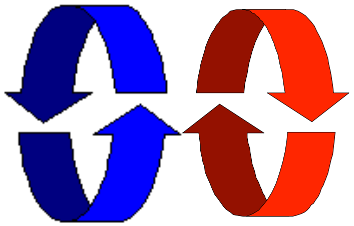
Chapter 3

Concurrent Execution



Concurrent execution

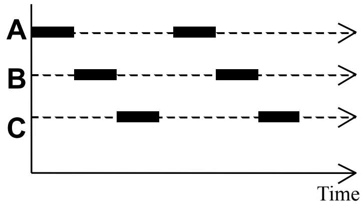
Concepts: processes - concurrent execution and interleaving.
process interaction.

Models: **parallel composition** of asynchronous processes - interleaving
interaction - shared actions
process labelling, and action relabelling and hiding
structure diagrams

Practice: Multithreaded Java programs

Definitions

- ***Concurrency***
  - *Logically* simultaneous processing.
  Does not imply multiple processing elements (PEs). Requires interleaved execution on a single PE.
- ***Parallelism***
  - *Physically* simultaneous processing.
  Involves multiple PEs and/or independent device operations.



Both concurrency and parallelism require controlled access to shared resources .We use the terms parallel and concurrent interchangeably and generally do not distinguish between real and pseudo-concurrent execution.

3.1 Modeling Concurrency

- How should we model process execution speed?
  - arbitrary speed
  (we abstract away time)
- How do we model concurrency?
  - arbitrary relative order of actions from different processes
  (**interleaving** but preservation of each process order)
- What is the result?
  - provides a general model independent of scheduling
  (**asynchronous** model of execution)

parallel composition - action interleaving

If P and Q are processes then (P||Q) represents the concurrent execution of P and Q. The operator || is the parallel composition operator.

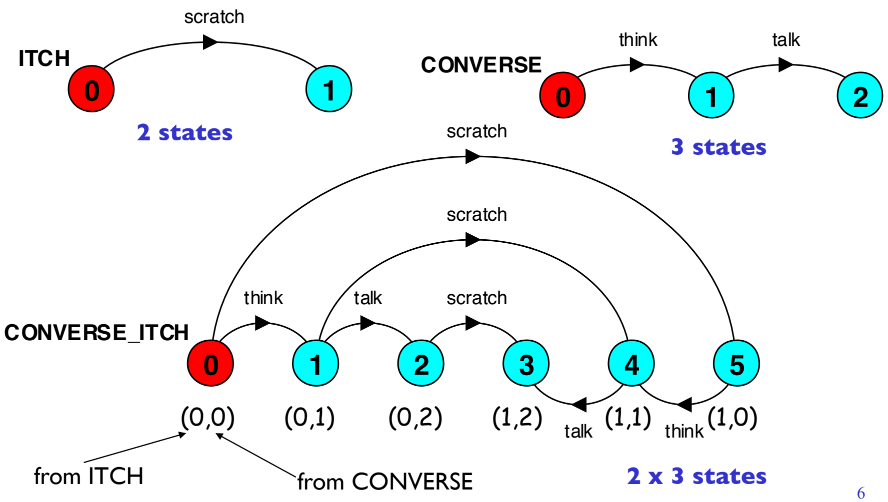
```
ITCH     = (scratch->STOP).
CONVERSE = (think->talk->STOP).

||CONVERSE_ITCH = (ITCH || CONVERSE).
```

Disjoint alphabets

```
think→talk→scratch
think→scratch→talk
scratch→think→talk
```

Possible traces as a result of action interleaving.

parallel composition - action interleaving



parallel composition - algebraic laws

Commutative: (P||Q) = (Q||P)
Associative: (P||(Q||R)) = ((P||Q)||R) = (P||Q||R).

Clock radio example:

```
CLOCK = (tick->CLOCK).
RADIO = (on->off->RADIO).

||CLOCK_RADIO = (CLOCK || RADIO).
```

LTS? Traces? Number of states?

modelling interaction - shared actions

If processes in a composition have actions in common, these actions are said to be ***shared***. Shared actions are the way that process interaction is modeled. While unshared actions may be arbitrarily interleaved, a shared action must be executed at the same time by all processes that participate in the shared action.

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

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

MAKER synchronizes with **USER** when **ready**.

