Interrupts, Etc.
Interrupts

Current thread’s user stack

User stack frames

Interrupt handler 1’s frame

Interrupt handler 2’s frame

Kernel stack frames

Current thread’s kernel stack
x86 Interrupt Architecture

Local APIC → Local APIC → Local APIC → Local APIC

I/O APIC → I/O APIC

external interrupts → external interrupts
Dealing with Interrupts

• Interrupt comes from external source
• Must execute code to handle it
• Which stack?
  – use current (kernel) stack
  or
  – use separate stack
Use the Current (Kernel) Stack

• Borrowed from the current thread
  – requires all threads to have sufficiently large kernel stacks
• Interrupted thread may not concurrently execute
  – would corrupt interrupt handler’s stack frames
• Interrupt handler should not block
  – may be waiting on interrupted thread
    - deadlock
  – threads must mask interrupts to protect data structures shared with interrupt handlers
Hierarchical Interrupt Masking

• Interrupts assigned priorities 1 – n
  – current interrupt priority level $i$
    - interrupts with priorities 1 – $i$ masked
  – IPL set to $i$
    - when interrupt of priority $i$ is handled
    - when IPL set explicitly to $i$

• Raising the IPL
  – protects data structures
    - good!
  – delays response to lower priority interrupts
    - bad!
Separate Interrupt Stack

• Single stack used strictly by interrupt handlers
  – hardware saves current register state on interrupt stack
  – no interrupt-handling space required for kernel stacks
    - all can be smaller
  – in principle, interrupted thread may continue to execute
    - won’t corrupt interrupt handler’s frames

Quiz 1
Is interrupt-masking still required?
a) yes
b) no
(Non-Quiz) Questions

1) Is interrupt masking still required? *Done*
2) May interrupt handler block?
3) Does it work on multiprocessors?
Answers

1) Masking is still required
   – if nothing else, to protect data structures shared by multiple interrupt handlers

2) Interrupt handlers should not block
   – would have to block with raised IPL
   – results in lengthy time with interrupts masked
     - delayed response

3) Yes, but each processor has its own interrupt stack
Interrupt Threads

• Give each interrupt instance its own stack
  – handlers effectively execute as separate threads
  – interrupted thread continues to run
  – but interrupts remain masked while interrupt thread is processing interrupt
Effect of Interrupts

• Normally don’t directly affect current thread
  – thread is interrupted
  – interrupt is dealt with
  – thread is resumed
• I/O-completion interrupts
  – may result in waking up higher-priority thread
• Clock interrupts
  – may trigger end of time slice
Synchronization and Interrupts

• Non-preemptive kernels
  – threads running in privileged mode yield the processor only voluntarily
  – involuntary thread switches happen only to threads in user mode
    - end of time slice
    - higher-priority thread is made runnable
  – inter-thread synchronization is easy

• Preemptive kernels
  – threads running in privileged mode may be forced to yield the processor
  – inter-thread sync is not easy
Non-Preemptive Kernel Sync.

```c
int X = 0;

void AccessXThread() {
    int oldIPL;
    oldIPL = setIPL(IHLevel);
    X = X + 1;
    setIPL(oldIPL);
}

void AccessXInterrupt() {
    ...
    X = X + 1;
    ...
}
```
void disk_intr(...)
{
    thread_t *thread;
    ...
    // handle disk interrupt
    ...
    thread = dequeue(disk_waitq);
    if (thread != 0) {
        enqueue(RunQueue, thread);
        // wakeup waiting thread
    }
    ...
}
Improved Disk I/O

```c
int disk_write(...) {
    ...
    oldIPL = setIPL(diskIPL);
    startIO();    // start disk operation
    ...
    enqueue(disk_waitq, CurrentThread);
    thread_switch();
    // wait for disk operation to complete
    setIPL(oldIPL);
    ...
}
```
Modified `thread_switch`

```c
void thread_switch() {
    thread_t *OldThread;
    int oldIPL;
    oldIPL = setIPL(HIGH_IPL);
    // protect access to RunQueue by masking all interrupts
    while (queue_empty(RunQueue)) {
        // repeatedly allow interrupts, then check RunQueue
        setIPL(0);  // IPL == 0 means no interrupts are masked
        setIPL(HIGH_IPL);
    }
    // We found a runnable thread
    OldThread = CurrentThread;
    CurrentThread = dequeue(RunQueue);
    swapcontext(OldThread->context, CurrentThread->context);
    setIPL(oldIPL);
}
```
Preemptive Kernels on MP

• What’s different?
• A thread accesses a shared data structure:
  1. it might be interrupted by an interrupt handler (running on its processor) that accesses the same data structure
  2. another thread running on another processor might access the same data structure
  3. it might be forced to give up its processor to another thread, either because its time slice has expired or it has been preempted by a higher-priority thread
  4. an interrupt handler running on another processor might access the same data structure
Solution?

```c
int x = 0;
SpinLock_t L = UNLOCKED;

void AccessXThread() {
    SpinLock(&L);
    x = x+1;
    SpinUnlock(&L);
}

void AccessXInterrupt() {
    ...
    SpinLock(&L);
    x = x+1;
    SpinUnlock(&L);
    ...
}
```
int x = 0;
SpinLock_t L = UNLOCKED;

void AccessXThread() {
    MaskInterrupts();
    SpinLock(&L);
    x = x+1;
    SpinUnlock(&L);
    UnMaskInterrupts();
}

void AccessXInterrupt() {
    ...
    SpinLock(&L);
    x = x+1;
    SpinUnlock(&L);
    ...
}
Quiz 2

