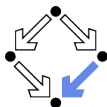
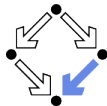


# Modeling Concurrent Systems

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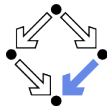
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## 1. A Client/Server System

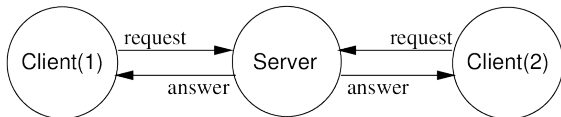
## 2. Modeling Concurrent Systems

## 3. A Model of the Client/Server System

## 4. Summary



# 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.

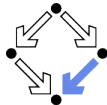
# System Implementation



```
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
```

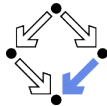
```
Client(ident):
  param ident
begin
  loop
    ...
    sendRequest()
    receiveAnswer()
    ... // critical region
    sendRequest()
  endloop
end Client
```

# 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?



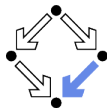
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## 1. A Client/Server System

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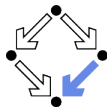
# System States

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:  $s = [x = 0, y = 1, \dots] = [0, 1, \dots]$ .
  - $Var$  ... 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  $s_0 \rightarrow s_1 \rightarrow s_2 \rightarrow \dots$  in the state space.

# Deterministic Systems

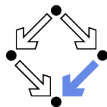


In a sequential system, each state typically determines its successor state.

- 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.
  - $s_0 \rightarrow s_1 = F(s_0) \rightarrow s_2 = F(s_1) \rightarrow \dots$
- A **deterministic system (model)** is a pair  $\langle I, F \rangle$ .
  - A set of initial states  $I \subseteq \text{State}$ 
    - **Initial state condition**  $I(s) :\Leftrightarrow s \in I$
  - A transition function  $F : \text{State} \xrightarrow{\text{partial}} \text{State}$ .
- A **run** of a deterministic system  $\langle I, F \rangle$  is a (finite or infinite) sequence  $s_0 \rightarrow s_1 \rightarrow \dots$  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  $s_n$ .



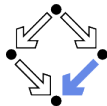
# Nondeterministic Systems



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

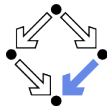
- The system is **nondeterministic**.
  - We have a **transition relation**  $R$  on states.
  - $R(s_0, s_1)$  means “ $s_1$  is a (possible) successor of  $s_0$ ”.
- Given an initial state  $s_0$ , the execution is not uniquely determined.
  - Both  $s_0 \rightarrow s_1 \rightarrow \dots$  and  $s_0 \rightarrow s'_1 \rightarrow \dots$  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  $s_0 \rightarrow s_1 \rightarrow s_2 \dots$  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  $R(s_n, t)$ .

# Derived Notions



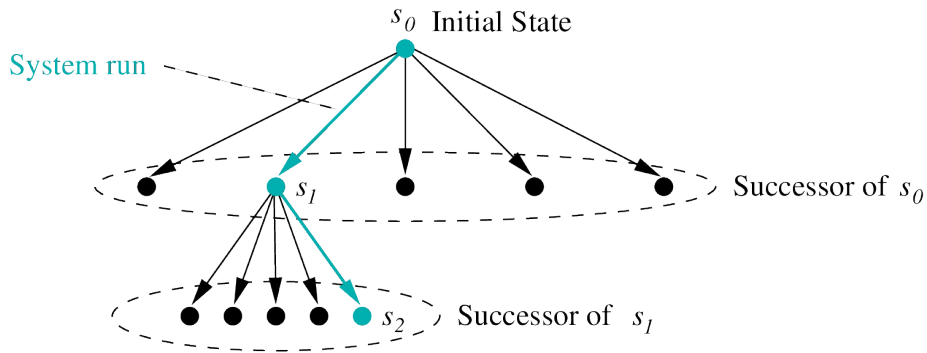
- Successor and predecessor:
  - State  $t$  is a **(direct) successor** of state  $s$ , if  $R(s, t)$ .
  - State  $s$  is then a **predecessor** of  $t$ .
    - A finite run  $s_0 \rightarrow \dots \rightarrow s_n$  ends in a state which has no successor.
- Reachability:
  - A state  $t$  is **reachable**, if there exists some run  $s_0 \rightarrow s_1 \rightarrow s_2 \rightarrow \dots$  such that  $t = s_i$  (for some  $i$ ).
  - A state  $t$  is **unreachable**, if it is not reachable.

Not all states are reachable (typically most are unreachable).



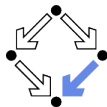
# Reachability Graph

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



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

# Examples



## 6 1. Automata



Fig. 1.1. A model of a watch

of  $\mathcal{A}_{c3}$  correspond to the possible counter values. Its transitions reflect the possible actions on the counter. In this example we restrict our operations to increments (**inc**) and decrements (**dec**).

