Concurrent Programming

Prof. O. Nierstrasz

IAM, University of Berne

Winter 2001/2002

Table of Contents

1. Concurrent Programming

Lecturer	Prof. Oscar Nierstrasz
Assistants	Franz Achermann, Nathanael Schaerli
Where	IWI 001, Mondays @ 10h15-12h00
WWW	www.iam.unibe.ch/~scg/Teaching/CP/
Texts	☞ D. Lea, *Concurrent Programming in Java: Design Principles and Patterns*, Addison-Wesley, 1996 ☞ J. Magee, J. Kramer, *Concurrency: State Models & Java Programs*, Wiley, 1999

Goals of this course

- Introduce *basic concepts* of concurrency
  - ☞ safety, liveness, fairness
- Present tools for *reasoning* about concurrency
  - ☞ LTS, Petri nets
- Learn the *best practice* programming techniques
  - ☞ idioms and patterns
- Get *experience* with the techniques
  - ☞ lab sessions

Schedule

1.	10 - 29	Introduction
2.	11 - 05	Concurrency and Java
3.	11 - 12	Safety and Synchronization
4.	11 - 19	Safety Patterns
5.	11 - 26	Liveness and Deadlock
6.	12 - 03	Liveness and Guarded Methods
7.	12 - 10	*Lab session*
8.	12 - 17	Liveness and Asynchrony
9.	01 - 07	Condition Objects
10.	01 - 14	Fairness and Optimism
11.	01 - 21	*Lab session*
12.	01 - 28	Architectural Styles for Concurrency
13.	02 - 04	Petri Nets

Introduction

Overview

- ❑ Concurrency and Parallelism
- ❑ Applications
- ❑ Difficulties
  - ☞ safety, liveness, non-determinism ...

Concurrent Programming Approaches

- ❑ Process creation
- ❑ Communication and synchronization
  - ☞ Shared variables
  - ☞ Message Passing Approaches

Recommended reading

- G.R. Andrews, *Concurrent Programming, Principles and Practice*, The Benjamin Cummings Publishing Co. Inc, 1991,
- M. Ben-Ari, *Principles of Concurrent and Distributed Programming*, Prentice Hall, 1990.
- A. Burns, G. Davies, *Concurrent Programming*, Addison-Wesley, 1993
- N. Carriero, D. Gelernter, *How to Write Parallel Programs: a First Course*, MIT Press, Cambridge, 1990.

Concurrency

- A sequential program has a *single thread of control*. Its execution is called a process.
- A concurrent program has *multiple threads of control*. These may be executed as parallel processes.

Parallelism

A concurrent program can be executed by:

Multiprogramming:	processes share one or more processors
Multiprocessing:	each process runs on its own processor but with shared memory
Distributed processing:	each process runs on its own processor connected by a network to others

*Assume only that all processes make **positive finite progress**.*

Why do we need concurrent programs?

Reactive programming

- ☞ minimize response delay; maximize throughput

Real-time programming

- ☞ process control applications

Simulation

- ☞ modelling real-world concurrency

Parallelism

- ☞ speed up execution by using multiple CPUs

Distribution

- ☞ coordinate distributed services

Difficulties

But concurrent applications introduce complexity:

Safety

- concurrent processes may corrupt shared data

Liveness

- processes may "starve" if not properly coordinated

Non-determinism

- the same program run twice may give different results

Run-time overhead

- thread construction, context switching and synchronization take time

Concurrency and atomicity

Programs P1 and P2 execute concurrently:

```
        { x = 0 }

P1:       x := x+1
P2:       x := x+2

        { x = ? }
```

✎ *What are possible values of x after P1 and P2 complete?*

✎ *What is the intended final value of x?*

Safety

Safety = ensuring *consistency*

A <u>safety property</u> says "nothing bad happens"

- ***Mutual exclusion:*** shared resources must be *updated atomically*
- ***Condition synchronization:*** operations may be *delayed* if shared resources are in the wrong state
  - ☞ (e.g., read from empty buffer)

Liveness

Liveness = ensuring *progress*

A liveness property says "something good happens"

- ***No Deadlock:*** *some* process can *always* access a shared resource
- ***No Starvation:*** *all* processes can *eventually* access shared resources

Expressing Concurrency

A programming language must provide mechanisms for:

Process creation

- how do you specify *concurrent processes*?

Communication

- how do processes *exchange information*?

Synchronization

- how do processes *maintain consistency*?

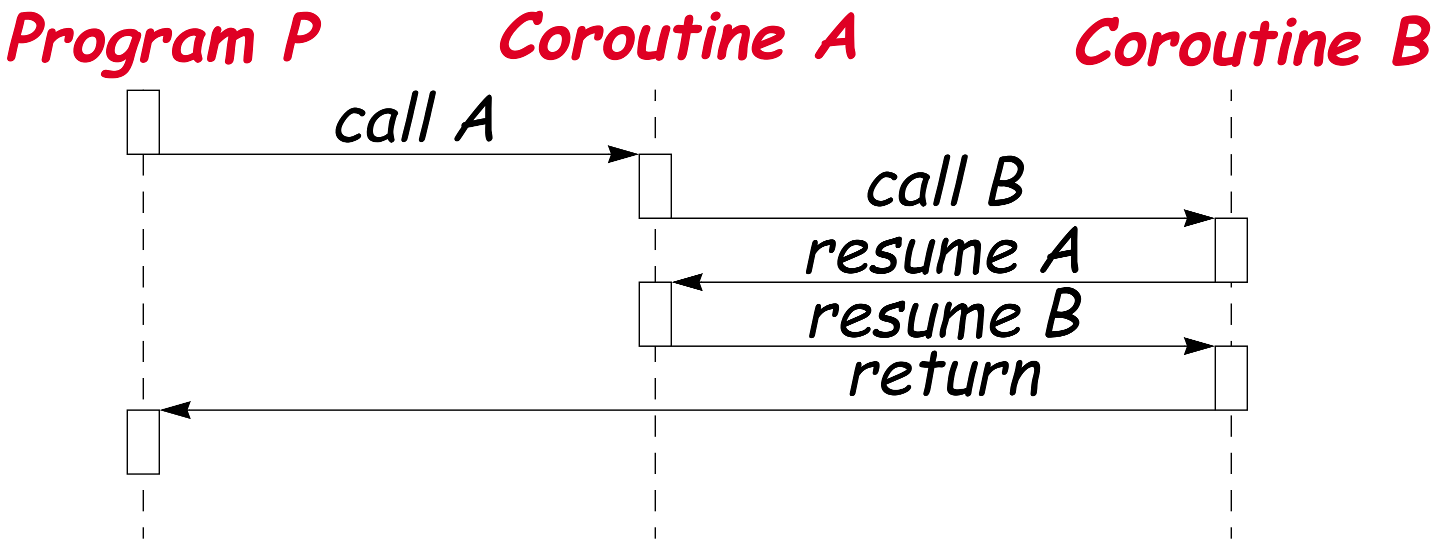
Process Creation

Most concurrent languages offer some variant of the following:

- Co-routines
- Fork and Join
- Cobegin/coend

Co-routines

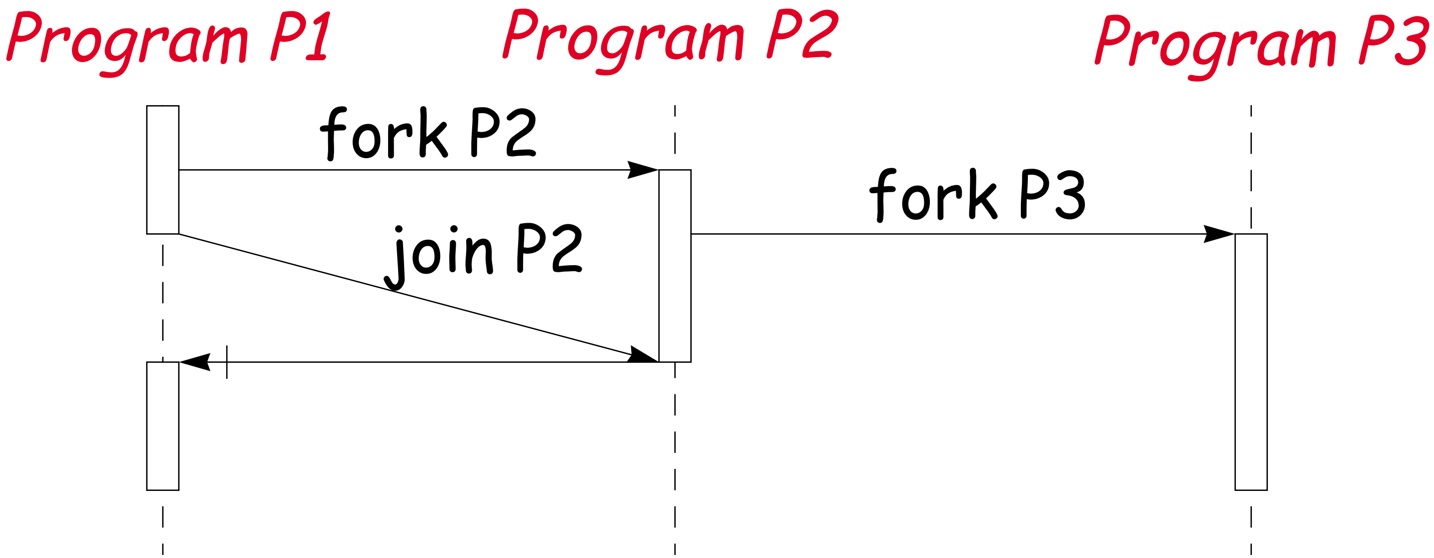
Co-routines are only *pseudo-concurrent* and require *explicit transfers of control*:



Co-routines can be used to implement most higher-level concurrent mechanisms.

Fork and Join

Fork can be used to create any number of processes:



Join waits for another process to terminate.

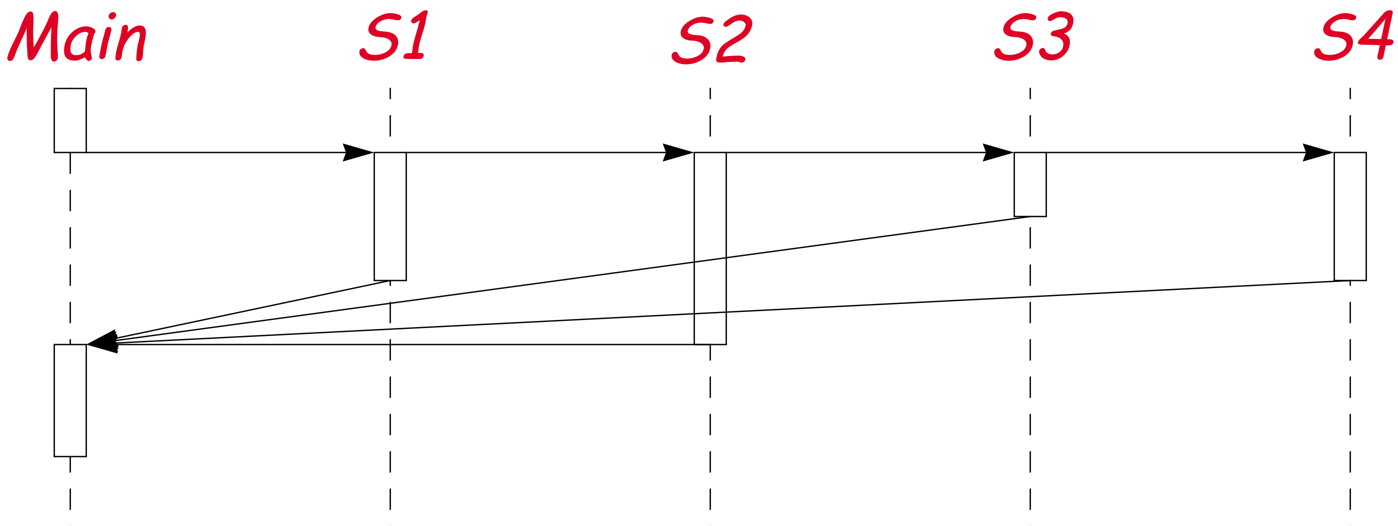
Fork and join are *unstructured*, so require *care and discipline*.

Cobegin/coend

Cobegin/coend blocks are *better structured*:

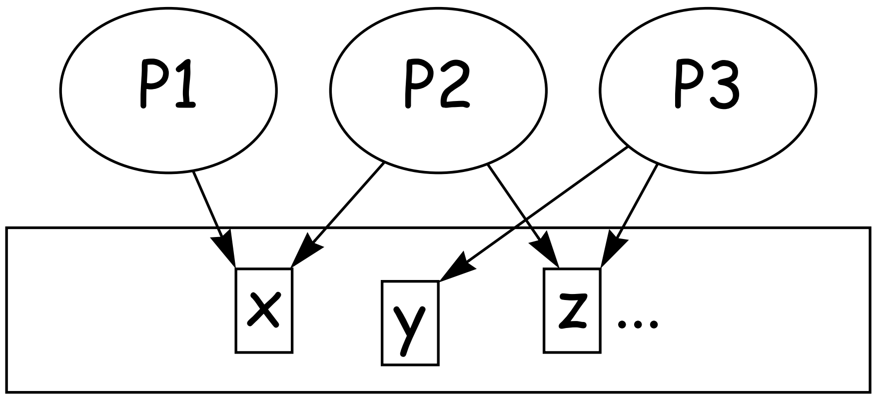
```
cobegin S1 || S2 || ... || Sn coend
```

but they can only create a *fixed number* of processes.



The caller continues when *all* of the coblocks have terminated.

Communication and Synchronization

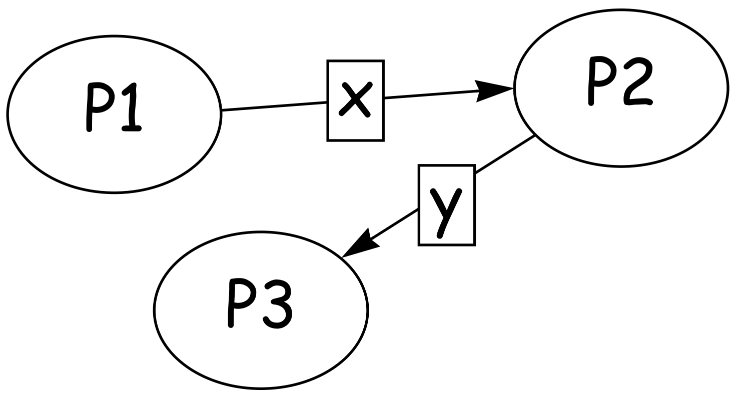


In approaches based on ***shared variables***, processes communicate *indirectly*.

Explicit synchronization mechanisms are needed.

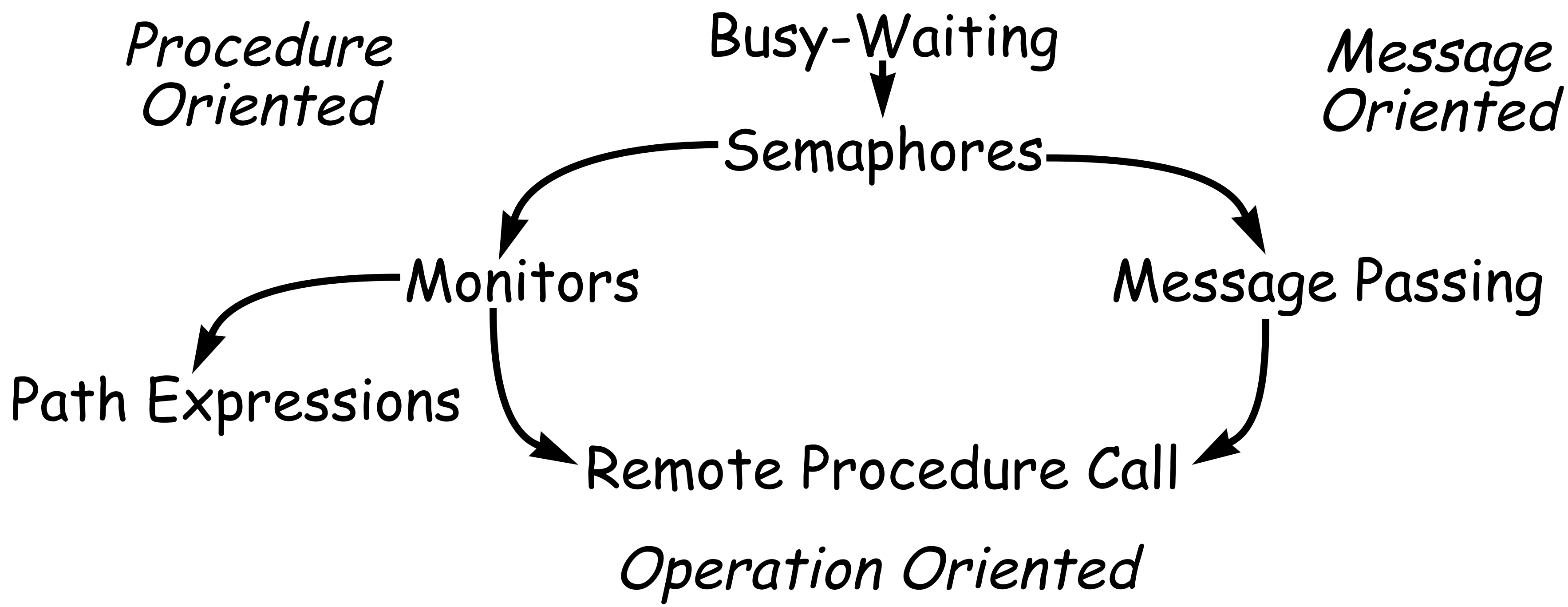
In ***message passing*** approaches, *communication and synchronization are combined*.

Communication may be either *synchronous* or *asynchronous*.



Synchronization Techniques

Different approaches are roughly *equivalent in expressive power* and can be used to implement each other.



Each approach emphasizes a different style of programming.

Busy-Waiting

Busy-waiting is primitive but effective

Processes *atomically set and test* shared variables.

Condition synchronization is easy to implement:

- to *signal* a condition, a process *sets* a shared variable
- to *wait* for a condition, a process *repeatedly tests* the variable

Mutual exclusion is more difficult to realize *correctly* and *efficiently*.

Semaphores

Semaphores were introduced by Dijkstra (1968) as a *higher-level primitive* for process synchronization.

A <u>*semaphore*</u> is a non-negative, integer-valued variable *s* with two operations:

P(s):	*delays* until $s>0$ then, *atomically* executes $s := s-1$
V(s)	atomically executes $s:= s+1$

Programming with semaphores

Many problems can be solved using *binary semaphores*, which take on values 0 or 1.

```
process P1
   loop
      P(mutex)  { wants to enter }
      Critical Section
      V(mutex)  { exits }
      Non-critical Section
   end
end
```

```
process P2
   loop
      P(mutex)
      Critical Section
      V(mutex)
      Non-critical Section
   end
end
```

Monitors

A *monitor* encapsulates *resources* and *operations* that manipulate them:

- operations are invoked like ordinary procedure calls
  - ☞ invocations are guaranteed to be *mutually exclusive*
  - ☞ *condition synchronization* is realized using *wait* and *signal* primitives
  - ☞ there exist many variations of *wait* and *signal* ...

Programming with monitors

```
type buffer(T) = monitor
   var
   slots : array [0..N-1] of T;
   head, tail : 0..N-1;
   size : 0..N;
   notfull, notempty:condition;

procedure deposit(p : T);
   begin
      if size = N then
         notfull.wait
      slots[tail] := p;
      size := size + 1;
      tail := (tail+1) mod N;
      notempty.signal
   end
```

```
procedure fetch(var it : T);
   begin
      if size = 0 then
         notempty.wait
      it := slots[head];
      size := size - 1;
      head := (head+1) mod N;
      notfull.signal
   end

begin
   size := 0;
   head := 0;
   tail := 0;
end
```

Problems with monitors

Monitors are more structured than semaphores, but they are still tricky to program:

- ☞ Conditions must be *manually checked*
- ☞ Simultaneous signal and return is *not supported*

A signalling process is temporarily *suspended* to allow waiting processes to enter!

- ❑ *Monitor state may change* between *signal* and resumption of signaller
- ❑ Unlike with semaphores, *multiple signals are not saved*
- ❑ *Nested monitor calls* must be specially handled to prevent deadlock

Path Expressions

Path expressions express the *allowable sequence of operations* as a kind of regular expression:

```
buffer : (put; get) *
```

Although they elegantly express solutions to many problems, path expressions are too limited for general concurrent programming.

Message Passing

Message passing combines communication and synchronization:

- The sender specifies the *message* and a *destination*
  - ☞ a process, a port, a set of processes, ...
- The receiver specifies message *variables* and a *source*
  - ☞ source may or may not be explicitly identified
- Message transfer may be:
  - ☞ *asynchronous:* send operations *never block*
  - ☞ *buffered:* sender may *block if the buffer is full*
  - ☞ *synchronous:* sender and receiver *must both be ready*

Send and Receive

In CSP and Occam, source and destination are explicitly named:

```
PROC buffer(CHAN OF INT give, take, signal)
  ...
  SEQ
    numitems := 0 ...
    WHILE TRUE
    ALT
      numitems ≤ size & give?thebuffer[inindex]
        SEQ
          numitems := numitems + 1
          inindex := (inindex + 1) REM size
      numitems > 0 & signal?any
        SEQ
          take!thebuffer[outindex]
          numitems := numitems - 1
          outindex := (outindex + 1) REM size
```

Remote Procedure Calls and Rendezvous

In Ada, the caller identity need not be known in advance:

```
task body buffer is ...
begin loop
    select
      when no_of_items < size =>
        accept give(x : in item) do
          the_buffer(in_index) := x;
        end give;
        no_of_items := no_of_items + 1; ...
    or
      when no_of_items > 0 =>
        accept take(x : out item) do
          x := the_buffer(out_index);
        end take;
        no_of_items := no_of_items - 1; ...
    end select;
  end loop; ...
```

What you should know!

- Why do we need *concurrent* programs?
- What *problems* do concurrent programs introduce?
- What are *safety* and *liveness*?
- What is the difference between *deadlock* and *starvation*?
- How are concurrent processes *created*?
- How do processes *communicate*?
- Why do we need *synchronization* mechanisms?
- How do *monitors* differ from *semaphores*?
- In what way are monitors *equivalent* to message-passing?

Can you answer these questions?

- What is the difference between concurrency and parallelism?
- When does it make sense to use busy-waiting?
- Are binary semaphores as good as counting semaphores?
- How could you implement a semaphore using monitors?
- How would you implement monitors using semaphores?
- What problems could nested monitors cause?
- Is it better when message passing is synchronous or asynchronous?

2. Java and Concurrency

Overview

- ❑ Modelling Concurrency
  - ☞ Finite State Processes
  - ☞ Labelled Transition Systems
- ❑ Java
  - ☞ Thread creation
  - ☞ Thread lifecycle
  - ☞ Synchronization

Selected material © Magee and Kramer

Modelling Concurrency

Because concurrent systems are *non-deterministic*, it can be difficult to build them and reason about their properties.

A model is an *abstraction of the real world* that makes it easier to focus on the points of interest.

Approach:

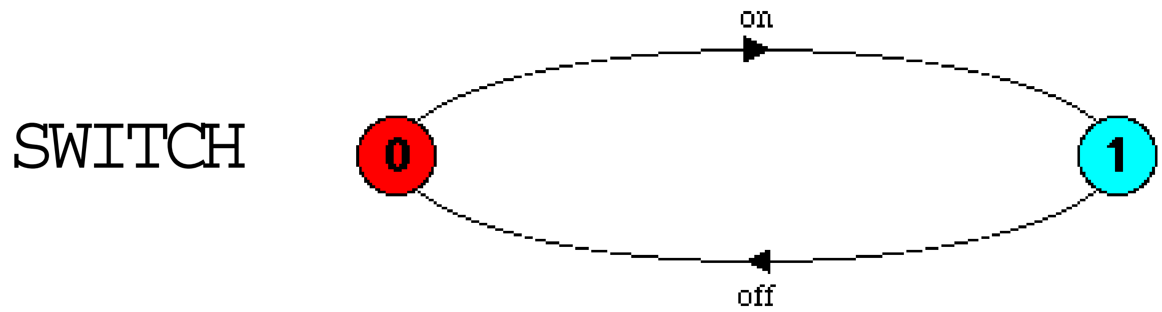
Model concurrent systems as sets of sequential *finite state processes*

Finite State Processes

FSP is a *textual* notation for specifying a finite state process:

```
SWITCH = (on -> off-> SWITCH).
```

LTS is a *graphical* notation for interpreting a processes as a labelled transition system:



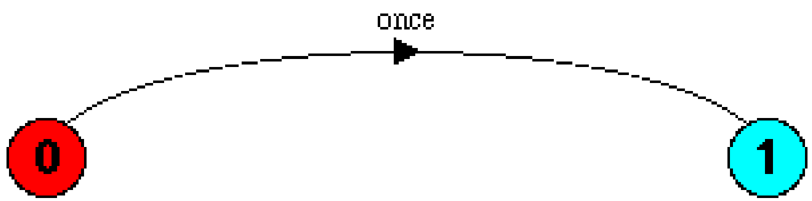
The meaning of a process is a set of possible *traces* :

on→off→on→off→on→off→on→off→on ...

FSP — Action Prefix

If `x` is an action and `P` a process then `(x-> P)` is a process that *initially engages in the action* `x` *and then behaves like* `P`.

```
ONESHOT = (once -> STOP).
```



terminating process

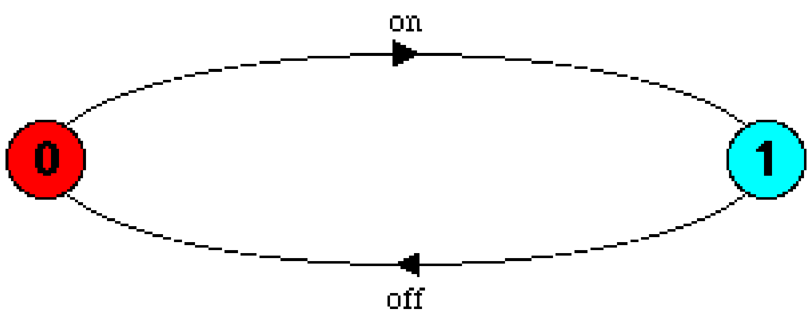
Convention:

- Processes start with UPPERCASE, actions start with lowercase.

FSP — Recursion

Repetitive behaviour uses recursion:

```
SWITCH  = OFF,
OFF     = (on -> ON),
ON      = (off-> OFF).
```

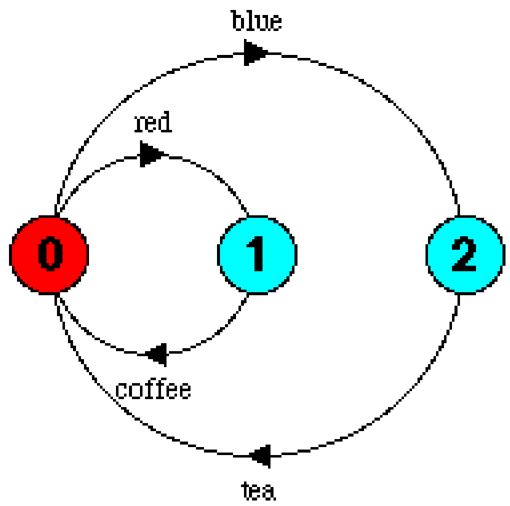


FSP — Choice

If `x` and `y` are actions then `(x->P | y->Q)` is a process which initially engages in *either of the actions* `x` or `y`.

If x occurs, the process then behaves like P; otherwise, if y occurs, it behaves like Q.

```
DRINKS = ( red ->coffee   -> DRINKS
         | blue->tea      -> DRINKS
         ).
```

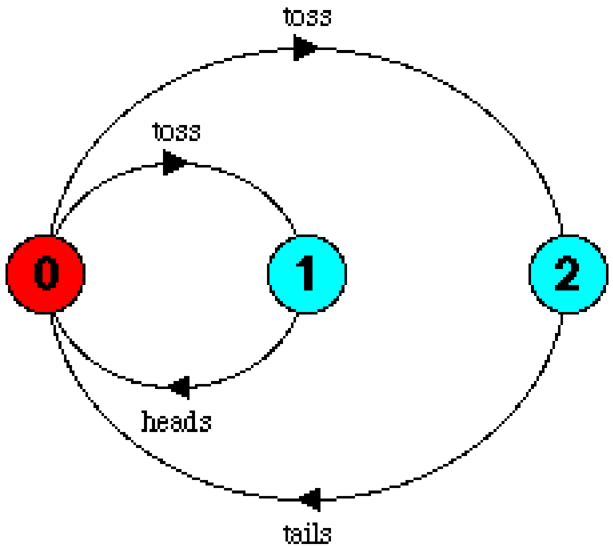


✎ *What are the possible traces of DRINKS?*

FSP — Non-determinism

`(x->P | x->Q)` performs `x` and then behaves as *either* `P` or `Q`.

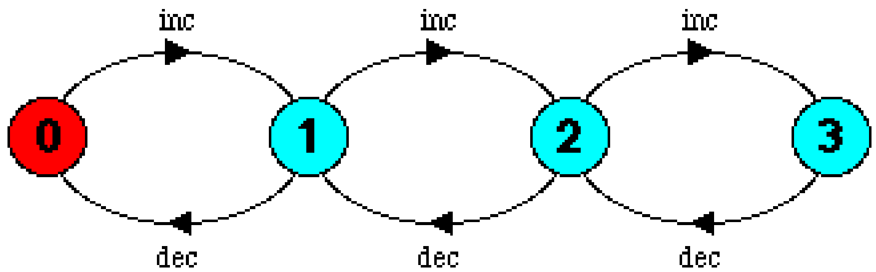
```
COIN = ( toss -> heads -> COIN
       | toss -> tails -> COIN
       ).
```



FSP — Guarded actions

(**when** `B x->P | y->Q`) means that *when the guard* `B` is *true* then *either* `x` or `y` may be chosen;
otherwise if `B` is false then *only* `y` may be chosen.

```
COUNT (N=3)     = COUNT[0],
COUNT[i:0..N]   = ( when(i<N) inc->COUNT[i+1]
                  | when(i>0) dec->COUNT[i-1]
                  ).
```



Java

Syntax resembles C++; semantics resembles Smalltalk:

- Strongly-typed, concurrent, *"pure" object-oriented*
- Single-inheritance but *multiple subtyping*
- Automatic *garbage collection*

Innovation in support for network applications:

- *Standard APIs* for concurrency, network interaction
- Classes can be *dynamically loaded* over network
- *Security model* protects clients from malicious objects

Java applications do not have to be installed by users

Threads

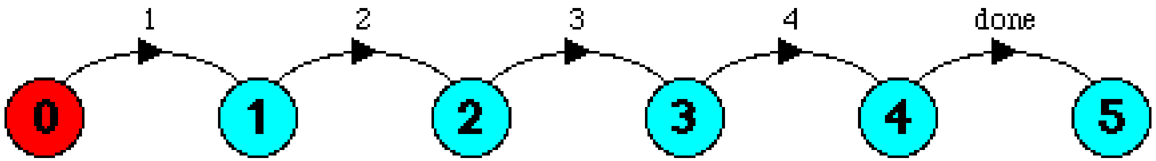
A Java Thread has a *run method* defining its behaviour:

```
class SimpleThread extends Thread {
  public SimpleThread(String str) {
    super(str);            // Call Thread constructor
  }
  public void run() {        // What the thread does
    for (int i=0; i<5; i++) {
      System.out.println(i + " " + getName());
      try { sleep((int)(Math.random()*1000));
      } catch (InterruptedException e) { } }
    System.out.println("DONE! " + getName());
  }
}
```

SimpleThread FSP

SimpleThread can be modelled as a single, sequential, finite state process:

```
Simple = ([1]->[2]->[3]->[4]-> done-> STOP).
```



Or, more generically:

```
const N = 5
Simple          = Print[1],
Print[n:1..N]   = ( when(n<N) [n] -> Print[n+1]
                  | when(n==N) done -> STOP).
```

Multiple Threads ...

A Thread's *run method is never called directly* but is executed when the Thread is *started*:

```
class TwoThreadsDemo {
  public static void main (String[] args) {
    // Instantiate a Thread, then start it:
    new SimpleThread("Jamaica").start();
    new SimpleThread("Fiji").start();
  }
}
```

Running the TwoThreadsDemo

In this implementation of Java, the execution of the two threads is *interleaved*.

☞ This is *not guaranteed* for all implementations!

✎ *Why are the output lines never garbled?*

E.g.

