Software Verification and Validation (VIMMD052)

# Formal verification: Basic formalisms

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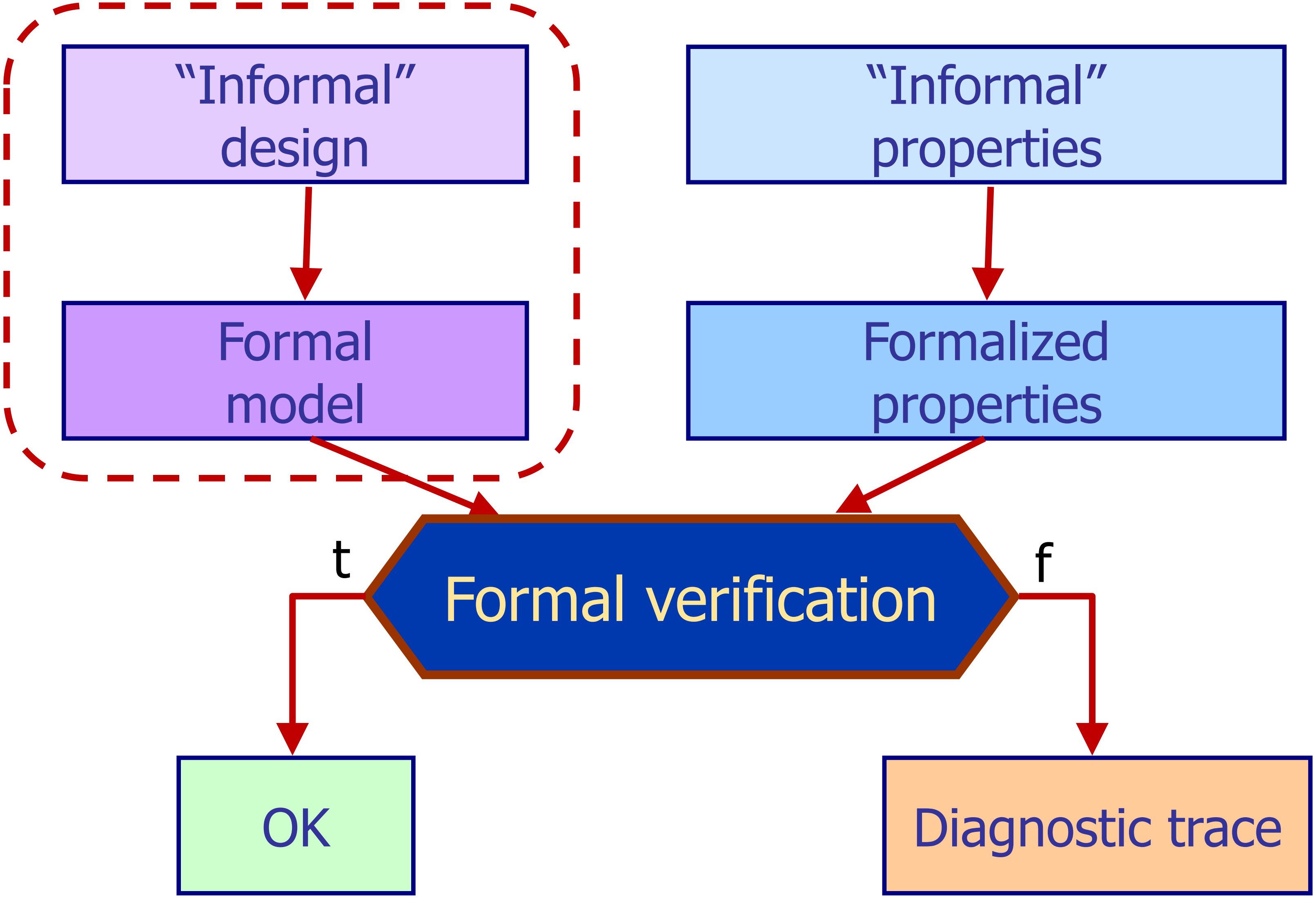
# Recap: The goal of formal verification


“Informal” design

Formal model

“Informal” properties

Formalized properties

Formal verification

t

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OK

Diagnostic trace

# Basic structures

Kripke structure (KS)

Labeled transition system (LTS)

Kripke transition system (KTS)

Finite state automata (FSA)

# 1. Kripke structure

Basic characteristics:

- Capturing properties of states: labeling by atomic propositions
- Possibly more than one labels per state
- Application: description of behavior or algorithm