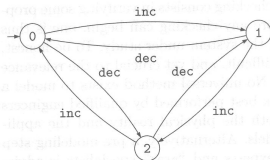
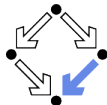


Fig. 1.2.  $\mathcal{A}_{c3}$  : a modulo 3 counter

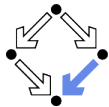
B.Berard et al: "Systems and Software Verification", 2001.

# Examples



- A deterministic system  $W = (I_W, F_W)$  (“watch”).
  - $State := \mathbb{N}_{24} \times \mathbb{N}_{60}$ .
    - $\mathbb{N}_n := \{i \in \mathbb{N} : i < n\}$ .
  - $I_W(h, m) :\Leftrightarrow h = 0 \wedge m = 0$ .
    - $I_W := \{\langle h, m \rangle : h = 0 \wedge m = 0\} = \{\langle 0, 0 \rangle\}$ .
  - $F_W(h, m) :=$ 
    - if**  $m < 59$  **then**  $\langle h, m + 1 \rangle$
    - else if**  $h < 23$  **then**  $\langle h + 1, 0 \rangle$
    - else**  $\langle 0, 0 \rangle$ .
- A nondeterministic system  $C = (I_C, R_C)$  (modulo 3 “counter”).
  - $State := \mathbb{N}_3$ .
  - $I_C(i) :\Leftrightarrow i = 0$ .
  - $R_C(i, i') :\Leftrightarrow inc(i, i') \vee dec(i, i')$ .
    - $inc(i, i') :\Leftrightarrow$  **if**  $i < 2$  **then**  $i' = i + 1$  **else**  $i' = 0$ .
    - $dec(i, i') :\Leftrightarrow$  **if**  $i > 0$  **then**  $i' = i - 1$  **else**  $i' = 2$ .

# Composing Systems



Compose  $n$  components  $S_i$  to a concurrent system  $S$ .

- **State space**  $State := State_0 \times \dots \times State_{n-1}$ .
  - $State_i$  is the state space of component  $i$ .
  - State space is Cartesian product of component state spaces.
  - Size of state space is product of the sizes of the component spaces.
- **Example:** three counters with state spaces  $\mathbb{N}_2$  and  $\mathbb{N}_3$  and  $\mathbb{N}_4$ .

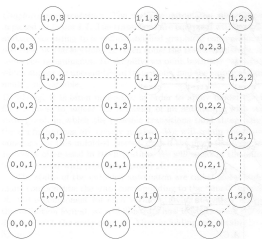
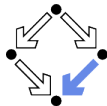


Fig. 1.9. The states of the product of the three counters

B.Berard et al: "Systems and Software Verification", 2001.

# Initial States of Composed System

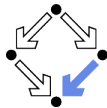


What are the initial states  $I$  of the composed system?

- **Set**  $I := I_0 \times \dots \times I_{n-1}$ .
  - $I_i$  is the set of initial states of component  $i$ .
  - Set of initial states is Cartesian product of the sets of initial states of the individual components.
- **Predicate**  $I(s_0, \dots, s_{n-1}) :\Leftrightarrow I_0(s_0) \wedge \dots \wedge I_{n-1}(s_{n-1})$ .
  - $I_i$  is the initial state condition of component  $i$ .
  - Initial state condition is conjunction of the initial state conditions of the components **on the corresponding projection** of the state.

Size of initial state set is the product of the sizes of the initial state sets of the individual components.

# Transitions of Composed System



Which transitions can the composed system perform?

- **Synchronized composition.**

- At each step, every component **must** perform a transition.

- $R_i$  is the transition relation of component  $i$ .

$$R(\langle s_0, \dots, s_{n-1} \rangle, \langle s'_0, \dots, s'_{n-1} \rangle) :\Leftrightarrow \\ R_0(s_0, s'_0) \wedge \dots \wedge R_{n-1}(s_{n-1}, s'_{n-1}).$$

- **Asynchronous composition.**

- At each moment, every component **may** perform a transition.

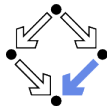
- At least one component performs a transition.

- Multiple simultaneous transitions are possible

- With  $n$  components,  $2^n - 1$  possibilities of (combined) transitions.

$$R(\langle s_0, \dots, s_{n-1} \rangle, \langle s'_0, \dots, s'_{n-1} \rangle) :\Leftrightarrow \\ (R_0(s_0, s'_0) \wedge \dots \wedge s_{n-1} = s'_{n-1}) \vee \\ \dots \\ (s_0 = s'_0 \wedge \dots \wedge R_{n-1}(s_{n-1}, s'_{n-1})) \vee \\ \dots \\ (R_0(s_0, s'_0) \wedge \dots \wedge R_{n-1}(s_{n-1}, s'_{n-1})).$$





# Example

System of three counters with state space  $\mathbb{N}_2$  each.

