Concurrent Systems, CSP, and FDR

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Why Concurrent Systems Design??

- Many systems are naturally concurrent!!
- Better engineering:
  - Modularity
  - Simplicity
- Reliability & Fault Tolerance
- Speed – on multiple processors

What Are Concurrent Systems?

Any system where tasks run concurrently

- time-sliced on one processor
- and/or on multiple processors

Concurrent Systems

Time-sliced examples:

- Multiple independent jobs
    - Operating system
        - comms, I/O, user management
    - Multiple users’ jobs
- Multithreading within one job
    - C++
    - Java

Concurrent Systems

Multiprocessor examples:

- Distributed memory (message-passing) systems (e.g, Intel, NCube)
- Shared memory systems (e.g., Sun)

Concurrent Systems

Example applications

- Numerical computation on multiprocessors
  - ♦ typically regular communication patterns
  - ♦ relatively easy to handle

Concurrent Systems

Example applications

- Real-time systems on multiple processors
  - ♦ e.g., flight control, communications routers
  - ♦ irregular communication, often in closed loops
  - ♦ difficult to get correct
  - ♦ may be prone to deadlock and livelock ☹

Concurrent Systems

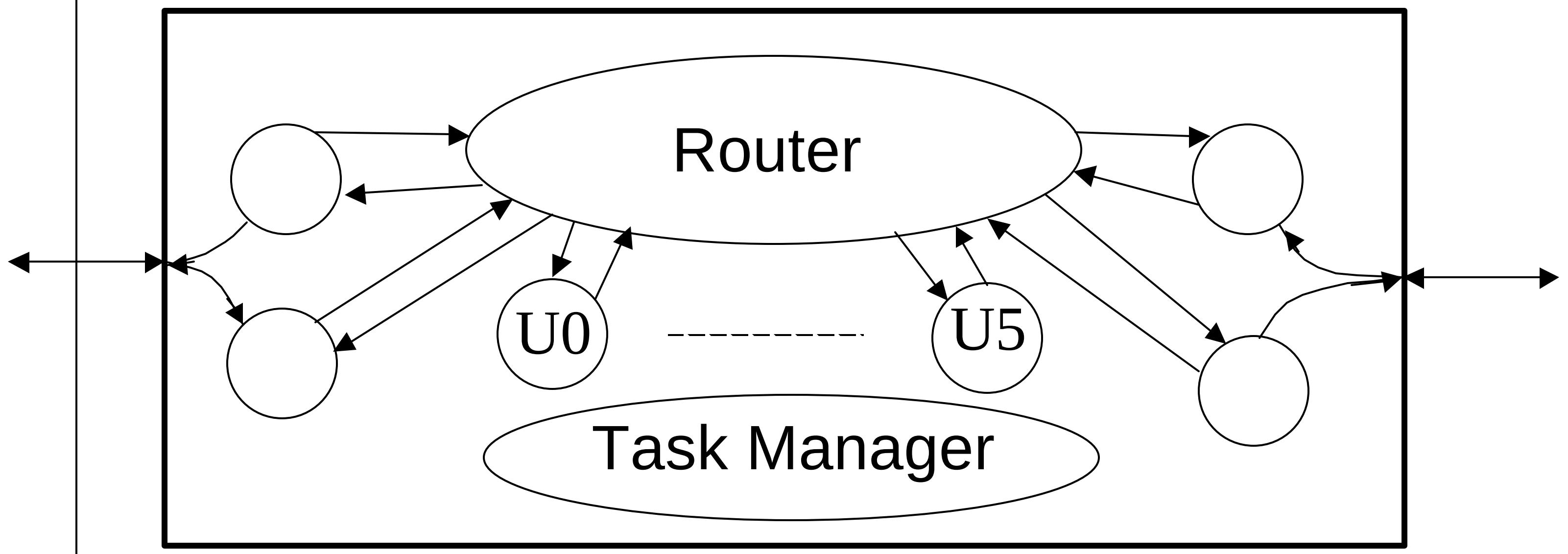
Example applications

- System routines on one multiprocessor node
  - ♦ Manage multiple user tasks
  - ♦ Manage communications
    - • Route messages between tasks on node
    - • Route messages to tasks on other nodes
    - • Manage multiple links to other nodes
    - • Manage I/O, interrupts, etc.

Concurrent Systems

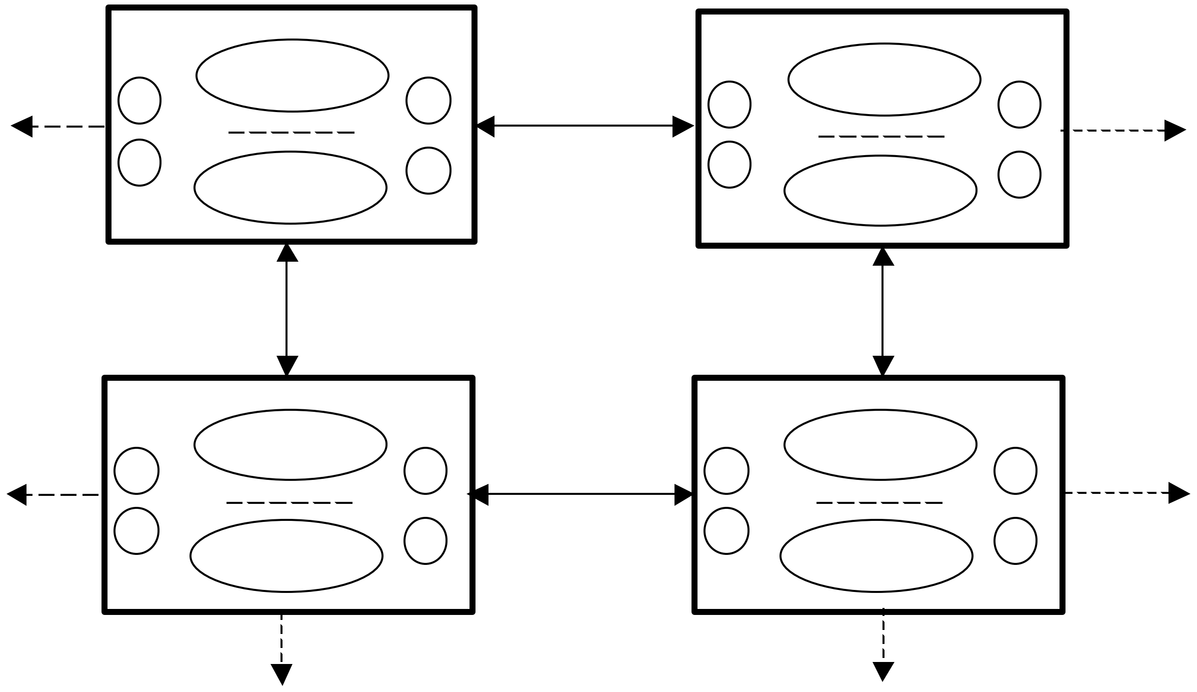
Example applications

- System routines on one multiprocessor node



Concurrent Systems

Example: complete routing system



What Is “Difficult” About Concurrent Systems?

- Correctness
- Deadlock
- Livelock

Why is Correctness an Issue?

- Multiple processes execute their instructions more or less at the same time.
- The actual operations may interleave in time in a great number of ways:
  - For *n* processes with *m* instructions, there are (*nm*)!/(*m*!)^*n* interleavings.
  - Two processes of 10 instructions each have 184,756 interleavings!!