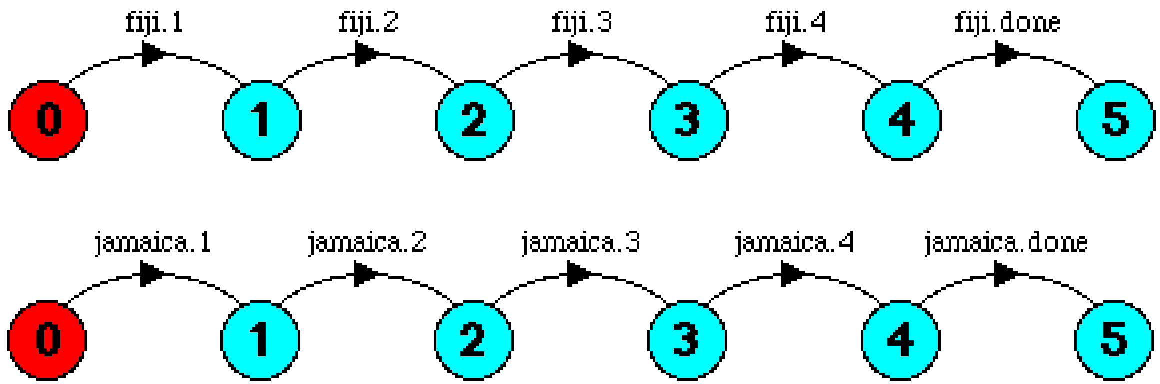
```
0 Ja0 Fimajiica
...
```

```
0 Jamaica
0 Fiji
1 Jamaica
1 Fiji
2 Fiji
3 Fiji
2 Jamaica
4 Fiji
3 Jamaica
DONE! Fiji
4 Jamaica
DONE! Jamaica
```

FSP — Concurrency

We can *relabel* the transitions of Simple and concurrently *compose* two copies of it:

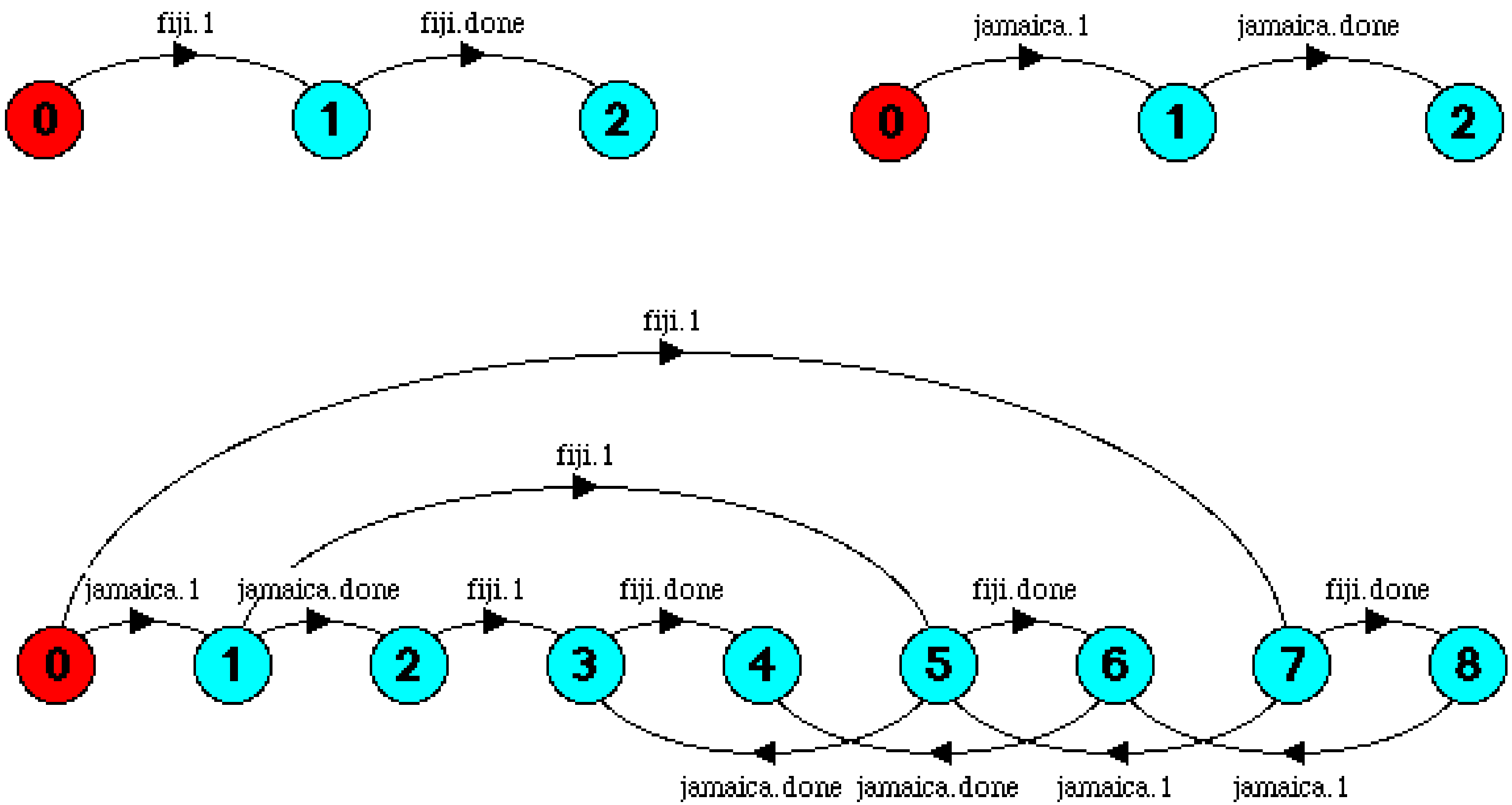
```
||TwoThreadsDemo =     ( fiji:Simple
                       || jamaica:Simple
                       ).
```



✎ *What are all the possible traces?*

FSP — Composition

If we restrict ourselves to two steps, the composition will have nine states:



java.lang.Thread (creation)

A Java thread can either *inherit* from java.lang.Thread, or *contain* a Runnable object:

```
public class java.lang.Thread
  extends java.lang.Object
  implements java.lang.Runnable
{
  public Thread();
  public Thread(Runnable target);
  public Thread(Runnable target, String name);
  public Thread(String name);
...
```

java.lang.Thread (methods)

A thread must be created, and then *started:*

```
...
  public void run();
  public synchronized void start();
  public static void sleep(long millis)
                throws InterruptedException;
  public static void yield();
  public final String getName();
...
}
```

NB: suspend(), resume() and stop() are now deprecated!

java.lang.Runnable

```
public interface java.lang.Runnable
{
  public abstract void run();
}
```

Since Java does not support multiple inheritance, it is impossible to inherit from both Thread and another class.

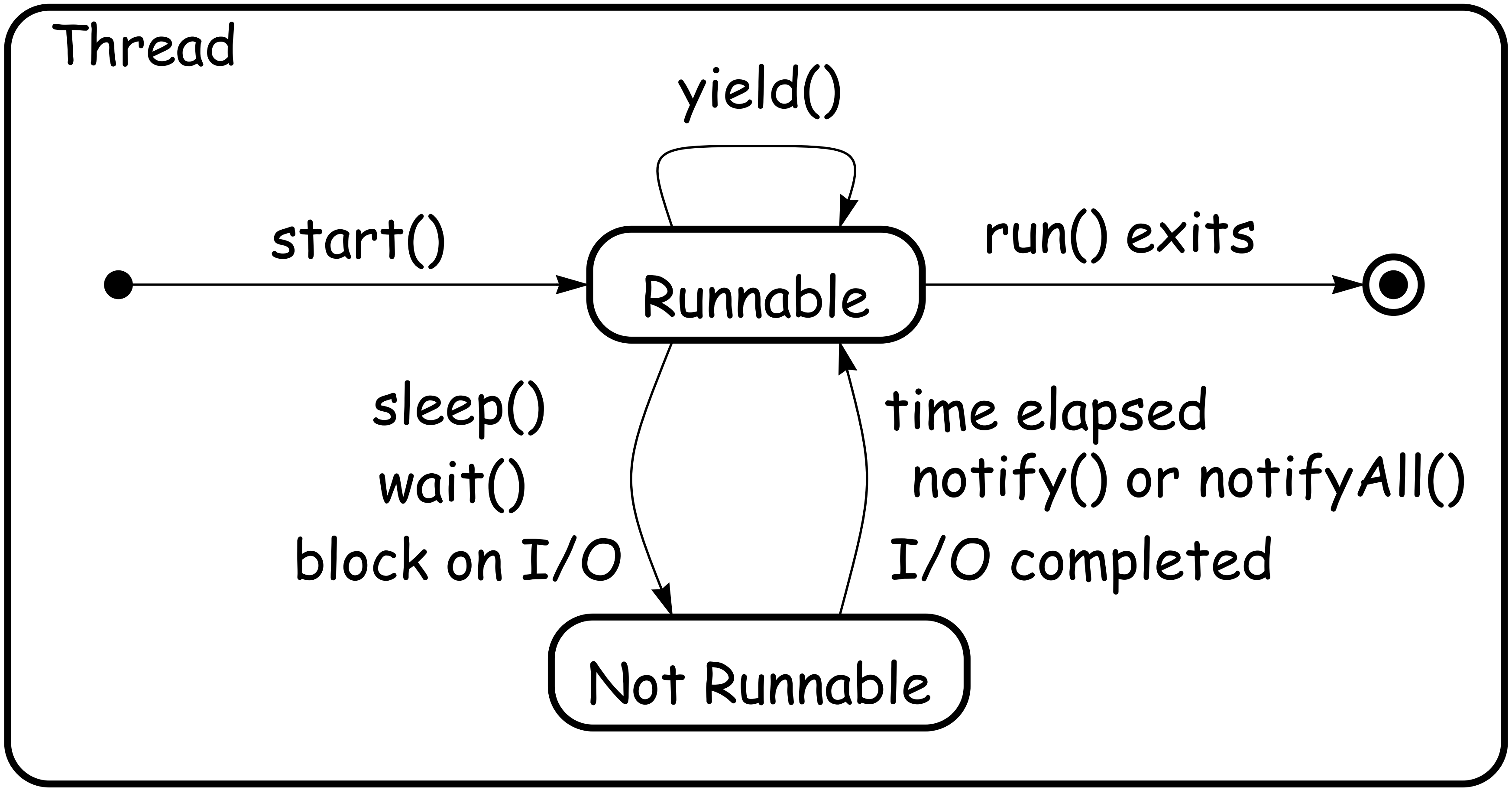
Instead, simply define:

```
class MyStuff extends UsefulStuff
  implements Runnable ...
```

and instantiate:

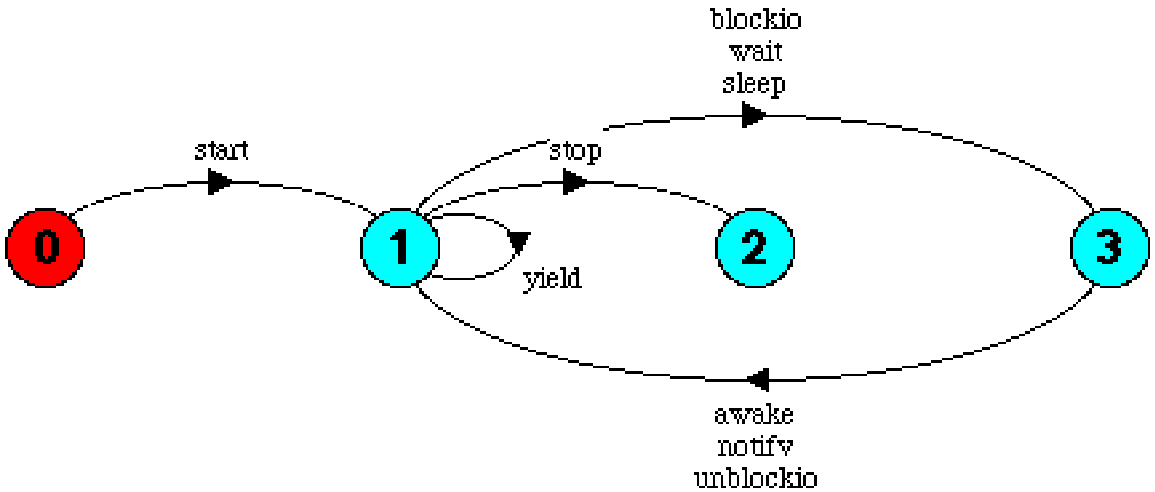
```
new Thread(new MyStuff);
```

Transitions between Thread States



LTS for Threads

```
Thread = ( start -> Runnable ),
Runnable =
   ( yield -> Runnable
   | {sleep, wait, blockio} -> NotRunnable
   | stop -> STOP ),
NotRunnable =
   ( {awake, notify, unblockio} -> Runnable ).
```



Creating Threads

This Clock applet uses a thread to update the time:

```
public class Clock
  extends java.applet.Applet
  implements Runnable
{
  Thread clockThread = null;
  public void start() {
    if (clockThread == null) {
      clockThread = new Thread(this, "Clock");
      clockThread.start();
    }
  } ...
```

Creating Threads ...

```
...
public void run() {
  // stops when clockThread is set to null
  while(Thread.currentThread()==clockThread){
    repaint();
    try { clockThread.sleep(1000); }
    catch (InterruptedException e){ }
  }
}
...
```

... And stopping them

```
...
  public void paint(Graphics g) {
    Date now = new Date();
    g.drawString(now.getHours()
      + ":" + now.getMinutes()
      + ":" + now.getSeconds(), 5, 10);
  }
  // When the applet stops, stop its thread
  public void stop() { clockThread = null; }
}
```

Be careful — Applets and Threads have strangely similar interfaces!

Synchronization

Without synchronization, an arbitrary number of threads may run at any time within the methods of an object.

- ☞ Class invariant may not hold when a method starts!
- ☞ So can't guarantee any post-condition!

A solution: consider a method to be a *critical section* which locks access to the object while it is running.

This works as long as methods cooperate in locking and unlocking access!

Synchronized methods

Either: declare an entire method to be *synchronized* with other synchronized methods of an object:

```
public class PrintStream extends FilterOutputStream {
    ...
    public synchronized void println(String s);
    public synchronized void println(char c);
    ...
}
```

Synchronized blocks

Or: synchronize an individual block within a method with respect to some object:

```
public Object aMethod() {
  // unsynchronized code
  ...
  synchronized(resource) { // Lock resource
    ...
  } // unlock resource
  ...
}
```

wait and notify

Synchronization must sometimes be interrupted:

```
class Slot implements Buffer {
  private Object slotVal;
  public synchronized void put(Object val) {
    while (slotVal != null) { // wait till empty
      try { wait(); }
      catch (InterruptedException e) { }
    }
    slotVal = val;
    notifyAll();
    return;
  } ...
}
```

java.lang.Object

wait() and notify() are methods rather than keywords:

```
public class java.lang.Object
{
  ...
  public final void wait()
    throws InterruptedException;
  public final void notify();
  public final void notifyAll();
  ...
}
```

What you should know!

- *What are finite state processes?*
- *How are they used to model concurrency?*
- *What are traces, and what do they model?*
- *How can the same FSP have multiple traces?*
- *How do you create a new thread in Java?*
- *What states can a Java thread be in?*
  How can it change state?
- *What is the* `Runnable` *interface good for?*
- *What is a critical section?*
- *When should you declare a method to be* `synchronized`*?*

Can you answer these questions?

- *How would you specify an FSP that repeatedly performs* `hello`*, but may stop at any time?*
- *How many states and how many possible traces does the full* `TwoThreadsDemo` *FSP have?*
- *When should you inherit from* `Thread`*?*
- *How can concurrency invalidate a class invariant?*
- *What happens if you call* `wait` *or* `notify` *outside a synchronized method or block?*
- *When is it better to use synchronized blocks rather than methods?*
- *How would you model synchronization in FSP?*

3. Safety and Synchronization

Overview

- Modelling interaction in FSP
- Safety — synchronizing *critical sections*
  - Locking for atomicity
  - The busy-wait mutual exclusion protocol
- Conditional synchronization
  - Slots in FSP
  - wait(), notify() and notifyAll()
  - Slots in Java

Modelling interaction — shared actions

Actions that are common between two processes are *shared* and can be used to model *process interaction:*

- ❑ Unshared actions may be *arbitrarily interleaved*
- ❑ Shared actions occur *simultaneously* for all participants

```
MAKER    = ( make -> ready -> MAKER ).
USER     = ( ready -> use -> USER ).

||MAKER_USER = ( MAKER || USER ).
```

✎ *What are the states of the LTS?*

✎ *The traces?*

Modelling interaction — handshake

A *handshake* is an action that signals acknowledgement

```
MAKERv2   = ( make -> ready -> used -> MAKERv2 ).
USERv2    = ( ready -> use -> used -> USERv2 ).

||MAKER_USERv2 = ( MAKERv2 || USERv2 ).
```

✎ *What are the states and traces of the LTS?*

Modelling interaction — multiple processes

Shared actions can be used to *synchronize multiple processes:*

```
MAKE_A   = ( makeA -> ready -> used -> MAKE_A ).
MAKE_B   = ( makeB -> ready -> used -> MAKE_B ).
ASSEMBLE = ( ready -> assemble -> used -> ASSEMBLE ).

||FACTORY = ( MAKE_A || MAKE_B || ASSEMBLE ).
```

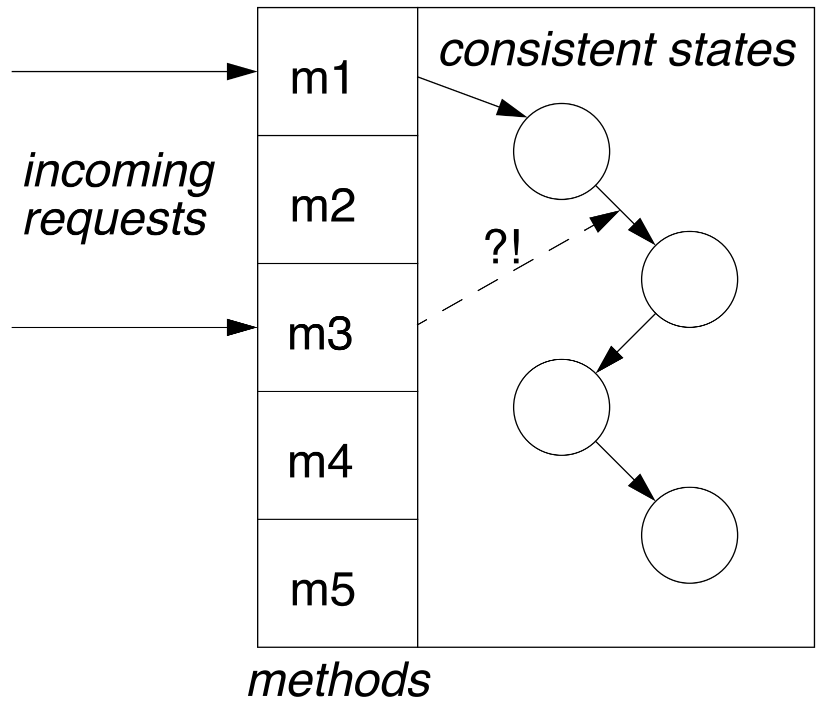
✎ *What are the states and traces of the LTS?*

Safety problems

Objects must only be accessed when they are in a consistent state, formalized by a *class invariant.*

Each method *assumes* the class invariant holds when it starts, and it *re-establishes* it when done.

If methods interleave arbitrarily, an inconsistent state may be accessed, and the object may be left in a "dirty" state.



Where shared resources are updated may be a *critical section*.

Atomicity and interference

Consider the two processes:

$$\{\ x = 0\ \}$$

```
AInc:     x := x+1
BInc:     x := x+1
```

$$\{\ x = ?\ \}$$

✎ *How can these processes interfere?*

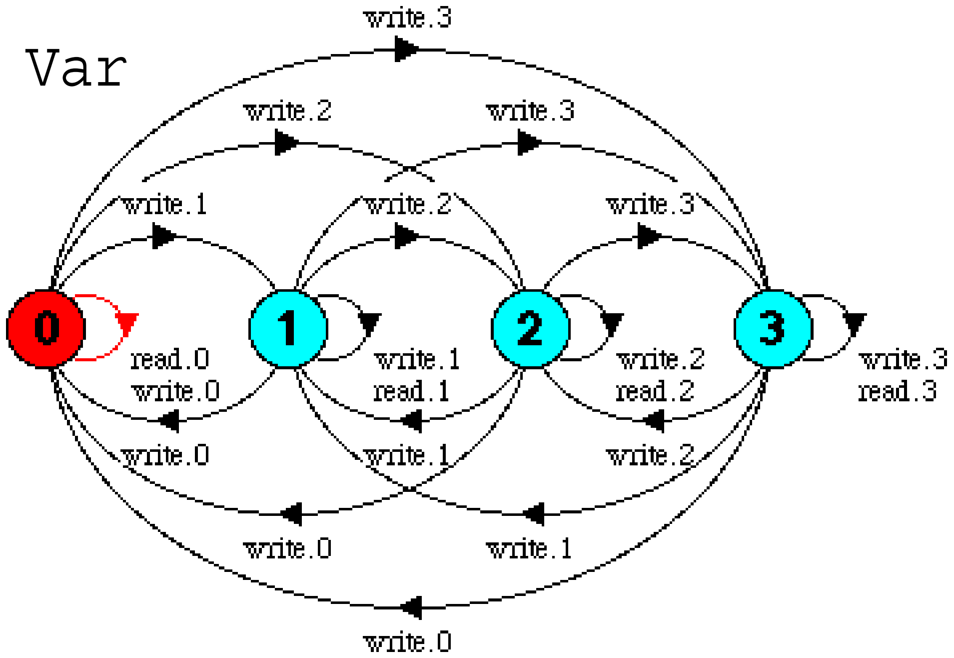
Atomic actions

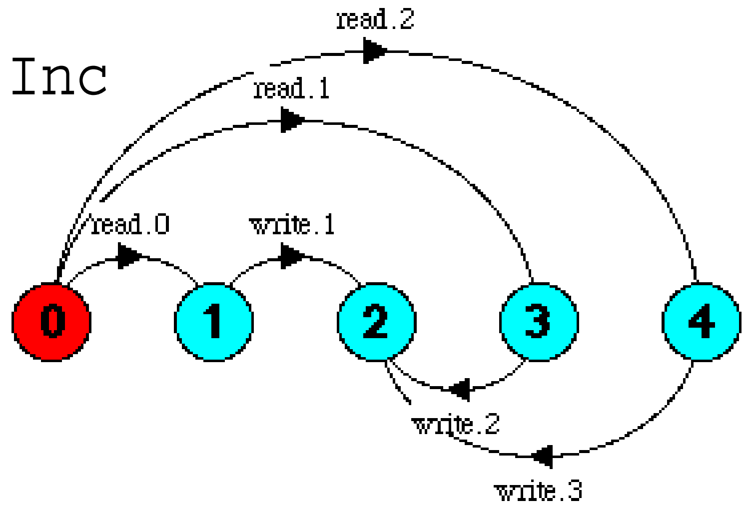
Individual reads and writes may be atomic actions:

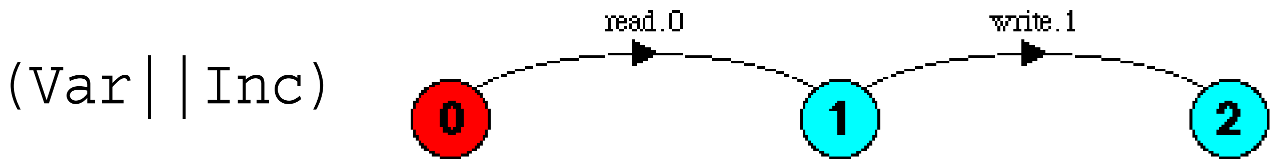
```
const N = 3
range T = 0..N
Var = Var[0],
Var[u:T] = ( read[u]        -> Var[u]
           | write[v:T]     -> Var[v]).
set VarAlpha = { read[T], write[T] }

Inc = (   read[v:0..N-1]
      ->  write[v+1]
      ->  STOP           )    +VarAlpha.
```

Sequential behaviour

A single sequential thread requires no synchronization:

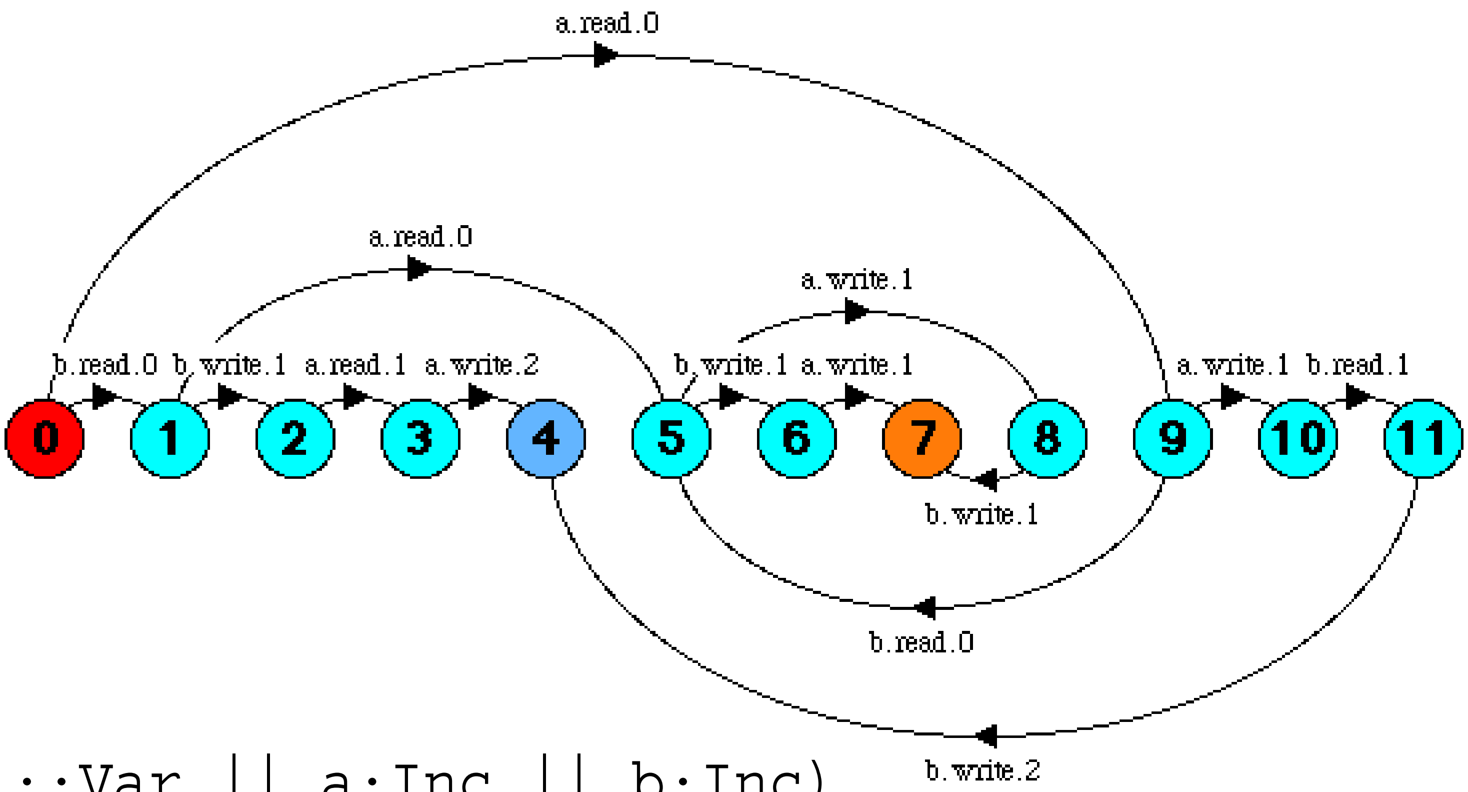






Concurrent behaviour

Without synchronization, concurrent threads may interfere:

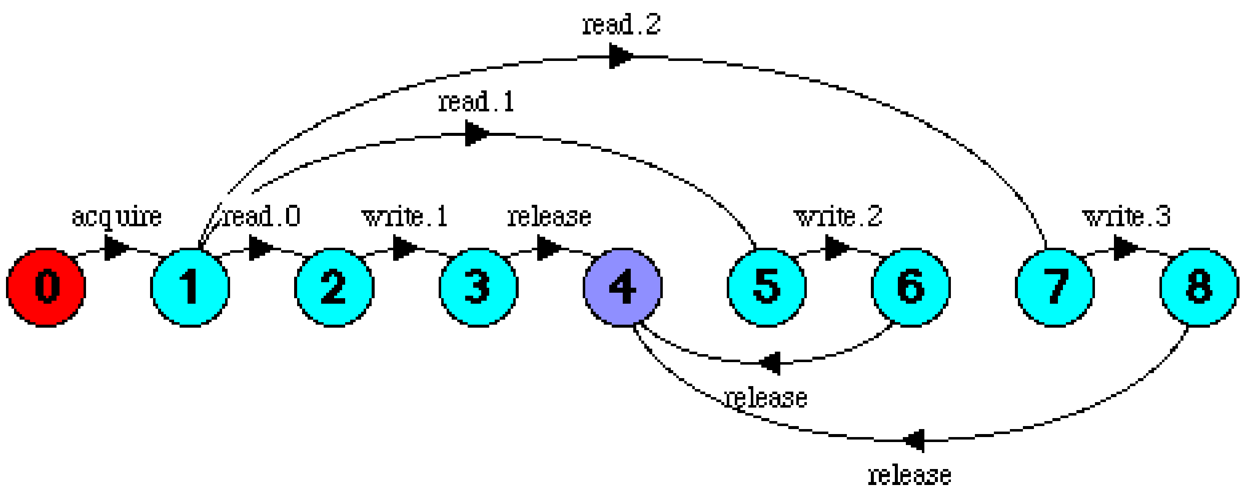



```
({a,b}::Var || a:Inc || b:Inc)
```

Locking

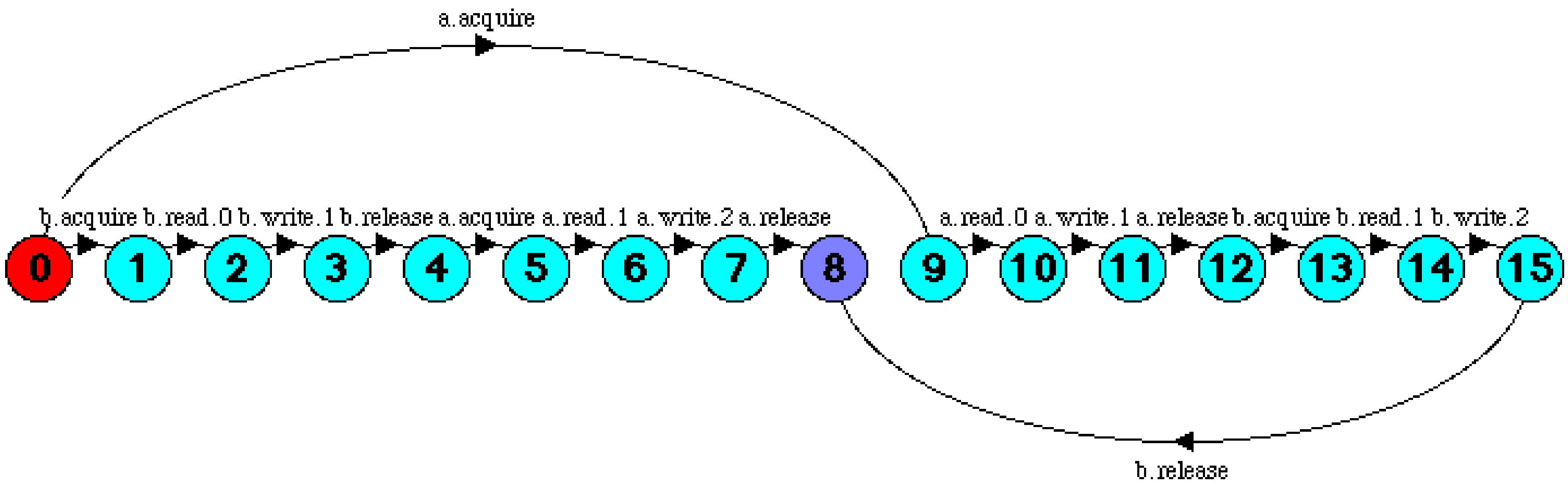
Locks are used to make a critical section atomic:

```
LOCK = ( acquire -> release -> LOCK ).
INC  =   (    acquire
         ->   read[v:0..N-1]
         ->   write[v+1]
         ->   release
         ->   STOP           )           +VarAlpha.
```



Synchronization

Processes can synchronize critical sections by sharing a lock:



`({a,b}::VAR||{a,b}::LOCK||a:INC||b:INC)`

Synchronization in Java

Java Threads also synchronize using locks:

```
synchronized T m() {
  // method body
}
```

is just convenient syntax for:

```
T m() {
  synchronized (this) {
    // method body
  }
}
```

Every object has a lock, and Threads *may* use them to synchronize with each other.

