Threads and concurrency

- Motivation: operating systems getting really complex
  - Multiple users, programs, I/O devices, etc.
  - How to manage this complexity?
- Main techniques to manage complexity in programs?
  - Divide and conquer
  - Modularity and abstraction

```
main() {
    getInput();
    computeResult();
    printOutput();
}
```


Processes

- Processes decompose mix of activities running on a computer into several "independent" tasks that run in parallel

job 1	job 2	job 3

- Process is the key abstraction that made is simple to run multiple things simultaneously
  - Each process need not know about the others
- Remember, for each area of OS, ask
  - What interface does the hardware provide?
  - What interface does the OS provide?

What's a process?

- Informal definition
  - A program in execution. A running piece of code along with all the things the program can read/write
  - Process != program
- Formal definition
  - One or more threads in an address space
- Thread
  - Sequence of execution instructions from a program (i.e., the running computation)
  - Active
  - Play analogy
- Address space
  - All the memory data the process uses as it runs
  - Passive
  - Play analogy

Categories of data in an address space

Multiple threads

- Can have several threads in a single address space
  - Sometimes they interact
  - Sometimes they work independently
- State that is private to a thread

- State that is shared between threads

Upcoming topics

- Concurrency: multiple threads active at one time
  - Thread is the unit of concurrency
  - How multiple threads can cooperate to accomplish a single task
  - How multiple threads can share a limited number of CPUs

- Address spaces
  - Address space is the unit of state partitioning
  - How multiple address spaces can share a single physical memory efficiently, flexibly, and safely?

Web server example

- How to build a web server
  - Receives multiple simultaneous requests
  - Reads web pages from disk to satisfy each request
- Option 1: handle one request at a time

  Request 1 arrives

  Server receives request 1

  Server starts disk I/O 1a

  Request 2 arrives

  Server waits for I/O 1a to finish
  - Easy to program, but slow
  - Can't overlap disks requests with computation, or with network receives

Event-driven web server (asynchronous I/O)

- Issue I/Os, but don't wait for them to complete

  Request 1 arrives

  Server receives request 1

  Server starts disk I/O 1a to satisfy request 1

  Request 2 arrives

  Server receives request 2

  Server starts disk I/O 2a to satisfy request 2

  Request 3 arrives

  Disk I/O 1a finishes
  - Web server must remember
    - What requests are being serviced, and what stage they're in
    - What disk I/Os are outstanding (and which requests they belong to)
    - Lots of extra state!

Multi-threaded web server

- One thread per request
  - Thread issues disk (or network) I/O, then waits for it to finish
  - Even though thread is blocked on I/O, other threads can run
  - Where is the state of each request stored?

Thread 1	Thread 2	Thread 3
Request 1 arrives		
Receive request 1		
Start disk I/O 1a		
	Request 2 arrives	
	Receive request 2	
	Start disk I/O 2a	
		Request 3 arrives
		Receive request 3
Disk I/O 1a finishes		
Continue handling request 1		

Benefits of threads

- Thread manager takes care of sharing CPUs among several threads
  - A thread can issue blocking I/Os, while other threads can still make progress
  - Private state for each thread
- Applications get a simpler programming model
  - The illusion of a dedicated CPU per thread
- Domains that use multiple threads
  - Multiple things happening at once
  - Usually some slow resource
  - Examples
    - Network server
    - Controlling a physical system
    - Window system
    - Parallel programming

Can threads truly be independent?

- Example 1: Microsoft Word
  - One thread formats document
  - Another thread spell checks document

- Example 2: desktop computer
  - One thread plays World of Warcraft
  - Another thread compiles EECS 482 project

- Two types of sharing

- Example of non-interacting threads:

Cooperating threads

- How multiple threads can cooperate on a single task
  - Assume each thread has a dedicated processor
  - Later we'll talk about how to provide the illusion of infinite processors
- Main problem: ordering of events from different threads is non-deterministic
  - Speed of each processor is unpredictable

```
Thread A ------------------------------------->
Thread B -   -    -    -    -    -    -    -    >
Thread C - - - - - - - - - - - - - - - - - - - - - ->
```

  - Global ordering of events
  - Many possible orderings (some of which may produce incorrect results)

Non-deterministic ordering produces non-deterministic results

- Printing example

Thread A	Thread B
Print ABC	Print 123

  - Possible outputs?
  - Impossible outputs?
  - Ordering within thread is sequential, but many ways to merge per-thread order into a global order
  - What's being shared between these threads?

Non-deterministic ordering produces non-deterministic results

- Arithmetic example (y is initially 10)

Thread A	Thread B
x = y + 1	y = y * 2

  - What's being shared between these threads?
  - Possible results?

- Another arithmetic example (x is initially 0)

Thread A	Thread B
x = 1	x = -1

  - Possible results?
  - Impossible results?

Atomic operations

- Before we can reason at all about cooperating threads, we must know that some operation is **atomic**
  - Indivisible, i.e., happens in its entirety or not at all
  - No events from other threads can occur in between the start and end of an atomic operation
- Arithmetic example: what if assignment were atomic?
- Print example:
  - What if each print statement were atomic?
  - What if printing a single character were not atomic?

- Most computers
  - Memory load and store are atomic
  - Many other instructions are not atomic (e.g., double-precision floating point)
  - Need an atomic operation to build a bigger atomic operation

Example

x is shared and initialized to 0

Thread A

```
while (x<10) {
    x++
}
print "A finished"
```

Thread B

```
while (x> -10) {
    x--
}
print "B finished"
```

- Which thread will finish first?
- Is the winner guaranteed to print first?
- Is it guaranteed that someone will will?
- What if both threads run at exactly the same speed, and start close together? Is it guaranteed that both threads will loop forever?