Correctness

Example: the bank balance problem

```
ATM:
    fetch balance
    balance = balance – $100
    store balance
Payroll Computer:
    fetch balance
    balance = balance + $1000
    store balance
```

Bank Balance

Original balance = $1000

Interleaving 1:

	ATM	Payroll Computer
t_1	fetch $1000	
t_2	balance = $1000 - $100	
t_3	store $900	
t_4		fetch $900
t_5		balance = $900 + $1000
t_6		store $1900

Final balance = $1900: Correct!

Bank Balance

Original balance = $1000

Interleaving 2:

	ATM	Payroll Computer
t_1	fetch $1000	
t_2		fetch $1000
t_3		balance = $1000 + $1000
t_4		store $2000
t_5	balance = $1000 - $100	
t_6	store $900	

Final balance = $900: WRONG!

Bank Balance

Only 2 of the twenty possible interleavings are correct!!

Concurrent systems must have some means of guaranteeing that operations in different processes are executed in the proper order.

Deadlock

All processes stopped:

- often because each is waiting for an action of another process
- processes cannot proceed until action occurs

Deadlock

Example: Shared Resource

Two processes wish to print disk files. Neither can proceed until it controls both the printer and the disk; one requests the disk first, the other the printer first:

	Proc A	**Proc B**
t1	acquire disk	
t2		acquire printer
t3	try to acquire printer	DEADLOCK!!

Livelock

- Program performs an infinite unbroken sequence of internal actions
- Refuses (unable) to interact with its environment.
- Outward appearance is similar to deadlock - but the internal causes differ significantly.
- Example: two processes get stuck sending error messages to each other.

Concurrent Designs Requires:

- Means to guarantee correct ordering of operations
- Models to avoid and tools to detect
  - Deadlock
  - Livelock

CSP: A Solution

Communicating Sequential Processes (CSP)

- Processes interact only via explicit blocking events.
  - Blocking: neither process proceeds until both processes have reached the event.
- There is absolutely no use of shared variables outside of events.
- Can be done - with care – from semaphores, wait, etc.

CSP

A *process algebra* –

Provides formal (mathematical) means and CASE tools for

- ♦ Describing systems of interacting concurrent processes
- ♦ Proving properties of concurrent systems
  - • Agreement with specifications
  - • Deadlock freedom
  - • Divergence freedom

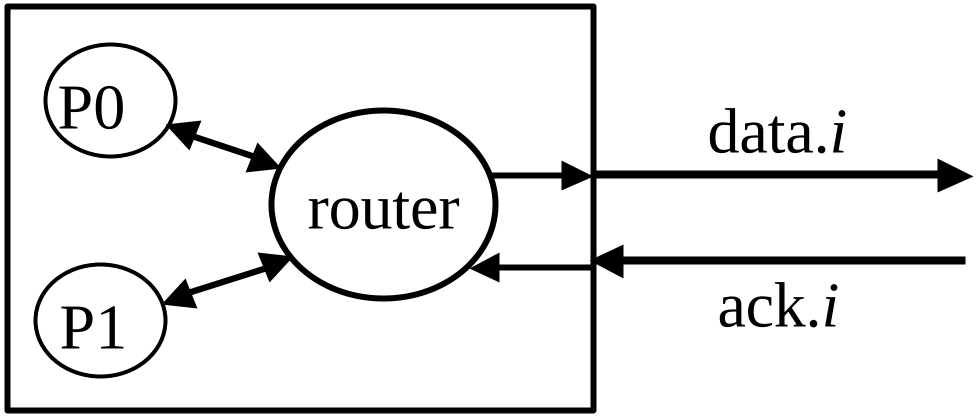
CSP Design Philosophy

- Complex applications are generally <u>far</u> easier to design as systems of
  - many small, simple processes
  - that interact <u>only</u> via explicit events.
- Unconstrained use of shared memory can lead to designs that
  - are extremely difficult to implement
  - are not verifiable

CSP Design Example

Virtual Channel System

- Two processes must be able to send identifiable messages over a single wire.
- Solution: append channel identifier to messages, and wait for ack to control flow.



CSP Design Example

Router: single process design

- Software state machine
- State variables are the message states:
  - 0: waiting to input
  - 1: waiting to send downstream
  - 2: waiting for ack
- Result: 3 x 3 = 9 state case statement

CSP Design Example

Router: single process design

Example case clause:

```
(S0 = input0, S1 = input1):
Read(channel0, channel1)
        If (channel0)
            write data.0
            S0 = send0;
        Else
            write data.1
            S1 = send1;
```

CSP Design Example

Router: single process design

- Nine states – not too bad, but complex enough to require care in the implementation.
- But: if we add another input, it goes to 27 states, and a fourth gives us 81 states!!!
- What are your odds of getting this right the first time?
- Would debugging 81 states be much fun???

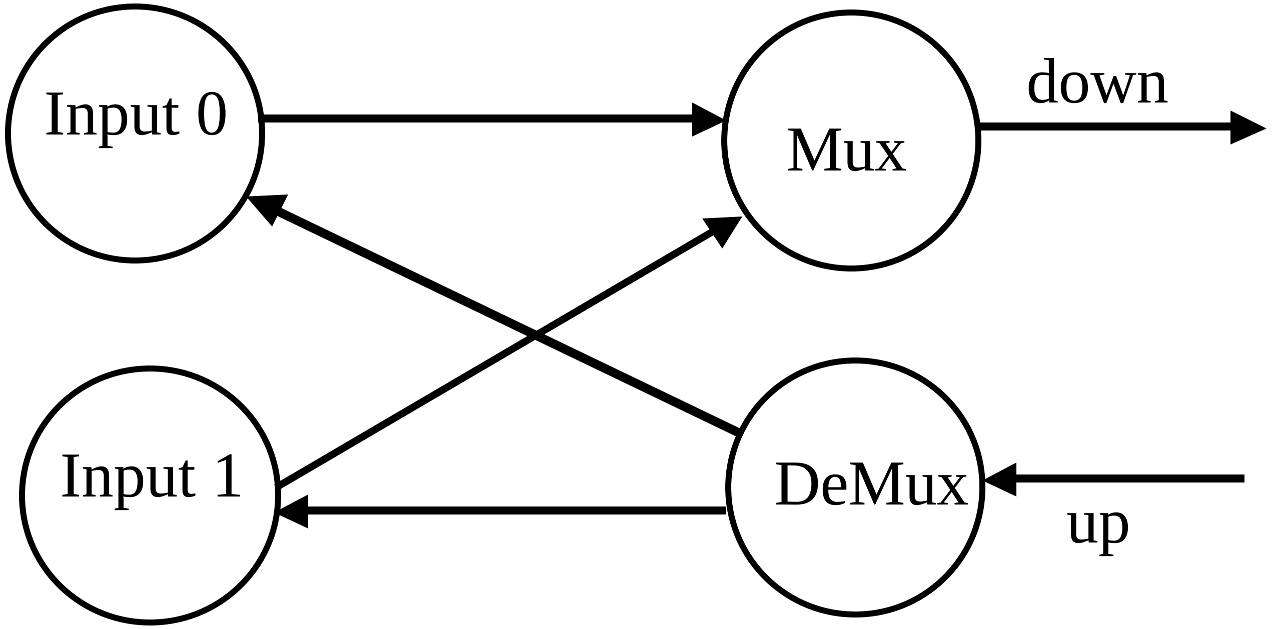
CSP Design Example

Router: multiple process design

- One process to monitor each input and wait for the ack (these are identical)
- One multiplexer process to send the inputs downstream
- One demultiplexer process to accept and distribute the acks

CSP Design Example

- Router: multiple process design: block diagram



CSP Design Example

Router: multiple process design

Input process:

```
While (true)
    read input;
    write input to Mux;
    wait for ack from DeMux;
```

CSP Design Example

Router: multiple process design

Mux process

```
While (true)
    read (input0, input1)
    if (input0) write data.0
    else write data.1;
```

CSP Design Example

Router: multiple process design

- DeMux process

```
While (true)
    read ack;
    if (ack == 0) write ack0
    else write ack1;
```

CSP Design Example

- Router:multiple process design; Summary
  - Three processes – 4 lines each!!
  - Add another input?
    - Add one input process
    - Mux modified to look at 3 inputs
    - Demux modified to handle 3 different acks
- Which implementation would you rather build?

