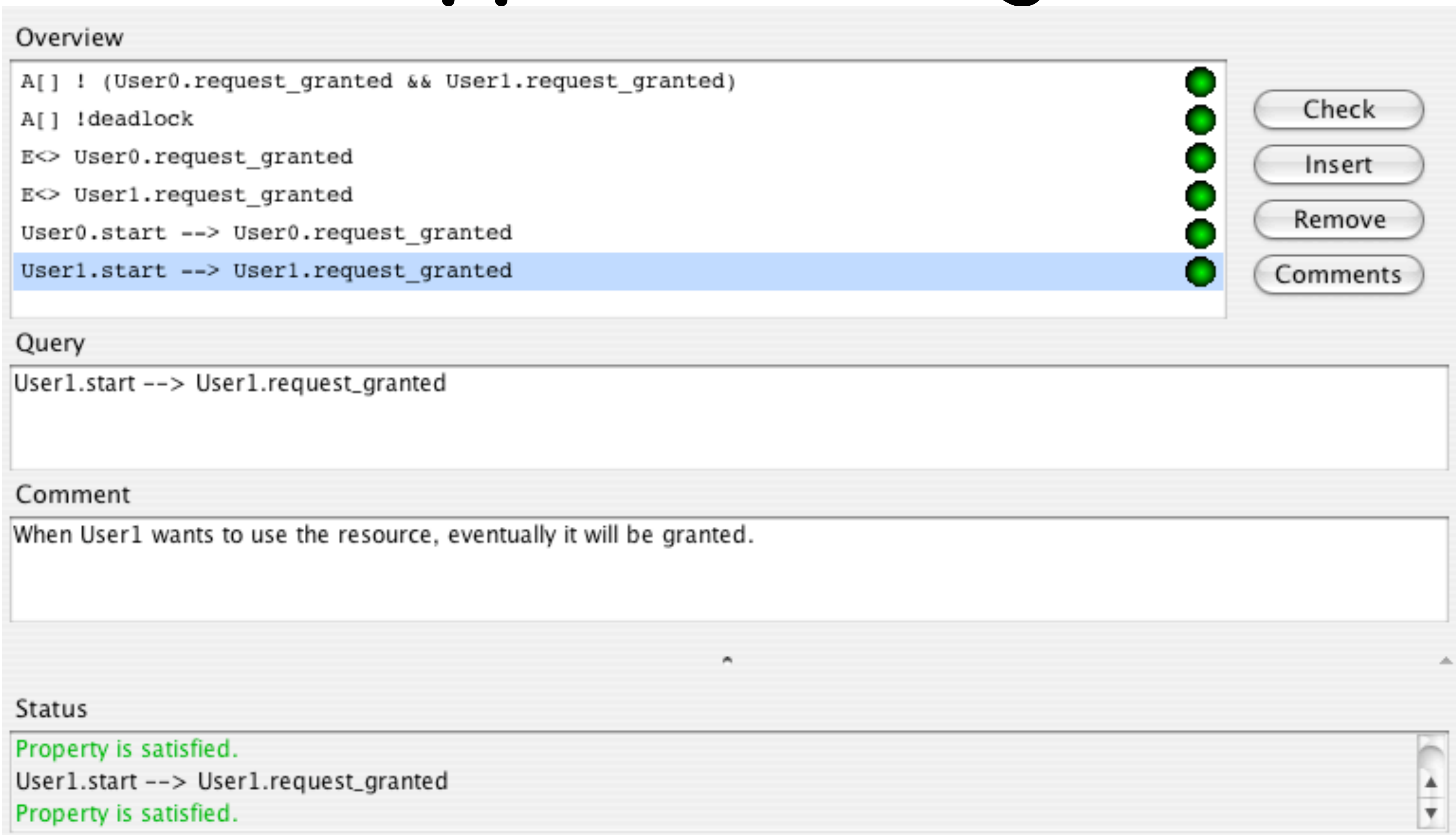
- E<> User0.granted
- E<> User1.granted

More Exacting Requirement

- *P* --> *Q* means whenever P is true, there is a path in which *Q* becomes true subsequently.

- User0.start --> User0.granted
- User1.start --> User1.granted

Uppaal Proving



What can't be proved in this model?

A<> User0.request_granted

(From every state, eventually the user's request will be granted.)

