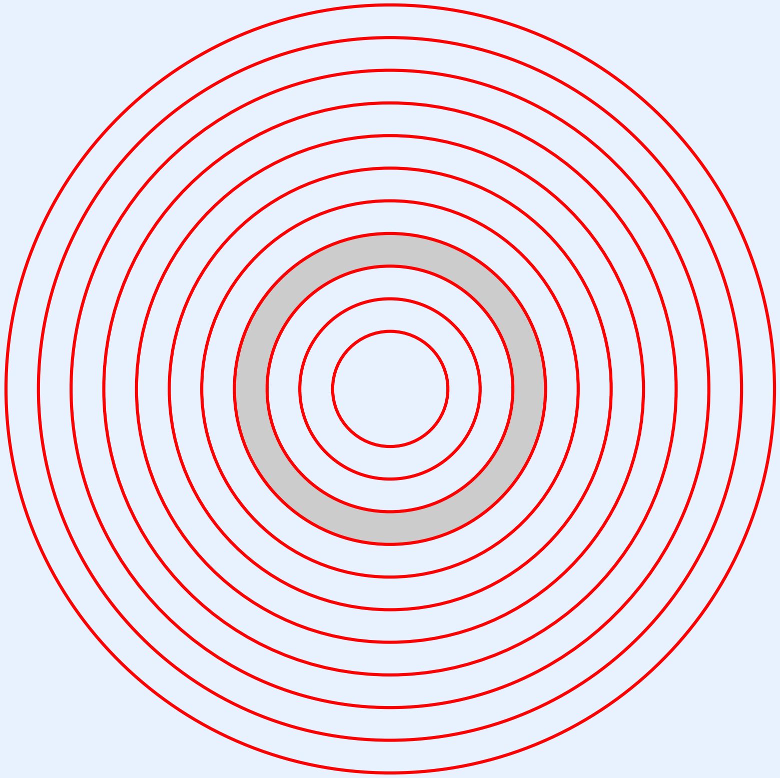
PART 5

Process Coordination And Synchronization

Location Of Process Coordination In The Xinu Hierarchy



Coordination Of Processes

- Necessary in a concurrent system
- Avoids conflicts when accessing shared items
- Allows processes to cooperate
- Can be used when
  - Process waits for I/O
  - Process waits for another process
- Example of cooperation among processes: UNIX pipes

Two Approaches To Process Coordination

- Use facilities supplied by hardware
- Use facilities supplied by the operating system

