Recall: Multithreaded Stack Example

• Consider the following code blocks:

```cpp
proc A() {
    B();
}
proc B() {
    while(TRUE) {
        yield();
    }
}
```

• Suppose we have 2 threads:
  – Threads S and T

Thread S's switch returns to Thread T's (and vice versa)
Recall: Use of Timer Interrupt to Return Control

• Solution to our dispatcher problem
  – Use the timer interrupt to force scheduling decisions

  Timer Interrupt routine:

  ```c
  TimerInterrupt() {
    DoPeriodicHouseKeeping();
    run_new_thread();
  }
  ```
Hardware context switch support in x86

- **Syscall/Intr (U → K)**
  - PL 3 → 0;
  - TSS ← EFLAGS, CS:EIP;
  - SS:ESP ← k-thread stack (TSS PL 0);
  - push (old) SS:ESP onto (new) k-stack
  - push (old) eflags, cs:eip, <err>
  - CS:EIP ← <k target handler>

- **Then**
  - *Handler saves other regs, etc*
  - *Does all its works, possibly choosing other threads, changing PTBR (CR3)*
  - kernel thread has set up user GPRs

- **iret (K → U)**
  - PL 0 → 3;
  - Eflags, CS:EIP ← popped off k-stack
  - SS:ESP ← popped off k-stack

---

Pintos: tss.c, intr-stubs.S

pg 2,942 of 4,922 of x86 reference manual
Pintos: Kernel Crossing on Syscall or Interrupt

user stack

user code

kernel code

kernel thread stack

PTBR

TCB

cs:eip
ss:esp

 syscall / interrupt

saves

processing...

ready to resume

iret

Time

…
Pintos: Context Switch – Scheduling

- **user code** vs **kernel code**
- **user stack** vs **kernel thread stack**
- **syscall / interrupt** vs **ready to resume**
- **PTBR** vs **TCB**
- **cs:eip** vs **ss:esp**

Switch to kernel threads: 

- **iret**
- **Pintos: switch.S**
• Each user process/thread associated with a kernel thread, described by a 4KB page object containing TCB and kernel stack for the kernel thread.
In User thread, w/ Kernel thread waiting

- x86 CPU holds interrupt SP in register
- During user thread execution, associated kernel thread is “standing by”
In Kernel Thread: No User Component

- Kernel threads execute with small stack in thread structure
- Pure kernel threads have no corresponding user-mode thread
User → Kernel (exceptions, syscalls)

- Mechanism to resume k-thread goes through interrupt vector
• Interrupt return (iret) restores user stack, IP, and PL
Pintos Interrupt Processing

intrNN_stub()

push 0x20 (int #)
jmp intr_entry

push 0x21 (int #)
jmp intr_entry

intr_entry:
  save regs as frame
  set up kernel env.
  call intr_handler

intr_exit:
  restore regs
  iret

Wrapper for generic handler

stubs.S
Interrupt transfers control through the Interrupt Vector (IDT in x86)
iret restores user stack and priority level (PL)
Switch to Kernel Thread for Process
Pintos Interrupt Processing

intrNN_stub()

push 0x20 (int #)
jmp intr_entry

push 0x21 (int #)
jmp intr_entry

intr_entry:
save regs as frame
set up kernel env.
call intr_handler

intr_exit:
restore regs
iret

Interrupt Processing

intr_handlers

0x20

0x21

timer.c

Intr_handler(*frame)
- classify
- dispatch
- ack IRQ
- maybe thread yield

timer_intr(*frame)
tick++thread_tick()

intr_entry:
save regs as frame
set up kernel env.
call intr_handler

intr_exit:
restore regs
iret

stubs.S

Hardware interrupt vector

Interrupt Processing

intr_handlers

0x20

0x21

timer.c

Intr_handler(*frame)
- classify
- dispatch
- ack IRQ
- maybe thread yield

timer_intr(*frame)
tick++thread_tick()
Timer may trigger thread switch

- thread_tick
  - Updates thread counters
  - If quanta exhausted, sets yield flag
- thread_yield
  - On path to rtn from interrupt
  - Sets current thread back to READY
  - Pushes it back on ready_list
  - Calls schedule to select next thread to run upon iret
- Schedule
  - Selects next thread to run
  - Calls switch_threads to change regs to point to stack for thread to resume
  - Sets its status to RUNNING
  - If user thread, activates the process
  - Returns back to intr_handler
Thread Switch (switch.S)