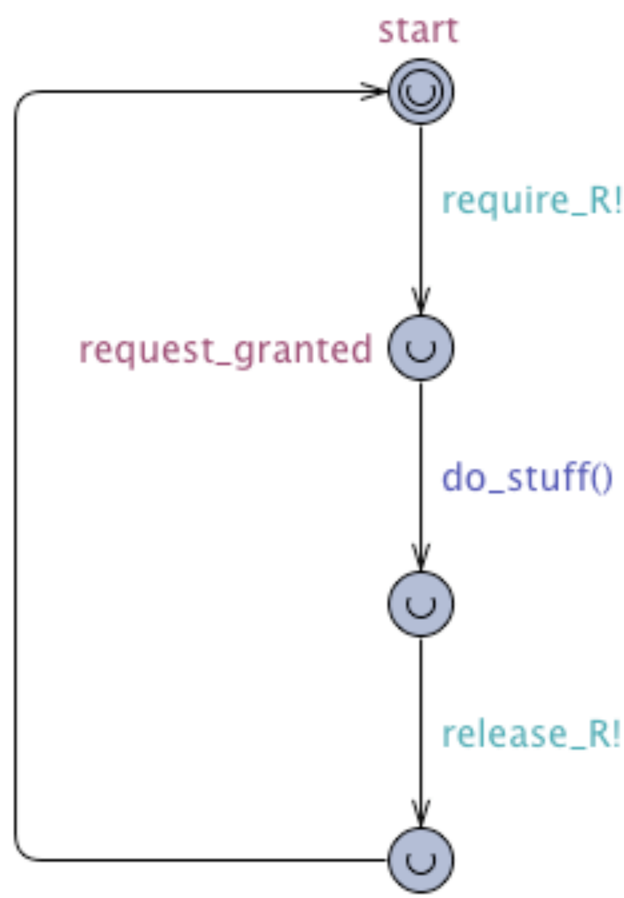
Two reasons:

- A user is not forced to move.
- One user could be "starved" by the other.