Busy-Wait Mutual Exclusion Protocol

P1 sets `enter1 := true` when it wants to enter its CS, but sets `turn := "P2"` to *yield priority* to P2:

```
process P1
   loop
      enter1 := true
      turn := "P2"
      while enter2 and
               turn = "P2"
         do skip
      Critical Section
      enter1 := false
      Non-critical Section
   end
end
```

```
process P2
   loop
      enter2 := true
      turn := "P1"
      while enter1 and
               turn = "P1"
         do skip
      Critical Section
      enter2 := false
      Non-critical Section
   end
end
```

✎ *Is this protocol correct? Is it fair? Deadlock-free?*

Atomic read and write

We can model integer and boolean variables as processes with *atomic read and write actions:*

```
range T = 1..2

Var = Var[1],
Var[u:T] =
    ( read[u]           -> Var[u]
    | write[v:T]        -> Var[v]).

set Bool = {true,false}

BOOL(Init='false) = BOOL[Init],
BOOL[b:Bool] =
    ( is[b]             -> BOOL[b]
    | setTo[x:Bool]     -> BOOL[x]).
```

Modelling the busy-wait protocol

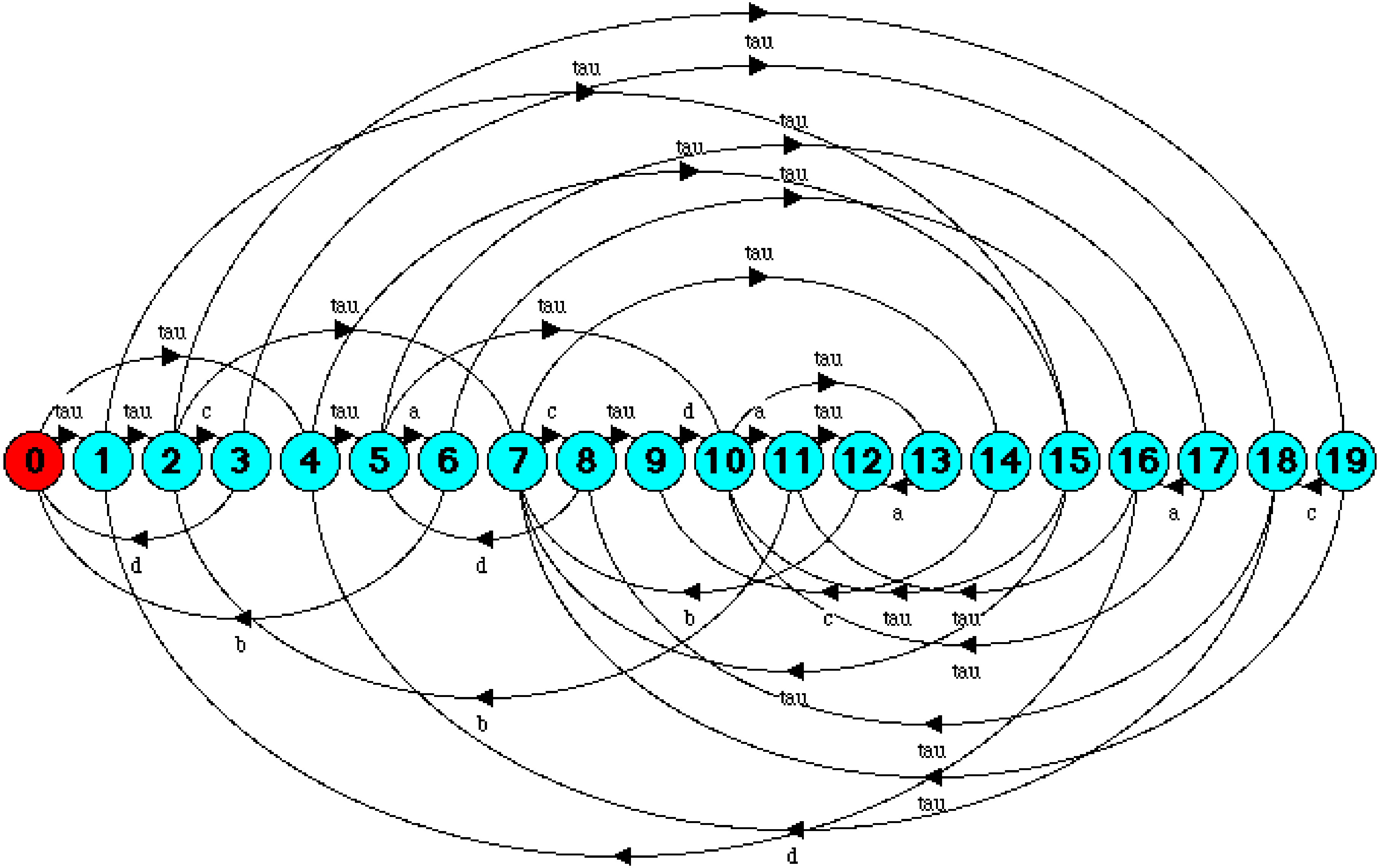
Each process performs two actions in its CS:

```
P1 = ( enter1.setTo['true]
   -> turn.write[2]
   -> Gd1),
Gd1 =
   ( enter2.is['false] -> CS1
   | enter2.is['true] ->
      ( turn.read[1] -> CS1
      | turn.read[2] -> Gd1)),
CS1 = ( a -> b
   -> enter1.setTo['false]
   -> P1).
```

```
P2 = ( enter2.setTo['true]
   -> turn.write[1]
   -> Gd2),
Gd2 =
   ( enter1.is['false] -> CS2
   | enter1.is['true] ->
      ( turn.read[2] -> CS2
      | turn.read[1] -> Gd2)),
CS2 = ( c -> d
   -> enter2.setTo['false]
   -> P2).
```

```
||Test = (enter1:BOOL||enter2:BOOL||turn:Var||P1||P2)@{a,b,c,d}.
```

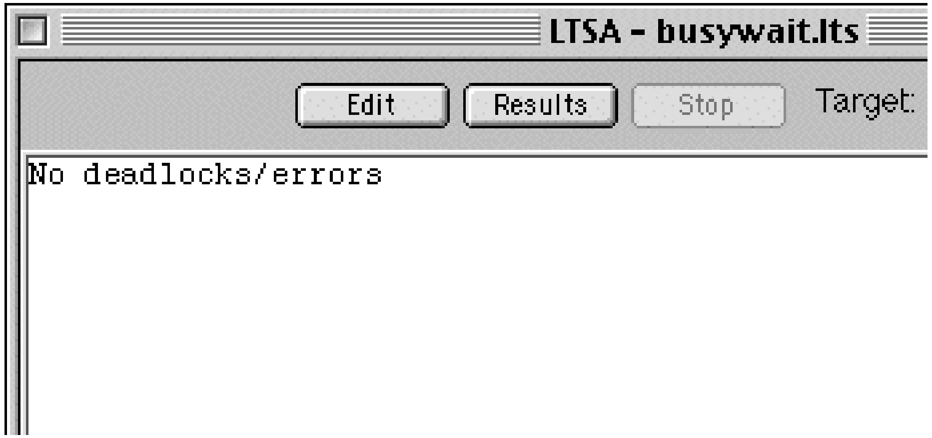
Busy-wait composition



Checking for errors

We can check for errors by composing our system with an agent that moves to the `ERROR` state if atomicity is violated:

```
Ok = ( a -> ( c -> ERROR | b -> Ok )
     | c -> ( a -> ERROR | d -> Ok )).
```



✎ *What happens if we break the protocol?*

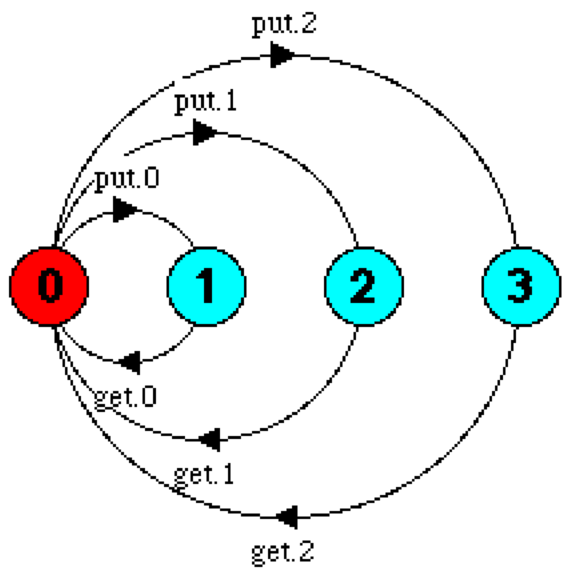
Conditional synchronization

A lock *delays* an acquire request if it is already locked:

```
LOCK = ( acquire -> release -> LOCK ).
```

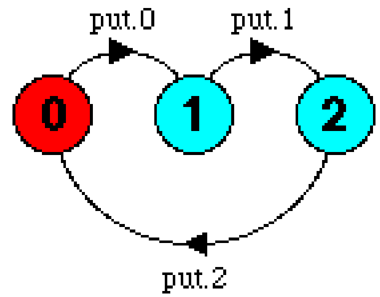
Similarly, a one-slot buffer delays a `put` request if it is *full* and delays a `get` request if it is *empty:*

```
const N = 2
Slot = ( put[v:0..N]
         -> get[v]
         -> Slot ).
```

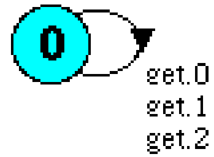


Producer/Consumer composition

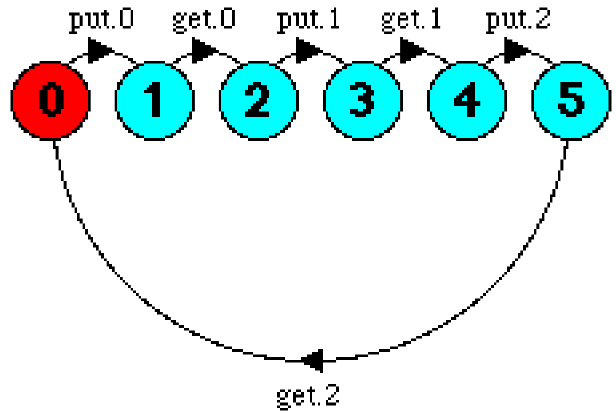
```
Producer = ( put[0]
           -> put[1]
           -> put[2]
           -> Producer).
```




```
Consumer = ( get[x:0..N]
           -> Consumer ).
```




```
||Chain =  ( Producer
           ||Slot
           ||Consumer )
```



Wait and notify

A Java object whose methods are all synchronized behaves like a monitor

Within a synchronized method or block:

- `wait()` suspends the current thread, *releasing the lock*
- `notify()` wakes up *one thread waiting on that object*
- `notifyAll()` wakes up *all* threads waiting on that object

Outside of a synchronized block, `wait()` and `notify()` will raise an `IllegalMonitorStateException`

*Always use notifyAll() unless you are **sure** it doesn't matter which thread you wake up!*

Slot (put)

```
class Slot implements Buffer {
  private Object slotVal;

  public synchronized void put(Object val) {
    while (slotVal != null) {
      try { wait(); } // become NotRunnable
      catch (InterruptedException e) { }
    }
    slotVal = val;
    notifyAll(); // make waiting threads Runnable
    return;
  }
...
```

Slot (get)

```
...
  public synchronized Object get() {
    Object rval;
    while (slotVal == null) {
      try { wait(); }
      catch (InterruptedException e) { }
    }
    rval = slotVal;
    slotVal = null;
    notifyAll();
    return rval;
  }
}
```

Producer in Java

The Producer puts `_count` *messages to the slot:*

```
class Producer extends Thread {
   protected int _count;
   protected Buffer _slot;
   Producer(String name,
      Buffer slot, int count) {
      super(name);
      _slot = slot;
      _count = count;
   }

   public void run() {
      int i;
      for (i=1;i<=_count;i++) {
         this.action(i);
      }
   }
```

```
   protected void action(int n) {
      String message;
      message = this.getName() + "("
         + String.valueOf(n) + ")";
      _slot.put(message);
      System.out.println(getName()
         + " put " + message);
   }
}
```

Consumer in Java

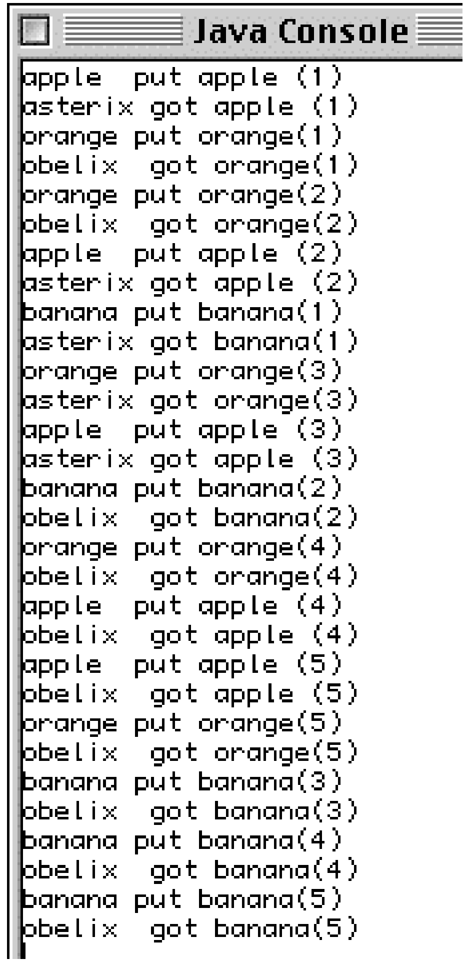
... and the Consumer gets them:

```
class Consumer extends Producer { // code reuse only!
   Consumer(String name, Buffer slot, int count) {
      super(name, slot, count);
   }
   protected void action(int n) {
      String message;
      message = (String) _slot.get();
      System.out.println(getName() + " got " + message);
   }
}
```

Composing Producers and Consumers

Multiple producers and consumers may *share* the buffer:

```
public static void main(String args[]) {
   Buffer slot = new Slot();
   new Producer("apple ", slot, count).start();
   new Producer("orange", slot, count).start();
   new Producer("banana", slot, count).start();

   new Consumer("asterix", slot, count).start();
   new Consumer("obelix ", slot, 2*count).start();
}
```



What you should know!

- How do you model *interaction* with FSP?
- What is a *critical section*? What is critical about it?
- Why don't *sequential programs* need synchronization?
- How do *locks* address safety problems?
- What *primitives* do you need to implement the busy-wait mutex protocol?
- How can you use FSP to check for *safety violations*?
- What happens if you call `wait` or `notify` *outside* a synchronized method or block?
- When is it safe to use `notifyAll()`?

Can you answer these questions?

- ✎ What is an example of an *invariant* that might be violated by interfering, concurrent threads?
- ✎ What constitute *atomic actions in Java*?
- ✎ Can you ensure *safety* in concurrent programs *without using locks*?
- ✎ When should you use `synchronize(this)` rather than `synchronize(someObject)`?
- ✎ Is the *busy-wait* mutex protocol *fair*? *Deadlock-free*?
- ✎ How would you implement a *Lock* class *in Java*?
- ✎ Why is the Java Slot class so much more *complex* than the FSP Slot specification?

4. Safety Patterns

Overview

- Immutability:
  - ☞ *avoid* safety problems by avoiding state changes
- Full Synchronization:
  - ☞ *dynamically* ensure exclusive access
- Partial Synchronization:
  - ☞ restrict synchronization to *"critical sections"*
- Containment:
  - ☞ *structurally* ensure exclusive access

Idioms, Patterns and Architectural Styles

*Idioms, patterns and architectural styles express **best practice** in resolving common design problems.*

Idioms

> *"an implementation technique"*

Design patterns

> *"a commonly-recurring structure of communicating components that solves a general design problem within a particular context"*

Architectural patterns

> *"a fundamental structural organization schema for software systems"*

Pattern: Immutable classes

Intent: *Bypass safety issues by not changing an object's state after creation.*

Applicability

- When *objects represent values* of simple ADTs
  - ☞ colours (java.awt.Color), numbers (java.lang.Integer)
- When classes can be separated into *mutable and immutable versions*
  - ☞ java.lang.String vs. java.lang.StringBuffer
- When *updating by copying is cheap*
  - ☞ "hello" + " " + "world" → "hello world"
- When *multiple instances* can represent the *same value*
  - ☞ i.e., two copies of 712 represent the same integer

Immutability variants

Variants

Stateless methods

- methods that do not access an object's state do not need to be `synchronized` (can be declared `static`)
- any temporary state should be local to the method

Stateless objects

- an object whose "state" is *dynamically* computed needs no synchronization!

"Hardening"

- object becomes immutable after a mutable phase
- expose to concurrent threads only *after* hardening

Immutable classes — design steps

Declare a class with instance variables that are never changed after construction.

```
class Relay {        // helper for some Server class
  private final Server server_;

  Relay(Server s) {     // blank finals must be
    server_ = s;        // initialized in all
  }                     // constructors

  void doIt() {
    server_.doIt();
  }
}
```

Design steps ...

- Especially if the class represents an immutable data abstraction (such as `String`), consider *overriding* `Object.`*`equals`* and `Object.`*`hashCode`*.

- Consider writing *methods that generate new objects* of this class.
(e.g., String concatenation)

- Consider declaring the class as *`final`*.

- If only some variables are immutable, use synchronization or other techniques for the methods that are not stateless.

Pattern: Fully Synchronized Objects

Intent: *Maintain consistency by **fully synchronizing all methods**. At most one method will run at any point in time.*

Applicability

- You want to *eliminate all possible* read/write and write/write *conflicts*, regardless of the context in which it the object is used.
- All methods can *run to completion* without waits, retries, or infinite loops.
- You *do not need* to use instances in *a layered design* in which other objects control synchronization of this class.

Applicability ...

- You can *avoid or deal with liveness failures*, by:
  - Exploiting partial immutability
  - Removing synchronization for accessors
  - Removing synchronization in invocations
  - Arranging per-method concurrency
  - ...

Full Synchronization — design steps

- Declare *all methods* as `synchronized`

  - ☞ *Do not allow any direct access to state* (i.e, no `public` instance variables; no methods that return references to instance variables).

  - ☞ Constructors cannot be marked as `synchronized` in Java. *Use a synchronized block* in case a constructor passes `this` to multiple threads.

  - ☞ Methods that access `static` variables must either do so via `static synchronized` methods or within blocks of the form `synchronized(getClass()) { ... }`.

Design steps ...

- Ensure that every `public` method exits leaving the object in a consistent state, *even if it exits via an exception*.
- Keep methods short so they can *atomically run to completion*.

Design steps ...

- State-dependent actions must rely on *balking*:
  - *Return failure* (i.e., exception) to client if preconditions fail
  - If the precondition does not depend on state (e.g., just on the arguments), then *check outside synchronized code*
  - Provide *public accessor methods* so that clients can check conditions before making a request

Example: a BalkingBoundedCounter

```
public class BalkingBoundedCounter {
   protected long count_ = BoundedCounter.MIN; // between MIN and MAX
   public synchronized long value() { return count_; }
   public synchronized void inc()
      throws CannotIncrementException {
      if (count_ >= BoundedCounter.MAX)           // if pre fails
         throw new CannotIncrementException();   // throw exception
      else
         ++count_;
   }
   public synchronized void dec() ... { ... }   // analogous
}
```

✎ *What safety problems could arise if this class were not fully synchronized?*

Example: an ExpandableArray

A simplified variant of java.util.Vector:

```
import java.util.NoSuchElementException;
public class ExpandableArray {
   protected Object[] data_;                 // the elements
   protected int size_;                      // the number of slots used
   public ExpandableArray(int cap) {
      data_ = new Object[cap];               // reserve some space
      size_ = 0;
   }
   public synchronized int size() { return size_; }
   public synchronized Object at(int i) // array indexing
      throws NoSuchElementException {
      if (i < 0 || i >= size_ )
         throw new NoSuchElementException();
      else
         return data_[i];
   } ...
```

Example ...

```
public synchronized void append(Object x) {     // add at end
   if (size_ >= data_.length) {                  // need a bigger array
      Object[] olddata = data_;                  // so increase ~50%
      data_ = new Object[3 * (size_ + 1) / 2];
      for (int i = 0; i < size_; ++i)
         data_[i] = olddata[i];
   }
   data_[size_++] = x;
}
public synchronized void removeLast()
   throws NoSuchElementException {
   if (size_ == 0)
         throw new NoSuchElementException();
   else
      data_[--size_] = null;
}
}
```

Bundling Atomicity

- Consider adding synchronized methods that perform *sequences of actions as a single atomic action*

```
public interface Procedure { // apply an operation to an object
   public void apply(Object x);
}
public class ExpandableArrayV2 extends ExpandableArray {
   public ExpandableArrayV2(int cap) { super(cap); }
   public synchronized void applyToAll(Procedure p) {
      for (int i = 0; i < size_; ++i) {
         p.apply(data_[i]);
      }
   }
}
```

✎ *What possible liveness problems does this introduce?*

Using inner classes

Use *anonymous inner classes* to pass procedures:

```
class ExpandableArrayUser {
   public static void main(String[] args) {
      ExpandableArrayV2 a = new ExpandableArrayV2(100);
      for (int i = 0; i < 100; ++i)                   // fill it up
         a.append(new Integer(i));
      a.applyToAll(new Procedure () {                // print all elements
                     public void apply(Object x) {
                        System.out.println(x);
                     }
                  }
      )
   }
}
```

NB: Any variables shared with the host object must be declared `final` *(immutable).*

Pattern: Partial Synchronization

Intent: *Reduce overhead by synchronizing only within "critical sections".*

Applicability

- When objects have *both mutable and immutable* instance variables.
- When methods can be split into a *"critical section"* that deals with mutable state and a part that does not.

Partial Synchronization — design steps

- Fully *synchronize all methods*
- *Remove* synchronization for *accessors to atomic or immutable* values
- *Remove* synchronization for methods that access mutable state through a single other, *already synchronized* method
- *Replace* method synchronization by block synchronization for methods where access to mutable state is restricted to a *single, critical section*

Example: LinkedCells

```
public class LinkedCell {
   protected double value_;              // NB: doubles are not atomic!
   protected final LinkedCell next_;     // fixed

   public LinkedCell (double val, LinkedCell next) {
      value_ = val; next_ = next;
   }

   public synchronized double value() { return value_; }
   public synchronized void setValue(double v) { value_ = v; }

   public LinkedCell next() {            // not synched!
      return next_;                      // next_ is immutable
   }
   ...
```

Example ...

```
   ...
   public double sum() {          // add up all element values
      double v = value();         // get via synchronized accessor
      if (next() != null)
         v += next().sum();
      return v;
   }

   public boolean includes(double x) {      // search for x
      synchronized(this) {                  // synch to access value
         if (value_ == x) return true;
      }
      if (next() == null) return false;
      else return next().includes(x);
   }
}
```

Pattern: Containment

Intent: *Achieve safety by avoiding shared variables. Unsynchronized objects are "contained" inside other objects that have at most one thread active at a time.*

Applicability

- There is *no need for shared access* to the embedded objects.
- The embedded objects can be conceptualized as *exclusively held resources*.

Applicability ...

- Embedded objects *must be structured as islands* — communication-closed sets of objects reachable only from a single unique reference.

  They cannot contain methods that reveal their identities to other objects.

- You are *willing to hand-check designs* for compliance.

- You can deal with or *avoid indefinite postponements* or deadlocks in cases where host objects must transiently acquire multiple resources.

Contained Objects — design steps

- Define the *interface* for the outer host object.
  - ☞ The host could be, e.g., an Adaptor, a Composite, or a Proxy, that provides synchronized access to an *existing, unsynchronized class*
- Ensure that the host is *either* fully synchronized, or is in turn a contained object.

Design steps ...

- Define instances variables that are *unique* references to the contained objects.
  - ☞ Make sure that these references *cannot leak* outside the host!
  - ☞ Establish *policies* and *implementations* that ensure that acquired references are really unique!
  - ☞ Consider methods to *duplicate* or *clone contained objects*, to ensure that copies are unique

Managed Ownership

- Model contained objects as *physical resources*:
  - If you have one, then *you can do something* that you couldn't do otherwise.
  - If you have one, then *no one else has it*.
  - If you give one to someone else, then *you no longer have it*.
  - If you *destroy* one, then *no one will ever have it*.

Managed Ownership ...

- If contained objects can be passed among hosts, define a *transfer protocol*.
  - ☞ Hosts should be able to *acquire*, *give*, *take*, *exchange* and *forget* resources
  - ☞ Consider using a *dedicated class* to manage transfer

A minimal transfer protocol class

A simple buffer for transferring objects between threads:

```
public class ResourceVariable {
   protected Object ref_;
   public ResourceVariable(Object res) { ref_ = res; }
   public synchronized Object resource() { return ref_; }
   public synchronized Object exchange(Object r) {
      Object old = ref_;
      ref_ = r;
      return old;
   }
}
```

✎ *What are the weaknesses of this class?*

✎ *How would you fix them?*

What you should know!

- Why are immutable classes inherently safe?
- Why doesn't a "relay" need to be synchronized?
- What is "balking"? When should a method balk?
- When is partial synchronization better than full synchronization?
- How does containment avoid the need for synchronization?

Can you answer these questions?

- When is it all right to declare only *some* methods as `synchronized`?
- When is an *inner class* better than an explicitly named class?
- What could happen if any of the ExpandableArray methods were *not synchronized*?
- What *liveness problems* can *full synchronization* introduce?
- Why is it a *bad idea* to have *two separate critical sections* in a single method?
- Does it matter if a *contained* object is *synchronized* or not?

5. Liveness and Deadlock

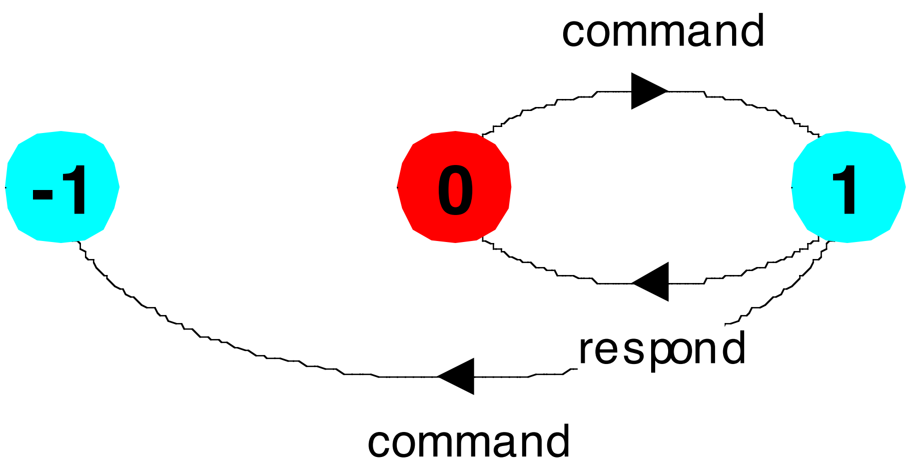
Overview

- Safety revisited
  - `ERROR` conditions
- Liveness
  - Progress Properties
- Deadlock
  - The Dining Philosophers problem
  - Detecting and avoiding deadlock

Safety revisited

*A safety property asserts that **nothing bad happens***

`ERROR` process (-1) to detect erroneous behaviour



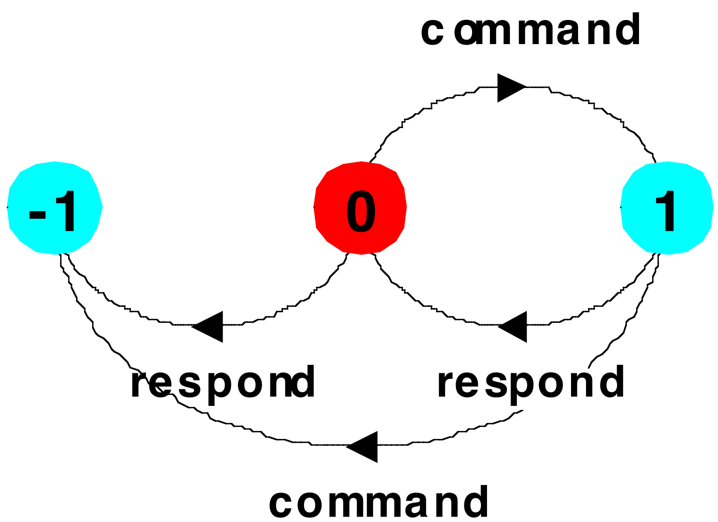

```
ACTUATOR
   = (command -> ACTION),
ACTION
   = (respond -> ACTUATOR
     |command -> ERROR).
```

`Trace to ERROR: command command`

Safety — property specification

`ERROR` conditions state what is *not* required

In complex systems, it is usually better to specify directly what *is* required.




```
property SAFE_ACTUATOR
   = (command
      -> respond
      -> SAFE_ACTUATOR
      ).
```

```
Trace to property violation in SAFE_ACTUATOR:
   command command
```

Safety properties

*A safety property P defines a **deterministic** process that asserts that any trace including actions in the alphabet of P is accepted by P.*

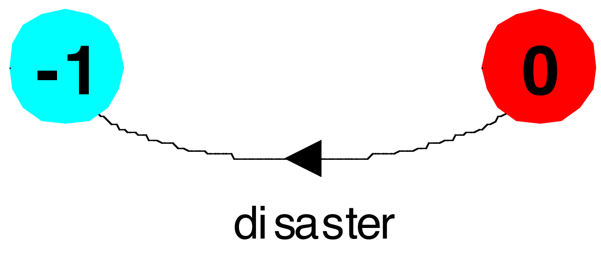
Transparency of safety properties:

- Since all actions in the alphabet of a property are eligible choices, *composing* a property with a set of processes *does not affect their correct behaviour*.
- If a behaviour can occur which *violates* the safety property, then `ERROR` is reachable.

Properties must be deterministic to be transparent.

Safety properties

How can we specify that some action, disaster, never occurs?




```
property CALM = STOP + {disaster}.
```

A safety property must be specified so as to include *all the acceptable, valid behaviours* in its alphabet.

Liveness

*A liveness property asserts that something good **eventually** happens.*

*A progress property asserts that it is **always** the case that an action is **eventually** executed.*

Progress is the opposite of *starvation*, the name given to a concurrent programming situation in which an action is never executed.

Liveness Problems

A program may be "safe", yet suffer from various kinds of liveness problems:

Starvation: (AKA "indefinite postponement")

- ❑ The system as a whole makes progress, but some individual processes don't

Dormancy:

- ❑ A waiting process fails to be woken up

Premature termination:

- ❑ A process is killed before it should be

Deadlock:

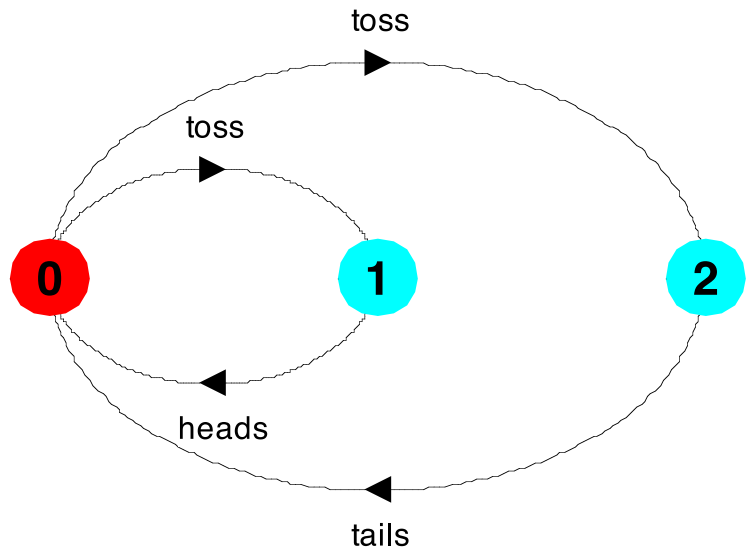
- ❑ Two or more processes are blocked, each waiting for resources held by another

Progress properties — fair choice

Fair Choice: If a choice over a set of transitions is executed infinitely often, then *every* transition in the set will be executed infinitely often.

If a coin were tossed an infinite number of times, we would expect that both heads and tails would each be chosen infinitely often.

This assumes fair choice !




```
COIN =  (toss->heads->COIN
        |toss->tails->COIN).
```

Progress properties

```
progress P = {a1,a2..an}
```

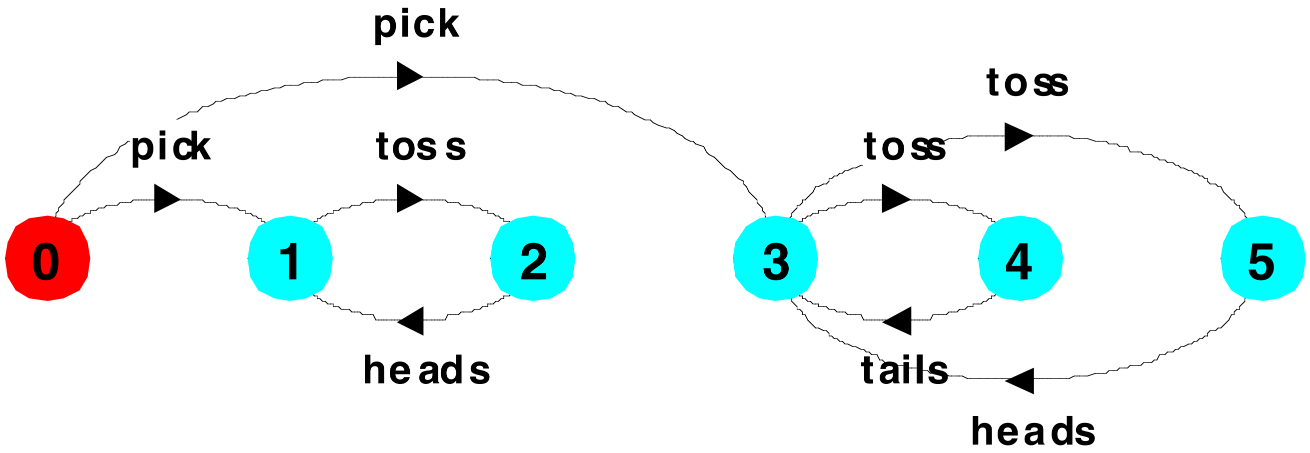
asserts that in an infinite execution of a target system, *at least one* of the actions `a1,a2...an` will be executed *infinitely often*.

COIN system:

```
        progress HEADS = {heads}
        progress TAILS = {tails}

...

No progress violations detected.
```

Progress properties

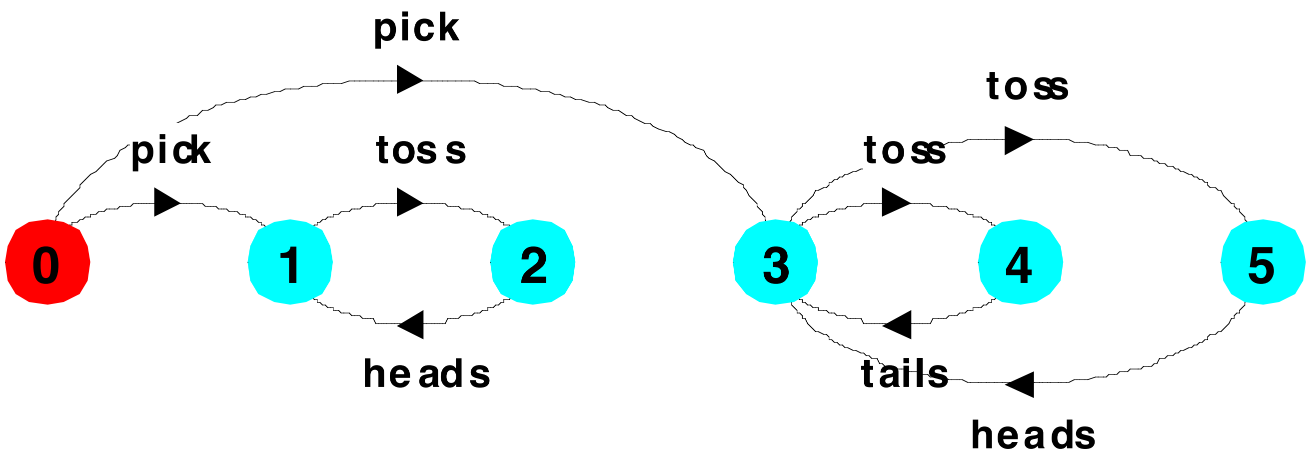
Suppose we have both a normal coin and a *trick coin*




```
TWOCOIN   = (pick->COIN|pick->TRICK),
TRICK     = (toss->heads->TRICK),
COIN      = (toss->heads->COIN|toss->tails->COIN).
progress HEADS = {heads}
progress TAILS = {tails}
progress HEADSorTAILS = {heads,tails}
```

Progress analysis

```
Progress violation: TAILS
Trace to terminal set of states: pick
Actions in terminal set: {toss, heads}
```



A *__terminal set__* *of states is one in which every state is mutually reachable but no transitions leads out of the set.*

The terminal set {1, 2} violates progress property `TAILS`

Deadlock

Four necessary and sufficient conditions:

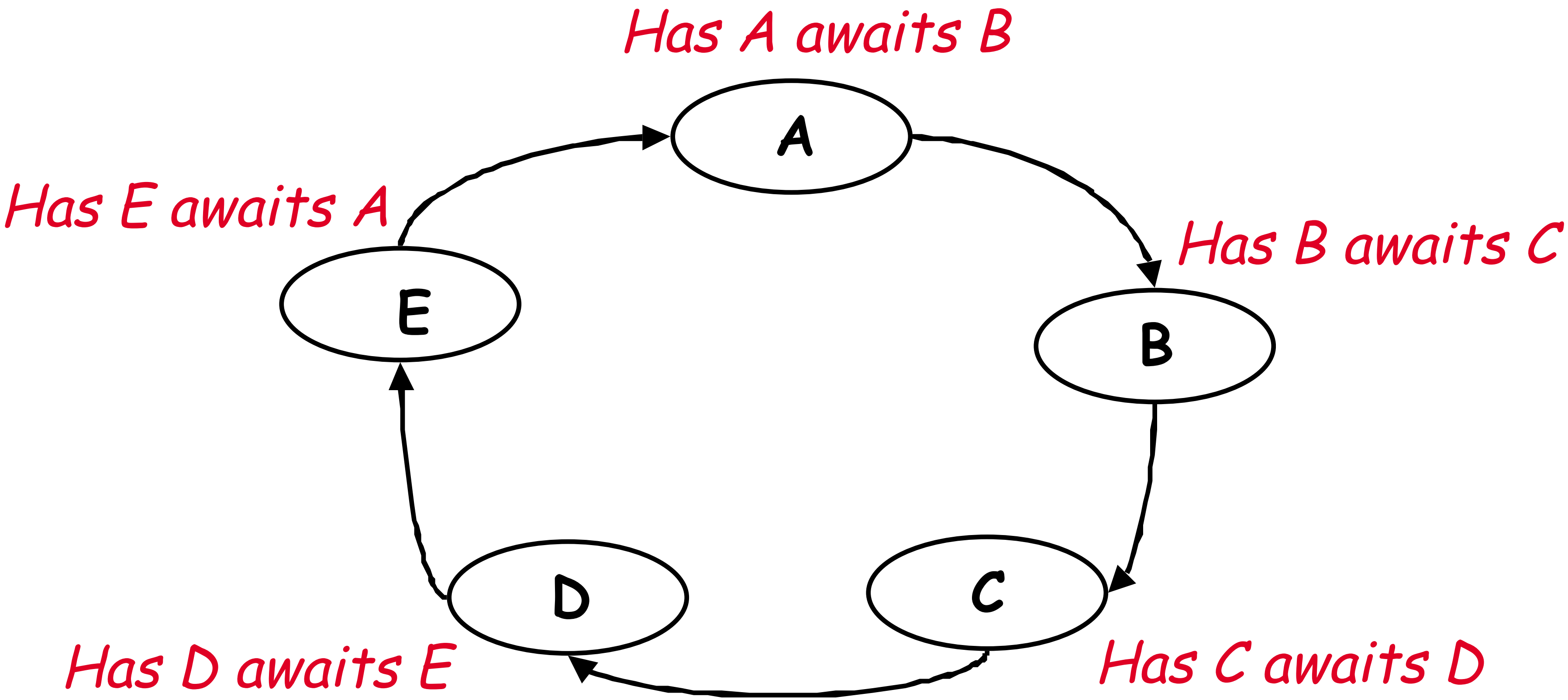
Serially reusable resources: the deadlocked processes *share resources* under *mutual exclusion*.