## Definition:

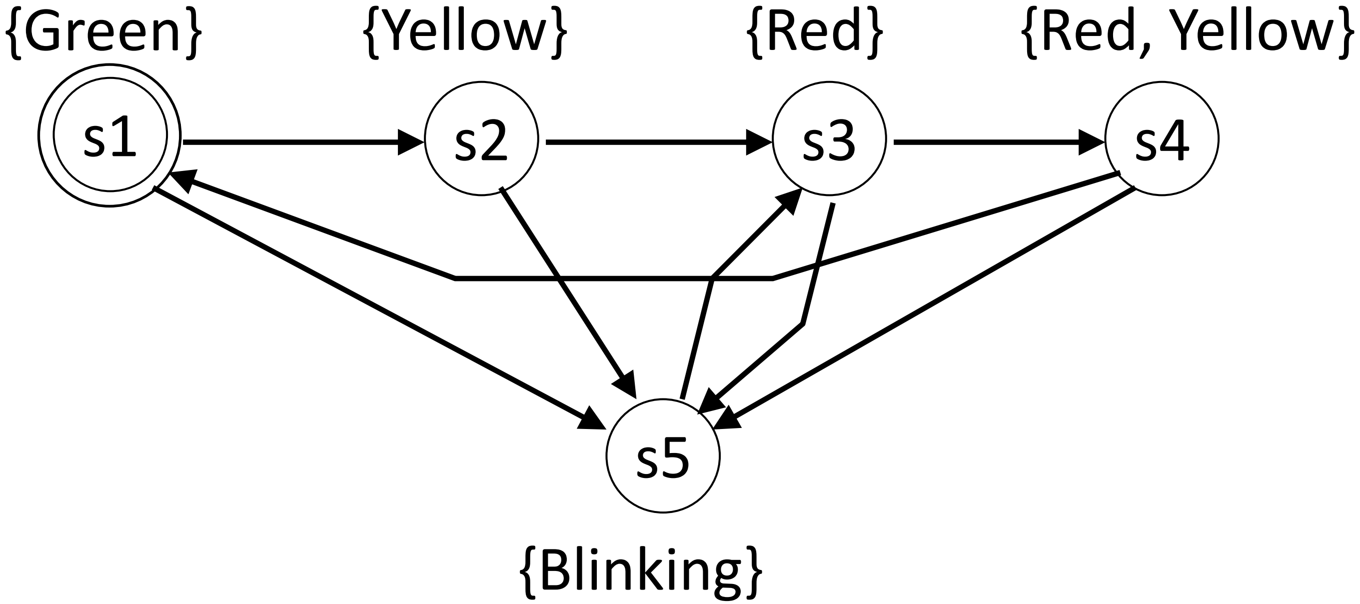
A Kripke structure $KS$ over a set of atomic propositions $AP = \{P, Q, R, \dots\}$ is a tuple $(S, R, L)$ where

- $S = \{s_1, s_2, \dots, s_n\}$ is a finite set of states,
  $I \subseteq S$ is the set of initial states,
- $R \subseteq S \times S$ is the set of transitions and
- $L : S \rightarrow 2^{AP}$ is the labeling of states by atomic propositions

# Example: Kripke structure

Traffic light controller

- $\mathrm{AP} = \{\mathrm{Green}, \mathrm{Yellow}, \mathrm{Red}, \mathrm{Blinking}\}$
- $S = \{s_1, s_2, s_3, s_4, s_5\}$



# 2. Labeled transition system

Basic characteristics:

- Capturing properties of transitions: labeling by actions
- Exactly one action per transition
- Application: modeling of communication and protocols

Definition:

A labeled transition system $LTS$ over a set of actions $Act = \{a, b, c, \dots\}$ is a triple $(S, Act, \rightarrow)$ where

- $S = \{s_1, s_2, \dots, s_n\}$ is a finite set of states,

  $I \subseteq S$ is the set of initial states,
- $\rightarrow : S \times Act \times S$ is the set of transitions

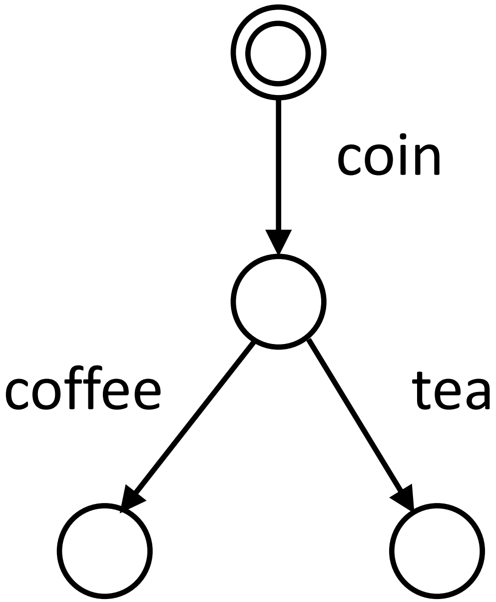
We denote by $s \overset{a}{\rightarrow} s'$ iff $(s, a, s') \in \rightarrow$

# Example: Labeled transition system

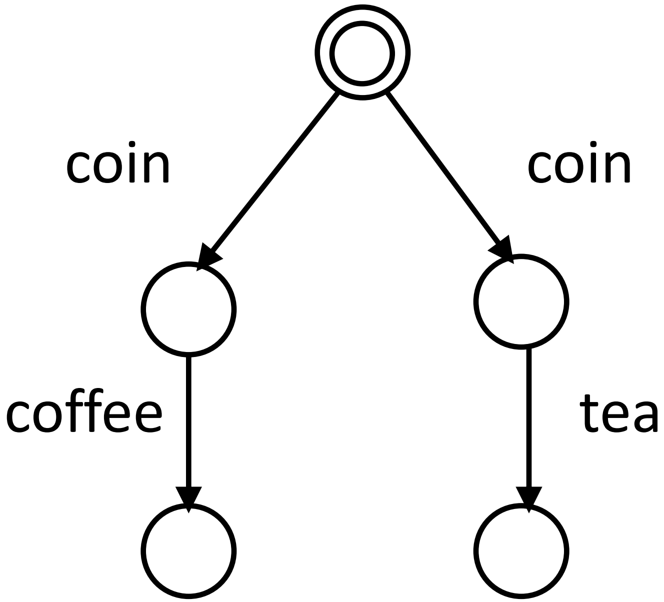
## Vending machine

- $\mathrm{Act} = \{\mathrm{coin}, \mathrm{coffe}, \mathrm{tea}\}$

T1



T2



# 3. Kripke transition system

Basic characteristics:

- Capturing properties of both states and transitions: labeling by atomic propositions and actions
- Possibly more than one labels per state, exactly one action per transition

