What You Need to Know for Project One

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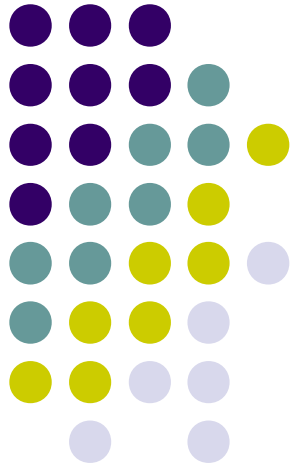
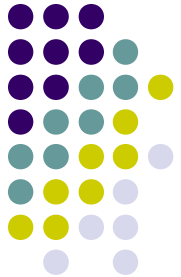
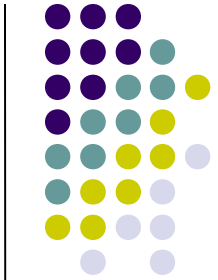


Synchronization



- Please read the syllabus
  - Some of your questions are answered there :-)
  - We would rather teach than tear our hair out
- Also, please read the Project 1 handout
  - Please don't post about “Why did my screen turn purple?”
- Partner registration -- please do if you can!
  - Status: ~7 groups registered (thanks!)
    - Hint: https://www.cs.cmu.edu/~410/seeking-partner.pdf
  - Also 2 groups have half-way registered
    - *Please complete 1-way registrations (ahem!!)*

Synchronization



- Anti-catastrophe reminder: this is ***not*** a Stack Overflow class!
  - Also not Chegg, etc.
- We realize that we are asking you to do things differently than you have in the past
  - We realize that can be disorienting

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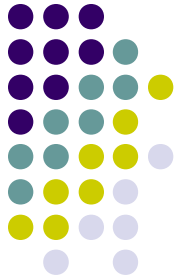
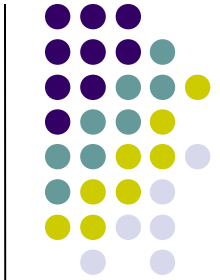


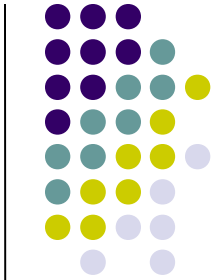
- Anti-catastrophe reminder: this is ***not*** a Stack Overflow class!
  - Also not Chegg, etc.
- We realize that we are asking you to do things differently than you have in the past
  - We realize that can be disorienting
  - Please commit – right away now – to doing new and disorienting things, or else please drop the class – right away now
- Thanks!

Synchronization



- Final-exam date???
  - We don't choose it – the Registrar does
  - It's not decided yet – the Registrar decides when

Synchronization



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- When can I *get out of Pittsburgh*???

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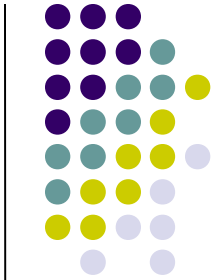

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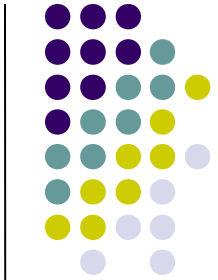

- Final-exam date???
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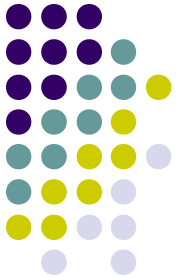
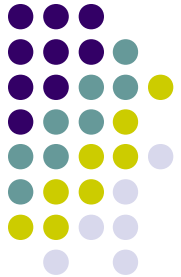
- When can I *get out of Pittsburgh*???
  - It's not decided yet – the Registrar decides when
  - If you must buy tickets now, you need to buy them for the day ***after*** the “Makeup Final Examination” day!

Overview



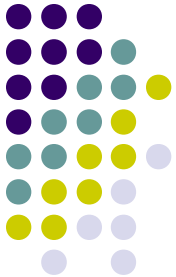
- Project 1 motivation
- Mundane details (x86/IA-32 version)
  PICs, hardware interrupts, software interrupts and exceptions, the IDT, privilege levels, segmentation
- Writing a device driver
- Using Simics
- Project 1 pieces

Project 1 Motivation

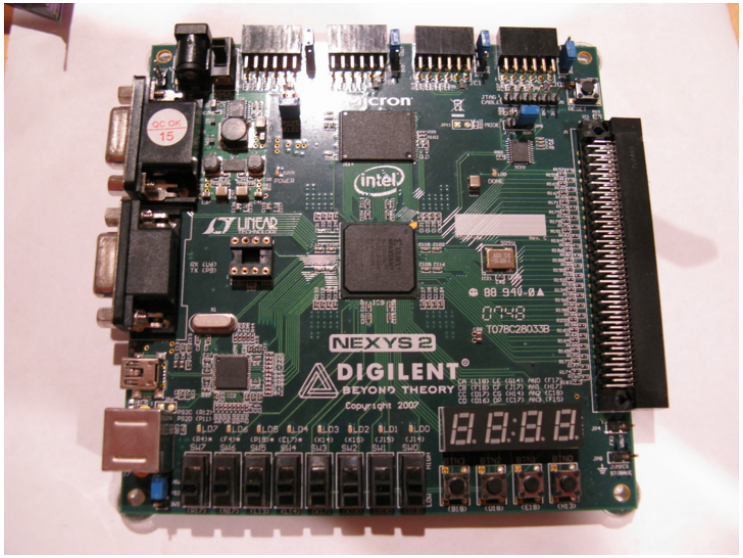


- Project 1 implements a game that runs directly on x86 hardware (no OS)
- What are our hopes for Project 1?
  - introduction to kernel programming
  - a better understanding of the x86 arch
  - hands-on experience with hardware interrupts and device drivers
  - get acquainted with the simulator (Simics) and development tools

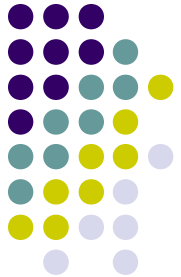
Why do you care?



- You'll need this for Project 3
- Lots of programs run on bare hardware

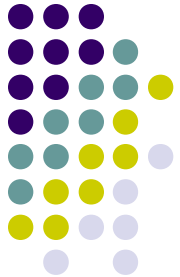


Mundane Details in x86

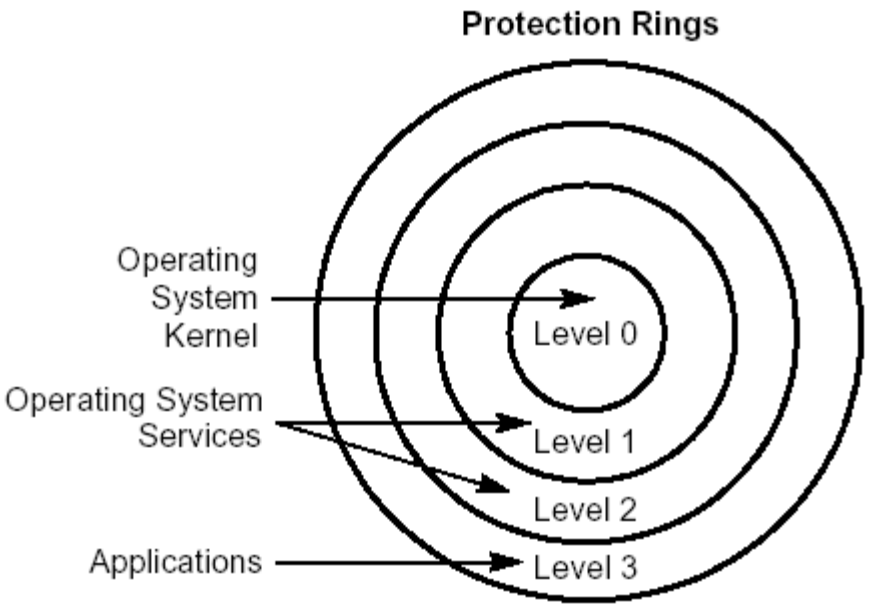


- Kernels work closely with hardware
- This means you need to know about hardware
- Some knowledge (registers, stack conventions) is assumed from 15-213
- You will learn more x86 details as the semester goes on
- Use the Intel PDF files as reference (http://www.cs.cmu.edu/~410/projects.html)