- Non-deterministic interleaving makes debugging challenging
  - Heisenbug: a bug that occurs non-deterministically

Synchronization

- Must constrain the interleavings between threads
  - Some events are independent of each other, so their order is irrelevant
  - Other events are dependent, so their order matters
- All possible interleavings must produce a correct result
  - A correct concurrent program should work correctly no matter how fast the processors are that execute the threads

- Try to constrain thread executions as little as possible

- Controlling the execution and order of threads is called synchronization

Too much milk

- Problem definition
  - Janet and Peter want to keep their refrigerator stocked with at most one milk jug
  - If either sees fridge empty, she/he goes to buy milk
- Solution #0 (no synchronization)

<u>Peter</u>	<u>Janet</u>
if (noMilk) {	if (noMilk) {
buy milk	buy milk
}	}

First type of synchronization: mutual exclusion

- Mutual exclusion
  - Ensure that only 1 thread is doing a certain thing at one time (other threads are excluded). E.g., only 1 person goes shopping at a time.
  - Constrains interleavings of threads: “not at the same time”
  - Does this remind you of any other concept we’ve talked about?

Critical section

- A section of code that needs to be run atomically with respect to selected other pieces of code
- If code A and code B are critical sections with respect to each other, then multiple threads should not be able to interleave events from A and B (code A and B mutually exclude each other). Often A and B are the same piece of code.
- Critical sections must be atomic with respect to each other because they access some shared resource

- In Too much milk, critical section is “if (no milk) buy milk”

Too much milk (solution #1)

- Assume the only atomic operations are load and store
- Leave note that you're going to check on the milk, so other person doesn't also buy

Peter
```
if (noNote) {
   leave note
   if (noMilk) {
      buy milk
   }
   remove note
}
```

Janet
```
if (noNote) {
   leave note
   if (noMilk) {
      buy milk
   }
   remove note
}
```

- Does this work?
- Is solution #1 better than solution #0?

Too much milk (solution #2)

- Change the order of "leave note" and "check note". Notes need to be labelled (otherwise you'll see your note and think the other person left it).

Peter
```
leave notePeter
if (no noteJanet) {
   if (noMilk) {
      buy milk
   }
}
remove notePeter
```

Janet
```
leave noteJanet
if (no notePeter) {
   if (noMilk) {
      buy milk
   }
}
remove noteJanet
```

- Does this work?

Too much milk (solution #3)

- Decide who will buy milk when both leave notes at the same time. Peter hangs around to make sure job is done.

Peter	Janet
leave notePeter	leave noteJanet
while (noteJanet) {	
do nothing	
}	if (no notePeter) {
if (noMilk) {	if (noMilk) {
buy milk	buy milk
}	}
remove notePeter	}
	remove noteJanet

- Peter's "while (noteJanet)" prevents him from entering the critical section at the same time as Janet

Proof of correctness

- Janet
  - if no notePeter, then Peter hasn't started yet, so it's safe to buy. Peter will wait for Janet to be done before checking.
  - if notePeter, then Peter is in the body of the code and will eventually buy milk if needed. Note that Peter may be waiting for Janet to exit.
- Peter
  - if no noteJanet, it's safe to buy. Peter has already left notePeter, and Janet will check notePeter in the future.
  - if noteJanet, Peter waits to see what Janet does
    - Janet may have checked notePeter before Peter left note. In this case, Janet will buy milk.
    - Janet may have checked notePeter after Peter left note. In this case, Janet will not buy milk.

Analysis of solution #3

- Good
  - It works
  - What operations must be atomic?

- Bad
  - Complicated; not obviously correct
  - Asymmetric
  - Not obvious how to scale to three people
  - Peter consumes CPU time while waiting. This is called **busy-waiting**.

Higher-level synchronization

- Raise the level of abstraction to make life easier for programmers

concurrent programs
high-level synchronization operations provided by software e.g., locks, monitors, semaphores
low-level atomic operations provided by hardware e.g., load/store, interrupt enable/disable, test&set

Locks (mutexes)

- A lock prevents another thread from entering a critical section
  - e.g., lock fridge while you're checking the milk status and shopping
- Two operations
  - lock(): wait until lock is free, then acquire it

```
do {
    if (lock is free) {          atomic
        acquire lock
        break
    }
} while (1)
```

  - unlock(): release lock
- Why was the note in Too much milk (solutions #1 and #2) not a good lock?

Locks (mutexes)

- Lock usage
  - Lock is initialized to be free
  - Thread acquires lock before entering critical section (waiting if needed)
  - Thread that has acquired lock should release when done with critical section
- All synchronization involves waiting
- Thread can be running or blocked

- Locks make Too much milk easy to solve

Peter	Janet
milk.lock();	milk.lock()
if (noMilk) {	if (noMilk) {
buy milk	buy milk
}	}
milk.unlock()	milk.unlock()

Efficiency

- But this prevents Janet from doing things while Peter is buying milk.
- How to minimize the time the lock is held?

Thread-safe queue with locks

```
enqueue(new_element) {

    // find tail of queue
    for (ptr=head; ptr->next != NULL; ptr = ptr->next) {}

    // add new element to tail of queue
    ptr->next = new_element;
}

dequeue() {

    element = NULL;
    // if something on queue, then remove it
    if (head->next != NULL) {
        element = head->next;
        head->next = head->next->next;
    }

    return(element);
}
```

- What bad things can happen if two threads manipulate queue at same time?

Invariants for thread-safe queue

- Can enqueue() unlock anywhere?

- This stable state is called an invariant: a condition that is "always" true for the linked list. E.g., each node appears exactly one when traversing from head to tail.
  - Is invariant ever allowed to be false?

- Hold lock whenever you're manipulating shared data, i.e., whenever you're breaking the invariant

- What if you're only reading the data?

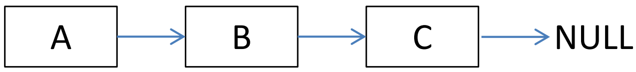
Don't break assumptions

```
enqueue(new_element) {
    lock
    // find tail of queue
    for (ptr=head; ptr->next != NULL; ptr = ptr->next) {}
    unlock

    lock
    // add new element to tail of queue
    ptr->next = new_element;
    unlock
}
```

- Does this work?