• switch_threads: save regs on current small stack, change SP, return from destination threads call to switch_threads
Pintos Return from Processing

intrNN_stub()

intr_entry:
- push 0x20 (int #)
- jmp intr_entry

intr_exit:
- save regs as frame
- set up kernel env.
- call intr_handler
- restore regs
- iret

interrupt.c

Intr_handler(*frame)
- classify
- dispatch
- ack IRQ
- maybe thread yield

timer.c

timer_intr(*frame)
- tick++
- thread_tick()

thread_yield()
- schedule

Pintos intr_handlers
- switch

stubs.S

Resume Some Thread

Hardware interrupt vector

0x20 0

255

0x20
Kernel → Different User Thread

- iret restores user stack and priority level (PL)
Famous Quote WRT Scheduling: Dennis Ritchie

Dennis Richie, Unix V6, slp.c:

```
2230 /* If the new process paused because it was
2231 swapped out, set the stack level to the last call
2232 to savu(u_ssav). This means that the return
2233 which is executed immediately after the call to aretu
2234 actually returns from the last routine which did
2235 the savu.
2236 */
2237
2238 * You are not expected to understand this.
2239 */
```

“If the new process paused because it was swapped out, set the stack level to the last call to savu(u_ssav). This means that the return which is executed immediately after the call to aretu actually returns from the last routine which did the savu.”

“You are not expected to understand this.”

Source: Dennis Ritchie, Unix V6 slp.c (context-switching code) as per The Unix Heritage Society(tuhs.org); gif by Eddie Koehler.

Included by Ali R. Butt in CS3204 from Virginia Tech
Administrivia

• Midterm Thursday 2/17
  – No class on day of midterm
  – 7-9PM

• Project 1 Design Document due next Friday 2/11
• Project 1 Design reviews upcoming
  – High-level discussion of your approach
    » What will you modify?
    » What algorithm will you use?
    » How will things be linked together, etc.
    » Do not need final design (complete with all semicolons!)
  – You will be asked about testing
    » Understand testing framework
    » Are there things you are doing that are not tested by tests we give you?

• Do your own work!
  – Please do not try to find solutions from previous terms
  – We will be on the look out for anyone doing this…today
Goals for Rest of Today

• Challenges and Pitfalls of Concurrency
• Synchronization Operations/Critical Sections
• How to build a lock?
• Atomic Instructions
Recall: Multiprocessing vs Multiprogramming

• Some Definitions:
  – Multiprocessing ≡ Multiple CPUs
  – Multiprogramming ≡ Multiple Jobs or Processes
  – Multithreading ≡ Multiple threads per Process

• What does it mean to run two threads “concurrently”?
  – Scheduler is free to run threads in any order and interleaving: FIFO, Random, …
  – Dispatcher can choose to run each thread to completion or time-slice in big chunks or small chunks
ATM Bank Server

ATM server problem:
- Service a set of requests
- Do so without corrupting database
- Don’t hand out too much money
ATM bank server example

• Suppose we wanted to implement a server process to handle requests from an ATM network:

   BankServer() {
       while (TRUE) {
           ReceiveRequest(&op, &acctId, &amount);
           ProcessRequest(op, acctId, amount);
       }
   }

   ProcessRequest(op, acctId, amount) {
       if (op == deposit) Deposit(acctId, amount);
       else if ...  
   }

   Deposit(acctId, amount) {
       acct = GetAccount(acctId); /* may use disk I/O */
       acct->balance += amount;
       StoreAccount(acct); /* Involves disk I/O */
   }

• How could we speed this up?
  – More than one request being processed at once
  – Event driven (overlap computation and I/O)
  – Multiple threads (multi-proc, or overlap comp and I/O)
Event Driven Version of ATM server

• Suppose we only had one CPU
  – Still like to overlap I/O with computation
  – Without threads, we would have to rewrite in event-driven style
• Example

```c
BankServer() {
    while(TRUE) {
        event = WaitForNextEvent();
        if (event == ATMRequest)
            StartOnRequest();
        else if (event == AcctAvail)
            ContinueRequest();
        else if (event == AcctStored)
            FinishRequest();
    }
}
```

– This technique is used for graphical programming

• Complication:
  – What if we missed a blocking I/O step?
  – What if we have to split code into hundreds of pieces which could be blocking?
Can Threads Make This Easier?