Incremental acquisition: processes *hold on to acquired resources* while *waiting* to obtain additional ones.

No pre-emption: once acquired by a process, *resources cannot be pre-empted* but only released voluntarily.

Wait-for cycle: a *cycle* of processes exists in which *each process holds a resource which its successor in the cycle is waiting to acquire*.

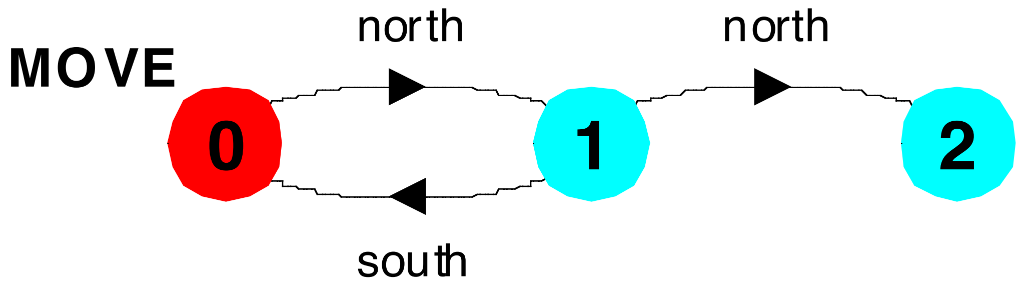
Waits-for cycle



Deadlock analysis - primitive processes

- A deadlocked state is one with *no outgoing transitions*
- In FSP: `STOP` process

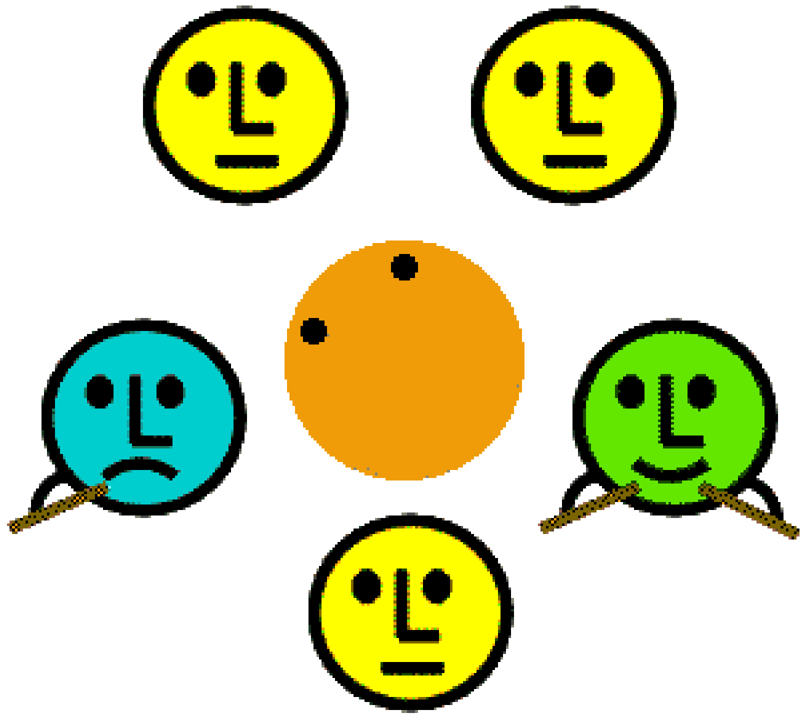
MOVE = (north->(south->MOVE|north->STOP)).




```
Progress violation for actions: {north, south}
Trace to terminal set of states: north north
Actions in terminal set: {}
```

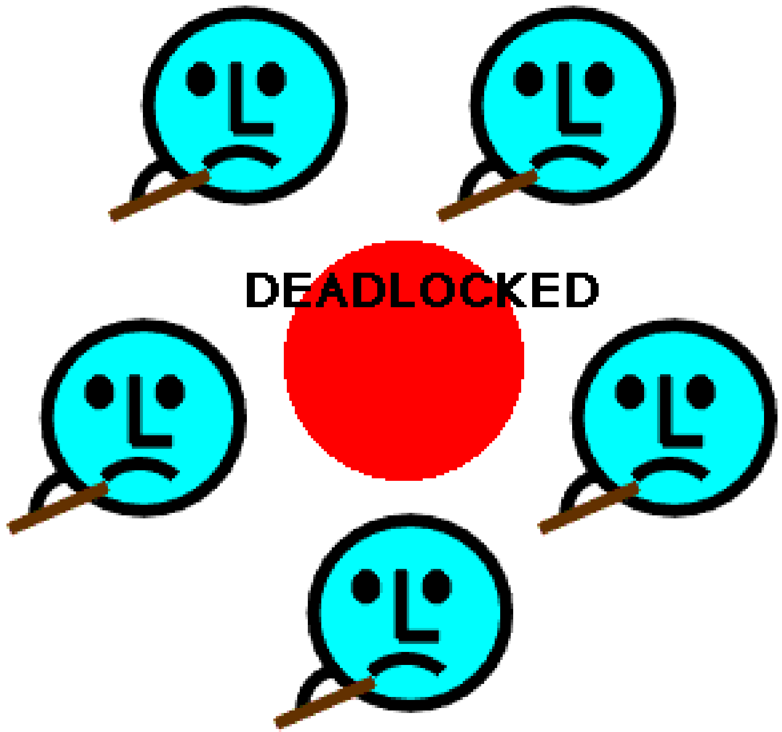
The Dining Philosophers Problem

- Philosophers alternate between *thinking* and *eating*.
- A philosopher needs *two forks* to eat.
- No two philosophers may hold the same fork simultaneously.
- There must be *no deadlock* and *no starvation*.
- Want efficient behaviour under absence of contention.



Deadlocked diners

A deadlock occurs if a *waits-for cycle* arises in which each philosopher grabs one fork and waits for the other.



Dining Philosophers, Safety and Liveness

Dining Philosophers illustrate many classical safety and liveness issues:

Mutual Exclusion	Each fork can be used by one philosopher at a time
Condition synchronization	A philosopher needs two forks to eat
Shared variable communication	Philosophers share forks ...
Message-based communication	... or they can pass forks to each other

Dining Philosophers ...

Busy-waiting	A philosopher can poll for forks ...
Blocked waiting	... or can sleep till woken by a neighbour
Livelock	All philosophers can grab the left fork and busy-wait for the right ...
Deadlock	... or grab the left one and wait (sleep) for the right
Starvation	A philosopher may starve if the left and right neighbours are always faster at grabbing the forks

Modeling Dining Philosophers

```
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].left,phil[((i-1)+N)%N].right}::FORK).
```

✎ *Is this system safe? Is it live?*

Dining Philosophers Analysis

```
Trace to terminal set of states:
  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
Actions in terminal set: {}
```

No further progress is possible due to the waits-for cycle

Eliminating Deadlock

There are two fundamentally different approaches to eliminating deadlock.

Deadlock detection:

- *Repeatedly check for waits-for cycles.* When detected, choose a victim and force it to release its resources.
  - ☞ Common in transactional systems; the victim should "roll-back" and try again

Deadlock avoidance:

- Design the system so that *a waits-for cycle cannot possibly arise*.

Dining Philosopher Solutions

There are countless solutions to the Dining Philosophers problem that use various concurrent programming styles and patterns, and offer varying degrees of liveness guarantees:

Number the forks

- ❑ Philosophers grab the lowest numbered fork first.

Philosophers queue to sit down

- ❑ allow no more than four at a time to sit

✎ *Do these solutions avoid deadlock?*

✎ *What about starvation?*

✎ *Are they "fair"?*

What you should know!

- ✎ What are *safety properties*? How are they modelled in FSP?
- ✎ What *kinds of liveness problems* can occur in concurrent programs?
- ✎ Why is *progress* a liveness rather than a safety issue?
- ✎ What is *fair choice*? Why do we need it?
- ✎ What is a *terminal set* of states?
- ✎ What are *necessary and sufficient* conditions for *deadlock*?
- ✎ How can you *detect deadlock*? How can you *avoid* it?

Can you answer these questions?

- *How would you manually check a safety property?*
- *Why must safety properties be deterministic to be transparent?*
- *How would you manually check a progress property?*
- *What is the difference between starvation and deadlock?*
- *How would you manually detect a waits-for cycle?*
- *What is fairness?*

6. Liveness and Guarded Methods

Overview

- Guarded Methods
  - Checking guard conditions
  - Handling interrupts
  - Structuring notification
    - Encapsulating assignment
    - Tracking state
    - Tracking state variables
    - Delegating notifications

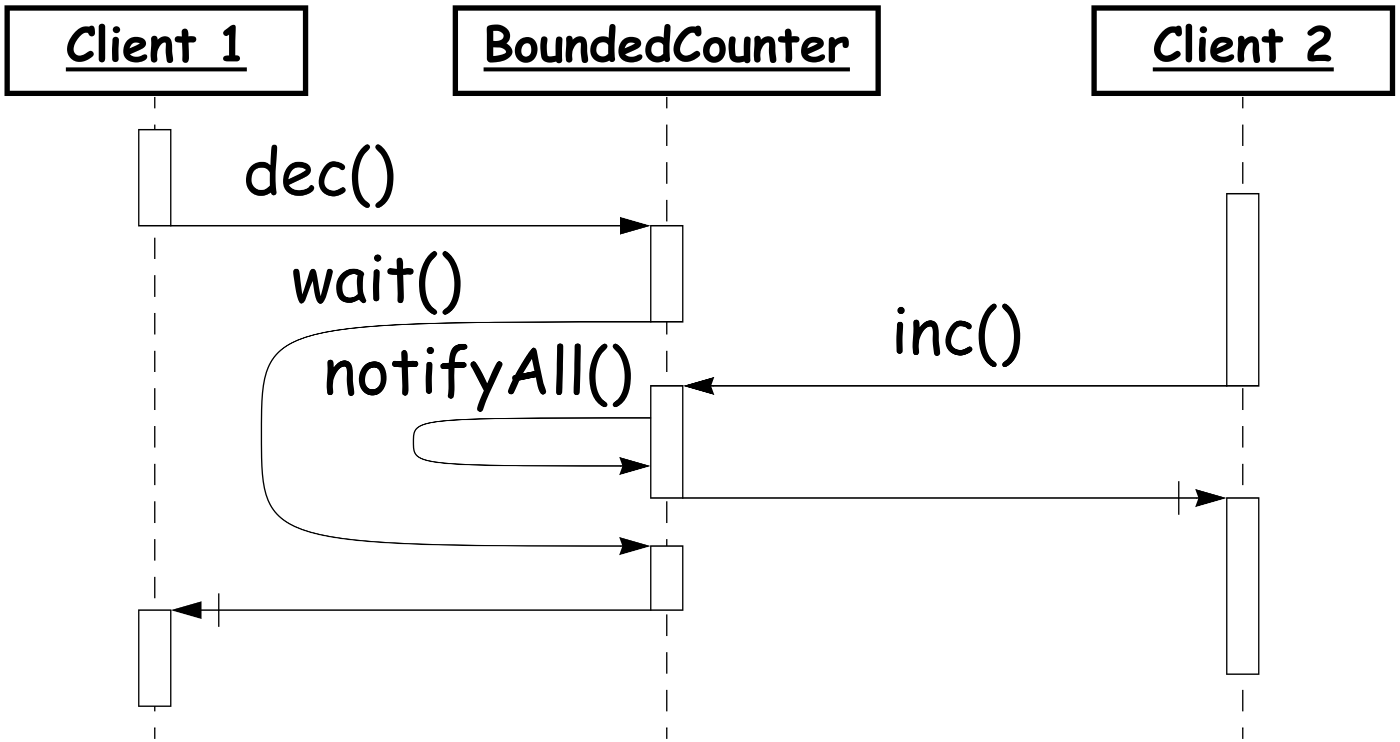
Achieving Liveness

There are various strategies and techniques to ensure liveness:

- Start with *safe design* and selectively *remove* synchronization
- Start with *live design* and selectively *add* safety
- Adopt *design patterns* that limit the need for synchronization
- Adopt standard *architectures* that avoid cyclic dependencies

Pattern: Guarded Methods

Intent: *Temporarily suspend an incoming thread when an object is not in the right state to fulfil a request, and wait for the state to change rather than balking (raising an exception).*



Guarded Methods — applicability

- Clients can *tolerate indefinite postponement*. (Otherwise, use a *balking design*.)
- You can guarantee that the *required states are eventually reached* (via other requests), or if not, that it is acceptable to block forever.
- You can arrange that *notifications occur after all relevant state changes*. (Otherwise consider a design based on a *busy-wait spin loop*.)
- You can *avoid* or cope with liveness problems due to waiting threads retaining all synchronization locks.

Applicability ...

- You can *construct computable predicates* describing the state in which actions will succeed. (Otherwise consider an *optimistic design*.)
- Conditions and actions are managed *within a single object*. (Otherwise consider a *transactional form*.)

Guarded Methods — design steps

The basic recipe is to use `wait` *in a conditional loop to block until it is safe to proceed, and use* `notifyAll` *to wake up blocked threads.*

```
public synchronized Object service() {
  while (wrong State) {
    try { wait(); }
    catch (InterruptedException e) { }
  }
  // fill request and change state ...
  notifyAll();
  return result;
}
```

Step: Separate interface from policy

- Define *interfaces* for the methods, so that classes can implement guarded methods according to different *policies*.

```
public interface BoundedCounter {
  public static final long MIN = 0;   // min value
  public static final long MAX = 10;  // max value
  public long value(); // inv't: MIN <= value() <= MAX
                       // init: value() == MIN
  public void inc();   // pre: value() < MAX
  public void dec();   // pre: value() > MIN
}
```

Step: Check guard conditions

- Define a *predicate* that precisely describes the conditions under which actions may proceed.
  (This can be encapsulated as a *helper method*.)

- Precede the conditional actions with a *guarded wait loop* of the form:

```
while (!condition)
  try { wait(); }
  catch (InterruptedException ex) { ... }
```

Optionally, encapsulate this code as a helper method.

Step: Check guard conditions ...

- If there is only *one possible condition* to check in this class (and all plausible subclasses), and notifications are issued only when the condition is true, then there is *no need to re-check* the condition after returning from `wait()`

- Ensure that the object is in a *consistent state* (*i.e., the class invariant holds*) before entering any `wait` (since wait releases the synchronization lock).

  The easiest way to do this is to perform the guards *before* taking any actions.

Step: Handle interrupts

- Establish a *policy* to deal with `InterruptedException`s. Possibilities include::
  - ☞ *Ignore interrupts* (i.e., an empty `catch` clause), which preserves safety at the possible expense of liveness.
  - ☞ *Terminate* the current thread (`stop`). This preserves safety, though brutally! *(Not recommended.)*
  - ☞ *Exit* the method, possibly raising an exception. This preserves liveness but may require the caller to take special action to preserve safety.
  - ☞ *Cleanup* and *restart*.
  - ☞ Ask for *user intervention* before proceeding.

Interrupts can be useful to signal that the guard can never become true because, for example, the collaborating threads have terminated.

Step: Signal state changes

- *Add notification code* to each method of the class that changes state in any way *that can affect the value of a guard condition*. Some options are:

  ☞ use `notifyAll` to wake up *all* threads that are blocked in waits for the host object.

…

Notify() vs notifyall()

...

- use `notify` to wake up *only one* thread (if any exist). This is best treated as an *optimization* where:
  - *all* blocked threads are necessarily waiting for conditions signalled by the *same* notifications,
  - *only one* of them can be enabled by any given notification, *and*
  - *it does not matter* which one of them becomes enabled.

- You *build your own* special-purpose notification methods using `notify` and `notifyAll`. (For example, to selectively notify threads, or to provide certain *fairness* guarantees.)

Step: Structure notifications

- Ensure that *each wait is balanced by at least one notification*. Options include:

Blanket Notifications	Place a *notification at the end of every method* that can cause any state change (i.e., assigns any instance variable). Simple and reliable, but may cause performance problems ...
Encapsulating Assignment	*Encapsulate assignment* to each variable mentioned in any guard condition *in a helper method* that performs the notification after updating the variable.

Tracking State	Only issue notifications for the *particular state changes* that could actually unblock waiting threads. May improve performance, at the cost of flexibility (i.e., subclassing becomes harder.)
Tracking State Variables	Maintain an *instance variable that represents control state*. Whenever the object changes state, invoke a helper method that re-evaluates the control state and will issue notifications if guard conditions are affected.
Delegating Notifications	Use *helper objects to maintain aspects of state* and have these helpers issue the notifications.

Encapsulating assignment

Guards and assignments are encapsulated in helper methods:

```
public class BoundedCounterV1
    implements BoundedCounter {
  protected long count_ = MIN;
  public synchronized long value() { return count_; }
  public synchronized void inc() {
    awaitIncrementable();
    setCount(count_ + 1);
  }
  public synchronized void dec() {
    awaitDecrementable();
    setCount(count_ - 1);
  }
```

```
  protected synchronized void awaitIncrementable() {
    while (count_ >= MAX)
    try { wait(); }
    catch(InterruptedException ex) {};
  }
  protected synchronized void awaitDecrementable() {
    while (count_ <= MIN)
      try { wait(); }
      catch(InterruptedException ex) { };
  }
  protected synchronized void setCount(long newValue) {
    count_ = newValue;
    notifyAll();
  }
}
```

Tracking State

*The only transitions that can possibly affect waiting threads are those that step away from logical states **top** and **bottom**:*

```
public class BoundedCounterVST
    implements BoundedCounter {
  protected long count_ = MIN; // ...
  public synchronized void inc() {
    while (count_ == MAX)
      try { wait(); }
      catch(InterruptedException ex) {};
    if (count_++ == MIN)
      notifyAll();                  // just left bottom state
  }
  ...
}
```

Tracking State Variables

```
public class BoundedCounterVSV
    implements BoundedCounter {
  static final int BOTTOM = 0; // logical states
  static final int MIDDLE = 1;
  static final int TOP    = 2;
  protected int state_ = BOTTOM; // state variable
  protected long count_ = MIN;
  public synchronized void inc() {
    while (state_ == TOP) // consult logical state
      try { wait(); }
      catch(InterruptedException ex) {};
    ++count_;                      // modify actual state
    checkState();                  // sync logical state
  } ...
```

```
...
  public synchronized void dec() { ... }
  public synchronized long value() { return count_; }

  protected synchronized void checkState() {
    int oldState = state_;
    if (count_ == MIN)        state_ = BOTTOM;
    else if (count_ == MAX)   state_ = TOP;
    else                      state_ = MIDDLE;
    if (state_ != oldState
          && (oldState == TOP
            || oldState == BOTTOM))
        notifyAll();
  }
}
```

Delegating notifications

```
public class NotifyingLong {
  private long value_;
  private Object observer_;
  public NotifyingLong(Object o, long v) {
    observer_ = o; value_ = v;
  }
  public synchronized long value() { return value_; }
  public void setValue(long v) {
    synchronized(this) { value_ = v; }
    synchronized(observer_) {
      observer_.notifyAll(); // NB: must be synched!
    }
  }
}
```

Delegating notifications ...

Notification is delegated to the helper object:

```
public class BoundedCounterVNL
    implements BoundedCounter {
  private NotifyingLong c_ =
    new NotifyingLong(this, MIN);
  public synchronized void inc() {
    while (c_.value() >= MAX)
      try { wait(); }
      catch(InterruptedException ex) {};
    c_.setValue(c_.value()+1);
  }
  ...
}
```

What you should know!

- *When can you apply the Guarded Methods pattern?*
- *When should methods recheck guard conditions after waking from a* `wait()`*?*
- *Why should you usually prefer* `notifyAll()` *to* `notify()`*?*
- *When and where should you issue notification?*
- *Why must you re-establish the class invariant before calling* `wait()`*?*
- *What should you do when you receive an* `InterruptedException`*?*
- *What is the difference between tracking state and using state-tracking variables?*

Can you answer these questions?

- ✎ *When are guarded methods better than balking?*
- ✎ *When should you use helper methods to implement guarded methods?*
- ✎ *What is the best way to structure guarded methods for a class if you would like it to be easy for others to define correctly functioning subclasses?*
- ✎ *When is the complexity of delegating notifications worthwhile?*

7. Lab session I

The lab exercises will be available on the course web page:

www.iam.unibe.ch/~scg/Teaching/CP/

8. Liveness and Asynchrony

Overview

- Asynchronous invocations
  - Simple Relays
    - Direct Invocations
    - Thread-based messages; Gateways
    - Command-based messages
  - Tail calls
  - Early replies
  - Futures

Pattern: Asynchronous Invocations

Intent: *Avoid waiting for a request to be serviced by decoupling sending from receiving.*

Applicability

- When a host object can *distribute* services amongst *multiple helper objects*.
- When an object *does not immediately need* the result of an invocation to continue doing useful work.
- When invocations that are *logically asynchronous*, regardless of whether they are coded using threads.
- During *refactoring*, when classes and methods are split in order to *increase concurrency* and *reduce liveness problems*.

Asynchronous Invocations — form

Asynchronous invocation typically looks like this:

```
class Host {
  public service() {
    pre();            // code to run before invocation
    invokeHelper();   // the invocation
    during();         // code to run in parallel
    post();           // code to run after completion
  }
}
```

Asynchronous Invocations — design steps

Consider the following issues:

Does the Host need results back from the Helper?	Not if, e.g., the Helper returns results directly to the Host's caller!
Can the Host process new requests while the Helper is running?	Might depend on the kind of request ...
Can the Host do something while the Helper is running?	i.e., in the `during()` code
Does the Host need to synchronize pre-invocation processing?	i.e., if `service()` is guarded or if `pre()` updates the Host's state

Does the Host need to synchronize post-invocation processing?	i.e., if `post()` updates the Host's state
Does post-invocation processing only depend on the Helper's result?	... or does the host have to wait for other conditions?
Is the same Helper always used?	Is a new one generated to help with each new service request?

Simple Relays — three variants

A *relay method* obtains all its functionality by delegating to the helper, without any `pre()`, `during()`, or `post()` actions.

Direct invocations: Invoke the Helper directly, but *without synchronization*

Thread-based messages: Create a *new thread* to invoke the Helper

Command-based messages: Pass the request to *another object that will run it*

Relays are commonly seen in *Adaptors*.

Variant: Direct invocations

Asynchrony is achieved by avoiding synchronization.

```
class Host {
  protected Helper helper_ = new Helper();
  public void service() {      // unsynchronized!
    invokeHelper();            // (stateless method)
  }
  protected void invokeHelper() {
    helper_.help();            // unsynchronized!
  }
}
```

The Host is free to accept other requests, while *the Host's caller must wait* for the reply.

Direct invocations ...

If `helper_` is mutable, it can be protected with an accessor:

```
class Host2 extends Host {
  protected Helper helper_ = new Helper();
  protected synchronized Helper helper() {
    return helper_;
  }
  public void service() { // unsynchronized
    helper().help();      // partially synchronized
  }
}
```

Variant: Thread-based messages

The invocation can be performed *within a new thread:*

```
protected void invokeHelper() {
  new Thread() {                     // An inner class
    final Helper h_ = helper_;      // Must be final!
    public void run() { h_.help() ; }
  }.start();
}
```

Thread-based messages ...

The cost of evaluating Helper.help() should outweigh the overhead of creating a thread!

- If the Helper is a *daemon* (loops endlessly)
- If the Helper does *I/O*
- Possibly, if *multiple* helper methods are invoked

Thread-per-message Gateways

The Host may construct a *new Helper* to service *each* request.

```
public class FileIO {
  public void writeBytes(String file, byte[] data) {
    new Thread (new FileWriter(file, data)).start();
  }
  public void readBytes(...) { ... }
}
class FileWriter implements Runnable {
  private String nm_;            // hold arguments
  private byte[] d_;
  public FileWriter(String name, byte[] data) { ... }
  public void run() { ... }      // write to file ...
}
```

Variant: Command-based messages

The Host can also put a *Command object* in a *queue* for another object that will invoke the Helper:

```
protected EventQueue q_;
protected invokeHelper() {
  q_.put(new HelperMessage(helper_));
}
```

Command-based forms are especially useful for:

- *scheduling* of helpers
- *undo* and *replay* capabilities
- transporting messages over *networks*

Tail calls

Applies when the helper method is the *last* statement of a method. Only `pre()` code is synchronized.

```
class Subject {
   protected Observer obs_ = new ...;
   protected double state_;
   public void updateState(double d) {          // not synched
      doUpdate(d);                                // synched
      sendNotification();                         // not synched
   }
   protected synchronized doUpdate(double d) {   // synched
      state_ = d;
   }
   protected void sendNotification() {          // not synched
      obs_.changeNotification(this);
   }
}
```

The host is immediately available to accept new requests

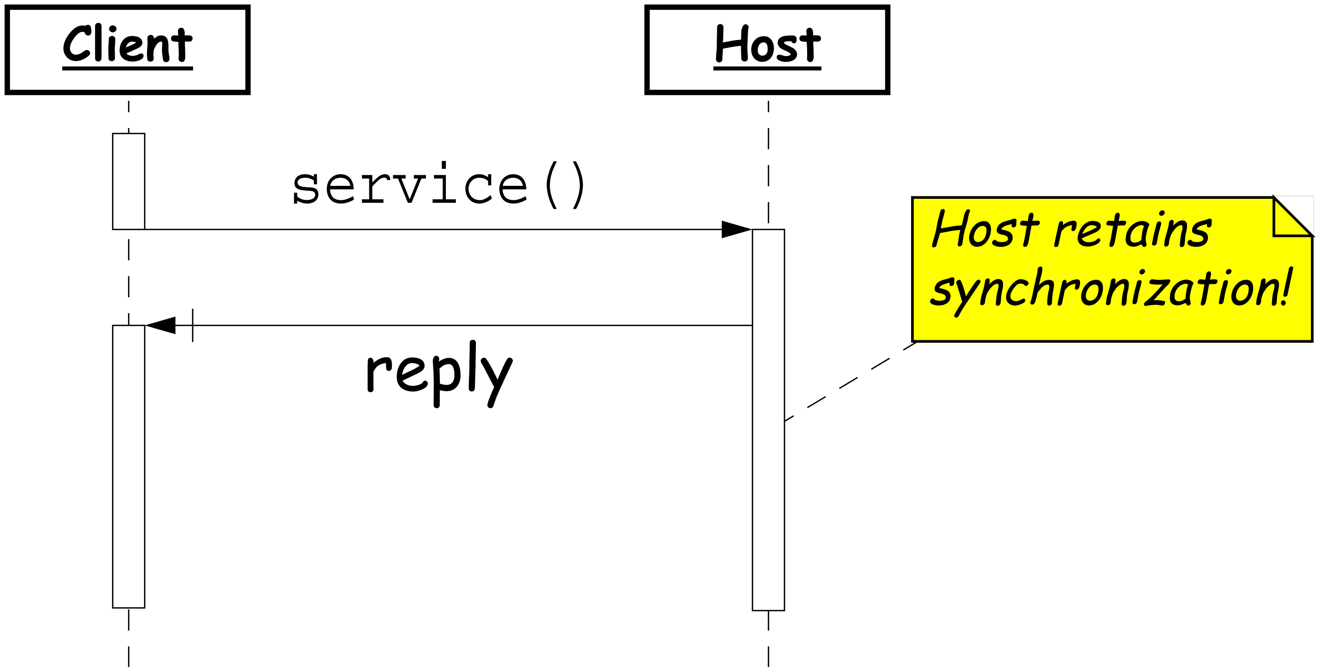
Tail calls with new threads

Alternatively, the tail call may be made in a separate thread:

```
public synchronized void updateState(double d) {
  state_ = d;
  new Thread() {
    final Observer o_ = obs_;
    public void run() {
      o_.changeNotification(Subject.this);
    }
  }.start();
}
```

Early Reply

Early reply allows a host to perform useful activities *after returning a result* to the client:

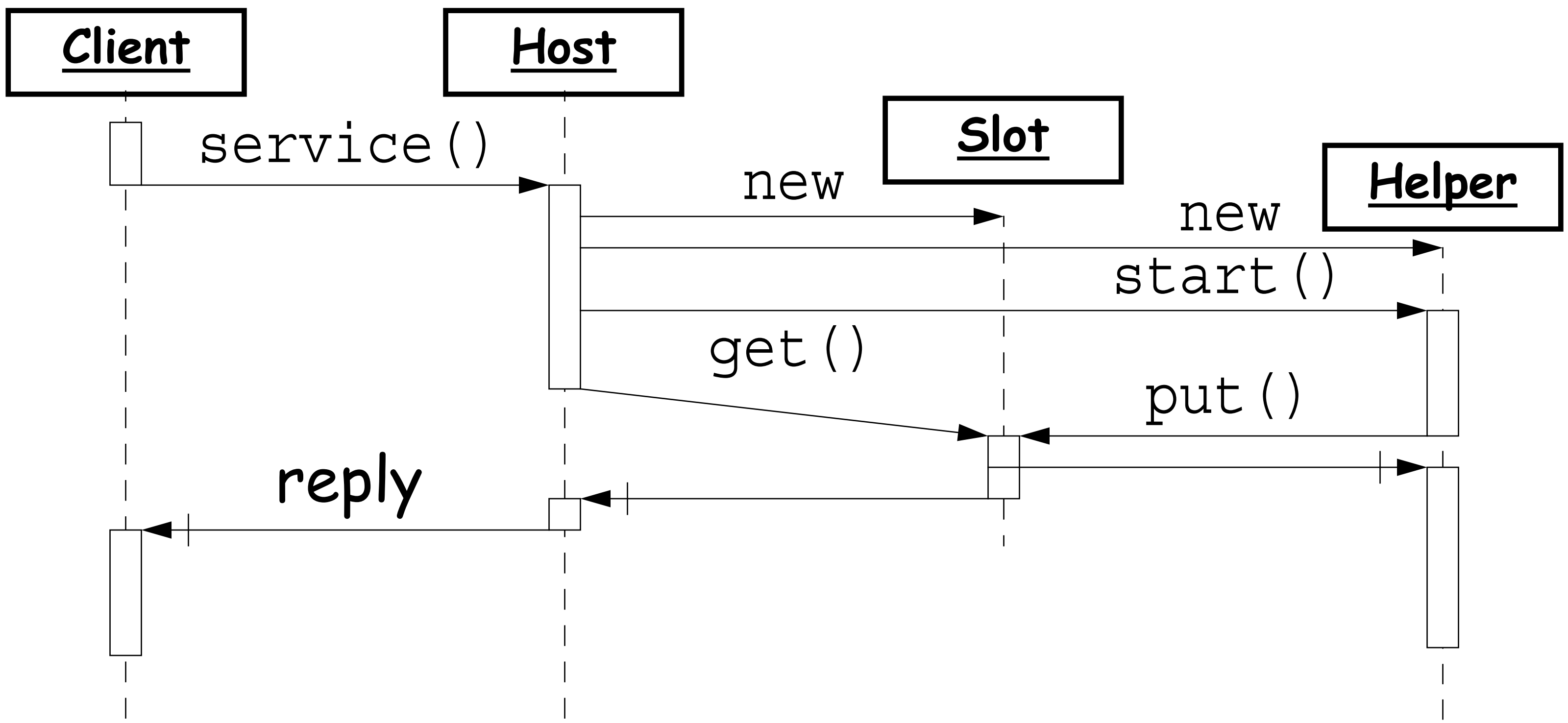


Early reply is a built-in feature in some programming languages.

It can be easily *simulated* when it is not a built-in feature.

