SE3BB4

Section 11

Concurrent (Software) Architectures

SOFTWARE ARCHITECTURE

- *Architecture* is used as a term to descrobe the gross structure of a system/application in terms of the structure of *components* and *connectors* comprising the system.
- The client-server architectures used in previous sections are examples of a standardised structure for a system.
  - the architecture can be described *without knowing the exact functionality and purpose of the system or its components*
  - only need info about how the components interact
  - can implement framework for system without knowing “internals”
- We look at some standard architectures for concurrent systems.

PIPES AND FILTERS

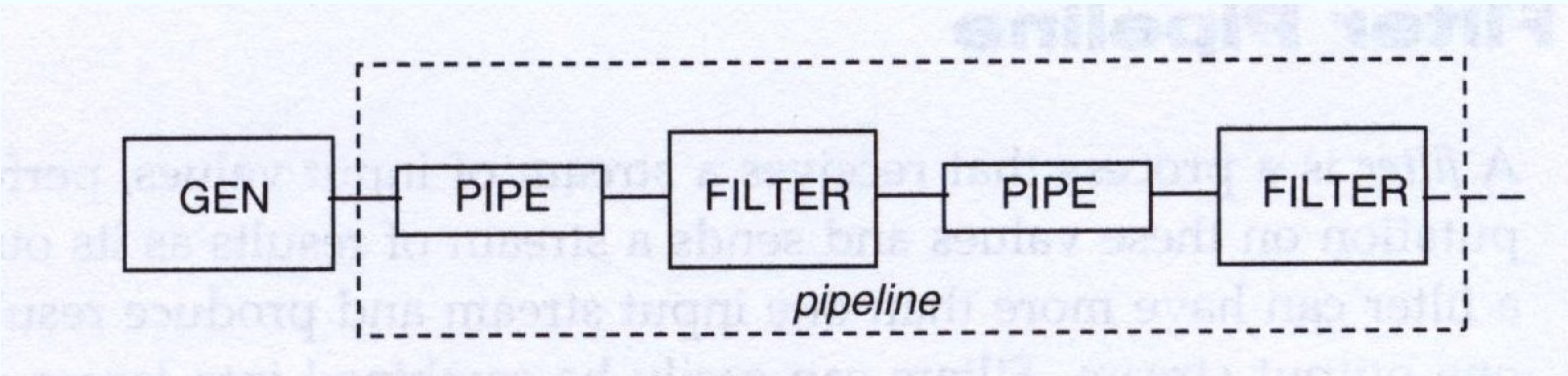
- A filter is a process that transforms a stream of inputs into a stream of outputs.
  - multiple input streams and multiple output streams possible
- Filters are connected together via pipes to form complex networks of processes, including feedback.
  - e.g., Unix
  - pipes may have buffered memory
- We study the classical algorithm called the sieve of Aritosthenes
  - provide a concurrent implementation via pipes and filters

SIEVE OF ARITOSTHENES

- Find all the primes between 2 and n:
  - list all the numbers between 2 and n
  - cross out all the numbers in the list divisible by 2
  - move to the next uncrossed out number and remove all multiples from the list
  - repeat the previous step until the end of the list is reached
  - the uncrossed out numbers are the primes
- The primes act as a sieve for the other numbers ...

SIEVE OF ARITOSTHENES

- The concurrent version generates a stream of numbers.
- Multiples (non primes) are removed by filter processes.
- The architecture is depicted below (without action and process labels):



McMaster University

SIEVE OF ARITOSTHENES

- We must define
  - the filtering processes
  - the interactions defined by pipes
- In the terminology of SW Architectures, pipes are connectors.
  - connectors define interaction between components in the architecture
  - both connectors and components are defined as processes in FSP

```
const MAX = 9
range NUM = 2..9
set S = {[NUM], eos}
PIPE = (put [x:S] -> get [x] -> PIPE)
```

SIEVE OF ARITOSTHENES

- The pipe processes numbers from 2 to MAX and the signal eos (end of stream signal).
- Need a new FSP mechanism: the conditional process.

if B **then** P **else** Q behaves as P if B is true and Q otherwise. If the ‘else’ is missing and B is false, it behaves like STOP.

```
GEN = GEN [2],
GEN [X:NUM] = (out.put [x] ->
               if x<MAX then
               GEN [X+1]
               else
               (out.put.eos -> enf -> GEN)
               ).
```


McMaster University

SIEVE OF ARITOSTHENES

- The filter process records the first value it gets and filters out multiples of that value.

```
FILTER = (in.get [x:NUM] ->
         |in.get.eos -> ENDFILTER
         ),
FILTER [P:NUM] = (in,get [x:NUM] ->
                   if x%p != 0 then
                        (out.put [x] -> FILTER
[p])
                   else FILTER [p]
                 |in.get.eos -> ENDFILTER
                 ),
ENDFILTER = (out.put.eos -> end -> FILTER).
```