Formal Methods

- Formal methods: mathematical means for designing and proving properties of systems.
- Such techniques have been in use for decades in
  - Analog electronics
    - Filter design: passband, roll-off, etc
    - Controls: response time, phase characteristics

Formal Methods

Digital design

- ♦ Logic minimization
- ♦ Logical description to gate design
- ♦ Formal language description of algorithm to VLSI masks

  (e.g., floating-point processor design)

Formal Methods

Two methods of formal design:

- 1. <u>Derive</u> a design from the specifications.
- 2. <u>Assume</u> a design and prove that it meets the specifications.

CSP

- CSP: deals <u>only</u> with interactions between processes.
- CSP: does <u>not</u> deal (easily) with the internal behavior of processes.
- Hence other software engineering techniques must be used to develop & verify the internal workings of processes.

CSP

The two components of CSP systems:

- *Processes*: indicated by upper-case: *P*, *Q*, *R*, *…*
- *Events*: indicated by lower-case: *a*, *b*, *c*, *…*

CSP

Example: a process *P* engages in events *a*, *b*, *c*, *a*, and then *STOP*s:

$P = a \rightarrow b \rightarrow c \rightarrow a \rightarrow STOP$

"$\rightarrow$" is the *prefix* operator;

STOP is a special process that never engages in any event.

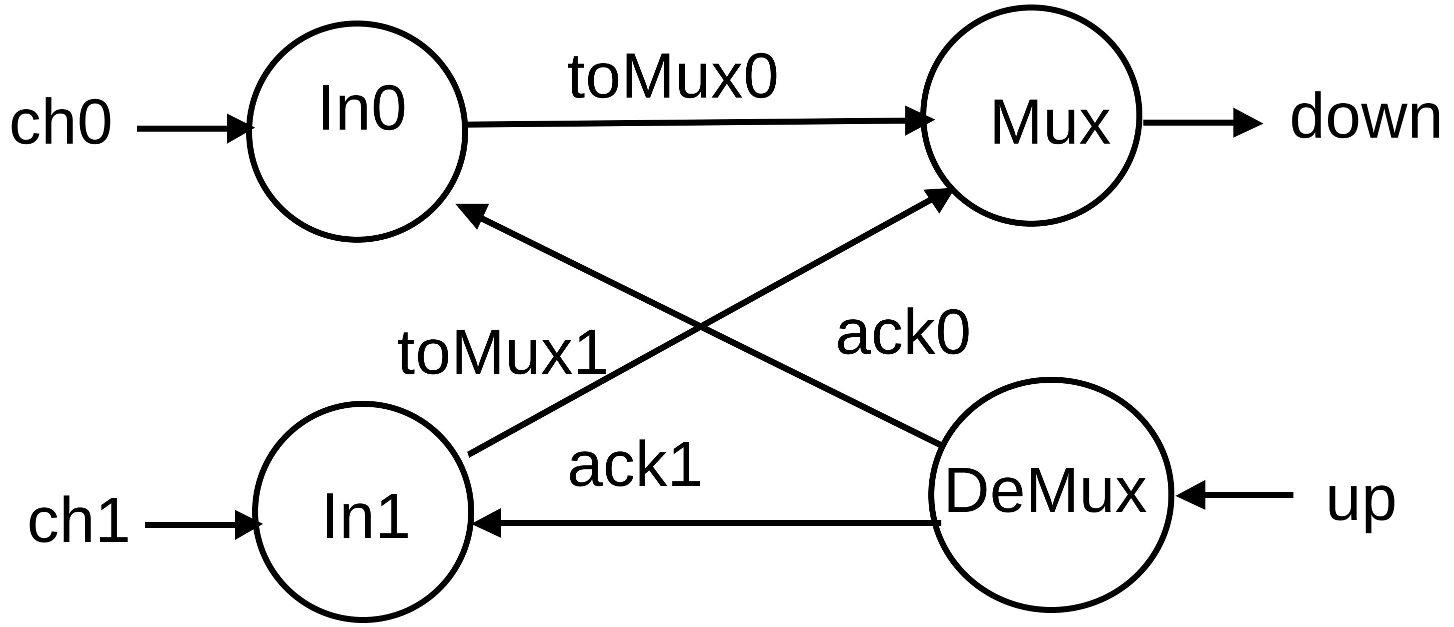
CSP Example

A practical example: a simple pop machine accepts a coin, returns a can of pop, and then repeats:

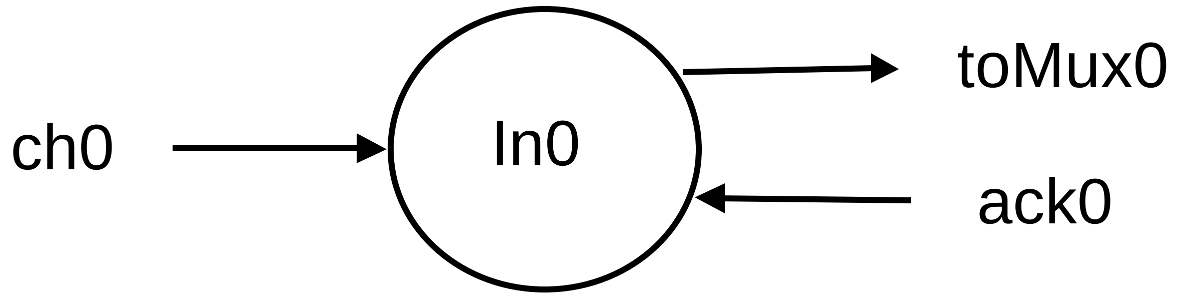
- $PM = coin \rightarrow pop \rightarrow PM$
- Note the recursive definition - which is acceptable; substituting the *rhs* for the occurrence of *PM* in the *rhs*, we get
- $PM = coin \rightarrow pop \rightarrow coin \rightarrow pop \rightarrow PM$
- (RT processes are often non-terminating.)

