CS 134:
Operating Systems
Computer Hardware
Synchronization

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Overview

Overview
Administrivia
Hardware
Overview
I/O Hardware
Interrupts
Synchronization
Critical Sections
Hardware Support
Higher-Level Mechanisms
Dining Philosophers

A Bit on OS/161 & Homeworks

Status: I'm working on it; initial setup takes a bit of time

- So when I post homework, plan for that time!

First assignment will be "get going"

You should have your group formed by now

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In the Meantime. . .

Activities to do before Thursday:

- Find out about system calls
  - Read manual pages on `getpid`, `stime`, `readdir`
  - About how many system calls does Linux have? (Hint: manual pages live in `/usr/share/man`
  - Run `strace` (on Knuth or other Linux) on a simple program such as `true`, `echo`, or `ls`

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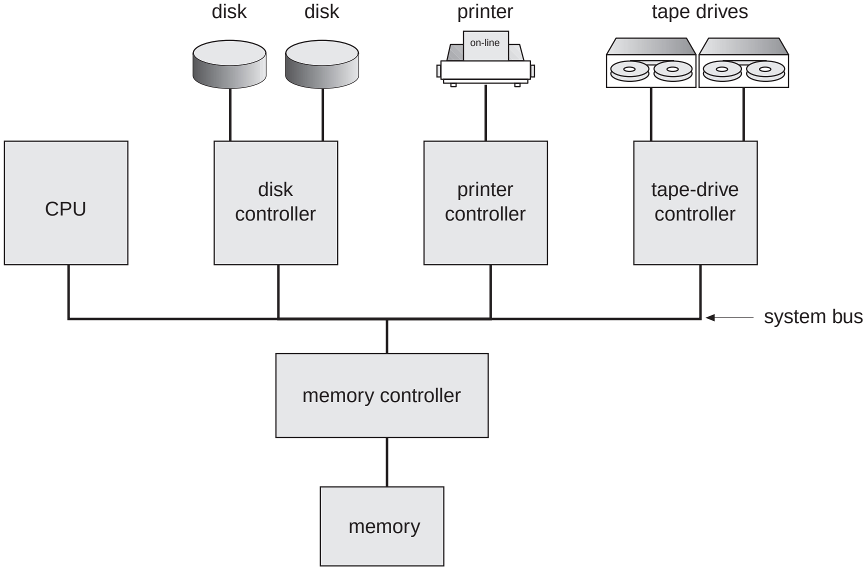
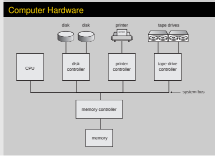
Computer Hardware





Computer Hardware—CPU & Memory

Need to perform computation!

- Memory contains program instructions and program data
- Processor registers maintain processor state. Registers include:
  - General purpose (address & data) registers
  - Instruction pointer (aka program counter)
  - Stack pointer(s)
  - Control and status registers

Computer Hardware—CPU & Memory
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Start
Fetch Instruction
Execute Instruction
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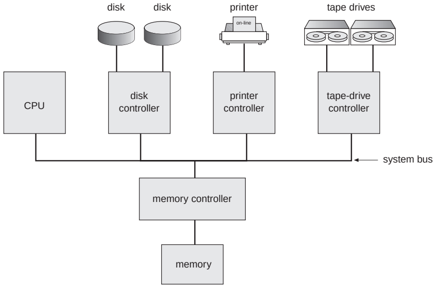
Stack pointer(s)
Control and status registers

Computer Hardware—I/O Devices

Need to communicate with the world!

- I/O devices and CPU execute concurrently
- Devices have hardware controllers
  - Handles devices of a particular device type
  - Some level of autonomy
  - Local buffer
- I/O is from the device to local buffer of controller



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└Hardware
 └I/O Hardware
  └Computer Hardware—I/O Devices

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Programmed I/O

After I/O starts, control returns to user program only on I/O completion

- CPU waits until I/O completes.
- At most one I/O request is outstanding at a time
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Polled I/O

Polling == Querying the I/O device
Separate I/O into two parts:

- Initiation
- Polling

Advantages?

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Interrupt-Driven I/O

Separate I/O into two parts:

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I/O in User-Level Code

User-level code almost always uses “programmed I/O” (e.g. `read` and `write` on a file)

Why?