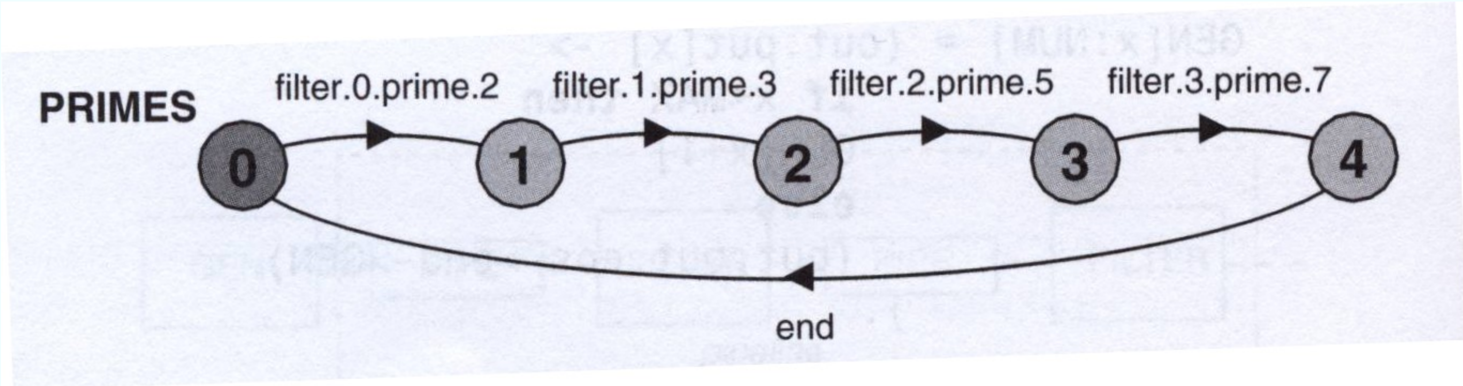
SIEVE OF ARITOSTHENES

- The composite structure is:

```
||PRIMES (N=4) =
    (gen:GEN
    ||pipe [0..N-1]:PIPE
    ||filter [0..N-1]:FILTER
    )/{  pipe [0]/gen.out,
         pipe [0..N-1]/filter [i].in,
         pipe [i:1..N-1]/filter [i-1].out,
         end/{filter [0..N-1].end, gen.end}
      }@{filter [0..N-1].prime, end}.
```

SIEVE OF ARITOSTHENES

- No deadlocks or errors detected!
  - used ‘end’ to differentiate normal termination in the model so that any error or deadlock was detectable as being different
- Minimised LTS:



- NOTE: model does not compute all primes between 2 and MAX! Computes first N primes where N is number of filters! (Change MAX too 11 and recompute LTS ...)

SIEVE OF ARITOSTHENES

- Previous model uses single slot buffers.
- What happens if we use no buffering?
- Construct a model in which pipes are omitted and filters interact via shared actions (the LTS will be the same!):

