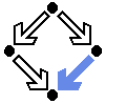
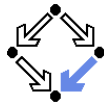


# Modeling Concurrent Systems

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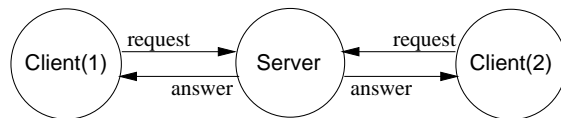
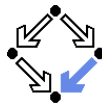
## 1. A Client/Server System

## 2. Modeling Concurrent Systems

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

## 4. Summary

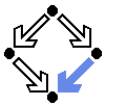
# A Client/Server System



- 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.

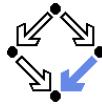
# System Implementation



```
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
        end if
        sendAnswer(given)
      endif
    end loop
  end Server

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

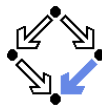
# Desired System Properties



- 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:  $s = [x = 0, y = 1, \dots] = [0, 1, \dots]$ .
  - $Var$  ... 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.

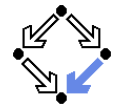
# 1. A Client/Server System

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# 4. Summary

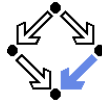
# Deterministic Systems



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  $I \subseteq State$ 
      - **Initial state condition**  $I(s) :\Leftrightarrow s \in I$
    - A transition function  $F : State \xrightarrow{\text{partial}} State$ .
  - 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  $s_n$ .

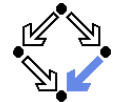
# Nondeterministic Systems



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  $R(s_n, t)$ .

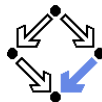
# Derived Notions



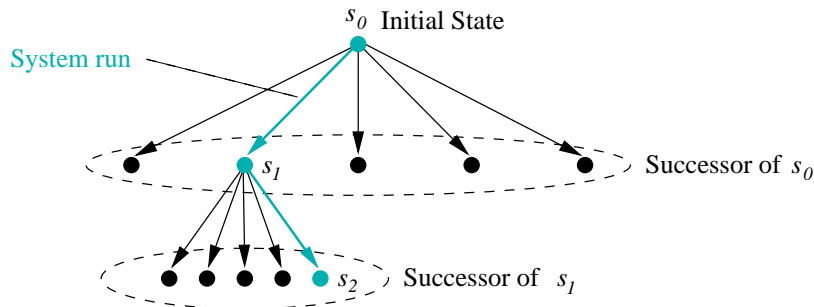
- **Successor and predecessor:**
  - State  $t$  is a (**direct**) **successor** of state  $s$ , if  $R(s, t)$ .
  - State  $s$  is then a **predecessor** of  $t$ .
    - A finite run  $s_0 \rightarrow \dots \rightarrow s_n$  ends in a state which has no successor.
- **Reachability:**
  - A state  $t$  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

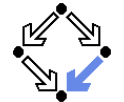


Fig. 1.1. A model of a watch

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).

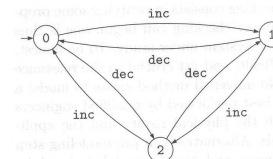
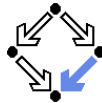


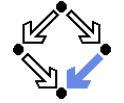
Fig. 1.2.  $\mathcal{A}_{c3}$ : a modulo 3 counter

## 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  $\mathbb{N}_4$ .

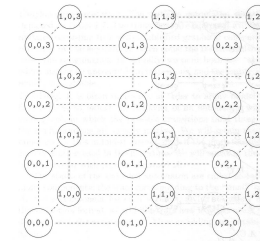