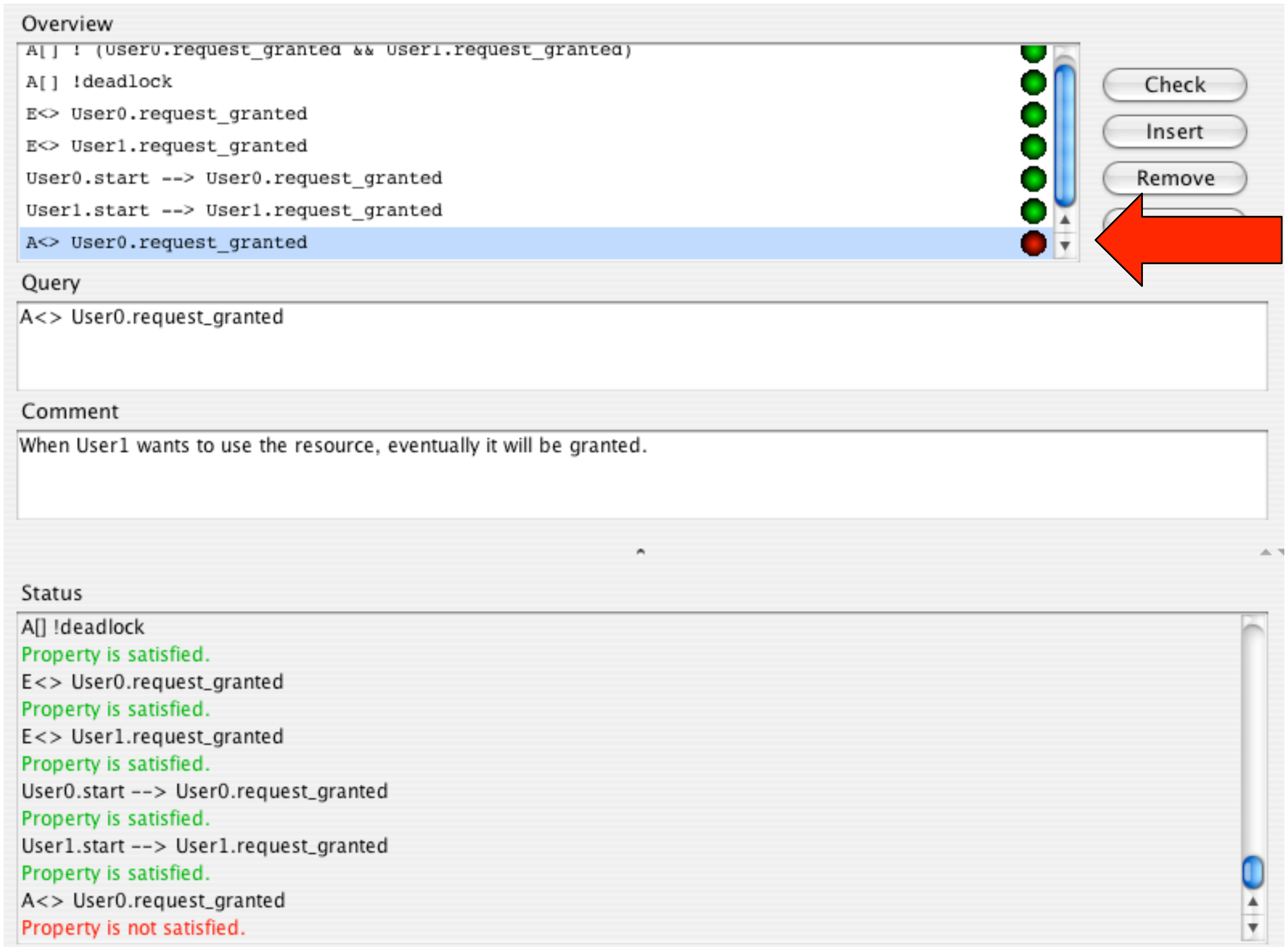
Forcing Motion

- States can be marked "urgent", meaning cannot dwell in this state.
- The system must move from that state if possible.