Note: we will focus on latter

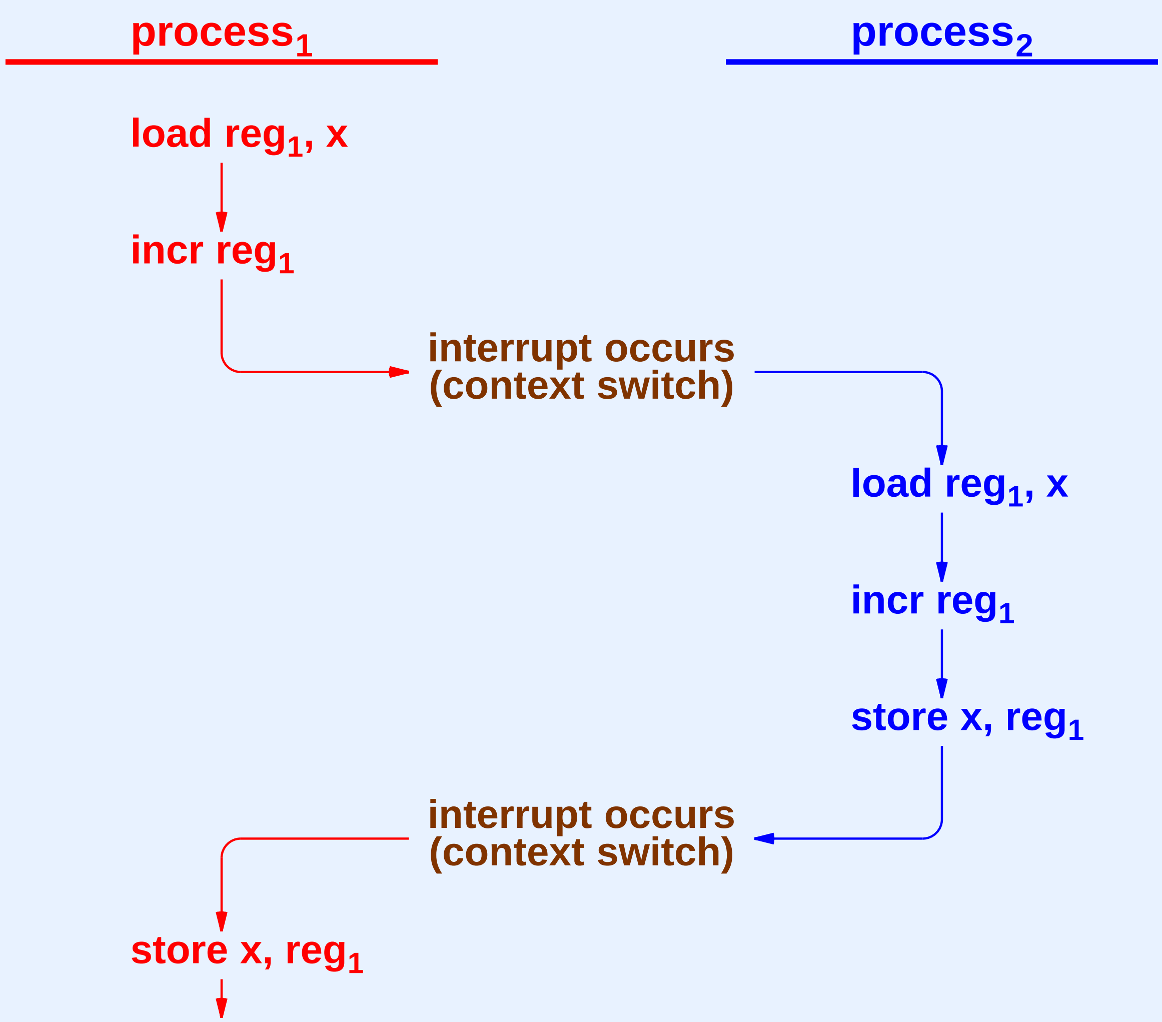
Important Problems That Process Coordination Mechanisms Solve

- Mutual exclusion
- Producer / consumer interaction

Mutual Exclusion Problem

- Concurrent processes access shared data
- Nonatomic operations can produce unexpected results
- Example: multiple steps used to increment variable *z*
  - Load variable *z* into register *i*
  - Increment register *i*
  - Store register *i* in variable *x*

Illustration Of Two Processes Attempting To Increment A Shared Variable Concurrently



To Prevent Problems

- Insure that only one process accesses a shared item at any time
- Trick: once a process obtains access, make all other processes wait
- Two solutions
  - Test-and-set (implemented in hardware)
  - Semaphores (implemented in software)

Handling Mutual Exclusion With Hardware (Using The Test-And-Set Instruction)

- Atomic hardware operation, *tset*, tests whether a memory location is zero and sets it to nonzero
- Initialization (or to declare the shared item is not in use): set memory location to zero

  $m = 0;$

- To obtain access, execute the following loop:

```
while tset(m)
        ;  /* do nothing */
```

- Only one process can access at any time
- Approach known as *busy waiting*
- Used in multiprocessors

Handling Mutual Exclusion With Software (Using An Operating System Facility)

- Operating System
  - Supplies abstraction to control mutual exclusion
  - Mechanism used to protect a given shared object is known as a *mutex* facility
  - Guarantees only one process passes a mutex at any time
- Applications must be programmed to use mutex mechanisms
- Unlike test-and-set, mutex implementations avoid busy waiting

Terminology For Mutual Exclusion

- Each item of shared data must be protected from concurrent access
- Calls to OS functions inserted in code
  - Before access to shared data
  - After access to shared data
- Protected code known as *critical section*
- OS ensures at most one process executes critical section at any time

At what level of granularity should mutual exclusion be applied in an operating system?

Low-Level Mutual Exclusion

- Mutual exclusion needed
  - By application processes
  - Inside operating system
- Mutual exclusion can be guaranteed provided no context switching occurs
- Context changed by
  - Interrupts
  - Calls to *resched*
- Low-level mutual exclusion: mask interrupts and avoid rescheduling

Interrupt Mask

- Hardware mechanism that controls interrupts
- Internal register; may be part of processor status word
- Typically, zero value means interrupts can occur
- OS can
  - Examine current interrupt mask (find out whether interrupts are enabled)
  - Set interrupt mask to allow or prevent interrupts

Masking Interrupts

- Important principle:

No operating system function should contain code to explicitly enable interrupts.

