CS162
Operating Systems and Systems Programming
Lecture 5

Concurrency and Mutual Exclusion

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Recall: Fork, Wait, and (optional) Exec

```
cpid = fork();
if (cpid > 0) {                    // Parent Process
  mypid = getpid();
  printf("[%d] parent of [%d]\n", mypid, cpid);
  tcpid = wait(&status);
  printf("[%d] bye %d\n", mypid, tcpid);
} else if (cpid == 0) {            // Child Process
  mypid = getpid();
  printf("[%d] child\n", mypid);
  execl(filename,(char *)0);       // Opt: start new program
} else { // Error! }
```

- Return value from Fork: integer
  - When > 0: return value is pid of new child (Running in Parent)
  - When = 0: Running in new Child process
  - When < 0: Error! Must handle somehow
- Wait() system call: wait for next child to exit
  - Return value is PID of terminating child
  - Argument is pointer to integer variable to hold exit status
- Exec() family of calls: replace process with new executable

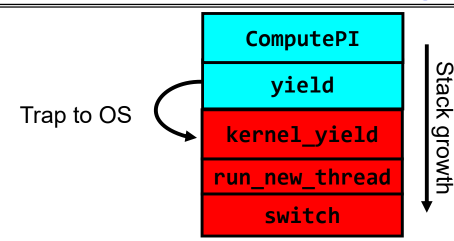
The way how shell works ?

Recall: Internal Events

- Blocking on I/O
  - The act of requesting I/O implicitly yields the CPU
- Waiting on a “signal” from other thread
  - Thread asks to wait and thus yields the CPU
- Thread executes a `yield()`
  - Thread volunteers to give up CPU

```
computePI() {
   while(TRUE) {
      ComputeNextDigit();
      yield();
   }
}
```


Recall: Stack for Yielding Thread



- How do we run a new thread?

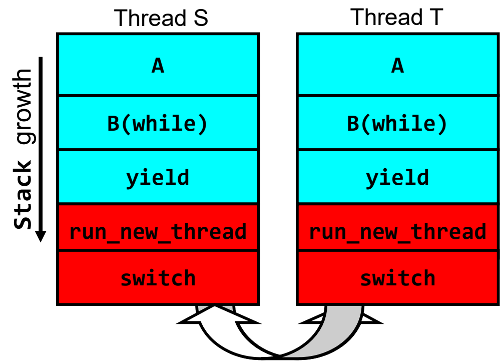
```
run_new_thread() {
   newThread = PickNewThread();
   switch(curThread, newThread);
   ThreadHouseKeeping(); /* Do any cleanup */
}
```

- How does dispatcher switch to a new thread?
  - Save anything next thread may trash: PC, regs, stack pointer
  - Maintain isolation for each thread