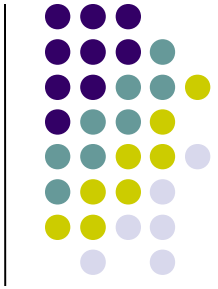
Mundane Details in x86: Privilege Levels



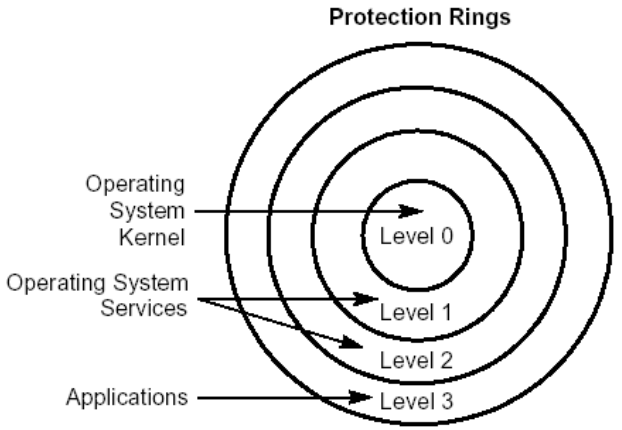
- Processor has 4 "privilege levels" (PLs)
- Zero most-privileged, three least-privileged
- Processor executes at one of the four PLs at any given time
- PLs protect privileged data, cause general protection faults



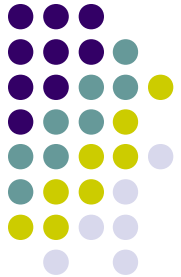
Mundane Details in x86: Privilege Levels



- Nearly unused in Project 1
- For projects 2 through 4
  - PL0 is “kernel”
  - PL3 is “user”
  - Interrupts & exceptions usually transfer from 3 to 0
    - Sometimes: from 0 to 0
  - Running user code means getting from 0 to 3

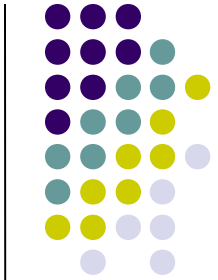


Memory Segmentation



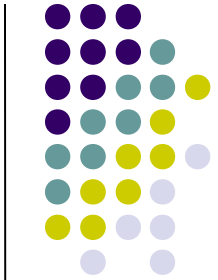
- There are different “kinds” of memory
- Hardware “kinds”
  - Read-only memory (for booting)
  - Video memory (painted onto screen)
  - ...
- Software “kinds”
  - Read-only memory (typically, program code)
  - Stack (grows down), heap (grows up)
  - ...

Memory Segmentation



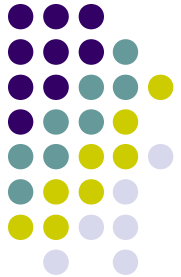
- Memory segment is a range of “the same kind”
- Hardware “kind”
  - Mark video memory as “don't buffer writes”
- Software “kind”
  - Mark all code pages read-only
- Fancy software
  - Process uses many separate segments
  - Windows: each DLL is multiple segments
    - (Well, Win16... and Win32... but not Win64...)

Memory Segmentation



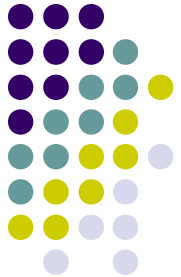
- x86 hardware ***loves*** segments
- Mandatory segments
  - Stack
  - Code
  - Data
- Segments interact with privilege levels
  - Kernel stack / user stack
  - Kernel code / user code
  - ...

x86 Segmentation Road Map



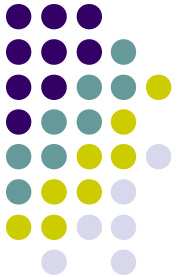
- Segment = range of “same kind of memory”
- Segment ***register*** = %CS, %SS, %DS, ... %GS
- Segment ***selector*** = contents of a segment register
  - Which segment table and index do we mean?
  - What access privilege do we have to the segment?
- Segment ***descriptor*** = definition of segment
  - Which memory range?
  - What are its properties?

Memory Segmentation

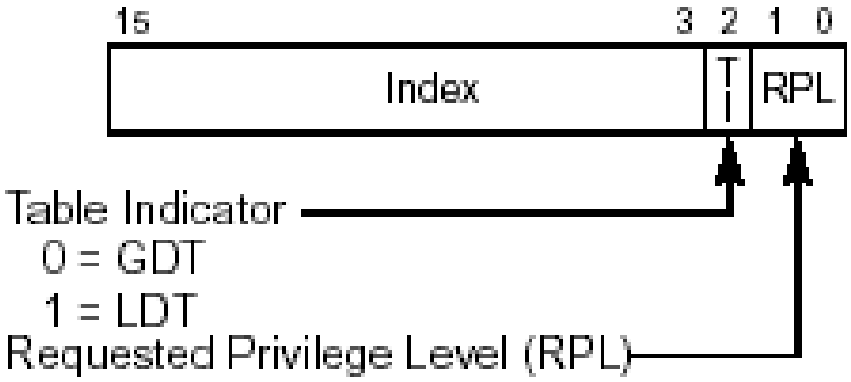


- When fetching an instruction, the processor asks for an address that looks like this: %CS:%EIP
- So, if %EIP is 0xface then %CS:%EIP is the 64206th byte of the “code segment”.

Mundane Details in x86: Segmentation



- When fetching an instruction, the processor asks for an address that looks like this: %CS: %EIP
- The CPU looks at the ***segment selector*** in the %CS ***segment register***
- A segment selector looks like this:



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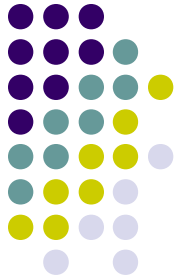
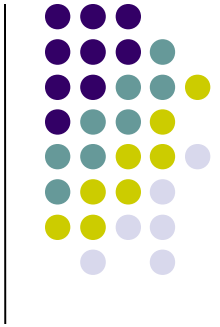


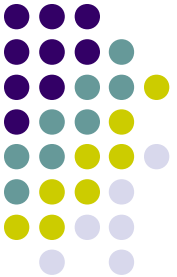
- Segment selector has a segment number, table selector, and requested privilege level (RPL)
- The table-select flag selects a descriptor table
  - *global descriptor table or local descriptor table*
- Segment number indexes into that descriptor table
  - 15-410 uses only global descriptor table (whew!)
- Descriptor tables set up by operating system
  - 15-410 support code builds GDT for you (whew!)
- *You will still need to understand this, though...*

Mundane Details in x86: Segmentation



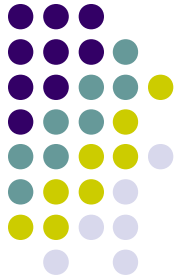
- Segment selector has a segment number, table selector, and requested privilege level (RPL)
- Table selector (done)
- Segment number/index (done)
- RPL ***generally*** means “what access do I have?”
- Magic special case: RPL in %CS
  - Defines ***current processor privilege level***
  - Think: “user mode” vs. “kernel mode”
  - Remember this for Project 3!!!

