Chapter 9

Labelled Transition Systems

System Composition

- A system specification is **decomposed** into process specifications.
- A system implementation is **composed** from process implementations.

- **Sequential composition:** every event in P_1 occurs before every event in P_2
- **Concurrent composition:** No such clear ordering imposed a priori.
- Sequential processes are basic building blocks.

Systems and Processes

Remember: **Abstractly, what is a Process?**

- **Processes** are subsets of the events occurring in a system.
- In a **sequential process**, the events are fully ordered in time.

Therefore:

- A system specification is **decomposed** into process specifications.
- A system implementation is **composed** from process implementations.

Processes, Actions, Events

- A **process** is a subset of the events occurring in a system.
- The simplest possible process: empty set of events, called STOP.
- More interesting processes have events, which can also be interpreted as **actions**.
- We assume that all actions can be decomposed into **atomic actions**.
- In a system, each event belongs to **at least one** process.
- Events can be **shared** between processes — several processes can **together** engage in a single action.

Processes and State

- Processes perform **state transitions** — in different states, a processs will be able to engage in different sets of actions.

  — After some action, the set of possible continuing actions may be different from before.

- Atomic actions induce **indivisible state changes**.

- A system composed of several processes has a state that is composed from the states of the individual processes.

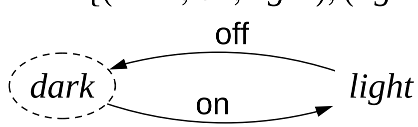
Labelled Transition Systems (LTSs)

Definition: A **labelled transition system** (S, s_0, L, δ) consists of

– a set S of *states*
– an *initial state* $s_0 : S$
– a set L of *action labels*
– a *transition relation* $\delta : \mathbb{P}\,(S \times L \times S)$.

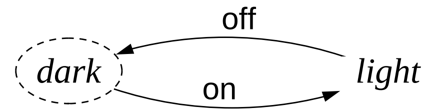
Example:

$$LightSwitch_1 = (\{dark, light\}, dark, \{\mathsf{on}, \mathsf{off}\}, \{(dark, \mathsf{on}, light), (light, \mathsf{off}, dark)\})$$

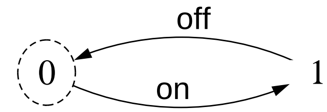


Another LTS …

$$LightSwitch_1 = (\{dark, light\}, dark, \{\mathsf{on}, \mathsf{off}\}, \{(dark, \mathsf{on}, light), (light, \mathsf{off}, dark)\})$$



$$LightSwitch_2 = (\{0, 1\}, 0, \{\mathsf{on}, \mathsf{off}\}, \{(0, \mathsf{on}, 1), (1, \mathsf{off}, 0)\})$$



Different, but **isomorphic**, where the isomorphism preserves action labels and the transition relation.

— *The identity of the states does not matter.*

Traces

Definition: A **trace** of an LTS is a sequence (finite or infinite) of action labels that results from a maximal path (with respect to the prefix ordering) starting at the initial state.

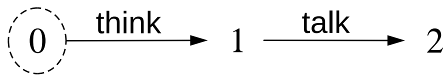
Example:

- Sequences of action labels that result from finite paths starting at the initial state:
  on
  on, off
  on, off, on
  on, off, on, off
- $LightSwitch_1$ has only **one infinite trace**:
  on, off, on, off, on, off, …
- $LightSwitch_2$ has the same set of traces as $LightSwitch_1$ — they are **behaviourally equivalent**.

Concurrent Composition

- A system composed of several processes has a state that is composed from the states of the individual processes.

Converse =

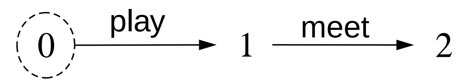


Itch =

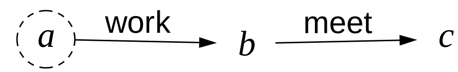
Converse || *Itch* =

Shared Actions

Bill =



Ben =



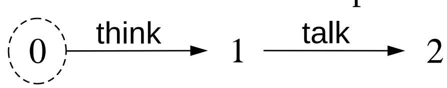
In the composition *Bill* || *Ben*,

- play and work are *concurrent actions* — the order in which they are observed does not matter.
- The **shared** action meet *synchronizes* the execution of the two constituent processes.
- Traces of the composition: play, work, meet
  work, play, meet

Concurrent Composition

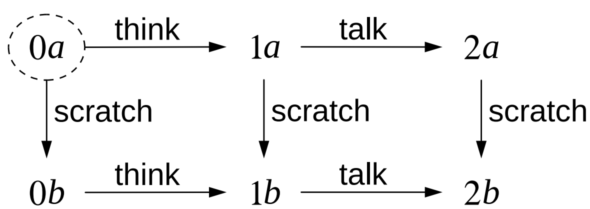
- A system composed of several processes has a state that is composed from the states of the individual processes.

Converse =



Itch =

Converse || *Itch* =



While *Converse* and *Itch* have only one trace each, their composition has three, representing *arbitrary interleaving*.

Concurrent Composition of LTSs

Definition: For $P_1 = (S_1, s_1, L_1, \delta_1)$ and $P_2 = (S_2, s_2, L_2, \delta_2)$, the **concurrent composition** $P_1 \parallel P_2$ is the LTS

$$(S_1 \times S_2,\ (s_1, s_2),\ L_1 \cup L_2,\ \delta)$$

where

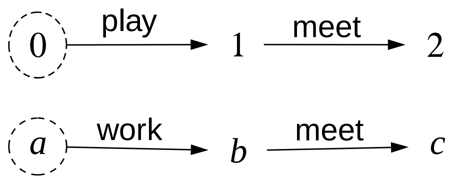
$$((x_1, x_2), a, (y_1, y_2)) \in \delta$$

$$\Leftrightarrow \begin{cases} (x_1, a, y_1) \in \delta_1 \quad \wedge \quad x_2 = y_2 \quad \wedge \quad a \in L_1 - L_2 \\ \vee \\ x_1 = y_1 \quad \wedge \quad (x_2, a, y_2) \in \delta_2 \quad \wedge \quad a \in L_2 - L_1 \\ \vee \\ (x_1, a, y_1) \in \delta_1 \quad \wedge \quad (x_2, a, y_2) \in \delta_2 \quad \wedge \quad a \in L_1 \cap L_2 \end{cases}$$