Simulating Early Reply

A *one-slot buffer* can be used to pick up the reply from a helper thread:



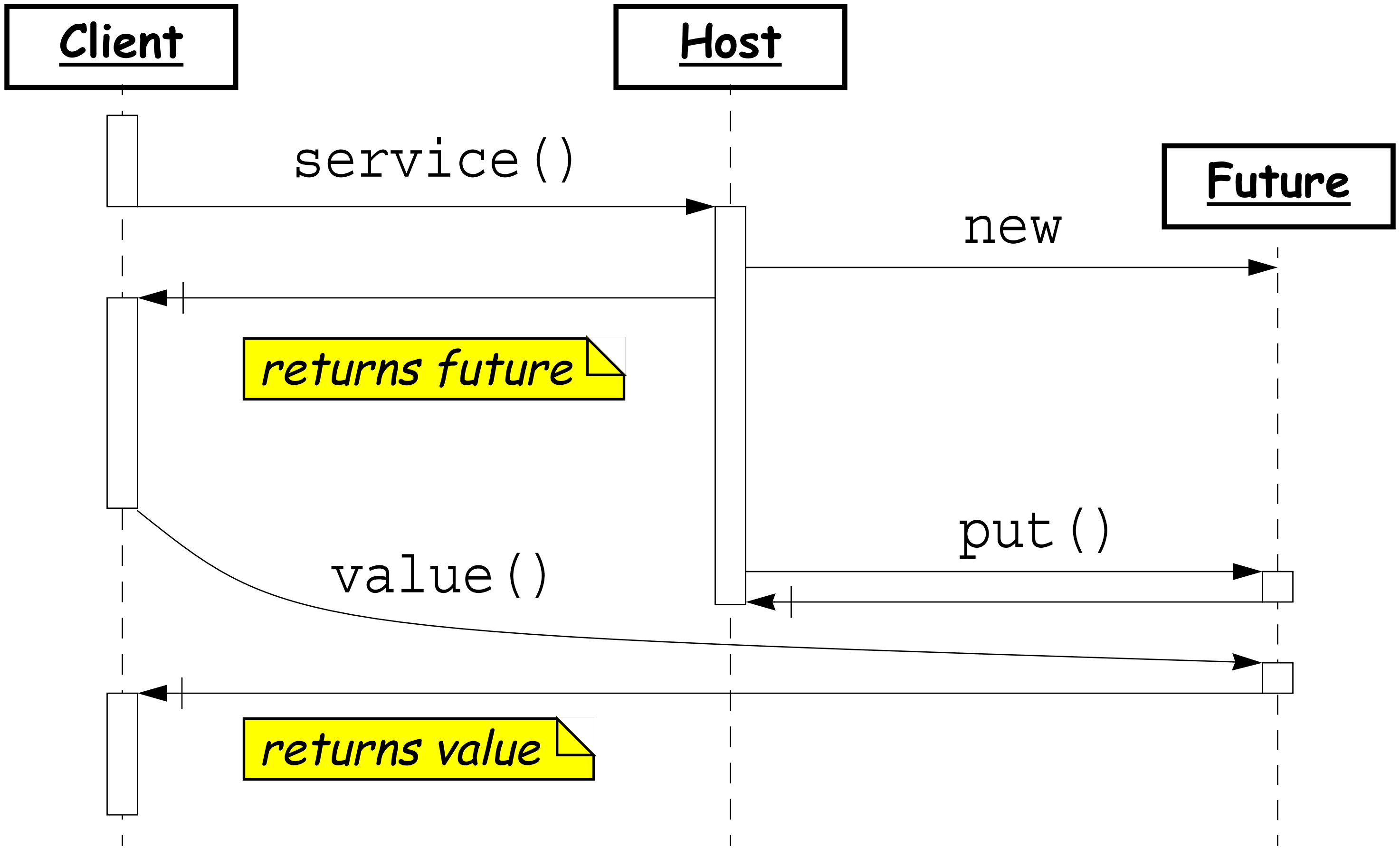
A one-slot buffer is a simple abstraction that can be used to implement many higher-level concurrency abstractions ...

Early Reply in Java

```
public class Host { ...
  public Object service() {      // unsynchronized
    final Slot reply = new Slot();
    final Host host = this;
    new Thread() {                 // Helper
      public void run() {
        synchronized (host) {
          reply.put(host.compute());
          host.cleanup();          // retain lock
      } }
    }.start();
    return reply.get();            // early reply
  } ...
}
```

Futures

Futures allow a client to continue in parallel with a host until the future value is needed:



A Future Class

Futures can be implemented as a layer of abstraction around a shared Slot:

```
class Future {
  private Object val_;   // initially null
  private Slot slot_;    // shared with some worker
  public Future(Slot slot) {
    slot_ = slot;
  }
  public Object value() {
    if (val_ == null)
      val_ = slot_.get();
    return val_;
  }
}
```

Using Futures in Java

*Without special language support, the client must **explicitly** request a value() from the future object.*

```
public Future service () {       // unsynchronized
  final Slot slot = new Slot();
  new Thread() {
    public void run() {
      slot.put(compute());
    }
  }.start();
  return new Future(slot);
}
protected synchronized Object compute() { ... }
```

What you should know!

- What general form does an asynchronous invocation take?
- When should you consider using asynchronous invocations?
- In what sense can a direct invocation be "asynchronous"?
- Why (and how) would you use inner classes to implement asynchrony?
- What is "early reply", and when would you use it?
- What are "futures", and when would you use them?
- How can implement futures and early replies in Java?

Can you answer these questions?

- *Why might you want to increase concurrency on a single-processor machine?*
- *Why are servers commonly structured as thread-per-message gateways?*
- *Which of the concurrency abstractions we have discussed till now can be implemented using one-slot-buffers as the only synchronized objects?*
- *When are futures better than early replies? Vice versa?*

9. Condition Objects

Overview

- ❑ Condition Objects
  - ☞ Simple Condition Objects
  - ☞ The "Nested Monitor Problem"
  - ☞ Permits and Semaphores
  - ☞ Using Semaphores

Pattern: Condition Objects

Intent: *Condition objects encapsulate the waits and notifications used in guarded methods.*

Applicability

- To simplify class design by *off-loading waiting* and *notification* mechanics.
  - ☞ Because of the limitations surrounding the use of condition objects in Java, in some cases the use of condition objects will *increase* rather than decrease design complexity!

Condition Objects — applicability

- As an *efficiency* manoeuvre.
  - ☞ By isolating conditions, you can often *avoid notifying* waiting threads that *could not possibly proceed* given a particular state change.
- As a means of encapsulating special scheduling policies surrounding notifications, for example to impose *fairness* or *prioritization* policies.
- In the particular cases where conditions take the form of *"permits"* or *"latches"*.

Condition Objects

Condition objects implement this interface:

```
public interface Condition {
  public void await();  // wait for some condition
  public void signal(); // signal that condition
}
```

A client that awaits a condition blocks until another object signals that the condition now *may* hold.

A Simple Condition Object

We can encapsulate guard conditions with this class:

```
public class SimpleConditionObject
    implements Condition
{
  public synchronized void await() {
    try { wait(); }
    catch (InterruptedException ex) {}
  }
  public synchronized void signal() {
    notifyAll();
  }
}
```

Careless use can lead to the "Nested Monitor Problem"

The Nested Monitor problem

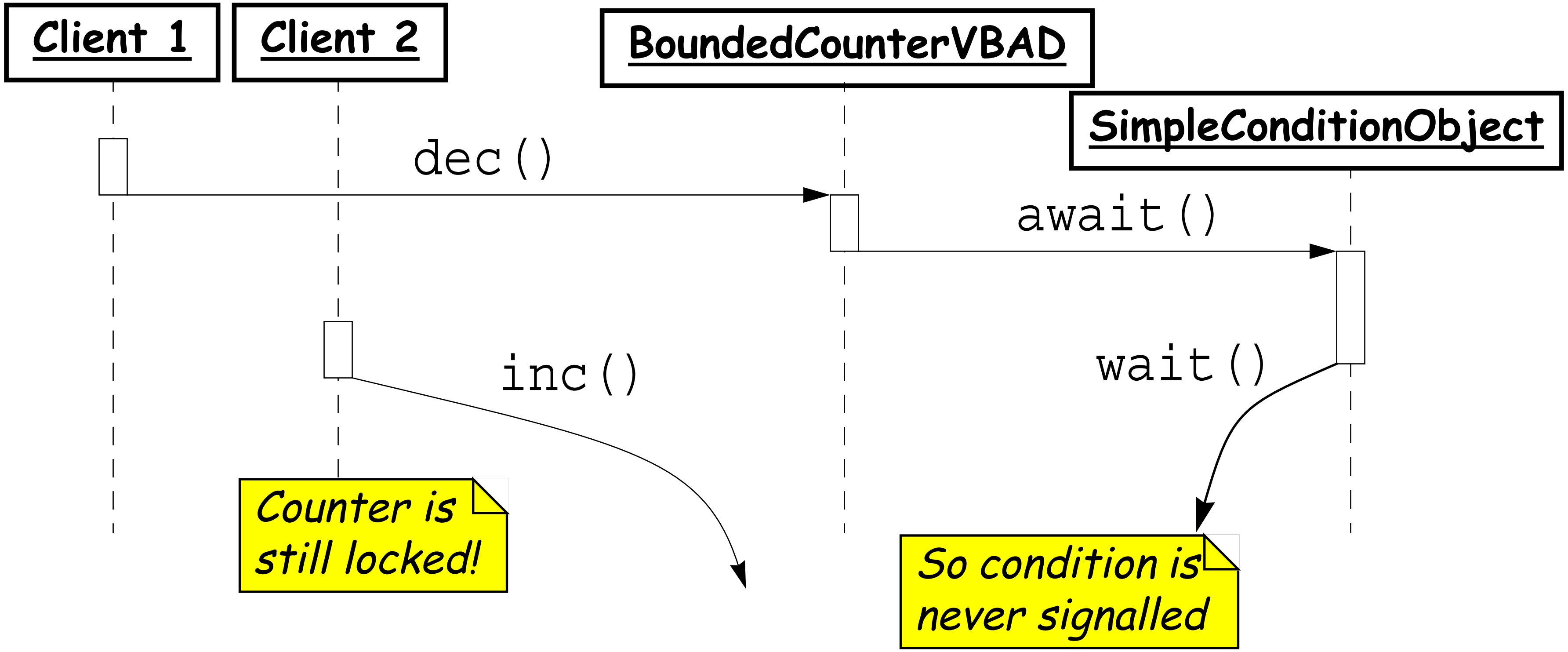
We want to avoid waking up the wrong threads by separately notifying the conditions notMin and notMax:

```
public class BoundedCounterVBAD
  implements BoundedCounter {
  protected long count_ = MIN;
  protected Condition
    notMin_ = new SimpleConditionObject();
  protected Condition
    notMax_ = new SimpleConditionObject();
  public synchronized long value() {
    return count_;
  }
...
```

The Nested Monitor problem ...

```
public synchronized void dec() {
  while (count_ == MIN)
    notMin_.await();      // wait till count not MIN
  if (count_-- == MAX)
    notMax_.signal();
}
public synchronized void inc() { // can't get in!
  while (count_ == MAX)
    notMax_.await();
  if (count_++ == MIN)
    notMin_.signal();    // we never get here!
}
}
```

The Nested Monitor problem ...



Nested monitor lockouts occur whenever a blocked thread holds the lock for an object containing the method that would otherwise provide a notification to unblock the wait.

Nested Monitors in FSP

Nested Monitors typically arise when one synchronized object is implemented using another.

Recall our one Slot buffer in FSP:

```
const N = 2
Slot = (put[v:0..N] -> get[v] -> Slot).
```

Suppose we try to implement a call/reply protocol using a private instance of Slot:

```
ReplySlot =
   ( put[v:0..N] -> my.put[v] -> ack -> ReplySlot
   | get -> my.get[v] -> ret[v] -> ReplySlot ).
```

Nested Monitors in FSP ...

Our producer/consumer chain obeys the new protocol:

```
Producer = (   put[0] -> ack
            -> put[1] -> ack
            -> put[2] -> ack -> Producer ).

Consumer = ( get-> ret[x:0..N]->Consumer ).

||Chain = (Producer||ReplySlot||my:Slot||Consumer).
```

Nested Monitors in FSP ...

But now the chain may deadlock:

```
Progress violation for actions: {put.0, ack, put.1,
put.2, my.put.0, my.put.1, my.put.2, get, my.get.2,
ret.2..........}
Trace to terminal set of states:
  get
  ret.0
Actions in terminal set: {}
```

Solving the Nested Monitors problem

You must ensure that:

- *Waits* do not occur while *synchronization* is held on the *host* object.
  - ☞ This leads to a guard loop that *reverses* the synchronization seen in the faulty version.
- *Notifications* are never missed.
  - ☞ The entire guard wait loop should be enclosed within *synchronized* blocks on the *condition* object.

...

Solving Nested Monitors ...

...

- *Notifications* do not *deadlock*.
  - All *notifications* should be performed *only upon release of all synchronization* (except for the notified condition object).
- Helper and host state must be *consistent*.
  - If the helper object maintains any state, it must always be consistent with that of the host, and if it *shares* any state with the host, that access is properly *synchronized*.

Example solution

```
public class BoundedCounterVCV implements BoundedCounter { ...
   public void dec() {                           // not synched!
      boolean wasMax = false;                    // record notification condition
      synchronized(notMin_) {                    // synch on condition object
         while (true) {                          // new guard loop
            synchronized(this) {
               if (count_ > MIN) {               // check and act
                  wasMax = (count_ == MAX);
                  count_--;
                  break;
               }
            }
            notMin_.await();                     // release host synch before wait
         }
      }
      if (wasMax) notMax_.signal();              // first release all synchs!
   }
}
```

Pattern: Permits and Semaphores

Intent: *Bundle synchronization in a condition object when synchronization depends on the value of a counter.*

Applicability

- When any given `await` may proceed only if there have been *more signals than awaits*.
  - ☞ I.e., when `await` decrements and `signal` increments the number of available "permits".
- You need to guarantee the *absence of missed signals*.
  - ☞ Unlike simple condition objects, semaphores work even if one thread enters its await *after* another thread has signalled that it may proceed.
- The host classes can arrange to invoke `Condition` methods *outside* of synchronized code.

Permits and Semaphores — design steps

- Define a class implementing `Condition` that maintains a permit count, and *immediately* releases await if there are already enough permits.
  - ☞ *e.g.*, `BoundedCounter`

```
public class CountCondition implements Condition {
  protected BoundedCounter
    counter_ = new BoundedCounterV0();
  public void await() { counter_.dec(); }
  public void signal() { counter_.inc(); }
}
```

Design steps ...

- As with all kinds of condition objects, their clients must *avoid invoking await inside of synchronized code*.
  - ☞ You can use a *before/after design* of the form:

```
class Host {
  Condition aCondition_; ...
  public method m1() {
    aCondition_.await();      // not synched
    doM1();                   // synched
    for each Condition c enabled by m1()
      c.signal();             // not synched
  }
  protected synchronized doM1() { ... }
}
```

Variants

Permit Counters: (Counting Semaphores)

- Just keep track of the *number of "permits"*
- Can use `notify` instead of `notifyAll` if class is `final`

Fair Semaphores:

- Maintain *FIFO queue of threads* waiting on a `SimpleCondition`

Locks and Latches:

- Locks can be *acquired* and *released* in *separate methods*
- Keep track of thread holding the lock so locks can be *reentrant!*
- A *latch* is set to *true* by `signal`, and always *stays true*

See the On-line supplement for details!

Semaphores in Java

```
public class Semaphore { // simple version
  private int value;
  public Semaphore (int initial) { value = initial; }
  synchronized public void up() {        // AKA V
    ++value;
    notify();            // wake up just one thread!
  }
  synchronized public void down() {     // AKA P
    while (value==0)
      try { wait(); }
      catch(InterruptedException ex) { };
    --value;
  }
}
```

Using Semaphores

```
public class BoundedCounterVSem
    implements BoundedCounter {
  protected long count_ = MIN;
  protected Semaphore mutex;
  protected Semaphore full;    // number of items
  protected Semaphore empty;   // number of slots

  BoundedCounterVSem() {
    mutex = new Semaphore(1);
    full = new Semaphore(0);
    empty = new Semaphore(MAX-MIN);
  }
...
```

Using Semaphores ...

```
public long value() {
  mutex.down();          // grab the resource
  long val = count_;
  mutex.up();            // release it
  return val;
}
public void inc() {
  empty.down();          // grab a slot
  mutex.down();          // sequence is important!
  count_ ++;
  mutex.up();
  full.up();             // release an item
}
...
```

Using Semaphores ...

These would cause a nested monitor problem!

```
public void BADinc() {
  mutex.down(); empty.down(); // locks out BADdec!
  count_ ++;
  full.up(); mutex.up();
}

public void BADdec() {
  mutex.down(); full.down(); // locks out BADinc!
  count_ --;
  empty.up(); mutex.up();
}
```

What you should know!

- ✎ *What are "condition objects"? How can they make your life easier? Harder?*
- ✎ *What is the "nested monitor problem"?*
- ✎ *How can you avoid nested monitor problems?*
- ✎ *What are "permits" and "latches"? When is it natural to use them?*
- ✎ *How does a semaphore differ from a simple condition object?*
- ✎ *Why (when) can semaphores use* `notify()` *instead of* `notifyAll()`*?*

Can you answer these questions?

- *Why doesn't SimpleConditionObject need any instance variables?*
- *What is the easiest way to avoid the nested monitor problem?*
- *What assumptions do nested monitors violate?*
- *How can the obvious implementation of semaphores (in Java) violate fairness?*
- *How would you implement fair semaphores?*

10. Fairness and Optimism

- Concurrently available methods
  - ☞ Priority
  - ☞ Interception
  - ☞ Readers and Writers
- Optimistic methods

Pattern: Concurrently Available Methods

Intent: *Non-interfering methods are made concurrently available by implementing policies to enable and disable methods based on the current state and running methods.*

Applicability

- Host objects are accessed by *many different threads*.
- Host services are *not completely interdependent*, so need not be performed under mutual exclusion.
- You need to *improve throughput* for some methods by eliminating nonessential blocking.
- You want to *prevent* various accidental or malicious *starvation* due to some client forever holding its lock.
- Full synchronization would needlessly make host objects prone to *deadlock* or other *liveness problems*.

Concurrent Methods — design steps

Layer concurrency control policy over mechanism by:

Policy Definition:

- When may methods run *concurrently*?
- What happens when a *disabled method* is invoked?
- What *priority* is assigned to *waiting* tasks?

Instrumentation:

- Define *state variables* to detect and enforce policy.

Interception:

- Have the host object *intercept public messages* and then *relay* them *under the appropriate conditions* to protected methods that actually perform the actions.

Priority

Priority may depend on any of:

- *Intrinsic attributes* of tasks (class & instance variables).
- *Representations* of task *priority*, *cost*, *price*, or *urgency*.
- The *number* of tasks *waiting* for some condition.
- The *time* at which each task is added to a queue.
- *Fairness* — guarantees that each waiting task will eventually run.
- *Expected duration* or time to completion of each task.
- The *desired completion time* of each task.
- Termination *dependencies* among tasks.
- The *number* of tasks that have *completed*.
- The *current time*.

Fairness

There are subtle differences between definitions of fairness:

Weak fairness: If a process *continuously* makes a request, *eventually* it will be granted.

Strong fairness: If a process makes a request *infinitely often*, *eventually* it will be granted.

Linear waiting: If a process makes a request, it will be granted *before* any other process is granted the request *more than once*.

FIFO (first-in first out): If a process makes a request, it will be *granted before* that of any process making a *later* request.

Interception

Interception strategies include:

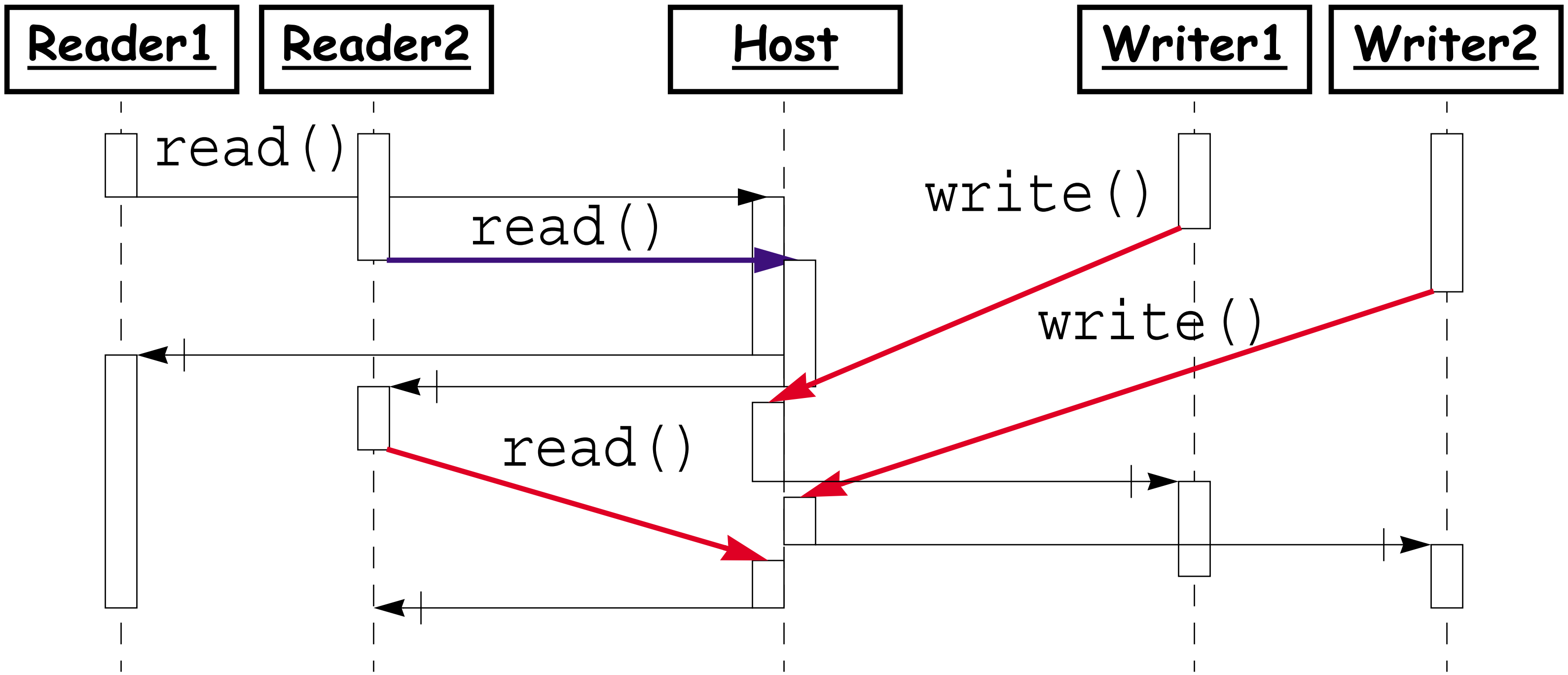
Pass-Throughs: The host maintains a set of *immutable references* to helper objects and simply *relays* all messages to them within *unsynchronized* methods.

Lock-Splitting: Instead of splitting the class, *split the synchronization locks* associated with subsets of the state.

Before/After methods: Public methods contain *before/after processing* surrounding calls to non-public methods in the host that perform the services.

Concurrent Reader and Writers

"Readers and Writers" is a family of concurrency control designs in which "Readers" *(non-mutating accessors)* may *concurrently* access resources while "Writers" *(mutative, state-changing operations)* require *exclusive access*..



Readers/Writers Model

We are interested only in capturing who gets access:

```
set Actions = { acquireRead, releaseRead,
  acquireWrite, releaseWrite}

READER = (    acquireRead
          ->  examine
          ->  releaseRead     ->  READER )
             +Actions \{examine}.

WRITER = (    acquireWrite
          ->  modify
          ->  releaseWrite    ->  WRITER )
              +Actions \{modify}.
```

A Simple RW Protocol

```
const Nread  = 2                // Maximum readers
const Nwrite = 2                // Maximum writers

RW_LOCK = RW[0][False],
RW[readers:0..Nread][writing:Bool] =
   ( when (!writing)
        acquireRead             -> RW[readers+1][writing]
   | releaseRead                -> RW[readers-1][writing]
   | when (readers==0 && !writing)
        acquireWrite            -> RW[readers][True]
   | releaseWrite               -> RW[readers][False]
   ).
```

Safety properties

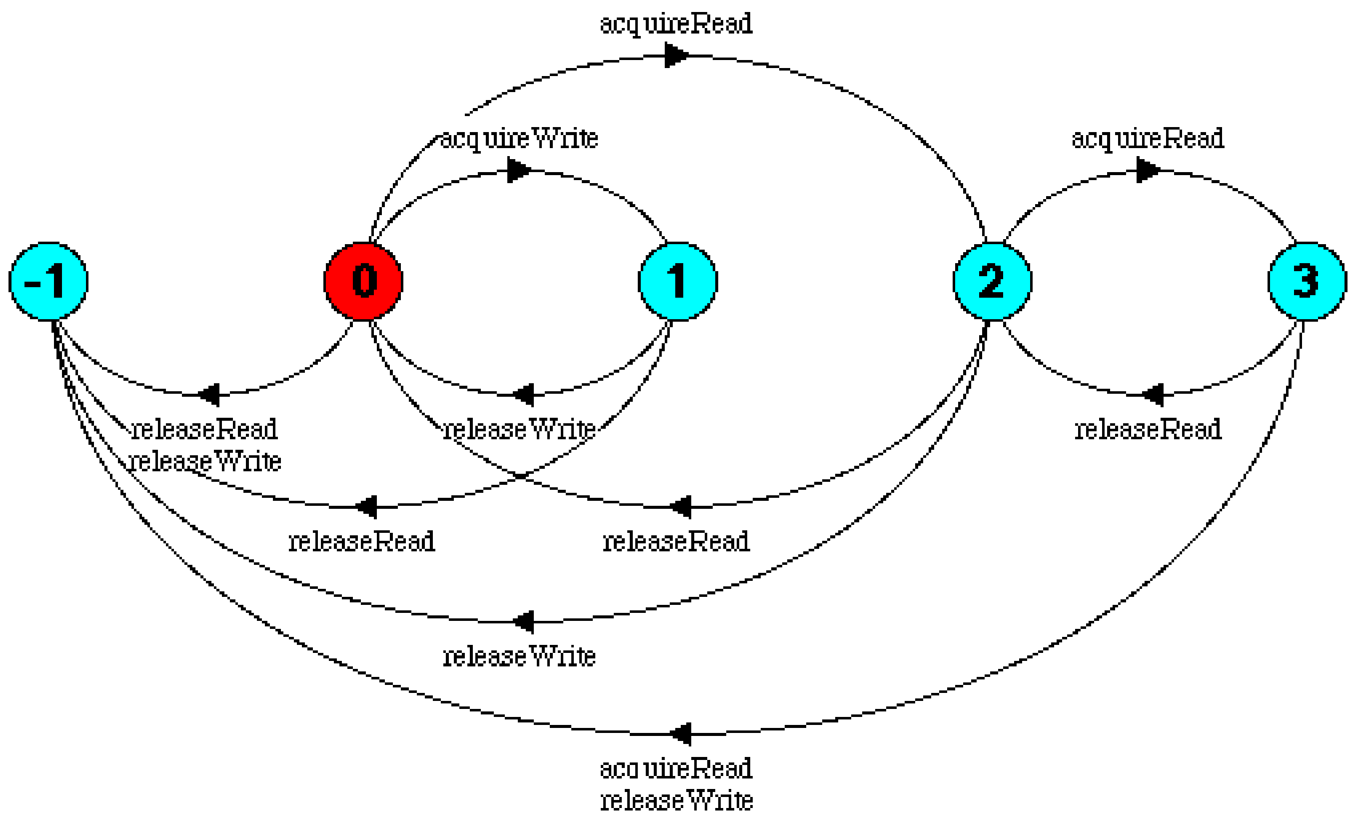
We specify the safe interactions:

```
property SAFE_RW =
   ( acquireRead                  -> READING[1]
   | acquireWrite                 -> WRITING ),
READING[i:1..Nread] =
   ( acquireRead                  -> READING[i+1]
   | when(i>1) releaseRead        -> READING[i-1]
   | when(i==1) releaseRead       -> SAFE_RW
   ),
WRITING = ( releaseWrite          -> SAFE_RW ).
```

Safety properties ...

And compose them with RW_LOCK:

```
||READWRITELOCK = (RW_LOCK || SAFE_RW).
```



Composing the Readers and Writers

We compose the READERS and WRITERS with the protocol and check for safety violations:

```
||READERS_WRITERS =
   (   reader[1..Nread]:READER
   ||  writer[1..Nwrite]:WRITER
   ||  {reader[1..Nread],
        writer[1..Nwrite]}::READWRITELOCK).
```

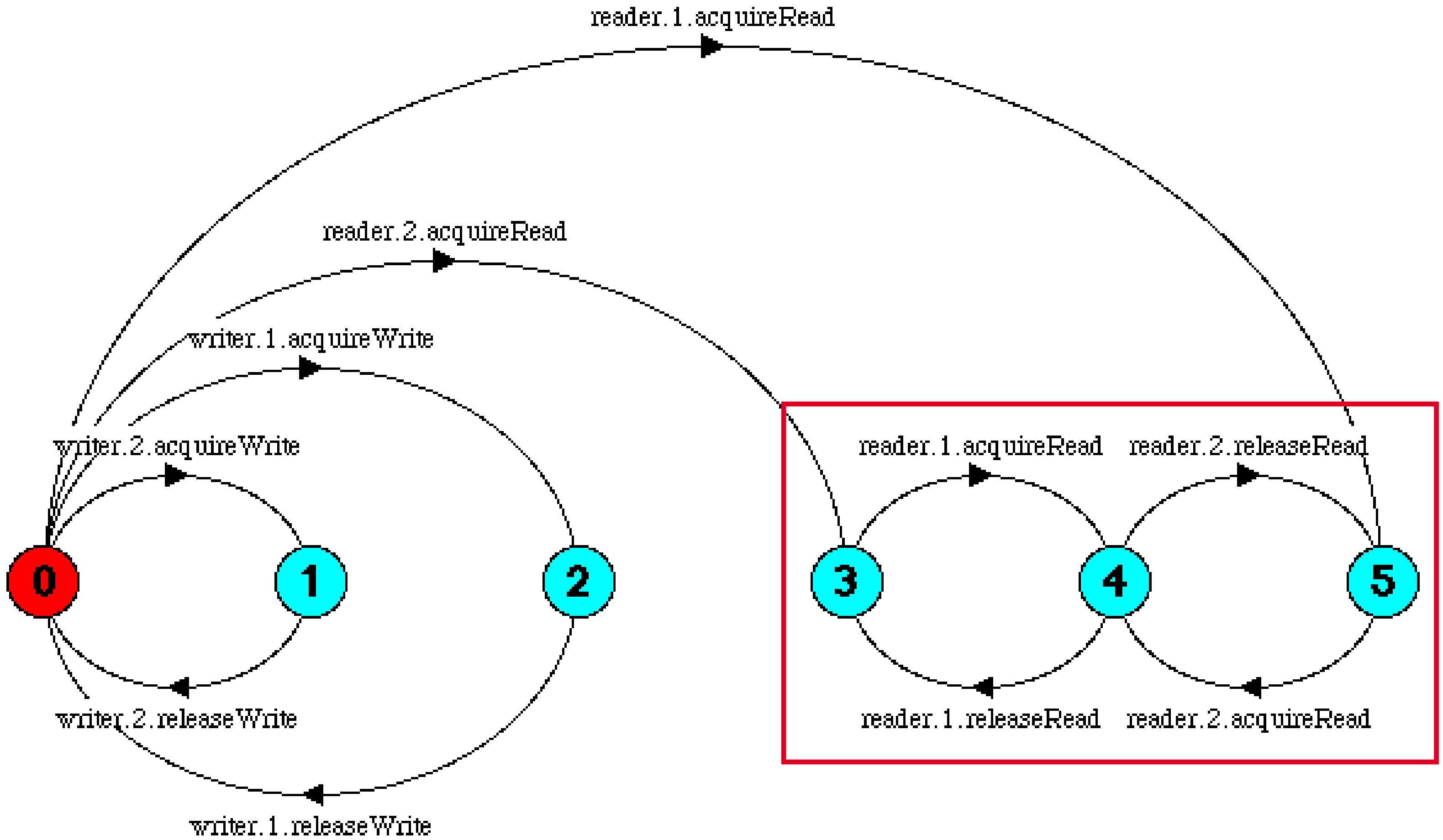
```
No deadlocks/errors
```

Progress properties

We similarly specify liveness properties:

```
||RW_PROGRESS = READERS_WRITERS
        >>{reader[1..Nread].releaseRead,
        writer[1..Nread].releaseWrite}.
progress WRITE[i:1..Nwrite] = writer[i].acquireWrite
progress READ[i:1..Nwrite]  = reader[i].acquireRead
Progress violation: WRITE.1 WRITE.2
Trace to terminal set of states:
  reader.1.acquireRead tau
Actions in terminal set:
  {reader.1.acquireRead, reader.1.releaseRead,
  reader.2.acquireRead, reader.2.releaseRead}
```

Starvation


reader.1.acquireRead
reader.2.acquireRead
writer.1.acquireWrite
writer.2.acquireWrite
0
1
2
3
4
5
writer.2.releaseWrite
writer.1.releaseWrite
reader.1.acquireRead
reader.2.releaseRead
reader.1.releaseRead
reader.2.acquireRead

Readers and Writers Policies

Individual policies must address:

- Can new Readers *join* already active Readers even if a Writer is *waiting*?
  - ☞ if yes, Writers may *starve*
  - ☞ if not, the *throughput* of Readers *decreases*
- If *both* Readers and Writers are *waiting* for a Writer to finish, which should you let in *first*?
  - ☞ Readers? A Writer? FCFS? Random? Alternate?
  - ☞ Similar choices exist after Readers finish.
- Can Readers *upgrade to Writers* without having to give up access?

Policies ...

A typical set of choices:

- *Block* incoming *Readers* if there are *waiting Writers*.
- *"Randomly" choose* among incoming threads (i.e., let the scheduler choose).
- *No upgrade* mechanisms.

Before/after methods are the simplest way to implement Readers and Writers policies.