Fine-grained locking

- Instead of one lock for the entire queue, use one lock per node of the queue
  - This is called fine-grained locking (not needed until Project 4)
  - Pros and cons
- Lock each node as the queue is traversed, then release as soon as it's safe, so other threads can also access the queue



- lock A
- get pointer to B
- unlock A
- lock B
- read B
- unlock B
- What bad thing could occur?

How to fix?

- Hand-over-hand locking
  - lock next node before releasing last node
  - Used in Project 4

Ordering constraints

- What if you wanted dequeue() to wait if the queue is empty?

```
dequeue() {
    queue.lock();
    // wait for queue to be non-empty




    // remove element
    element = head->next;
    head->next = head->next->next;

    queue.unlock();
    return(element);
}
```


Ordering constraints: solution?

```
dequeue() {








    // remove element
    element = head->next;
    head->next = head->next->next;

    queue.unlock();
    return(element);
}
```

Ordering constraints: solution?

```
dequeue() {









    // remove element
    element = head->next;
    head->next = head->next->next;

    queue.unlock();
    return(element);
}
```


Avoiding busy waiting

- Have waiting dequeuer "go to sleep"
  - Put dequeuer onto a waiting list, then go to sleep

```
if (queue is empty) {

    add myself to waiting list

    go to sleep
}
```

  - enqueuer wakes up sleeping dequeuer

When should dequeuer unlock?

```
enqueue()
    lock
    find tail of queue
    add new element to tail of queue
    if (dequeuer is waiting) {
        take waiting dequeuer off waiting list
        wake up deqeuer
    }
    unlock

dequeue()
    ...
    if (queue is empty) {

        unlock

        add myself to waiting list

        sleep
    }
    ...
```


When should dequeuer unlock?

```
enqueue()
    lock
    find tail of queue
    add new element to tail of queue
    if (dequeuer is waiting) {
        take waiting dequeuer off waiting list
        wake up deqeuer
    }
    unlock

dequeue()
    ...
    if (queue is empty) {

        add myself to waiting list

        unlock

        sleep
    }
    ...
```

Two types of synchronization

- Mutual exclusion
  - Ensures that only one thread is in critical section
  - "Not at the same time"
  - lock/unlock
- Ordering constraints
  - Used when thread must wait for another thread to do something
  - "Before after"
  - E.g., dequeuer must wait for enqueuer to add something to queue

Monitors

- Separate mechanisms for the two types of synchronization
  - Locks for mutual exclusion
  - Condition variables for ordering constraints

- A monitor = a lock + the condition variables associated with that lock

Condition variables

- Enable a thread to sleep inside a critical section, by
  - Releasing lock
  - Putting thread onto waiting list
  - Going to sleep

  (atomic)
  - After being woken, call lock()
- Each condition variable has a list of waiting threads
  - These threads are "waiting on that condition"
  - Each condition variable is associated with a lock
- Operations on a condition variable
  - wait(): atomically release lock, add thread to waiting list, go to sleep.
    - Thread must hold the lock when calling wait()
    - Should thread re-establish invariant before calling wait()?
  - signal(): wake up one thread waiting on this condition variable. If no thread is currently waiting, then signal does nothing
  - broadcast(): wake up all threads waiting on this condition variable. If no thread is currently waiting, then broadcast does nothing

Thread-safe queue with monitors

```
enqueue()
    queueMutex.lock()
    find tail of queue
    add new element to tail of queue
    if (dequeuer is waiting) {
        take waiting dequeuer off waiting list
        wake up deqeuer
    }
    queueMutex.unlock()
}

dequeue()
    queueMutex.lock()





    remove item from queue
    queueMutex.unlock()
    return removed item
}
```

Mesa versus Hoare monitors

- So far, I've described Mesa monitors
  - When waiter is woken, it must contend for the lock with other threads
  - So it must re-check the condition it was waiting for
- What would be required to ensure that the condition is met when the waiter returns from wait and starts running again?

- Hoare monitors give special priority to the woken-up waiter
  - Signalling thread immediately gives up lock to woken-up waiter
  - Signalling thread reacquires lock after waiter unlocks

- We (and most operating systems) use Mesa monitors
  - Waiter is solely responsible for ensuring condition is met

How to program with monitors

- List the shared data needed for the problem
- Assign locks to each group of shared data
- Each thread tries to go as fast as possible, without worrying about other threads
- Two reasons a thread needs to pause
  - Mutual exclusion. Enforce with lock/unlock.
  - Before-after conditions
    - A thread can't proceed because the condition of the shared state isn't satisfactory
    - Some other thread must do something
    - Assign a condition variable for each situation
      - Condition variable belongs to the lock that protects the shared data used to evaluate the condition
    - Use while(!condition) wait
    - Call signal() or broadcast() when a thread changes something that another thread might be waiting for.

How to program with monitors

- Typical code

```
lock
while (!condition) {
    wait
}

do stuff

signal about the stuff you did
unlock
```


Producer-consumer (bounded buffer)

- Producer puts things into a shared buffer; consumer takes them out of shared buffer. Need to synchronize actions of producer and consumer.

- The buffer allows producers and consumers to operate somewhat independently. Used in many situations
  - Unix pipes
  - Communication systems
  - Coke machine
    - Delivery person (producer) fills coke machines with cokes. Produce 1 coke at a time.
    - Students (consumer) buy cokes.
    - Coke machine has finite space.