Composition with Shared Actions

Bill =

Ben =



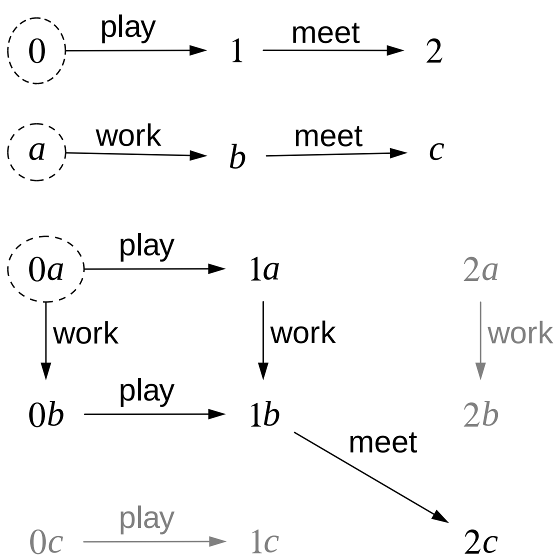
Bill || *Ben* =

Composition with Shared Actions

Bill =

Ben =

Bill || *Ben* =

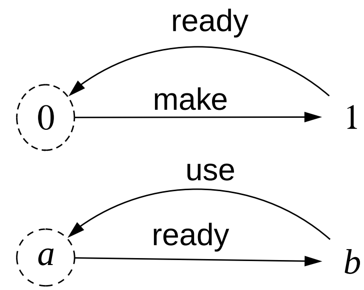


Unreachable states do not influence the behaviour!

Maker — User

Maker =

User =



Maker || *User* =

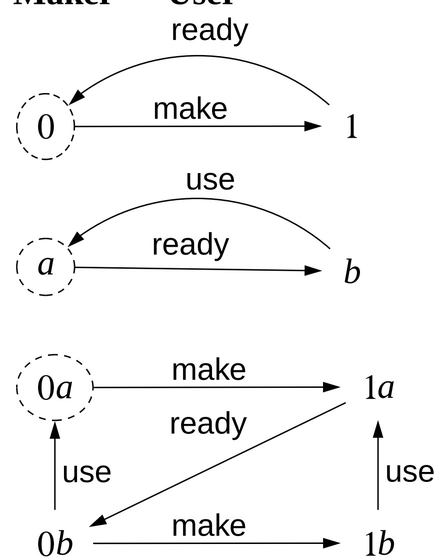
How many traces do these processes have?

Maker — User

Maker =

User =

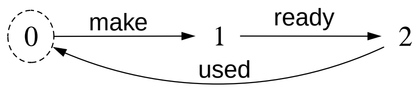
Maker || *User* =



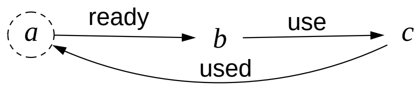
How many traces do these processes have?

Maker — User 2

$Maker_2$ =



$User_2$ =

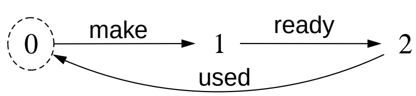


$Maker_2 \,||\, User_2$ =

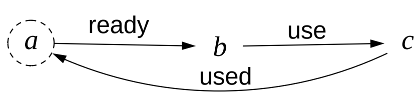
How many traces do these processes have?

Maker — User 2

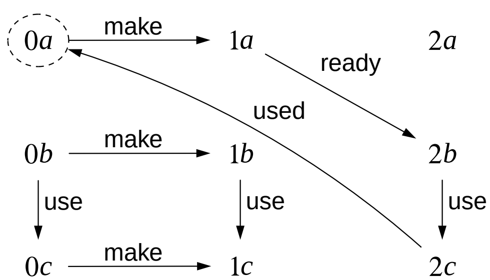
$Maker_2$ =



$User_2$ =



$Maker_2 \,||\, User_2$ =

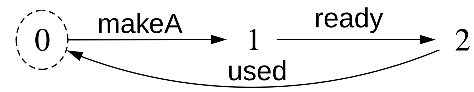


How many traces do these processes have?

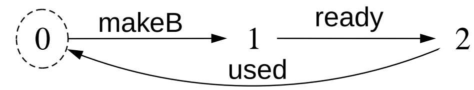
Factory

Factory = *MakerA* || *MakerB* || *Assemble*

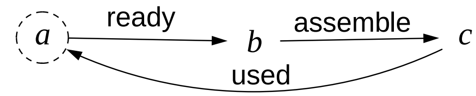
MakerA =



MakerB =



Assemble =



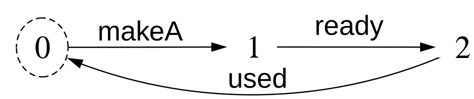
Factory =

How many **states** does *Factory* have?

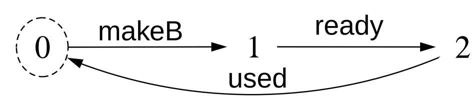
Factory

Factory = *MakerA* || *MakerB* || *Assemble*

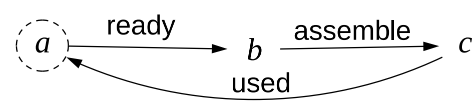
MakerA =



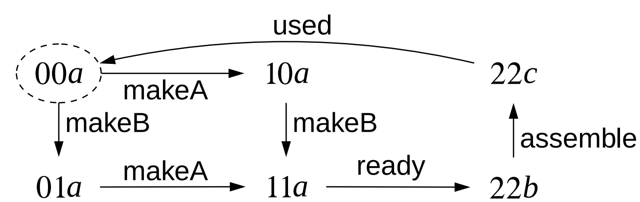
MakerB =



Assemble =



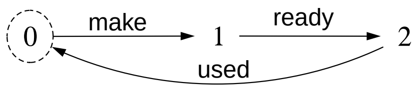
Factory =



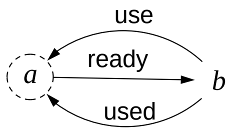
How many **states** does *Factory* have?

Maker — User 3

$Maker_2$ =



$User_3$ =

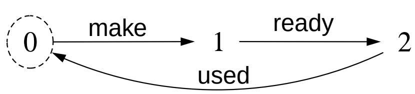


$Maker_2 \mid\mid User_3$ =

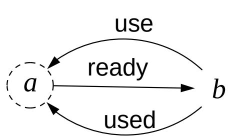
How many traces do these processes have?