Mundane Details in x86: Segment Descriptors

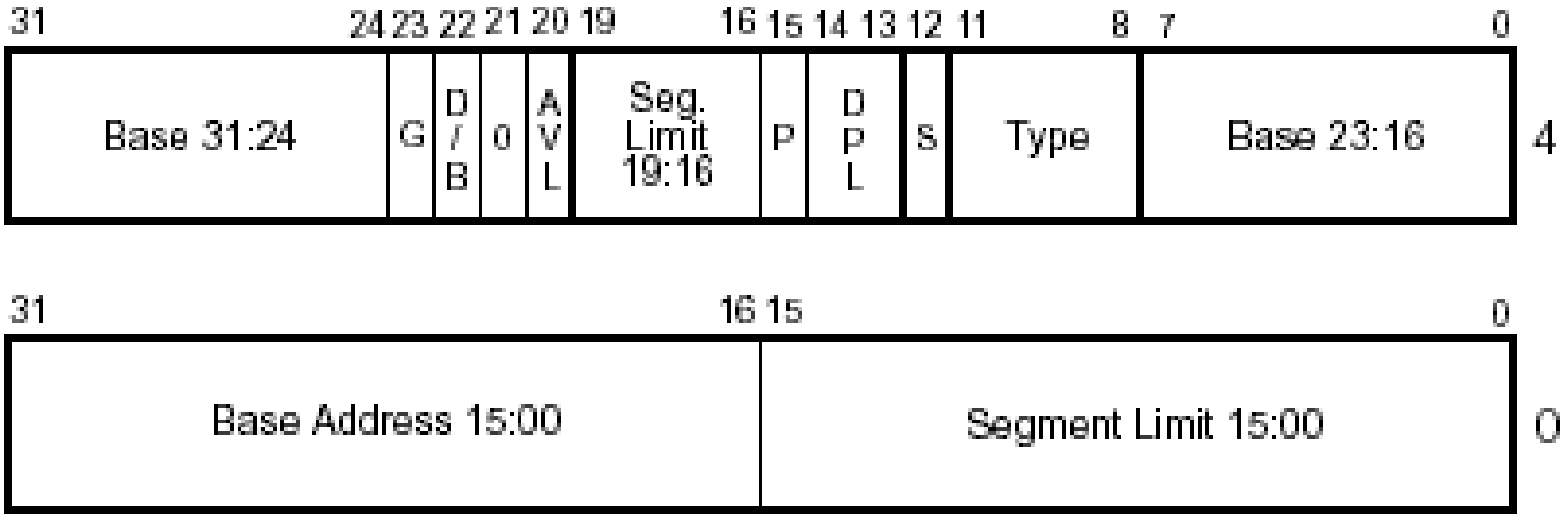


- Segment = area of memory with particular access/usage constraints
- Base, size, “stuff”
- Logically, base and size are two 32-bit numbers, “stuff” is flag/control bits

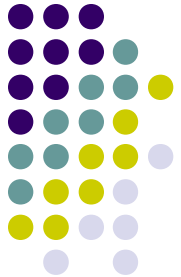
Mundane Details in x86: Segment Descriptors



- Segment = area of memory with particular access/usage constraints
- Base, size, “stuff”
- Layout:

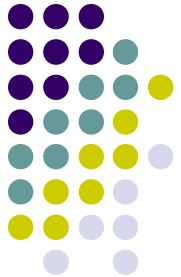


Mundane Details in x86: Segmentation



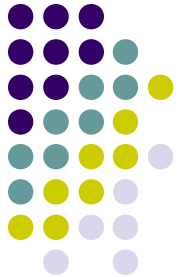
- Consider %CS segment register's segment selector's segment descriptor
  - Assume base = 0xfeed0000
  - Assume limit > 64206
- Assume %EIP contains 0xface
  - Then %CS:%EIP means “linear virtual address” 0xfeedface (0xfeed0000 + 0x0000face)
- “Linear virtual address” fed to virtual memory hardware, if it's turned on (Project 3, not Project 1)

Implied Segment Registers

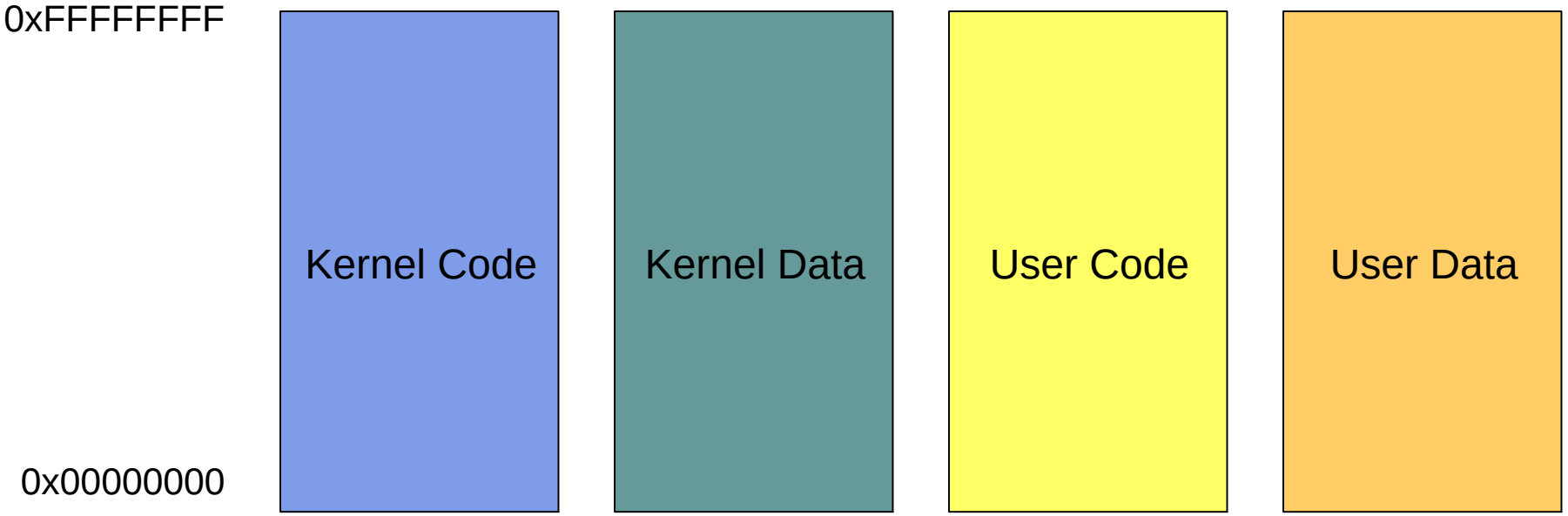


- Programmer doesn't usually ***specify*** segment
- Usually ***implied*** by “kind of memory access”
- CS is the segment register for fetching code
  - All instruction fetches are from %CS:%EIP
- SS is the segment register for the stack segment
  - PUSH, POP instructions use %SS:%ESP
- DS is the default segment register for data access
  - `MOVL (%EAX),%EBX` fetches from %DS:%EAX
  - But ES, FS, and GS can be specified instead

Mundane Details in x86: Segmentation



- Segments need not be fully backed by physical memory, and can overlap
- Segments defined for 15-410:



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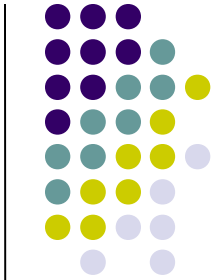
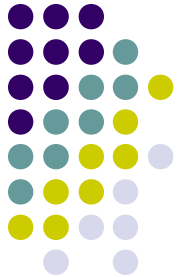
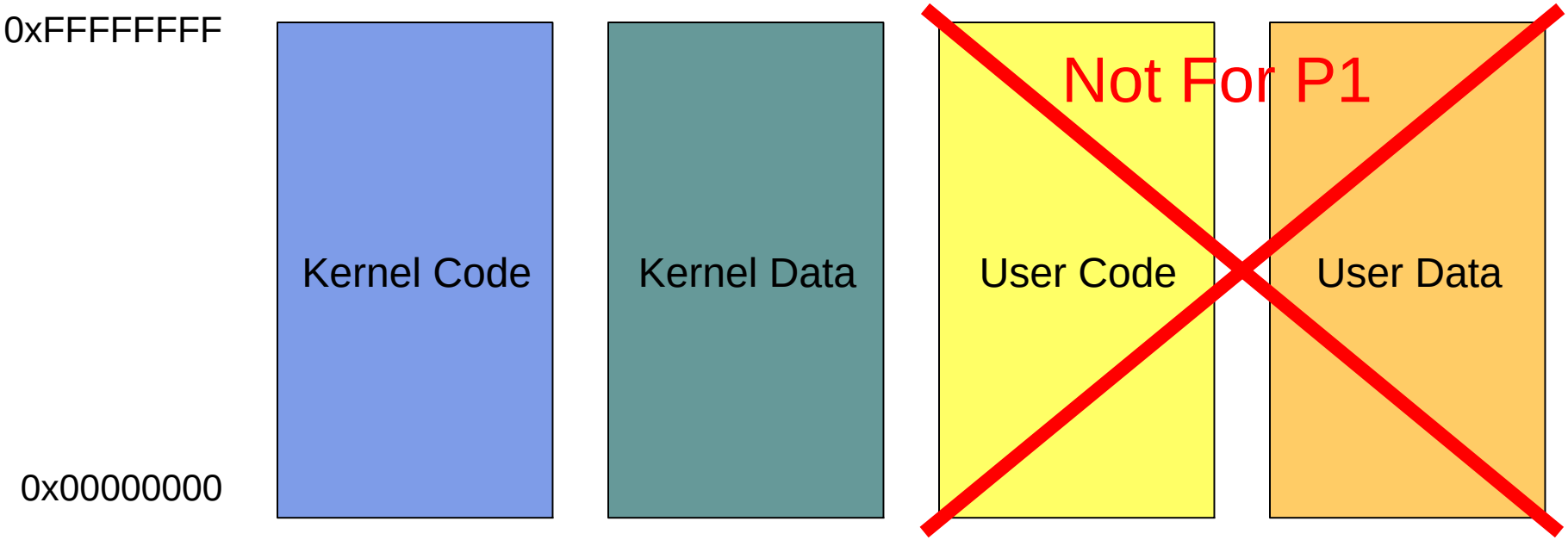


- Why so many?
- You can't specify a segment that is readable, writable *and* executable.
  - Need one for readable/executable code
  - Another for readable/writable data
- Need user and kernel segments in Project 3 for protection
- (Code, Data) X (User, Kernel) = 4

Mundane Details in x86: Segmentation





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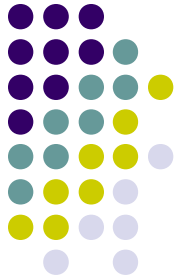
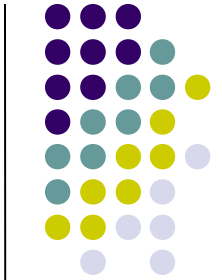


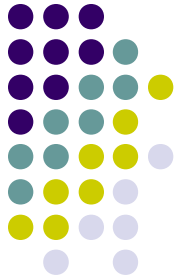
- Don’t need to be concerned with every detail of segments in this class
- For more information you can read the Intel docs
- Or our documentation at:
  - www.cs.cmu.edu/~410/doc/segments/segments.html

Execution Types



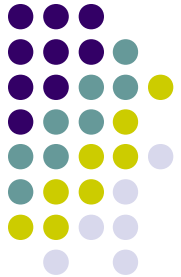
- From the processor's perspective, three kinds of instruction execution
  - Regular work – execute this one, then the next
  - Branch – execute this one, then somewhere else
  - ...?

Execution Types - Surprises



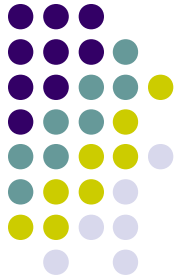
- From the processor's perspective, three kinds of instruction execution
  - Regular work – execute this one, then the next
  - Branch – execute this one, then somewhere else
  - “Surprise” – suddenly we must run a different body of code!
- Surprises
  - Exception/fault – this instruction can't be executed
  - Trap – voluntary transfer to different code
  - Interrupt – involuntary, unpredictable transfer to different code

Surprises



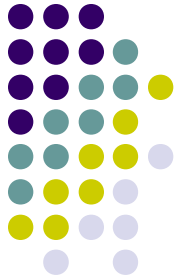
- Exception: a ***particular instruction*** broke
  - SIGSEGV, page fault, zero divide, illegal instruction
  - We may fix the conditions and re-run the instruction
  - We may kill the program
- Trap: a ***particular instruction*** asks for help
  - System call: “please invoke the kernel to ...”
  - We later resume at the instruction after the trap
- Interrupt: an I/O device needs attention
  - A ***random instruction*** is deferred while we run driver
  - We later resume the deferred instruction

Mundane Details in x86: Faults



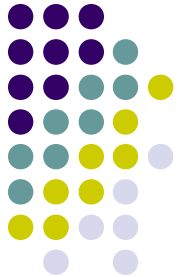
- Sometimes code does stupid things
  - `int gorgonzola = 128/0;`
  - `char* idiot_ptr = NULL; *idiot_ptr = 0;`
  - Executing bytes which don't encode an instruction
- Exceptions cause a handler routine to be run
  - Record information about which instruction broke
  - Record information about why it broke
  - Locate “exception handler”
  - Exception handler decides: fix/kill/crash

Mundane Details in x86: "Software Interrupts"

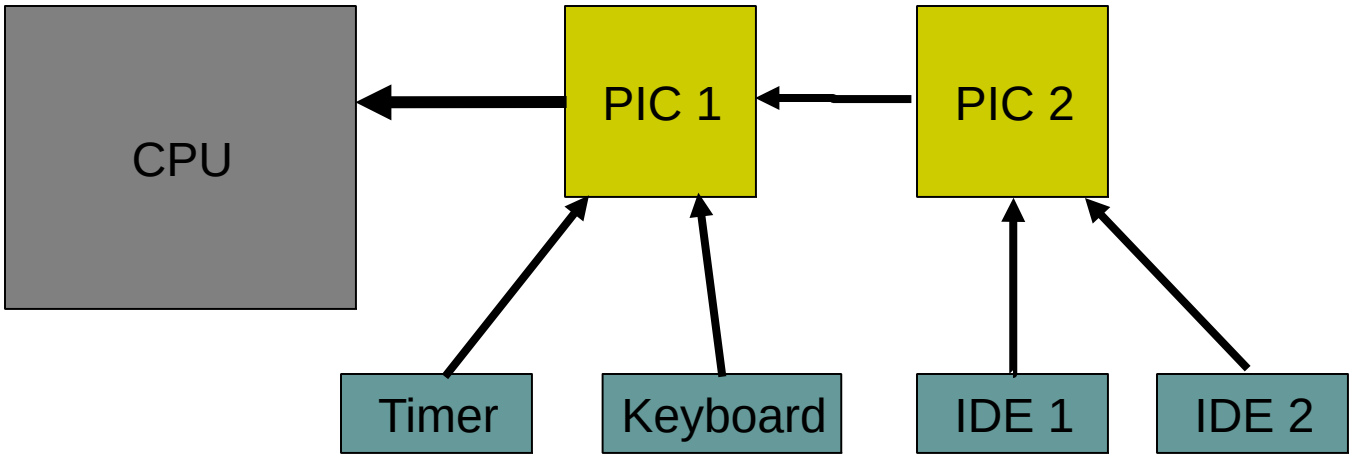


- A device gets the kernel's attention by raising a (hardware) interrupt
- User processes get the kernel's attention by raising a "software interrupt"
  - Which is not an interrupt even if Intel calls it one!
- x86 instruction `INT n`
  (more info on page 346 of intel-isr.pdf)
- Invokes handler routine: system call