CSP Example

The router:

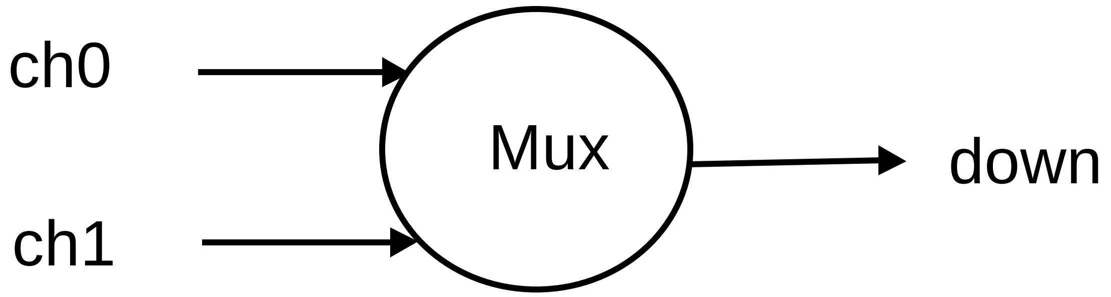


The router processes: Input



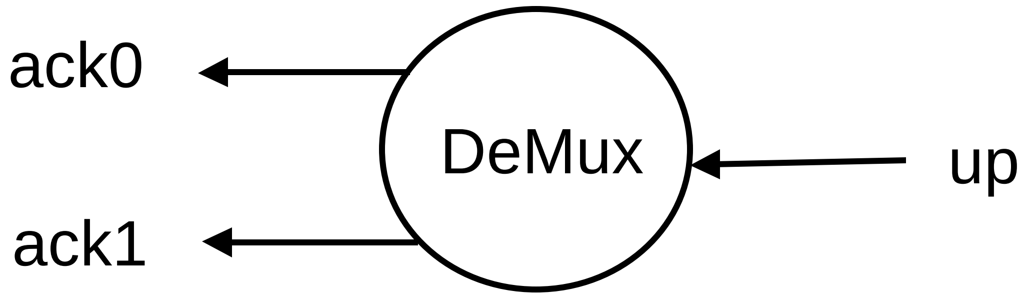
$$In0 = \; ch0?x \rightarrow toMux0!x \rightarrow ack0 \rightarrow In0$$

The router processes: Mux



$$\begin{aligned}\text{Mux} = \quad & \text{toMux0?x} \rightarrow \text{down!x.0} \rightarrow \text{Mux} \\ \square \quad & \\ & \text{toMux1?x} \rightarrow \text{down!x.1} \rightarrow \text{Mux}\end{aligned}$$

The router processes: DeMux



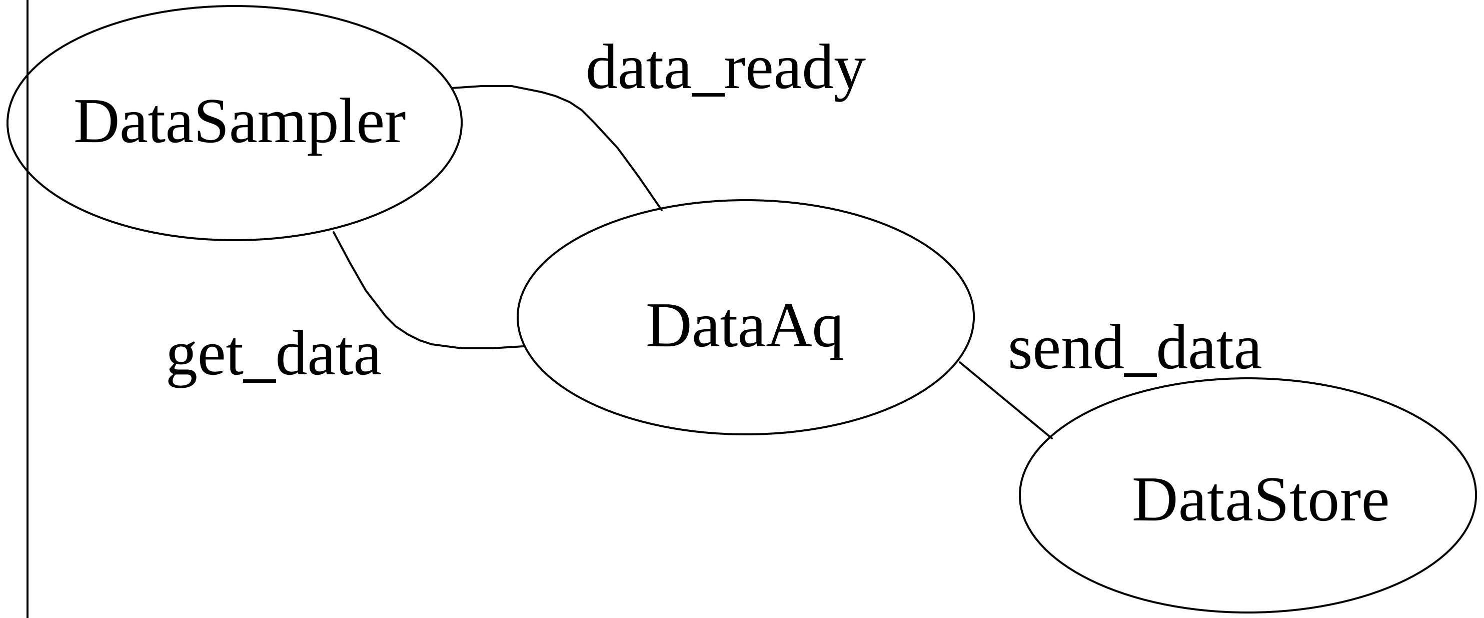
DeMux = up?x $\rightarrow$

(ack0 $\not<$ x == 0 $\not>$ ack1)

$\rightarrow$ DeMux

CSP

Example: the process graph of a data acquisition system (NB: no arrows...):



CSP

- DataAq: waits until it is notified by the sampler that data is ready, then gets and transforms the data, sends it on to be stored, and repeats:
  - $DataAq = data\_ready \rightarrow get\_data \rightarrow send\_data \rightarrow DataAq$
- Note that the transform is an internal process and is not visible; *data_ready, get_data,* and *send_data* are events engaged in with other processes.

CSP

- The data sampling process would engage in the events *data_ready* and *get_data*:

  DataSampler = *data_ready* $\rightarrow$ *get_data* $\rightarrow$ *DataSampler*

- Data store engages only in *send_data*:

  DataStore = *send_data* $\rightarrow$ *DataStore*

CSP

- We thus have three processes, each of which has an *alphabet* of events in which it can engage:
  - *DataSampler*: *ASa* = {*data_ready, get_data*}
  - *DataAq*: *ADA* = {*data_ready, get_data, send_data*}
  - *DataStore: ASt* = {*send_data*}
- The entire alphabet of the composite process is denoted by Σ .

CSP

- The entire data acquisition system would be indicated by the *alphabetized parallel* composition of the three processes:

  $DAS = DataSample \; {}_{ASa}||_{ADA} \; DataAq \; {}_{ADA}||_{ASt} \; DataStore$

- Two processes running in alphabetized parallel with each other must agree (synchronize) on events which are common to their alphabets.

CSP Details

Traces

- The *traces* of a process is the set of all possible sequences of events in which it can engage.
- The traces of *Data_Store* are simple:
  - $\{\langle\rangle, \langle \mathit{send\_data} \rangle^n, 0 \le n \le \infty\}$
  - <> is the empty trace.