We have a single-core system with a preemptible kernel. We’re concerned about data structure $X$, which is accessed by kernel threads as well as by an interrupt handler.

a) It’s sufficient for threads to mask interrupts while accessing $X$

b) In addition, threads must lock (blocking) mutexes before accessing $X$

c) Instead of b, threads must lock spinlocks before accessing $X$

d) In addition to c, the interrupt handler must lock a spinlock before accessing $X$
Deferred Work

• Interrupt handlers run with interrupts masked
  – both when executed in interrupt context or thread context
  – may interfere with handling of other interrupts

• Solution
  – do minimal work now
  – do rest later without interrupts masked
Deferred Processing

```c
void TopLevelInterruptHandler(int dev) {
    InterruptVector[dev]();  // call appropriate handler
    if (PreviousContext == ThreadContext) {
        UnMaskInterrupts();
        while (!Empty(WorkQueue)) {
            Work = DeQueue(WorkQueue);
            Work();
        }
    }
}

void NetworkInterruptHandler() {
    // deal with interrupt
    ...
    EnQueue(WorkQueue, MoreWork);
}
```
## Windows Interrupt Priority Levels

<table>
<thead>
<tr>
<th>Level</th>
<th>Priority</th>
</tr>
</thead>
<tbody>
<tr>
<td>31</td>
<td>High</td>
</tr>
<tr>
<td>30</td>
<td>Power fail</td>
</tr>
<tr>
<td>29</td>
<td>Inter-processor</td>
</tr>
<tr>
<td>28</td>
<td>Clock</td>
</tr>
<tr>
<td>4</td>
<td>Device 2</td>
</tr>
<tr>
<td>3</td>
<td>Device 1</td>
</tr>
<tr>
<td>2</td>
<td>DPC</td>
</tr>
<tr>
<td>1</td>
<td>APC</td>
</tr>
<tr>
<td>0</td>
<td>Thread</td>
</tr>
</tbody>
</table>

**hardware**

**software**
Deferred Procedure Calls

```c
void InterruptHandler( ) {
    // deal with interrupt
    ...
    QueueDPC(MoreWork, arg);
    /* enqueues MoreWork on
     * the DPC queue and
     * requests a DPC
     * interrupt
     */
}
```

```c
void DPCHandler( ... ) {
    while(!Empty(DPCQueue)) {
        Work = DeQueue(DPCQueue);
        Work();
    }
}
```
Software Interrupt Threads

```c
void InterruptHandler() {
    // deal with interrupt
    ...
    EnQueue(WorkQueue, MoreWork);
    SetEvent(Work);
}

void SoftwareInterruptThread() {
    while(TRUE) {
        WaitEvent(Work)
        while(!Empty(WorkQueue)) {
            Work = DeQueue(WorkQueue);
            Work();
        }
    }
}
```
Preemption: User-Level Only

```c
void ClockHandler() {
    // deal with clock interrupt
    ...
    if (TimeSliceOver())
        ShouldReschedule = 1;
}

void TopLevelInterruptHandler(int dev) {
    InterruptVector[dev]();
    if (PreviousMode == UserMode) {
        // the clock interrupted user-mode code
        if (ShouldReschedule)
            Reschedule();
    }
    ...
}

void TopLevelTrapHandler(...) {
    SpecificTrapHandler();
    ...
    if (ShouldReschedule) {
        /* the time slice expired while the thread
        was in kernel mode */
        Reschedule();
    }
}
```
Preemption: Full

```c
void ClockInterruptHandler( ) {
    // deal with clock interrupt
    ...
    if (TimeSliceOver)
        QueueDPC(Reschedule);
}
```
Directed Processing

• **Signals: Unix**
  – perform given action in context of a particular thread in user mode

• **APC: Windows asynchronous procedure calls**
  – roughly same thing, but also may be done in kernel mode
Asynchronous Procedure Calls

• Two uses
  – kernel APC: release of kernel resources
  – user APC: notifying a thread of an external event
Kernel APC

- Release of kernel resources
  - interrupt handler can’t free storage for buffer and control blocks until info passed to process
  - can’t be done unless in context of process
    - otherwise address space not mapped in
  - interrupt handler requests kernel APC to have thread, running in kernel mode, absorb info in buffer and control blocks and then free them
User APC

• Notifying thread of external event
  – example: asynchronous I/O
    - thread supplies *completion routine* when
      starting asynchronous I/O request
    - called in thread’s context when I/O completes
      • similar to a Unix signal
      • called only when thread is in *alertable wait state*
        – an option in certain blocking system calls
APC Implementation

• Per-thread list of pending APCs
  – on notification, thread executes them

• User APC
  – thread in alertable state is woken up and executes pending APCs when it returns to user mode

• Kernel APC
  – running thread interrupted by APC interrupt (lowest priority interrupt)
  – waiting thread is “unwaited”
  – execute pending kernel APCs