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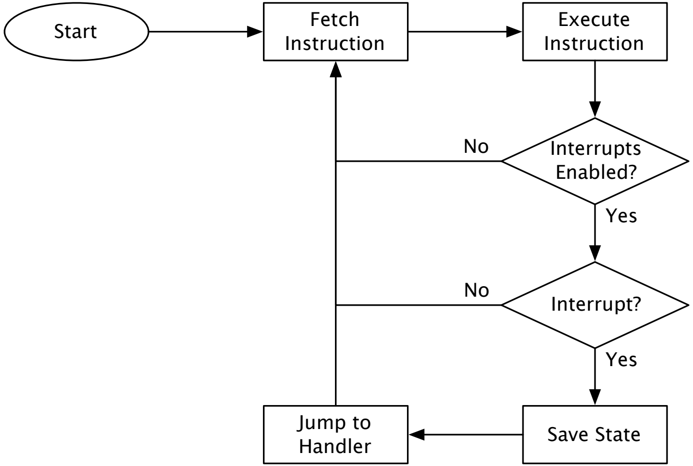
Why?

Computer Hardware—CPU with Interrupts

CPU needs another feature. . .



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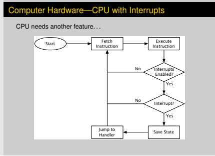
CS34
Hardware
Interrupts
Computer Hardware—CPU with Interrupts



Handling an Interrupt

What needs to happen:

- Save state
  - All registers
  - Switch stacks?
- Find out what interrupt was. . .
  - Polling
  - Vectored interrupts

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Types of Interrupts

Various types

- Software exception (also called a trap)
- Timer
- I/O
- Hardware failure

A modern operating system is *interrupt driven*

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Other Hardware Features

We've covered interrupts, but hardware has other cool features, including:

- Caches
- Memory management
- Protection

We'll come back to hardware as we address these topics.

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Recap

Solution to I/O waiting was:

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- Do something else during I/O!

But doing two (or more) things at once introduces headaches!

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Synchronization

Uncontrolled access to shared data

⇒ *Race conditions*

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Uncontrolled access to shared data
⇒ *Race conditions*

Example: The Bounded-Buffer Problem

Two threads:

- **Producer**: Creates data items
- **Consumer**: Uses them up

We'll look at the problem using a shared array. . .

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Two threads:
- **Producer**: Creates data items
- **Consumer**: Uses them up
We'll look at the problem using a shared array. . .

Okay?

```
enum { N = 128};          // maximum buffer capacity
volatile item buffer[N]; // the buffer itself
volatile int in = 0;     // buffer in cursor (moved by producer)
volatile int out = 0;    // buffer out cursor (moved by consumer)
```

```
void producer() {
  item made_item;
  for ( ; ; ) {
    made_item = make_item();
    while ((in + 1) % N == out) {
      /* buffer full---wait */
    }
    buffer[in] = made_item;
    in = (in + 1) % N;
  }
}
```

```
void consumer() {
  item usable_item;
  for ( ; ; ) {
    while ( in == out) {
      /* buffer empty---wait */
    }
    usable_item = buffer[out];
    out = (out + 1) % N;
    use_item(usable_item);
  }
}
```

Okay?

```
enum { N = 128 };          // maximum capacity of the buffer
volatile item buffer[N]; // the buffer itself
volatile int count = 0;  // how many things are in the buffer
```

```
void producer() {
  int in = 0;
  item made_item;

  for ( ; ; ) {
    made_item = make_item();
    while (count == N) {
      /* buffer full---wait */
    }
    buffer[in] = made_item;
    in = (in + 1) \% N;
    ++count;
  }
}
```

```
void consumer() {
  int out = 0;
  item usable_item;

  for ( ; ; ) {
    while ( count == 0) {
      /* buffer empty---wait */
    }
    usable_item = buffer[out];
    out = (out + 1) % N;
    --count;
    use_item(usable_item);
  }
}
```

Atomicity

The MIPS code for `++count` is as follows

```
lw      $2,count
nop
addu    $2,$2,1
sw      $2,count
```


Atomicity
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Critical-Section Problem

The critical section problem exists where $n > 1$ processes all compete to use some shared data

- But not always—certain other conditions apply
  - Roughly, different processes see conflicting data
- Code that accesses shared data = **critical section**
- Must ensure mutual exclusion for critical sections

Generic Example:

```
/* Shared data...  */
```

```
void foo()
{
  for ( ; ; ) {
    /* enter critical section */
    foo_cs_actions();
    /* leave critical section */
    foo_other_actions();
  }
}
```

```
void bar()
{
  for ( ; ; ) {
    /* enter critical section */
    bar_cs_actions();
    /* leave critical section */
    bar_other_actions();
  }
}
```


Critical-Section Problem

The critical section problem exists where $n > 1$ processes all compete to use some shared data

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Generic Example:

/* Shared data... */
void foo() { for (; ;) { /* enter critical section */ foo_cs_actions(); /* leave critical section */ foo_other_actions(); } }
void bar() { for (; ;) { /* enter critical section */ bar_cs_actions(); /* leave critical section */ bar_other_actions(); } }

Critical-Section Problem—Solution Requirements

Must satisfy the following requirements:

- **Mutual Exclusion**
- **Progress**
- **Bounded Waiting** (also known as **No Starvation**)

(Assume processes don't hang/die inside the critical section.)