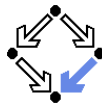


Fig. 1.9. The states of the product of the three counters

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

## Initial States of Composed System

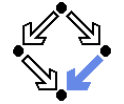


What are the initial states  $I$  of the composed system?

- **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.

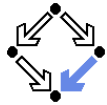
## Transitions of Composed System



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  $i$ .
- **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.

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



## Example

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

- Synchronous composition:

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

- Asynchronous composition:

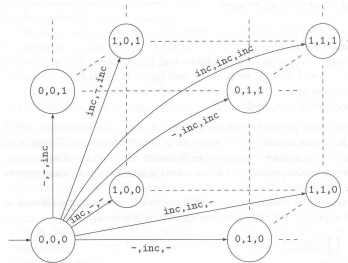
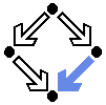


Fig. 1.10. A few transitions of the product of the three counters  
B.Berard et al: "Systems and Software Verification", 2001.



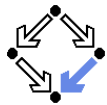
## Interleaving Execution

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.

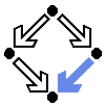
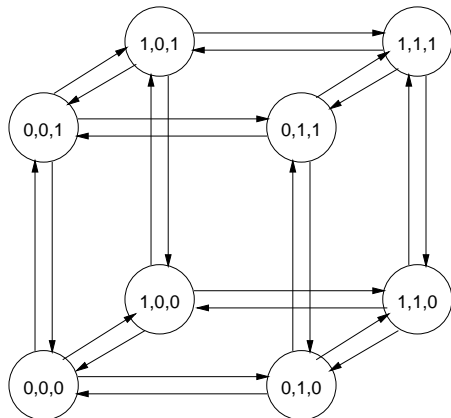
$$R(\langle s_0, s_1, \dots, s_{n-1} \rangle, \langle s'_0, s'_1, \dots, s'_{n-1} \rangle) :\Leftrightarrow \\ (R_0(s_0, s'_0) \wedge s_1 = s'_1 \wedge \dots \wedge s_{n-1} = s'_{n-1}) \vee \\ (s_0 = s'_0 \wedge R_1(s_1, s'_1) \wedge \dots \wedge s_{n-1} = s'_{n-1}) \vee \\ \dots \\ (s_0 = s'_0 \wedge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

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



## Example

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



## Digital Circuits

Synchronous composition of hardware components.

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

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

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

$$R_C(\langle v_0, v_1, v_2 \rangle, \langle v'_0, v'_1, v'_2 \rangle) :\Leftrightarrow \\ R_0(v_0, v'_0) \wedge \\ R_1(v_0, v_1, v'_1) \wedge \\ R_2(v_0, v_1, v_2, v'_2).$$

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

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

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

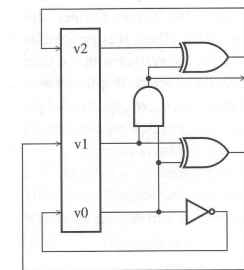
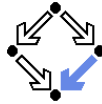


Figure 2.1  
Synchronous modulo 8 counter.  
Edmund Clarke et al: "Model Checking", 1999.

# Concurrent Software



Asynchronous composition of software components with shared variables.