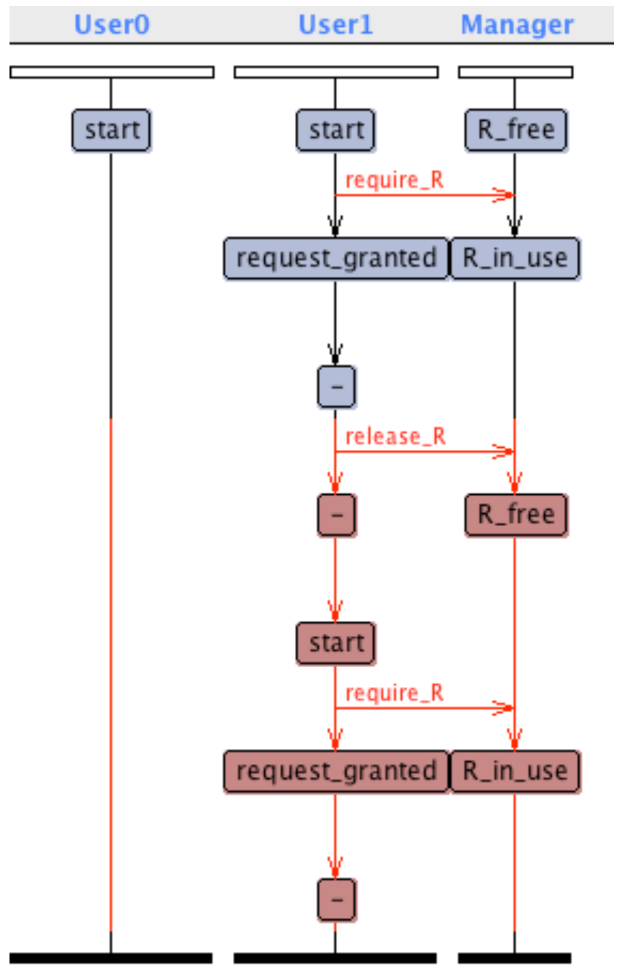
User with all states urgent



Uppaal Showing Property Failure



Certain Types of Failures (Deadlock, starvation, …) can be exhibited explicitly



Starvation can be avoided

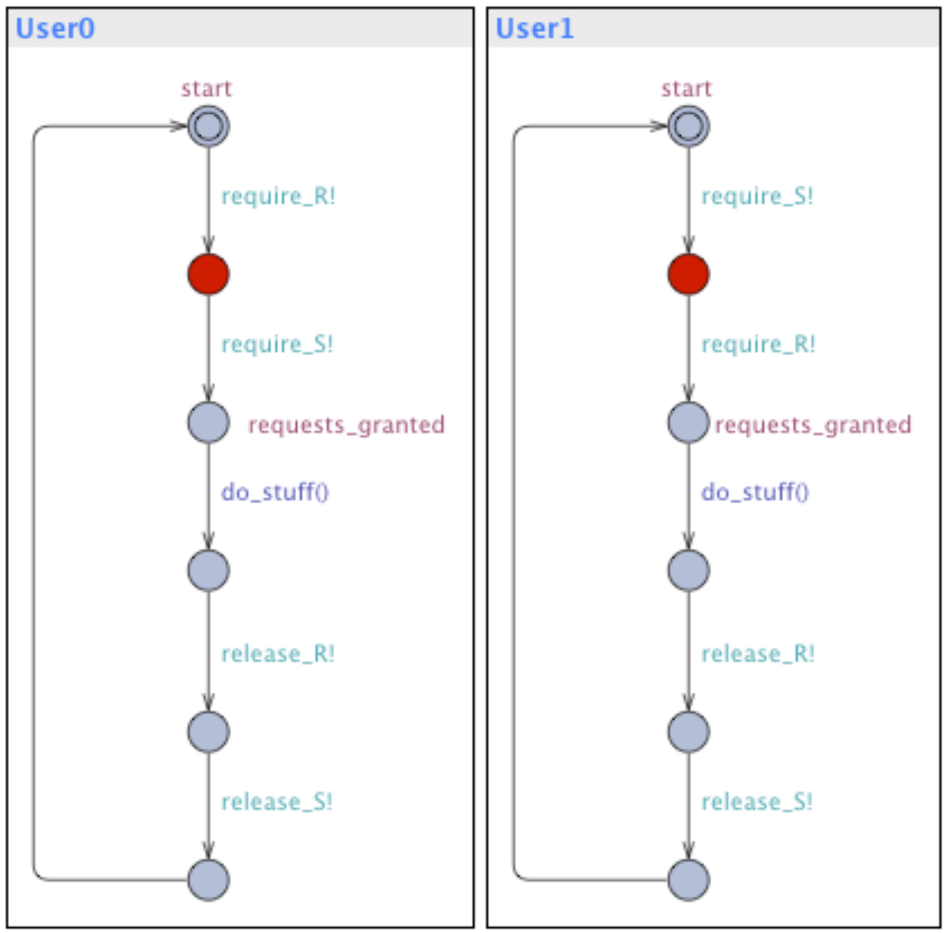
- with a more complicated system structure

- e.g. *conscience*: after using a resource, a user must give the other user a chance.

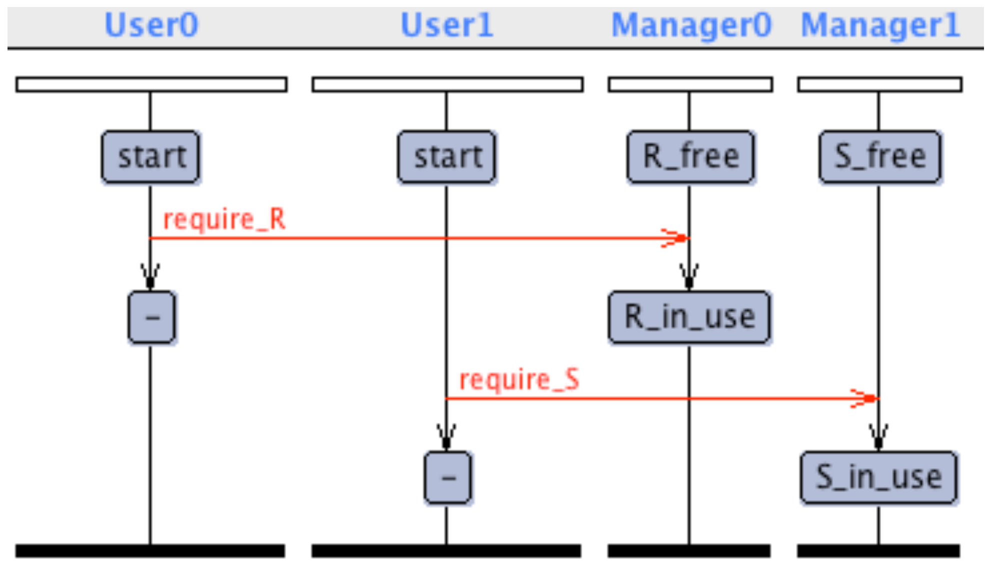
Deadlock Example

- 2 resources, 2 users
- Uppaal constructs the shortest sequence to deadlock state

Deadlock Example



Shortest Sequence to Deadlock Constructed by Uppaal



Overview

```
A[] ! (User0.requests_granted && User1.requests_granted)
A[] !deadlock
E<> User0.requests_granted
E<> User1.requests_granted
User0.start --> User0.requests_granted
User1.start --> User1.requests_granted
A<> User0.requests_granted
```

How to establish properties involving infinite sequences?