- Threads yield overlapped I/O and computation without “deconstructing” code into non-blocking fragments
  - One thread per request
- Requests proceeds to completion, blocking as required:

  ```c
  Deposit(acctId, amount) {
    acct = GetAccount(actId); /* May use disk I/O */
    acct->balance += amount;
    StoreAccount(acct); /* Involves disk I/O */
  }
  ```

- Unfortunately, shared state can get corrupted:

  Thread 1
  ```
  load r1, acct->balance
  add r1, amount1
  store r1, acct->balance
  ```

  Thread 2
  ```
  load r1, acct->balance
  add r1, amount2
  store r1, acct->balance
  ```
Recall: Possible Executions

Thread 1
Thread 2
Thread 3

a) One execution

Thread 1
Thread 2
Thread 3

b) Another execution

Thread 1
Thread 2
Thread 3

...
Problem is at the Lowest Level

• Most of the time, threads are working on separate data, so scheduling doesn’t matter:

<table>
<thead>
<tr>
<th>Thread A</th>
<th>Thread B</th>
</tr>
</thead>
<tbody>
<tr>
<td>x = 1;</td>
<td>y = 2;</td>
</tr>
</tbody>
</table>

• However, what about (Initially, y = 12):

<table>
<thead>
<tr>
<th>Thread A</th>
<th>Thread B</th>
</tr>
</thead>
<tbody>
<tr>
<td>x = 1;</td>
<td>y = 2;</td>
</tr>
<tr>
<td>x = y+1;</td>
<td>y = y*2;</td>
</tr>
</tbody>
</table>

  – What are the possible values of x?

• Or, what are the possible values of x below?

<table>
<thead>
<tr>
<th>Thread A</th>
<th>Thread B</th>
</tr>
</thead>
<tbody>
<tr>
<td>x = 1;</td>
<td>x = 2;</td>
</tr>
</tbody>
</table>

  – X could be 1 or 2 (non-deterministic!)
  – Could even be 3 for serial processors:

    » Thread A writes 0001, B writes 0010 → scheduling order ABABABBA yields 3!
Atomic Operations

• To understand a concurrent program, we need to know what the underlying indivisible operations are!

• Atomic Operation: an operation that always runs to completion or not at all
  – It is *indivisible*: it cannot be stopped in the middle and state cannot be modified by someone else in the middle
  – Fundamental building block – if no atomic operations, then have no way for threads to work together

• On most machines, memory references and assignments (i.e. loads and stores) of words are atomic
  – Consequently – weird example that produces “3” on previous slide can’t happen

• Many instructions are not atomic
  – Double-precision floating point store often not atomic
  – VAX and IBM 360 had an instruction to copy a whole array
Another Concurrent Program Example

- Two threads, A and B, compete with each other
  - One tries to increment a shared counter
  - The other tries to decrement the counter

<table>
<thead>
<tr>
<th>Thread A</th>
<th>Thread B</th>
</tr>
</thead>
<tbody>
<tr>
<td>i = 0;</td>
<td>i = 0;</td>
</tr>
<tr>
<td>while (i &lt; 10)</td>
<td>while (i &gt; -10)</td>
</tr>
<tr>
<td>i = i + 1;</td>
<td>i = i - 1;</td>
</tr>
<tr>
<td>printf(&quot;A wins!&quot;);</td>
<td>printf(&quot;B wins!&quot;);</td>
</tr>
</tbody>
</table>

- Assume that memory loads and stores are atomic, but incrementing and decrementing are not atomic
- Who wins? Could be either
- Is it guaranteed that someone wins? Why or why not?
- What if both threads have their own CPU running at same speed? Is it guaranteed that it goes on forever?
Hand Simulation Multiprocessor Example

• Inner loop looks like this:

<table>
<thead>
<tr>
<th>Thread A</th>
<th></th>
<th>Thread B</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>r1=0</td>
<td>load r1, M[i]</td>
<td>r1=0</td>
<td>load r1, M[i]</td>
</tr>
<tr>
<td>r1=1</td>
<td>add r1, r1, 1</td>
<td>r1=-1</td>
<td>sub r1, r1, 1</td>
</tr>
<tr>
<td>M[i]=1</td>
<td>store r1, M[i]</td>
<td>M[i]=-1</td>
<td>store r1, M[i]</td>
</tr>
</tbody>
</table>

• Hand Simulation:
  – And we’re off. A gets off to an early start
  – B says “hmph, better go fast” and tries really hard
  – A goes ahead and writes “1”
  – B goes and writes “-1”
  – A says “HUH?? I could have sworn I put a 1 there”