(Can't assume anything about execution speeds or number of CPUs.)

Critical-Section Problem—Solution Requirements
Must satisfy the following requirements:
Mutual Exclusion
Progress
Bounded Waiting (also known as No Starvation)
(Assume processes don't hang/die inside the critical section.)
(Can't assume anything about execution speeds or number of CPUs.)

Mutual exclusion: If a process is executing in its critical section, then no other processes can be executing in their critical sections.
Progress: If no process is executing in its critical section and there exist some processes that wish to enter their critical section, then the selection of the process that will enter its critical section next cannot be postponed indefinitely.
Bounded waiting: A bound must exist on the number of times that other processes are allowed to enter their critical sections after a process has asked to enter its critical section.

Critical-Section Problem—Solution?

```
/* Shared data---Whose turn it is */
volatile enum { Foo, Bar } turn = Foo;
```

```
void foo()
{
  for ( ; ; ) {
    while (turn != Foo) {
      /* let bar take its turn */
    }
    foo_cs_actions();
    turn = Bar;
    foo_other_actions();
  }
}
```

```
void bar()
{
  for ( ; ; ) {
    while (turn != Bar) {
      /* let foo take its turn */
    }
    bar_cs_actions();
    turn = Foo;
    bar_other_actions();
  }
}
```


Does this code satisfy our requirements?

Critical-Section Problem—Solution?

```
/* Shared data---Who is busy? */
volatile bool foo_busy = false;
volatile bool bar_busy = false;
```

```
void foo()
{
  for ( ; ; ) {
    foo_busy = true;
    while (bar_busy == true) {
      /* let bar finish */
    }
    foo_cs_actions();
    foo_busy = false;
    foo_other_actions();
  }
}
```

```
void bar()
{
  for ( ; ; ) {
    bar_busy = true;
    while (foo_busy == true) {
      /* let foo finish */
    }
    bar_cs_actions();
    bar_busy = false;
    bar_other_actions();
  }
}
```


Critical-Section Problem—Solution?

Critical-Section Problem—Solution?

How about this version?

```
void task(const int i)
{
  for ( ; ; ) {
    splhigh();
    cs_actions(i);
    spl0();
    other_actions(i);
  }
}
```


Critical-Section Problem—Solution?

How about this version?

void task(const int i)
{
  for (; ;) {
    splhigh();
    cs_actions(i);
    spl0();
    other_actions(i);
  }
}

Critical-Section Problem—Solution?

Or this one?

```
/* Shared data */
bool lock = false; // shared mutual exclusion lock

void task(const int i)
{
  for ( ; ; ) {
    while (test_and_set(lock)) {
        /* do nothing---wait for lock to be
           released */
    }
    cs_actions(i);
    lock = false;
    other_actions(i);
  }
}
```


Critical-Section Problem—Solution?
Or this one?
/* Shared data */
bool lock = false; // shared mutual exclusion lock
void task(const int i)
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for (; ;) {
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}
cs_actions(i);
lock = false;
other_actions(i);
}
}

Semaphores

You've seen 'em in 105:

```
void task(const int i) {
  for ( ; ; ) {
    P(oursem);
    cs_actions(i);
    V(oursem);
    other_actions(i);
  }
}
```


Semaphores

You've seen 'em in 105:

void task(const int i) {
  for (; ;) {
    P(oursem);
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    other_actions(i);
  }
}

Semaphores

Two fundamental operations

`P`	*proberen*	`down`	`dec`	`wait`	Try to grab the semaphore
`V`	*verhogen*	`up`	`inc`	`signal`	Release the semaphore

Semaphores
Two fundamental operations
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This slide has animations

Semaphores

Two fundamental operations

P *proberen*	down	dec	wait	Try to grab the semaphore
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Semaphores have an associated count!