- Synchronous composition:

$$[0, 0, 0] \Leftrightarrow [1, 1, 1]$$

- Asynchronous composition:

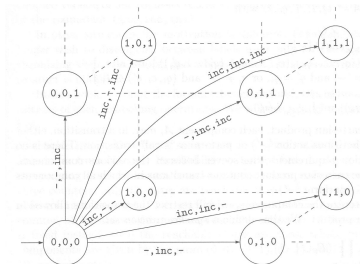
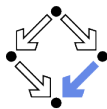


Fig. 1.10. A few transitions of the product of the three counters

B.Berard et al: "Systems and Software Verification", 2001.

# Interleaving Execution



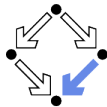
Simplified view of asynchronous execution.

- At each moment, only **one** component performs a transition.
  - Do not allow simultaneous transition  $t_i|t_j$  of two components  $i$  and  $j$ .
  - Transition sequences  $t_i; t_j$  and  $t_j; t_i$  are possible.
    - All possible **interleavings** of component transitions are considered.
    - Nondeterminism is used to simulate concurrency.
    - Essentially no change of system properties.
  - With  $n$  components, only  $n$  possibilities of a transition.

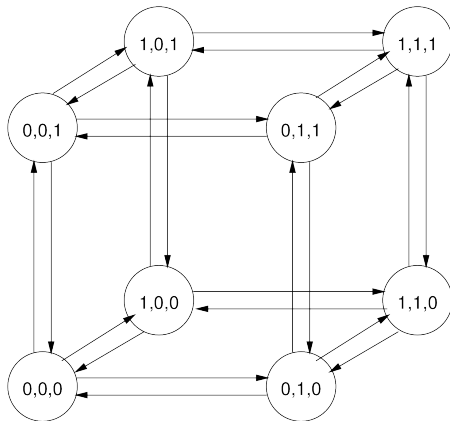
$$\begin{aligned} R(\langle s_0, s_1, \dots, s_{n-1} \rangle, \langle s'_0, s'_1, \dots, s'_{n-1} \rangle) : \Leftrightarrow \\ (R_0(s_0, s'_0) \wedge s_1 = s'_1 \wedge \dots \wedge s_{n-1} = s'_{n-1}) \vee \\ (s_0 = s'_0 \wedge R_1(s_1, s'_1) \wedge \dots \wedge s_{n-1} = s'_{n-1}) \vee \\ \dots \\ (s_0 = s'_0 \wedge s_1 = s'_1 \wedge \dots \wedge R_{n-1}(s_{n-1}, s'_{n-1})). \end{aligned}$$

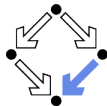
Interleaving model (respectively a variant of it) suffices in practice.

# Example



System of three counters with state space  $\mathbb{N}_2$  each.





Synchronous composition of hardware components.

- A modulo 8 counter  $C = \langle I_C, R_C \rangle$ .

$State := \mathbb{N}_2 \times \mathbb{N}_2 \times \mathbb{N}_2$ .

$I_C(v_0, v_1, v_2) :\Leftrightarrow v_0 = v_1 = v_2 = 0$ .

$R_C(\langle v_0, v_1, v_2 \rangle, \langle v'_0, v'_1, v'_2 \rangle) :\Leftrightarrow$

$R_0(v_0, v'_0) \wedge$   
 $R_1(v_0, v_1, v'_1) \wedge$   
 $R_2(v_0, v_1, v_2, v'_2)$ .

$R_0(v_0, v'_0) :\Leftrightarrow v'_0 = \neg v_0$ .

$R_1(v_0, v_1, v'_1) :\Leftrightarrow v'_1 = v_0 \oplus v_1$ .

$R_2(v_0, v_1, v_2, v'_2) :\Leftrightarrow v'_2 = (v_0 \wedge v_1) \oplus v_2$ .

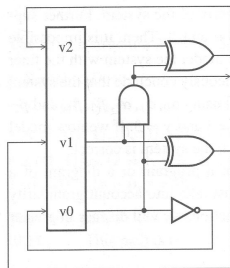
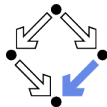


Figure 2.1  
Synchronous modulo 8 counter.

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

# Concurrent Software



Asynchronous composition of software components with shared variables.

$$\begin{array}{ll} P :: l_0 : \mathbf{while\ true\ do} & || \quad Q :: l_1 : \mathbf{while\ true\ do} \\ \quad NC_0 : \mathbf{wait\ } turn = 0 & \quad NC_1 : \mathbf{wait\ } turn = 1 \\ \quad CR_0 : turn := 1 & \quad CR_1 : turn := 0 \\ \mathbf{end} & \mathbf{end} \end{array}$$

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

State :=  $PC \times PC \times \mathbb{N}_2$ . // shared variable

$I_M(p, q, turn) :\Leftrightarrow p = l_0 \wedge q = l_1$ .