Producer-consumer with monitors

- Variables
  - Shared data describing state of coke machine buffers
  - numCokes (assume coke machine can hold at most MAX cokes)
  - One lock (cokeLock) to protect this data
- When must a thread pause?
  - Mutual exclusion (when acquiring a lock)
  - Consumer must wait if all buffers are empty
    - Use condition variable waitingConsumers
  - Producer must wait if all buffers are full
    - Use condition variable waitingProducers

Producer-consumer with monitors

Consumer

take coke out of machine

Producer

add coke to machine

Producer-consumer with monitors

- What if we wanted to have producer continuously loop? Can we put the loop inside the lock...unlock region?

- Can we use only 1 condition variable (waitingProducersAndConsumers)?

- Can we always use broadcast instead of signal?

Reader-writer locks

- With standard locks, threads acquire the lock to read (or write) shared data. This prevents other threads from accessing the data.
- Can we allow more concurrency without risking the viewing of unstable data?

- Problem definition
  - Shared data will be read and written by multiple threads
  - Allow multiple readers to access shared data, if no threads are writing data
  - A thread can write shared data only when no other thread is reading or writing the shared data

Reader-writer locks

- Implement a set of functions that a program can use to follow the "multiple-reader, single-writer" constraint
  - readerStart()
  - readerFinish()
  - writerStart()
  - writerFinish()

- Examples for Wolverine Access

```
readerStart()
print catalog
readerFinish()
```

```
writerStart()
change catalog
writerFinish()
```


Reader-writer locks with monitors

concurrent programs coordinates its accesses to shared data by using readerStart, readerFinish, writerStart, writerFinish
even higher-level synchronization primitives (readerStart, readerFinish, writerStart, writerFinish)
high-level synchronization operations provided by software (e.g., locks, monitors, semaphores)
low-level atomic operations provided by hardware (load/store, interrupt enable/disable, test&set)

Implementing reader-writer locks with monitors

- Shared data needed to implement readerStart, readerFinish, writerStart, writerFinish

- Use one lock (rwLock)
- Condition variables

Implementing reader-writer locks with monitors

Implementing reader-writer locks with monitors

- In readerFinish, could I switch the order of numReaders-- and broadcast?
- What will happen if a writer finishes and there are several waiting readers and writers? Will writerStart return, or will 1 readerStart return, or will all readerStart return?
- How long will a writer wait?
- How to give priority to a waiting writer?

Implementing reader-writer locks with monitors

- Why use broadcast?
- Note that at least 1 thread is woken up each time any thread leaves. How to decrease the number of spurious wakeups?

Semaphores

- Semaphores are a generalized lock/unlock
- Definition
  - A non-negative integer (initialized to user-specified value)
  - down(): wait for semaphore value to become positive, then atomically decrement semaphore value by 1.
  - up(): increment semaphore value by 1.
  - key parts are atomic, so two down() calls can't decrement value below 0
- Binary semaphore: value is 0 or 1
  - down waits for value to be 1, then sets it to 0
  - up sets value to 1

Semaphores can implement both mutual exclusion and ordering

- Mutual exclusion
  - Initial value is 1

```
down()
critical section
up()
```

- Ordering constraints
  - Usually, initial value is 0
  - Example: ensure that Thread A's task is done before Thread B's task

Thread A	Thread B
Task A	down()
up()	Task B

Implementing producer-consumer with semaphores

- Semaphore assignments
  - mutex: ensures mutual exclusion around code that manipulates coke machine. Initialized to 1.
  - fullSlots: counts the number of full slots in the coke machine. Initialized to 0.
  - emptySlots: counts of the number of empty slots in the coke machine. Initialized to MAX.

Implementing producer-consumer with semaphores

Consumer

take coke out of machine

Producer

add coke to machine

Implementing producer-consumer with semaphores

- Why do we need different semaphores for fullSlots and emptySlots?
- Does the order of down() matter?
- Does the order of up() matter?
- What needs to change to allow multiple producers (or multiple consumers)?
- What if there's 1 full buffer, and multiple consumers call down() at the same time?

Comparing monitors and semaphores

- Semaphores provide 1 mechanism that can accomplish both mutual exclusion and ordering (monitors use different mechanism for each)
  - Elegant mechanism
  - Can be difficult to use
- Monitor lock = binary semaphore (initialized to 1)
  - lock() = down()
  - unlock() = up()

Condition variable versus semaphore

Condition variable	**Semaphore**
while(cond) {wait();}	down()
Conditional code in user program	Conditional code in semaphore definition
User writes customized condition. More flexible	Condition specified by semaphore definition (wait if value == 0)
User provides shared variable; protects with lock	Semaphore provides shared variable (integer) and thread-safe operations on that variable (down, up)
No memory of past signals	Remembers past up calls

Implementing custom waiting condition with semaphores

- Semaphores work best if the shared integer and waiting condition (value==0) map naturally to problem domain
- How to implement custom waiting condition with semaphores
  - Create one semaphore per waiting thread
  - Implement condition variable as a queue of semaphores
  - To wait, push that thread's semaphore onto waiting queue
  - To signal, up one semaphore from the waiting queue and remove that thread from the queue.

Producer-consumer with semaphores (monitor style)

Consumer

```
mutex.down()
// wait for full slot
while(numCokes==0)




take coke out of machine
// signal producer
...
mutex.up()
```

Producer

```
mutex.down()
// wait for empty slot
...
add coke to machine
// signal consumer
```


Implementing threads

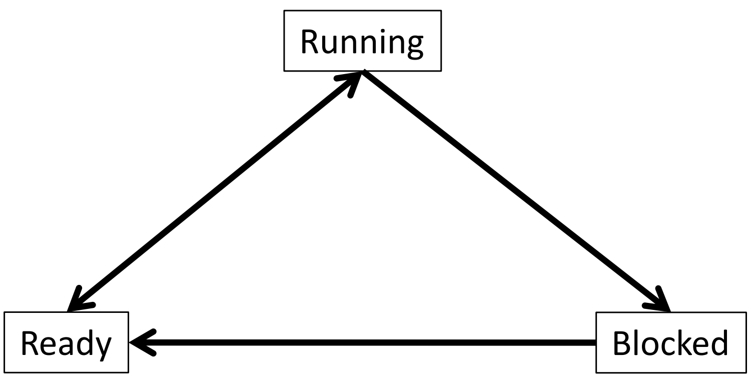
- We've been assuming that each thread has a dedicated processor
- But what if there are more threads than processors?