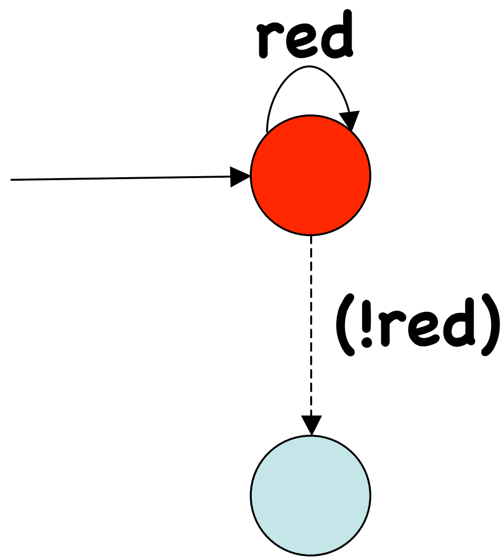
- Certain temporal properties are exemplified by “Buchi automata”:
  - Finite-state automata
  - A special notion of acceptance for *infinite* sequences of states *of the model*.

- Such automata can be “crossed” with a system and the result analyzed by state reachability to establish whether or not the property holds.

Properties of Infinite Sequences

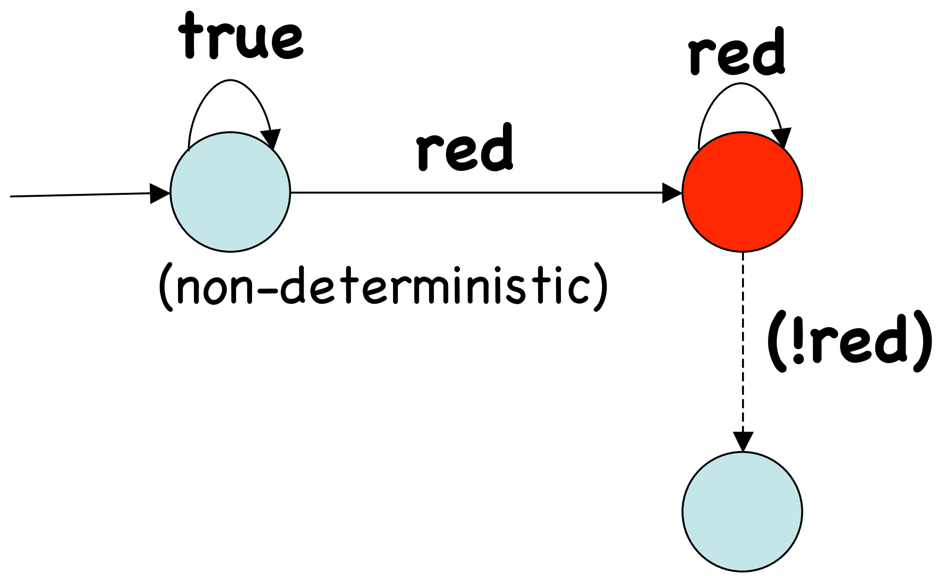
- red, red, red, red, … ■ red
- !red, !red, …, red, red, red, … ◆ ■ red
- !red, red, !red, red, !red, red, … ■ ◆ red

Buchi Automaton for ■ Red

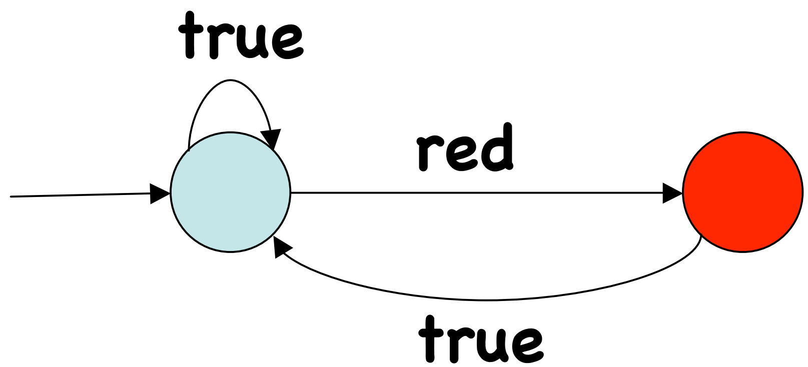


An infinite sequence is **accepted** iff
the red state is entered infinitely-often.