## Definition:

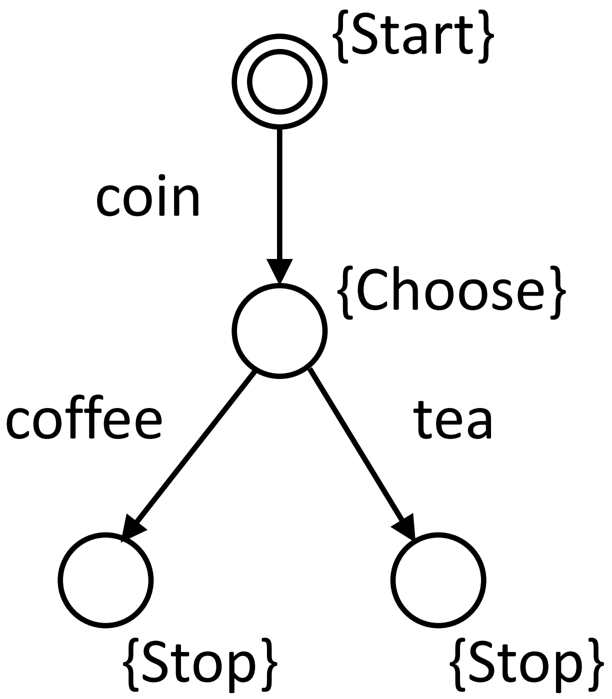
A Kripke transition system $KTS$ over a set of atomic propositions $AP$ and set of actions $Act$ is a tuple $(S, \rightarrow, L)$ where

- $S = \{s_1, s_2, \dots, s_n\}$ is a finite set of states,
  $I \subseteq S$ is the set of initial states,
- $\rightarrow : S \times Act \times S$ is the set of transitions
- $L : S \rightarrow 2^{AP}$ is the labeling of states by atomic propositions

# Example: Kripke transition system

Vending machine with state labeling

- $Act = \{\text{coin}, \text{coffee}, \text{tea}\}$
- $AP = \{\text{Start}, \text{Choose}, \text{Stop}\}$



# 4. Automata on finite words

- $A=(\Sigma, S, S_0, \rho, F)$ where
  - $\Sigma$ alphabet, $S$ states, $S_0$ initial states
  - $\rho$ state transition relation, $\rho: S \times \Sigma \to 2^S$
  - $F$ set of accepting states
- Run of an automaton
  - State sequence $r=(s_0, s_1, s_2, \dots s_n)$ on the incoming word $w=(a_0, a_1, a_2, \dots a_n)$
  - $r$ is an accepting run if $s_n \in F$
  - A word $w$ is accepted by the automaton, if there is an accepting run over $w$
- Language $L$ accepted by the automaton $A$:

$$L(A)=\{ w \in \Sigma^* \mid w \text{ accepted}\}$$

# Automata on infinite words

- Infinite word: Accepting state at the end of an input word cannot be checked
- Büchi acceptance criterion:
  - On the incoming infinite word $w=(a_0, a_1, a_2, \ldots)$ there is an $r=(s_0, s_1, s_2, \ldots)$ infinite state sequence
  - $\lim(r)=\{s \mid s$ occurs infinitely often,
    i.e., there is no $j$, such that $\forall k>j: s \neq s_k\}$
  - Accepting run: $\lim(r) \cap F \neq 0$
  - A word w is accepted by the automaton,
    if there is an accepting run over w
    (i.e., accepting state occurs infinitely often along w)
- Language L accepted by the automaton A:

$$L(A)=\{ w \in \Sigma^* \mid w \text{ accepted}\}$$

# Timed Automata:
# Finite State Automata with Time

Timed Automata in the UPPAAL model checker

# Timed Automata: Extension with variables

- Basic formalism: Finite state automaton (FSA)
  - Control locations (named) – part of the state of the automaton
  - Edges – define state transitions
- Language extension: integer variables
  - Variables with restricted domain (e.g. int[0, 10] id)
  - Constants (e.g., const int N = 6)
  - Integer arithmetic
- Use of variables: on transitions
  - Guard: predicate over variables
    - The state transition can occur only if the predicate holds
  - Action: variable assignment

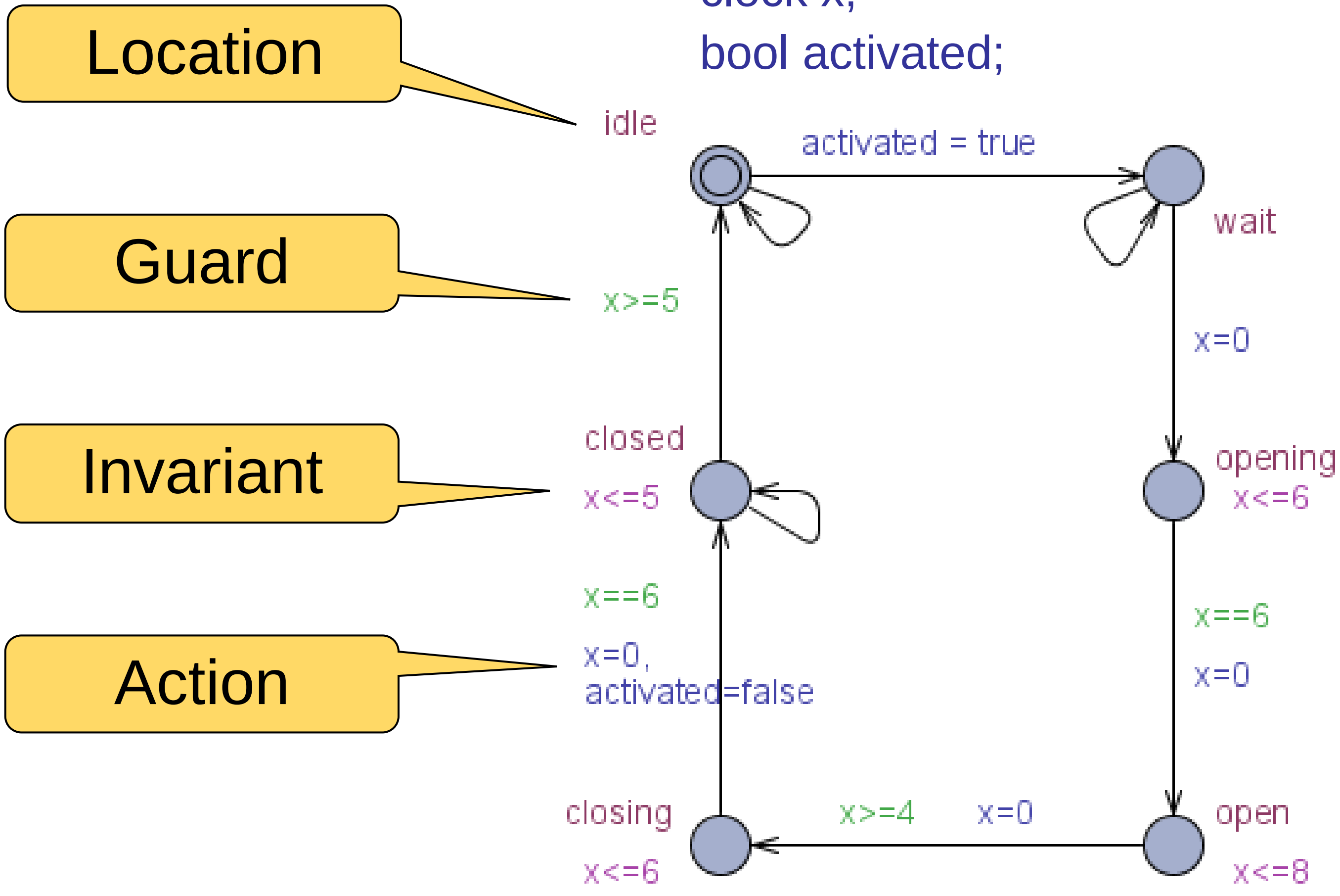
# Timed automata: Extension with clock variables