$R_M(\langle p, q, turn \rangle, \langle p', q', turn' \rangle) :\Leftrightarrow$

$(P(\langle p, turn \rangle, \langle p', turn' \rangle) \wedge q' = q) \vee (Q(\langle q, turn \rangle, \langle q', turn' \rangle) \wedge p' = p)$ .

$P(\langle p, turn \rangle, \langle p', turn' \rangle) :\Leftrightarrow$

$(p = l_0 \wedge p' = NC_0 \wedge turn' = turn) \vee$

$(p = NC_0 \wedge p' = CR_0 \wedge turn = 0 \wedge turn' = turn) \vee$

$(p = CR_0 \wedge p' = l_0 \wedge turn' = 1)$ .

$Q(\langle q, turn \rangle, \langle q', turn' \rangle) :\Leftrightarrow$

$(q = l_1 \wedge q' = NC_1 \wedge turn' = turn) \vee$

$(q = NC_1 \wedge q' = CR_1 \wedge turn = 1 \wedge turn' = turn) \vee$

$(q = CR_1 \wedge q' = l_1 \wedge turn' = 0)$ .

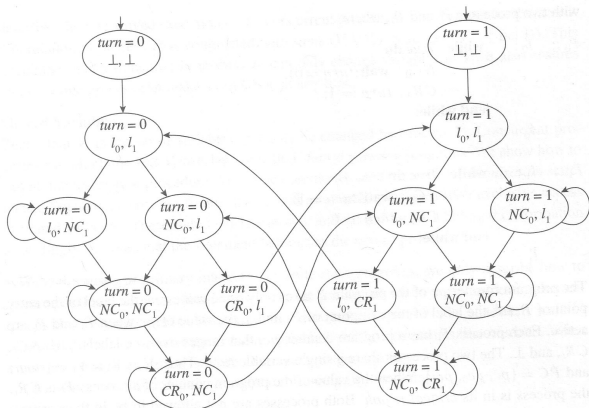
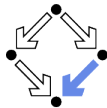
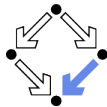


Figure 2.2  
Reachable states of Kripke structure for mutual exclusion example.

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

Model guarantees mutual exclusion.

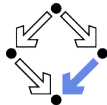
# Modeling Commands



Transition relations are typically described in a particular form.

- $R(s, s') : \Leftrightarrow P(s) \wedge s' = F(s)$ .
  - **Guard condition**  $P$  on state in which transition can be performed.
    - If  $P(s)$  holds, then there exists some  $s'$  such that  $R(s, s')$ .
  - Transition function  $F$  that determines the successor of  $s$ .
    - $F$  is defined for all states for which  $s$  holds:  
 $F : \{s \in State : P(s)\} \rightarrow State$ .
- Examples:
  - Assignment:  $l : x := e; m : \dots$ 
    - $R(\langle pc, x, y \rangle, \langle pc', x', y' \rangle) : \Leftrightarrow pc = l \wedge (x' = e \wedge y' = y \wedge pc' = m)$ .
  - Wait statement:  $l : \mathbf{wait} P(x, y); m : \dots$ 
    - $R(\langle pc, x, y \rangle, \langle pc', x', y' \rangle) : \Leftrightarrow$   
 $pc = l \wedge P(x, y) \wedge (x' = x \wedge y' = y \wedge pc' = m)$ .
  - Guarded assignment:  $l : P(x, y) \rightarrow x := e; m : \dots$ 
    - $R(\langle pc, x, y \rangle, \langle pc', x', y' \rangle) : \Leftrightarrow$   
 $pc = l \wedge P(x, y) \wedge (x' = e \wedge y' = y \wedge pc' = m)$ .

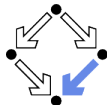
Most programming language commands can be translated into this form.



- 
1. A Client/Server System
  2. Modeling Concurrent Systems
  - 3. A Model of the Client/Server System**
  4. Summary

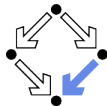


# Modelling Message Passing Systems



How to model an asynchronous system without shared variables where the components communicate/synchronize by exchanging messages?

- Given a label set  $Label = Int \cup Ext \cup \overline{Ext}$ .
  - Disjoint sets  $Int$  and  $Ext$  of internal and external labels.
    - “Anonymous” label  $_ \in Int$ .
    - Complementary label set  $\bar{L} := \{\bar{l} : l \in L\}$ .
- A **labeled system** is a pair  $\langle I, R \rangle$ .
  - Initial state condition  $I \subseteq State$ .
  - Labeled transition relation  $R \subseteq Label \times State \times State$ .
- A **run** of a labeled system  $\langle I, R \rangle$  is a (finite or infinite) sequence  $s_0 \xrightarrow{l_0} s_1 \xrightarrow{l_1} \dots$  of states such that
  - $s_0 \in I$ .
  - $R(l_i, s_i, s_{i+1})$  (for all sequence indices  $i$ ).
  - If  $s$  ends in a state  $s_n$ , there is no label  $l$  and state  $t$  s.t.  $R(l, s_n, t)$ .