```

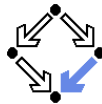
P :: l0 : while true do
    NC0 : wait turn = 0
    CR0 : turn := 1
end
    ||
Q :: l1 : while true do
    NC1 : wait turn = 1
    CR1 : turn := 0
end
    
```

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

```

State := PC × PC × N2. // shared variable
IM(p, q, turn) ⇔ p = l0 ∧ q = l1.
RM((p, q, turn), (p', q', turn')) ⇔
    (P((p, turn), (p', turn')) ∧ q' = q) ∨ (Q((q, turn), (q', turn')) ∧ p' = p).
P((p, turn), (p', turn')) ⇔
    (p = l0 ∧ p' = NC0 ∧ turn' = turn) ∨
    (p = NC0 ∧ p' = CR0 ∧ turn = 0 ∧ turn' = turn) ∨
    (p = CR0 ∧ p' = l0 ∧ turn' = 1).
Q((q, turn), (q', turn')) ⇔
    (q = l1 ∧ q' = NC1 ∧ turn' = turn) ∨
    (q = NC1 ∧ q' = CR1 ∧ turn = 1 ∧ turn' = turn) ∨
    (q = CR1 ∧ q' = l1 ∧ turn' = 0).
    
```

# Modeling Commands



Transition relations are typically described in a particular form.

- $R(s, s') \Leftrightarrow P(s) \wedge s' = F(s)$ .
  - Precondition  $P$  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:  $l : \text{wait } P(x, y); m : \dots$ 
    - $R(\langle pc, x, y \rangle, \langle pc', x', y' \rangle) \Leftrightarrow pc = l \wedge P(x, y) \wedge (x' = x \wedge y' = y \wedge pc' = m)$ .
  - 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.

# Concurrent Software

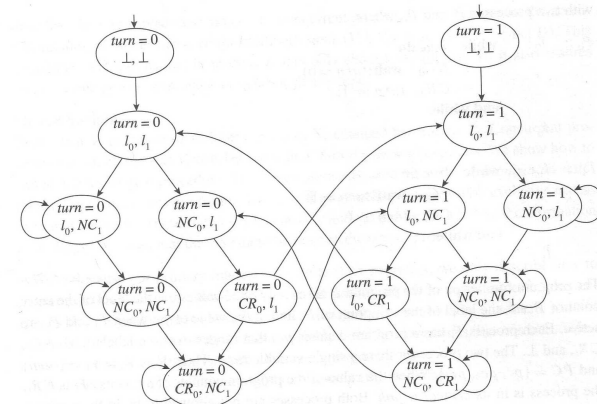
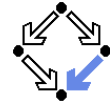


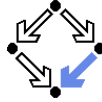
Figure 2.2 Reachable states of Kripke structure for mutual exclusion example.

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

Model guarantees mutual exclusion.

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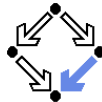
## Modelling Message Passing Systems



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  $\overline{L} := \{\bar{l} : l \in L\}$ .
- 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.  $R(l, s_n, t)$ .

## Example



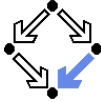
```

0 :: loop
  a0 : send(i)
  a1 : i := receive()
  a2 : i := i + 1
end

1 :: loop
  b0 : j := receive()
  b1 : j := j + 1
  b2 : send(j)
end
    
```

- Two labeled systems  $\langle I_0, R_0 \rangle$  and  $\langle I_1, R_1 \rangle$ .
  - $State_0 = State_1 = PC \times \mathbb{N}$ ,  $Internal := \{A, B\}$ ,  $External := \{M, N\}$ .
  - $I_0(p, i) :\Leftrightarrow p = a_0 \wedge i \in \mathbb{N}$ ;  $I_1(q, j) :\Leftrightarrow q = b_0$ .
  - $R_0(l, \langle p, i \rangle, \langle p', i' \rangle) :\Leftrightarrow$ 
    - $(l = \overline{M} \wedge p = a_0 \wedge p' = a_1 \wedge i' = i) \vee$
    - $(l = N \wedge p = a_1 \wedge p' = a_2 \wedge i' = j) \vee$  // illegal!
    - $(l = A \wedge p = a_2 \wedge p' = a_0 \wedge i' = i + 1)$ .
  - $R_1(l, \langle q, j \rangle, \langle q', j' \rangle) :\Leftrightarrow$ 
    - $(l = M \wedge q = b_0 \wedge q' = b_1 \wedge j' = j) \vee$  // illegal!
    - $(l = B \wedge q = b_1 \wedge q' = b_2 \wedge j' = j + 1) \vee$
    - $(l = \overline{N} \wedge q = b_2 \wedge q' = b_0 \wedge j' = j)$ .

## 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**

$$R(I, \langle s_i \rangle_{i \in \mathbb{N}_n}, \langle s'_i \rangle_{i \in \mathbb{N}_n}) \Leftrightarrow$$

$$(l \in Int \wedge \exists i \in \mathbb{N}_n :$$

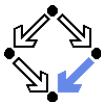
$$R_i(l, s_i, s'_i) \wedge \forall k \in \mathbb{N}_n \setminus \{i\} : s_k = s'_k) \vee$$

$$(l = \_ \wedge \exists l \in Ext, i \in \mathbb{N}_n, j \in \mathbb{N}_n :$$

$$R_i(l, s_i, s'_i) \wedge R_j(\bar{l}, s_j, s'_j) \wedge \forall k \in \mathbb{N}_n \setminus \{i, j\} : s_k = s'_k).$$

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

## Example (Continued)



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

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

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

$$R(I, \langle p, i, q, j \rangle, \langle p', i', q', j' \rangle) :\Leftrightarrow$$

$$(l = A \wedge (p = a_2 \wedge p' = a_0 \wedge i' = i + 1) \wedge (q' = q \wedge j' = j)) \vee$$

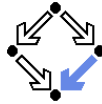
$$(l = B \wedge (p' = p \wedge i' = i) \wedge (q = b_1 \wedge q' = b_2 \wedge j' = j + 1)) \vee$$

$$(l = \_ \wedge (p = a_0 \wedge p' = a_1 \wedge i' = i) \wedge (q = b_0 \wedge q' = b_1 \wedge j' = i)) \vee$$

$$(l = \_ \wedge (p = a_1 \wedge p' = a_2 \wedge i' = j) \wedge (q = b_2 \wedge q' = b_0 \wedge j' = j)).$$

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

## Example (Revised)