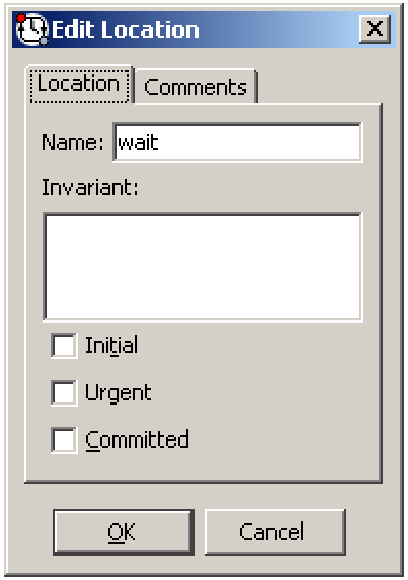
- Goal: modeling time-dependent behavior
  - Time passes in given states of the component
  - Relative time measurement by resetting and reading timers, behavior depends on timer value (e.g., timeout)
- Language extension: clock variables
  - Measuring time elapse by a constant rate
- Use of clock variables on transitions
  - Guard: predicate over clock variables
  - Action: resetting clocks to zero
- Use of clock variables on locations
  - Location invariant: predicate over clock variables; being in a location is valid until its invariant holds

# Timed automata in UPPAAL

Example: revolving door

clock x;
bool activated;





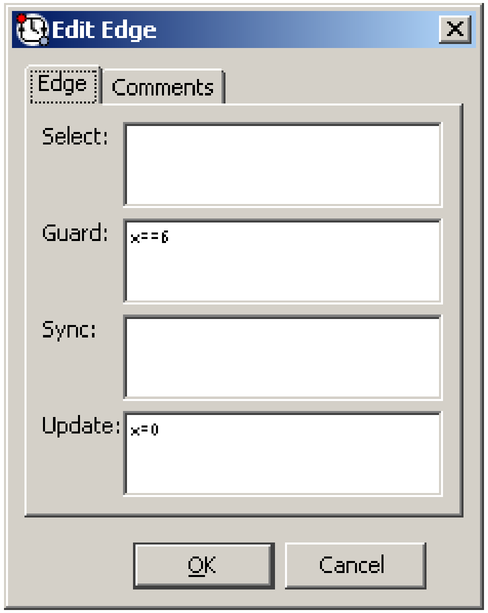
Name: wait

Invariant:

☐ Initial

☐ Urgent

☐ Committed



Select:

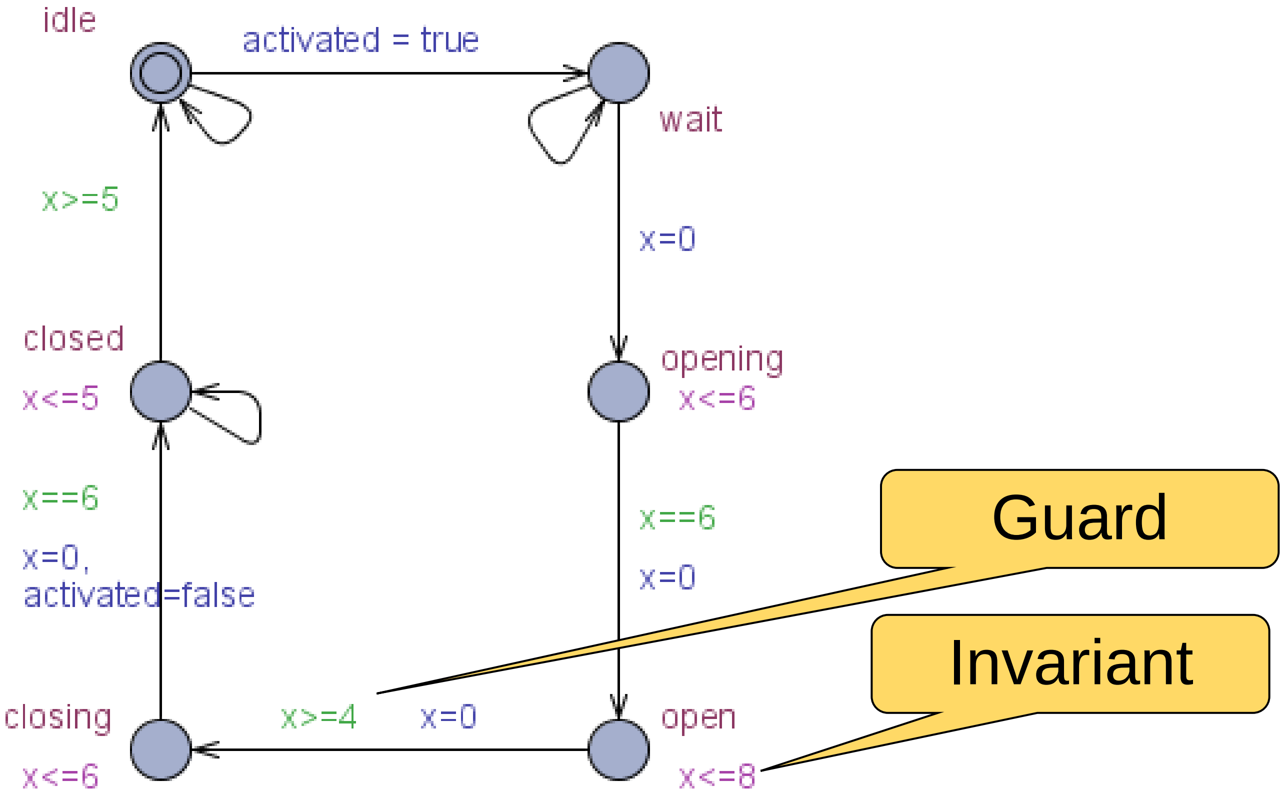
Guard: x==6

Sync:

Update: x=0

# Role of guards and invariants

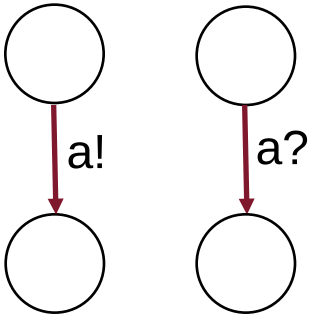
clock x;



Upon exiting location open, the value of clock is in interval [4, 8]

# Extensions for concurrency

- Goal: modeling networks of automata
  - Interaction: Synchronization between automata transitions
  - Synchronous communication (handshake, rendezvous)
    - Sending and receiving a message occurs at the same time
    - Modeling of asynchronous behavior is possible by modeling channels
- Language extension: synchronized actions
  - Declaring channels for sending messages
  - Sending a message: ! operator
    Receiving a message: ? operator
  - E.g.: synchronization labels a! and a? for channel a
- Parameterization
  - Arrays of channels: E.g. channel a[id] for a variable id
  - Useful in case of several participants and interactions



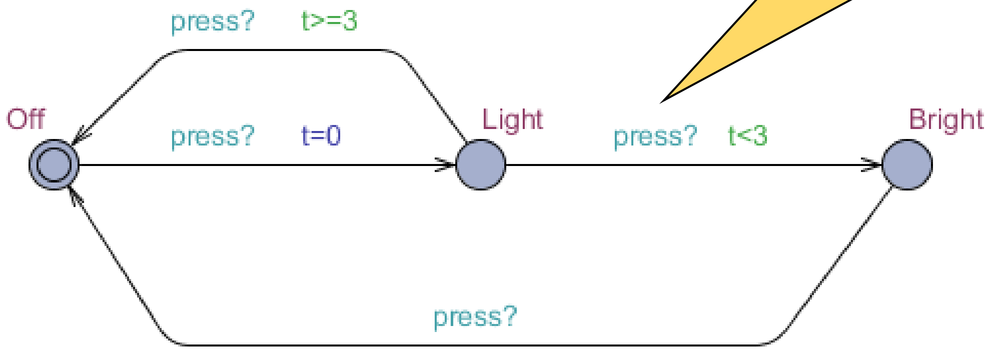
chan a

# Example for clocks and synchronization

Declarations:

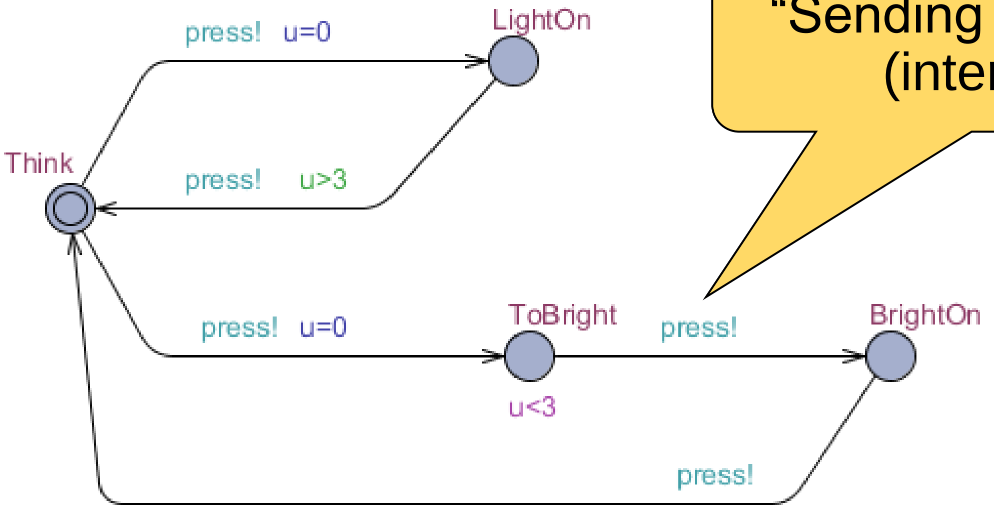
```
clock t, u;
chan press;
```

Switch:



“Receiving a message” (interaction)

User:

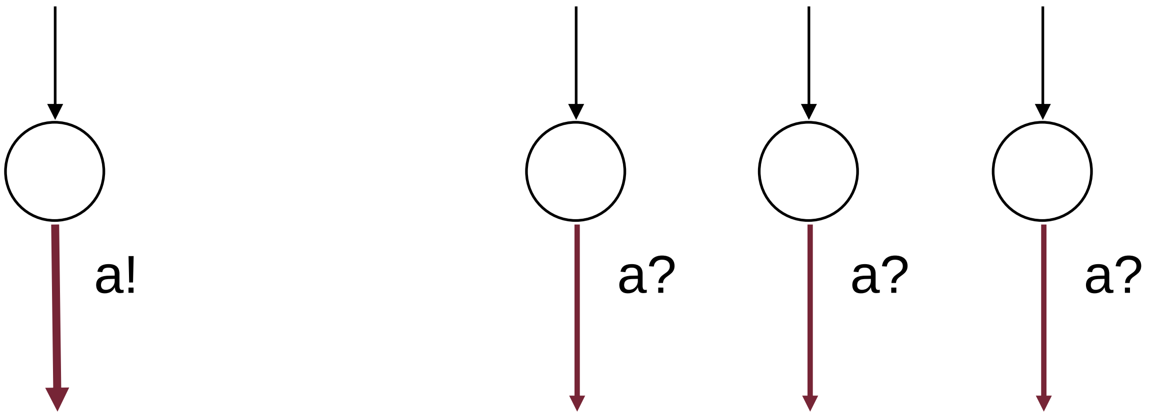


“Sending a message” (interaction)

# Further extensions: broadcast channel

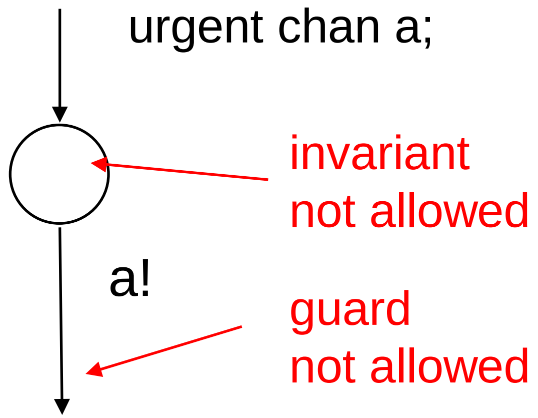
- Broadcast channel: one-to-many communication
  - Sending a message: unconditional
    - No handshake needed
  - Receiving a message: synchronized to the sender
    - All processes that are ready to receive the message will synchronize
  - Restriction: no guard on receiving edge

`broadcast chan a;`



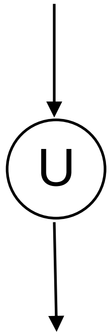
# Further extensions: urgent channel

- Urgent channel: prohibit time delay (waiting for synchronization)
  - The synchronization is executed without delay
    (other edges might be traversed before, but only instantly)
  - Restrictions:
    - No guard is allowed on an edge labeled with the name of an urgent channel
    - No invariant is allowed on a location that is the source of an edge labeled with the name of an urgent channel

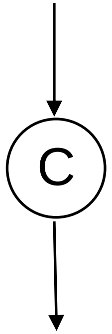


# Further extensions: special locations

- Urgent location: prohibit time delay (waiting in location)
  - Time is not allowed to progress in the location
  - Equivalent model:
    - Introduce a clock variable: clock x
    - Reset clock on all incoming edges: x:=0
    - Add invariant: x<=0



- Committed location: even more restrictive
  - A committed location is urgent
  - Committed state: at least one committed location is active
  - The next transition from a committed state must involve at least one out-edge of an active committed location
  - Simpler case: If only one committed location is active then its out-edge shall immediately follow its in-edge