Buchi Automaton for ◆ ■ Red



Buchi Automaton for ■ ◆ Red



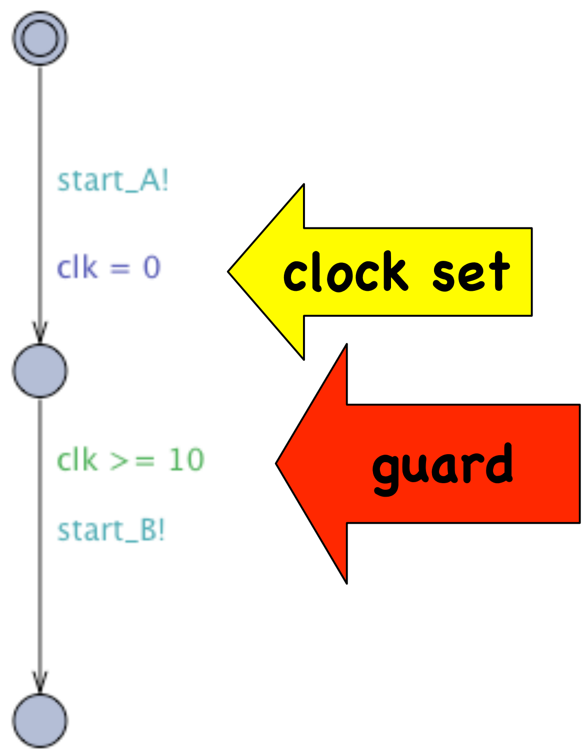
An infinite sequence is accepted iff
the red state is entered infinitely-often.

Real-Timing

- Uppaal is somewhat novel in providing for real-time.
- Based on *timed automata*.
- *Clock* variables can be introduced.
- Time is *continuous*!
- Time inequalities analyzed *symbolically*.

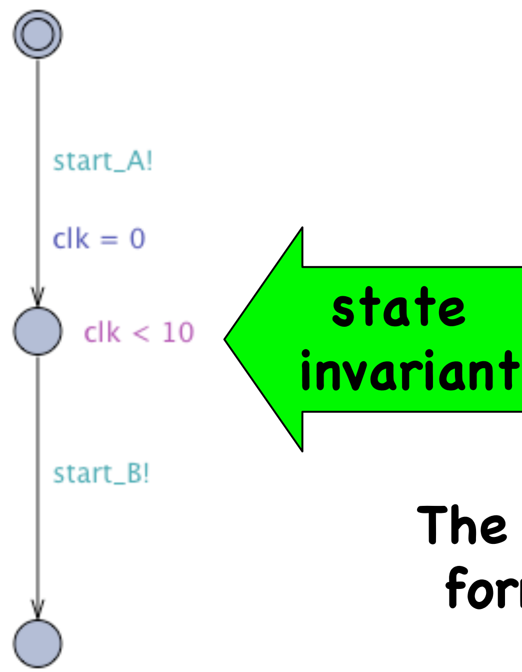
Real-Time Examples

- Start B no sooner than 10 seconds after A starts



Real-Time Examples

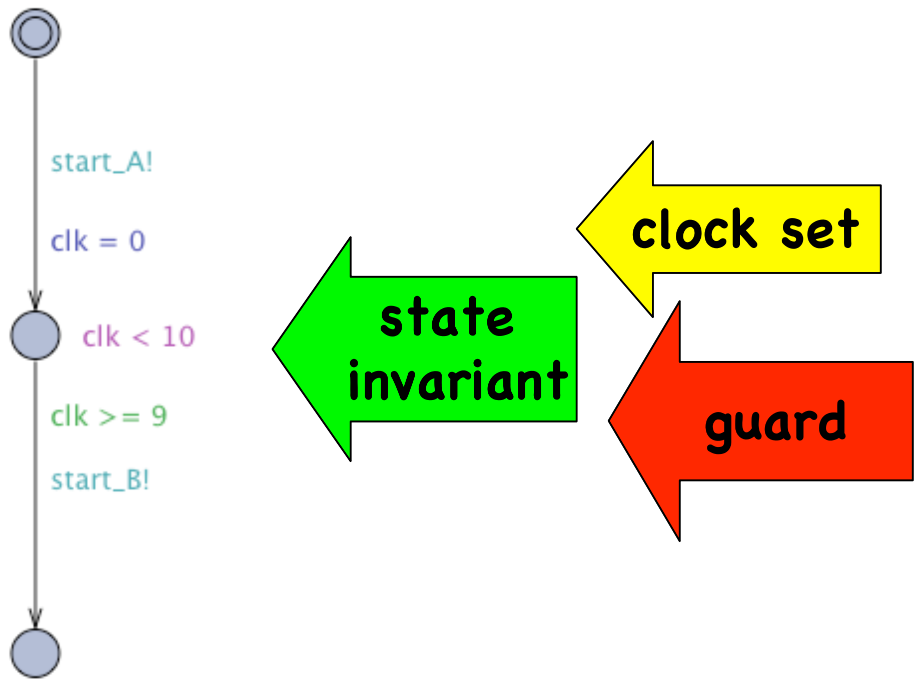
- Start B no later than 10 seconds after A starts