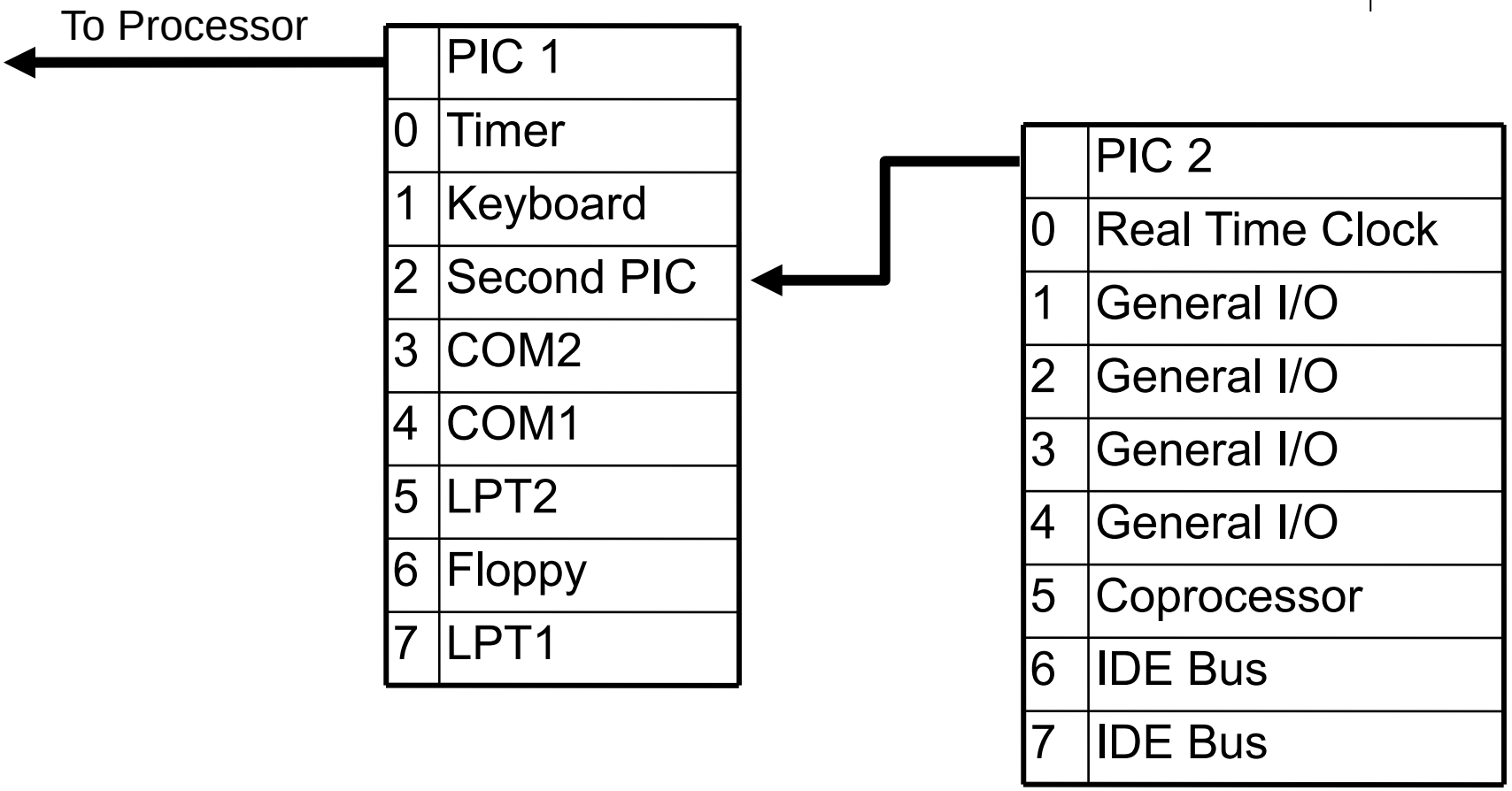
Mundane Details in x86: Interrupts and the PIC



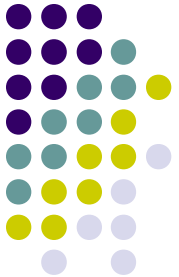
- Devices raise interrupts through the Programmable Interrupt Controller (PIC)
- The PIC serializes interrupts, delivers them
- There are actually two “daisy-chained” PICs

