Verifying Concurrent Systems with the Model Checker Spin

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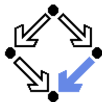
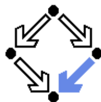
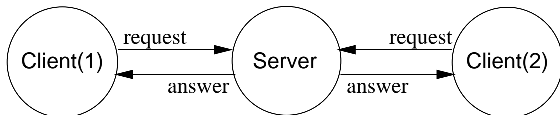


A Client/Server System

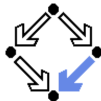




- System of one server and two clients.
  - Three concurrently executing system components.
- Server manages a resource.
  - An object that only one system component may use at any time.
- Clients request resource and, having received an answer, use it.
  - Server ensures that not both clients use resource simultaneously.
  - Server eventually answers every request.

Set of system requirements.

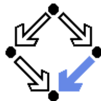
System Implementation



```
Server:
  local given, waiting, sender
begin
  given := 0; waiting := 0
  loop
    sender := receiveRequest()
    if sender = given then
      if waiting = 0 then
        given := 0
      else
        given := waiting; waiting := 0
        sendAnswer(given)
      endif
    elsif given = 0 then
      given := sender
      sendAnswer(given)
    else
      waiting := sender
    endif
  endloop
end Server
```

```
Client(ident):
  param ident
begin
  loop
    ...
    sendRequest()
    receiveAnswer()
    ... // critical region
    sendRequest()
  endloop
end Client
```

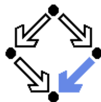
Desired System Properties



- Property: mutual exclusion.
  - At no time, both clients are in critical region.
    - Critical region: program region after receiving resource from server and before returning resource to server.
  - The system shall only reach states, in which mutual exclusion holds.
- Property: no starvation.
  - Always when a client requests the resource, it eventually receives it.
  - Always when the system reaches a state, in which a client has requested a resource, it shall later reach a state, in which the client receives the resource.
- Problem: each system component executes its own program.
  - Multiple program states exist at each moment in time.
  - Total system state is combination of individual program states.
  - Not easy to see which system states are possible.

How can we verify that the system has the desired properties?

System States

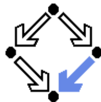


At each moment in time, a system is in a particular state.

- A state $s : Var \rightarrow Val$
  - A state s is a mapping of every system variable x to its value $s(x)$.
    - Typical notation: $s = [x = 0, y = 1, \ldots] = [0, 1, \ldots]$.
  - Var ... the set of system variables
    - Program variables, program counters, ...
  - Val ... the set of variable values.
- The state space $State = \{s \mid s : Var \rightarrow Val\}$
  - The state space is the set of possible states.
    - The system variables can be viewed as the coordinates of this space.
  - The state space may (or may not) be finite.
    - If $|Var| = n$ and $|Val| = m$, then $|State| = m^n$.
    - A word of $\log_2 m^n$ bits can represent every state.

A system execution can be described by a path $s_0 \rightarrow s_1 \rightarrow s_2 \rightarrow \ldots$ in the state space.

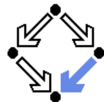
Deterministic Systems



In a sequential system, each state typically determines its successor state.

- The system is deterministic.
  - We have a (possibly not total) transition function F on states.
  - $s_1 = F(s_0)$ means "s_1 is the successor of s_0".
- Given an initial state s_0, the execution is thus determined.
  - $s_0 \rightarrow s_1 = F(s_0) \rightarrow s_2 = F(s_1) \rightarrow \ldots$
- A deterministic system (model) is a pair $\langle I, F \rangle$.
  - A set of initial states $I \subseteq State$
    - Initial state condition $I(s) :\Leftrightarrow s \in I$
  - A transition function $F : State \stackrel{partial}{\rightarrow} State$.
- A run of a deterministic system $\langle I, F \rangle$ is a (finite or infinite) sequence $s_0 \rightarrow s_1 \rightarrow \ldots$ of states such that
  - $s_0 \in I$ (respectively $I(s_0)$).
  - $s_{i+1} = F(s_i)$ (for all sequence indices i)
  - If s ends in a state s_n, then F is not defined on s_n.

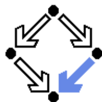
Nondeterministic Systems



In a concurrent system, each component may change its local state, thus the successor state is not uniquely determined.