• Could this happen on a uniprocessor? With Hyperthreads?
  – Yes! Unlikely, but if you are depending on it not happening, it will and your system will break…
Definitions

• **Synchronization**: using atomic operations to ensure cooperation between threads
  - For now, only loads and stores are atomic
  - We are going to show that it’s hard to build anything useful with only reads and writes

• **Mutual Exclusion**: ensuring that only one thread does a particular thing at a time
  - One thread *excludes* the other while doing its task

• **Critical Section**: piece of code that only one thread can execute at once. Only one thread at a time will get into this section of code
  - Critical section is the result of mutual exclusion
  - Critical section and mutual exclusion are two ways of describing the same thing
**Locks**

- **Lock**: prevents someone from doing something
  - `Lock()` before entering critical section and before accessing shared data
  - `Unlock()` when leaving, after accessing shared data
  - *Wait* if locked
    » Important idea: all synchronization involves waiting

- Locks need to be allocated and initialized:
  - structure `Lock mylock` or `pthread_mutex_t mylock;`
  - `lock_init(&mylock)` or `mylock = PTHREAD_MUTEX_INITIALIZER;`

- Locks provide two **atomic** operations:
  - `acquire(&mylock)` – wait until lock is free; then mark it as busy
    » After this returns, we say the calling thread *holds* the lock
  - `release(&mylock)` – mark lock as free
    » Should only be called by a thread that currently holds the lock
    » After this returns, the calling thread no longer holds the lock
Fix banking problem with Locks!

- Identify critical sections (atomic instruction sequences) and add locking:

```
Deposit(acctId, amount) {
    acquire(&mylock) // Wait if someone else in critical section!
    acct = GetAccount(actId);
    acct->balance += amount;
    StoreAccount(acct);
    release(&mylock) // Release someone into critical section
}
```

- Must use SAME lock (mylock) with all of the methods (Withdraw, etc…)
  - Shared with all threads!

Threads serialized by lock through critical section. Only one thread at a time
Correctness Requirements

- Threaded programs must work for all interleavings of thread instruction sequences
  - Cooperating threads inherently non-deterministic and non-reproducible
  - Really hard to debug unless carefully designed!
- Example: Therac-25
  - Machine for radiation therapy
    » Software control of electron accelerator and electron beam/Xray production
    » Software control of dosage
  - Software errors caused the death of several patients
    » A series of race conditions on shared variables and poor software design
    » “They determined that data entry speed during editing was the key factor in producing the error condition: If the prescription data was edited at a fast pace, the overdose occurred.”
Motivating Example: “Too Much Milk”

- Great thing about OS’s – analogy between problems in OS and problems in real life
  - Help you understand real life problems better
  - But, computers are much stupider than people

- Example: People need to coordinate:

<table>
<thead>
<tr>
<th>Time</th>
<th>Person A</th>
<th>Person B</th>
</tr>
</thead>
<tbody>
<tr>
<td>3:00</td>
<td>Look in Fridge. Out of milk</td>
<td></td>
</tr>
<tr>
<td>3:05</td>
<td>Leave for store</td>
<td></td>
</tr>
<tr>
<td>3:10</td>
<td>Arrive at store</td>
<td>Look in Fridge. Out of milk</td>
</tr>
<tr>
<td>3:15</td>
<td>Buy milk</td>
<td>Leave for store</td>
</tr>
<tr>
<td>3:20</td>
<td>Arrive home, put milk away</td>
<td>Arrive at store</td>
</tr>
<tr>
<td>3:25</td>
<td></td>
<td>Buy milk</td>
</tr>
<tr>
<td>3:30</td>
<td></td>
<td>Arrive home, put milk away</td>
</tr>
</tbody>
</table>
Solve with a lock?