Ready threads

- What to do with thread while it's not running?
  - What is a non-running thread?
  - Must save its private state somewhere
- This information is called the thread "context" and is stored in a "thread control block" when the thread isn't running
  - To save space, share code among all threads
  - To save space, don't copy stack to the thread control block. Instead, use multiple stacks and just copy the stack pointer to the thread control block.
  - Keep track of ready threads (e.g., on a queue)
  - Thread state can now be running (on the CPU), ready (waiting for the CPU), or blocked (waiting for a synchronization operation from a thread).

Thread states

- 3 thread states
  - Running (currently using CPU)
  - Ready (waiting for CPU)
  - Blocked (waiting for a synchronization operation from another thread, e.g., unlock, signal, broadcast, up)



Switching threads

- Steps to switch to a different thread
  - Current thread returns control to OS
  - OS chooses new thread to run
  - OS saves state of current thread from CPU to its thread control block
  - OS loads context of next thread from its thread control block
  - OS runs next thread

Returning control to OS

- How does thread return control back to OS, so we can save the state of the current thread and run a new thread?

Choosing the next thread to run

- Many ways to choose which thread to run next (CPU scheduling)
  - FIFO
  - Priority

- What should CPU do if there are no other ready threads?

Saving state of current thread

- Save registers, PC, stack pointer
- Typically very tricky assembly-language code
  - E.g., why won't the following code work?

```
100   save PC (i.e., value 100)
101switch to next thread
```

- In Project 2, we'll use Linux's swapcontext()

Loading context of next thread and running it

- How to load registers?
- How to load stack?
- How to resume execution?
- Who is carrying out these steps?

Example of thread switching

```
Thread 1
        print "start thread 1"
        yield()
        print "end thread 1"

Thread 2
        print "start thread 2"
        yield()
        print "end thread 2"

yield()
        print "start yield (thread %d)"
        switch to next thread (swapcontext)
        print "end yield (thread %d)"
```

Example of thread switching

Thread 1 output

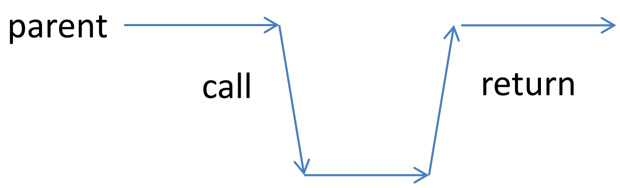
Thread 2 output

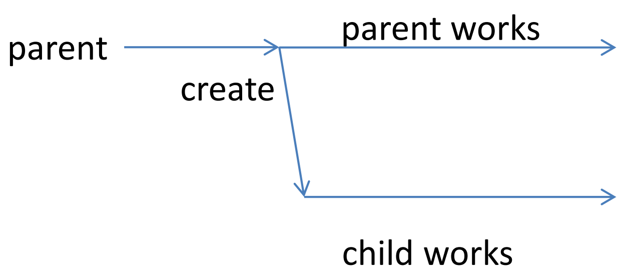
Creating a new thread

- Create state for thread and it to ready queue
  - When pausing a running thread, we saved its state to its thread control block.
  - We can **construct** the state in the thread control block as if it had been running and got paused.
- Steps
  - Allocate and initialize new thread control block
  - Allocate and initialize new stack
  - In Project 2, this is done via makecontext()
  - Add thread control block to ready queue
- Unix fork() is related but different.
  - Unix fork() creates a new process (new thread + new address space)

How to use new thread

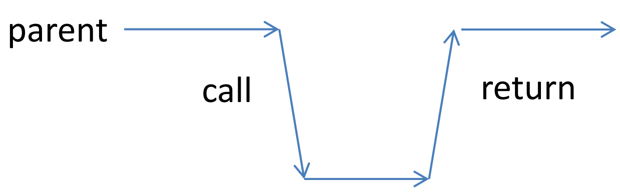
- Creating a thread is like an asynchronous procedure call

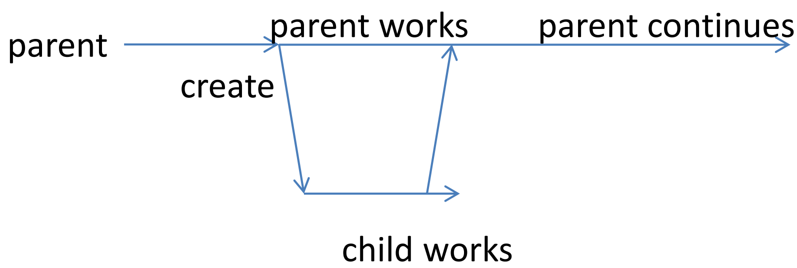




Synchronizing with child

- What if parent wants to work for a while, then wait for child to finish?





Synchronizing with child

- Does this work?

```
parent()

        create child thread

        print "parent works"

        print "parent continues"



child()

        print "child works"
```


Synchronizing with child

- Does this work?

```
parent()
        create child thread
        lock
        print "parent works"
        wait
        print "parent continues"
        unlock

child()
        lock
        print "child works"
        signal
        unlock
```

Synchronizing with child

- join(): wait for another thread to finish

```
parent()
        create child thread
        lock
        print "parent works"
        unlock

        join

        lock
        print "parent continues"
        unlock

child()
        lock
        print "child works"
        unlock
```


Implementing locks -- atomicity in the thread library

- Concurrent programs use high-level synchronization operations

concurrent programs
high-level synchronization operations provided by software (e.g., locks, monitors, semaphores)
low-level atomic operations provided by hardware (load/store, interrupt enable/disable, test&set)

- How to implement these high-level synchronization operations?
  - Used by multiple threads, so must be thread safe
  - Can't use high-level synchronization operations

Can use interrupt disable/enable to ensure atomicity (on uniprocessor)

- On uniprocessor, operation is atomic if context switch doesn't occur
  - How does a thread get switched out?