Maker — User 3

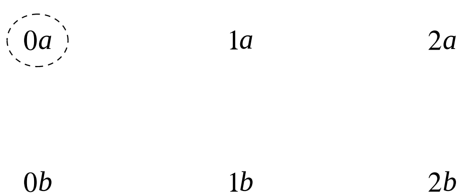
$Maker_2$ =



$User_3$ =



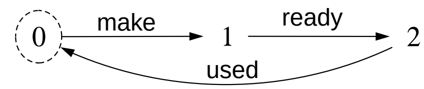
$Maker_2 \mid\mid User_3$ =



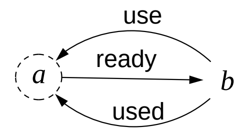
How many traces do these processes have?

Maker — User 3

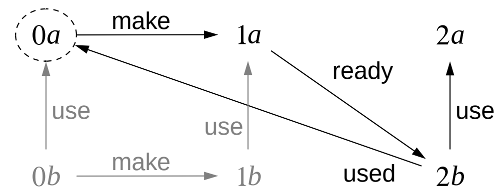
$Maker_2$ =



$User_3$ =



$Maker_2 \mid\mid User_3$ =



How many traces do these processes have?

Deadlock

- **Deadlock** occurs in a **system** when **all** its constituent **processes** are blocked.
- A system is **deadlocked** if there are no actions it can perform.
- A **deadlock state** in an LTS is a reachable state with no outgoing transitions.
- An LTS has a deadlock state iff it has a **finite trace**.

- A terminating constituent process introduces “atypical” deadlock.
- **“Typical”** deadlocks occur in **concurrent compositions** of processes that individually are deadlock-free.

Liveness and Safety Properties

A **safety property** asserts:

“something **bad** will **never** happen”

A **liveness property** asserts:

“something **good** will **eventually** happen”

Safety

A **safety** property asserts:

“something **bad** will **never** happen”

Important safety conditions:

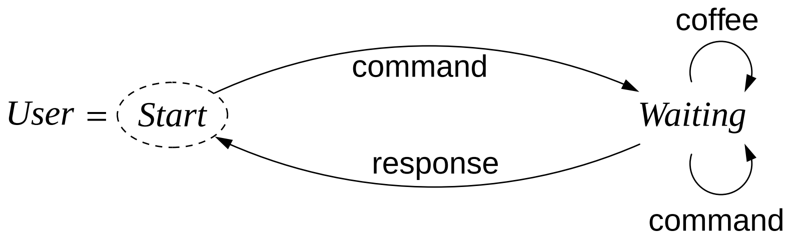
- **Partial correctness**
  - *State predicate:* If in a proper termination state, then postcondition is satisfied.
- **Invariants**
  - If in a certain kind of state, or before or after a certain kind of action, then the invariant holds for the current state.
- **Safe access sequences to resources**
  - Certain actions happen only conforming to a fixed pattern.

Such properties are often formulated using **temporal logic**.

Safe Access Sequences

- Given a system modelled as an LTS $P = (S, s, L, \delta)$, accesses to some resource (set) involve actions of a subset $A \subseteq L$.
- For every trace t of P, only its **projection** on A is considered, i.e., the sequence of those elements of t that are in A.
- These projections need to satisfy some **predicate.**
- **Conveniently:** These projections have to be traces of some (simpler) LTS

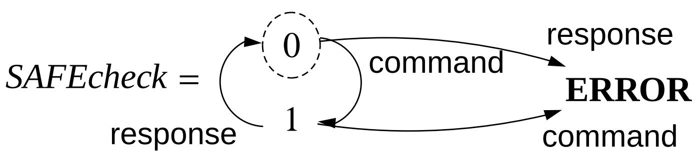
Example: $SAFE$ = command $\rightarrow$ response $\rightarrow$ $SAFE$

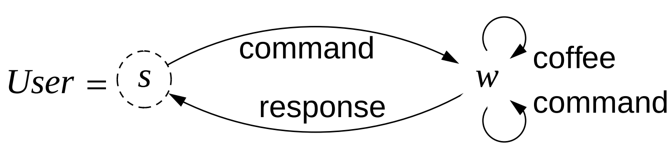


Checking Safe Access Sequences using ||

$SAFE$ = command $\rightarrow$ response $\rightarrow$ $SAFE$

Add **catch-all error state**:





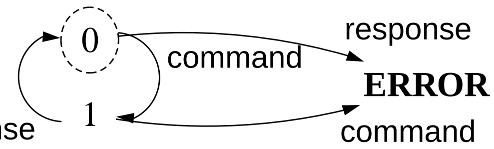
$User \parallel SAFEcheck =$

Checking Safe Access Sequences using ||

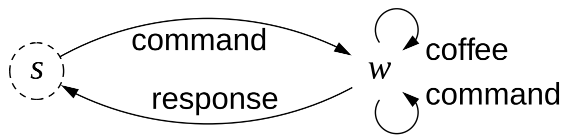
SAFE = command → response → *SAFE*

Add **catch-all error state**:

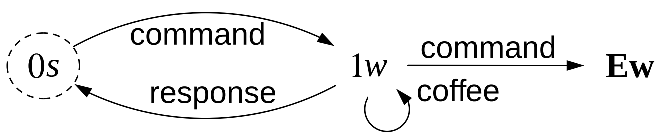
SAFEcheck =



User =



U || *Sc* =



Safety

Ideally, a software system will be safe if it satisfies its specification.

— However, the specification may not guarantee safety.

Safety is a greater concern in a concurrent software system because the order of events is harder to control

Fundamental Safety Failure: An action by a process or thread that is ***intended to be atomic*** is breached by another process or thread.

– The code that implements the atomic action is called a **critical section**
– The breach of the atomic action may be unpredictable due to **race conditions**

Liveness

A **liveness** property asserts:

> "*no matter when we start to look*,
> something **good** will **eventually** happen"

Example: "Philosopher *i* cannot starve at the table."

– *No matter when we start to look, if philosopher i is at the table, he will eventually be eating*
– **This can be expressed in terms of traces:**

Philosopher phil.*i* "cannot starve at the table" **iff** for every trace *t* and every position *m* such that t_m = phil.*i*.sitdown there is a position *n* with $n > m$ such that t_n = phil.*i*.eat.

Liveness

Ideally, a software system will be live if it satisfies its specification.

— However, the specification may not guarantee liveness.

Fundamental Liveness Failure:

A process (thread) waits for an event that will never happen.