```

0 :: loop
  a0 : send(i)
  a1 : i := receive()
  a2 : i := i + 1
end

1 :: loop
  b0 : j := receive()
  b1 : j := j + 1
  b2 : send(j)
end
  
```

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

...

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

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

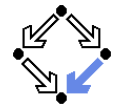
$(I = \overline{M}_i \wedge p = a_0 \wedge p' = a_1 \wedge i' = i) \vee$   
 $(\exists k \in \mathbb{N} : I = N_k \wedge p = a_1 \wedge p' = a_2 \wedge i' = k) \vee$   
 $(I = A \wedge p = a_2 \wedge p' = a_0 \wedge i' = i + 1)$ .

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

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

Encode message value in label.

## Example (Continued)



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

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

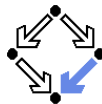
$I(p, i, q, j) :\Leftrightarrow p = a_0 \wedge i \in \mathbb{N} \wedge q = b_0$ .

$R(I, \langle p, i, q, j \rangle, \langle p', i', q', j' \rangle) :\Leftrightarrow$

$(I = A \wedge (p = a_2 \wedge p' = a_0 \wedge i' = i + 1) \wedge (q' = q \wedge j' = j)) \vee$   
 $(I = B \wedge (p' = p \wedge i' = i) \wedge (q = b_1 \wedge q' = b_2 \wedge j' = j + 1)) \vee$   
 $(I = \_ \wedge \exists k \in \mathbb{N} : k = i \wedge$   
 $(p = a_0 \wedge p' = a_1 \wedge i' = i) \wedge (q = b_0 \wedge q' = b_1 \wedge j' = k)) \vee$   
 $(I = \_ \wedge \exists k \in \mathbb{N} : k = j \wedge$   
 $(p = a_1 \wedge p' = a_2 \wedge i' = k) \wedge (q = b_2 \wedge q' = b_0 \wedge j' = j))$ .

Logically equivalent to previous definition of transition relation.

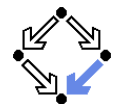
## The Client/Server System



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

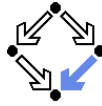


- $Ext := \{REQ_1, REQ_2, ANS_1, ANS_2\}$ .
  - Transition labeled  $REQ_i$  transmits a request from client  $i$  to server.
    - Enabled when  $request \neq 0$  in client  $i$ .
    - Effect in client  $i$ :  $request' = 0$ .
    - Effect in server:  $rbuffer'(i) = 1$ .
  - Transition labeled  $ANS_i$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

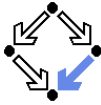
```

ICi(pc, request, answer) ⇔
  pc = R ∧ request = 0 ∧ answer = 0.
RCi(l, ⟨pc, request, answer⟩,
  ⟨pc', request', answer'⟩) ⇔
  (l = Ri ∧ pc = R ∧ request = 0 ∧
  pc' = S ∧ request' = 1 ∧ answer' = answer) ∨
  (l = Si ∧ pc = S ∧ answer ≠ 0 ∧
  pc' = C ∧ request' = request ∧ answer' = 0) ∨
  (l = Ci ∧ pc = C ∧ request = 0 ∧
  pc' = R ∧ request' = 1 ∧ answer' = answer) ∨
  ( l =  $\overline{REQ}_i$  ∧ request ≠ 0 ∧
  pc' = pc ∧ request' = 0 ∧ answer' = answer) ∨
  (l = ANSi ∧
  pc' = pc ∧ request' = request ∧ 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 :=  $\{D1, D2, F, A1, A2, W\}$ .

```

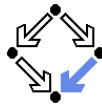
IS(given, waiting, sender, rbuffer, sbuffer) ⇔
  given = waiting = sender = 0 ∧
  rbuffer(1) = rbuffer(2) = sbuffer(1) = sbuffer(2) = 0.
RS(l, ⟨given, waiting, sender, rbuffer, sbuffer⟩,
  ⟨given', waiting', sender', rbuffer', sbuffer'⟩) ⇔
  ∃ i ∈ {1, 2} :
    (l = Di ∧ sender = 0 ∧ rbuffer(i) ≠ 0 ∧
    sender' = i ∧ rbuffer'(i) = 0 ∧
    U(given, waiting, sbuffer) ∧
    ∀ j ∈ {1, 2} \ {i} : Uj(rbuffer)) ∨
    ...
  