  - Can prevent context switches during an operation by preventing these events
- User code could disable interrupts to ensure atomicity

```
disable interrupts
if (no milk) {
    buy milk
}
enable interrupts
```

- Problems?

Lock implementation #1 (uniprocessor): disable interrupts, busy wait

```
lock() {
        disable interrupts
        while (status != FREE) {
                enable interrupts
                disable interrupts
        }
        status = BUSY
        enable interrupts
}

unlock() {
        disable interrupts
        status = FREE
        enable interrupts
}
```

- Why does lock() disable interrupts?
- Why is it ok for lock() to disable interrupts?
- Does unlock() need to disable interrupts?
- Why does while loop enable, then disable interrupts?

Another atomic primitive: read-modify-write instruction

- Interrupt disable works on uniprocessor by preventing the current thread from being switched out
- But this doesn't work on a multiprocessor
  - Other processors are still running threads
  - Not acceptable to stop all other processors from executing
- Could use atomic load/store (Too much milk solution #3)
- Modern processors provide an easier way: atomic read-modify-write instructions
  - atomically {read value from memory into register; write new value to memory}

Atomic read-modify-write instructions

- test_and_set: atomically write 1 to a memory location (set) and return the value that was there before (test)

```
test_and_set(X) {
        tmp = X
        X = 1
        return(tmp
}
```

- exchange
  - swap value between register and memory

Lock implementation #2 (test_and_set with busy waiting)

```
// status=0 means lock is free
lock() {
        while (test_and_set(status) == 1) {
        }
}

unlock() {
        status = 0
}
```

- If lock is free, test_and_set changes status to 1 and returns 0, so while loop finishes
- If lock is busy, test_and_set leaves status as 1 and returns 1, so while loop continues
- test_and_set is atomic, so only one thread will see transition from 0 to 1.

Busy waiting

- Problem with lock implementation #1 and #2
  - Waiting thread uses lots of CPU time just checking for lock to become free.
  - Better for thread to sleep and let other threads run
  - Solution: integrate lock implementation with thread dispatch; have lock implementation manipulate thread queues
    - Waiting thread gives up processor, so other threads can run. Someone wakes up thread when lock is free.

Lock implementation #3 (interrupt disable, no busy waiting)

```
lock() {
        disable interrupts
        if (status == FREE) {
                status = BUSY
        } else {


                add thread to queue of threads waiting for lock


                switch to next ready thread
        }
        enable interrupts
}

unlock() {
        disable interrupts
        status = FREE
        if (any thread is waiting for this lock) {
                move waiting thread to ready queue
                status = BUSY
        }
        enable interrupts
}
```

- Handoff lock
  - Unlocker is giving the lock to the waiting locker
- What does it mean for lock() to add current thread to lock wait queue?

- Why have a separate waiting queue for the lock? Why not put waiting thread onto ready queue?

- Normally, when you lock (or disable interrupts), you unlock (or enable interrupts) to clean up. When should lock() re-enable interrupts before calling switch?

Interrupt enable/disable pattern

- Enable interrupts before adding thread to wait queue?

```
lock() {
       disable interrupts
       ...
       if (lock is busy) {
              enable interrupts
              add thread to queue of threads waiting for lock
              switch to next ready thread
       }
       enable interrupts
}
```

- When could this fail?

Interrupt enable/disable pattern

- Enable interrupts after adding thread to wait queue, but before switching to next thread?

```
lock() {
       disable interrupts
       ...
       if (lock is busy) {
              add thread to queue of threads waiting for lock
              enable interrupts
              switch to next ready thread
       }
       enable interrupts
}
```

- This fails if interrupt occurs before switch
  - lock() adds thread to wait queue
  - lock() enables interrupts
  - interrupt occurs, causing switch to another thread. Now thread is on two queues (ready and lock waiting)!

Interrupt enable/disable pattern

- So, adding thread to lock wait queue and switching must be **atomic**
- Thread leaves interrupts disabled when calling switch

- What can lock() assume about the state of interrupts after switch returns?

- How does lock() wake up from switch?

- Switch invariant
  - All threads promise to have interrupts disabled when calling switch
  - All threads assume interrupts are disabled when returning from switch

Thread A	Thread B
	yield() {
	disable interrupts
	switch
enable interrupts	
}	
<user code runs>	
lock() {	
disable interrupts	
...	
switch	
	back from switch
	enable interrupts
	}
	<user code runs>
	unlock() (move thread A to ready queue)
	yield() {
	disable interrupts
	switch
back from switch	
enable interrupts	
}	

Lock implementation #4 (test_and_set, minimal busy waiting)

- Can’t implement locks using test_and_set without some busy-waiting, but can minimize it
- Use busy waiting only to atomically execute lock code. Give up CPU if busy.

```
lock() {
        disable interrupts
        while (test_and_set(guard)) {}

        if (status == FREE) {
                status = BUSY
        } else {


                add thread to queue of threads waiting for lock


                switch to next ready thread
        }
        guard = 0
        enable interrupts
}
```

```
unlock() {
        disable interrupts
        while (test_and_set(guard)) {}

        status = FREE
        if (any thread is waiting for this lock) {
                move waiting thread to ready queue
                status = BUSY
        }

        guard = 0
        enable interrupts
}
```

- What’s the switch invariant for multiprocessors?

How did we atomically {add thread to waiting list and sleep}?