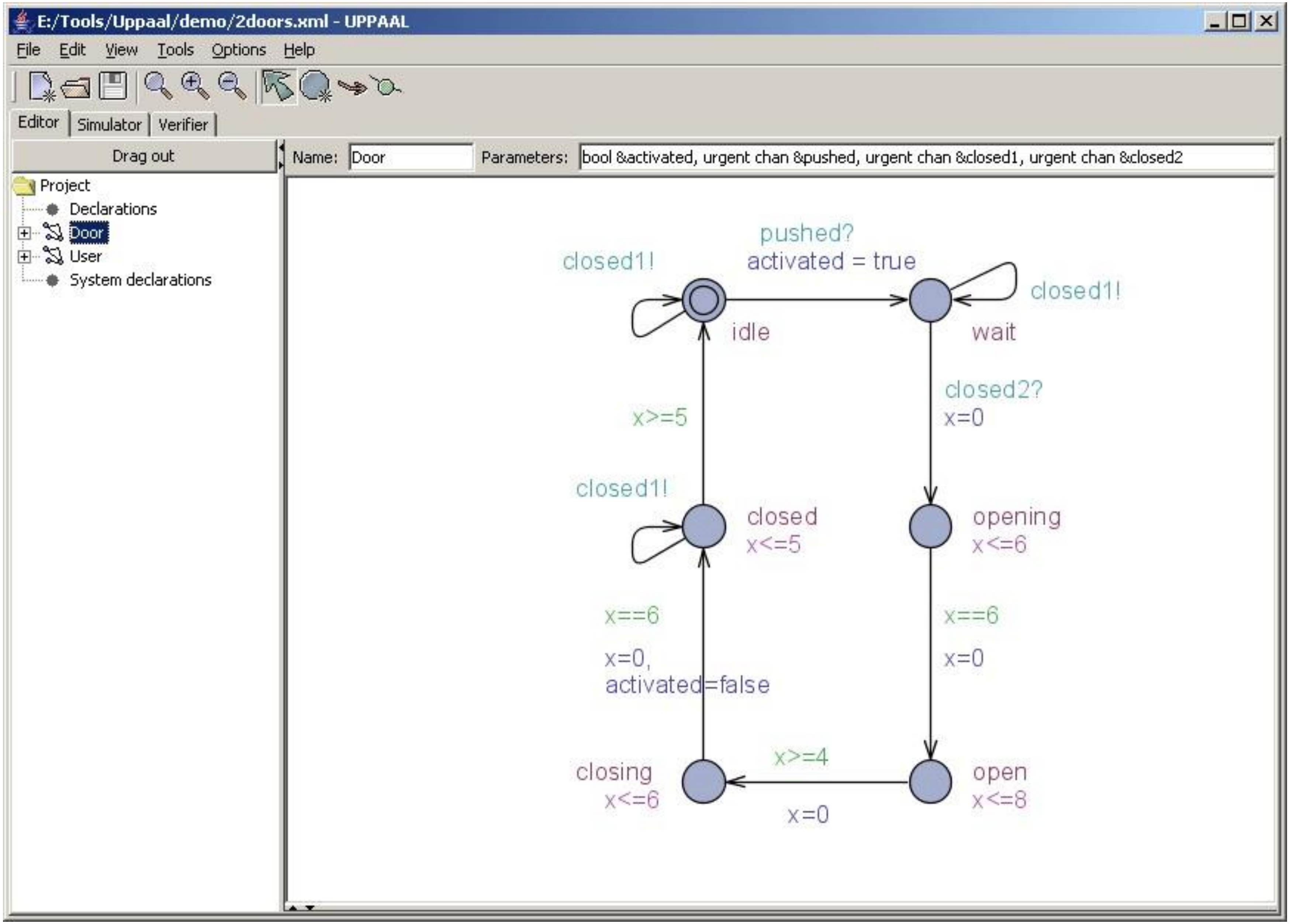
# The UPPAAL model checker

- Development (1999-):
  - Uppsala University, Sweden
  - Aalborg University, Denmark
- Web page (information, examples, download):

  http://www.uppaal.org/
- Related tools:
  - UPPAAL CoVer:  Test generation
  - UPPAAL TRON:  On-line testing
  - UPPAAL PORT:  Component based modeling
  - …
- Commercial version:

  http://www.uppaal.com/

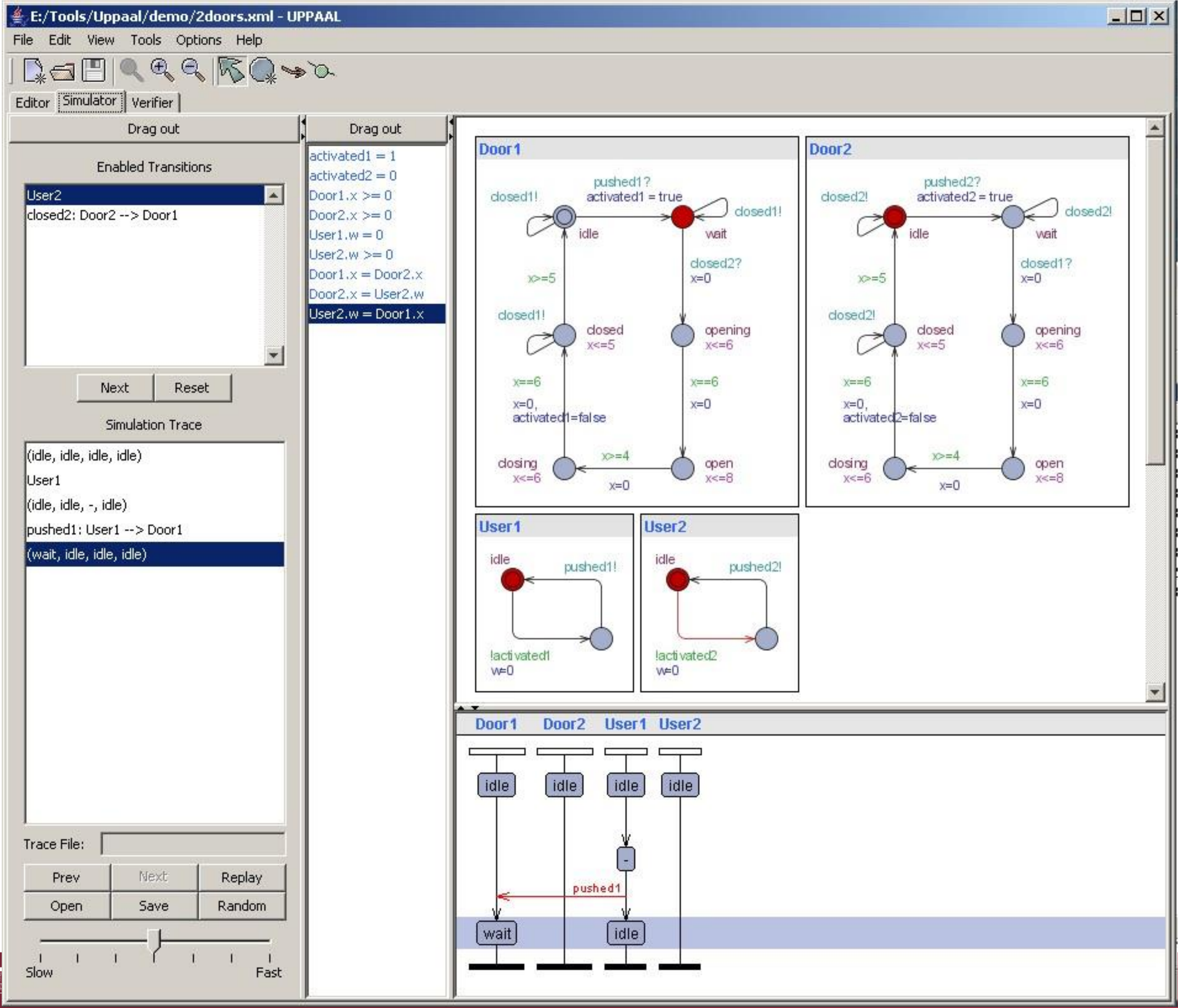
# Automaton model



Name: Door

Parameters: bool &activated, urgent chan &pushed, urgent chan &closed1, urgent chan &closed2