Non-disjoint alphabets

LTS? Traces? Number of states?

modelling interaction - handshake

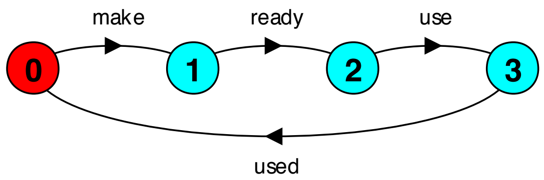
A handshake is an action acknowledged by another:

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

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

3 states

3 states

3 x 3 states?



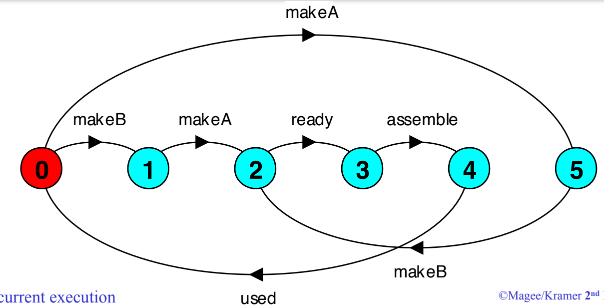
4 states

Interaction constrains the overall behaviour.

modelling interaction - multiple processes

Multi-party synchronization:

```
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).
```



composite processes

A composite process is a parallel composition of primitive processes. These composite processes can be used in the definition of further compositions.

```
||MAKERS = (MAKE_A || MAKE_B).

||FACTORY = (MAKERS || ASSEMBLE).
```

Substituting the definition for **MAKERS** in **FACTORY** and applying the **commutative** and **associative** laws for parallel composition results in the original definition for **FACTORY** in terms of primitive processes.

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


Example: a roller coaster model

A roller coaster control system only permits its car to depart when it is full.

Passengers arriving at the departure platform are registered by a turnstile. The controller signals the car to depart when there are enough passengers on the platform to fill the car to its maximum capacity of M passengers. The car then goes around the roller coaster track and then waits for another M passengers. A maximum of M passengers may occupy the platform.

The roller coaster consists of three interacting processes TURNSTILE, CONTROL and CAR.

Example: an abstract roller coaster model

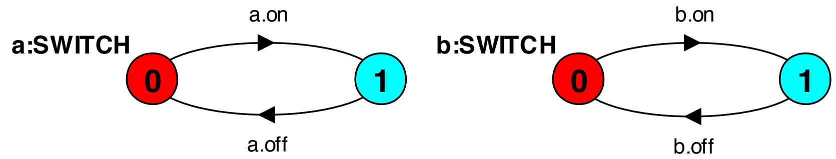
```
const M = 3

//turnstile simulates passenger arrival
TURNSTILE = ( … -> TURNSTILE).

//control counts passengers and signals when full
CONTROL          = CONTROL[0],
CONTROL[i:0..M]=( …              -> CONTROL[i+1]
                | …              -> CONTROL[0]
                ).

//car departs when signalled
CAR = ( … -> CAR).

||ROLLERCOASTER = ( … ).
```


process instances and labelling

a:P creates an instance of process P and prefixes each action label in the alphabet of P with a.

Two **instances** of a switch process:

```
SWITCH =  (on->off->SWITCH).
||TWO_SWITCH = (a:SWITCH || b:SWITCH).
```



An array of **instances** of the switch process:

```
||SWITCHES(N=3) = (forall[i:1..N] s[i]:SWITCH).
||SWITCHES(N=3) = (s[i:1..N]:SWITCH).
```

action relabelling

Relabelling functions are applied to processes to change the names of action labels. The general form of the relabeling function is:
/{*newlabel_1*/*oldlabel_1*,… *newlabel_n*/*oldlabel_n*}.

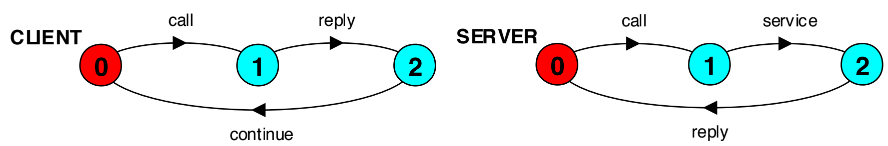
Relabelling to ensure that composed processes synchronize on particular actions.