- **Recall:** Lock prevents someone from doing something
  - Lock before entering critical section
  - Unlock when leaving
  - Wait if locked
  >> Important idea: all synchronization involves waiting

- **For example:** fix the milk problem by putting a key on the refrigerator
  - Lock it and take key if you are going to go buy milk
  - Fixes too much: roommate angry if only wants OJ

- **Of Course – We don’t know how to make a lock yet**
  - Let’s see if we can answer this question!
Too Much Milk: Correctness Properties

• Need to be careful about correctness of concurrent programs, since non-deterministic
  – Impulse is to start coding first, then when it doesn’t work, pull hair out
  – Instead, think first, then code
  – Always write down behavior first

• What are the correctness properties for the “Too much milk” problem???
  – Never more than one person buys
  – Someone buys if needed

• First attempt: Restrict ourselves to use only atomic load and store operations as building blocks
Too Much Milk: Solution #1

• Use a note to avoid buying too much milk:
  – Leave a note before buying (kind of “lock”)
  – Remove note after buying (kind of “unlock”)
  – Don’t buy if note (wait)
• Suppose a computer tries this (remember, only memory read/write are atomic):

```cpp
if (noMilk) {
    if (noNote) {
        leave Note;
        buy milk;
        remove note;
    }
}
```
Too Much Milk: Solution #1

• Use a note to avoid buying too much milk:
  – Leave a note before buying (kind of “lock”)
  – Remove note after buying (kind of “unlock”)
  – Don’t buy if note (wait)

• Suppose a computer tries this (remember, only memory read/write are atomic):

  Thread A
  if (noMilk) {
    if (noNote) {
      leave Note;
      buy Milk;
      remove Note;
    }
  }

  Thread B
  if (noMilk) {
    if (noNote) {
      leave Note;
      buy Milk;
      remove Note;
    }
    leave Note;
    buy Milk;
    remove Note;
  }
Too Much Milk: Solution #1

• Use a note to avoid buying too much milk:
  – Leave a note before buying (kind of “lock”)
  – Remove note after buying (kind of “unlock”)
  – Don’t buy if note (wait)

• Suppose a computer tries this (remember, only memory read/write are atomic):

```java
if (!noMilk) {
    if (!noNote) {
        leaveNote;
        buy milk;
        remove note;
    }
}
```

• Result?
  – Still too much milk but only occasionally!
  – Thread can get context switched after checking milk and note but before buying milk!

• Solution makes problem worse since fails intermittently
  – Makes it really hard to debug…
  – Must work despite what the dispatcher does!
Too Much Milk: Solution #1½

- Clearly the Note is not quite blocking enough
  - Let’s try to fix this by placing note first
- Another try at previous solution:

\[
\begin{align*}
\text{leave Note;} \quad & \\
\text{if (noMilk) } \{ \quad & \\
\text{\quad if (noNote) } \{ \quad & \\
\text{\quad \quad buy milk;} \quad & \\
\text{\quad } \} \quad & \\
\} \quad & \\
\text{remove Note;} \quad & \\
\end{align*}
\]

- What happens here?
  - Well, with human, probably nothing bad
  - With computer: no one ever buys milk
**Too Much Milk Solution #2**

- How about labeled notes?
  - Now we can leave note before checking
- Algorithm looks like this:
  ```
  Thread A                           Thread B
  leave note A;                     leave note B;
  if (noNote B) {
    if (noMilk) {
      buy Milk;
    }
  }
  remove note A;                    remove note B;
  
  if (noNoteA) {
    if (noMilk) {
      buy Milk;
    }
  }
  ```

- Does this work?
- Possible for neither thread to buy milk
  - Context switches at exactly the wrong times can lead each to think that the other is going to buy
- Really insidious:
  - Extremely unlikely this would happen, but will at worse possible time
  - Probably something like this in UNIX
Too Much Milk Solution #2: problem!

• *I’m* not getting milk, *You’re* getting milk
• This kind of lockup is called “starvation!”
Too Much Milk Solution #3

• Here is a possible two-note solution:

<table>
<thead>
<tr>
<th>Thread A</th>
<th>Thread B</th>
</tr>
</thead>
<tbody>
<tr>
<td>leave note A;</td>
<td>leave note B;</td>
</tr>
<tr>
<td>while (note B) {</td>
<td>if (noNote A) {</td>
</tr>
<tr>
<td>do nothing;</td>
<td>if (noMilk) {</td>
</tr>
<tr>
<td>}</td>
<td>buy milk;</td>
</tr>
<tr>
<td>if (noMilk) {</td>
<td>}</td>
</tr>
<tr>
<td>buy milk;</td>
<td>}</td>
</tr>
<tr>
<td>}</td>
<td>remove note B;</td>
</tr>
<tr>
<td>remove note A;</td>
<td></td>
</tr>
</tbody>
</table>

• Does this work? Yes. Both can guarantee that:
  – It is safe to buy, or
  – Other will buy, ok to quit

• At X:
  – If no note B, safe for A to buy,
  – Otherwise wait to find out what will happen