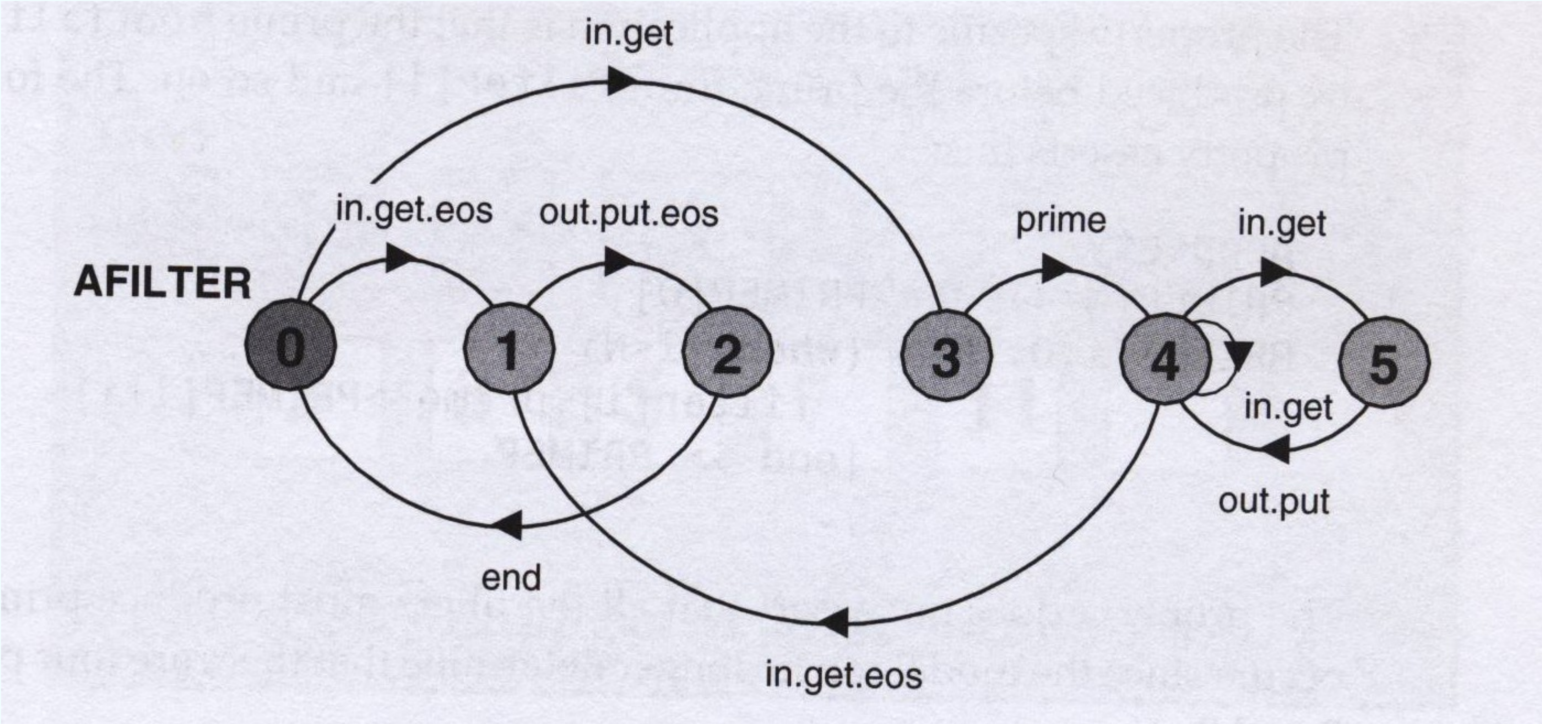
```
||PRIMESUNBUF (N=4) =
    (gen:GEN ||filter [0..N-1]:FILTER)
    /{   pipe [0]/gen.out.put,
         pipe [0..N-1]/filter [i].in.get,
         pipe[i:1..N-1]/filter[i-1].out.put,
         end/{filter [0..N-1].end, gen.end}
      }@{filter [0..N-1].prime, end}.
```

ABSTRACTING APPLICATION DETAIL

- If we want to analyse larger models, state space explosion becomes a problem.
- SOLUTION: abstract details of application
  - in this case details of sieve function
- MAGIC: relabel range of values NUM as a single value (independence from values).

```
||AGEN = GEN/{out.put/out.put [NUM]},
||AFILTER = FILTER/ {out.put/out.put [NUM]
                     in.get/in.get [NUM],
                     prime/prime [NUM]
                        }.
||APIPE = PIPE/{put/put [NUM], get/get [NUM]}.
```

ABSTRACTING APPLICATION DETAIL



- Determinitic conditional transition replaced here by nondeterministic choice:
- In state 4 after an `in.get`, the LTS goes to state 5 and does an `out.put` action or remains in state 4.

McMaster University

MORE BUFFERS

- Use a recursive definition of pipes to simulate multi slot buffer:

```
||MPIPE (B=4) =
    if B==1 then
        APIPE
    else
        (APIPE/{mid/get} || MPIPE (B-1)/
{mid/put})
    @{put,get}.
```

MORE BUFFERS

- The abstract model of the sieve architecture can be defined as follows, using `PRIMEP` defined later:

```
||APRIMES (N=4,B=3) =
   (gen:AGEN || PRIMEP (N)
   ||pipe [0..N-1]:MPIPE [B]
   ||filter [0..N-1]:AFILTER
   )/{  pipe [0]/gen.out,
        pipe [0..N-1]/filter [i].in,
        pipe [i:1..N-1]/filter [i-1].out,
        end/{filter [0..N-1].end, gen.end}
     }.
```

ARCHITECTURAL PROPERTIES

- Properties of such abstract models of software architectures are called architectural properties.
  - absence of deadlock
  - termination (absence of livelock)
- Termination is assured by the progress property `END`:

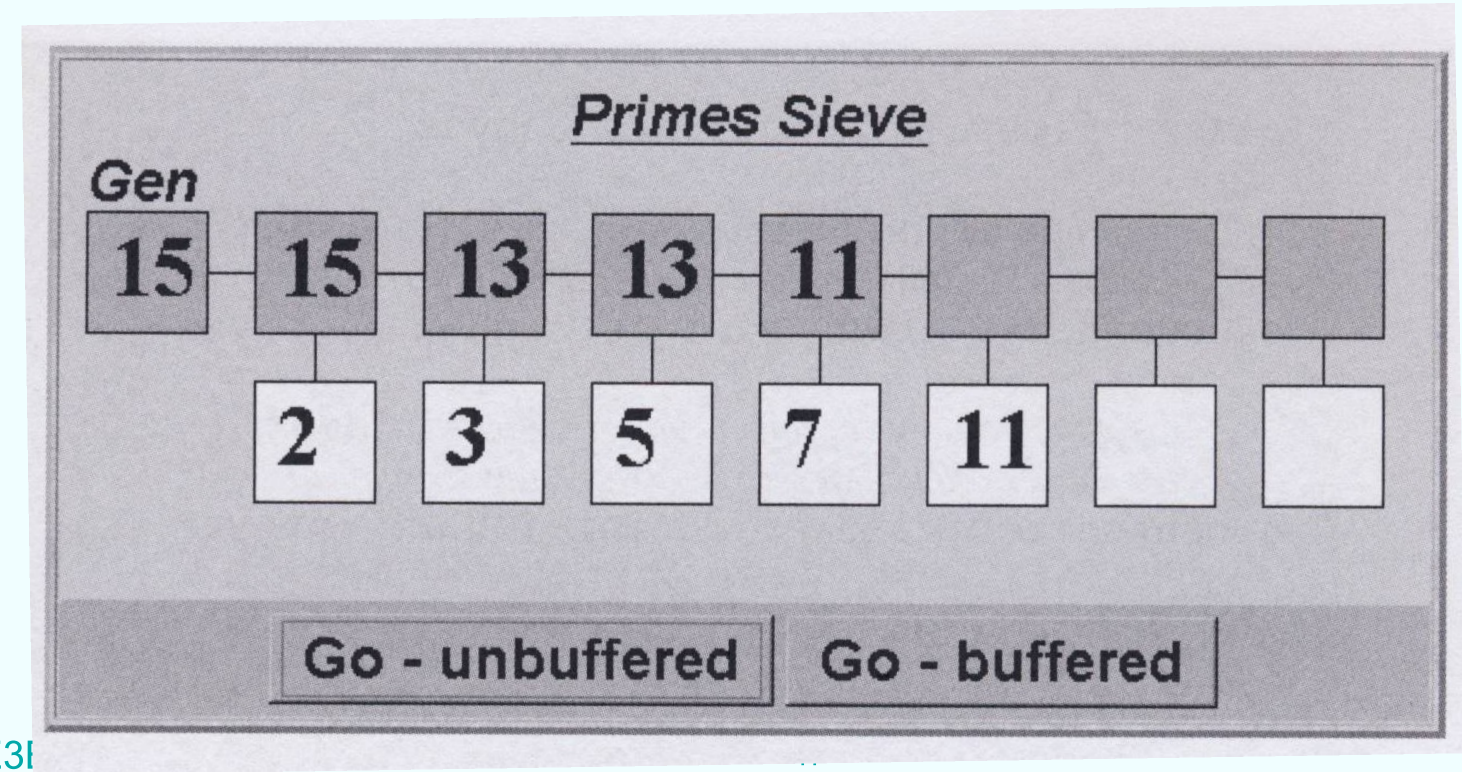
```
progress END = {end}
```

- An application specific property is that the prime from filter [0] should be produced before that from filter [1], etc

```
property
    PRIMEP(N=4)   = PRIMEP [0],
    PRIMEP[i:0..N] =(when (i<n)
                            filter[i].prime->PRIMEP[i+1]
                            |end -> PRIMEP ).
```