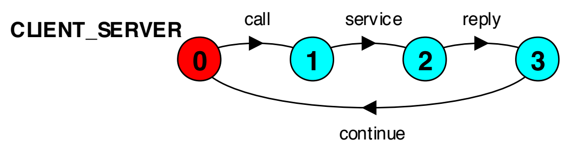
```
CLIENT = (call->wait->continue->CLIENT).
SERVER = (request->service->reply->SERVER).
```

Note that both *newlabel* and *oldlabel* can be sets of labels.

action relabelling

```
||CLIENT_SERVER = (CLIENT || SERVER)
                  /{call/request, reply/wait}.
```





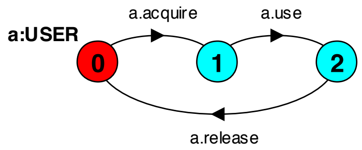
process labelling by a set of prefix labels

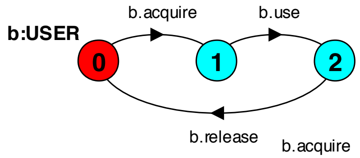
{a1,..,ax}::P replaces every action label n in the alphabet of P with the labels a1.n,…,ax.n. Thus, every transition (n->X) in the definition of P is replaced with the transitions ({a1.n,…,ax.n} ->X).

Process prefixing is useful for modelling **shared** resources:

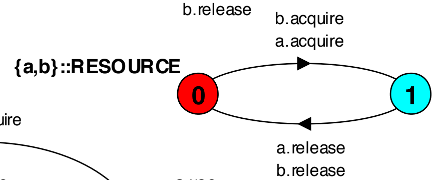
```
RESOURCE = (acquire->release->RESOURCE).
USER = (acquire->use->release->USER).

||RESOURCE_SHARE = (a:USER || b:USER
                    || {a,b}::RESOURCE).
```

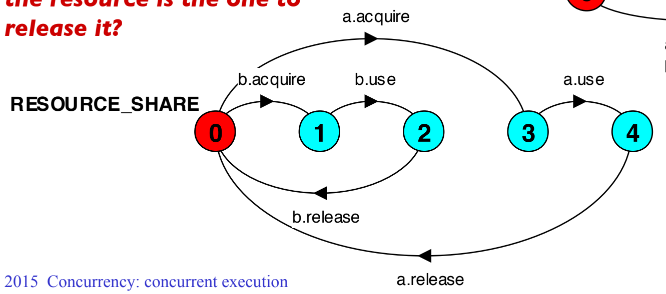

process prefix labels for shared resources





How does the model ensure that the user that acquires the resource is the one to release it?





Can this be achieved using relabelling rather than sharing? How?

action relabelling - prefix labels

An alternative formulation of the client server system is described below using qualified or prefixed labels:

```
SERVERv2 = (accept.request
           ->service->accept.reply->SERVERv2).
CLIENTv2 = (call.request
           ->call.reply->continue->CLIENTv2).

||CLIENT_SERVERv2 = (CLIENTv2 || SERVERv2)
                   /{call/accept}.
```


action hiding - abstraction to reduce complexity

When applied to a process P, the hiding operator \{a1..ax} removes the action names a1..ax from the alphabet of P and makes these concealed actions "silent". These silent actions are labeled tau. Silent actions in different processes are not shared.

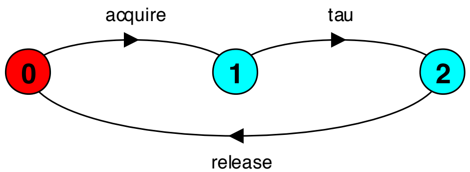
Sometimes it is more convenient to specify the set of labels to be exposed....

When applied to a process P, the interface operator @{a1..ax} hides all actions in the alphabet of P not labeled in the set a1..ax.

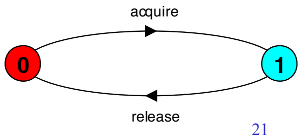
action hiding

The following definitions are equivalent:

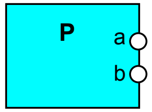
```
USER = (acquire->use->release->USER)
       \{use}.

USER = (acquire->use->release->USER)
        @{acquire,release}.
```



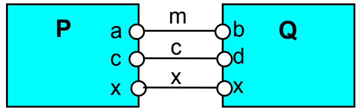
Minimization removes hidden **tau** actions to produce an LTS with equivalent observable behaviour.