CSP Details

Traces

DataAq can have engaged in *no* events, or any combination of the events *data_ready, get_data,* and *send_data* in the proper order:

CSP Details

Traces of *DataAq:*

$traces(DataAq) = \{\langle\rangle, \langle data\_ready\rangle,$
$\langle data\_ready, get\_data\rangle,$
$\langle data\_ready, get\_data, send\_data\rangle^n,$
$\langle data\_ready, get\_data, send\_data\rangle^n \,\hat{}\, \langle data\_ready\rangle, \langle data\_ready,$
$get\_data, send\_data\rangle^n \,\hat{}$
$\langle data\_ready, get\_data\rangle, 0 \leq n \leq \infty\}$

CSP Details

- Traces specify formally what a process can do - if it does anything at all.
- This is a *safety* property: the trace specification should not allow any unacceptable operations (e.g., we would not want to allow two stores without an intervening new sample; thus <*...send_data, send_data...*> is ruled out.

CSP Details

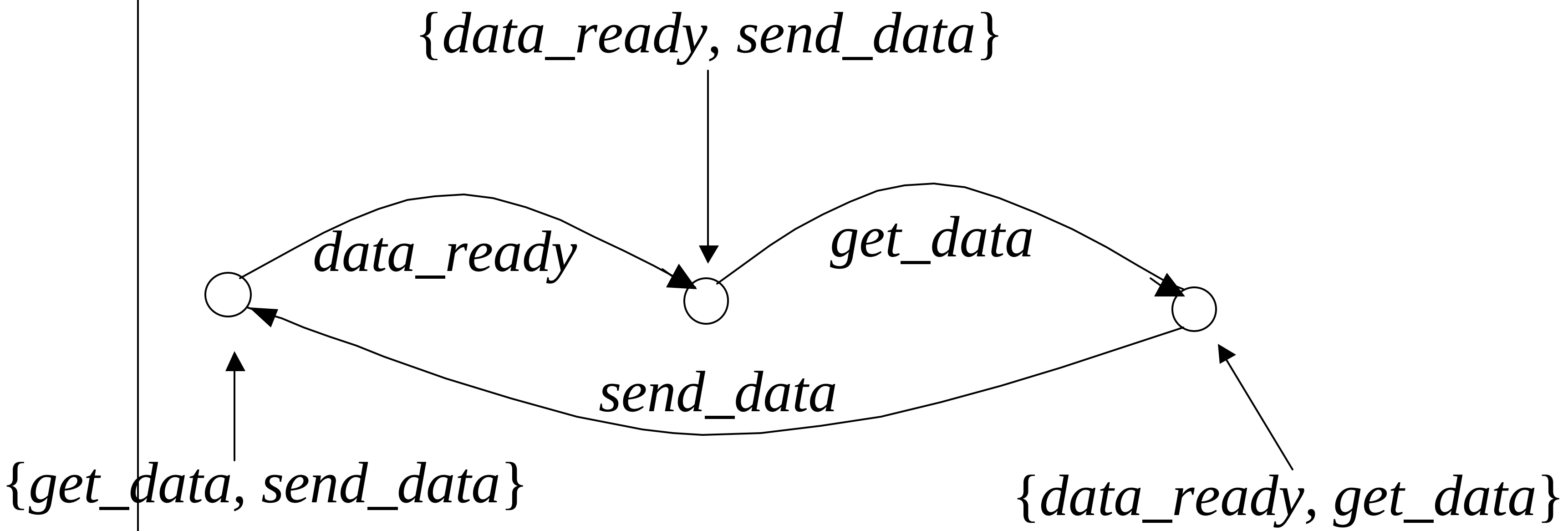
- Traces do not force a process do anything.
- We force action by limiting what a process can refuse to do. This is a *liveness* property.

CSP Details

- *refusal set*: a set of events which a process can refuse to engage in regardless of how long they are offered.
- E.g., the refusal set of *DataAq* after it has engaged in *data_ready* is {*data_ready, send_data*}.

CSP Details

Refusals can be shown nicely on the transition diagram of *DataAq*:



CSP Details

- A *failure* is a pair (*s*, *X*), where *s* is a trace and *X* is the set of events which are refused after that trace.
- We force a process to do the right things by specifying the acceptable failures - thus limiting the failures it can exhibit.

CSP Details

Failures

E.g., *DataAq* cannot fail to accept a new *data_ready* event after a complete cycle; its failures cannot contain (<*data_ready, get_data, send_data*>^{n}, {*data_ready*}).

CSP Details

- *traces*:

  specify what <u>can</u> be done
- *failures*:

  specify allowed failures
- Together, these guarantee that the appropriate things *will* be done.
- We have only to prevent deadlock and livelock...

CSP Details

Deadlock freedom:

A system is deadlock free if, after any possible trace, it cannot refuse the entire alphabet Σ :

$$\forall s \,.\, (s, \Sigma) \notin \mathit{failures}(\mathit{DAS})$$

CSP Details

Livelock (divergence) freedom:

- *divergences* of a process:

  the set of traces after which the process can enter an unending series of internal actions.

- A system is divergence free if there are no traces after which it can diverge:

  divergences(*DAS*) = {}

CSP Details

- A complete specification:
  - Acceptable traces
  - Acceptable failures
  - Deadlock freedom
  - Divergence freedom
- These properties can be checked by rigorous CASE tools – from FSE Ltd.

CSP Details

Refinement

- A specification is often a process that exhibits all acceptable implementations - which may be overkill, but easy to state.
- Implementation *Q* *refines* specification *P* ($P \sqsubseteq Q$) if:

  Q satisfies the properties of *P*:

  - the traces of *Q* are included in the traces of *P*;
  - the failures of *Q* are included in the failures of *P*.

CSP Details

Refinement of a design problem:

- Initial specification:
  - very general (often highly parallel)
  - correctness easy to verify.
- CASE tools:

  verify that a particular implementation (whose correctness may not be obvious) properly refines the original specification.

CSP Details

Algebraic manipulations

- Objects and operations within CSP form a rigorous algebra.
- Algebraic manipulations:
    - demonstrate the equivalence of processes
    - transform processes into ones that may be implemented more efficiently.

CSP Details

Algebraic manipulations: simple laws

- Alphabetized parallel composition obeys commutative laws

$$P\ {}_{A}\|_{B}\ Q = Q\ {}_{B}\|_{A}\ P$$

- and associative laws

$$(P\ {}_{A}\|_{B}\ Q)\ {}_{B}\|_{C}\ R = P\ {}_{A}\|_{B}\ (Q\ {}_{B}\|_{C}\ R\ )$$

- and many, many more...

CSP Details

Algebraic manipulations: step laws

Step laws:

convert parallel implementations into equivalent sequential (single-thread) implementations:

CSP Details

Step law example:

Assume $P = ?x{:}A \rightarrow P'$ and $Q = y{:}B \rightarrow Q'$

$$P\ {}_A\|_B\ Q = ?x{:}(A \cup B) \rightarrow \quad P'\ {}_A\|_B\ Q' \ \nless x \in (A \cap B) \ngtr \ P'\ {}_A\|_B\ Q \ \nless x \in A \ngtr \ P\ {}_A\|_B\ Q'$$

Repeated application results in a <u>sequence</u> of events.

CSP Details

Sequentialization

- The parallel composition of the *DataAq* and *DataStore* can be sequentialized - which may be more efficient on a single processor:

  $DataAq \;{}_{ADA}\|_{ASt}\; DataStore = DaDst =$
  $data\_ready \rightarrow get\_data \rightarrow send\_data \rightarrow DaDst$

- The CASE tools will verify that the sequential version refines the concurrent version.