Examples:

- Deadlock
- Missed signals
- Nested monitor lockouts
- Livelock
- Starvation
- Resource exhaustion
- Distributed failure

Branching Transitions

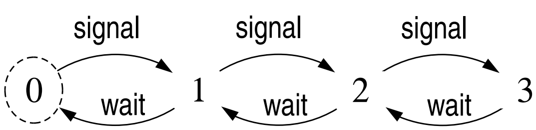
A state of a process from which several transitions exist usually models one of the following:

– In this state, the process is prepared to **react** to different environmental stimuli
– In this state, the process **acts** by making a (non-deterministic) choice
  - non-determinism could be intended
  - non-determinism could be the result of abstraction

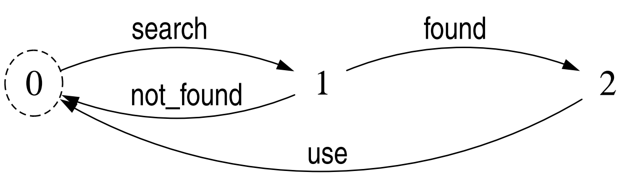
LTSs do not differentiate between **action** and **reaction**!

Reactive Choice

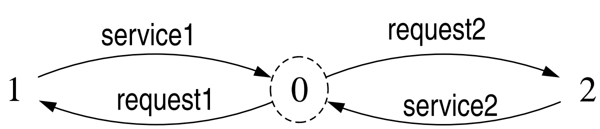
*Sema*3 =



Lookup =



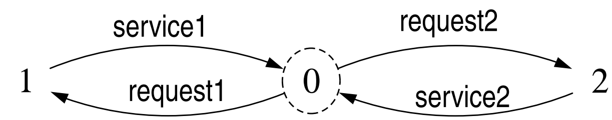
Server =



Active Non-Deterministic Choice

$$\begin{array}{lcl} Client1 & = & \mathsf{request\ 1} \rightarrow \mathsf{service\ 1} \rightarrow \mathsf{sleep} \rightarrow Client1 \\ Client2 & = & \mathsf{request\ 2} \rightarrow \mathsf{service\ 2} \rightarrow \mathsf{work} \rightarrow Client2 \\ Clients & = & Client1 \parallel Client2 \\ System & = & Clients \parallel Server \end{array}$$

Server =



Concurrency is a good source of non-determinism!

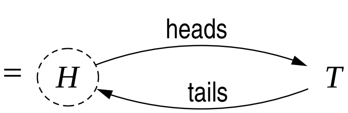
Distribution is one of the best sources of non-determinism!

Modelling Real Non-Deterministic Choice

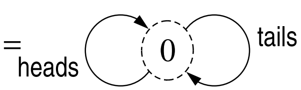
How should we model a process that repeatedly tosses a coin?

How should we model a process that bets on alternating outcomes?

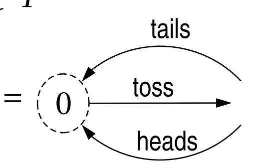
Bet =



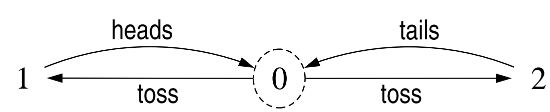
*Coin*1 =



*Coin*2 =

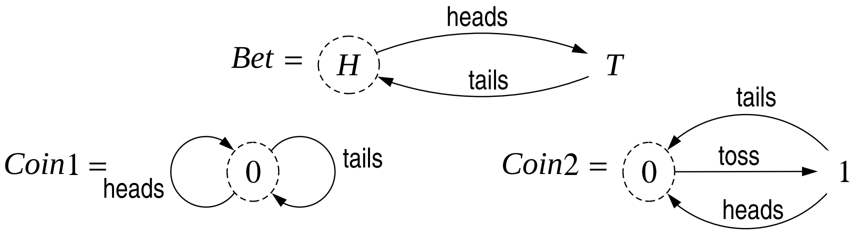


*Coin*3 =



Consider the compositions with *Bet*!

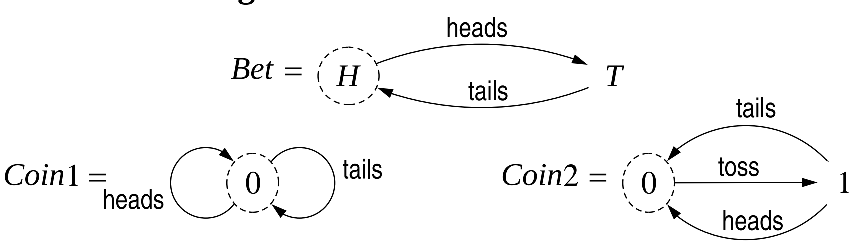
Betting Must Not Influence the Coin …



$Coin1 \parallel Bet =$

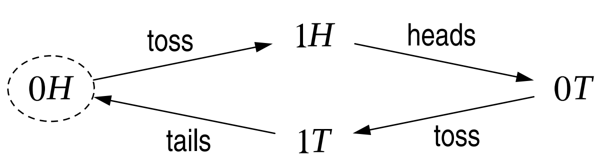
$Coin2 \parallel Bet =$

Betting Must Not Influence the Coin …

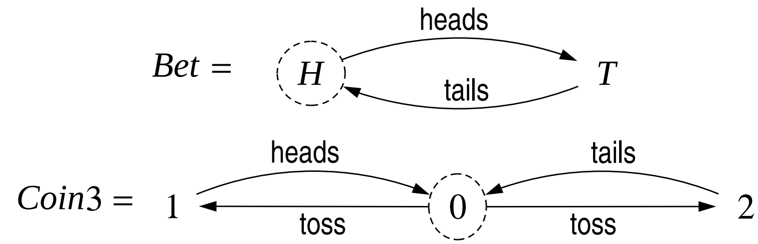


$Coin1 \parallel Bet \equiv Bet$

$Coin2 \parallel Bet =$

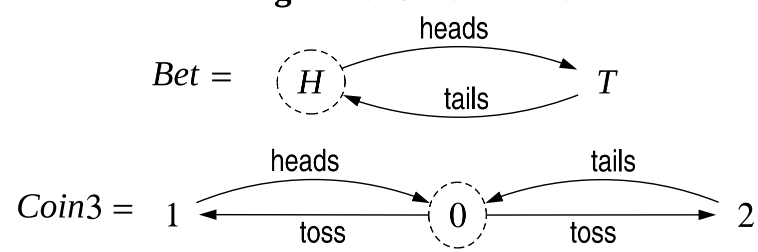


Betting Introduces Deadlock



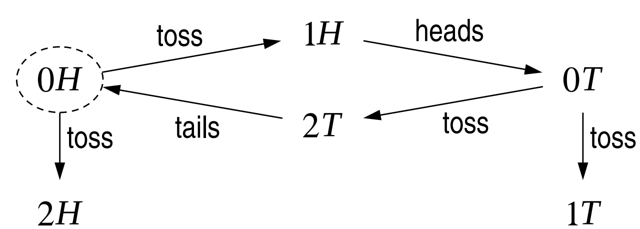
$Coin3 \parallel Bet =$

Betting Introduces Deadlock



A choice among equally labelled transitions cannot be “influenced” via composition!