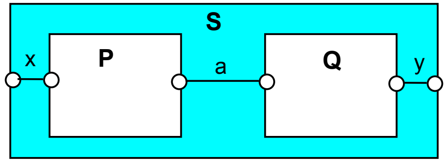
structure diagrams – systems as interacting processes



Process P with alphabet {a,b}.



Parallel Composition
(P||Q) / {m/a,m/b,c/d}

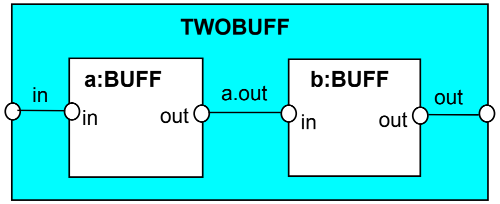


Composite process
||S = (P||Q) @ {x,y}

structure diagrams

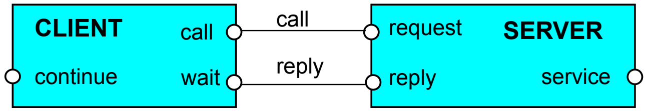
We use structure diagrams to capture the structure of a model expressed by the static combinators: *parallel composition*, *relabeling* and *hiding*.

```
range T = 0..3
BUFF = (in[i:T]->out[i]->BUFF).

||TWOBUF = ?
```

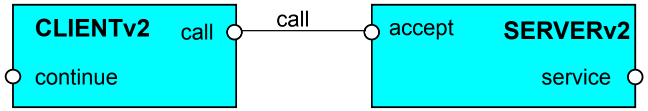


structure diagrams

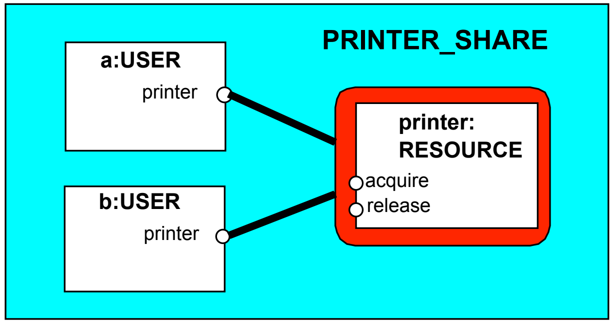
Structure diagram for **`CLIENT_SERVER`**



Structure diagram for **`CLIENT_SERVERv2`**



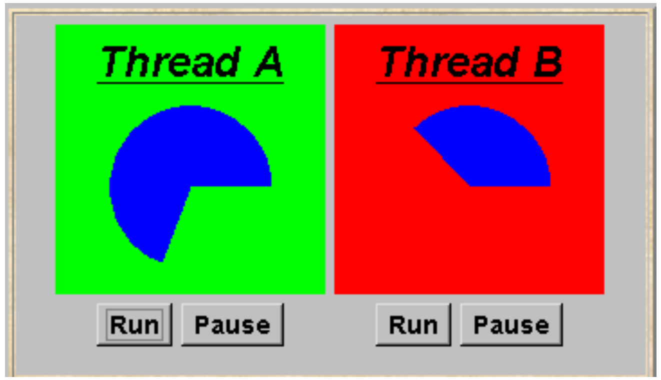
structure diagrams - resource sharing



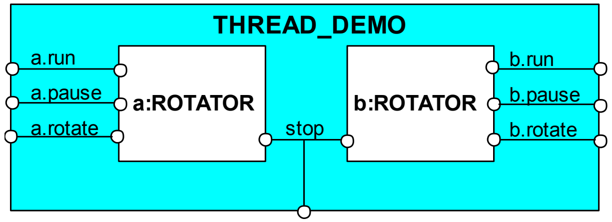

```
RESOURCE = (acquire->release->RESOURCE).
USER =     (printer.acquire->use
            ->printer.release->USER)\{use}.

||PRINTER_SHARE
  = (a:USER||b:USER||{a,b}::printer:RESOURCE).
```


3.2 Multi-threaded Programs in Java

Concurrency in Java occurs when more than one thread is alive. ThreadDemo has two threads which rotate displays.