Recall: Multithreaded Stack Switching

- Consider the following code blocks:

```
proc A() {
   B();

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



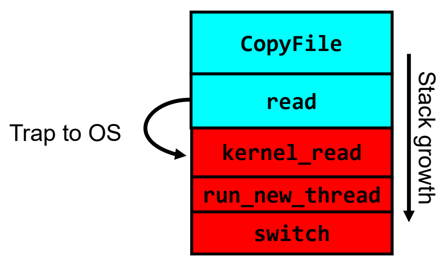
- Suppose we have 2 threads:
  – Threads S and T

Thread S's switch returns to Thread T's (and vice versa)

Goals for Today

- Finish discussion of Threads
- Concurrency and need for Synchronization Operations
- Basic Synchronization through Locks
- Initial Lock Implementations

What happens when thread blocks on I/O?

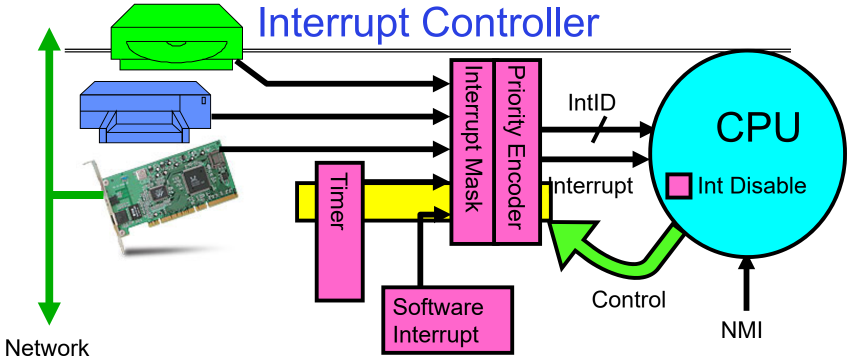


- What happens when a thread requests a block of data from the file system?
  – User code invokes a system call
  – Read operation is initiated
  – Run new thread/switch
- Thread communication similar
  – Wait for Signal/Join
  – Networking

External Events

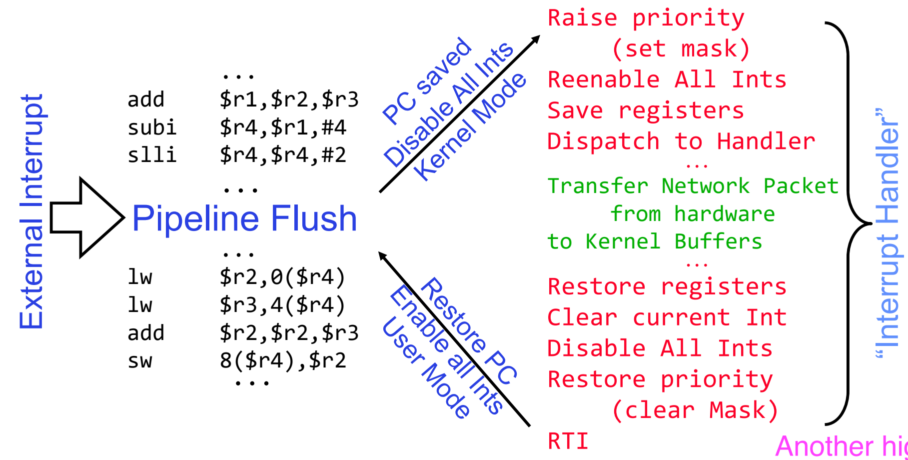
- What happens if thread never does any I/O, never waits, and never yields control?
  – Could the `ComputePI` program grab all resources and never release the processor?
    » What if it didn't print to console?
  – Must find way that dispatcher can regain control!
- Answer: utilize external events
  – Interrupts: signals from hardware or software that stop the running code and jump to kernel
  – Timer: like an alarm clock that goes off every some milliseconds
- If we make sure that external events occur frequently enough, can ensure dispatcher runs

Interrupt Controller



- Interrupts invoked with interrupt lines from devices
- Interrupt controller chooses interrupt request to honor
  - Interrupt identity specified with ID line
  - Mask enables/disables interrupts
  - Priority encoder picks highest enabled interrupt
  - Software Interrupt Set/Cleared by Software
- CPU can disable all interrupts with internal flag
- Non-Maskable Interrupt line (NMI) can't be disabled

Example: Network Interrupt

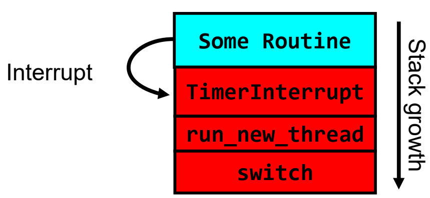


- An interrupt is a hardware-invoked context switch
  - No separate step to choose what to run next
  - Always run the interrupt handler immediately

Another high priority interrupt may comes in when an interrupt is handling.

Use of Timer Interrupt to Return Control

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



- Timer Interrupt routine:

```
TimerInterrupt() {
   DoPeriodicHouseKeeping();
   run_new_thread();
}
```


Hardware context switch support in x86

- Syscall/Intr (U → K)
  - PL 3 → 0; level goes 3 to 0
  - TSS ← EFLAGS, CS:EIP; task segment
  - SS:SP ← 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 then 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:SP ← user thread stack (TSS PL 3);

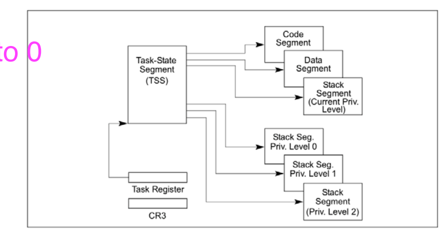
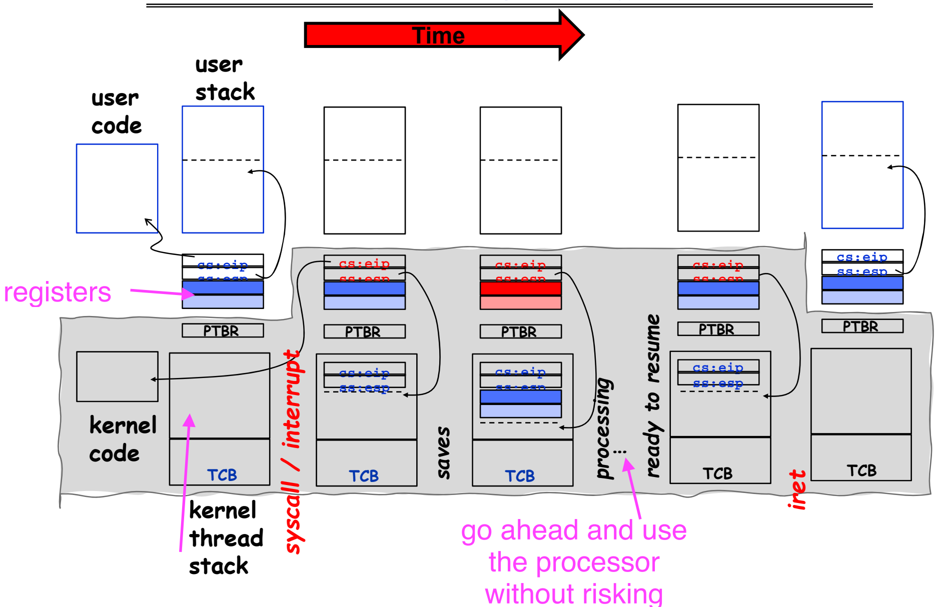


Figure 7-1. Structure of a Task

pg 2,942 of 4,922 of x86 reference manual

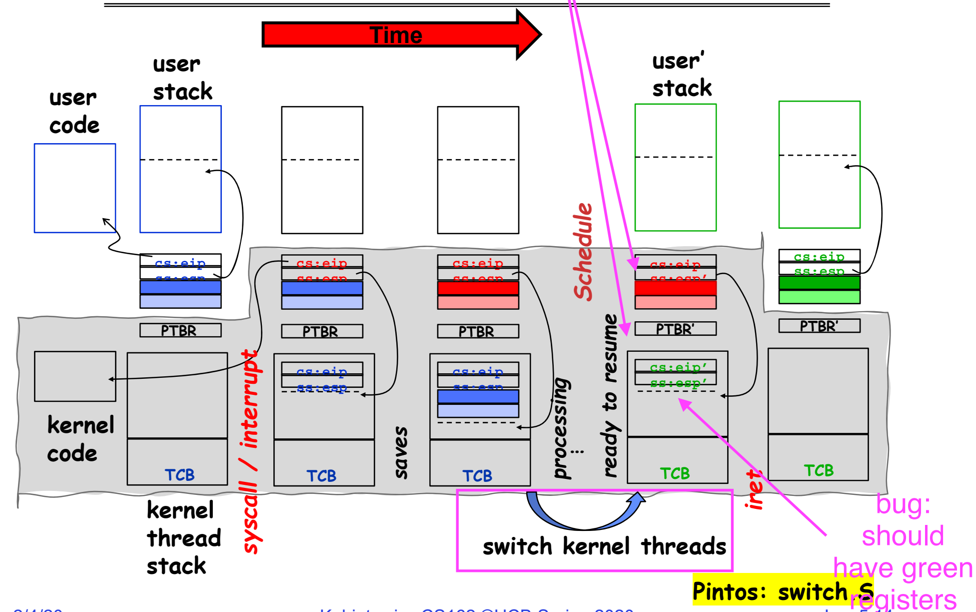
Pintos: tss.c, intr-stubs.S

Pintos: Kernel Crossing on Syscall or Interrupt



Page Table Base Register and the SP changed (notice the prime note)

Pintos: Context Switch – Scheduling



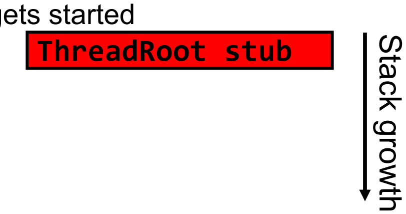
Instead of returning to previous running user program, we return to something else.

`ThreadFork()`: Create a New Thread

- `ThreadFork()` is a user-level procedure that creates a new thread and places it on ready queue
- Arguments to `ThreadFork()`
  - Pointer to application routine (`fcnPtr`)
  - Pointer to array of arguments (`fcnArgPtr`)
  - Size of stack to allocate
- Implementation
  - Sanity check arguments
  - Enter Kernel-mode and Sanity Check arguments again
  - Allocate new Stack and TCB
  - Initialize TCB and place on ready list (Runnable)

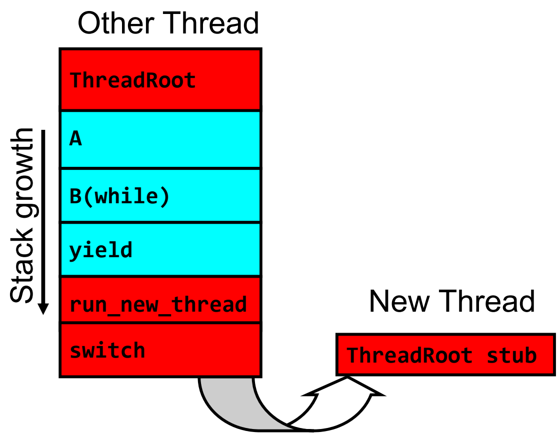
How do we initialize TCB and Stack?

- Initialize Register fields of TCB
  - Stack pointer made to point at stack
  - PC return address ⇒ OS (asm) routine `ThreadRoot()`
  - Two arg registers (say rdi and rsi for x86) initialized to `fcnPtr` and `fcnArgPtr`, respectively
- Initialize stack data?
  - No. Important part of stack frame is in registers (ra)
  - Think of stack frame as just before body of `ThreadRoot()` really gets started



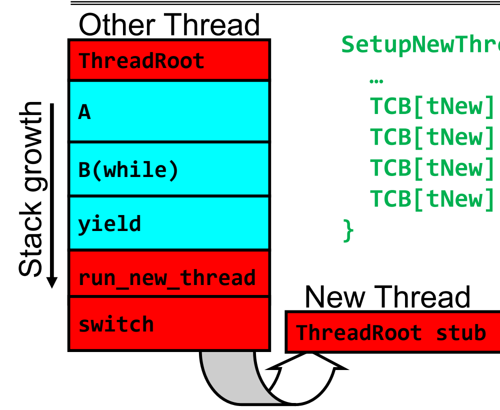
Initial Stack

How does Thread get started?



- Need to construct a new kernel thread that is ready to run when switch goes to it
- Note that switch doesn't know any difference between new or preexisting thread!

How does a thread get started?



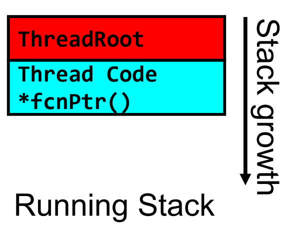