- The system is nondeterministic.
  - We have a transition relation R on states.
  - $R(s_0, s_1)$ means "s_1 is a (possible) successor of s_0.
- Given an initial state s_0, the execution is not uniquely determined.
  - Both $s_0 \rightarrow s_1 \rightarrow \ldots$ and $s_0 \rightarrow s_1' \rightarrow \ldots$ are possible.
- A non-deterministic system (model) is a pair $\langle I, R \rangle$.
  - A set of initial states (initial state condition) $I \subseteq State$.
  - A transition relation $R \subseteq State \times State$.
- A run s of a nondeterministic system $\langle I, R \rangle$ is a (finite or infinite) sequence $s_0 \rightarrow s_1 \rightarrow s_2 \ldots$ of states such that
  - $s_0 \in I$ (respectively $I(s_0)$).
  - $R(s_i, s_{i+1})$ (for all sequence indices i).
  - If s ends in a state s_n, then there is no state t such that $R(s_n, t)$.

Reachability Graph



The transitions of a system can be visualized by a graph.

s_0 Initial State

System run

s_1

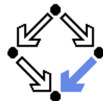
Successor of s_0

s_2

Successor of s_1

The nodes of the graph are the reachable states of the system.

Concurrent Systems



Asynchronous composition of system components.

$$P :: l_0 : \textbf{while } \text{true } \textbf{do} \quad NC_0 : \textbf{wait } turn = 0 \quad CR_0 : turn := 1 \quad \textbf{end}$$

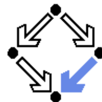
$$\|$$

$$Q :: l_1 : \textbf{while } \text{true } \textbf{do} \quad NC_1 : \textbf{wait } turn = 1 \quad CR_1 : turn := 0 \quad \textbf{end}$$

- A mutual exclusion program $M = \langle I_M, R_M \rangle$.

  $State := PC \times PC \times \mathbb{N}_2$. // shared variable
  $I_M(p, q, turn) :\Leftrightarrow p = l_0 \wedge q = l_1$.
  $R_M(\langle p, q, turn \rangle, \langle p', q', turn' \rangle) :\Leftrightarrow$
  $(P(\langle p, turn \rangle, \langle p', turn' \rangle) \wedge q' = q) \vee (Q(\langle q, turn \rangle, \langle q', turn' \rangle) \wedge p' = p)$.
  $P(\langle p, turn \rangle, \langle p', turn' \rangle) :\Leftrightarrow$
  $(p = l_0 \wedge p' = NC_0 \wedge turn' = turn) \vee$
  $(p = NC_0 \wedge p' = CR_0 \wedge turn = 0 \wedge turn' = turn) \vee$
  $(p = CR_0 \wedge p' = l_0 \wedge turn' = 1)$.
  $Q(\langle q, turn \rangle, \langle q', turn' \rangle) :\Leftrightarrow$
  $(q = l_1 \wedge q' = NC_1 \wedge turn' = turn) \vee$
  $(q = NC_1 \wedge q' = CR_1 \wedge turn = 1 \wedge turn' = turn) \vee$
  $(q = CR_1 \wedge q' = l_1 \wedge turn' = 0)$.

Concurrent Systems



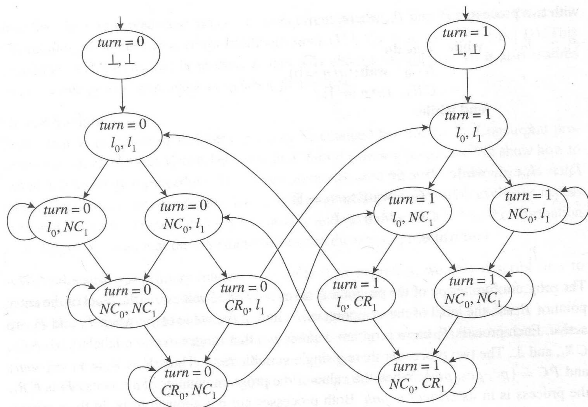
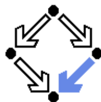


Figure 2.2
Reachable states of Kripke structure for mutual exclusion example.

Edmund Clarke et al: "Model Checking", 1999.

Model guarantees mutual exclusion.

Linear Time Logic (LTL)

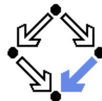


We use temporal logic to specify a system property P.