- Technique used: given function
  - Saves current interrupt status
  - Disables interrupts
  - Proceeds through critical section
  - Restores interrupt status from saved copy
- Important idea: allows nested calls

Why Interrupt Masking Is Insufficient

- It works! But...
- Stopping interrupts penalizes all processes when one process executes a critical section
  - Stops all I/O activity
  - Restricts execution to one process for the entire system
- Can interfere with the scheduling invariant (low-priority process can block a high-priority process for which I/O has completed)
- Does not permit a data access policy

High-Level Mutual Exclusion

- Idea is to create a facility with the following properties
  - Permit designer to specify multiple critical sections
  - Allow independent control of each critical section
  - Provide an access policy (e.g., FIFO)
- A single mechanism, the *counting semaphore*, suffices

Counting Semaphore

- Operating system abstraction
- Instance can be created dynamically
- Each instance given unique name
  - Typically an integer
  - Known as *semaphore id*
- Instance consists of a tuple (count, set)
  - *Count* is an integer
  - *Set* is a set of processes waiting on the semaphore

Operations On Semaphores

- *Create* new semaphore
- *Delete* existing semaphore
- *Wait* on existing semaphore
  - Decrements count
  - Adds calling process to set waiting if resulting count is negative
- *Signal* existing semaphore
  - Increments count
  - Makes a process ready if any waiting

Semaphore Invariant

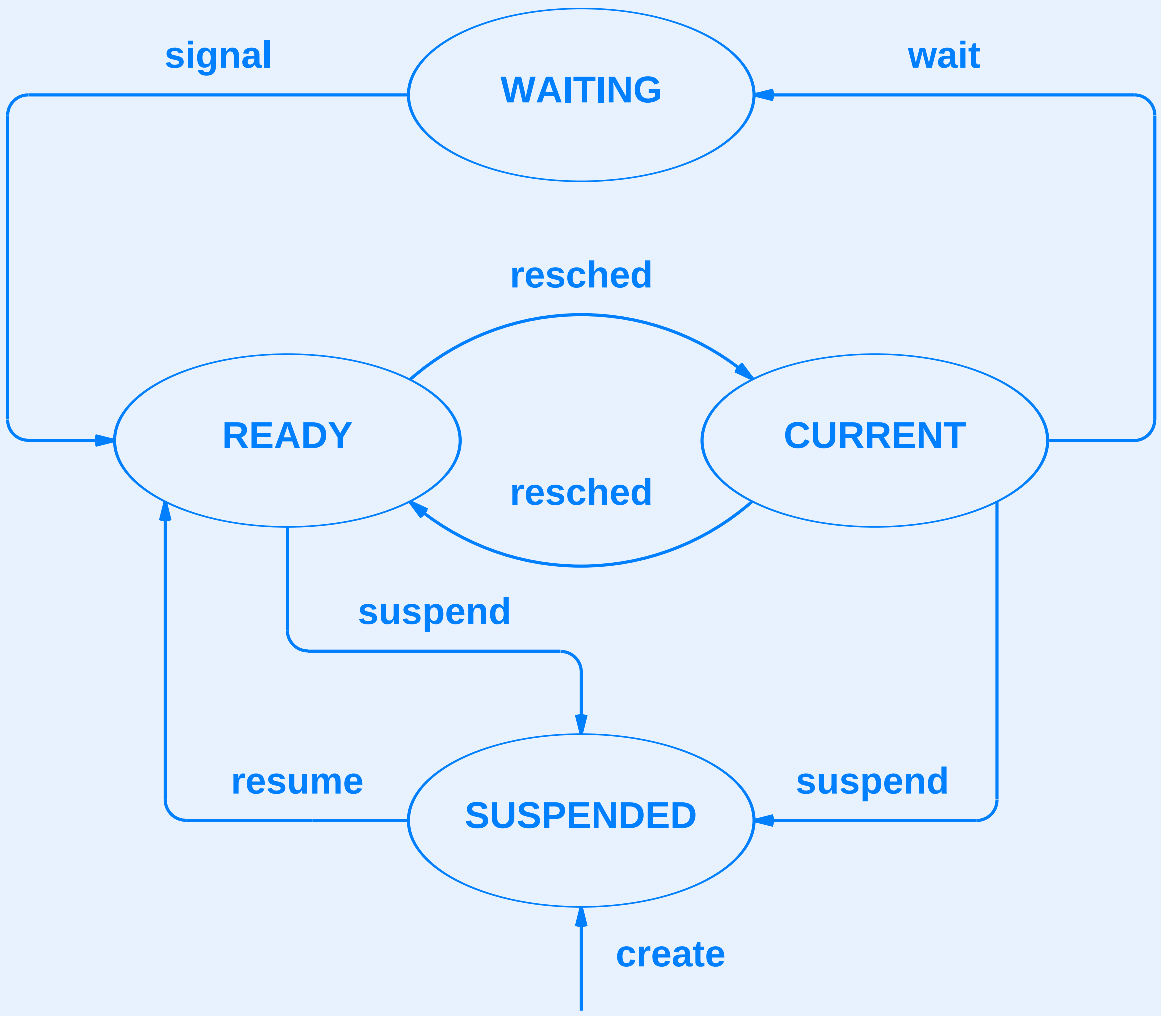
- Establishes relationship between conceptual purpose and implementation
- Must be re-established after each operation
- Surprisingly elegant:

> A nonnegative semaphore count means that the set is empty. A count of negative *N* means that the set contains *N* waiting processes.

Counting Semaphores In Xinu

- Stored in an array of semaphore entries
- Each entry
  - Corresponds to one instance
  - Contains an integer count and pointer to list of processes
- Semaphore ID is index into array
- Policy for management of waiting processes is FIFO
- Each process that is enqueued on a semaphore queue is in the *WAITING* state

State Transitions With Waiting State



Semaphore Definitions

```
/* semaphore.h - isbadsem */

#ifndef NSEM
#define NSEM            45      /* number of semaphores, if not defined */
#endif

/* Semaphore state definitions */

#define S_FREE  0               /* semaphore table entry is available   */
#define S_USED  1               /* semaphore table entry is in use      */

/* Semaphore table entry */
struct  sentry  {
        byte    sstate;         /* whether entry is S_FREE or S_USED    */
        int32   scount;         /* count for the semaphore              */
        qid16   squeue;         /* queue of processes that are waiting  */
                                /*    on the semaphore                  */
};

extern  struct  sentry semtab[];

#define isbadsem(s)     ((int32)(s) < 0 || (s) >= NSEM)
```

Implementation Of Wait

/* excerpt from wait.c - wait */

```
/*------------------------------------------------------------------------
 *  wait  -  Cause current process to wait on a semaphore
 *------------------------------------------------------------------------
 */
syscall wait(
          sid32          sem              /* semaphore on which to wait  */
        )
{
        intmask mask;                     /* saved interrupt mask        */
        struct  procent *prptr;           /* ptr to process' table entry  */
        struct  sentry *semptr;           /* ptr to sempahore table entry */

        mask = disable();
        if (isbadsem(sem)) {
                restore(mask);
                return SYSERR;
        }
        semptr = &semtab[sem];
        if (--(semptr->scount) < 0) {             /* if caller must block */
                prptr = &proctab[currpid];
                prptr->prstate = PR_WAIT;         /* set state to waiting */
                prptr->prsem = sem;               /* record semaphore ID  */
                enqueue(currpid,semptr->squeue);/* enqueue on semaphore */
                resched();                        /*   and reschedule     */
        }
        restore(mask);
        return OK;
}
```

Uses Of Semaphores

- Mutual exclusion
- Direct synchronization (e.g., producer-consumer)

Cooperative Mutual Exclusion

- Initialization

```
sid = semcreate (1);
```

- Use: bracket critical sections of code with calls to *wait* and *signal*

```
 wait(sid);
...critical section (use shared resource)...
signal(sid);
```

Producer-Consumer Synchronization

- Typical scenerio
  - Shared circular buffer
  - Producing process deposits items into buffer
  - Consuming process extracts items from buffer
- Must guarantee
  - Producer blocks when buffer full
  - Consumer blocks when buffer empty
- Can use two semaphores for synchronization