• At Y:
  – If no note A, safe for B to buy
  – Otherwise, A is either buying or waiting for B to quit
Case 1

• “leave note A” happens before “if (noNote A)"

```c
leave note A;
while (note B) {
    do nothing;
}

if (noMilk) {
    buy milk;
}
remove note B;

if (noMilk) {
    buy milk;
}
remove note A;
```
Case 1

• “leave note A” happens before “if (noNote A)”
Case 1

• “leave note A” happens before “if (noNote A)”

```
leave note A;
while (note B) {
    do nothing;
};
```

• Wait for note B to be removed

```
if (noMilk) {
    buy milk;
}
```

```
leave note B;
if (noNote A) {
    if (noMilk) {
        buy milk;
    }
}
```

• “leave note A” happens before “if (noNote A)”

```
remove note B;
```

```
remove note A;
```
Case 2

• “if (noNote A)” happens before “leave note A”
**Case 2**

- “if (noNote A)” happens before “leave note A”
Case 2

• “if (noNote A)” happens before “leave note A”
This Generalizes to $n$ Threads…

- Leslie Lamport’s “Bakery Algorithm” (1974)

---

A New Solution of Dijkstra’s Concurrent Programming Problem

Leslie Lamport
Massachusetts Computer Associates, Inc.

A simple solution to the mutual exclusion problem is presented which allows the system to continue to operate
Solution #3 discussion

• Our solution protects a single “Critical-Section” piece of code for each thread:

```java
if (noMilk) {
    buy milk;
}
```

• Solution #3 works, but it’s really unsatisfactory
  – Really complex – even for this simple an example
    » Hard to convince yourself that this really works
  – A’s code is different from B’s – what if lots of threads?
    » Code would have to be slightly different for each thread
  – While A is waiting, it is consuming CPU time
    » This is called “busy-waiting”

• There’s got to be a better way!
  – Have hardware provide higher-level primitives than atomic load & store
  – Build even higher-level programming abstractions on this hardware support
Too Much Milk: Solution #4?

- Recall our target lock interface:
  - `acquire(&milklock)` – wait until lock is free, then grab
  - `release(&milklock)` – Unlock, waking up anyone waiting
  - These must be atomic operations – if two threads are waiting for the lock and both see it’s free, only one succeeds to grab the lock

- Then, our milk problem is easy:

```c
acquire(&milklock);
if (nomilk)
    buy milk;
release(&milklock);
```
Where are we going with synchronization?

- We are going to implement various higher-level synchronization primitives using atomic operations
  - Everything is pretty painful if only atomic primitives are load and store
  - Need to provide primitives useful at user-level
Back to: How to Implement Locks?

• **Lock**: prevents someone from doing something
  – Lock before entering critical section and before accessing shared data
  – Unlock when leaving, after accessing shared data
  – Wait if locked
    » Important idea: all synchronization involves waiting
    » Should *sleep* if waiting for a long time

• **Atomic Load/Store**: get solution like Milk #3
  – Pretty complex and error prone

• **Hardware Lock instruction**
  – Is this a good idea?
  – What about putting a task to sleep?
    » What is the interface between the hardware and scheduler?
  – Complexity?
    » Done in the Intel 432
    » Each feature makes HW more complex and slow
Naïve use of Interrupt Enable/Disable

• How can we build multi-instruction atomic operations?
  – Recall: dispatcher gets control in two ways.
    » Internal: Thread does something to relinquish the CPU
    » External: Interrupts cause dispatcher to take CPU
  – On a uniprocessor, can avoid context-switching by:
    » Avoiding internal events (although virtual memory tricky)
    » Preventing external events by disabling interrupts

• Consequently, naïve Implementation of locks:
  
  LockAcquire { disable Ints; }
  LockRelease { enable Ints; }

• Problems with this approach:
  – Can’t let user do this! Consider following:
    
    LockAcquire();
    While(TRUE) {;}
  – Real-Time system—no guarantees on timing!
    » Critical Sections might be arbitrarily long
  – What happens with I/O or other important events?
    » “Reactor about to meltdown. Help?”
Better Implementation of Locks by Disabling Interrupts