- Core question: $S \models P$ ("P holds in system S").
  - System $S = \langle I, R \rangle$, temporal logic formula P.
- Linear time logic:
  - $S \models P \;:\Leftrightarrow\; r \models P$, for every run r of S.
  - Property P must be evaluated on every run r of S.
  - Given a computation tree with root s_0, P is evaluated on every path of that tree originating in s_0.
    - If P holds for every path, P holds on S.

LTL formulas are evaluated on system runs.

Formulas



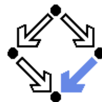
All formulas are path formulas.

- Every formula is evaluated on a path p.
  - Also every state formula f of classical logic (see below).
  - Let F and G denote formulas.
  - Then also the following are formulas:

    $\mathbf{X}\ F$ ("next time F"), often written $\bigcirc F$,
    $\mathbf{G}\ F$ ("always F"), often written $\Box F$,
    $\mathbf{F}\ F$ ("eventually F"), often written $\Diamond F$,
    $F\ \mathbf{U}\ G$ ("F until G").
- Semantics: $p \models P$ ("P holds in path p").
  - $p^i := \langle p_i, p_{i+1}, \ldots \rangle$.

    $p \models f :\Leftrightarrow p_0 \models f.$
    $p \models \mathbf{X}\ F\ :\Leftrightarrow p^1 \models F.$
    $p \models \mathbf{G}\ F\ :\Leftrightarrow \forall i \in \mathbb{N} : p^i \models F.$
    $p \models \mathbf{F}\ F\ :\Leftrightarrow \exists i \in \mathbb{N} : p^i \models F.$
    $p \models F\ \mathbf{U}\ G\ :\Leftrightarrow \exists i \in \mathbb{N} : p^i \models G \wedge \forall j \in \mathbb{N}_i : p^j \models F.$

Formulas



$F\varphi$

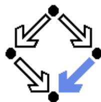
$G\varphi$

$X\varphi$

$\varphi U \psi$

Thomas Kropf: "Introduction to Formal Hardware Verification", 1999.

Frequently Used LTL Patterns

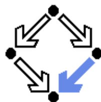


In practice, most temporal formulas are instances of particular patterns.

Pattern	Pronounced	Name
$\Box F$	always F	invariance
$\Diamond F$	eventually F	guarantee
$\Box\Diamond F$	F holds infinitely often	recurrence
$\Diamond\Box F$	eventually F holds permanently	stability
$\Box(F \Rightarrow \Diamond G)$	always, if F holds, then eventually G holds	response
$\Box(F \Rightarrow (G\ \mathbf{U}\ H))$	always, if F holds, then G holds until H holds	precedence

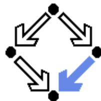
Typically, there are at most two levels of nesting of temporal operators.

Examples



- Mutual exclusion: $\Box\neg(pc_1 = C \wedge pc_2 = C)$.
  - Alternatively: $\neg\Diamond(pc_1 = C \wedge pc_2 = C)$.
  - Never both components are simultaneously in the critical region.
- No starvation: $\forall i : \Box(pc_i = W \Rightarrow \Diamond pc_i = R)$.
  - Always, if component i waits for a response, it eventually receives it.
- No deadlock: $\Box\neg\forall i : pc_i = W$.
  - Never all components are simultaneously in a wait state W.
- Precedence: $\forall i : \Box(pc_i \neq C \Rightarrow (pc_i \neq C \ \mathbf{U} \ lock = i))$.
  - Always, if component i is out of the critical region, it stays out until it receives the shared lock variable (which it eventually does).
- Partial correctness: $\Box(pc = L \Rightarrow C)$.
  - Always if the program reaches line L, the condition C holds.
- Termination: $\forall i : \Diamond(pc_i = T)$.
  - Every component eventually terminates.

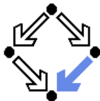
The Model Checker Spin



- Spin system:
  - Gerard J. Holzmann et al, Bell Labs, 1980–.
  - Freely available since 1991.
  - Workshop series since 1995 (12th workshop "Spin 2005").
  - ACM System Software Award in 2001.
- Spin resources:
  - Web site: http://spinroot.com.
  - Survey paper: Holzmann "The Model Checker Spin", 1997.
  - Book: Holzmann "The Spin Model Checker — Primer and Reference Manual", 2004.

Goal: verification of (concurrent/distributed) software models.

The Model Checker Spin

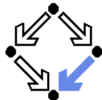


On-the-fly LTL model checking of finite state systems.