Readers and Writers example

Implement state tracking variables

```
public abstract class RWVT {
  protected int activeReaders_  = 0;   // zero or more
  protected int activeWriters_  = 0;   // zero or one
  protected int waitingReaders_  = 0;
  protected int waitingWriters_  = 0;

  protected abstract void read_();    // define in
  protected abstract void write_();   // subclass
...
```

Readers and Writers example

Public methods call protected before/after methods

```
...
  public void read() {   // unsynchronized
    beforeRead();        // obtain access
    read_();             // perform service
    afterRead();         // release access
  }
  public void write() {
    beforeWrite();
    write_();
    afterWrite();
  }
...
```

Readers and Writers example

Synchronized before/after methods maintain state variables

```
...
  protected synchronized void beforeRead() {
    ++waitingReaders_;   // available to subclasses
    while (!allowReader())
      try { wait(); }
      catch (InterruptedException ex) {}
    --waitingReaders_; ++activeReaders_;
  }
  protected synchronized void afterRead() {
    --activeReaders_; notifyAll();
  }
...
```

Readers and Writers example

Different policies can use the same state variables ...

```
...
  protected boolean allowReader() { // default policy
    return waitingWriters_ == 0
           && activeWriters_ == 0;
  }
...
```

✎ *Can you define suitable before/after methods for Writers?*

Pattern: Optimistic Methods

Intent: *Optimistic methods attempt actions, but rollback state in case of interference. After rollback, they either throw failure exceptions or retry the actions.*

Applicability

- Clients can *tolerate* either *failure* or *retries*.
  - ☞ If not, consider using guarded methods .
- You can avoid or cope with *livelock*.
- You can *undo* actions performed before failure checks
  - ☞ *Rollback/Recovery:* *undo effects* of each performed action. If messages are sent to other objects, they must be undone with "anti-messages"
  - ☞ *Provisional action:* "pretend" to act, *delaying commitment* until interference is ruled out.

Optimistic Methods — design steps

Collect and encapsulate all mutable state so that it can be tracked as a unit:

- Define an *immutable helper class* holding values of all instance variables.
- Define a representation class, but make it *mutable* (allow instance variables to change), and additionally include a *version number* (or transaction identifier) field or even a sufficiently precise time stamp.
- Embed all instance variables, plus a version number, in the host class, but define `commit` to take as *arguments all assumed values* and *all new values* of these variables.
- Maintain a *serialized copy* of object state.
- Various combinations of the above ...

Detect failure ...

Provide an operation that simultaneously detects version conflicts and performs updates via a method of the form:

```
class Optimistic {                    // code sketch
  private State currentState_;  // immutable values
  synchronized boolean
    commit(State assumed, State next)
  {
    boolean success = (currentState_ == assumed);
    if (success)
      currentState_ = next;
    return success;
  }
}
```

Detect failure ...

Structure the main actions of each public method as follows:

```
State assumed = currentState();
State next = ...           // compute optimistically
if (!commit(assumed, next))
  rollback();
else
  otherActionsDependingOnNewStateButNotChangingIt();
```

Handle conflicts ...

Choose and implement a policy for dealing with commit failures:

- *Throw an exception* upon commit failure that tells a client that it may retry.
- *Internally retry* the action until it succeeds.
- *Retry some bounded number of times*, or until a timeout occurs, finally throwing an exception.
- *Pessimistically synchronize selected methods* which should not fail.

Ensure progress ...

Ensure progress in case of internal retries

- *Immediately retrying* may be counterproductive!
- *Yielding* may only be effective if all threads have *reasonable priorities* and the Java scheduler at least approximates *fair choice* among waiting tasks (which it is not guaranteed to do)!
- *Limit retries* to avoid livelock

An Optimistic Bounded Counter

```
public class BoundedCounterVOPT
    implements BoundedCounter
{
  protected Long count_ = new Long(MIN);
  protected synchronized boolean
    commit(Long oldc, Long newc)
  {
    boolean success = (count_ == oldc);
    if (success) count_ = newc;
      return success;
  }
...
```

An Optimistic Bounded Counter

```
...
  public long value() { return count_.longValue(); }
  public void inc() {
    for (;;) {    // thinly disguised busy-wait!
      Long c = count_; long v = c.longValue();
      if (v < MAX && commit(c, new Long(v+1)))
        break;
      Thread.currentThread().yield();
      // is there another thread?!
    }
  }
...
```

What you should know!

- ✎ *What criteria might you use to prioritize threads?*
- ✎ *What are different possible definitions of fairness?*
- ✎ *What are readers and writers problems?*
- ✎ *What difficulties do readers and writers pose?*
- ✎ *When should you consider using optimistic methods?*
- ✎ *How can an optimistic method fail? How do you detect failure?*

Can you answer these questions?

- ✎ *When does it make sense to split locks? How does it work?*
- ✎ *When should you provide a policy for upgrading readers to writers?*
- ✎ *What are the dangers in letting the (Java) scheduler choose which writer may enter a critical section?*
- ✎ *What are advantages and disadvantages of encapsulating synchronization conditions as helper methods?*
- ✎ *How can optimistic methods livelock?*

11. Lab session II

The lab exercises will be available on the course web page:

www.iam.unibe.ch/~scg/Teaching/CP/

12. Architectural Styles for Concurrency

Overview

- What is Software Architecture?
- Three-layered application architecture
- Flow architectures
  - ☞ Active Prime Sieve
- Blackboard architectures
  - ☞ Fibonacci with Linda

Sources

- M. Shaw and D. Garlan, *Software Architecture: Perspectives on an Emerging Discipline*, Prentice-Hall, 1996.
- F. Buschmann, et al., *Pattern-Oriented Software Architecture — A System of Patterns*, John Wiley, 1996.
- D. Lea, *Concurrent Programming in Java — Design principles and Patterns*, The Java Series, Addison-Wesley, 1996.
- N. Carriero and D. Gelernter, *How to Write Parallel Programs: a First Course*, MIT Press, Cambridge, 1990.

Software Architecture

A Software Architecture defines a system in terms of computational components and interactions amongst those components.

An Architectural Style defines a family of systems in terms of a pattern of structural organization.

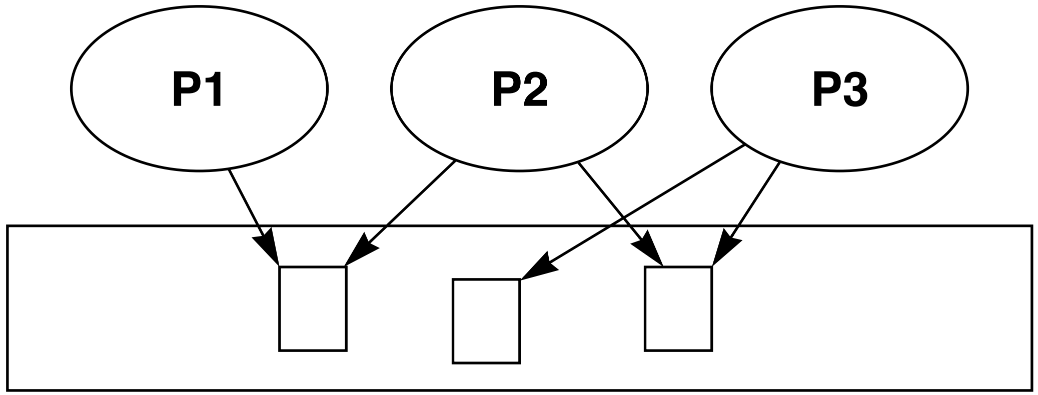
— cf. Shaw & Garlan, Software Architecture, pp. 3, 19

Architectural style

Architectural styles typically entail four kinds of properties:

- A *vocabulary* of design elements
  - e.g., “pipes”, “filters”, “sources”, and “sinks”
- A set of *configuration rules* that *constrain* compositions
  - e.g., pipes and filters must alternate in a linear sequence
- A *semantic interpretation*
  - e.g., each filter reads bytes from its input stream and writes bytes to its output stream
- A set of *analyses* that can be performed
  - e.g., if filters are “well-behaved”, no deadlock can occur, and all filters can progress in tandem

Communication Styles



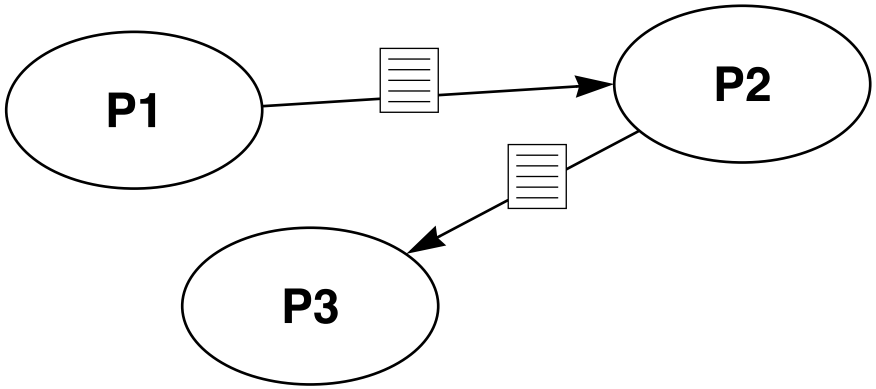
Shared Variables

Processes communicate *indirectly*.

Explicit synchronization mechanisms are needed.

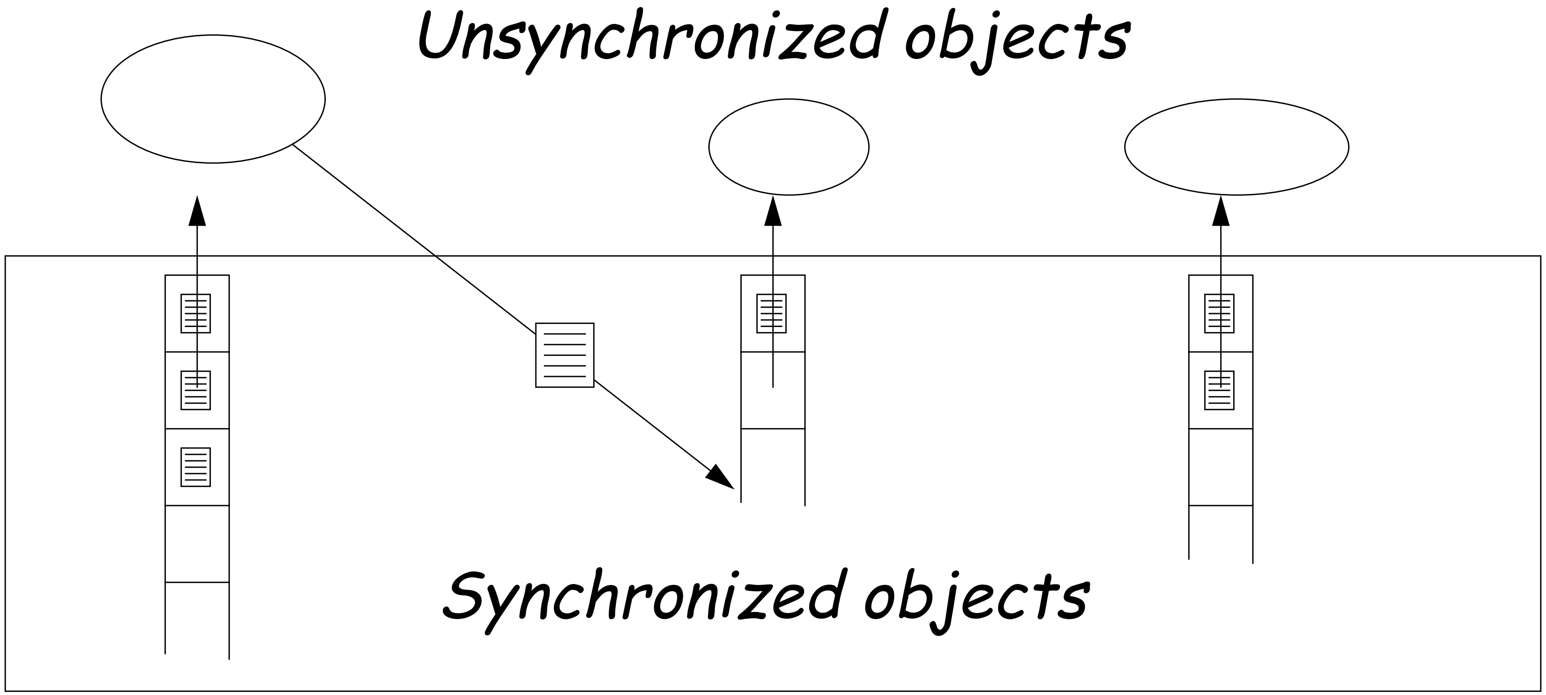
Message-Passing

Communication and synchronization are *combined*.



Simulated Message-Passing

Most concurrency and communication styles can be simulated by one another:



Message-passing can be modelled by associating message queues to each process.

Three-layered Application Architectures

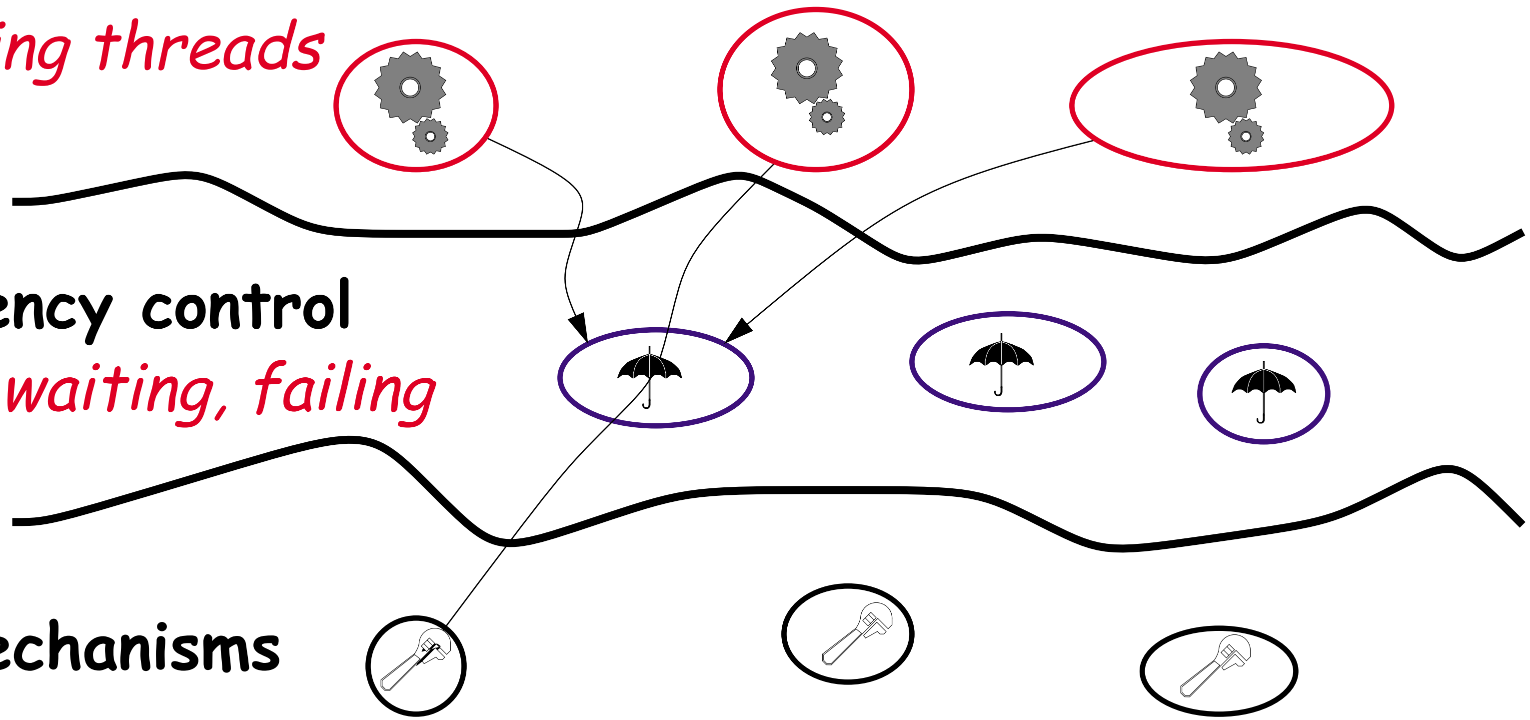
Interaction with external world

Generating threads

Concurrency control

Locking, waiting, failing

Basic mechanisms



This kind of architecture avoids nested monitor problems by restricting concurrency control to a single layer.

Problems with Layered Designs

Hard to extend beyond three layers because:

- Control may depend on *unavailable information*
  - ☞ Because it is not safely accessible
  - ☞ Because it is not represented (e.g., message history)
- Synchronization *policies* of different layers *may conflict*
  - ☞ E.g., nested monitor lockouts
- *Ground* actions may *need to know current policy*
  - ☞ E.g., blocking vs. failing

Flow Architectures

Many synchronization problems can be avoided by arranging things so that information only flows in one direction from sources to filters to sinks.

Unix "pipes and filters": Processes are connected in a linear sequence.

Control systems: events are picked up by sensors, processed, and generate new events.

Workflow systems: Electronic documents flow through workflow procedures.

Unix Pipes

Unix pipes are *bounded buffers* that *connect producer* and *consumer* processes (*sources*, *sinks* and *filters*):

```
cat file       # send file contents to output stream
 | tr -c 'a-zA-Z' '\012' # put each word on one line
 | sort        # sort the words
 | uniq -c     # count occurrences of each word
 | sort -rn    # sort in reverse numerical order
 | more        # and display the result
```

Unix Pipes

Processes should *read* from standard input and *write* to standard output streams:

- Misbehaving processes give rise to *"broken pipes"!*

Process creation and *scheduling* are handled by the O/S.

Synchronization is handled implicitly by the I/O system (through buffering).

Flow Stages

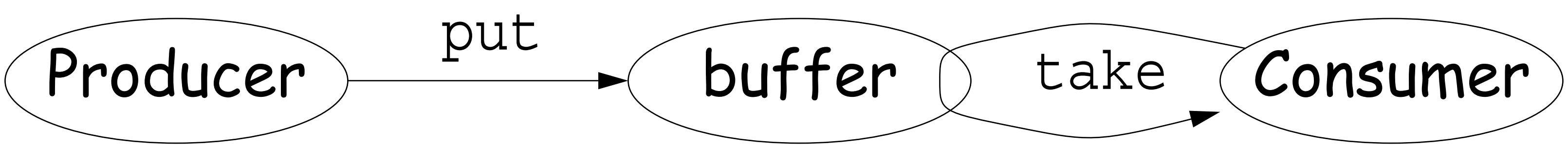
Every flow stage is a *producer* or *consumer* or both:

- *Splitters* (Multiplexers) have multiple successors
  - *Multicasters* clone results to multiple consumers
  - *Routers* distribute results amongst consumers
- *Mergers* (Demultiplexers) have multiple predecessors
  - *Collectors* interleave inputs to a single consumer
  - *Combiners* process multiple input to produce a single result
- *Conduits* have both multiple predecessors and consumers

Flow Policies

Flow can be *pull-based*, *push-based*, or a mixture:

- *Pull-based flow:* Consumers *take* results from Producers
- *Push-based flow:* Producers *put* results to Consumers
- Buffers:
  - *Put-only* buffers (*relays*) connect push-based stages
  - *Take-only* buffers (*pre-fetch buffers*) connect pull-based stages
  - *Put-Take* buffers connect (adapt) push-based stages to pull-based stages



Limiting Flow

Unbounded buffers: If *producers* are *faster* than consumers, buffers may *exhaust* available memory

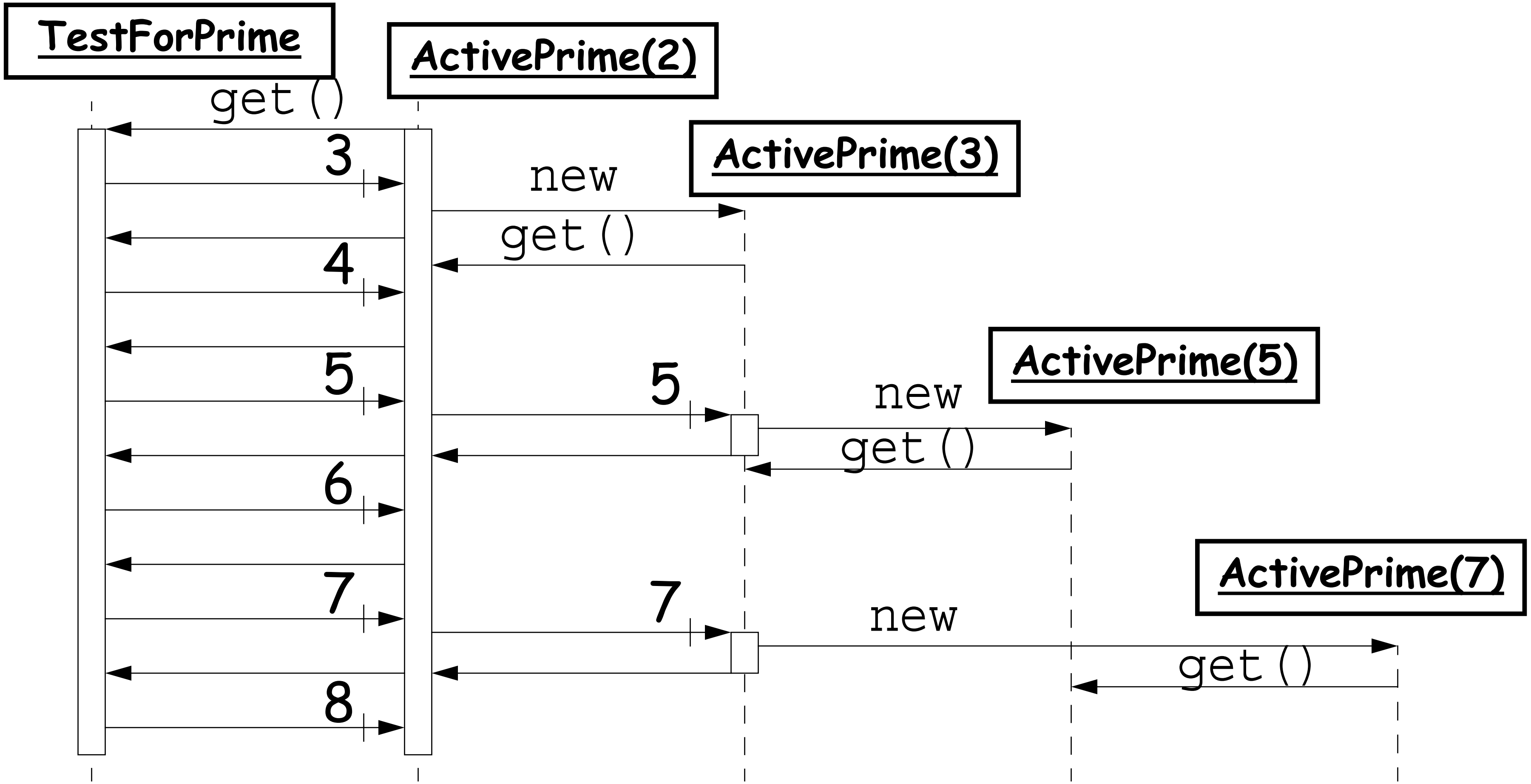
Unbounded threads: Having *too many threads* can exhaust system resources more quickly than unbounded buffers

Bounded buffers: Tend to be either *always full* or *always empty*, depending on relative speed of producers and consumers

Bounded thread pools: *Harder to manage* than bounded buffers

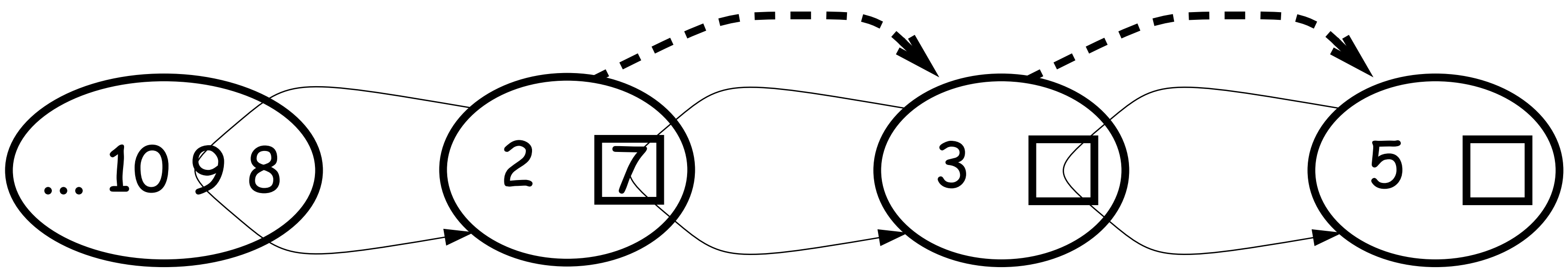
Example: a Pull-based Prime Sieve

Primes are agents that reject non-primes, pass on candidates, or instantiate new prime agents:



Using Put-Take Buffers

Each ActivePrime uses a one-slot buffer to feed values to the next ActivePrime.



The first ActivePrime *holds* the seed value 2, *gets* values from a TestForPrime, and *creates* new ActivePrime instances whenever it detects a prime value.

The PrimeSieve

The main PrimeSieve class creates the initial configuration

```
public class PrimeSieve {
  public static void main(String args[]) {
    genPrimes(1000);
  }
  public static void genPrimes(int n) {
    try {
      ActivePrime firstPrime =
        new ActivePrime(2, new TestForPrime(n));
    } catch (Exception e) { }
  }
}
```

Pull-based integer sources

Active primes get values to test from an `IntSource`*:*

```
interface IntSource { int getInt(); }
class TestForPrime implements IntSource {
  private int nextValue;
  private int maxValue;
  public TestForPrime(int max) {
    this.nextValue = 3; this.maxValue = max;
  }
  public int getInt() {          // not synched!
    if (nextValue < maxValue) { return nextValue++; }
    else { return 0; }
  }
}
```

The ActivePrime Class

ActivePrimes themselves implement IntSource

```
class ActivePrime
    extends Thread implements IntSource {
  private static IntSource lastPrime; // shared
  private int value;                 // this prime
  private int square;                // its square
  private IntSource intSrc;          // ints to test
  private Slot slot;                 // to pass values on
...
```

The ActivePrime Class

```
...
  public ActivePrime(int value, IntSource intSrc)
    throws ActivePrimeFailure
  {
    this.value = value;
    ...
    slot = new Slot();          // NB: private
    lastPrime = this;           // unsynchronized (safe!)
    this.start();               // become active
  }
...
```

It is impossible for primes to be discovered out of order!

The ActivePrime Class ...

```
...
  public int value() {
    return this.value;
  }
  private void putInt(int val) {      // may block
    slot.put()(new Integer(val));
  }
  public int getInt() {               // may block
    return ((Integer) slot.get()).intValue();
  }
...
```

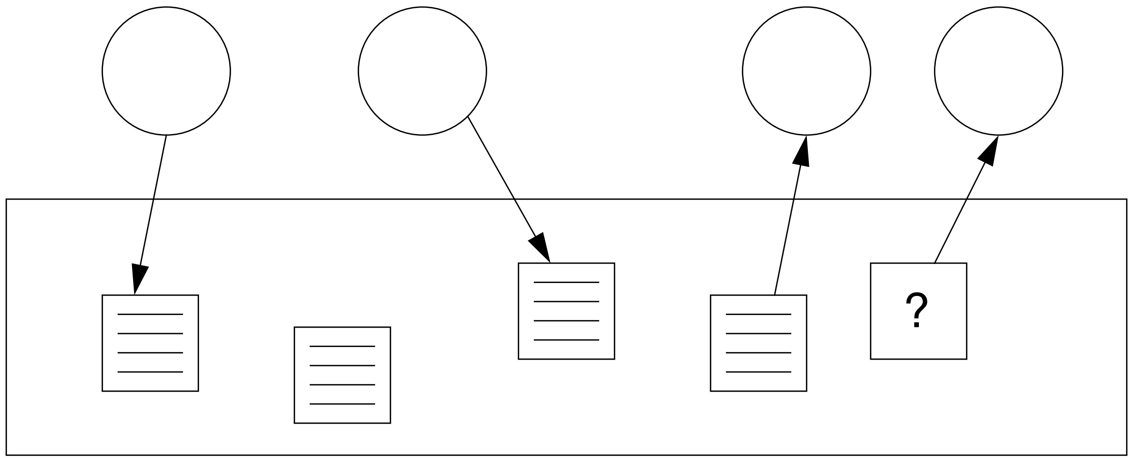
The only synchronization is hidden in the Slot class.

The ActivePrime Class ...

```
public void run() {
  int testValue = intSrc.getInt(); // may block
  while (testValue != 0) {         // stop
    if (this.square > testValue) { // got a prime
      try {
        new ActivePrime(testValue, lastPrime);
      } catch (Exception e) { break; } // exit loop
    } else if ((testValue % this.value) > 0) {
      this.putInt(testValue);      // may block
    }
    testValue = intSrc.getInt();   // may block
  }
  putInt(0);                       // stop next
}
```

Blackboard Architectures

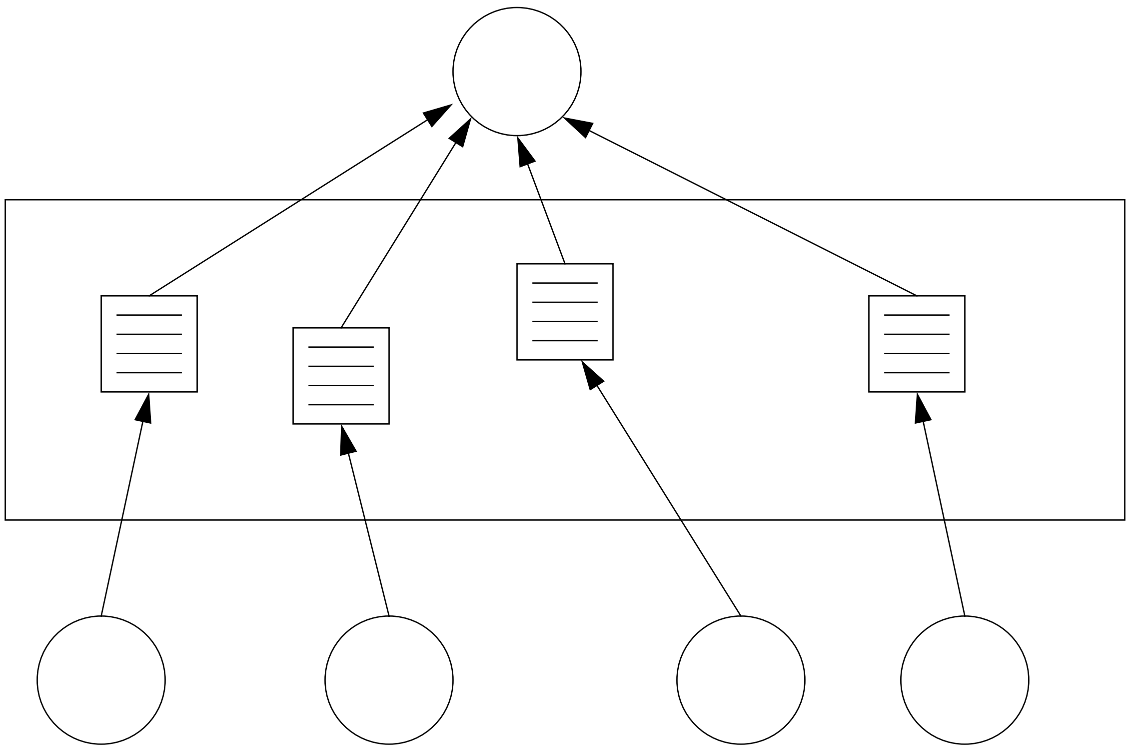
Blackboard architectures put all synchronization in a "coordination medium" where agents can exchange messages.



Agents do not exchange messages directly, but post messages to the blackboard, and retrieve messages either by reading from a specific location (i.e., a *channel*), or by posing a query (i.e., a *pattern* to match).

Result Parallelism

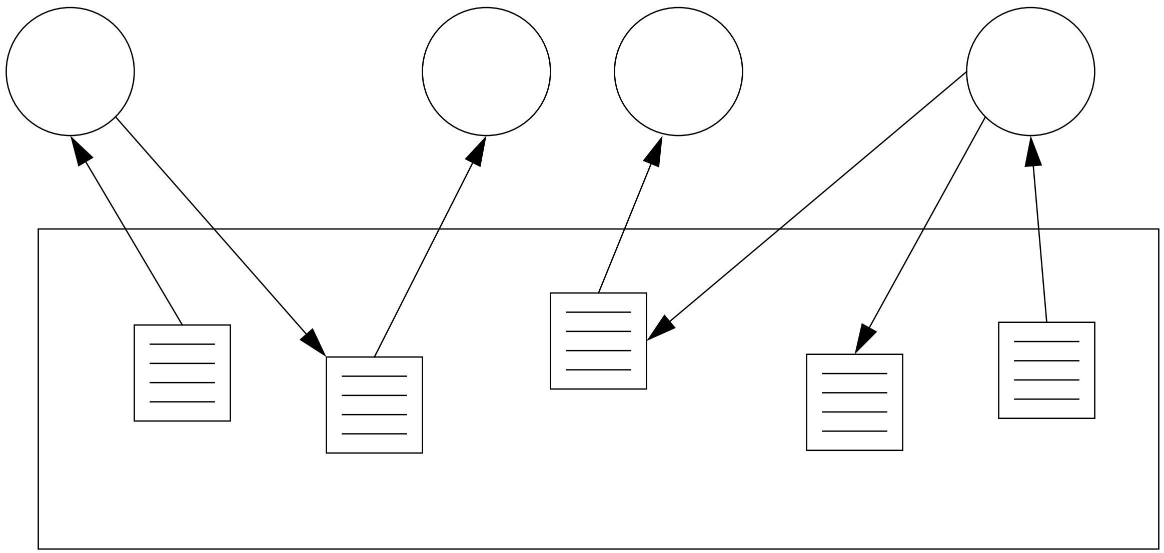
Result parallelism is a blackboard architectural style in which *workers* produce *parts* of a more complex whole.



Workers may be arranged hierarchically ...

Agenda Parallelism

Agenda parallelism is a blackboard style in which workers *retrieve tasks* to perform from a blackboard, and may *generate* new tasks to perform.