CSP Tools

ProBE

Process Behaviour Explorer

- ♦ Allows manual stepping through a CSP description
- ♦ Shows events acceptable at each state
- ♦ Records traces
- ♦ Allows manual check against specifications

CSP Tools

FDR (a model checker)

Failures-Divergences-Refinement

Mathematically tests for:

- Refinement of one process against another
  - Traces
  - Failures
  - Divergences
- Deadlock freedom
- Divergence freedom

CSP Compatibility

- "My work group uses the (Yourdon, Booch, UML, PowerBuilder, Delphi… software development system); can I still use CSP?"
- Certainly – CSP can be used <u>wherever</u> you design with processes that interact <u>only</u> via CSP-style explicit events.

CSP Compatibility

“CSP seems to be based on message passing; Can I use it with locks, critical sections, semaphores, mutexes and/or monitors???”

Absolutely! As long as your processes interact <u>only</u> via explicit locks, mutexes, etc., CSP can describe them – and prove them.

CSP Mutex

Modeling of shared-memory primitives

- Mutex:

```
claim mutex1;
modify shared variable;
release mutex1;
```

CSP Mutex

A CSP mutex process:

```
Mutex1 =
    claim → release → Mutex1
```

The process will not allow a second claim until a prior claim has been followed by a release.

CSP Mutex

Weaknesses:

- Compiler does not require use of mutex to access shared variables.
- A process may neglect to release the mutex, thus holding up further (proper) accesses.

CSP Mutex

A more robust version that allows only the process making the claim to complete the release:

```
RMutex =
   claim?ProcID® release!ProcID
    ® Rmutex
```

CSP Mutex

Use of the robust mutex:

```
Proc 29:
   claim!29;
   modify shared variable;
   release?29;
```

CSP Mutex

The way it should be done: the shared variable is modifiable only by a single process (which allows a read as well):

```
Robust(x) =
     ModifyX!y ® Robust(x + y)
   □
     readX?x ® Robust(x)
```

Semaphores

Definitions

(〈**x;**〉: operation x is atomic)

Claim semaphore s:

```
P(s): áawait (s > 0) s = s – 1;ñ
```

Release semaphore s:

```
V(s): ás = s + 1;ñ
```

Semaphores

A semaphore process (initialized to s = 1):

```
SemA          = SemA1(1)
SemA1(s)      =
  (pA ® SemA1(s-1))≮ s > 0 ≯ STOP
□
  (vA ® SemA1(s + 1)
```

Summary 1

Thirty+ years of experience shows that

- Complex applications are generally <u>far</u> easier to design as systems of
  - many (2 – 2000) small, simple processes
  - that interact <u>only</u> via explicit events.
- Careless use of shared memory can lead to designs that
  - are extremely difficult to implement
  - are not verifiable
  - are wrong!

Summary 2

CSP + Tools:

- Clean, simple specification of concurrent systems
- Rigorous verification against specifications
- Proof of deadlock and livelock freedom
- Verifiable conversion between concurrent and single-threaded implementations
- Works with <u>any</u> process-oriented development system.

CSP Applications

- Real-time & embedded systems
- Communications management
- Communications security protocols
- Digital design – from gate-level through FPGAs to multiple systems on a chip
- Parallel numerical applications
- Algorithm development

Example:
Ring Network Router

Don Rice, Bin Cai, Pichitpong Soontornpipit

ECE 6750 Class Project

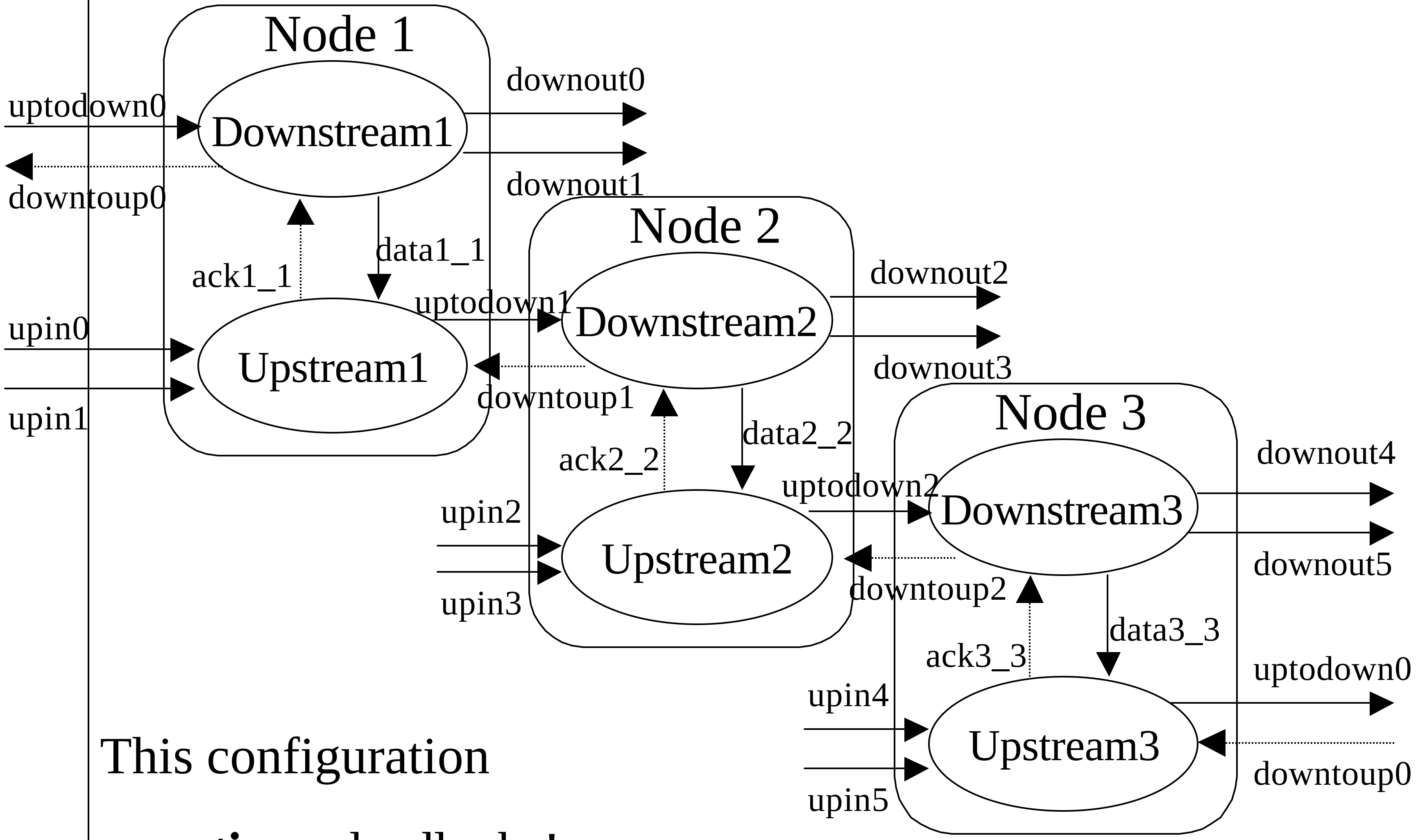
http://www.engineering.usu.edu/ece/

Utah State University

Ring Network Description

- Three nodes connected in a ring topology
- Two inputs and two outputs per node
- One transmit/receive pair between nodes
- Input must be acknowledged by destination before additional input is accepted
- Error-free network: packets are not lost, damaged, or duplicated