# Simulator



Enabled Transitions:

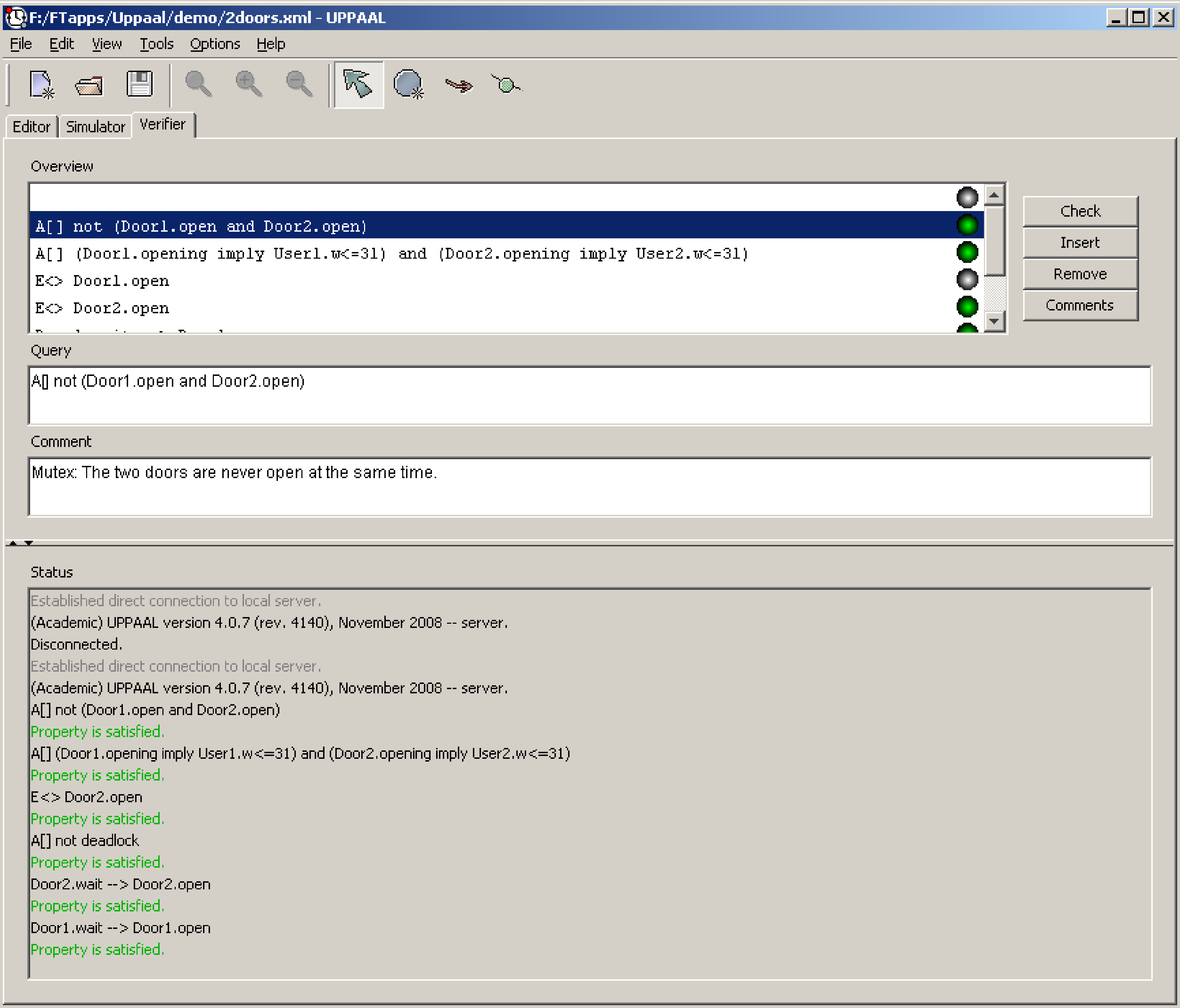
User2
closed2: Door2 --> Door1

```
activated1 = 1
activated2 = 0
Door1.x >= 0
Door2.x >= 0
User1.w = 0
User2.w >= 0
Door1.x = Door2.x
Door2.x = User2.w
User2.w = Door1.x
```

Simulation Trace:

```
(idle, idle, idle, idle)
User1
(idle, idle, -, idle)
pushed1: User1 --> Door1
(wait, idle, idle, idle)
```

# Verification



Overview

```
A[] not (Door1.open and Door2.open)
A[] (Door1.opening imply User1.w<=31) and (Door2.opening imply User2.w<=31)
E<> Door1.open
E<> Door2.open
```

Query

A[] not (Door1.open and Door2.open)

Comment

Mutex: The two doors are never open at the same time.

Status

```
Established direct connection to local server.
(Academic) UPPAAL version 4.0.7 (rev. 4140), November 2008 -- server.
Disconnected.
Established direct connection to local server.
(Academic) UPPAAL version 4.0.7 (rev. 4140), November 2008 -- server.
A[] not (Door1.open and Door2.open)
Property is satisfied.
A[] (Door1.opening imply User1.w<=31) and (Door2.opening imply User2.w<=31)
Property is satisfied.
E<> Door2.open
Property is satisfied.
A[] not deadlock
Property is satisfied.
Door2.wait --> Door2.open
Property is satisfied.
Door1.wait --> Door1.open
Property is satisfied.
```