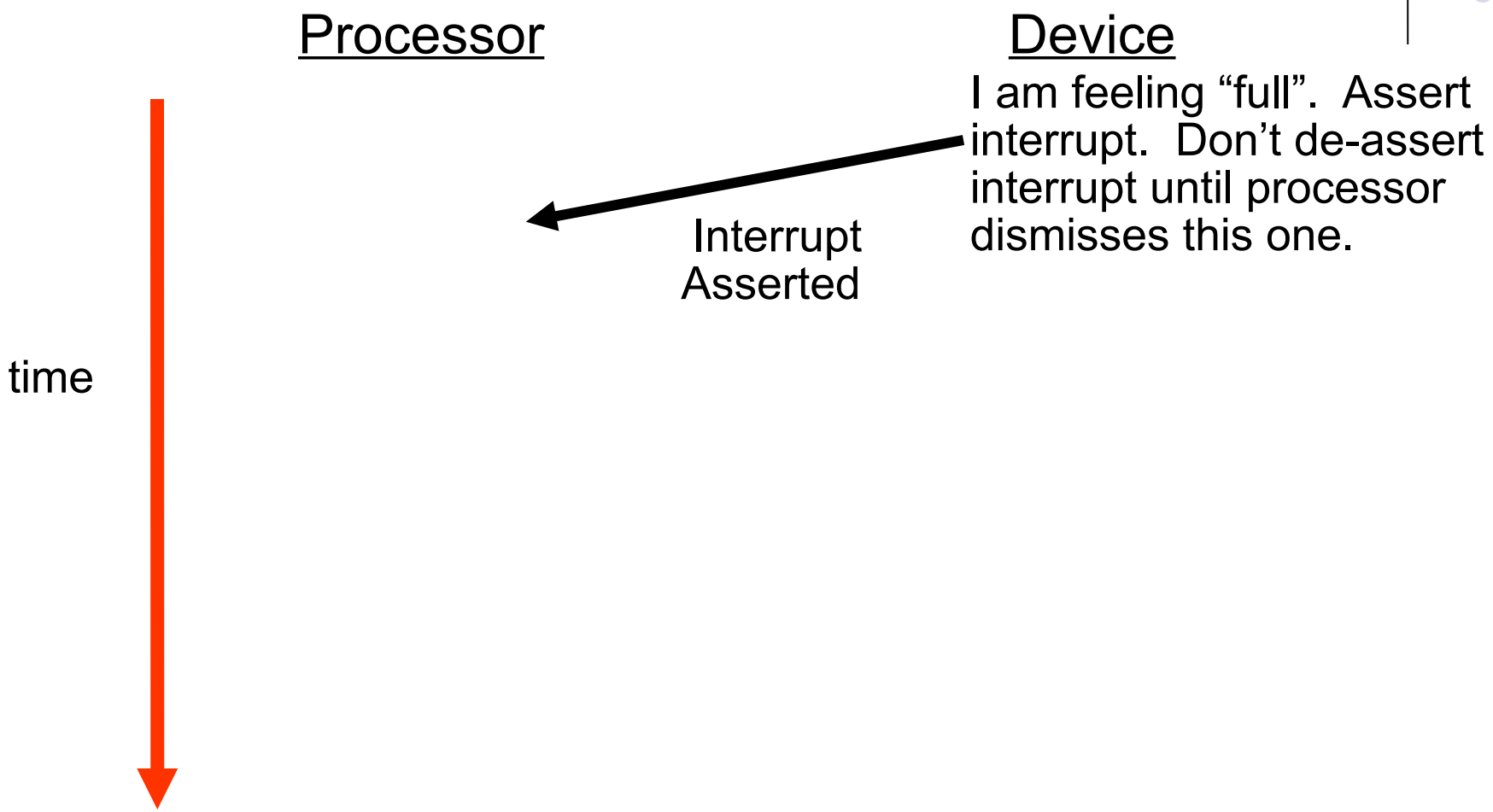


Mundane Details in x86: Interrupts and the PIC

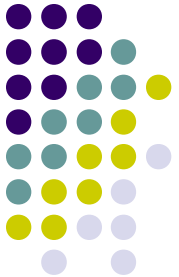


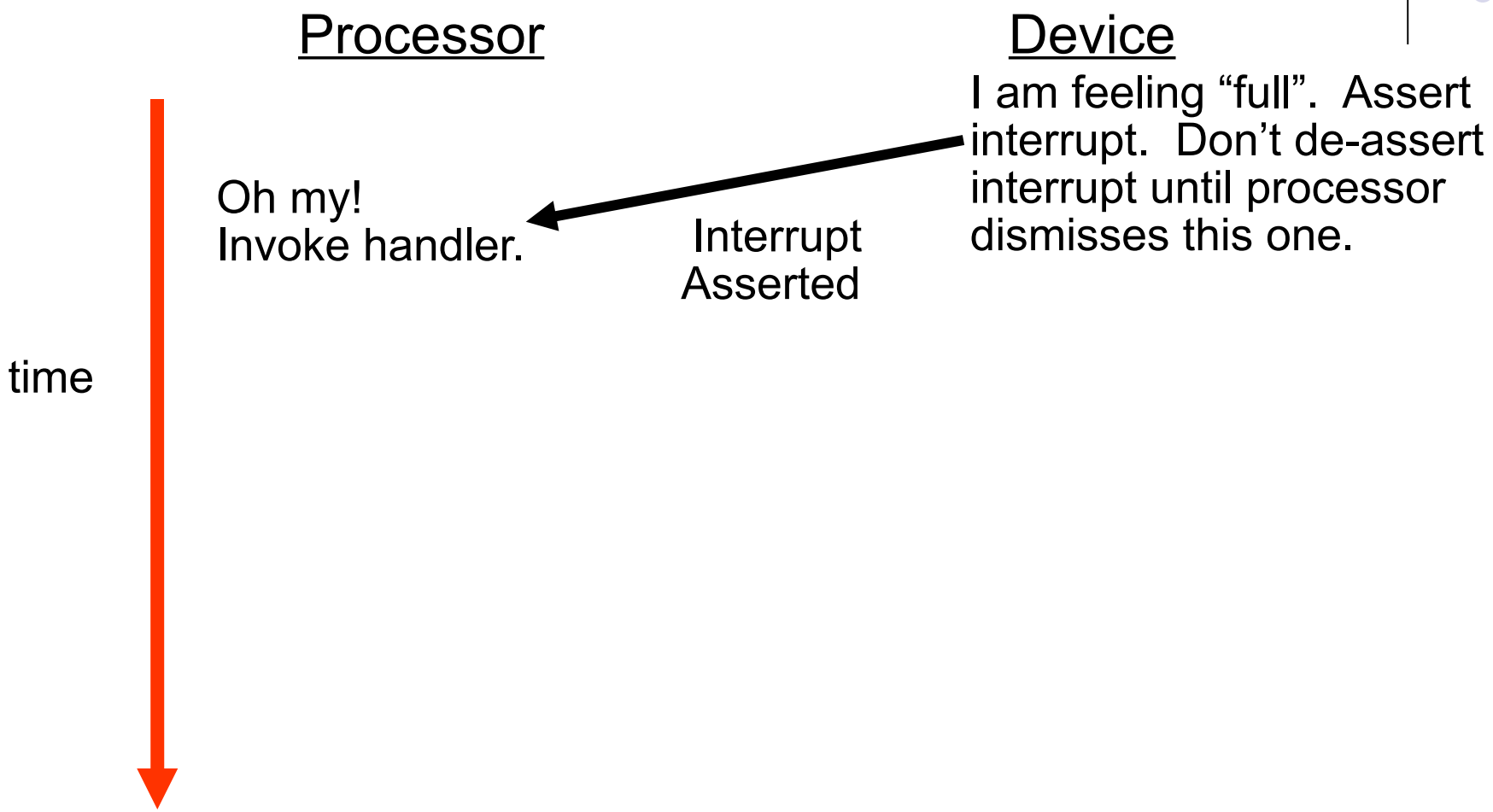
Typical Interrupt Handshake



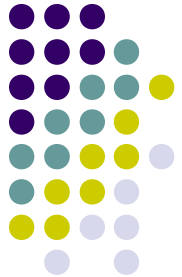


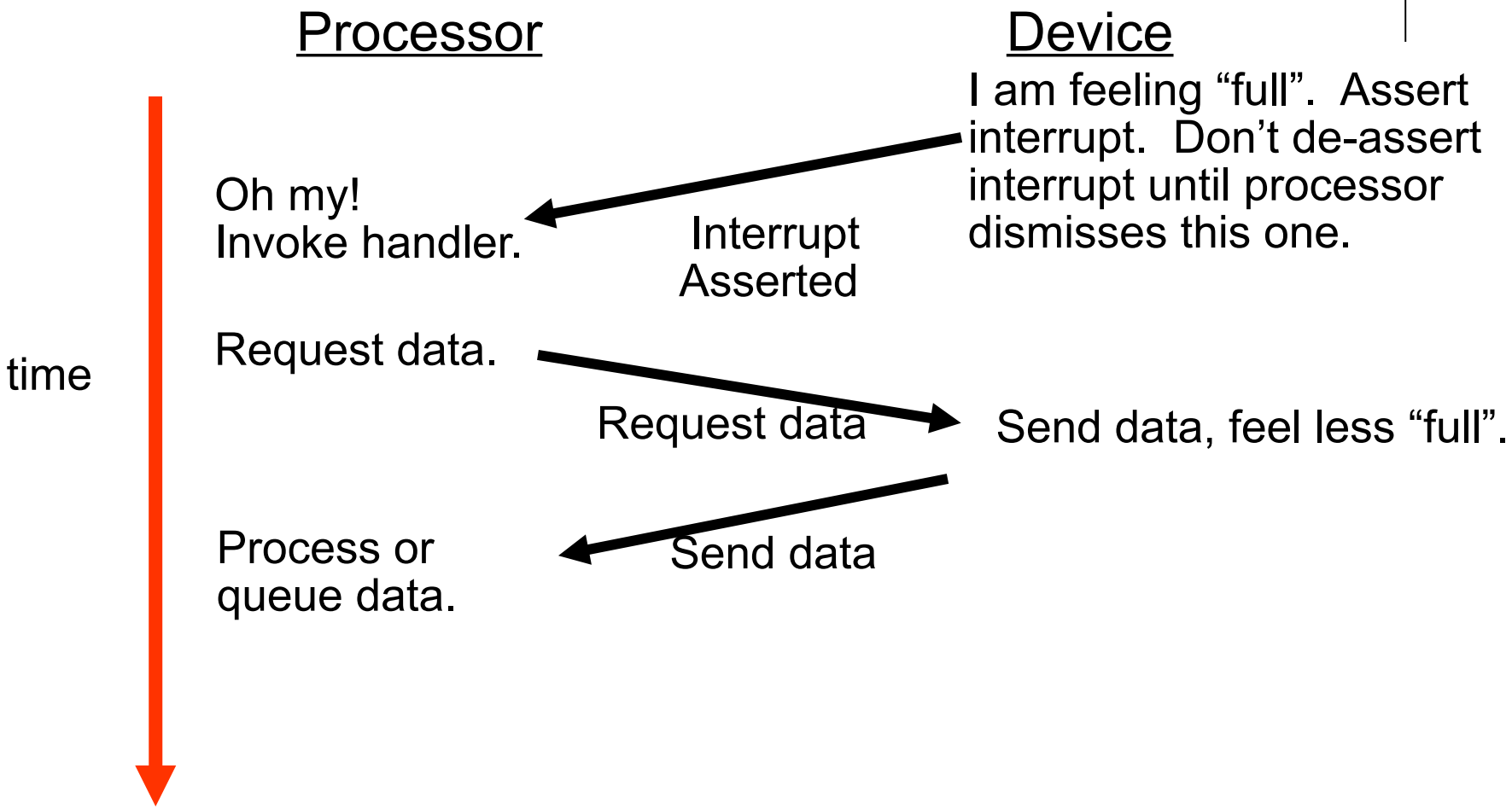
Typical Interrupt Handshake



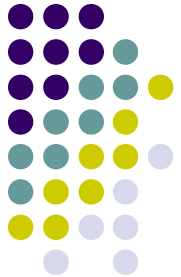


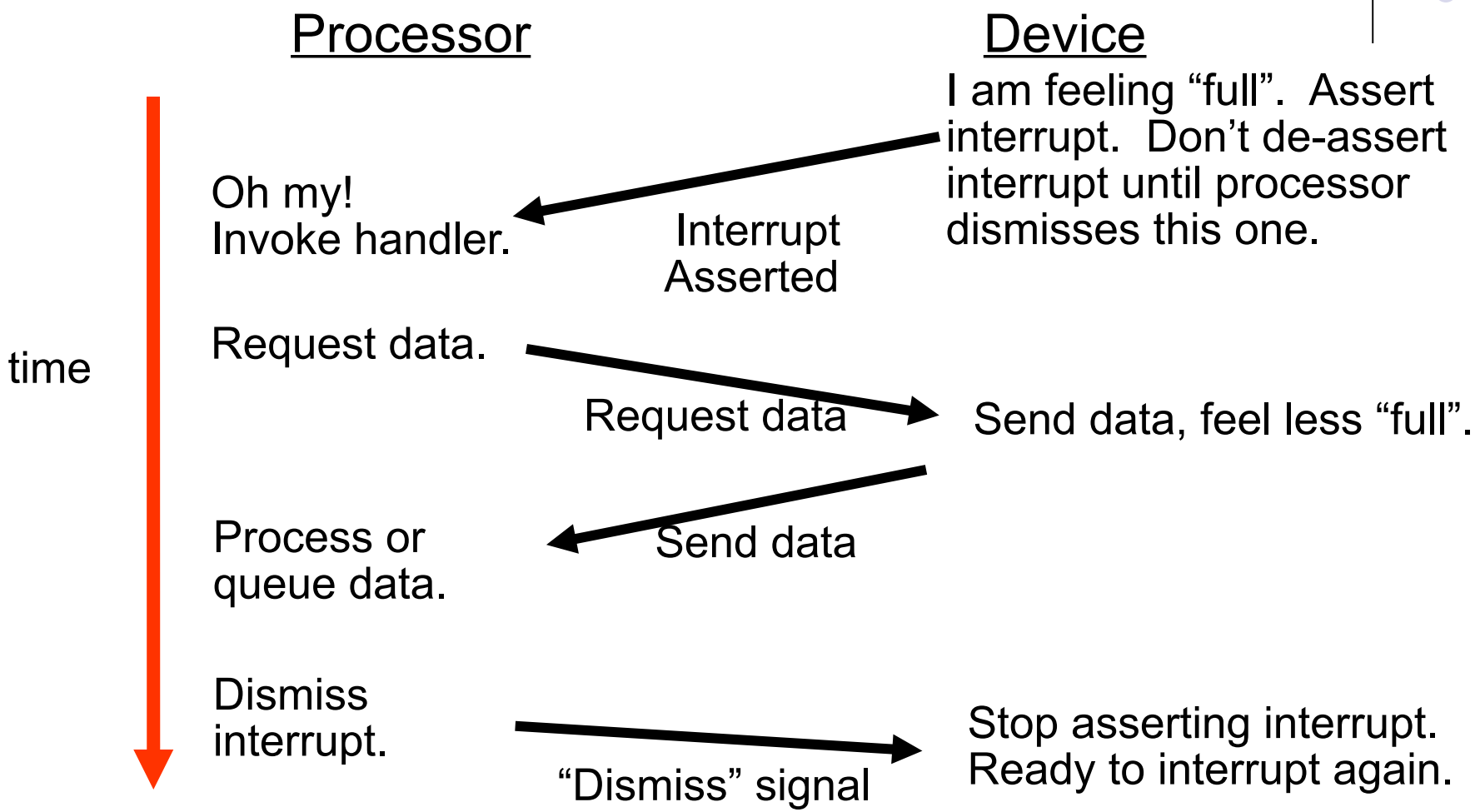
Typical Interrupt Handshake



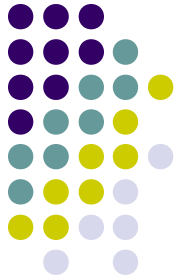


Typical Interrupt Handshake



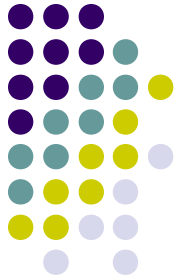


Enabling / Disabling Interrupts



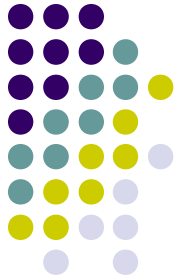