$Coin3 \parallel Bet =$



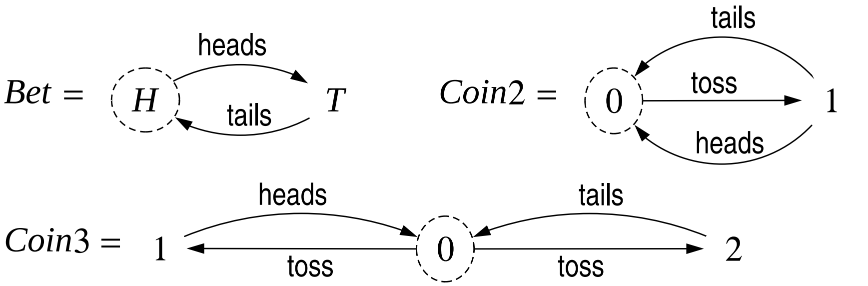
Non-Deterministic Choice, Traces, and Composition

*Coin*2 and *Coin*3 have the same trace set!

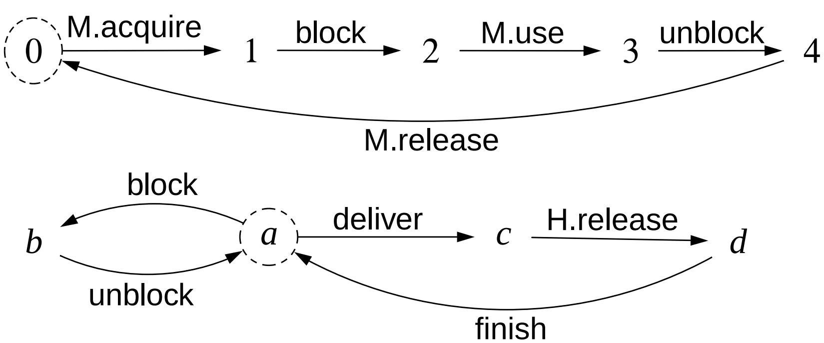
But, $Coin2 \parallel Bet$ and $Coin3 \parallel Bet$ have **different** trace sets!

$\Rightarrow$ Two LTSs P_1 and P_2 are **equivalent** iff for every LTS Q, the compositions $P_1 \parallel Q$ and $P_2 \parallel Q$ have the same trace set.

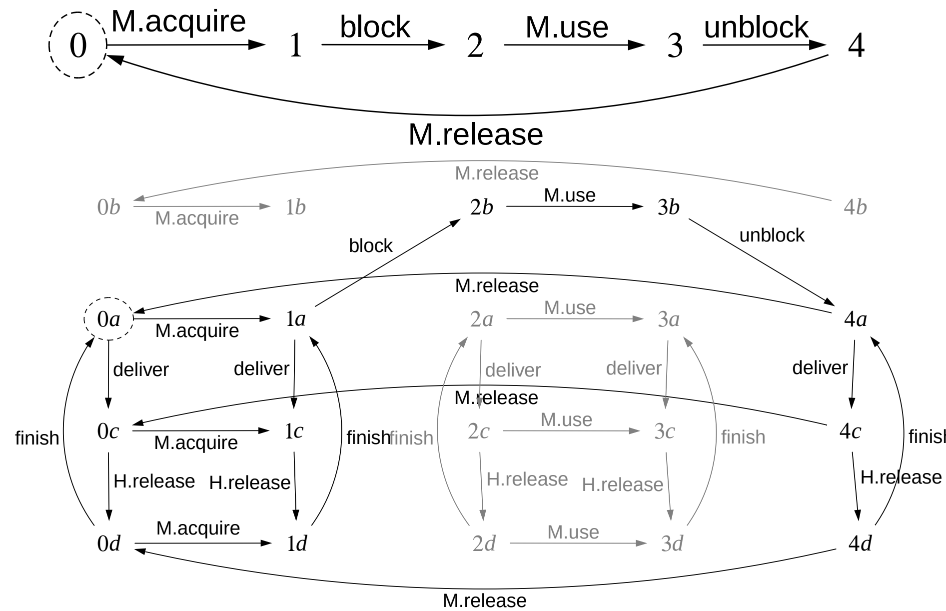
This is a *black-box* view: "No context enables distinction."