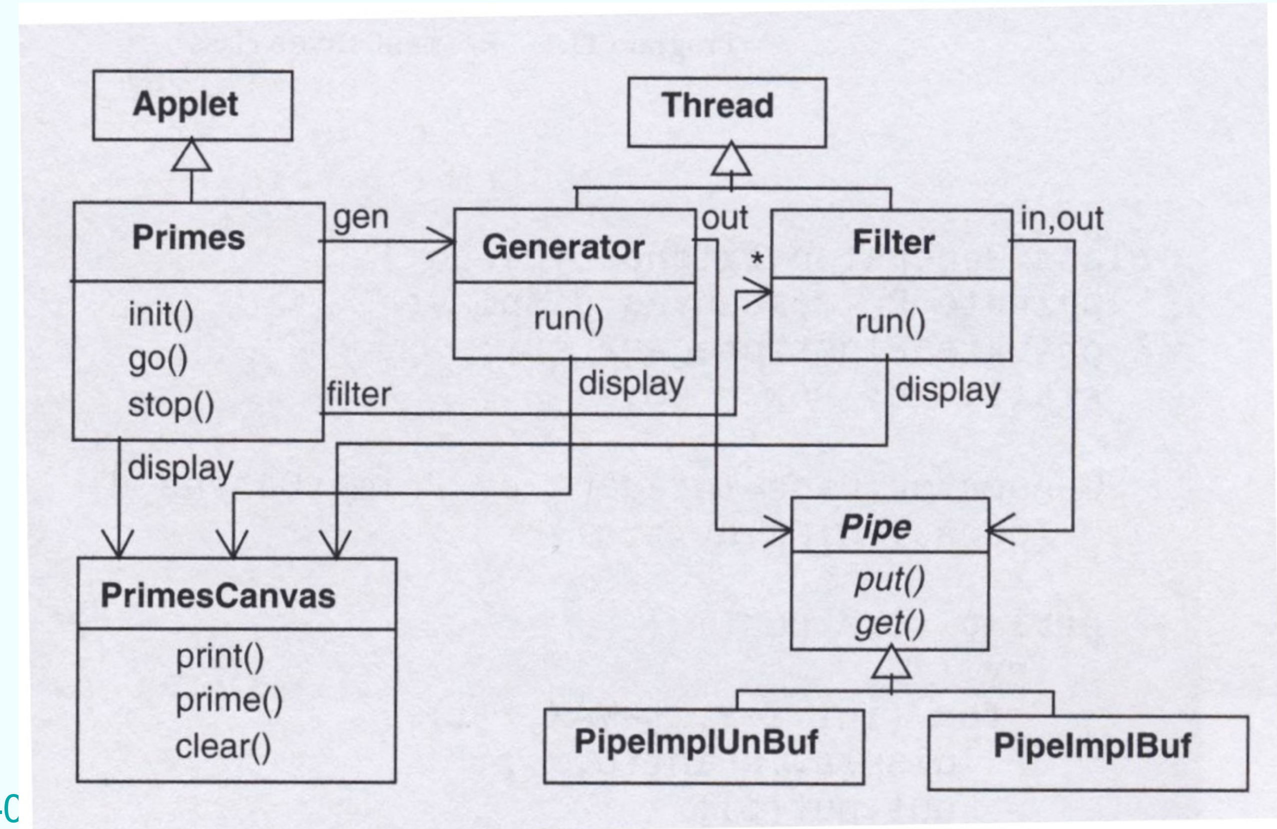
SIEVES IMPLEMENTATION

- Aplet displays with an unbuffered implementation.
- Top numbers are latest numbers generated/received by corresponding filter.



SIEVES IMPLEMENTATION

- Number generator and filters are implemented as threads.
- Two implementations of the pipe connector.



McMaster University

SIEVES IMPLEMENTATION

- The display is handled by `PrimeCanvas`.

```
class PrimesCanvas extends Canvas {

   // display val in an upper box numbered index
   // boxes are numbered from the left
synchronized void print(int index, int val){...}

   // display val in a lower box numbered index
   // the lower box indexed by 0 is not displayed
synchronized void prime(int index, int val){...}

   // clear all boxes
synchronized void clear(){...}

}
```

SIEVES IMPLEMENTATION: Generator

```
class Generator extends Thread {
  private PrimesCanvas display;
  private Pipe<Integer> out;
  static int MAX = 50;

  Generator(Pipe<Integer> c, PrimesCanvas d)
    {out=c; display = d;}

  public void run() {
    try {
      for (int i=2;i<=MAX;++i) {
        display.print(0,i);
        out.put(i);
        sleep(500);
      }
      display.print(0,Primes.EOS);
      out.put(Primes.EOS);
    } catch (InterruptedException e){}
  }

}
```

```
class Filter extends Thread {
  private PrimesCanvas display;
  private Pipe<Integer> in,out;
  private int index;

  Filter(Pipe<Integer> i, Pipe<Integer> o,
    int id, PrimesCanvas d)
    {in = i; out=o;display = d; index = id;}

  public void run() {
    int i,p;
    try {
      p = in.get();
      display.prime(index,p);
      if (p==Primes.EOS && out!=null) {
        out.put(p); return;
      }
      while(true) {
        i= in.get();
        display.print(index,i);
        sleep(1000);
        if (i==Primes.EOS) {
          if (out!=null) out.put(i); break;
        } else if (i%p!=0 && out!=null)
          out.put(i);
      }
    } catch (InterruptedException e){}
  }

}
```