- When there’s another thread to run

- When there’s no other thread to run

Deadlock

- Resources
  - Something needed by a thread
  - A thread waits for resources
  - E.g., locks, disk space, memory, CPU
- Deadlock
  - A cyclical waiting for resources, which prevents the threads involved from making progress
- Example

Thread A	Thread B
x.lock	y.lock
y.lock	x.lock
...	...
y.unlock	x.unlock
x.unlock	y.unlock

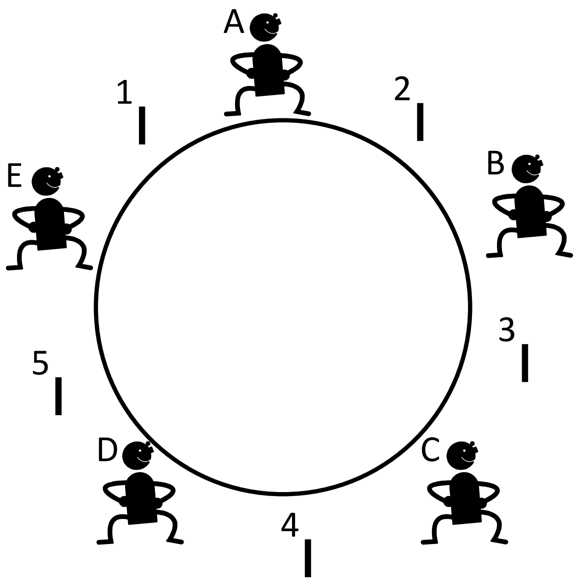
Generic example of multi-threaded program

```
phase 1:
while (!done) {
        acquire some resource
        work
}

phase 2:
release all resources
```

Assume phase 1 has finite amount of work

Dining philosophers

- 5 philosophers sit at round table. 1 chopstick between each pair of philosophers (5 chopsticks total). Each philosopher needs 2 chopsticks to eat.



Dining philosophers

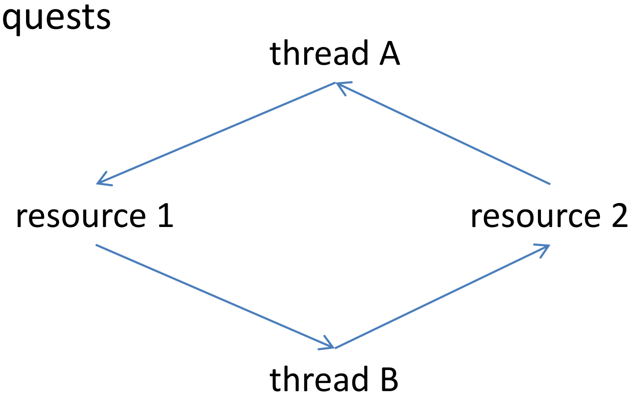
- Algorithm for philosopher

```
wait for chopstick on right to be free, then pick it up
wait for chopstick on left to be free, then pick it up
eat
put both chopsticks down
```

- Can this deadlock?

Four necessary conditions for deadlock

- Limited resource: not enough resources to serve all thread simultaneously
- Hold and wait: threads hold resources while waiting to acquire other resources
- No preemption: thread system can't force thread to give up resource
- Cyclical chain of requests



Strategies for handling deadlock

- General strategies
  - Ignore
  - Detect and fix
  - Prevent
- Detect and fix
  - Detect cycles in the wait-for graph
  - How to fix once detected?

Deadlock prevention

- Eliminate one of the four necessary conditions
- Increase resources to decrease waiting

- Eliminate hold and wait
  - Move resource acquisition to beginning

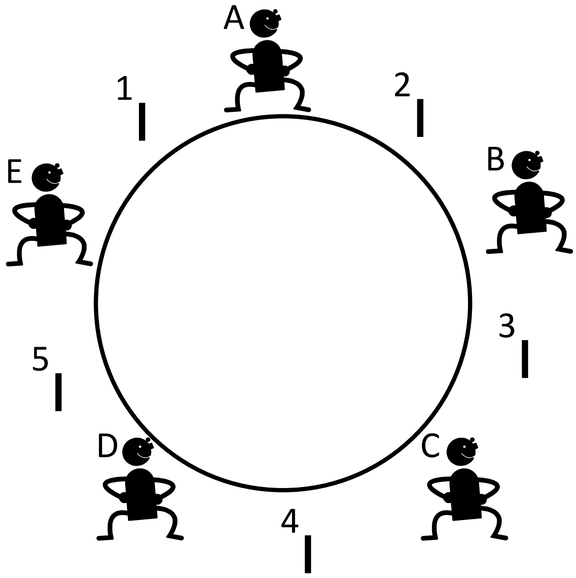
```
Phase 1a: acquire all resources
Phase 1b: while (!done) {
              work
          }

Phase 2: release all resources
```


- Wait until all resources you'll need are free, then grab them all atomically

- If you encounter a busy resource, release all acquired resources and start over
  - Problems?

- Allow preemption
  - Preempt CPU by saving its state to thread control block and resuming later
  - Preempt memory by swapping memory to disk and loading it back later
  - Can you preempt a lock?

Eliminate cyclical chain of requests



Banker's algorithm

- Similar to reserving all resources at beginning, but allows more concurrency
- State maximum resource needs in advance (but don't actually acquire the resources). May block when thread tries to acquire the resource.
- General structure of thread code

```
Phase 1a: state maximum resource needed
Phase 1b: while (!done) {
              acquire some resource (blocking if not safe)
              work
          }
Phase 2: release all resources
```

- Delays when resources are acquired (and when blocking may be needed), relative to acquiring all resources at beginning
- Phase 1a informs system, so it can tell when it's safe to satisfy a resource acquisition in Phase 1b.
- "Safe" means deadlock is impossible (i.e., all threads are guaranteed to be able to finish).

Example of Banker's algorithm

- Model a bank loaning money to its customers
  - Bank has $6000
  - Customers establish credit limit (i.e., maximum resources needed)
  - Customers borrow money in stages. When finished, they return all money.
- Solution 1: Bank promises to give money immediately upon request, up to customer's credit limit.
  - `Ann asks for credit limit of $2000`
  - `Bob asks for credit limit of $4000`
  - `Charlie asks for credit limit of $6000`

  - Can bank approve all these credit limits?