- Key idea: maintain a lock variable and impose mutual exclusion only during operations on that variable

```c
int value = FREE;

Acquire() {
    disable interrupts;
    if (value == BUSY) {
        put thread on wait queue;
        Go to sleep();
        // Enable interrupts?
    } else {
        value = BUSY;
    }
    enable interrupts;
}

Release() {
    disable interrupts;
    if (anyone on wait queue) {
        take thread off wait queue
        Place on ready queue;
    } else {
        value = FREE;
    }
    enable interrupts;
} 
```
New Lock Implementation: Discussion

• Why do we need to disable interrupts at all?
  – Avoid interruption between checking and setting lock value
  – Otherwise two threads could think that they both have lock

```c
Acquire() {
    disable interrupts;
    if (value == BUSY) {
        put thread on wait queue;
        Go to sleep();
        // Enable interrupts?
    } else {
        value = BUSY;
    }
    enable interrupts;
}
```

• Note: unlike previous solution, the critical section (inside Acquire()) is very short
  – User of lock can take as long as they like in their own critical section: doesn’t impact global machine behavior
  – Critical interrupts taken in time!
Interrupt Re-enable in Going to Sleep

• What about re-enabling ints when going to sleep?

```java
Acquire() {
    disable interrupts;
    if (value == BUSY) {
        put thread on wait queue;
        Go to sleep();
    } else {
        value = BUSY;
    }
    enable interrupts;
}
```
Interrupt Re-enable in Going to Sleep

• What about re-enabling ints when going to sleep?

```c
void Acquire()
{
    disable interrupts;
    if (value == BUSY) {
        put thread on wait queue;
        Go to sleep();
    } else {
        value = BUSY;
    }
    enable interrupts;
}
```

• Before Putting thread on the wait queue?
Interrupt Re-enable in Going to Sleep

- What about re-enabling ints when going to sleep?
  ```c
  Acquire() {
    disable interrupts;
    if (value == BUSY) {
      put thread on wait queue;
      Go to sleep();
    } else {
      value = BUSY;
    }
    enable interrupts;
  }
  ```

- Before Putting thread on the wait queue?
  - Release can check the queue and not wake up thread
Interrupt Re-enable in Going to Sleep

• What about re-enabling ints when going to sleep?

```c
Acquire() {
    disable interrupts;
    if (value == BUSY) {
        put thread on wait queue;
        Go to sleep();
    } else {
        value = BUSY;
    }
    enable interrupts;
}
```

• Before Putting thread on the wait queue?
  – Release can check the queue and not wake up thread

• After putting the thread on the wait queue
Interrupt Re-enable in Going to Sleep

- What about re-enabling ints when going to sleep?
  ```
  Acquire() {
    disable interrupts;
    if (value == BUSY) {
      put thread on wait queue;
      Go to sleep();
    } else {
      value = BUSY;
    }
    enable interrupts;
  }
  ```

- Before Putting thread on the wait queue?
  - Release can check the queue and not wake up thread
- After putting the thread on the wait queue
  - Release puts the thread on the ready queue, but the thread still thinks it needs to go to sleep
  - Misses wakeup and still holds lock (deadlock!)
Interrupt Re-enable in Going to Sleep

• What about re-enabling ints when going to sleep?

\[
\text{Acquire() \{} \\
\quad \text{disable interrupts;} \\
\quad \text{if (value == BUSY) \{} \\
\quad\quad \text{put thread on wait queue;} \\
\quad\quad \text{Go to sleep();} \\
\quad \} \text{ else \{} \\
\quad\quad \text{value = BUSY;} \\
\quad \} \\
\quad \text{enable interrupts;} \\
\\}
\]

• Before Putting thread on the wait queue?
  – Release can check the queue and not wake up thread

• After putting the thread on the wait queue
  – Release puts the thread on the ready queue, but the thread still thinks it needs to go to sleep
  – Misses wakeup and still holds lock (deadlock!)

• Want to put it after `sleep()`. But – how?
How to Re-enable After Sleep()?

- In scheduler, since interrupts are disabled when you call sleep:
  - Responsibility of the next thread to re-enable ints
  - When the sleeping thread wakes up, returns to acquire and re-enables interrupts

```
Thread A                      Thread B
 .
 .
 disable ints                sleep
 sleep                       sleep return
 context switch
 enable ints
 .
 .
 .
 disable int                sleep
 context switch
 enable ints
 .
 .
```
**In-Kernel Lock: Simulation**

```c
INIT
    int value = 0;

Acquire() {
    disable interrupts;
    if (value == 1) {
        put thread on wait-queue;
        go to sleep() //??
    } else {
        value = 1;
    }
    enable interrupts;
}

Release() {
    disable interrupts;
    if anyone on wait queue {
        take thread off wait-queue
        Place on ready queue;
    } else {
        value = 0;
    }
    enable interrupts;
}

lock.Acquire();
...
critical section;
...
lock.Release();
```
In-Kernel Lock: Simulation