# Synchronization by Message Passing

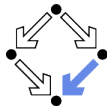
Compose a set of  $n$  labeled systems  $\langle I_i, R_i \rangle$  to a system  $\langle I, R \rangle$ .

- **State space**  $State := State_0 \times \dots \times State_{n-1}$ .
- **Initial states**  $I := I_0 \times \dots \times I_{n-1}$ .
  - $I(s_0, \dots, s_{n-1}) :\Leftrightarrow I_0(s_0) \wedge \dots \wedge I_{n-1}(s_{n-1})$ .
- **Transition relation**

$$\begin{aligned} R(I, \langle s_i \rangle_{i \in \mathbb{N}_n}, \langle s'_i \rangle_{i \in \mathbb{N}_n}) \Leftrightarrow \\ (I \in \mathit{Int} \wedge \exists i \in \mathbb{N}_n : \\ R_i(I, s_i, s'_i) \wedge \forall k \in \mathbb{N}_n \setminus \{i\} : s_k = s'_k) \vee \\ (I = \_ \wedge \exists l \in \mathit{Ext}, i \in \mathbb{N}_n, j \in \mathbb{N}_n : \\ R_i(I, s_i, s'_i) \wedge R_j(\bar{l}, s_j, s'_j) \wedge \forall k \in \mathbb{N}_n \setminus \{i, j\} : s_k = s'_k). \end{aligned}$$

Either a component performs an internal transition or two components simultaneously perform an external transition with complementary labels.

# Example



```
0 :: loop                                1 :: loop
  a0 : send(i)                            b0 : j := receive()
  a1 : i := receive()                      ||      b1 : j := j + 1
  a2 : i := i + 1                          ||      b2 : send(j)
end                                         end
```

- Two labeled systems  $\langle I_0, R_0 \rangle$  and  $\langle I_1, R_1 \rangle$ .

$State_0 = State_1 = PC \times \mathbb{N}$ ,  $Internal := \{A, B\}$ ,  $External := \{M, N\}$ .

$I_0(p, i) :\Leftrightarrow p = a_0 \wedge i \in \mathbb{N}$ ;  $I_1(q, j) :\Leftrightarrow q = b_0$ .

$R_0(l, \langle p, i \rangle, \langle p', i' \rangle) :\Leftrightarrow$

$(l = \bar{M} \wedge p = a_0 \wedge p' = a_1 \wedge i' = i) \vee$

$(l = N \wedge p = a_1 \wedge p' = a_2 \wedge i' = j) \vee$  // illegal!

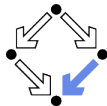
$(l = A \wedge p = a_2 \wedge p' = a_0 \wedge i' = i + 1)$ .

$R_1(l, \langle q, j \rangle, \langle q', j' \rangle) :\Leftrightarrow$

$(l = M \wedge q = b_0 \wedge q' = b_1 \wedge j' = i) \vee$  // illegal!

$(l = B \wedge q = b_1 \wedge q' = b_2 \wedge j' = j + 1) \vee$

$(l = \bar{N} \wedge q = b_2 \wedge q' = b_0 \wedge j' = j)$ .



## Example (Continued)

Composition of  $\langle I_0, R_0 \rangle$  and  $\langle I_1, R_1 \rangle$  to  $\langle I, R \rangle$ .

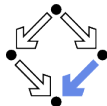
$$\text{State} = (PC \times \mathbb{N}) \times (PC \times \mathbb{N}).$$

$$I(p, i, q, j) :\Leftrightarrow p = a_0 \wedge i \in \mathbb{N} \wedge q = b_0.$$

$$\begin{aligned} R(I, \langle p, i, q, j \rangle, \langle p', i', q', j' \rangle) :\Leftrightarrow \\ (I = A \wedge (p = a_2 \wedge p' = a_0 \wedge i' = i + 1) \wedge (q' = q \wedge j' = j)) \vee \\ (I = B \wedge (p' = p \wedge i' = i) \wedge (q = b_1 \wedge q' = b_2 \wedge j' = j + 1)) \vee \\ (I = \_ \wedge (p = a_0 \wedge p' = a_1 \wedge i' = i) \wedge (q = b_0 \wedge q' = b_1 \wedge j' = i)) \vee \\ (I = \_ \wedge (p = a_1 \wedge p' = a_2 \wedge i' = j) \wedge (q = b_2 \wedge q' = b_0 \wedge j' = j)). \end{aligned}$$

**Problem:** state relation of each component refers to local variable of other component (variables are shared).

# Example (Revised)



$0 :: \text{loop}$		$1 :: \text{loop}$
$a_0 : \text{send}(i)$		$b_0 : j := \text{receive}()$
$a_1 : i := \text{receive}()$	$\parallel$	$b_1 : j := j + 1$
$a_2 : i := i + 1$		$b_2 : \text{send}(j)$
<b>end</b>		<b>end</b>

- Two labeled systems  $\langle I_0, R_0 \rangle$  and  $\langle I_1, R_1 \rangle$ .