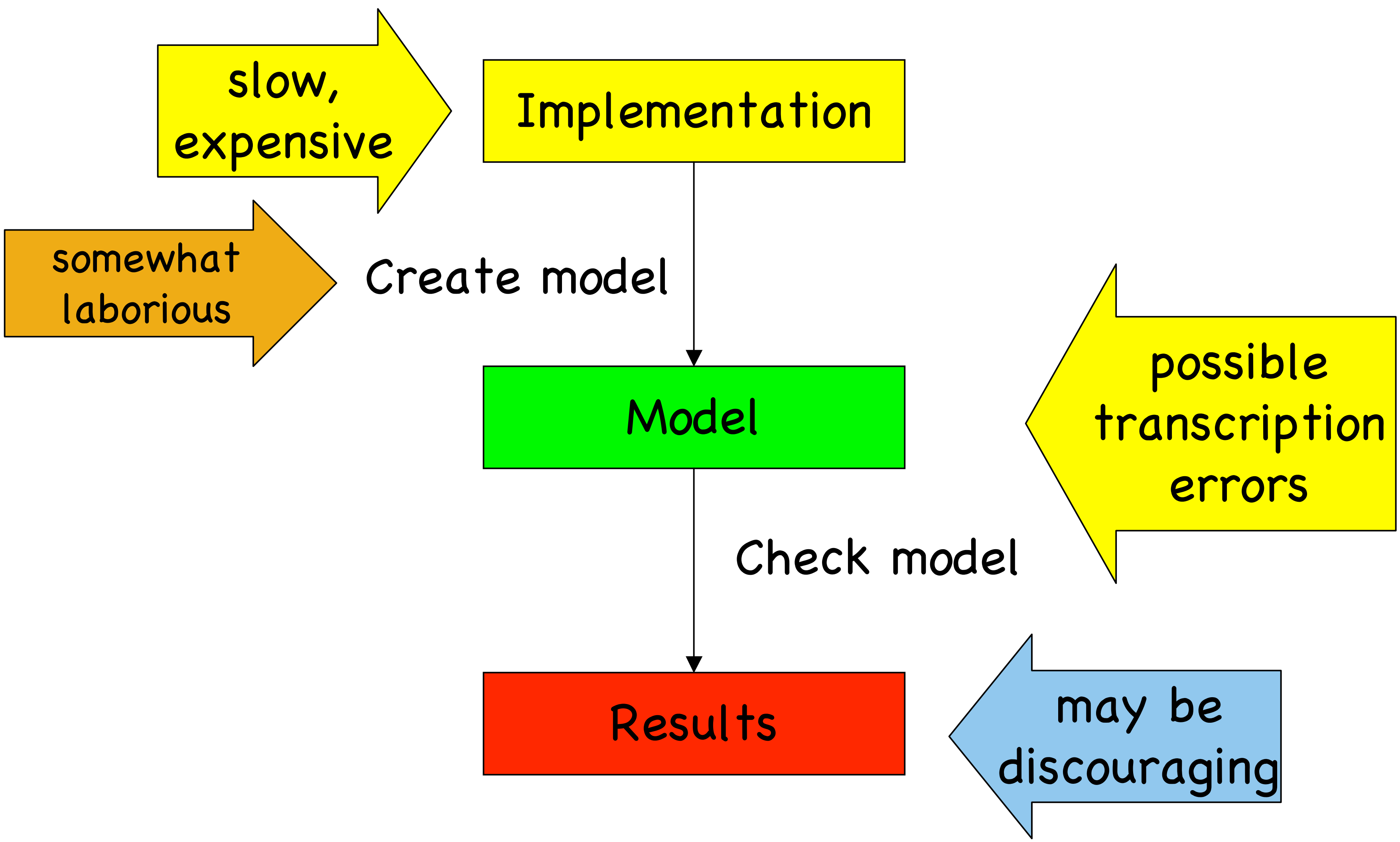
The invariant is a form of *implicit* control.