SIEVES IMPLEME

- The implementation reuses classes developed earlier:
  - synchronous message passing class `Channel` unbuffered pipes
  - and bounded buffer class `BufferImpl` used to implement buffered pipes

```
public interface Pipe<T> {

  public void put(T o)
     throws InterruptedException; // put object into buffer

  public T get()
     throws InterruptedException; // get object from buffer
}

// Unbuffered pipe implementation
public class PipeImplUnBuf<T> implements Pipe<T> {
  Channel<T> chan = new Channel<T>();

  public void put(T o)
    throws InterruptedException {
    chan.send(o);
  }

  public T get()
    throws InterruptedException {
    return chan.receive();
  }
}

// Buffered pipe implementation
public class PipeImplBuf<T> implements Pipe<T> {
  Buffer<T> buf = new BufferImpl<T>(10);

  public void put(T o)
    throws InterruptedException {
    buf.put(o);
  }

  public T get()
    throws InterruptedException {
    return buf.get();
  }
}
```

SIEVES IMPLEMENTATION

```
private void go(boolean buffered) {
    display.clear();

    //create channels
    ArrayList<Pipe<Integer>> pipes =
      new ArrayList<Pipe<Integer>>();
      for (int i=0; i<N; ++i)
        if (buffered)
          pipes.add(new PipeImplBuf<Integer>());
        else
          pipes.add(new PipeImplUnBuf<Integer>());

    //create threads
    gen = new Generator(pipes.get(0),display);
    for (int i=0; i<N; ++i)
      filter[i] = new Filter(pipes.get(i),
                 i<N-1?pipes.get(i+1):null,i+1,display);
      gen.start();
      for (int i=0; i<N; ++i) filter[i].start();
  }
```

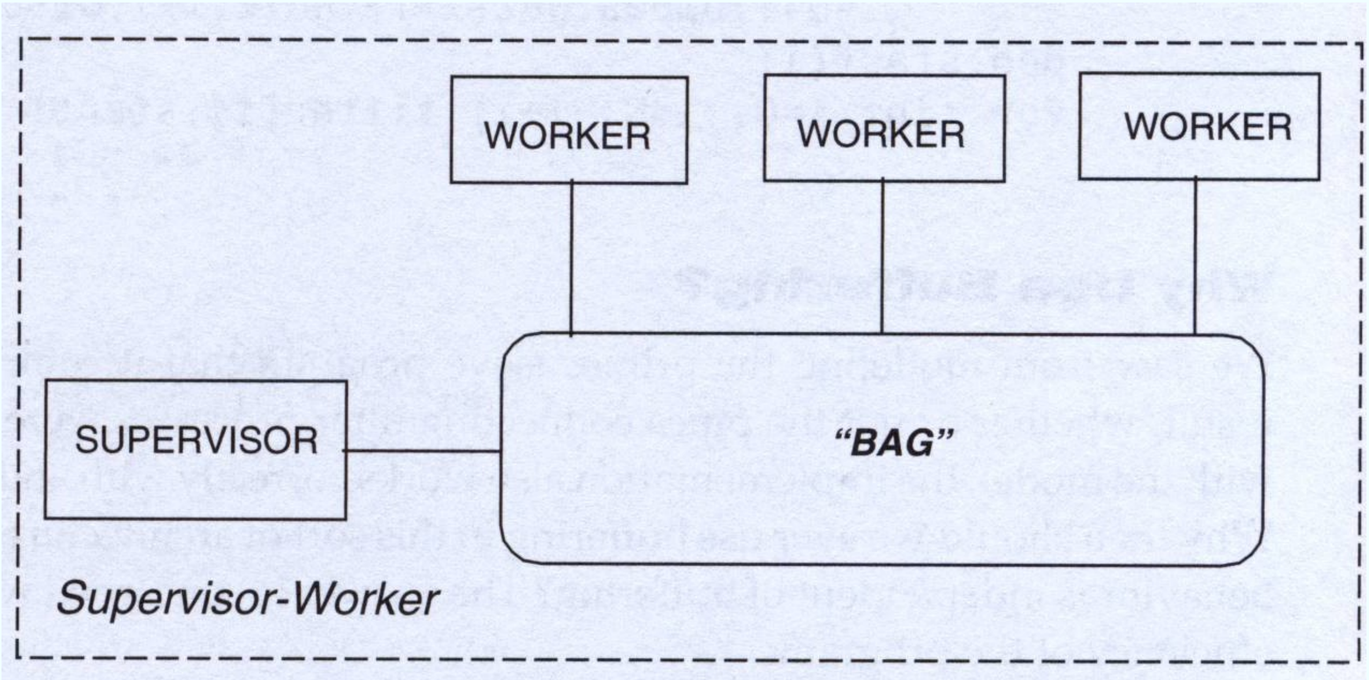

McMaster University

USING BUFFERS OR NOT

- Unbuffered version of the sieve algorithm works correctly.
- Why use buffers?
- Answer: efficiency!
- Process or thread suspension involves a context switch and this is expensive.
  - (thread switch less expensive than process switch)
- Concurrent programs run more efficiently if there are fewer context switches.
- No buffering means generator and filter threads are suspended every time they produce an item until consumed by next thread.
- With buffers, only a full buffer causes suspension.