...

$External := \{M_k : k \in \mathbb{N}\} \cup \{N_k : k \in \mathbb{N}\}$ .

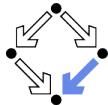
$R_0(I, \langle p, i \rangle, \langle p', i' \rangle) :\Leftrightarrow$

$(I = \overline{M}_i \wedge p = a_0 \wedge p' = a_1 \wedge i' = i) \vee$   
 $(\exists k \in \mathbb{N} : I = N_k \wedge p = a_1 \wedge p' = a_2 \wedge i' = k) \vee$   
 $(I = A \wedge p = a_2 \wedge p' = a_0 \wedge i' = i + 1)$ .

$R_1(I, \langle q, j \rangle, \langle q', j' \rangle) :\Leftrightarrow$

$(\exists k \in \mathbb{N} : I = M_k \wedge q = b_0 \wedge q' = b_1 \wedge j' = k) \vee$   
 $(I = B \wedge q = b_1 \wedge q' = b_2 \wedge j' = j + 1) \vee$   
 $(I = \overline{N}_j \wedge q = b_2 \wedge q' = b_0 \wedge j' = j)$ .

Encode message value in label.



## Example (Continued)

Composition of  $\langle I_0, R_0 \rangle$  and  $\langle I_1, R_1 \rangle$  to  $\langle I, R \rangle$ .

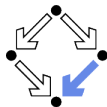
$$\text{State} = (PC \times \mathbb{N}) \times (PC \times \mathbb{N}).$$

$$I(p, i, q, j) :\Leftrightarrow p = a_0 \wedge i \in \mathbb{N} \wedge q = b_0.$$

$$\begin{aligned} R(I, \langle p, i, q, j \rangle, \langle p', i', q', j' \rangle) :\Leftrightarrow \\ & (I = A \wedge (p = a_2 \wedge p' = a_0 \wedge i' = i + 1) \wedge (q' = q \wedge j' = j)) \vee \\ & (I = B \wedge (p' = p \wedge i' = i) \wedge (q = b_1 \wedge q' = b_2 \wedge j' = j + 1)) \vee \\ & (I = \_ \wedge \exists k \in \mathbb{N} : k = i \wedge \\ & \quad (p = a_0 \wedge p' = a_1 \wedge i' = i) \wedge (q = b_0 \wedge q' = b_1 \wedge j' = k)) \vee \\ & (I = \_ \wedge \exists k \in \mathbb{N} : k = j \wedge \\ & \quad (p = a_1 \wedge p' = a_2 \wedge i' = k) \wedge (q = b_2 \wedge q' = b_0 \wedge j' = j)). \end{aligned}$$

Logically equivalent to previous definition of transition relation.

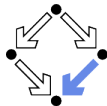
# The Client/Server System



Asynchronous composition of three components  $Client_1$ ,  $Client_2$ ,  $Server$ .

- $Client_i$ :  $State := PC \times \mathbb{N}_2 \times \mathbb{N}_2$ .
  - Three variables  $pc$ ,  $request$ ,  $answer$ .
  - $pc$  represents the program counter.
  - $request$  is the buffer for outgoing requests.
    - Filled by client, when a request is to be sent to server.
  - $answer$  is the buffer for incoming answers.
    - Checked by client, when it waits for an answer from the server.
- $Server$ :  $State := (\mathbb{N}_3)^3 \times (\{1, 2\} \rightarrow \mathbb{N}_2)^2$ .
  - Variables  $given$ ,  $waiting$ ,  $sender$ ,  $rbuffer$ ,  $sbuffer$ .
  - No program counter.
    - We use the value of  $sender$  to check whether server waits for a request ( $sender = 0$ ) or answers a request ( $sender \neq 0$ ).
  - Variables  $given$ ,  $waiting$ ,  $sender$  as in program.
  - $rbuffer(i)$  is the buffer for incoming requests from client  $i$ .
  - $sbuffer(i)$  is the buffer for outgoing answers to client  $i$ .

# External Transitions

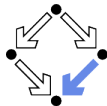


- $Ext := \{REQ_1, REQ_2, ANS_1, ANS_2\}$ .
  - Transition labeled  $REQ_i$  transmits a request from client  $i$  to server.
    - Enabled when  $request \neq 0$  in client  $i$ .
    - Effect in client  $i$ :  $request' = 0$ .
    - Effect in server:  $rbuffer'(i) = 1$ .
  - Transition labeled  $ANS_i$  transmits an answer from server to client  $i$ .
    - Enabled when  $sbuffer(i) \neq 0$ .
    - Effect in server:  $sbuffer'(i) = 0$ .
    - Effect in client  $i$ :  $answer' = 1$ .