ThreadDemo model

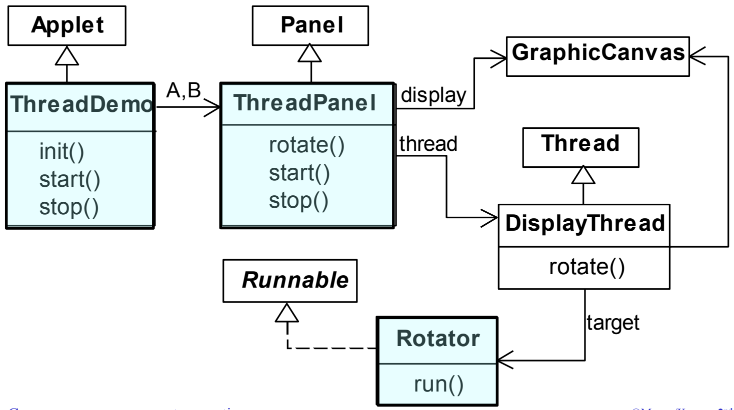



```
ROTATOR = PAUSED,
PAUSED  = (run->RUN | pause->PAUSED
          |interrupt->STOP),
RUN     = (pause->PAUSED |{run,rotate}->RUN
          |interrupt->STOP).

||THREAD_DEMO = (a:ROTATOR || b:ROTATOR)
 /{stop/{a,b}.interrupt}.
```

Interpret run, pause, interrupt as inputs, rotate as an output.

ThreadDemo implementation in Java - class diagram

`ThreadDemo` creates two **`ThreadPanel`** displays when initialized. **`ThreadPanel`** manages the display and control buttons, and delegates calls to **`rotate()`** to **`DisplayThread`**. **`Rotator`** implements the **`runnable`** interface.



Rotator class

```
class Rotator implements Runnable {

  public void run() {
    try {
      while(true) ThreadPanel.rotate();
    } catch(InterruptedException e) {}
  }
}
```

Rotator implements the **runnable** interface, calling **ThreadPanel.rotate()** to move the display.

run() finishes if an exception is raised by **Thread.interrupt()**.

ThreadPanel class

```
public class ThreadPanel extends Panel {

  // construct display with title and segment color c
  public ThreadPanel(String title, Color c) {…}

  // rotate display of currently running thread 6 degrees
  // return value not used in this example
  public static boolean rotate()
         throws InterruptedException {…}

  // create a new thread with target r and start it running
  public void start(Runnable r) {
        thread = new DisplayThread(canvas,r,…);
        thread.start();
  }

  // stop the thread using Thread.interrupt()
  public void stop() {thread.interrupt();}
}
```

ThreadPanel manages the display and control buttons for a thread.

Calls to **rotate()** are delegated to **DisplayThread**.

Threads are created and started by the **start()** method, and terminated by the **stop()** method.

ThreadDemo class

```
public class ThreadDemo extends Applet {
  ThreadPanel A; ThreadPanel B;

  public void init() {
    A = new ThreadPanel("Thread A",Color.blue);
    B = new ThreadPanel("Thread B",Color.blue);
    add(A); add(B);
  }

  public void start() {
    A.start(new Rotator());
    B.start(new Rotator());
  }

  public void stop() {
    A.stop();
    B.stop();
  }
}
```

ThreadDemo creates two **ThreadPanel** displays when initialized and two threads when started.

ThreadPanel is used extensively in later demonstration programs.

3.3 Java Concurrency Utilities Package

Java SE 5 introduced a package of advanced concurrency utilities in *java.util.concurrent* (more later). This was extended in Java SE 7 to include additional constructs to separate thread creation and management from the rest of the application using *executors*, *thread pools*, and *fork/join*.

Executor interface:	replacement for thread creation, usually using existing thread: replace *(new Thread(r)).start();* *runnable object r* with *e.execute(r);* *Executor object e*
ExecutorService:	manage termination; return a *Future* for tracking thread status
Thread Pools:	used to minimize the overhead of thread creation /termination *ExecutorService newFixedThreadPool(int nThreads)* - creates a fixed number with at most *nThreads* active threads - tasks are allocated from a shared unbounded queue
Fork/Join:	for recursive decomposition of tasks using thread pools

Summary

- Concepts
  - **concurrent processes and process interaction**
- Models
  - **Asynchronous** (arbitrary speed) **&** **interleaving** (arbitrary order).
  - **Parallel composition as a finite state process with action interleaving.**
  - **Process interaction by shared actions.**
  - **Process labeling and action relabeling and hiding.**
  - **Structure diagrams**
- Practice
  - **Multiple threads in Java.**