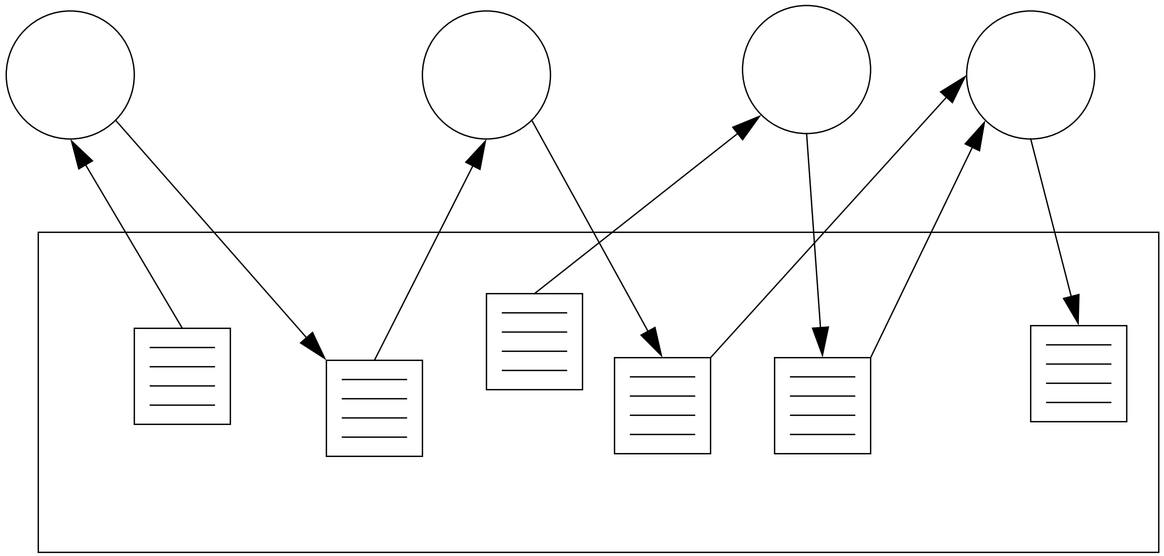


Workers repeatedly retrieve tasks until everything is done.

Workers are typically able to perform *arbitrary tasks*.

Specialist Parallelism

Specialist parallelism is a style in which each worker is *specialized* to perform a particular task.



Specialist designs are equivalent to message-passing, and are often organized as *flow architectures*, with each specialist producing results for the next specialist to consume.

Linda

Linda is a *coordination medium*, with associated primitives for coordinating concurrent processes, that can be *added to an existing programming language*.

The coordination medium is a *tuple-space*, which can contain:

- *data tuples* — tuples of primitives vales (numbers, strings ...)
- *active tuples* — expressions which are evaluated and eventually turn into data tuples

Linda primitives

Linda's coordination primitives are:

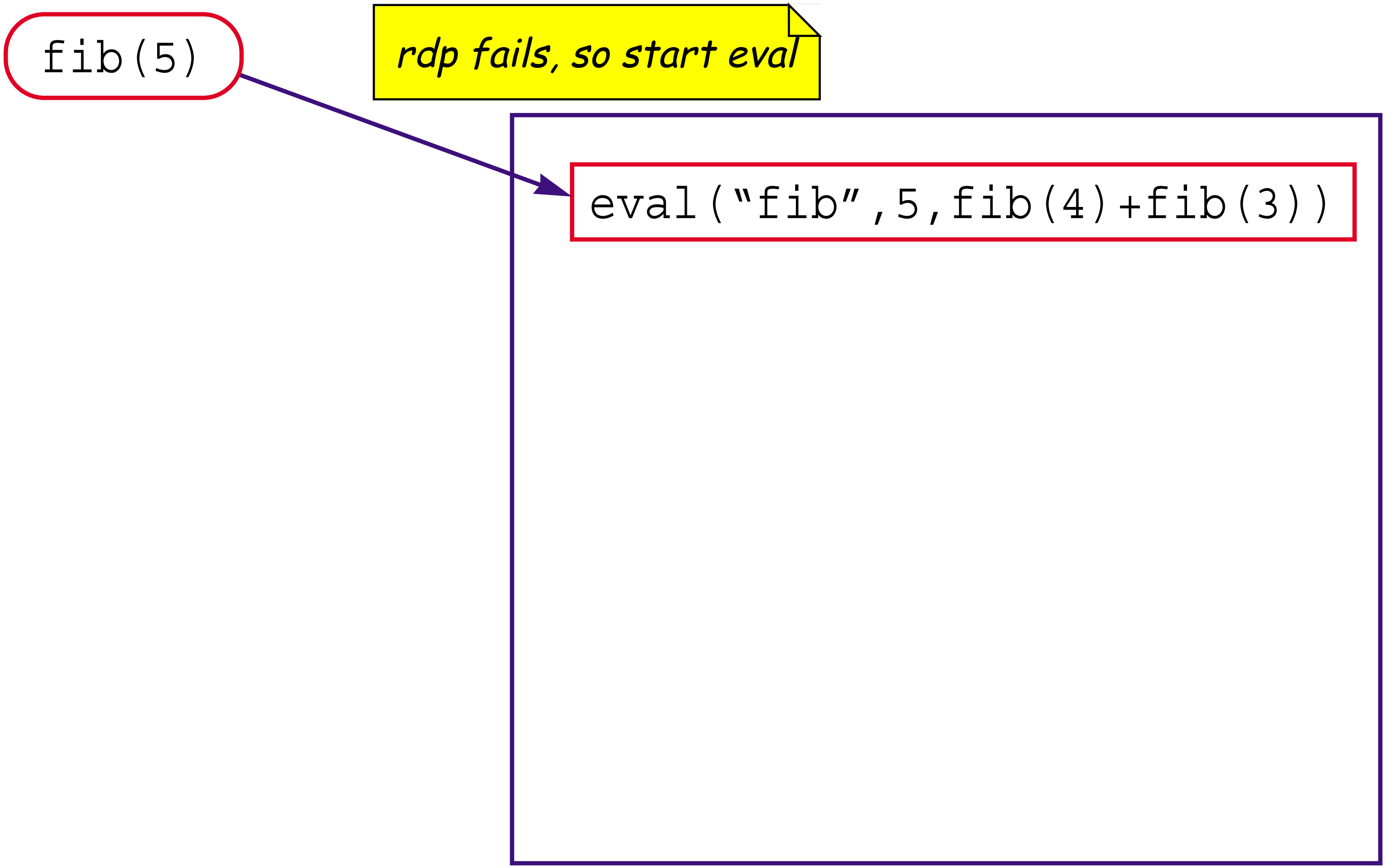
`out(T)`	*output* a tuple T to the medium (non-blocking) e.g., `out("employee", "pingu", 35000)`
`in(S)`	*destructively input* a tuple matching S (blocking) e.g., `in("employee", "pingu", ?salary)`
`rd(S)`	*non-destructively input* a tuple (blocking)
`inp(S)` `rdp(S)`	*try* to input a tuple *report success* or failure (non-blocking)
`eval(E)`	evaluate E in a *new process* leave the result in the tuple space

Example: Fibonacci

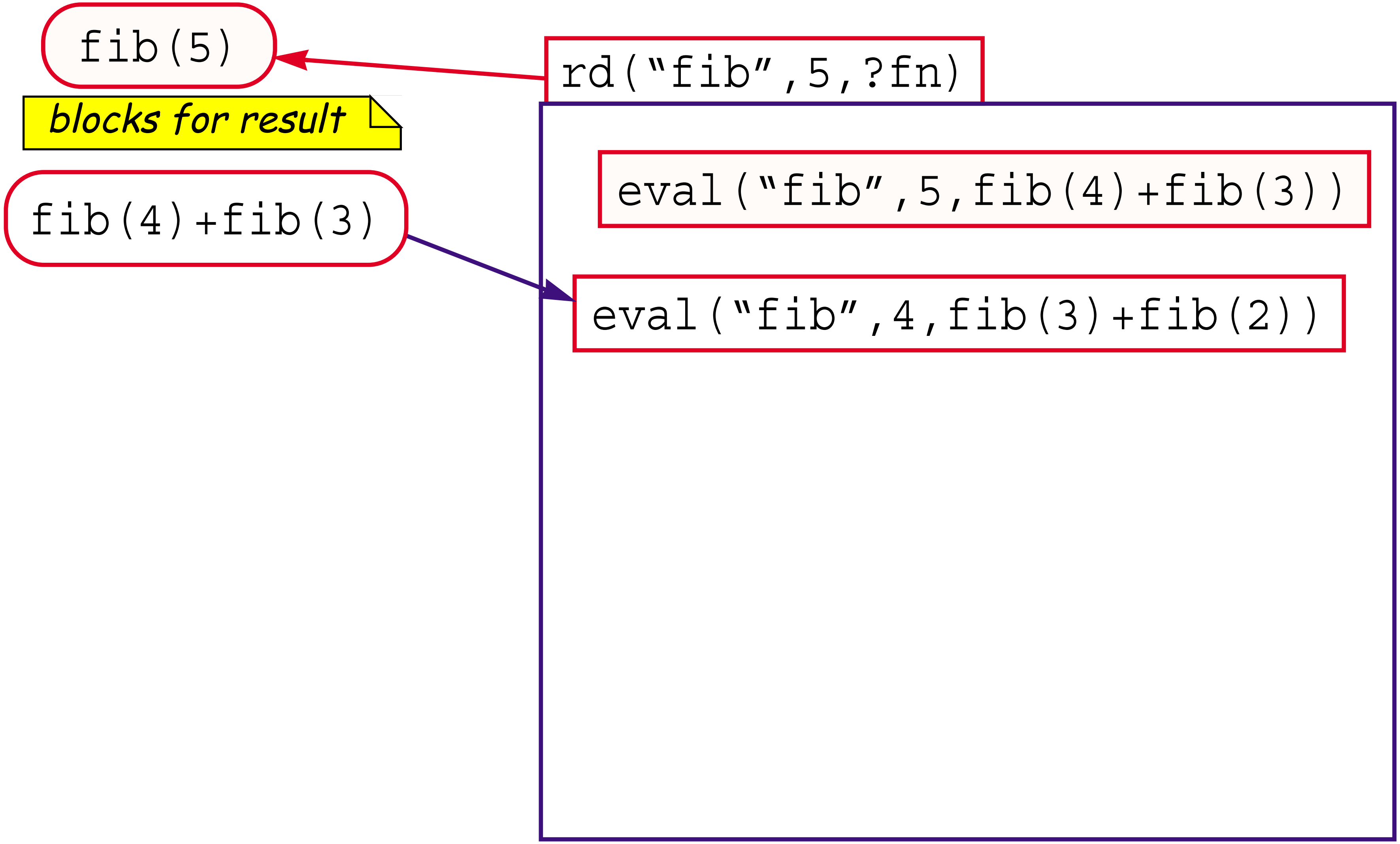
A (convoluted) way of computing Fibonacci numbers with Linda:

```
int fib(int n) {
  if (rdp("fib", n, ?fibn))       // non-blocking
    return fibn;
  if (n<2) {
    out("fib", n, 1);             // non-blocking
    return 1;
  }
  eval("fib", n, fib(n-1) + fib(n-2)); // asynch
  rd("fib", n, ?fibn);            // blocks
  return(fibn);

} // Post-condition: rdp("fib",n,?fibn) == True
```

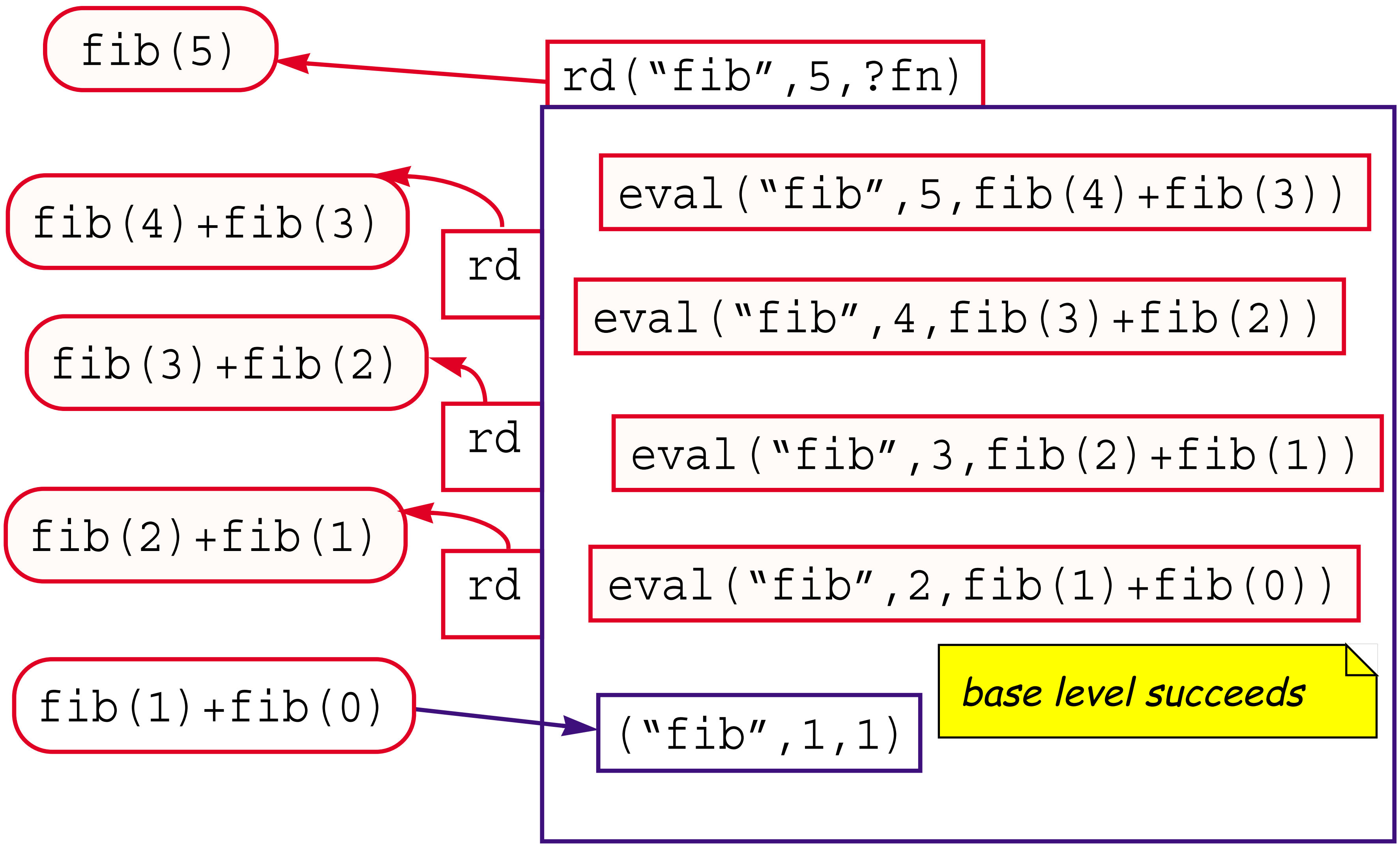
Evaluating Fibonacci



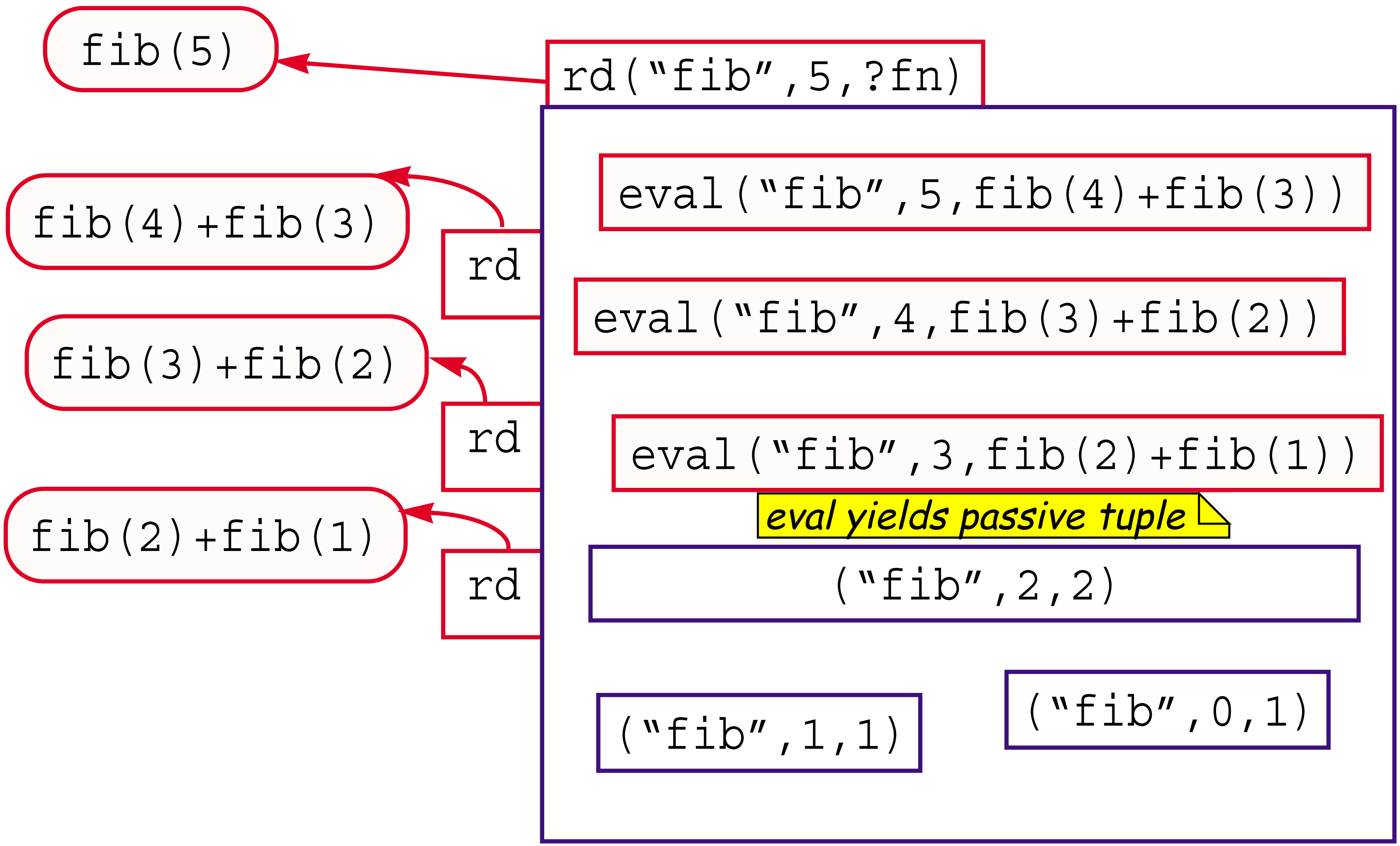
Evaluating Fibonacci



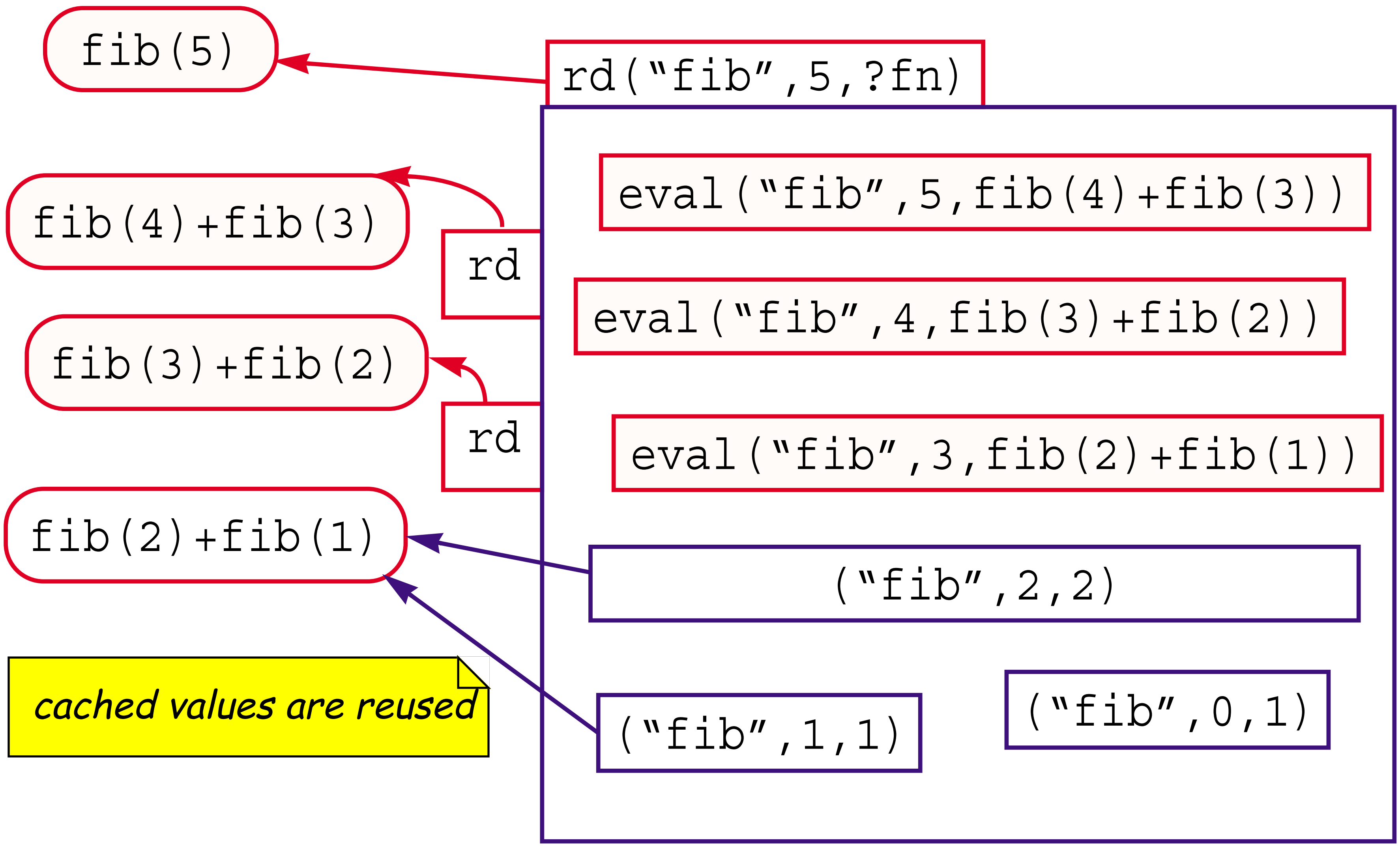
Evaluating Fibonacci



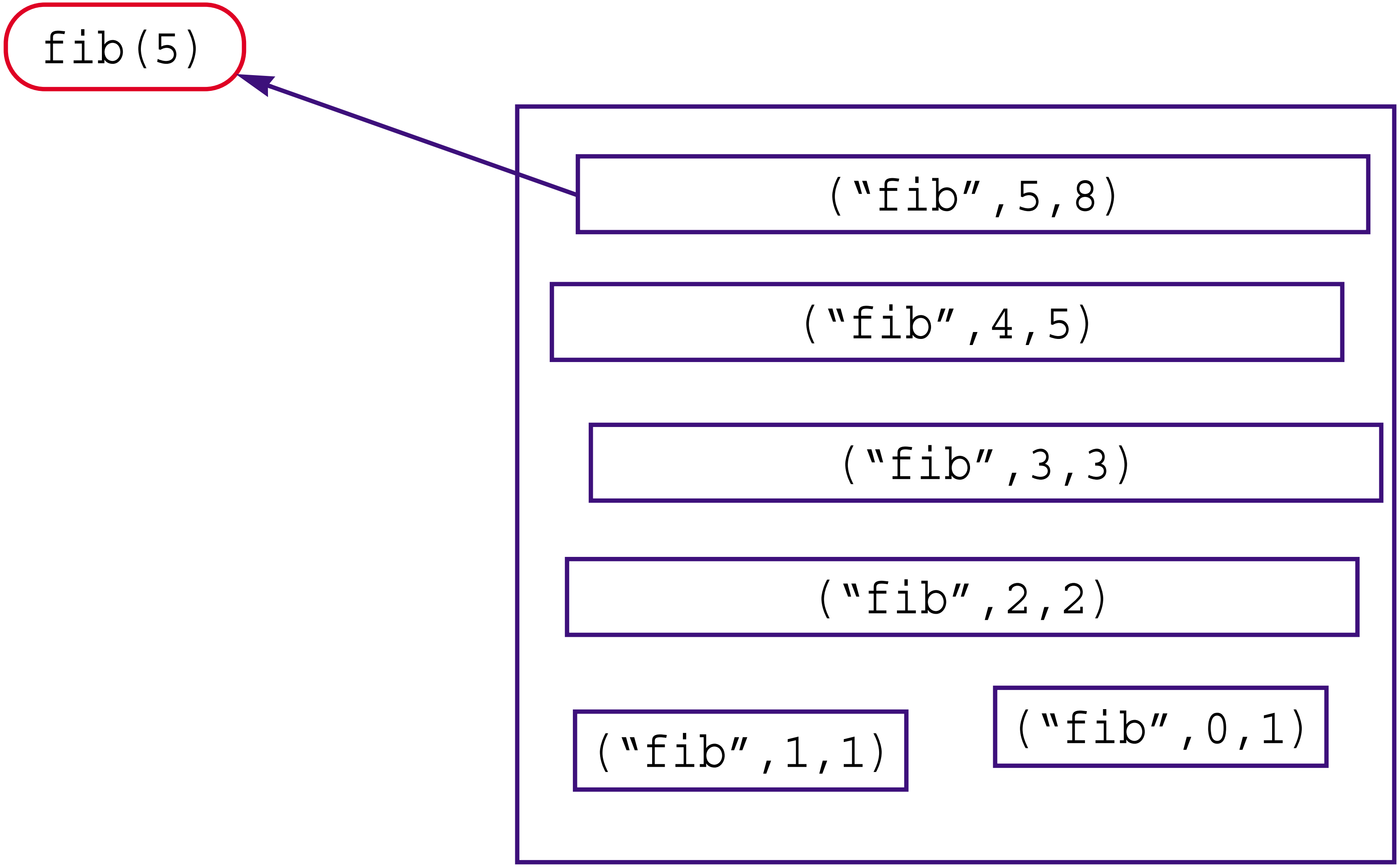
Evaluating Fibonacci



Evaluating Fibonacci



Evaluating Fibonacci



What you should know!

- ✎ *What is a Software Architecture?*
- ✎ *What are advantages and disadvantages of Layered Architectures?*
- ✎ *What is a Flow Architecture? What are the options and tradeoffs?*
- ✎ *What are Blackboard Architectures? What are the options and tradeoffs?*
- ✎ *How does result parallelism differ from agenda parallelism?*
- ✎ *How does Linda support coordination of concurrent agents?*

Can you answer these questions?

- ✎ How would you model message-passing agents in Java?
- ✎ How would you classify Client/Server architectures?
- ✎ Are there other useful styles we haven't yet discussed?
- ✎ How can we prove that the Active Prime Sieve is correct? Are you sure that new Active Primes will join the chain in the correct order?
- ✎ Which Blackboard styles are better when we have multiple processors?
- ✎ Which are better when we just have threads on a monoprocessor?
- ✎ What will happen if you start two concurrent Fibonacci computations?

13. Petri Nets

Overview

- ❑ Definition:
  - ☞ places, transitions, inputs, outputs
  - ☞ firing enabled transitions
- ❑ Modelling:
  - ☞ concurrency and synchronization
- ❑ Properties of nets:
  - ☞ liveness, boundedness
- ❑ Implementing Petri net models:
  - ☞ centralized and decentralized schemes

Reference: J. L. Peterson, *Petri Nets Theory and the Modelling of Systems*, Prentice Hall, 1983.

Petri nets: a definition

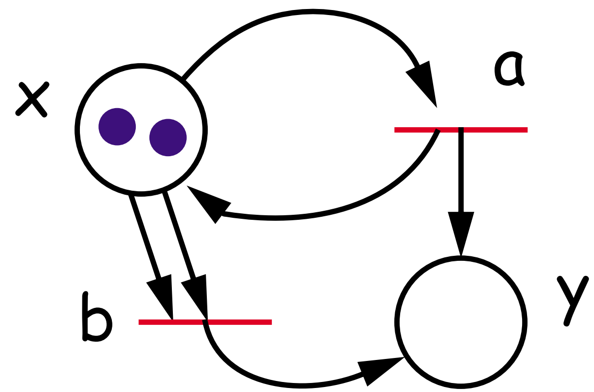
A *Petri net* C = ⟨P,T,I,O⟩ consists of:

1. A finite set P of *places*
2. A finite set T of *transitions*
3. An *input* function I: $T \rightarrow \mathcal{N}^P$ (maps to *bags* of places)
4. An *output* function O: $T \rightarrow \mathcal{N}^P$

A *marking* of C is a mapping $\mu: P \rightarrow \mathcal{N}$

Example:

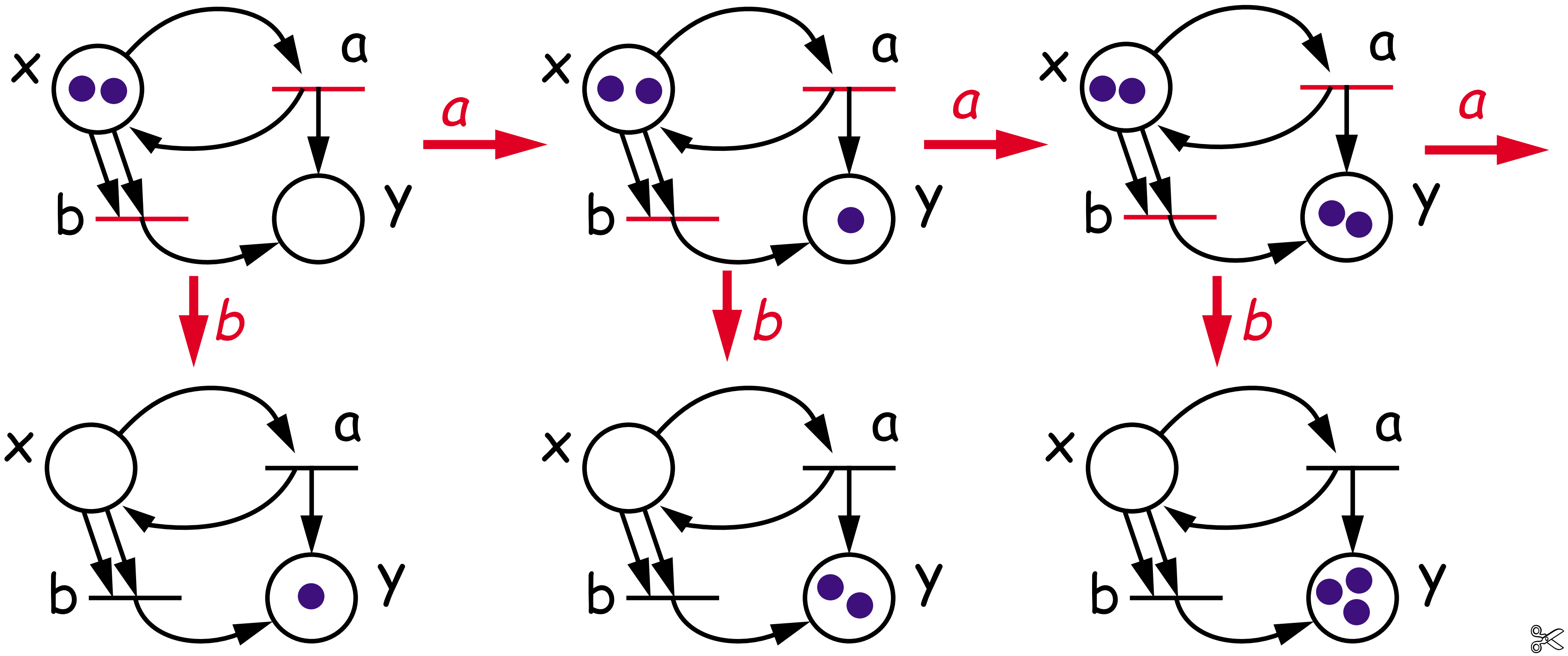
P = { x, y }
T = { a, b }
I(a) = { x }, I(b) = { x, x }
O(a) = { x, y }, O(b) = { y }
μ = { x, x }



Firing transitions

To fire a transition t:

1. There must be enough input tokens: $\mu \geq I(t)$
2. Consume inputs and generate output: $\mu' = \mu - I(t) + O(t)$



Modelling with Petri nets

Petri nets are good for modelling:

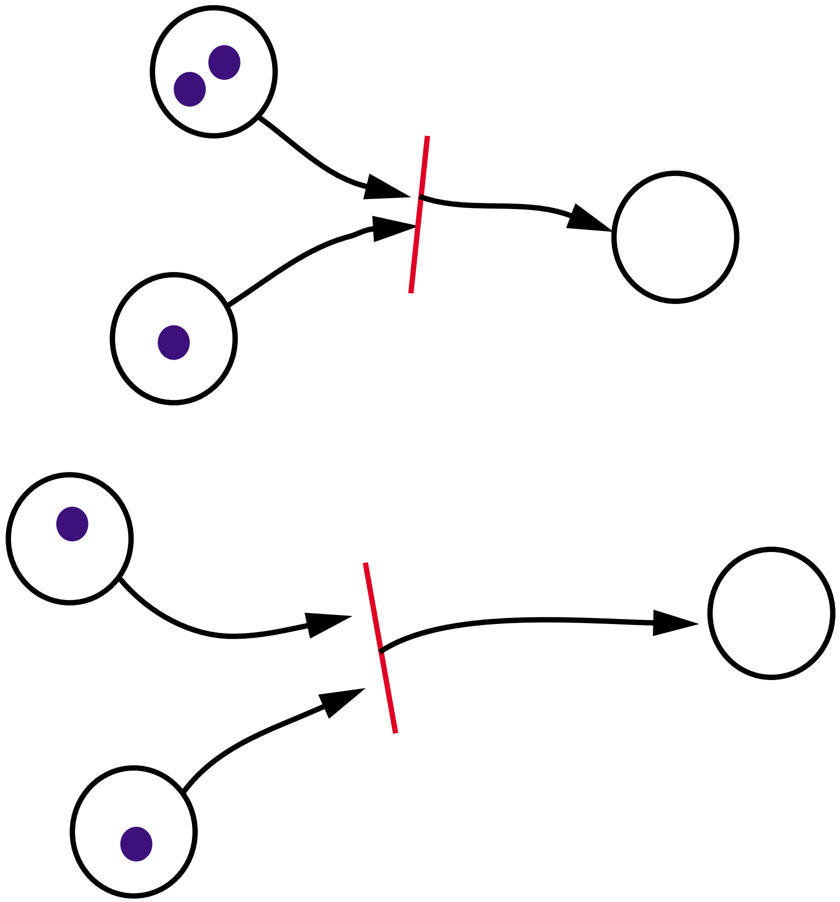
- concurrency
- synchronization

Tokens can represent:

- resource availability
- jobs to perform
- flow of control
- synchronization conditions ...