The external transitions correspond to system-level actions of the communication subsystem (rather than to the user-level actions of the client/server program).



# The Client



Client system  $C_i = \langle IC_i, RC_i \rangle$ .

State :=  $PC \times \mathbb{N}_2 \times \mathbb{N}_2$ .

Int :=  $\{R_i, S_i, C_i\}$ .

$IC_i(pc, request, answer) : \Leftrightarrow$   
 $pc = R \wedge request = 0 \wedge answer = 0$ .

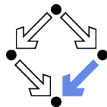
$RC_i(I, \langle pc, request, answer \rangle,$   
 $\langle pc', request', answer' \rangle) : \Leftrightarrow$   
 $(I = R_i \wedge pc = R \wedge request = 0 \wedge$   
 $pc' = S \wedge request' = 1 \wedge answer' = answer) \vee$   
 $(I = S_i \wedge pc = S \wedge answer \neq 0 \wedge$   
 $pc' = C \wedge request' = request \wedge answer' = 0) \vee$   
 $(I = C_i \wedge pc = C \wedge request = 0 \wedge$   
 $pc' = R \wedge request' = 1 \wedge answer' = answer) \vee$

---

$(I = \overline{REQ}_i \wedge request \neq 0 \wedge$   
 $pc' = pc \wedge request' = 0 \wedge answer' = answer) \vee$   
 $(I = \overline{ANS}_i \wedge$   
 $pc' = pc \wedge request' = request \wedge answer' = 1).$

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

# The Server



Server system  $S = \langle IS, RS \rangle$ .

$State := (\mathbb{N}_3)^3 \times (\{1, 2\} \rightarrow \mathbb{N}_2)^2$ .

$Int := \{D1, D2, F, A1, A2, W\}$ .

$IS(given, waiting, sender, rbuffer, sbuffer) :\Leftrightarrow$   
 $given = waiting = sender = 0 \wedge$   
 $rbuffer(1) = rbuffer(2) = sbuffer(1) = sbuffer(2) = 0$ .

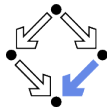
$RS(I, \langle given, waiting, sender, rbuffer, sbuffer \rangle,$   
 $\langle given', waiting', sender', rbuffer', sbuffer' \rangle) :\Leftrightarrow$   
 $\exists i \in \{1, 2\} :$   
 $(I = D_i \wedge sender = 0 \wedge rbuffer(i) \neq 0 \wedge$   
 $sender' = i \wedge rbuffer'(i) = 0 \wedge$   
 $U(given, waiting, sbuffer) \wedge$   
 $\forall j \in \{1, 2\} \setminus \{i\} : U_j(rbuffer)) \vee$   
...

$U(x_1, \dots, x_n) :\Leftrightarrow x'_1 = x_1 \wedge \dots \wedge x'_n = x_n$ .

$U_j(x_1, \dots, x_n) :\Leftrightarrow x'_1(j) = x_1(j) \wedge \dots \wedge x'_n(j) = x_n(j)$ .

```
Server:
  local given, waiting, sender
begin
  given := 0; waiting := 0
  loop
D:   sender := receiveRequest()
      if sender = given then
          if waiting = 0 then
F:     given := 0
          else
A1:    given := waiting;
          waiting := 0
          sendAnswer(given)
          endif
          elsif given = 0 then
A2:    given := sender
          sendAnswer(given)
          else
W:     waiting := sender
          endif
      endloop
end Server
```

# The Server (Contd)



...

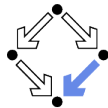
$$(I = F \wedge sender \neq 0 \wedge sender = given \wedge waiting = 0 \wedge given' = 0 \wedge sender' = 0 \wedge U(waiting, rbuffer, sbuffer)) \vee$$
$$(I = A1 \wedge sender \neq 0 \wedge sbuffer(waiting) = 0 \wedge sender = given \wedge waiting \neq 0 \wedge given' = waiting \wedge waiting' = 0 \wedge sbuffer'(waiting) = 1 \wedge sender' = 0 \wedge U(rbuffer) \wedge \forall j \in \{1, 2\} \setminus \{waiting\} : U_j(sbuffer)) \vee$$
$$(I = A2 \wedge sender \neq 0 \wedge sbuffer(sender) = 0 \wedge sender \neq given \wedge given = 0 \wedge given' = sender \wedge sbuffer'(sender) = 1 \wedge sender' = 0 \wedge U(waiting, rbuffer) \wedge \forall j \in \{1, 2\} \setminus \{sender\} : U_j(sbuffer)) \vee$$

...