```
SetupNewThread(tNew) {
  …
  TCB[tNew].regs.sp = newStackPtr;
  TCB[tNew].regs.retpc = &ThreadRoot;
  TCB[tNew].regs.r0 = fcnPtr
  TCB[tNew].regs.r1 = fcnArgPtr
}
```

- How do we make a ***new*** thread?
  - Setup TCB/kernel thread to point at new user stack and ThreadRoot code
  - Put pointers to start function and args in registers
  - This depends heavily on the calling convention (i.e. RISC-V vs x86)
- Eventually, `run_new_thread()` will select this TCB and return into beginning of `ThreadRoot()`
  - This really starts the new thread

What does `ThreadRoot()` look like?

- `ThreadRoot()` is the root for the thread routine:

```
ThreadRoot(fcnPTR,fcnArgPtr) {
   DoStartupHousekeeping();
   UserModeSwitch(); /* enter user mode */
   Call fcnPtr(fcnArgPtr);
   ThreadFinish();
}
```



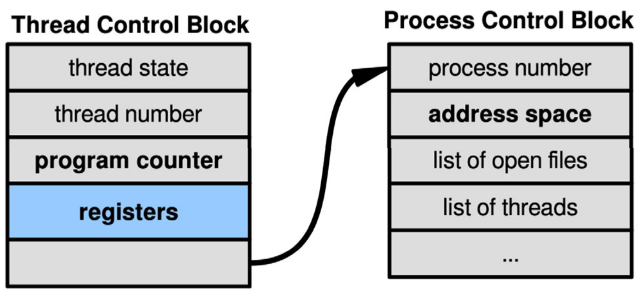
- Startup Housekeeping
  - Includes things like recording start time of thread
  - Other statistics
- Stack will grow and shrink with execution of thread
- Final return from thread returns into `ThreadRoot()` which calls `ThreadFinish()`
  - `ThreadFinish()` wake up sleeping threads

Administrivia

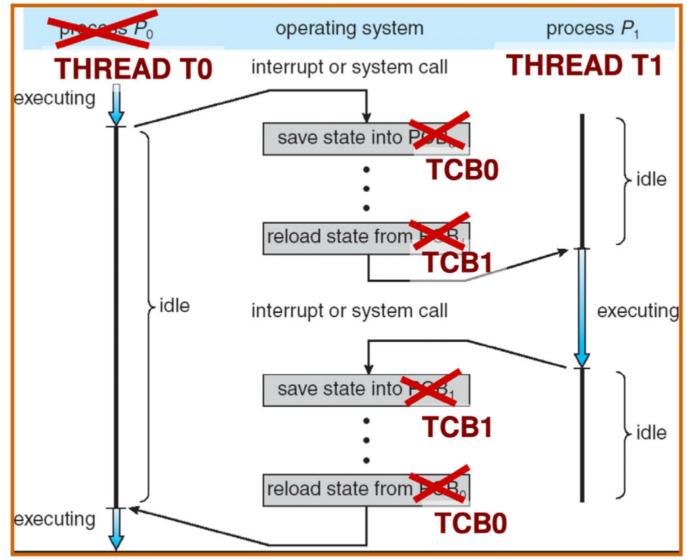
- Group Creation Deadline is TONIGHT!
  - Need 4 people in a group
  - If you signup with less, we may end up adding another person to your group!
- All members of a group need to have the same TA
  - Priority for same section; if cannot make this work, keep same TA
  - Remember: Your TA needs to see you in section!

Kernel-Supported Threads

- Each thread has a **thread control block**
  - CPU registers, including PC, pointer to stack
  - Scheduling info: priority, etc.
  - Pointer to **Process control block**
- OS scheduler uses TCBs, not PCBs



Kernel-Supported User Threads



User-level Multithreading: *pthreads*

- `int pthread_create(pthread_t *thread, const pthread_attr_t *attr, void *(*start_routine)(void*), void *arg);`
  - thread is created executing *start_routine* with *arg* as its sole argument. (return is implicit call to pthread_exit)
- `void pthread_exit(void *value_ptr);`
  - terminates and makes *value_ptr* available to any successful join
- `int pthread_join(pthread_t thread, void **value_ptr);`
  - suspends execution of the calling thread until the target *thread* terminates.
  - On return with a non-NULL *value_ptr* the value passed to *pthread_exit()* by the terminating thread is made available in the location referenced by *value_ptr*.

man pthread
https://pubs.opengroup.org/onlinepubs/7908799/xsh/pthread.h.html

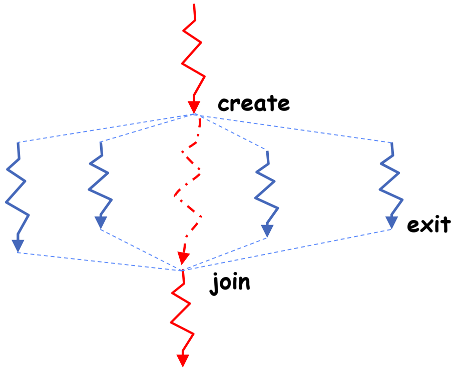
Little Example