SUPERVISOR-WORKER ARCHITECTURE

- Concurrent architecture to speed up execution of suitable applications.
  - applies when a problem can be split into a number of independent sub-problems
  - referred to as tasks



SUPERVISOR-WORKER ARCHITECTURE

- Supervisor and worker processes interact via a connector bag
  - supervisor puts initial set of tasks in bag
  - supervisor gets results from bag and determines when computation has finished
- Each worker repetitively
  - takes a task from the bag
  - computes the result and puts it back in bag
- Supervisor determines end of computation
- Workers can put new tasks into the bag
- Any number of workers is possible

LINDA TUPLE SPACES

- Interaction mechanism suitable for implementing bag
- Linda is a model of (parallel) computation
- Consists of a set of primitive operations used to access a data structure called a tuple space
- A tuple space is a shared associative memory with a collection of tagged data records

  (“tag”, value1, ..., valuen)
    - the tag is a literal string used to categorize tuples
    - valuei is a data value like integer, floating point, other data values
- Basic operations:
    - deposit a tuple in the space **out**(“tag”, expr1, ..., exprn)
    - execution completes when expri are evaluated and tuple is put in the tuple space

LINDA TUPLE SPACES

- similar to an asynchronous send, but “message” stored in tuple space instead of queue associated with a port
- **in**(“tag”, field1, ..., fieldn) removes tuple from space
- each fieldi is either an expression or a formal parameter of the form   ?var (var local to executing process)
- arguments to **in** are called templates
- process executing **in** blocks until there is a tuple in the space to match the template
- template match is defined as:
  - tags identical
  - same number of fields
  - expressions in template have same values as corresponding values in tuple
  - variables in template have same type as corresponding values in tuple
- like receive with matching used to identify “port”

LINDA TUPLE SPACES

- **rd**(“tag”, field1, ..., fieldn) reads a value from the tuple space without removing it
  - same conditions as **in**
- Linda provides nonblocking versions of **in** and **rd**, called **inp** and **rdp**, that return true tuple if tuple is there, false otherwise
- **eval** creates an active/process tuple
  - like **out**, but one of the arguments is a procedure that operates on other arguments
  - becomes a passive tuple when evaluation terminates

TUPLE SPACE MODEL

- Use finite set of tuple values
- Have to fix maximum number of copies of some tuple allowed

```
const N = ...
set Tuples = {...}
```

- N and Tuples depend on context
- Each tuple value modelled by FSP label of the form *tag.val1.....valn*
- Have a process to manage each tuple value and tuple space is parallel composition of all these processes