Example of Banker's algorithm

- Solution 2: Banker's algorithm
  - Bank approves all credit limits, but may block customer when he/she asks for the money.
  - `Ann asks for credit limit of $2000 (bank ok's)`
  - `Bob asks for credit limit of $4000 (bank ok's)`
  - `Charlie asks for credit limit of $6000 (bank ok's)`

  - `Ann takes out $1000 (bank has $5000 left)`
  - `Bob takes out $2000 (bank has $3000 left)`
  - `Charlie wants to take out $2000. Is this allowed?`
- Allow only if, after giving the money, there exists way to fulfill all maximum resource requests
  - `Give $2000 to Charlie (bank has $1000 left)`
  - `Give $1000 to Ann, then Ann finishes (bank has $2000)`
  - `Give $2000 to Bob, then Bob finishes (bank has $4000)`
  - `Give $4000 to Charlie, then Charlie finishes`

Example of Banker's algorithm

- Another scenario
  - `Ann asks for credit limit of $2000 (bank ok's)`
  - `Bob asks for credit limit of $4000 (bank ok's)`
  - `Charlie asks for credit limit of $6000 (bank ok's)`

  - `Ann takes out $1000 (bank has $5000 left)`
  - `Bob takes out $2000 (bank has $3000 left)`
  - `Charlie wants to take out $2500.  Is this allowed?`
- Banker's algorithm allows system to overcommit resources without deadlock
  - Sum of max resource needs can be greater than total resources, as long as threads are guaranteed to be able to finish
- How to apply Banker's algorithm to dining philosophers?

- But difficult to anticipate maximum resources needed

CPU scheduling

- How to choose next thread to run? What are the goals of a CPU scheduler?

- Minimize average response time
  - Elapsed time to do each job

- Maximize throughput of entire system
  - Rate at which jobs complete in the system

- Fairness
  - Share CPU among threads in some equitable manner

First-come, first-served (FCFS)

- FIFO ordering between jobs
- No preemptions
  - Thread runs until it calls yield() or blocks
  - No timer interrupts
- Pros and cons

  + simple

  - short jobs can get stuck behind long jobs

  - not interactive
- Example (Job A takes 100 seconds; job B takes 1 second)

  Time 0: Job A arrives and starts

  Time 0+: Job B arrives

  Time 100: Job A ends (response time = 100); job B starts

  Time 101: Job B ends (response time = 101)

  Average response time = 100.5

Round robin

- Goal: improve average response time for short jobs
- Periodically preempt all jobs (viz. long-running ones)
- Is FCFS or round robin more fair?

- Example (Job A takes 100 seconds; job B takes 1 second; 1 second time slice)

  Time 0: Job A arrives and starts

  Time 0+: Job B arrives

  Time 1: Job A is preempted; job B starts

  Time 2: Job B ends (response time = 2)

  Time 101: Job A ends (response time = 101)

  Average response time = 51.5

Round robin

- Does round robin always achieve lower response time than FCFS?

- Pros and cons

  + good for interactive computing

  - more context-switching overhead

- How to choose time slice?
  - Big time slice: degenerates to FCFS
  - Small time slice: more overhead due to context switching
  - Typically a compromise, e.g., 10 ms (if each context switch takes 0.1 ms, then this leads to 1% overhead)

STCF (shortest time to completion first)

- Run whichever job has least amount of work to do before finishing or blocking
  - Preempt current job if shorter job arrives
- Finish short jobs first
  - Improves response time of short jobs (by a lot)
  - Hurts response time of long jobs (by a little)
- STCF gives optimal response time
- Example (Job A takes 100 seconds; job B takes 1 second; 1 second time slice)

  Time 0: Job A arrives and starts

  Time 0+: Job B arrives and preempts job A

  Time 1: Job B ends (response time = 1)

  Time 101: Job A ends (response time = 101)

  Average response time = 51

STCF

- Pros and cons
  + optimal average response time
  - long jobs can get stuck **forever** behind short jobs (starvation)
  - needs knowledge of future

- How to predict the future?

Example

- Job A: compute for 1000 seconds
- Job B: compute for 1000 seconds
- Job C

```
while (1) {
        compute for 1 ms
        Disk I/O for 10 ms
}
```

- A and B can each use 100% of CPU; C can use 91% of disk I/O. What happens when we run them together?
- Goal: keep both CPU and disk busy

- FCFS
  – If A or B run before C, disk will be idle for 1000-2000 seconds

- Round robin with 100 ms time slice

```
CA---------B----------CA----------B----------
|-|                   |-|
C’s                   C’s
I/O                   I/O
```

  – Disk is idle most of the time

- Round robin with 1 ms time slice

```
CABABABABABCABABABABABC-
|----------|----------|
   C’s I/O    C’s I/O
```

  – Disk is utilized about 90% of the time, but lots of context switches

- STCF

```
CA---------C
 |--------|
   C’s I/O
```


Real-time scheduling

- So far, we’ve focused on **average** response time
- But sometimes, the goal is to meet deadlines (irrelevant how far ahead of time the job completes)
  – Video or audio output
  – Control of physical systems
- This requires **worst-case** analysis
- How do we schedule for deadlines in life?

Earliest-deadline first (EDF)

- Always run job with the earliest deadline
- Preempt current job if a new job arrives with earlier deadline
- Optimal: will meet all deadlines if it's possible to do so
- Example
  - Job A: Takes 15 seconds; deadline is 20 seconds after arrival
  - Job B: Takes 10 seconds; deadline is 30 seconds after arrival
  - Job C: Takes 5 seconds; deadline is 10 seconds after arrival

```
    0  5  10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85
A   +
B   +
C   +
```