Server:

```
local given, waiting, sender
begin
  given := 0; waiting := 0
  loop
D: sender := receiveRequest()
    if sender = given then
      if waiting = 0 then
F:       given := 0
        else
A1:      given := waiting;
          waiting := 0
          sendAnswer(given)
        endif
      elsif given = 0 then
A2:      given := sender
          sendAnswer(given)
        else
W:       waiting := sender
        endif
      endloop
    end Server
```

# The Server (Contd'2)



...  
 $(I = W \wedge sender \neq 0 \wedge sender \neq given \wedge given \neq 0 \wedge$   
 $waiting' := sender \wedge sender' = 0 \wedge$   
 $U(given, rbuffer, sbuffer)) \vee$

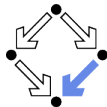
$\exists i \in \{1, 2\} :$

$(I = REQ_i \wedge rbuffer'(i) = 1 \wedge$   
 $U(given, waiting, sender, sbuffer) \wedge$   
 $\forall j \in \{1, 2\} \setminus \{i\} : U_j(rbuffer)) \vee$

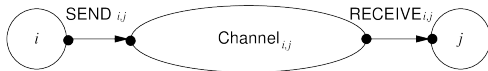
$(I = \overline{ANS}_i \wedge sbuffer(i) \neq 0 \wedge$   
 $sbuffer'(i) = 0 \wedge$   
 $U(given, waiting, sender, rbuffer) \wedge$   
 $\forall j \in \{1, 2\} \setminus \{i\} : U_j(sbuffer)).$

```
Server:
  local given, waiting, sender
begin
  given := 0; waiting := 0
  loop
D: sender := receiveRequest()
    if sender = given then
      if waiting = 0 then
F:        given := 0
          else
A1:       given := waiting;
           waiting := 0
           sendAnswer(given)
          endif
      elsif given = 0 then
A2:       given := sender
           sendAnswer(given)
          else
W:        waiting := sender
          endif
          endloop
end Server
```

# Communication Channels



We also model the communication medium between components.



- **Bounded channel**  $Channel_{i,j} = (ICH, RCH_{i,j})$ .
  - Transfers message from component with address  $i$  to component  $j$ .
    - May hold at most  $N$  messages at a time (for some  $N$ ).
  - $State := Value^*$ .
    - Sequence of values of type  $Value$ .
  - $Ext := \{SEND_{i,j}(m) : m \in Value\} \cup \{RECEIVE_{i,j}(m) : m \in Value\}$ .
    - By  $SEND_{i,j}(m)$ , channel receives from sender  $i$  a message  $m$  destined for receiver  $j$ ; by  $RECEIVE_{i,j}(m)$ , channel forwards that message.

$ICH(queue) :\Leftrightarrow queue = \langle \rangle$ .

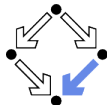
$RCH_{i,j}(l, queue, queue') :\Leftrightarrow$

$\exists m \in Value :$

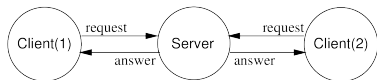
$(l = SEND_{i,j}(m) \wedge |queue| < N \wedge queue' = queue \circ \langle m \rangle) \vee$

$(l = \overline{RECEIVE}_{i,j}(m) \wedge |queue| > 0 \wedge queue = \langle m \rangle \circ queue')$ .

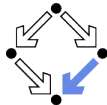
# Client/Server Example with Channels



- Server receives address 0.
  - Label  $\overline{REQ}_i$  is renamed to  $\overline{RECEIVE}_{i,0}(R)$ .
  - Label  $\overline{ANS}_i$  is renamed to  $\overline{SEND}_{0,i}(A)$ .
- Client  $i$  receives address  $i$  ( $i \in \{1, 2\}$ ).
  - Label  $\overline{REQ}_i$  is renamed to  $\overline{SEND}_{i,0}(R)$ .
  - Label  $\overline{ANS}_i$  is renamed to  $\overline{RECEIVE}_{0,i}(A)$ .
- System is composed of seven components:
  - $Server$ ,  $Client_1$ ,  $Client_2$ .
  - $Channel_{0,1}$ ,  $Channel_{1,0}$ .
  - $Channel_{0,2}$ ,  $Channel_{2,0}$ .

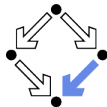


Also channels are active system components.



- 
1. A Client/Server System
  2. Modeling Concurrent Systems
  3. A Model of the Client/Server System
  - 4. Summary**

# Summary



- A system is described by
  - its (finite or infinite) **state space**,
  - the **initial state condition** (set of input states),
  - the **transition relation** on states.
- State space of composed system is **product of component spaces**.
  - Variable shared among components occurs only once in product.
- System composition can be
  - **synchronous**: conjunction of individual transition relations.
    - Suitable for digital hardware.
  - **asynchronous**: disjunction of relations.
    - **Interleaving** model: each relation conjoins the transition relation of one component with the identity relations of all other components.
    - Suitable for concurrent software.
- **Message passing systems** may be modeled by using labels:
  - Synchronize transitions of sender and receiver.
  - Carry values to be transmitted from sender to receiver.