Three Two-Input Node Ring



This configuration

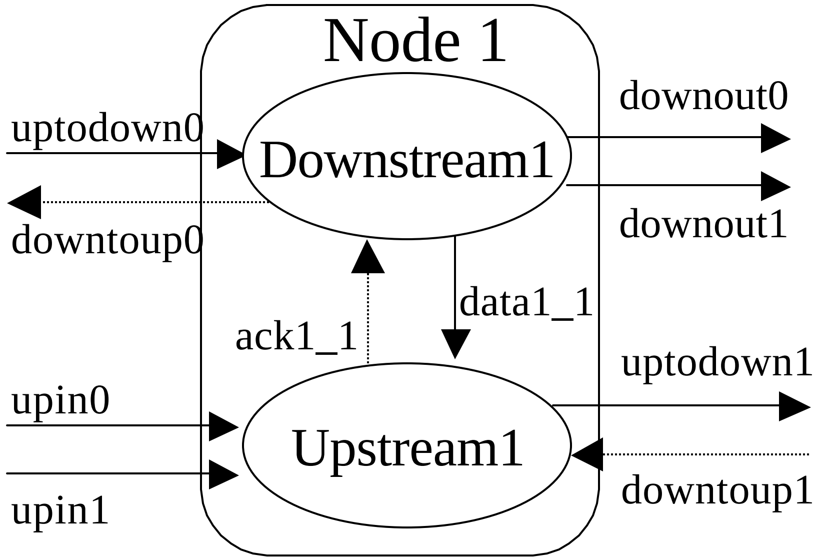
sometimes deadlocks!

Design Procedure

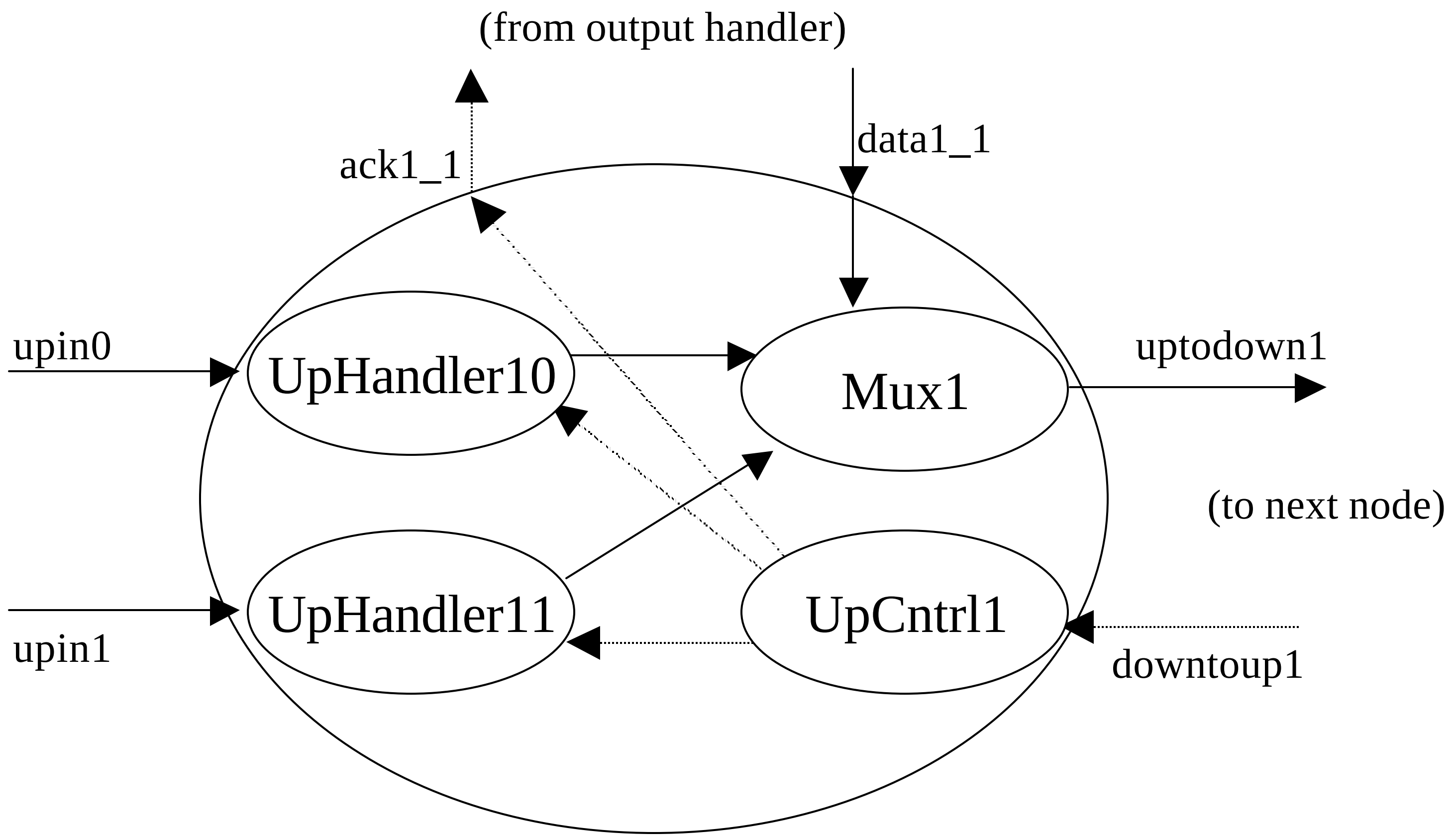
- Began with two-node topologies in CSP
- Used ProBE and FDR to explore designs
  - Identified deadlock scenarios
  - Verified deadlock-free design
- Implemented application with Java CTJ
- Ported to JCSP applet

Two-Input/Two-Output Node

- Inputs upin0, upin1 accept data value and destination ID [0,5]
- Outputs downout0, downout1 produce data value, source ID [0,5]
- Data flows on solid lines (e.g., uptodown bus,) acknowledgments flow on dashed lines (e.g., downtoup bus)



Input Handler: “Upstream”