```
(base) CullerMac19:code04 culler$ ./pthread 4
Main stack: 7ffee2c6b6b8, common: 10cf95048 (162)
Thread #1 stack: 70000d83bef8 common: 10cf95048 (162)
Thread #3 stack: 70000d941ef8 common: 10cf95048 (164)
Thread #2 stack: 70000d8beef8 common: 10cf95048 (165)
Thread #0 stack: 70000d7b8ef8 common: 10cf95048 (163)
```

```
#include <stdio.h>
#include <stdlib.h>
#include <pthread.h>
#include <string.h>

int common = 162;

void *threadfun(void *threadid)
{
  long tid = (long)threadid;
  printf("Thread #%lx stack: %lx common: %lx (%d)\n", tid,
         (unsigned long) &tid, (unsigned long) &common, common++);
  pthread_exit(NULL);
}

int main (int argc, char *argv[])
{
  long t;
  int nthreads = 2;
  if (argc > 1) {
    nthreads = atoi(argv[1]);
  }
  pthread_t *threads = malloc(nthreads*sizeof(pthread_t));
  printf("Main stack: %lx, common: %lx (%d)\n",
         (unsigned long) &t,(unsigned long) &common, common);
  for(t=0; t<nthreads; t++){
    int rc = pthread_create(&threads[t], NULL, threadfun, (void *)t);
    if (rc){
      printf("ERROR; return code from pthread_create() is %d\n", rc);
      exit(-1);
    }
  }