Producer-Consumer Synchronization

- Initialization

```
psem = semcreate(buffer-size);
csem = semcreate(0);
```

- Use by producer

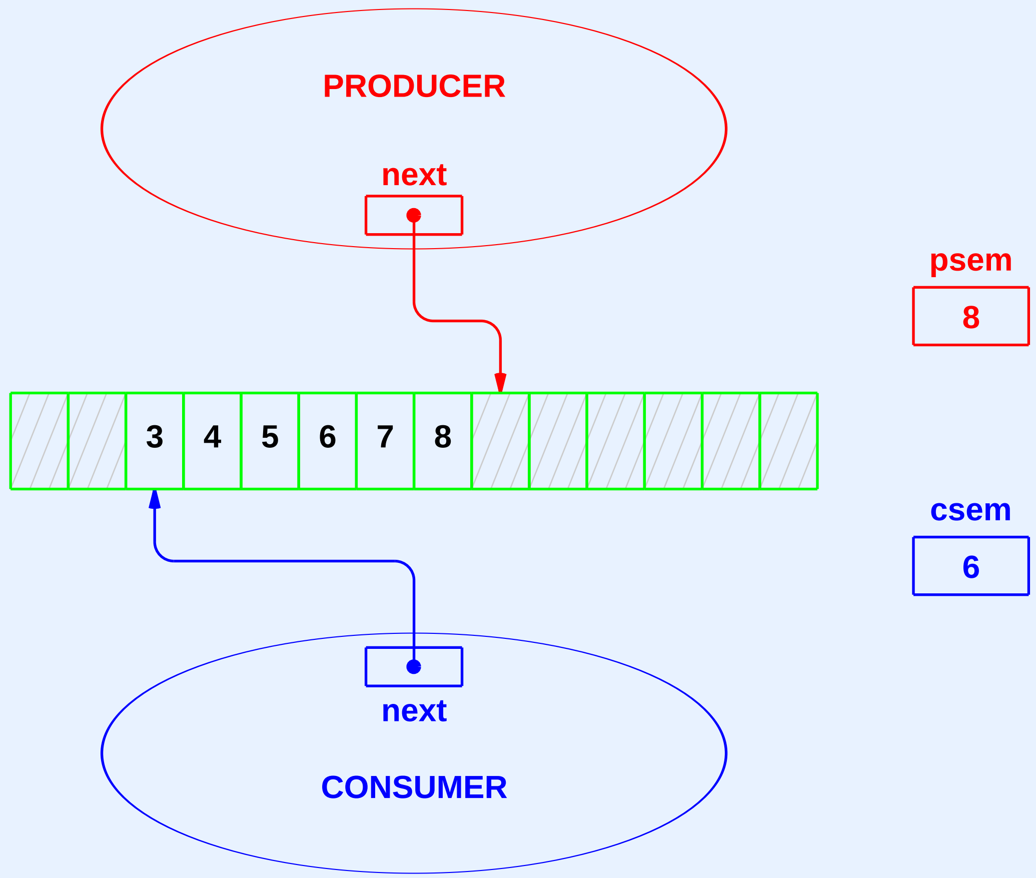
```
repeat forever {
        wait(psem);
        fill_next_buffer_slot;
        signal(csem);
}
```

Producer-Consumer Synchronization (continued)

- Use by consumer

```
repeat forever {
        wait(csem);
        extract_from_buffer_slot;
        signal(psem);
}
```

Illustration Of Producer-Consumer



- *csem* counts items currently in buffer
- *psem* counts unused slots in buffer

Semaphore Queuing Policy

- Used when *signal* called
- Determines which process to select among those waiting
- Examples
  - First-Come-First-Served (FCFS or FIFO)
  - Process priority
  - Random

Question

- The goal is “fairness”
- Which semaphore queuing policy implements goal best?
- In other words, how should we interpret fairness?
  - Should a low-priority process be allowed to run if a high-priority process is also waiting?
  - Should a low-priority process be blocked forever if high-priority processes use a resource?

Choosing A Semaphore Queueing Policy

- Difficult
- No single best answer
  - Fairness not easy to define
  - Scheduling and coordination interact
  - May affect other OS policies
- Interactions of heuristics may produce unexpected results

Example Semaphore Queuing Policy

- First-come-first-serve
- Straightforward to implement
- Works well for traditional uses of semaphores
- Potential problem: low-priority process can access while high-priority process remains waiting

Implementation Of FIFO Semaphore Policy

- Each semaphore uses a list to manage waiting processes
- List is run as a queue: insertions at one end and deletions at the other
- Example implementation follows

/* signal.c - signal */

```
/*------------------------------------------------------------------------
 *  signal  -  Signal a semaphore, releasing a process if one is waiting
 *------------------------------------------------------------------------
 */
syscall signal(
          sid32         sem              /* id of semaphore to signal    */
        )
{
        intmask mask;                    /* saved interrupt mask         */
        struct  sentry *semptr;          /* ptr to sempahore table entry */

        mask = disable();
        if (isbadsem(sem)) {
                restore(mask);
                return SYSERR;
        }
        semptr= &semtab[sem];
        if (semptr->sstate == S_FREE) {
                restore(mask);
                return SYSERR;
        }
        if ((semptr->scount++) < 0) {   /* release a waiting process */
                ready(dequeue(semptr->squeue), RESCHED_YES);
        }
        restore(mask);
        return OK;
}
```