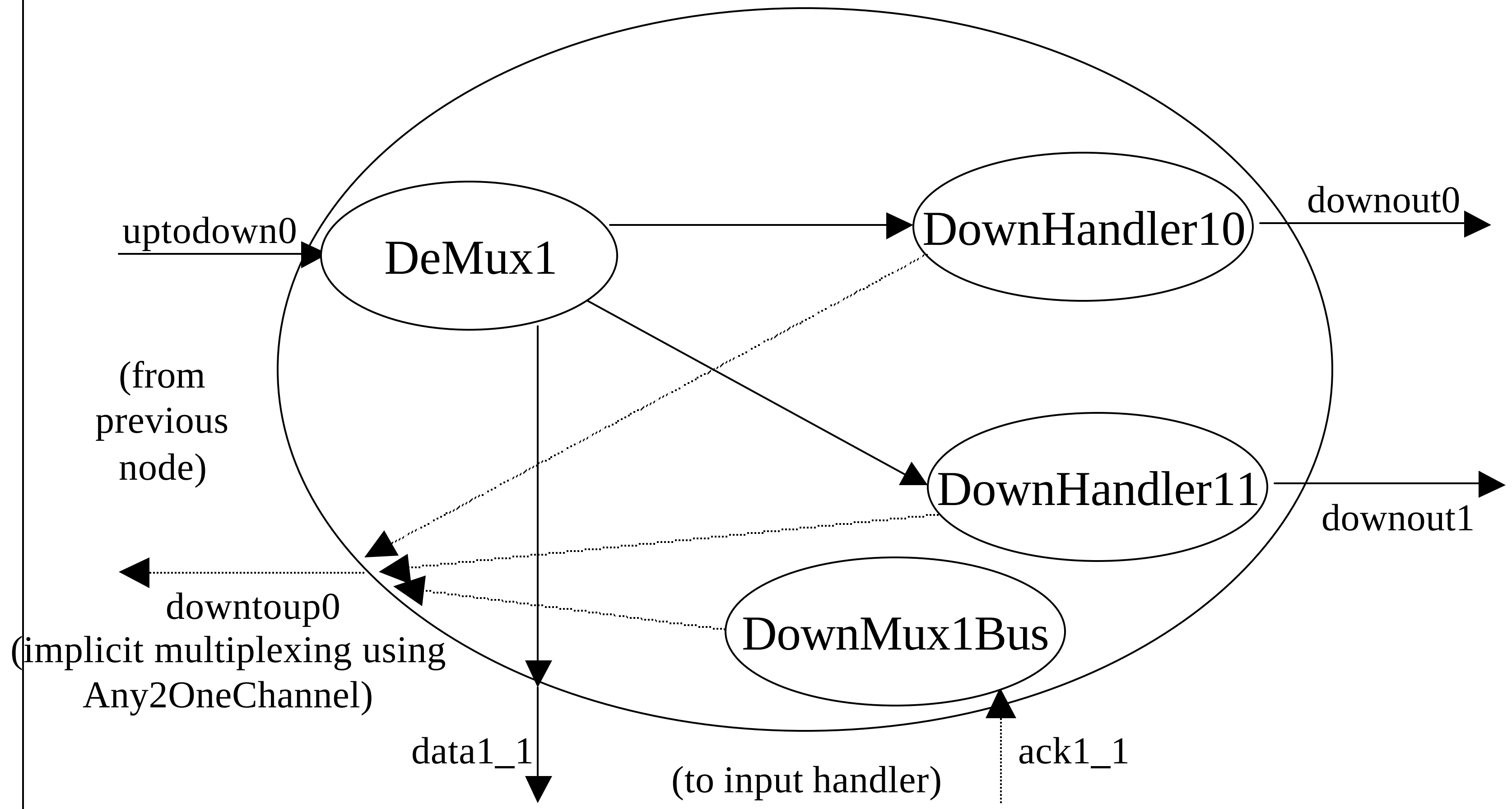
Sample Code from “UpHandler”

Java processes developed from CSP are typically very simple.

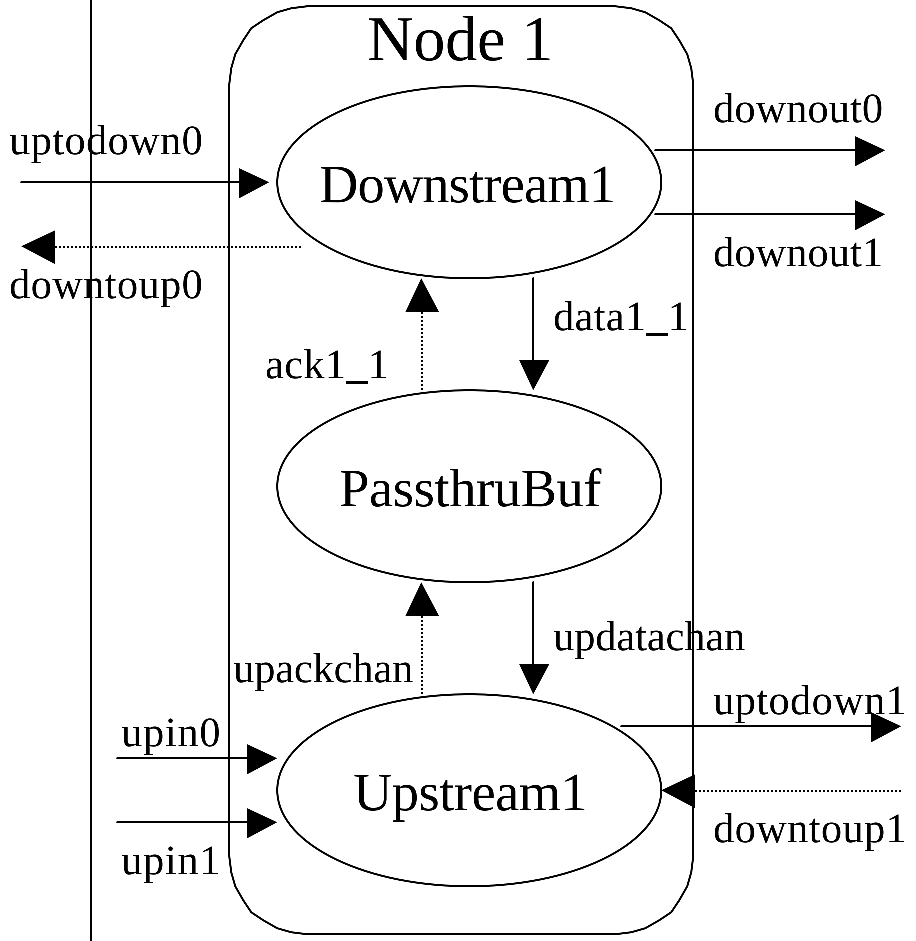
```
public void run()
    {
        intArray packet = null; // packet from test source class
        ChanIO UpH      = new ChanIO("UpHandler"+Identity);  // IO wrapper
        int ack         = 0;  // acknowledgment from destination
        boolean Running = true;  //allow for external control someday

        // Repeatedly read data and pass it on:
        while(Running)
        {
            packet = UpH.Read(input, " d.d" );   // Read destination, data from test source
            UpH.Write(output, packet, " d.d" );  // Write destination, data to Mux

            ack = UpH.Read(ackin, " ack" );      // Wait for ack from UpCntrl

        } // End while.

    } // End run
```

Read() and Write() methods were wrappers for CTJ try/catch clauses; wrappers were converted to JCSP with little impact on router functions.

Output Handler: “Downstream”



Deadlock Prevention



- Used FDR to evaluate alternatives
- A single buffer added to the system was necessary and sufficient to prevent deadlock
- Added “passthru” buffer to Node 1 in Java version

Conclusions

- Design in CSP with FDR testing and verification provides confidence not possible with Java trial-and-error testing
- Model optimization was critical to operate FDR in student lab environment
- Conversion from CSP to Java CTJ or JCSP is largely cut-and-paste exercise once basic examples are provided…
(designers had little prior Java experience)

Related USU Projects

- Creation of Java code directly from CSP
  - E.g., the simple router
- Automatic conversion of CSP from parallel to sequential
- Compilation of Java to VHDL/FPGA
- Analysis of autonomous vehicle software
- Analysis of internet protocols

Courses:

- ECE 5740
  - Concurrent Programming (under Win32)
  - Fall
- ECE 6750
  - Concurrent Systems Engineering I (CSP I; Java)
  - Spring
- ECE 7710
  - Concurrent Systems Engineering II (CSP II; Java, C)
  - Add real-time specifications
  - Alternate Falls