- System S modeled by automaton S_A.
  - Explicit representation of automaton states.
  - There exist various other approaches (discussed later).
- On-the-fly model checking.
  - Reachable states of S_A are only expended on demand.
  - *Partial order reduction* to keep state space manageable.
- LTL model checking.
  - Property P to be checked described in PLTL.
    - Propositional linear temporal logic.
  - Description converted into property automaton P_A.
    - Automaton accepts only system runs that do not satisfy the property.

Model checking based on automata theory.

The Spin System Architecture



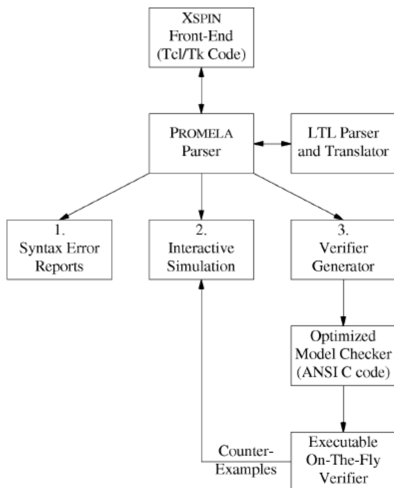
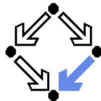


Fig. 1. The structure of SPIN simulation and verification.

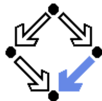
Features of Spin



- System description in Promela.
  - Promela = Process Meta-Language.
    - Spin = Simple Promela Interpreter.
  - Express coordination and synchronization aspects of a real system.
  - Actual computation can be e.g. handled by embedded C code.
- Simulation mode.
  - Investigate individual system behaviors.
  - Inspect system state.
  - Graphical interface XSpin for visualization.
- Verification mode.
  - Verify properties shared by all possible system behaviors.
  - Properties specified in PLTL and translated to "never claims".
    - Promela description of automaton for negation of the property.
  - Generated counter examples may be investigated in simulation mode.

Verification and simulation are tightly integrated in Spin.

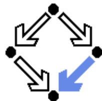
The Client/Server System in Promela



```
/* definition of a constant MESSAGE */
mtype = { MESSAGE };

/* two arrays of channels of size 2,
   each channel has a buffer size 1 */
chan request[2] = [1] of { mtype };
chan answer [2] = [1] of { mtype };

/* two global arrays for monitoring
   the states of the clients */
bool inC[2]  = false;
bool wait[2] = false;

/* the system of three processes */
init
{
  run client(1);
  run client(2);
  run server();
}
```

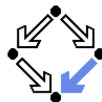
```
/* the client process type */
proctype client(byte id)
{
  do :: true ->
    request[id-1] ! MESSAGE;

    wait[id-1] = true;
    answer[id-1]  ? MESSAGE;
    wait[id-1] = false;

    inC[id-1] = true;
    skip; // the critical region
    inC[id-1] = false;

    request[id-1] ! MESSAGE
  od;
}
```

The Client/Server System in Promela



```
/* the server process type */
proctype server()
{
  /* three variables of two bit each */
  unsigned given   : 2 = 0;
  unsigned waiting : 2 = 0;
  unsigned sender  : 2;

  do :: true ->

    /* receiving the message */
    if
    :: request[0] ? MESSAGE ->
      sender = 1
    :: request[1] ? MESSAGE ->
      sender = 2
    fi;

    /* answering the message */
    if
    :: sender == given ->
      if
      :: waiting == 0 ->
        given = 0
      :: else ->
        given = waiting;
        waiting = 0;
        answer[given-1] ! MESSAGE
      fi;
    :: given == 0 ->
      given = sender;
      answer[given-1] ! MESSAGE
    :: else
      waiting = sender
    fi;

  od;
}
```

Spin Simulation Options



Simulation Options

Display Mode

- [x] MSC Panel - with:
  - (•) Step Number Labels
  - ( ) Source Text Labels
  - (•) Normal Spacing
  - ( ) Condensed Spacing
- [ ] Time Sequence Panel - with:
  - (•) Interleaved Steps
  - ( ) One Window per Process
  - ( ) One Trace per Process
- [x] Data Values Panel
  - [x] Track Buffered Channels
  - [x] Track Global Variables
  - [ ] Track Local Variables
  - [ ] Display vars marked 'show' in MSC
- [ ] Execution Bar Panel