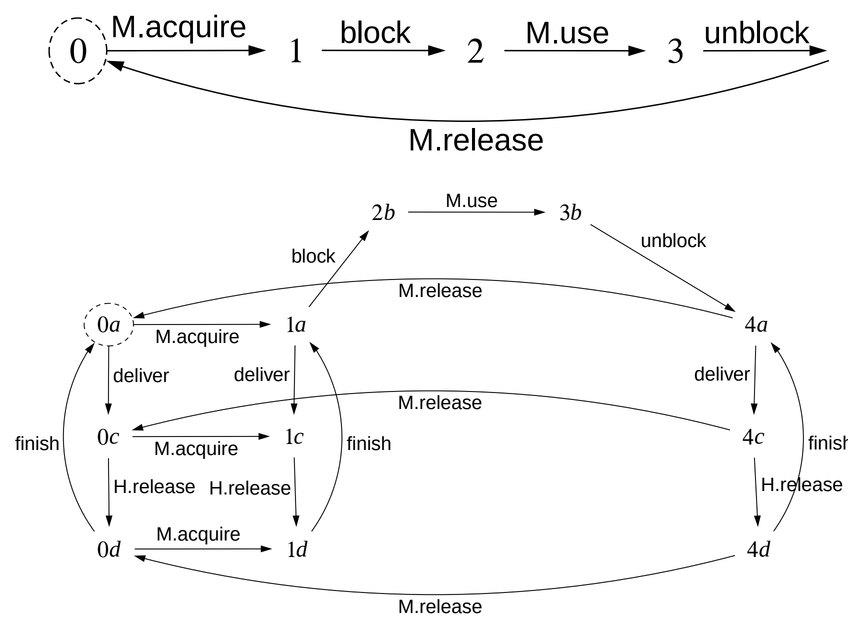
How Not to Model Signal Handling



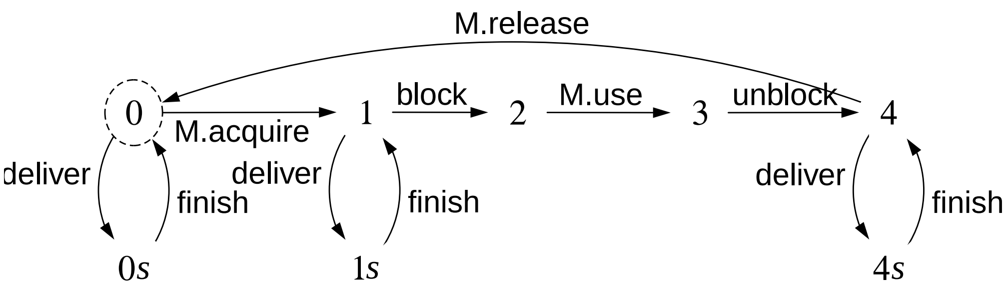
How Not to Model Signal Handling



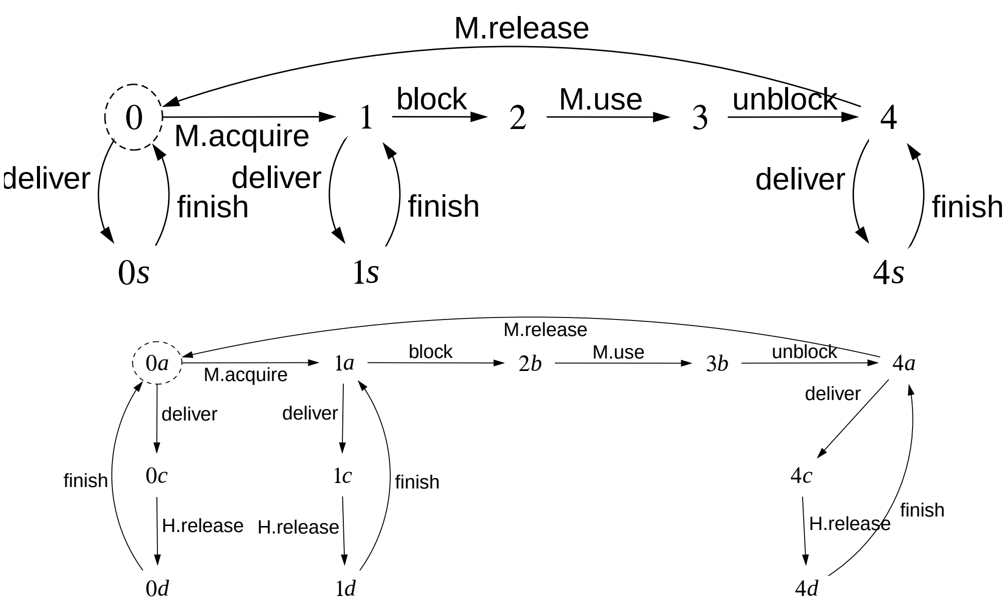
How Not to Model Signal Handling



Modelling Signal Handling

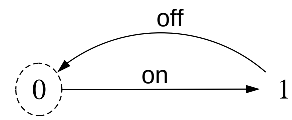


Modelling Signal Handling

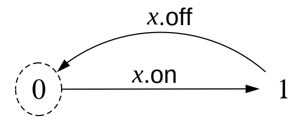


Labelling: Switches

Switch =



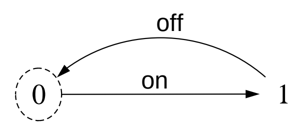
x:*Switch* =



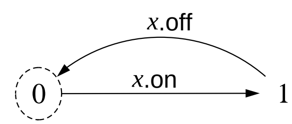
a:*Switch* || b:*Switch* =

Labelling: Switches

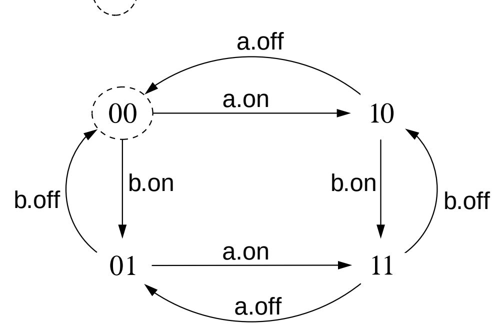
Switch =



x:*Switch* =



a:*Switch* || b:*Switch* =



Labelling and Sharing

Definition: For an action label set L and a label set A, we let A::L denote the following set of **labelled actions**:

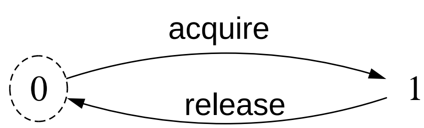
$$F::L = \{f : F; q : L \bullet f.q\}$$

For an LTSs $P = (S, s_0, L, \delta)$, we define:

- The LTS P **labelled** with a label f is $f{:}P = (S, s_0, \{f\}::L, \delta_f)$, where
  $(x, a, y) \in \delta_f \;\Leftrightarrow\; \exists a_0 : L \bullet a = f.a_0 \;\wedge\; (x, a_0, y) \in \delta.$
- The LTS P **shared** among a label set F is $F::P = (S, s_0, F::L, \delta_F)$, where
  $(x, a, y) \in \delta_F \;\Leftrightarrow\; \exists f : F; a_0 : L \bullet a = f.a_0 \;\wedge\; (x, a_0, y) \in \delta.$

Sharing: Resources

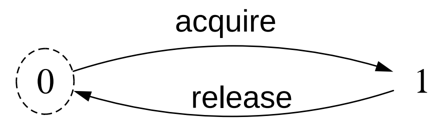
$Resource$ =



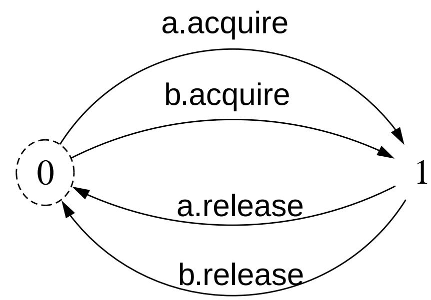
$\{\mathsf{a}, \mathsf{b}\}::Resource$ =

Sharing: Resources

$Resource$ =



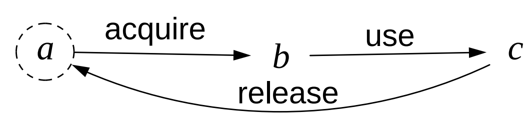
$\{\mathsf{a}, \mathsf{b}\}::Resource$ =