- PIC automatically defers new interrupts from a device until old one dismissed by processor.
- We also provide `disable_interrupts()`, which "disables" interrupts from ALL devices. Think of this as deferring interrupts. They are still out there, waiting to happen.
- We provide `enable_interrupts()`, which re-enables interrupts.
- Finer-grained control is also possible.

Interrupt Descriptor Table – IDT

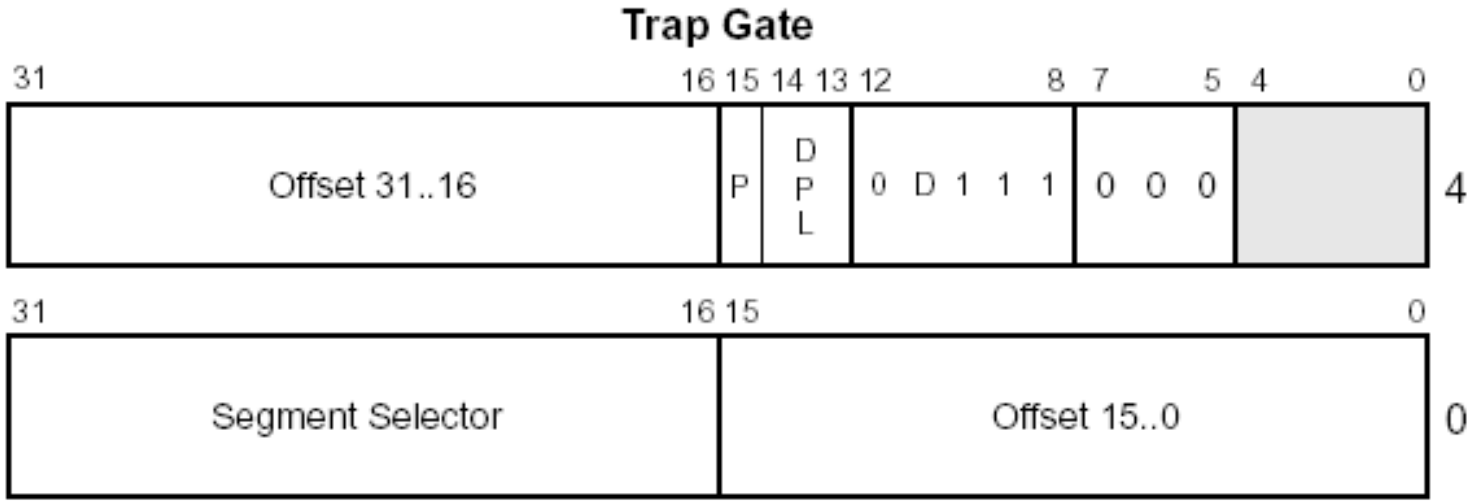


- Processor needs info on which handler to run when
- Processor reads appropriate IDT entry depending on the interrupt, exception *or* `INT n` instruction
- Logically, an IDT entry contains a function pointer and some flags