```

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

```

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
          A2: given := sender
              sendAnswer(given)
            else
          W: waiting := sender
            endif
        endloop
      end Server
  
```

## The Server (Contd)



```

...
(l = F ∧ sender ≠ 0 ∧ sender = given ∧ waiting = 0 ∧
  given' = 0 ∧ sender' = 0 ∧
  U(waiting, rbuffer, sbuffer)) ∨

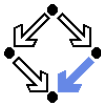
(l = A1 ∧ sender ≠ 0 ∧ sbuffer(waiting) = 0 ∧
  sender = given ∧ waiting ≠ 0 ∧
  given' = waiting ∧ waiting' = 0 ∧
  sbuffer'(waiting) = 1 ∧ sender' = 0 ∧
  U(rbuffer) ∧
  ∀ j ∈ {1, 2} \ {waiting} : Uj(sbuffer)) ∨

(l = A2 ∧ sender ≠ 0 ∧ sbuffer(sender) = 0 ∧
  sender ≠ given ∧ given = 0 ∧
  given' = sender ∧
  sbuffer'(sender) = 1 ∧ sender' = 0 ∧
  U(waiting, rbuffer) ∧
  ∀ j ∈ {1, 2} \ {sender} : Uj(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
          A2: given := sender
              sendAnswer(given)
            else
          W: waiting := sender
            endif
        endloop
      end Server
  
```

## The Server (Contd'2)



```

...
(l = W ∧ sender ≠ 0 ∧ sender ≠ given ∧ given ≠ 0 ∧
  waiting' := sender ∧ sender' = 0 ∧
  U(given, rbuffer, sbuffer)) ∨

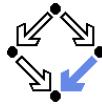
∃ i ∈ {1, 2} :
  (l = REQi ∧ rbuffer'(i) = 1 ∧
  U(given, waiting, sender, sbuffer) ∧
  ∀ j ∈ {1, 2} \ {i} : Uj(rbuffer)) ∨

  (l =  $\overline{ANS}_i$  ∧ sbuffer(i) ≠ 0 ∧
  sbuffer'(i) = 0 ∧
  U(given, waiting, sender, rbuffer) ∧
  ∀ j ∈ {1, 2} \ {i} : Uj(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
          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**  $Channel_{i,j} = (ICH, RCH)$ .
  - Transfers message from component with address  $i$  to component  $j$ .
    - May hold at most  $N$  messages at a time (for some  $N$ ).
  - $State := \langle Value \rangle$ .
    - 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.

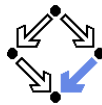
$ICH(queue) :\Leftrightarrow queue = \langle \rangle$ .

$RCH(l, queue, queue') :\Leftrightarrow$

$\exists i \in Address, j \in Address, m \in Value :$

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

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



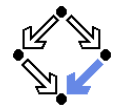
## 1. A Client/Server System

## 2. Modeling Concurrent Systems

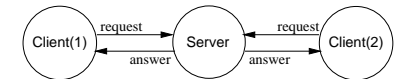
## 3. A Model of the Client/Server System

## 4. Summary

# Client/Server Example with Channels

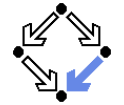


- Server receives address 0.
  - Label  $REQ_i$  is renamed to  $RECEIVE_{i,0}(R)$ .
  - Label  $ANS_i$  is renamed to  $SEND_{0,i}(A)$ .
- Client  $i$  receives address  $i$  ( $i \in \{1, 2\}$ ).
  - Label  $REQ_i$  is renamed to  $SEND_{i,0}(R)$ .
  - Label  $ANS_i$  is renamed to  $RECEIVE_{0,i}(A)$ .
- 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.

# 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.