Sharing Resources

$ResSharing = \mathsf{a}{:}\,\mathsf{User} \parallel \mathsf{b}{:}\,\mathsf{User} \parallel \{\mathsf{a}, \mathsf{b}\}::Resource$

$User$ =

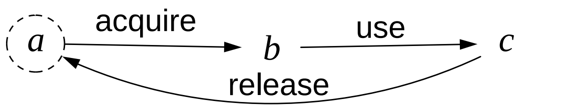


$ResSharing$ =

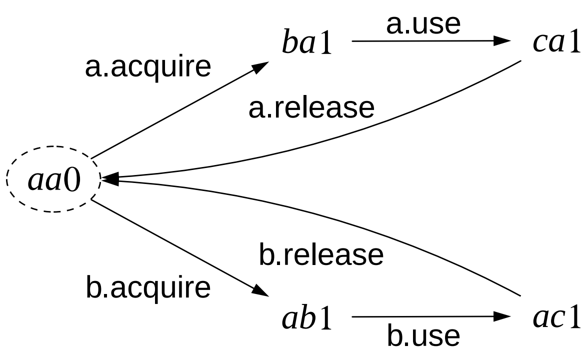
Sharing Resources

$\mathit{ResSharing} = \mathsf{a}{:}\mathit{User} \parallel \mathsf{b}{:}\mathit{User} \parallel \{\mathsf{a}, \mathsf{b}\}{::}\mathit{Resource}$

$\mathit{User} =$



$\mathit{ResSharing} =$



Blocking Resources

$\mathit{ResBlocking} = \mathsf{a}{:}\mathit{Abuser} \parallel \mathsf{b}{:}\mathit{User} \parallel \{\mathsf{a}, \mathsf{b}\}{::}\mathit{Resource}$

$\mathit{Abuser} =$

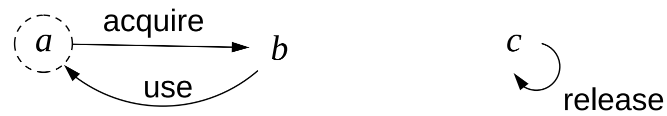
$\mathit{ResBlocking} =$

How many traces do these processes have?

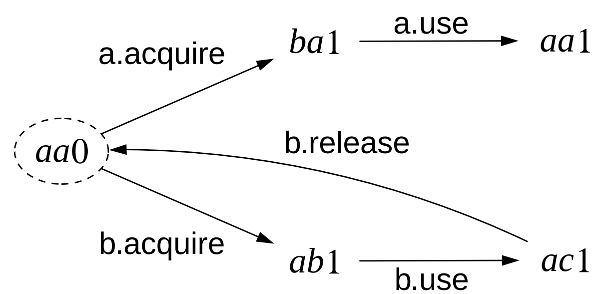
Blocking Resources

$\mathit{ResBlocking} = \mathsf{a}{:}\mathit{Abuser} \parallel \mathsf{b}{:}\mathit{User} \parallel \{\mathsf{a}, \mathsf{b}\}{::}\mathit{Resource}$

$\mathit{Abuser} =$



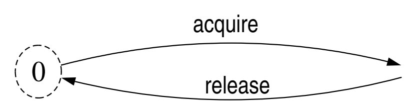
$\mathit{ResBlocking} =$



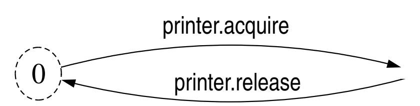
How many traces do these processes have?

Sharing a Labelled Resource

$\mathit{Resource} =$



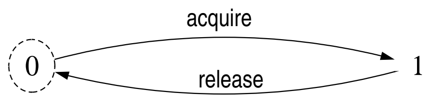
$\mathsf{printer}{:}\mathit{Resource} =$



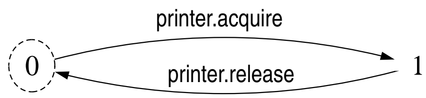
$\{\mathsf{a}, \mathsf{b}\}{::}\mathsf{printer}{:}\mathit{Resource} =$

Sharing a Labelled Resource

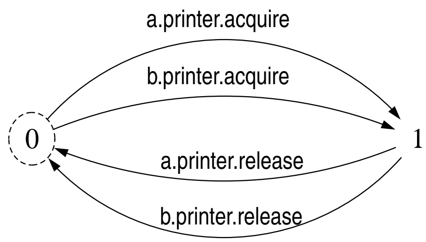
Resource =



printer:*Resource* =

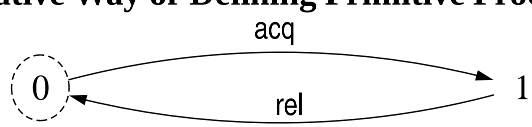


{a, b}::printer:*Resource* =

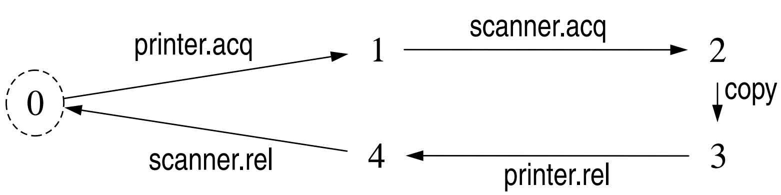


An Alternative Way of Defining Primitive Processes

Resource =



A =



Process Calculus Notation:

$Resource = \mathsf{acq} \rightarrow \mathsf{rel} \rightarrow Resource$

$A = \mathsf{printer.acq} \rightarrow \mathsf{scanner.acq} \rightarrow \mathsf{copy} \rightarrow \mathsf{printer.rel} \rightarrow \mathsf{scanner.rel} \rightarrow A$

Sharing Two Resources

$Resource = \mathsf{acq} \rightarrow \mathsf{rel} \rightarrow Resource$

$A = \mathsf{pr.acq} \rightarrow \mathsf{sc.acq} \rightarrow \mathsf{copy} \rightarrow \mathsf{pr.rel} \rightarrow \mathsf{sc.rel} \rightarrow A$

$B = \mathsf{sc.acq} \rightarrow \mathsf{pr.acq} \rightarrow \mathsf{copy} \rightarrow \mathsf{sc.rel} \rightarrow \mathsf{pr.rel} \rightarrow B$