  for(t=0; t<nthreads; t++){
    pthread_join(threads[t], NULL);
  }
  pthread_exit(NULL);          /* last thing in the main thread  */
}
```

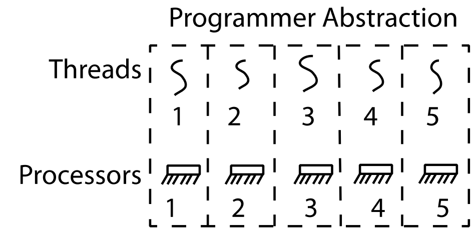
How to tell if something is done?
Really done?
OK to reclaim its resources?

Fork-Join Pattern



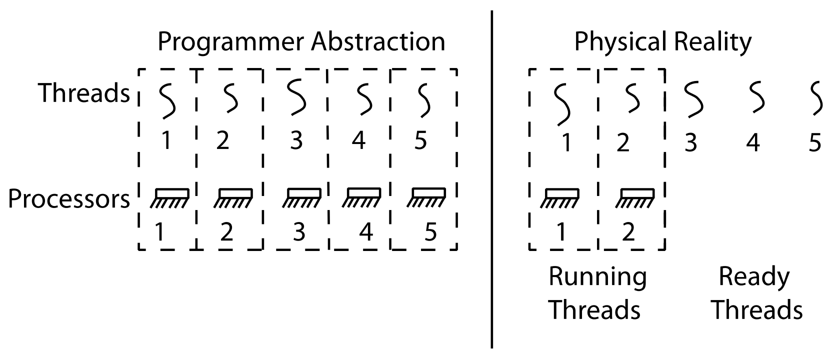
- Main thread *creates* (forks) collection of sub-threads passing them args to work on, *joins* with them, collecting results.

Thread Abstraction



- Illusion: Infinite number of processors

Thread Abstraction



- Illusion: Infinite number of processors
- Reality: Threads execute with variable speed
  – Programs must be designed to work with any schedule

Programmer vs. Processor View

Programmer's View	Possible Execution #1
.	.
.	.
.	.
x = x + 1;	x = x + 1;
y = y + x;	y = y + x;
z = x +5y;	z = x + 5y;
.	.
.	.
.	.

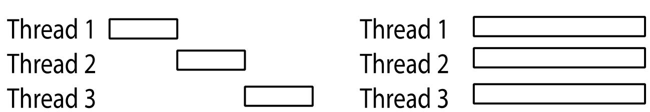
Programmer vs. Processor View

Programmer's View	Possible Execution #1	Possible Execution #2
.	.	.
.	.	.
.	.	.
x = x + 1;	x = x + 1;	x = x + 1
y = y + x;	y = y + x;	....
z = x +5y;	z = x + 5y;	thread is suspended
.	.	other thread(s) run
.	.	thread is resumed
.	.	....
		y = y + x
		z = x + 5y

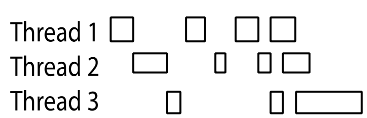
Programmer vs. Processor View

Programmer's View	Possible Execution #1	Possible Execution #2	Possible Execution #3
.	.	.	.
.	.	.	.
.	.	.	.
x = x + 1;	x = x + 1;	x = x + 1	x = x + 1
y = y + x;	y = y + x;	....	y = y + x
z = x +5y;	z = x + 5y;	thread is suspended	....
.	.	other thread(s) run	thread is suspended
.	.	thread is resumed	other thread(s) run
.	.	....	thread is resumed
		y = y + x	....
		z = x + 5y	z = x + 5y

Possible Executions



a) One execution b) Another execution



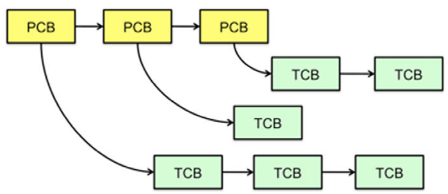
c) Another execution

Per Thread Descriptor (Kernel Supported Threads)

- Each Thread has a *Thread Control Block* (TCB)
  - Execution State: CPU registers, program counter (PC), pointer to stack (SP)
  - Scheduling info: state, priority, CPU time
  - Various Pointers (for implementing scheduling queues)
  - Pointer to enclosing process (PCB) – user threads
  - … (add stuff as you find a need)
- OS Keeps track of TCBs in "kernel memory"
  - In Array, or Linked List, or …
  - I/O state (file descriptors, network connections, etc)

Multithreaded Processes

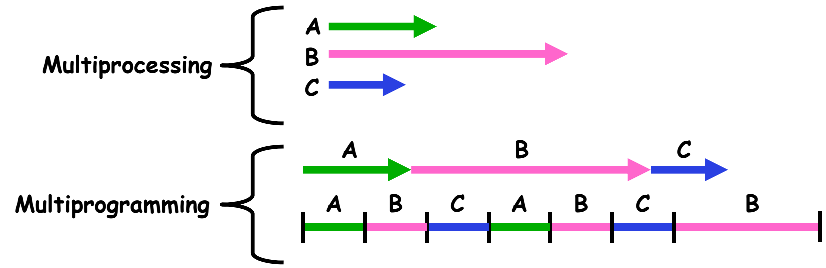
- Process Control Block (PCBs) points to multiple Thread Control Blocks (TCBs):



- Switching threads within a block is a simple thread switch
- Switching threads across blocks requires changes to memory and I/O address tables

Multiprocessing vs Multiprogramming

- Remember 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



Correctness for systems with concurrent threads

- If dispatcher can schedule threads in any way, programs must work under all circumstances
  - Can you test for this?
  - How can you know if your program works?
- Independent Threads:
  - No state shared with other threads
  - Deterministic ⇒ Input state determines results
  - Reproducible ⇒ Can recreate Starting Conditions, I/O
  - Scheduling order doesn't matter (if `switch()` works!!!)
- Cooperating Threads:
  - Shared State between multiple threads
  - Non-deterministic
  - Non-reproducible
- Non-deterministic and Non-reproducible means that bugs can be intermittent
  - Sometimes called "Heisenbugs"

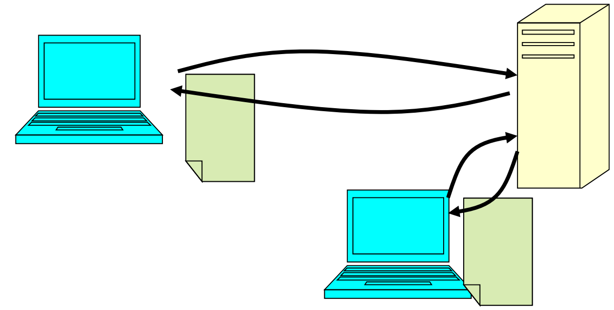
Interactions Complicate Debugging

- Is any program truly independent?
  - Every process shares the file system, OS resources, network, etc
  - Extreme example: buggy device driver causes thread A to crash "independent thread" B
- You probably don't realize how much you depend on reproducibility:
  - Example: Evil C compiler
    - » Modifies files behind your back by inserting errors into C program unless you insert debugging code
  - Example: Debugging statements can overrun stack
- Non-deterministic errors are really difficult to find
  - Example: Memory layout of kernel+user programs
    - » depends on scheduling, which depends on timer/other things
    - » Original UNIX had a bunch of non-deterministic errors
  - Example: Something which does interesting I/O
    - » User typing of letters used to help generate secure keys

Why allow cooperating threads?

- People cooperate; computers help/enhance people's lives, so computers must cooperate
  - By analogy, the non-reproducibility/non-determinism of people is a notable problem for "carefully laid plans"
- Advantage 1: Share resources
  - One computer, many users
  - One bank balance, many ATMs
    - » What if ATMs were only updated at night?
  - Embedded systems (robot control: coordinate arm & hand)
- Advantage 2: Speedup
  - Overlap I/O and computation
    - » Many different file systems do read-ahead
  - Multiprocessors – chop up program into parallel pieces
- Advantage 3: Modularity
  - More important than you might think
  - Chop large problem up into simpler pieces
    - » To compile, for instance, gcc calls cpp | cc1 | cc2 | as | ld
    - » Makes system easier to extend

High-level Example: Web Server



- Server must handle many requests
- Non-cooperating version:

```
serverLoop() {
    con = AcceptCon();
    ProcessFork(ServiceWebPage(),con);
}
```

- What are some disadvantages of this technique?

Threaded Web Server

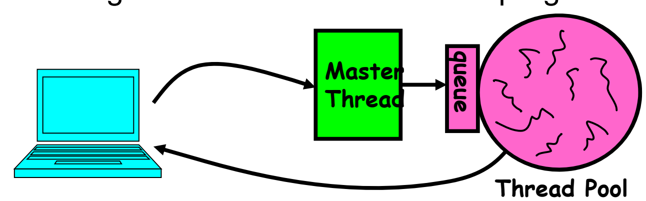
- Now, use a single process
- Multithreaded (cooperating) version:

```
serverLoop() {
     connection = AcceptCon();
     ThreadFork(ServiceWebPage(),connection);
  }
```

- Looks almost the same, but has many advantages:
  - Can share file caches kept in memory, results of CGI scripts, other things
  - Threads are *much* cheaper to create than processes, so this has a lower per-request overhead
- Question: would a user-level (say one-to-many) thread package make sense here?
  - When one request blocks on disk, all block…
- What about Denial of Service attacks or digg / Slash-dot effects?

Thread Pools

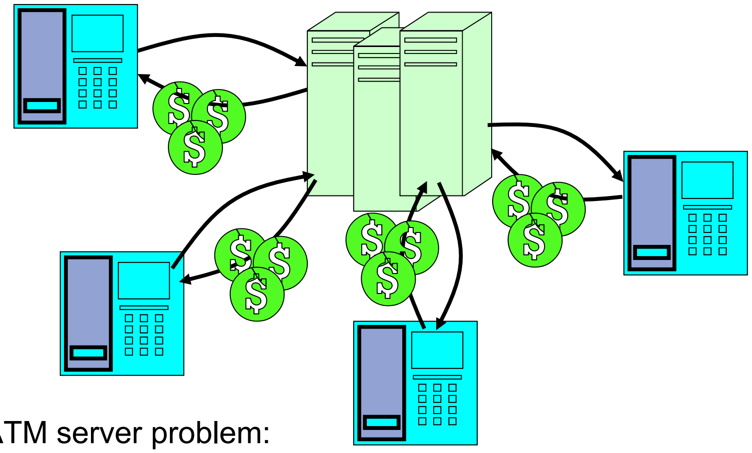
- Problem with previous version: Unbounded Threads
  - When web-site becomes too popular – throughput sinks
- Instead, allocate a bounded "pool" of worker threads, representing the maximum level of multiprogramming




```
master() {
   allocThreads(worker,queue);
   while(TRUE) {
      con=AcceptCon();
      Enqueue(queue,con);
      wakeUp(queue);
   }
}
```

```
worker(queue) {
   while(TRUE) {
      con=Dequeue(queue);
      if (con==null)
         sleepOn(queue);
      else
         ServiceWebPage(con);
   }
}
```

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

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

  – What if we missed a blocking I/O step?
  – What if we have to split code into hundreds of pieces which could be blocking?
  – This technique is used for graphical programming

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:

```
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	Thread 2
`load r1, acct->balance`	
	`load r1, acct->balance`
	`add r1, amount2`
	`store r1, acct->balance`
`add r1, amount1`	
`store r1, acct->balance`	

Problem is at the Lowest Level

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

Thread A	Thread B
x = 1;	y = 2;

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

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

  – What are the possible values of x?
- Or, what are the possible values of x below?

Thread A	Thread B
x = 1;	x = 2;

  – 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

Thread A
```
i = 0;
while (i < 10)
  i = i + 1;
printf("A wins!");
```

Thread B
```
i = 0;
while (i > -10)
  i = i – 1;
printf("B wins!");
```

- 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:

Thread A		Thread B	
r1=0	load r1, M[i]		
		r1=0	load r1, M[i]
r1=1	add r1, r1, 1		
		r1=-1	sub r1, r1, 1
M[i]=1	store r1, M[i]		
		M[i]=-1	store r1, M[i]

- 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…

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."