Techniques Combined

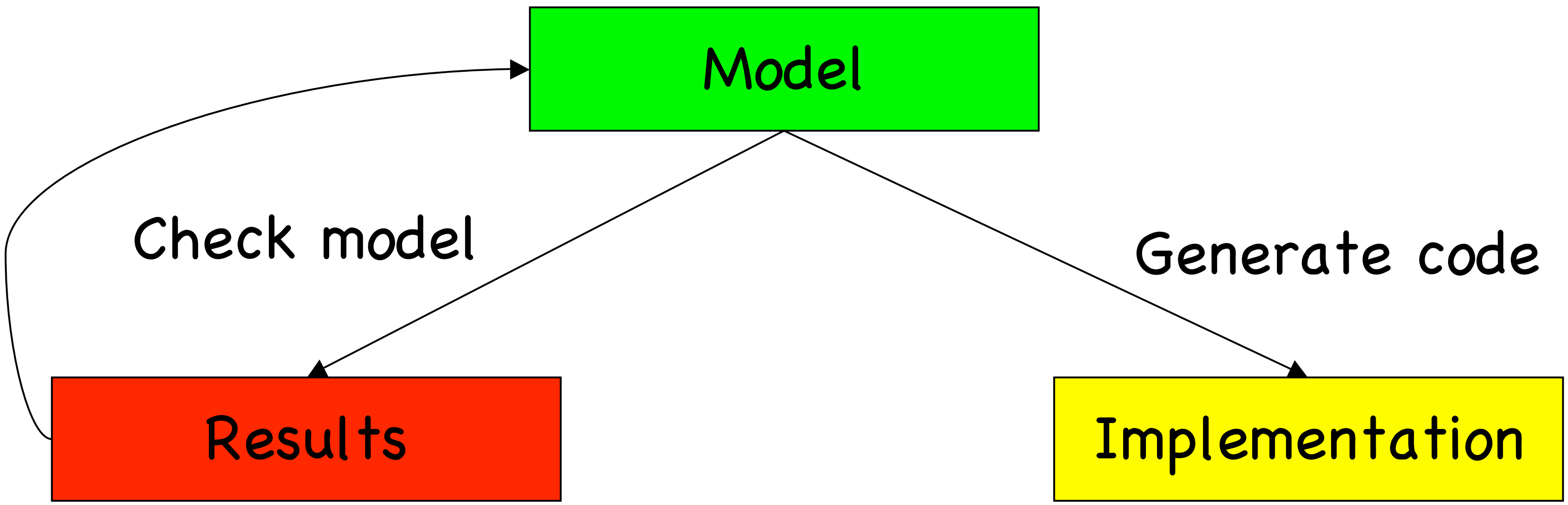
- Start B between 9 and 10 seconds after A starts



Downside on Methodology: Is there a better way?

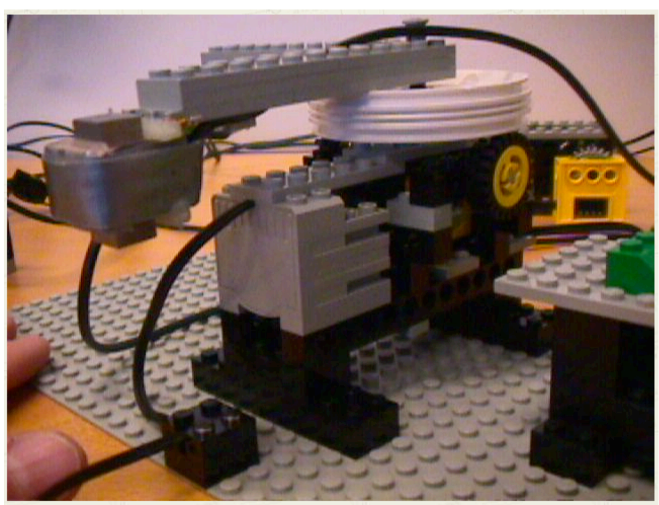


Cleaner Way



Code Generation Efforts

- Larsen, Yi, et al. generated C code from Uppaal, e.g. for real-time control of Aibo robot and a "production cell" model.



Complementary Tools & Related Research Areas

- Static analysis tools
  analyze code symbolically,
  stopping short of being full verification.

- Theorem provers can be combined with M-C.

- UML (if formal semantics can be devised).

Conclusions

- Illustrated the idea of model-checking.
- Demonstrated temporal logic for specifications.
- Exemplified with Uppaal.
- Contrasted to other approaches.
- Discussed representation of timing.
- Future approaches likely to invert the order (model, then code).

References

- Uppaal: Kim Larsen, et al., www.uppaal.com
- SPIN: Gerard Holzmann, www.spinroot.com
- CMU: Ed Clarke, http://www.cs.cmu.edu/%7Emodelcheck/