- P—Sleep until count is nonzero; once positive, decrement count
- V—Increment count, wake any sleepers

Semaphores
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P proberen down dec wait Try to grab the semaphore
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Semaphores have an associated count!
P—Sleep until count is nonzero; once positive, decrement count
V—Increment count, wake any sleepers

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Bounded Buffer with Semaphores

```
enum { N = 128 };          // maximum capacity of the buffer
volatile item buffer[N]; // the buffer itself
struct sem *empty_slot;  // any free slots?  (initialized to N)
struct sem *filled_slot; // any filled slots? (initialized to 0)
```

```
void producer()
{
  int in = 0;
  item made_item;

  for ( ; ; ) {
    made_item = make_item();
    P(empty_slot)
    buffer[in] = made_item;
    in = (in + 1) % N;
    V(filled_slot);
  }
}
```

```
void consumer()
{
  int out = 0;
  item usable_item;

  for ( ; ; ) {
    P(filled_slot);
    usable_item = buffer[out];
    out = (out + 1) % N;
    V(empty_slot);
    use_item(usable_item);
  }
}
```

Bounded Buffer with Semaphores

```
enum { N = 128 };          // maximum capacity of the buffer
item_queue buffer;         // the buffer itself
struct sem *empty_slot;    // any free slots? (initialized to N)
struct sem *filled_slot;   // any filled slots? (initialized to 0)
struct sem *mutex;         // protection for the buffer (initialized to 1)
```

```
void producer()
{
  item made_item;

  for ( ; ; ) {
    made_item = make_item();
    P(empty_slot)
    P(mutex);
    put_item(buffer, made_item);
    V(mutex);
    V(filled_slot);
  }
}
```

```
void consumer()
{
  item usable_item;

  for ( ; ; ) {
    P(filled_slot);
    P(mutex);
    usable_item = get_item(buffer);
    V(mutex);
    V(empty_slot);
    use_item(usable_item);
  }
}
```


Bounded Buffer with Semaphores

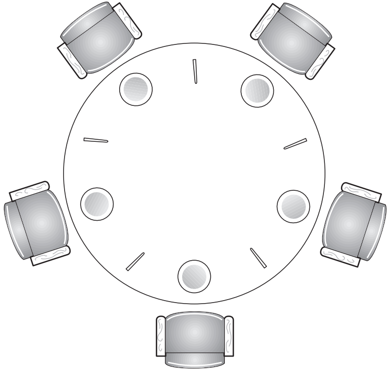
Dining Philosophers

Each philosopher alternates between periods of

- Thinking
- Eating

Each philosopher

- Shares chopsticks with neighbors
- Must not starve



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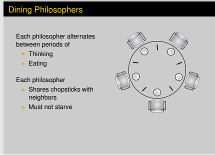

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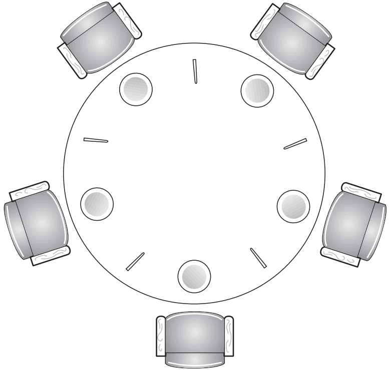
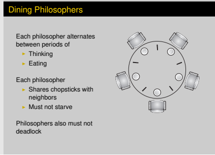
Philosophers also must not deadlock





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Philosophers with Semaphores

```
enum { N = 5 };        // five philosophers
enum { HUNGRY, THINKING, EATING } state[N]; // everyone's state
struct sem mutex = 1; // mutual exclusion for critical regions
struct sem s[N];       // one semaphore per philosopher

void philosopher(int i)
{
  for ( ; ; ) {
    think();              // philosopher is thinking
    take_chopsticks(i); // acquire chopsticks (block if need be)
    eat();                // yum-yum
    put_chopsticks(i);
  }
}

void test(int i)
{
  if (state[i] == HUNGRY && state[left(i)] != EATING
   && state[right(i)] != EATING) {
    state[i] = EATING;
    V(s[i]);  // let philosopher i eat!
  }
}
```


Philosophers with Semaphores

Dining Philosophers: With Semaphores (cont'd)

```
void take_chopsticks(int i)
{
  P(mutex);  // enter critical region
  state[i] = HUNGRY;
  test(i);   // try to acquire 2 chopsticks
  V(mutex);  // exit critical region
  P(s[i]);   // block if chopsticks were not acquired
}

void put_chopsticks(int i)
{
  P(mutex);   // enter critical region
  state[i] = THINKING;
  test(left(i));  // see if left neighbor can now eat
  test(right(i)); // see if right neighbor can now eat
  V(mutex);   // exit critical region
}
```


Dining Philosophers: With Semaphores (cont'd)