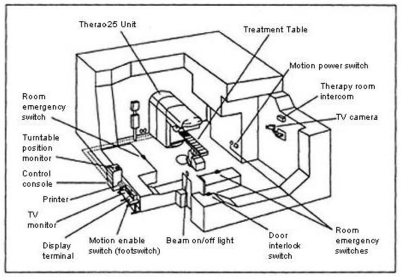


Figure 1. Typical Therac-25 facility

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:

Time	Person A	Person B
3:00	Look in Fridge. Out of milk	
3:05	Leave for store	
3:10	Arrive at store	Look in Fridge. Out of milk
3:15	Buy milk	Leave for store
3:20	Arrive home, put milk away	Arrive at store
3:25		Buy milk
3:30		Arrive home, put milk away

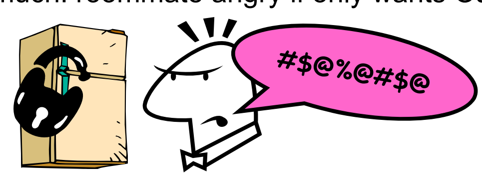
Definitions

- Synchronization: using atomic operations to ensure cooperation between threads
  - For now, only loads and stores are atomic
  - We are going to show that its 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

More Definitions

- 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

- 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

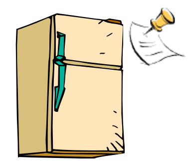
Too Much Milk: Correctness Properties

- 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
- 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):

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



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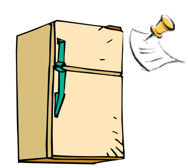
  - Leave a note before buying (kind of "lock")
  - Remove note after buying (kind of "unlock")
  - Don't buy if note (wait)
- Suppose a computer tries this (remember, only memory read/write are atomic):

```
Thread A                          Thread B
if (noMilk) {
                                  if (noMilk) {
                                     if (noNote) {
   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):

```
if (noMilk) {
    if (noNote) {
        leave Note;
        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:

```
leave Note;
if (noMilk) {
   if (noNote) {
      buy milk;
   }
}
remove Note;
```

- 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

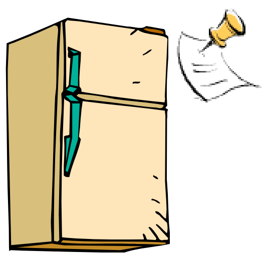
```
leave note A;
if (noNote B) {
   if (noMilk) {
      buy Milk;
   }
}
remove note A;
```

Thread B

```
leave note B;
if (noNoteA) {
   if (noMilk) {
      buy Milk;
   }
}
remove note B;
```

- 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:

Thread A

```
leave note A;
while (note B) {\\X
   do nothing;
}
if (noMilk) {
   buy milk;
}
remove note A;
```

Thread B

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

- 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)`"

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

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

happened before

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


Case 1

- "`leave note A`" happens before "`if (noNote A)`"

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

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

happened before

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


Case 1

- "`leave note A`" happens before "`if (noNote A)`"

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

Wait for note B to be removed

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

happened before

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


Case 2

- "`if (noNote A)`" happens before "`leave note A`"

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

happened before

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

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

Case 2

- "`if (noNote A)`" happens before "`leave note A`"

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

happened before

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

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


Case 2

- "`if (noNote A)`" happens before "`leave note A`"

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

happened before

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

Wait for note B to be removed

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


Solution #3 discussion

- Our solution protects a single "Critical-Section" piece of code for each thread:

```
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 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

- Suppose we have some sort of implementation of a lock
  - `lock.Acquire()` – wait until lock is free, then grab
  - `lock.Release()` – 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:

```
milklock.Acquire();
if (nomilk)
   buy milk;
milklock.Release();
```

- Once again, section of code between `Acquire()` and `Release()` called a "Critical Section"
- Of course, you can make this even simpler: suppose you are out of ice cream instead of milk
  - Skip the test since you always need more ice cream ;-)

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

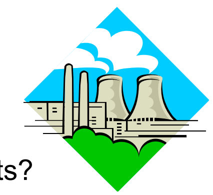
- How can we build multi-instruction atomic operations?
  - Recall: dispatcher gets control in two ways.
    - » Internal: Thread does something to relinquish the CPU
    - » External: Interrupts cause dispatcher to take CPU
  - On a uniprocessor, can avoid context-switching by:
    - » Avoiding internal 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

```
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;
}
```


Where are we going with synchronization?

Programs	Shared Programs
Higher-level API	Locks Semaphores Monitors Send/Receive
Hardware	Load/Store Disable Ints Test&Set Compare&Swap

- 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

Summary

- Concurrent threads are a very useful abstraction
  - Allow transparent overlapping of computation and I/O
  - Allow use of parallel processing when available
- 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