$Sys = \mathsf{a}{:}A \parallel \{\mathsf{a}, \mathsf{b}\}{::}\mathsf{pr}{:}Resource \parallel \{\mathsf{a}, \mathsf{b}\}{::}\mathsf{sc}{:}Resource \parallel \mathsf{b}{:}B$

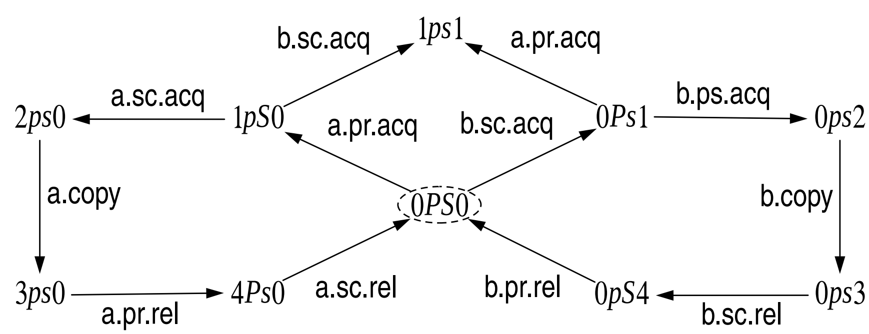
Sharing Two Resources

$Resource = \mathsf{acq} \rightarrow \mathsf{rel} \rightarrow Resource$

$A = \mathsf{pr.acq} \rightarrow \mathsf{sc.acq} \rightarrow \mathsf{copy} \rightarrow \mathsf{pr.rel} \rightarrow \mathsf{sc.rel} \rightarrow A$

$B = \mathsf{sc.acq} \rightarrow \mathsf{pr.acq} \rightarrow \mathsf{copy} \rightarrow \mathsf{sc.rel} \rightarrow \mathsf{pr.rel} \rightarrow B$

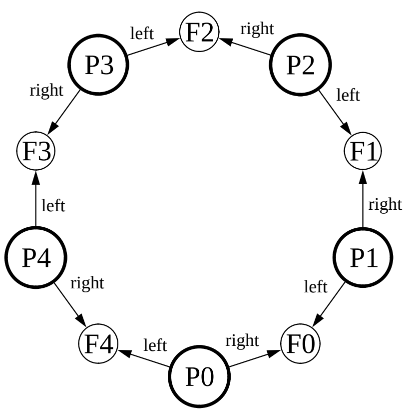
$Sys = \mathsf{a}{:}A \parallel \{\mathsf{a}, \mathsf{b}\}{::}\mathsf{pr}{:}Resource \parallel \{\mathsf{a}, \mathsf{b}\}{::}\mathsf{sc}{:}Resource \parallel \mathsf{b}{:}B$



The Dining Philosophers

- Five philosophers live together in a house.
- The live of a philosopher essentially consists of alternating phases of thinking and eating.
- For eating, there is a round table with five seats and a large bowl of spaghetti on it; between adjacent seats there is always one fork.
- Each philosopher needs two forks in order to be able to eat.
- When hungry, each philosopher will sit down on a free chair, take up the fork to his left, take up the fork to his right, eat, put down the forks, and leave for more thinking.
- *Is it possible that the philosophers all starve to death?*

The Dining Philosophers



$Fork = \mathsf{get} \longrightarrow \mathsf{put} \longrightarrow Fork$

$Phil = \mathsf{sitdown} \longrightarrow \mathsf{right.get} \longrightarrow \mathsf{left.get} \longrightarrow \mathsf{eat} \longrightarrow \mathsf{left.put} \longrightarrow \mathsf{right.put} \longrightarrow \mathsf{arise} \longrightarrow Phil$

Let $N = 5$

Let $succ_N(i) = (i + 1)\%N$

$Diners =$

$$\|_{i=0}^{N-1} \left(\mathsf{phil}{:}i{:}Phil \parallel \{\mathsf{phil}.i.\mathsf{right}, \mathsf{phil}.succ_N(i).\mathsf{left}\}{::}Fork\right)$$

Model-Checking the Dining Philosophers Using LTSA

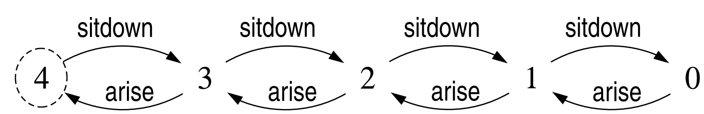
```
PHIL = (sitdown->right.get
  ->left.get->eat->left.put
  ->right.put->arise->PHIL).

FORK = (get -> put -> FORK).

||DINERS(N=5)=
   forall [i:0..N-1]
   (phil[i]:PHIL
   ||{phil[i].right,
     phil[(i+1)%N].left}::FORK).
```

```
Trace to DEADLOCK:
  phil.0.sitdown
  phil.0.right.get
  phil.1.sitdown
  phil.1.right.get
  phil.2.sitdown
  phil.2.right.get
  phil.3.sitdown
  phil.3.right.get
  phil.4.sitdown
  phil.4.right.get
```


Solutions to the Dining Philosophers Problem

Original solution: Introduce a **butler** who restricts the maximum number of sitting philosophers to 4.

Butler =

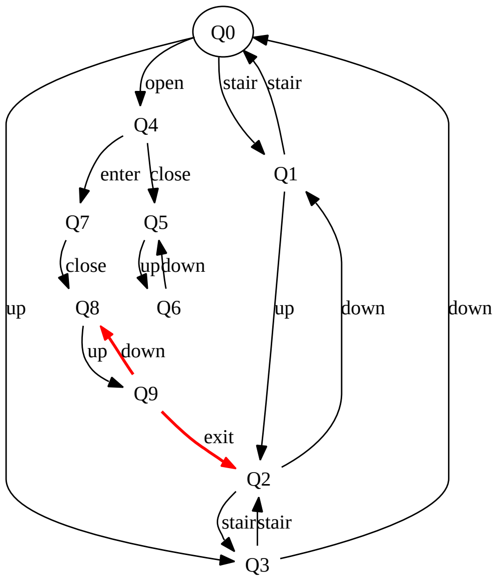


The butler is a counting semaphore!

Some other solutions:

- Have some philosophers pick up the left fork first.
- Make picking up both forks atomic.
- Have all philosophers decide randomly which fork to pick up, and give priority to “hungrier” neighbours.

Fairness



Fairness assumption:

If a choice is arrived at infinitely often, then all of its branches are taken infinitely often.

Assuming fairness, additional lifeness properties hold, e.g.: "After an enter, there will eventually be an exit."