Semaphore Allocation

- Static
  - Semaphores defined at compile time
  - More efficient, but less powerful
- Dynamic
  - Semaphore created at runtime
  - More flexible

Xinu Semcreate (part 1)

```
/* semcreate.c - semcreate, newsem */

local   sid32   newsem(void);

/*------------------------------------------------------------------------
 *  semcreate  -  create a new semaphore and return the ID to the caller
 *------------------------------------------------------------------------
 */
sid32   semcreate(
          int32         count           /* initial semaphore count      */
        )
{
        intmask mask;                   /* saved interrupt mask         */
        sid32   sem;                    /* semaphore ID to return       */

        mask = disable();

        if (count < 0 || ((sem=newsem())==SYSERR)) {
                restore(mask);
                return SYSERR;
        }
        semtab[sem].scount = count;     /* initialize table entry       */

        restore(mask);
        return sem;
}
```

Xinu Semcreate (part 2)

```
/*------------------------------------------------------------------------
 *  newem  -  allocate an unused semaphore and return its index
 *------------------------------------------------------------------------
 */
local   sid32   newsem(void)
{
        static  sid32   nextsem = 0;    /* next semaphore index to try  */
        sid32   sem;                    /* semaphore ID to return       */
        int32   i;                      /* iterate through # entries    */

        for (i=0 ; i<NSEM ; i++) {
                sem = nextsem++;
                if (nextsem >= NSEM)
                        nextsem = 0;
                if (semtab[sem].sstate == S_FREE) {
                        semtab[sem].sstate = S_USED;
                        return sem;
                }
        }
        return SYSERR;
}
```

Semaphore Deletion

- Processes may be waiting
- Must choose a disposition for each
- Example: make process ready

Xinu Semdelete (part 1)

```
/* semdelete.c - semdelete */

#include <xinu.h>

/*------------------------------------------------------------------------
 * semdelete  --  Delete a semaphore by releasing its table entry
 *------------------------------------------------------------------------
 */
syscall semdelete(
          sid32          sem            /* ID of semaphore to delete    */
        )
{
        intmask mask;                   /* saved interrupt mask         */
        struct  sentry *semptr;         /* ptr to sempahore table entry */

        mask = disable();
        if (isbadsem(sem)) {
                restore(mask);
                return SYSERR;
        }

        semptr = &semtab[sem];
        if (semptr->sstate == S_FREE) {
                restore(mask);
                return SYSERR;
        }
        semptr->sstate = S_FREE;
```

Xinu Semdelete (part 2)

```
        while (semptr->scount++ < 0) {  /* free all waiting processes   */
                ready(getfirst(semptr->squeue), RESCHED_NO);
        }
        resched();
        restore(mask);
        return OK;
}
```

Do you understand semaphores?

Thought Problem
(The Convoy)

- One process creates a semaphore

```
mutex = screate(1);
```

- Three processes execute the following

```
PROCESS convoy(char_to_print)
   do forever {
        think (i.e., use CPU);
        wait(mutex);
        print(char_to_print);
        signal(mutex);
   }
```

- The processes print characters *A*, *B*, and *C*, respectively

Convoy Problem
(continued)

- Initial output
  - 20 *A*’s, 20 *B*’s, 20 *C*’s, 20 *A*’s, etc.
- After tens of seconds
  ABCABCABC...
- Facts
  - Everything is correct
  - No other processes are executing
  - Print is nonblocking (polled I/O)

Convoy Problem
(continued)

- Questions
  - How long is thinking time?
  - Why does convoy start?
  - Will output switch back given enough time?
  - Did knowing the policies or the implementation of the scheduler and semaphore mechanisms make the convoy behavior obvious?

Summary

- Process synchronization fundamental
  - Supplied to applications
  - Used inside OS
- Low-level mutual exclusion
  - Masks hardware interrupts
  - Avoids rescheduling
  - Insufficient for all coordination

Summary
(continued)

- High-level coordination
  - Used by subsets of processes
  - Available inside and outside OS
  - Implemented with counting semaphore
- Counting semaphore
  - Powerful abstraction
  - Provides mutual exclusion and producer / consumer synchronization