Simulation Style

- (•) Random (using seed)
  - Seed Value: 1
- ( ) Guided
  - (•) Using pan_in.trail
  - ( ) Use [ ] Browse
- Steps Skipped: 0
- ( ) Interactive

A Full Queue

- (•) Blocks New Msgs
- ( ) Loses New Msgs

Hide Queues in MSC

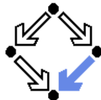
Queue nr:

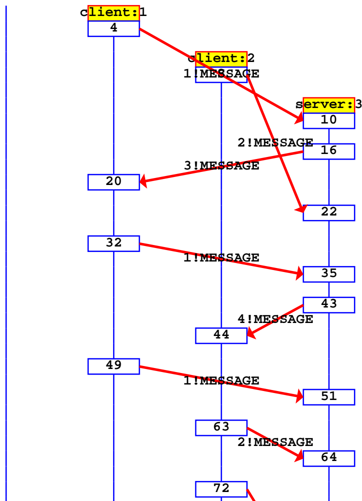
Queue nr:

Queue nr:

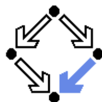
Help | Cancel | Start

Simulating the System Execution in Spin





Spin Verification Options



Basic Verification Options

Correctness Properties

- ◆ Safety (state properties)
  - ☐ Assertions
  - ■ Invalid Endstates
- ◇ Liveness (cycles/sequences)
  - ◇ Non-Progress Cycles
  - ◇ Acceptance Cycles
  - ☐ With Weak Fairness
- ☐ Apply Never Claim (If Present)
- ■ Report Unreachable Code
- ☐ Check xr/xs Assertions

Search Mode

- ◆ Exhaustive
- ◇ Supertrace/Bitstate
- ◇ Hash-Compact

A Full Queue

- ◆ Blocks New Msgs
- ◇ Loses New Msgs

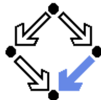
[Add Never Claim from File]

[Verify an LTL Property]

[Set Advanced Options]

Help | Cancel | Run

Specifying a System Property in Spin



Linear Time Temporal Logic Formulae

Formula: [] !(c1 && c2) Load...

Operators: [] <> U -> and or not

Property holds for: ◆ All Executions (desired behavior) ◇ No Executions (error behavior)

Notes [file clientServer2-mutex.ltl]:

Symbol Definitions:

```
#define c1 inC[0]==1
#define c2 inC[1]==1
```

Never Claim: Generate

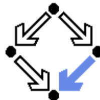
```
        /*
         * Formula As Typed: [] !(c1 && c2)
         * The Never Claim Below Corresponds
         * To The Negated Formula !([] !(c1 && c2))
         * (formalizing violations of the original)
         */

never {    /* !([] !(c1 && c2)) */
```

Verification Result: valid Run Verification

```
warning: for p.o. reduction to be valid the never claim must be stutter-invariant
(never claims generated from LTL formulae are stutter-invariant)
(Spin Version 4.2.2 -- 12 December 2004)
        + Partial Order Reduction

Full statespace search for:
        never claim             +
```

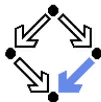
Help Clear Close Save As..

Spin Verification Output



```
(Spin Version 4.2.2 -- 12 December 2004)
+ Partial Order Reduction

Full statespace search for:
never claim            +
assertion violations + (if within scope of claim)
acceptance   cycles  + (fairness disabled)
invalid end states - (disabled by never claim)

State-vector 48 byte, depth reached 477, errors: 0
     499 states, stored
     395 states, matched
     894 transitions (= stored+matched)
       0 atomic steps
hash conflicts: 0 (resolved)

Stats on memory usage (in Megabytes):
...
0.00user 0.01system 0:00.01elapsed 83%CPU (0avgtext+0avgdata 0maxresident)k
0inputs+0outputs (0major+737minor)pagefaults 0swaps
```

Summary



- Concurrent systems can be modelled as graphs:
  - Concurrency replaced by non-determinism.
  - Graph nodes represent system states, edges represent transitions.
  - Paths in graph describe possible runs of the system.
- Properties of such graphs may be specified by LTL formulas:
  - Formula must hold on every path in graph originating in root.
  - Formulas must hold for every possible system run.
- If graph is finite, property can be automatically verified.
  - Finite (approximation of) system state space.
  - E.g. by the model checker SPIN.

Verify correctness of concurrent systems, communication protocols, security protocols, etc.