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

```c
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 it 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

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?

<table>
<thead>
<tr>
<th>Thread 1</th>
<th>Thread 2</th>
<th>Thread 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Request 1 arrives</td>
<td>Receive request 1</td>
<td>Request 2 arrives</td>
</tr>
<tr>
<td>Receive request 1</td>
<td>Start disk I/O 1a</td>
<td>Receive request 2</td>
</tr>
<tr>
<td>Start disk I/O 1a</td>
<td>Disk I/O 1a finishes</td>
<td>Start disk I/O 2a</td>
</tr>
<tr>
<td></td>
<td>Continue handling request 1</td>
<td>Request 3 arrives</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Receive request 3</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Thread A</th>
<th>Thread B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Print ABC</td>
<td>Print 123</td>
</tr>
</tbody>
</table>

  – 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)

<table>
<thead>
<tr>
<th>Thread A</th>
<th>Thread B</th>
</tr>
</thead>
<tbody>
<tr>
<td>( x = y + 1 )</td>
<td>( y = y \times 2 )</td>
</tr>
</tbody>
</table>

  – What’s being shared between these threads?
  – Possible results?

• Another arithmetic example (x is initially 0)

<table>
<thead>
<tr>
<th>Thread A</th>
<th>Thread B</th>
</tr>
</thead>
<tbody>
<tr>
<td>( x = 1 )</td>
<td>( x = -1 )</td>
</tr>
</tbody>
</table>

  – 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

Thread A (i is private)

i=0
while (i<10) {
    i++
}
print “A finished”

Thread B (i is private)

i=0
while (i> -10) {
    i--
}
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)

Peter
if (noMilk) {
    buy milk
}

Janet
if (noMilk) {
    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

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

```java
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).

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

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

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

<table>
<thead>
<tr>
<th>concurrent programs</th>
</tr>
</thead>
<tbody>
<tr>
<td>high-level synchronization operations provided by software</td>
</tr>
<tr>
<td>e.g., locks, monitors, semaphores</td>
</tr>
<tr>
<td>low-level atomic operations provided by hardware</td>
</tr>
<tr>
<td>e.g., load/store, interrupt enable/disable, test&amp;set</td>
</tr>
</tbody>
</table>
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) {
        acquire lock
        break
      }
    } while (1)
    ```
  - unlock(): release lock
- Why was the note in Too much milk (solutions #1 and #2) not a good lock?

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

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

  A → B → C → NULL

  • 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?

dqueue() {
    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);
}

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 dequeuer
  }
  unlock

decqueue()
  ...
  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 dequeuer
  }
  unlock

decqueue()
  ...
  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
  – 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 (dequeueuer is waiting) {
        take waiting dequeueuer off waiting list
        wake up dequeueuer
    }
    queueMutex.unlock()
}

dehqueue()
    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 re-acquires 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**

- add coke to machine

**Consumer**

- take coke out of 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

```plaintext
readerStart()            writerStart()
print catalog            change catalog
readerFinish()           writerFinish()
```

Reader-writer locks with monitors

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

• 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?

• 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)
  - \texttt{down()}: wait for semaphore value to become positive, then atomically decrement semaphore value by 1.
  - \texttt{up()}: increment semaphore value by 1.
  - Key parts are atomic, so two \texttt{down()} calls can’t decrement value below 0
- Binary semaphore: value is 0 or 1
  - \texttt{down} waits for value to be 1, then sets it to 0
  - \texttt{up} sets value to 1

Semaphores can implement both mutual exclusion and ordering

- Mutual exclusion
  - Initial value is 1
  \begin{verbatim}
  \texttt{down()}
  \texttt{critical section}
  \texttt{up()}
  \end{verbatim}
- Ordering constraints
  - Usually, initial value is 0
  - Example: thread A wants to wait for thread B to finish

\begin{verbatim}
Thread A
\texttt{down()}
\texttt{continue execution}

Thread B
\texttt{do task}
\texttt{up()}
\end{verbatim}
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

Producer

take coke out of machine

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

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

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)
    101 switch 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)"
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

```plaintext
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

<table>
<thead>
<tr>
<th>concurrent programs</th>
</tr>
</thead>
<tbody>
<tr>
<td>high-level synchronization operations provided by software (e.g., locks, monitors, semaphores)</td>
</tr>
<tr>
<td>low-level atomic operations provided by hardware (load/store, interrupt enable/disable, test&amp;set)</td>
</tr>
</tbody>
</table>

- 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

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

unlock() {
    disable interrupts
    status = FREE
    enable 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)

  ```c
  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)

```c
// 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)

```c
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
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.

```cpp
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
  - x.lock
  - y.lock
  - ...
  - y.unlock
  - x.unlock

  Thread B
  - y.lock
  - x.lock
  - ...
  - 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.

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

![Diagram of threads and resources](image)

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?
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
  
  ```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
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