TUPLE SPACE MODEL

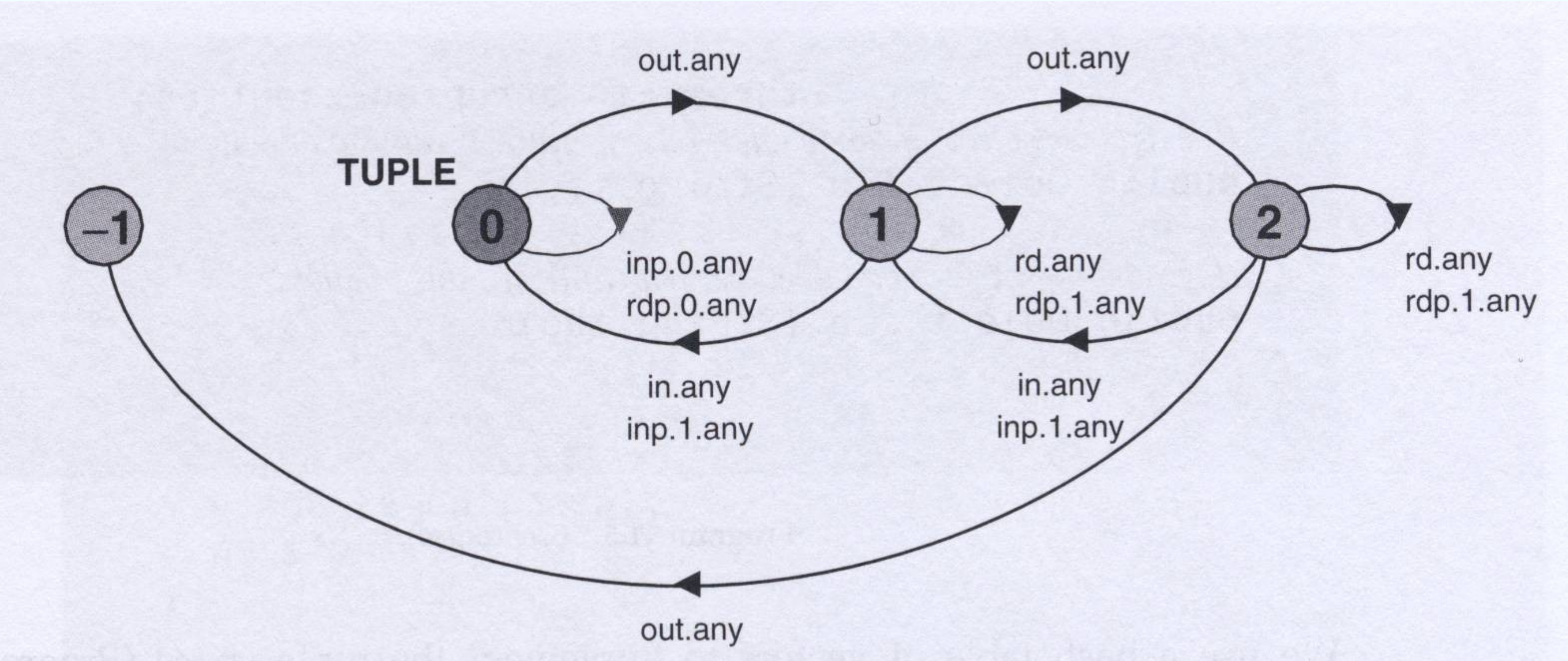
```
const False = 0
const True = 1
range Bool = False..True
TUPLE (T='any) = TUPLE [0].
TUPLE [i:0..N] =
  (out[T]                        ->    TUPLE[i+1]
  |when (i>0) in[T]              ->    TUPLE[i+1]
  |when (i>0) inp[True][T]       ->    TUPLE[i+1]
  |when (i==0) inp[False][T]     ->    TUPLE[i]
  |when (i>0) rd[T]              ->    TUPLE[i]
  rdp[i>0][T]
  ).

||TUPLESPACE = forall [t:Tuples] TUPLE(t).
```


McMaster University

TUPLE SPACE MODEL

- LTS for tuple value for `any` with N=2 is:



McMaster University

TUPLE SPACE MODEL

- Exceeding capacity with more than 2 **out** ops leads to an ERROR
- Example of a conditional operation on the tuple space

  inp [b:Bool][t:Tuples]
  - value of t only valid when b is True
- Each specific TUPLE process has in its alphabet the ops on one specific tuple value
- The alphabet of TUPLESPACE is

  set TupleAlpha = {{in,out,rd,rdp[Bool], inp[Bool]}.Tuples}

McMaster University

TUPLE SPACE IMPLEMENTATION

- Implement as centralized system for demo
- Matching of templates only on tag field
- Use a hash table of vectors to implement the space
- For simplicity, tuples stored in FIFO order for a particular tag
- New tuples appended at end of a vector for a tag and removed from its head
- Naively, all threads woken up whenever a new tuple is added
- More efficiently, we would wake only those waiting for tuple with the same tag

TUPLE SPACE IMPLEMENTATION

```
public interface TupleSpace {

   // deposits data in tuple space
   public void out (String tag, Object data);

   // extracts object with tag from tuple space, blocks if not available
   public Object in (String tag)
                          throws InterruptedException;
   // reads object with tag from tuple space, blocks if not available
   public Object rd (String tag)
                          throws InterruptedException;
   // extracts object if available, return null if not available
   public Object inp (String tag);

   // reads object if available, return null if not available
   public Object rdp (String tag);

}
```

```java
class TupleSpaceImpl implements TupleSpace {
  private Hashtable tuples = new Hashtable();

  public synchronized void out(String tag,Object data){
    Vector v = (Vector) tuples.get(tag);
    if (v == null) {
      v = new Vector();
      tuples.put(tag,v);
    }
    v.addElement(data);
    notifyAll();
  }

  private Object get(String tag, boolean remove) {
    Vector v = (Vector) tuples.get(tag);
    if (v == null) return null;
    if (v.size() == 0) return null;
    Object o = v.firstElement();
    if (remove) v.removeElementAt(0);
    return o;
  }
```

```
  public synchronized Object in (String tag)
                         throws InterruptedException {
    Object o;
    while ((o = get(tag,true)) == null) wait();
    return o;
  }

  public Object rd (String tag)
                         throws InterruptedException {
    Object o;
    while ((o = get(tag,false)) == null) wait();
    return o;
  }

  public synchronized Object inp (String tag) {
    return get(tag,true);
  }

  public synchronized Object rdp (String tag) {
    return get(tag,false);
  }
}
```