**INIT**

```c
int value = 0;

Acquire() {
  disable interrupts;
  if (value == 1) {
    put thread on wait-queue;
    go to sleep() //??
  } else {
    value = 1;
  }
  enable interrupts;
}

Release() {
  disable interrupts;
  if anyone on wait queue {
    take thread off wait-queue
    Place on ready queue;
  } else {
    value = 0;
  }
  enable interrupts;
}
```

**Thread A**

**Value: 1**

**Thread B**

**Value: 1**

**Ready**

**lock.Acquire();**

...  

**critical section;**

...  

**lock.Release();**
int value = 0;

Acquire() {
    disable interrupts;
    if (value == 1) {
        put thread on wait-queue;
        go to sleep() //??
    } else {
        value = 1;
    }
    enable interrupts;
}

Release() {
    disable interrupts;
    if anyone on wait queue {
        take thread off wait-queue
        Place on ready queue;
    } else {
        value = 0;
    }
    enable interrupts;
}
int value = 0;

Acquire() {
    disable interrupts;
    if (value == 1) {
        put thread on wait-queue;
        go to sleep() //??
    } else {
        value = 1;
    }
    enable interrupts;
}

lock.Acquire();
...

lock.Release();

Release() {
    disable interrupts;
    if anyone on wait queue {
        take thread off wait-queue
        Place on ready queue;
    } else {
        value = 0;
    }
    enable interrupts;
}
int value = 0;

Acquire() {
    disable interrupts;
    if (value == 1) {
        put thread on wait-queue;
        go to sleep();
    } else {
        value = 1;
    }
    enable interrupts;
}

lock.Acquire();
…
critical section;
…
lock.Release();

Release() {
    disable interrupts;
    if anyone on wait queue {
        take thread off wait-queue
        Place on ready queue;
    } else {
        value = 0;
    }
    enable interrupts;
}
Lec 7.732/8/22
Joseph & Kubiatowicz CS162 © UCB Spring 2022

```
int value = 0;
Acquire() {
    disable interrupts;
    if (value == 1) {
        put thread on wait-queue;
        go to sleep() //??
    } else {
        value = 1;
    }
    enable interrupts;
}

Release() {
    disable interrupts;
    if anyone on wait queue {
        take thread off wait-queue
        Place on ready queue;
    } else {
        value = 0;
    }
    enable interrupts;
}
```

In-Kernel Lock: Simulation

```
lock.Acquire();
...
critical section;
...
lock.Release();

lock.Acquire();
...
critical section;
...
lock.Release();
```

Thread A

Thread B

Value: 1

waiters

owner

READY

INIT

int value = 0;

RUNNING

STOP

Thread A

Thread B

Value: 1

waiters

owner

READY

INIT

int value = 0;

RUNNING

STOP

Thread A

Thread B

Value: 1

waiters

owner

READY

INIT

int value = 0;

RUNNING

STOP

Thread A

Thread B

Value: 1

waiters

owner

READY

INIT

int value = 0;

RUNNING

STOP

Thread A

Thread B

Value: 1

waiters

owner

READY

INIT

int value = 0;

RUNNING

STOP

Thread A

Thread B

Value: 1

waiters

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READY

INIT

int value = 0;

RUNNING

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Thread A

Thread B

Value: 1

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int value = 0;

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int value = 0;

RUNNING

STOP

Thread A

Thread B

Value: 1

waiters

owner

READY

INIT

int value = 0;

RUNNING
Conclusion

• Concurrent threads introduce problems when accessing shared data
  – Programs must be insensitive to arbitrary interleavings
  – Without careful design, shared variables can become completely inconsistent

• Important concept: Atomic Operations
  – An operation that runs to completion or not at all
  – These are the primitives on which to construct various synchronization primitives

• Talked about hardware atomicity primitives:
  – Disabling of Interrupts, test&set, swap, compare&swap, load-locked & store-conditional

• Showed several constructions of Locks
  – Must be very careful not to waste/tie up machine resources
    » Shouldn’t disable interrupts for long
    » Shouldn’t spin wait for long
  – Key idea: Separate lock variable, use hardware mechanisms to protect modifications of that variable