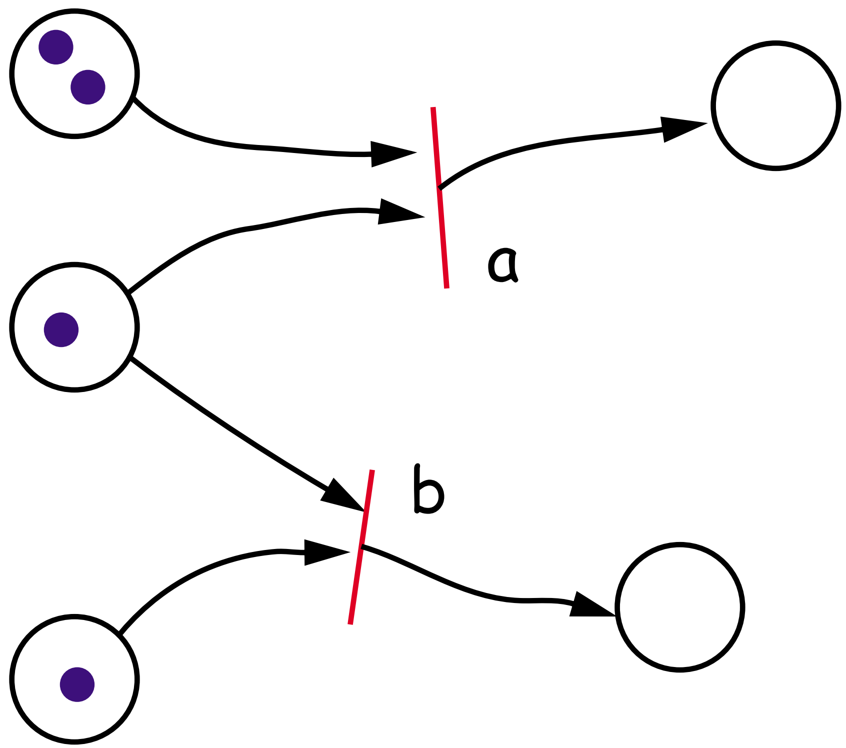
Concurrency

Independent inputs permit "concurrent" firing of transitions



Conflict

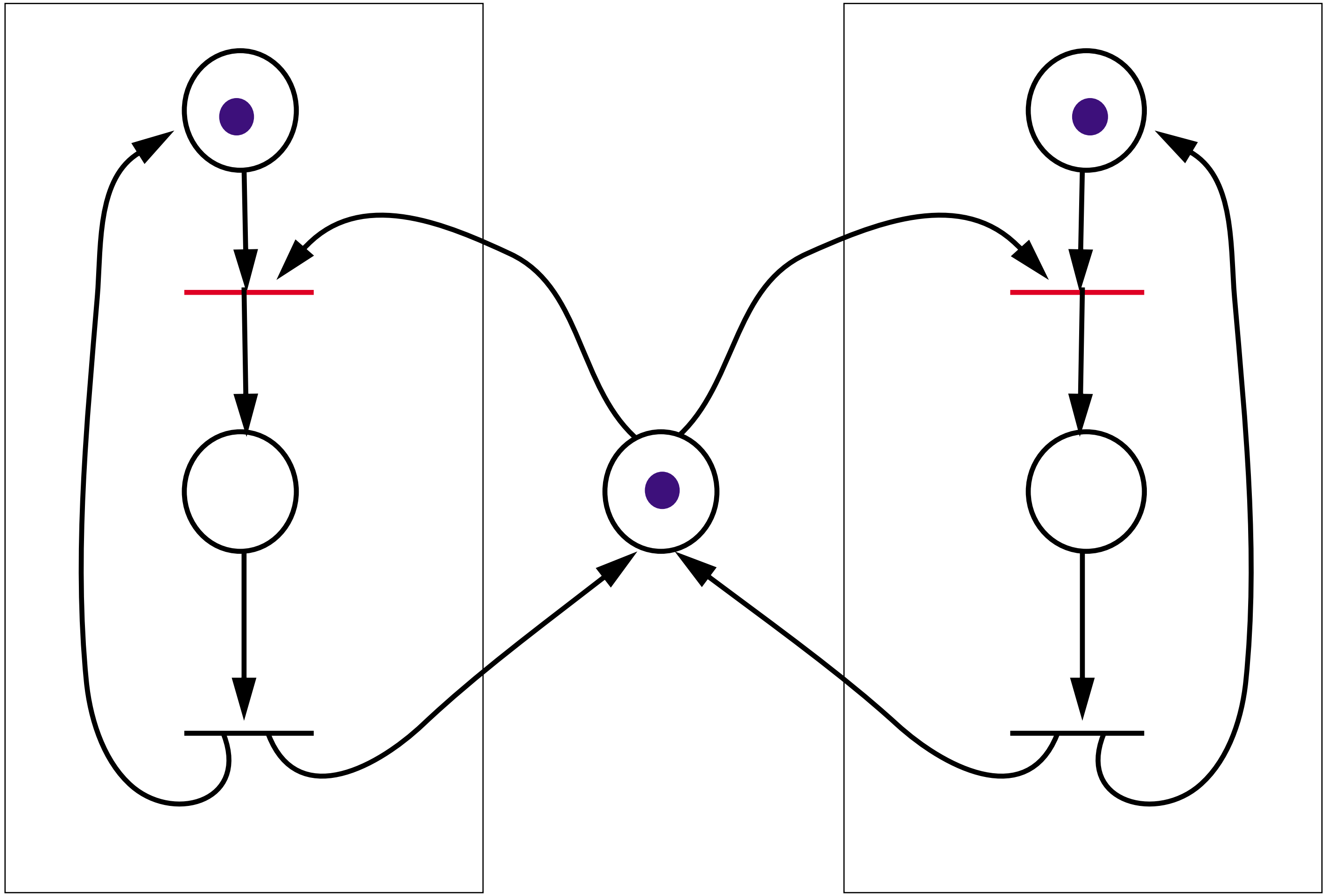
Overlapping inputs put transitions in conflict



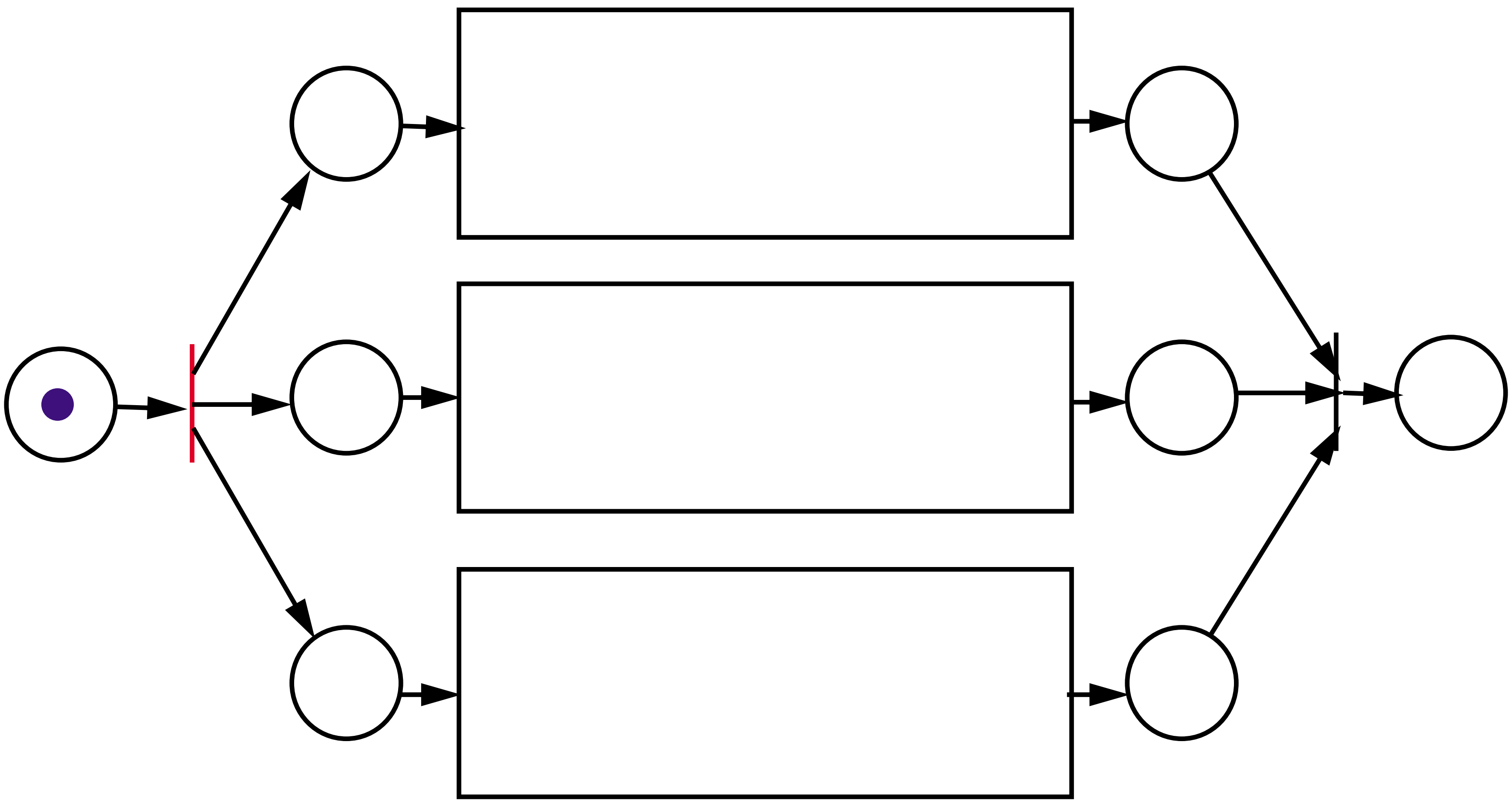
Only *one* of a or b may fire

Mutual Exclusion

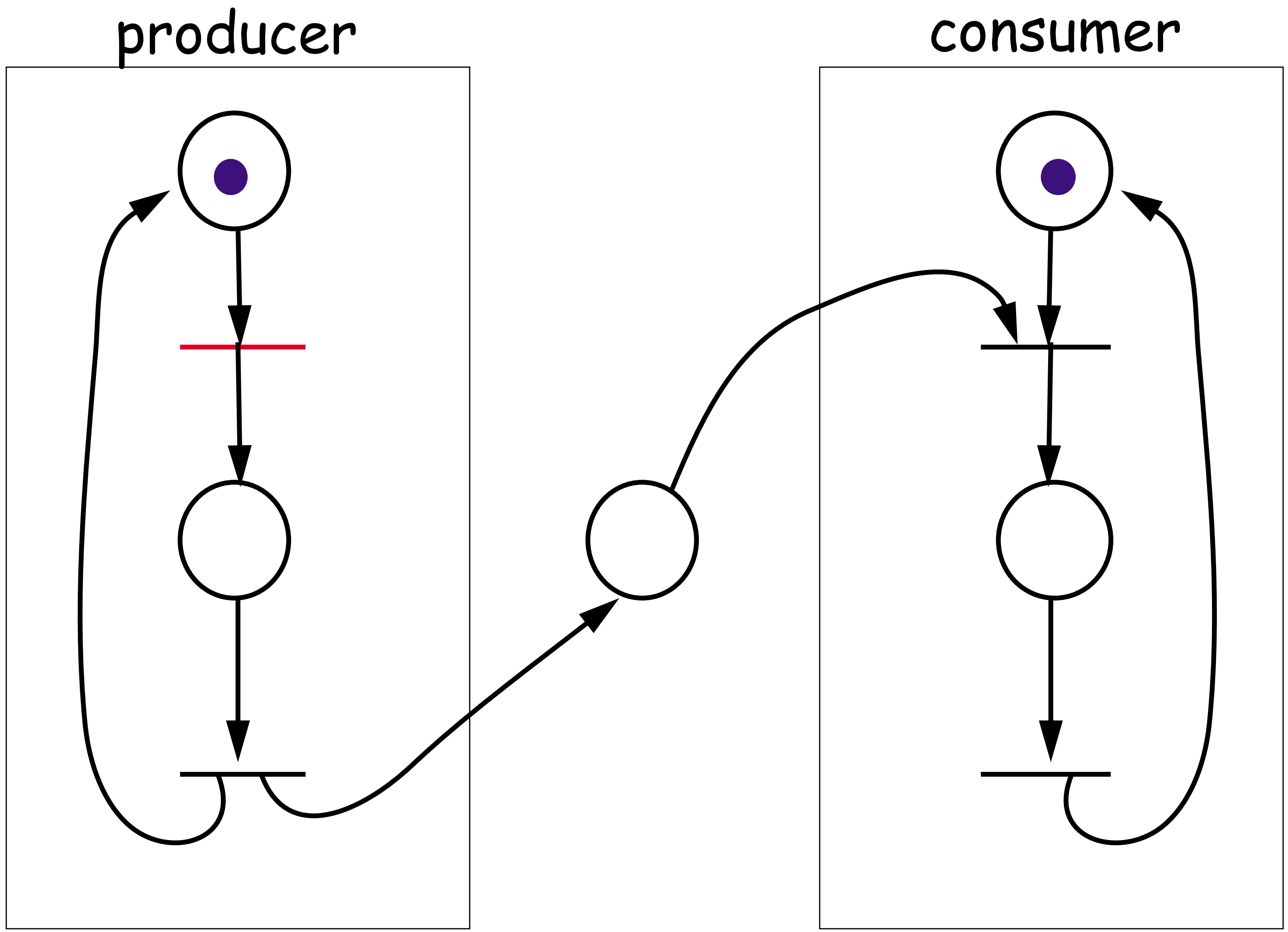
The two subnets are forced to synchronize



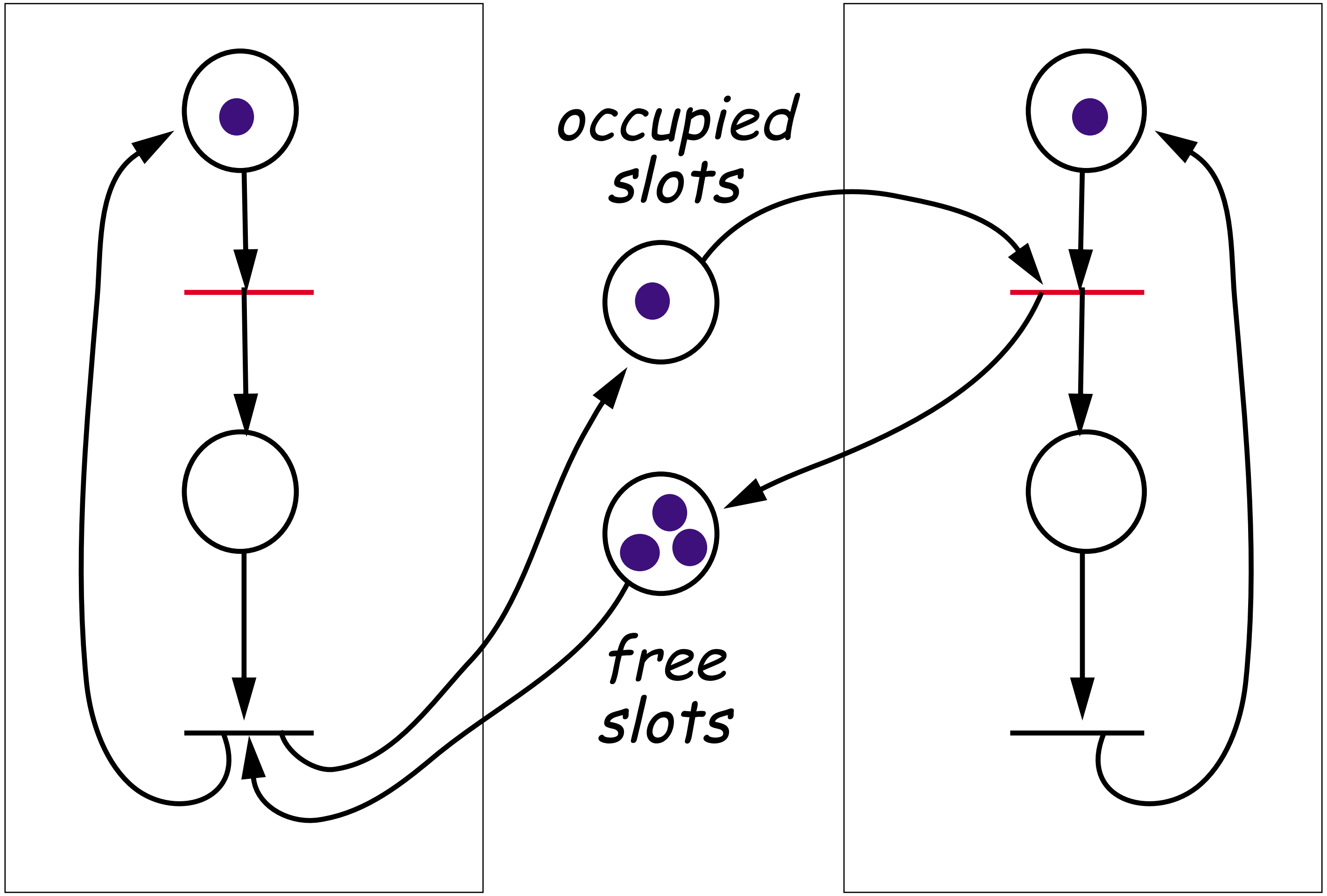
Fork and Join



Producers and Consumers



Bounded Buffers



Reachability and Boundedness

Reachability:

- The *reachability set* R(C,μ) of a net C is the set of all markings μ′ reachable from initial marking μ.

Boundedness:

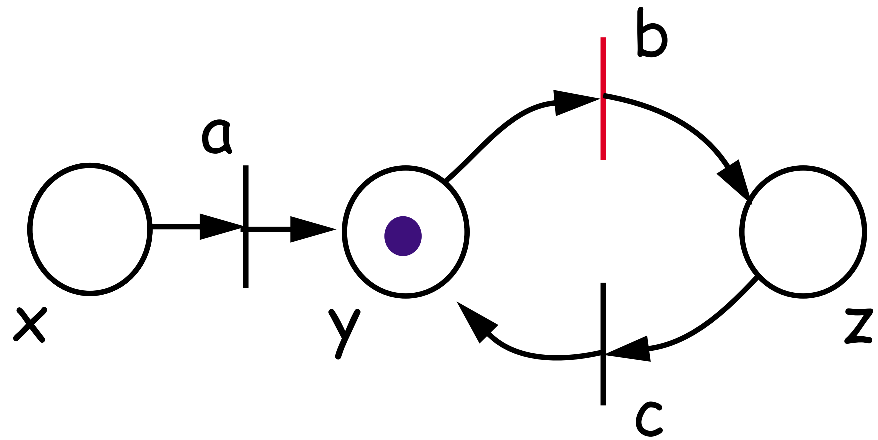
- A net C with initial marking μ is *safe* if places always hold at most 1 token.
- A marked net is *(k-)bounded* if places never hold more than k tokens.
- A marked net is *conservative* if the number of tokens is constant.

Liveness and Deadlock

Liveness:

- A transition is *deadlocked* if it can never fire.
- A transition is *live* if it can never deadlock.

This net is both *safe* and *conservative*.
Transition a is *deadlocked*.
Transitions b and c are *live*.
The *reachability set* is {{y}, {z}}.



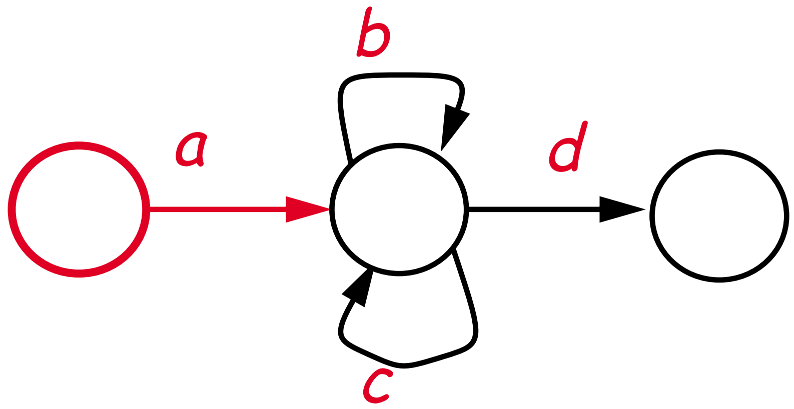
✎ *Are the examples we have seen bounded? Are they live?*

Related Models

Finite State Processes

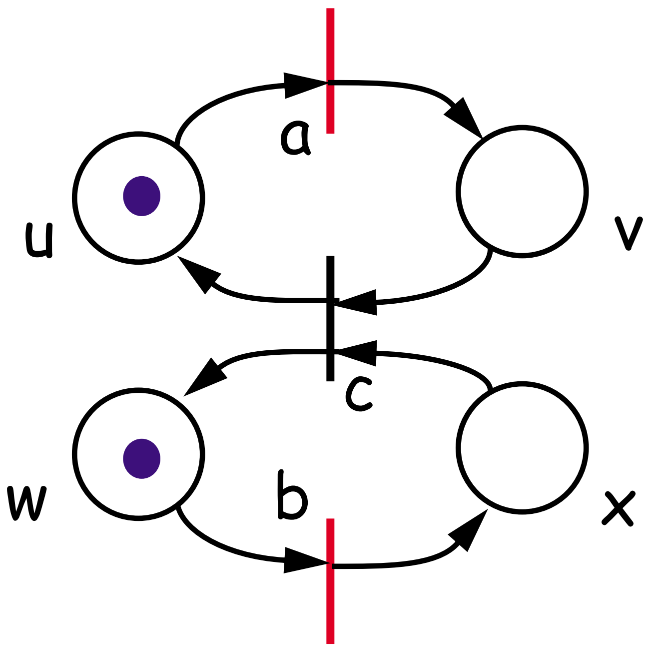
- Equivalent to *regular expressions*
- Can be modelled by *one-token conservative nets*

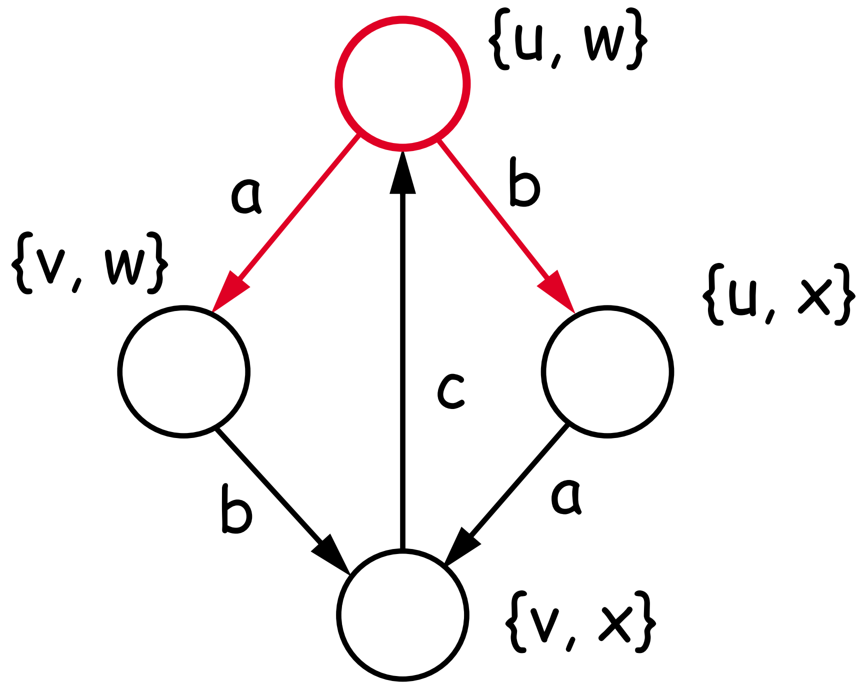
The FSA for: a(b|c)*d



Finite State Nets

Some Petri nets can be modelled by FSPs



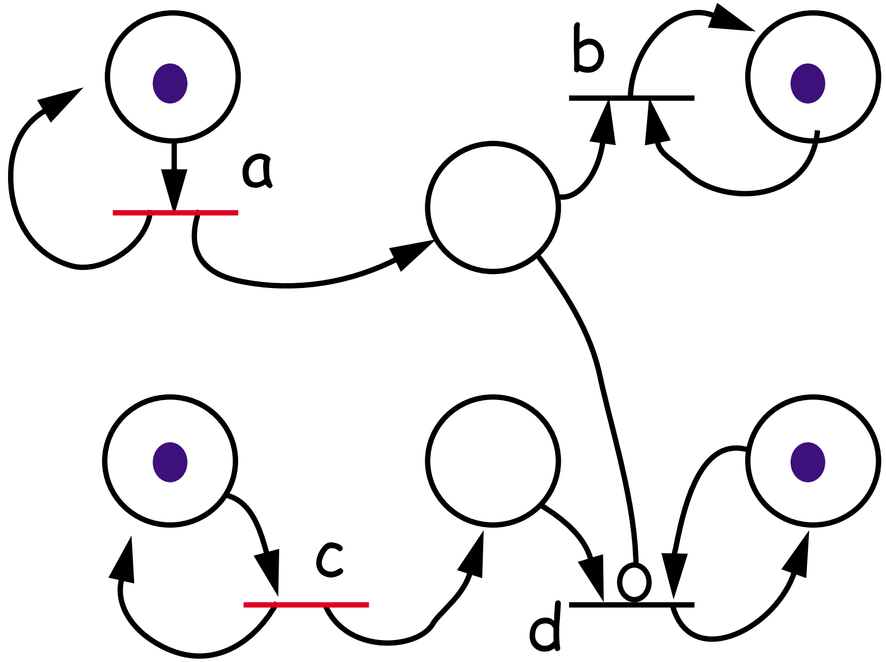


✎ *Precisely which nets can (cannot) be modelled by FSPs?*

Zero-testing Nets

Petri nets are not computationally complete

- Cannot model “zero testing”
- Cannot model priorities



A zero-testing net:

An equal number of
a and b transitions may fire
as a sequence during any
sequence of matching
c and d transitions.

(#a ≥ #b, #c ≥ #d)

Other Variants

There exist countless variants of Petri nets

Coloured Petri nets: Tokens are “coloured” to represent different *kinds* of resources

Augmented Petri nets: Transitions additionally depend on external *conditions*

Timed Petri nets: A *duration* is associated with each transition

Applications of Petri nets

Modelling information systems:

- Workflow
- Hypertext *(possible transitions)*
- Dynamic aspects of OODB design

Implementing Petri nets

We can implement Petri net structures in either *centralized* or *decentralized* fashion:

Centralized:

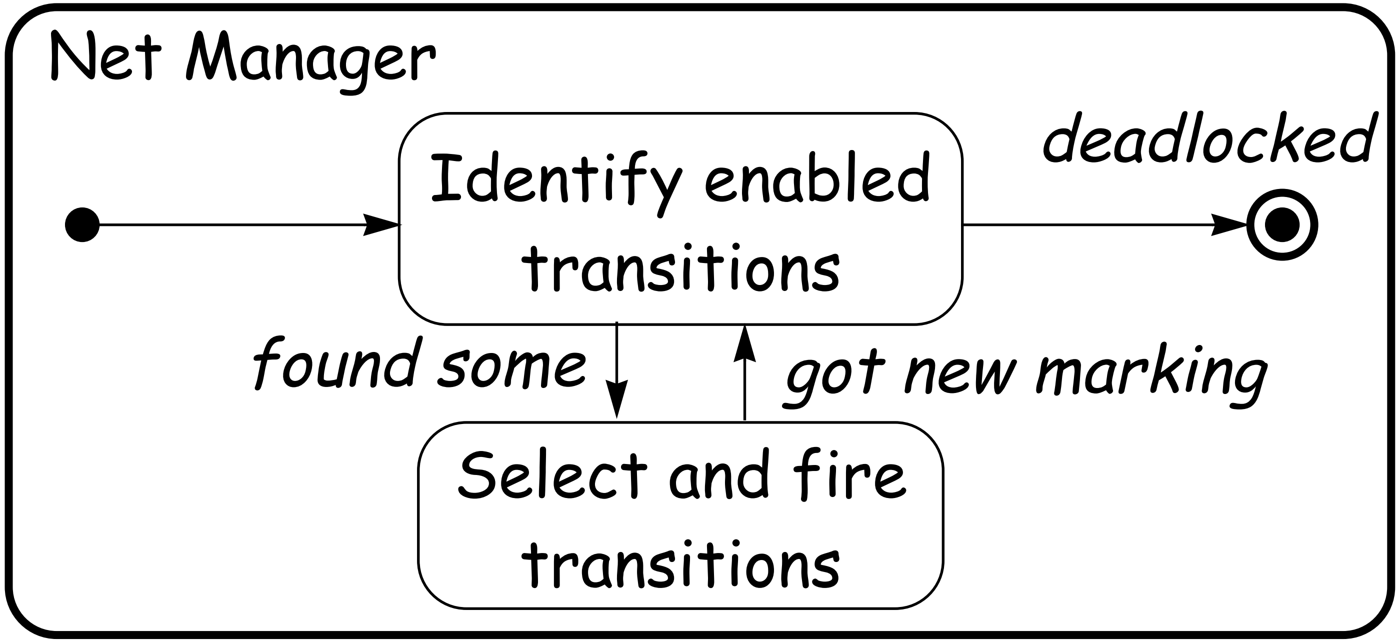
- A single *"net manager"* monitors the current state of the net, and fires enabled transitions.

Decentralized:

- *Transitions* are *processes*, *places* are shared *resources*, and transitions compete to obtain tokens.

Centralized schemes

In one possible centralized scheme, the Manager selects and fires enabled transitions.

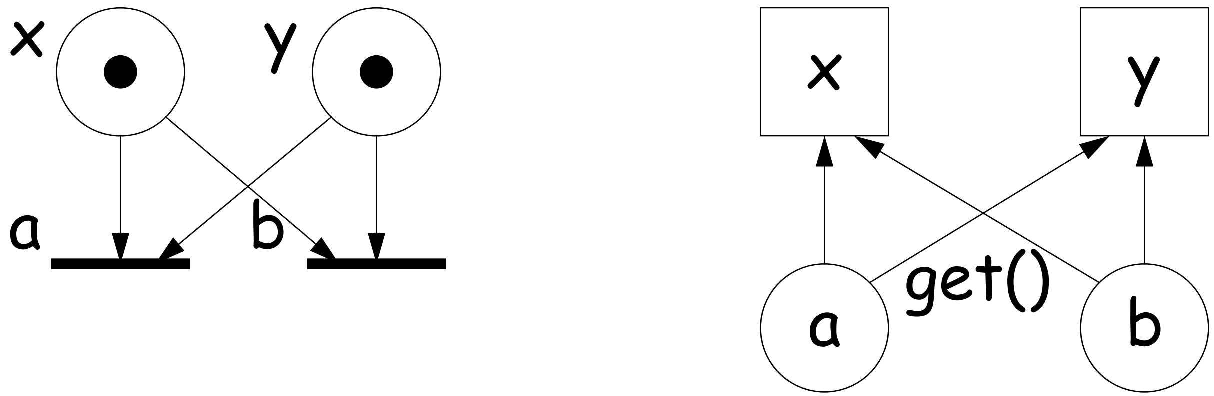


Concurrently enabled transitions can be fired in parallel.

✎ *What liveness problems can this scheme lead to?*

Decentralized schemes

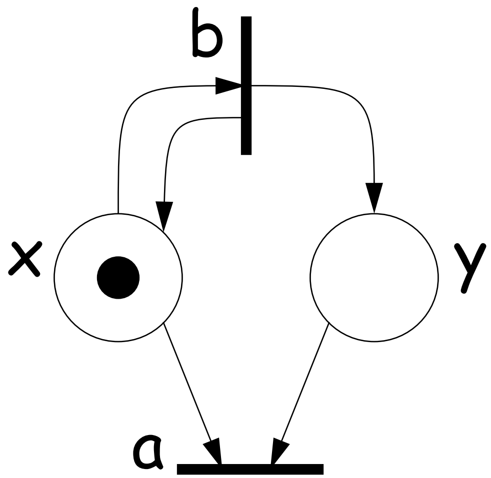
In decentralized schemes transitions are processes and tokens are resources held by places:



Transitions can be implemented as *thread-per-message gateways* so the same transition can be fired more than once if enough tokens are available.

Transactions

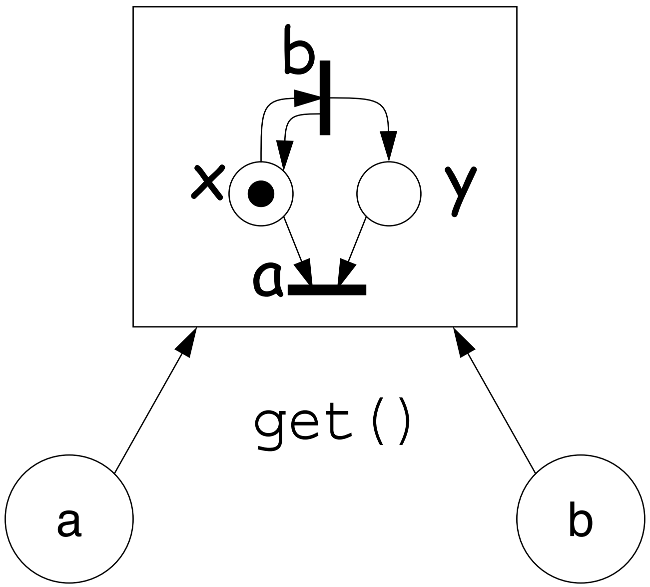
Transitions attempting to fire must grab their input tokens as an *atomic transaction*, or the net may deadlock even though there are enabled transitions!



If a and b are implemented by independent processes, and x and y by shared resources, this net can deadlock even though b is enabled if a (incorrectly) grabs x and waits for y.

Coordinated interaction

A simple solution is to treat the state of the entire net as a single, shared resource:



After a transition fires, it notifies waiting transitions.

✎ *How could you refine this scheme for a distributed setting?*

What you should know!

- ✎ *How are Petri nets formally specified?*
- ✎ *How can nets model concurrency and synchronization?*
- ✎ *What is the "reachability set" of a net? How can you compute this set?*
- ✎ *What kinds of Petri nets can be modelled by finite state processes?*
- ✎ *How can a (bad) implementation of a Petri net deadlock even though there are enabled transitions?*
- ✎ *If you implement a Petri net model, why is it a good idea to realize transitions as "thread-per-message gateways"?*

Can you answer these questions?

- *What are some simple conditions for guaranteeing that a net is bounded?*
- *How would you model the Dining Philosophers problem as a Petri net? Is such a net bounded? Is it conservative? Live?*
- *What could you add to Petri nets to make them Turing-complete?*
- *What constraints could you put on a Petri net to make it fair?*