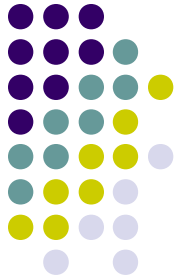
Interrupt Descriptor Table – IDT



- Processor needs info on which handler to run when
- Processor reads appropriate IDT entry depending on the interrupt, exception *or* `INT n` instruction
- An entry in the IDT looks like this:



Interrupt Descriptor Table – IDT

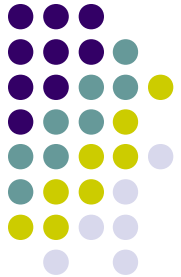


- The first 32 entries in the IDT correspond to processor exceptions. 31-255 correspond to hardware/software interrupts
- Some interesting entries:

IDT Entry	Interrupt
0	Divide by zero
14	Page fault
32	Keyboard interrupt

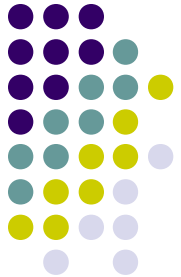
- More information in section 5.12 of intel-sys.pdf.
- Note: One “IDT” table is used for faults, traps, and interrupts

Classifying Surprises



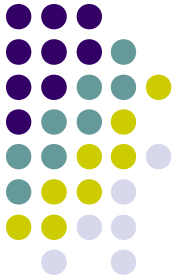
- Asynchronous or synchronous?
  - Asynchronous – happens at a random time
    - Can be deferred ("blocked") until a convenient time
  - Synchronous – a particular instruction is to blame
    - ***Cannot*** be deferred – happen when instruction happens
- What happens afterward?
  - ***Retry*** the surprising instruction (exception)
  - ***Kill*** program (exception)
  - ***Run*** the next instruction (trap, interrupt)

Mundane Details in x86: Communicating with Devices



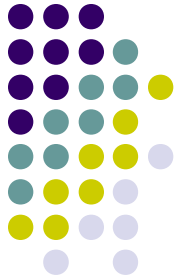
- I/O Ports
  - Use instructions like `inb(port)`, `outb(port,data)`
  - ***Are not memory!***
- Memory-Mapped I/O
  - Magic areas of memory tied to devices
- PC video hardware uses ***both***
  - **Cursor is controlled by I/O ports**
  - **Characters are painted from memory**

x86 Device Perversity



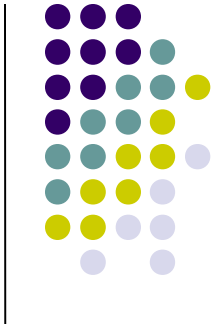
- Influence of ancient history
  - **IA-32 is fundamentally an 8-bit processor!**
  - **Primeval I/O devices had 8-bit ports**
- I/O devices have multiple “registers”
  - **Timer: waveform type, counter value**
  - **Screen: resolution, color depth, *cursor position***
- You must get the right value in the right device register

x86 Device Perversity



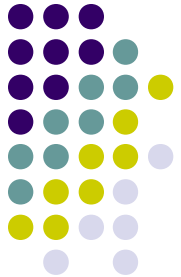
- Value/bus mismatch
  - **Counter value, cursor position are 16 bits**
  - **Primeval I/O devices *still* have 8-bit ports**
- Typical control flow
  - “I am about to tell you half of register 12”
  - “32”
  - “I am about to tell you the other half of register 12”
  - “0”

x86 Device Perversity



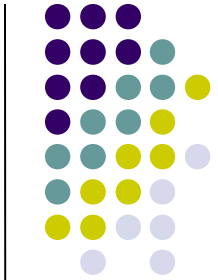
- Sample interaction
  - `outb(command_port, SELECT_R12_LOWER);`
  - `outb(data_port, 32);`
  - `outb(command_port, SELECT_R12_UPPER);`
  - `outb(data_port, 0);`
- This is not intuitive (for software people).
  - Why can't we just "`*R12 = 0x00000032`"?
- But you can't get anywhere on P1 without understanding it.

Writing a Device Driver



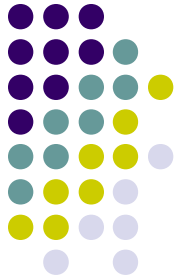
- Traditionally consist of two separate halves
  - Named “top” and “bottom” halves
  - BSD and Linux use these names “differently”
- One half is interrupt driven, executes quickly, queues work
- The other half processes queued work at a more convenient time

Writing a Device Driver



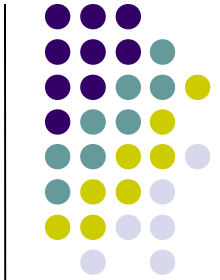
- For this project, your keyboard driver will likely have a top and bottom half
- Bottom half
  - Responds to keyboard interrupts and queues scan codes
- Top half
  - In readchar(), reads from the queue and processes scan codes into characters

Installing and Using Simics



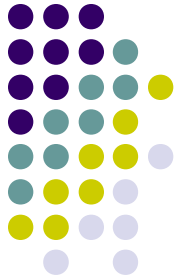
- Simics is an instruction set simulator
- Makes testing kernels much easier
- Project 1 Makefile builds floppy-disk images
- Simics boots and runs them
  - Launch `simics46` in your build directory
- Your 15-410 AFS space has p1/, scratch/
- If you work in scratch/, we can read your files, and answering questions can be much faster.

Installing and Using Simics: Running on Personal PC



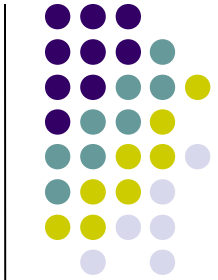
- SSH with X Windows forwarding to LINUX.ANDREW
  - See “15-410 Software Setup Guide”
  - Especially see “Using Virtual Andrew” if/when you are far away from Pittsburgh

Installing and Using Simics: Overview of usage



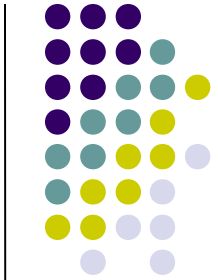
- Run simulation with r, stop with ^C
- Magic instruction
  - `xchg %bx,%bx` (wrapper in interrupts.h)
    - This may change -- use the macros!
- Memory access breakpoints
  - break 0x2000 –x OR break (sym init_timer)
- Symbolic debugging
  - psym foo OR print (sym foo)
- See our local Simics hints! (on Project page)

Simics vs. gdb



- Similar jobs: symbolic debugging
- Random differences
  - Details of commands and syntax
- Notable differences
  - Simics knows ***everything*** about PC hardware – all magic registers, TLB contents, interrupt masks, etc.
  - Simics is scriptable in Python

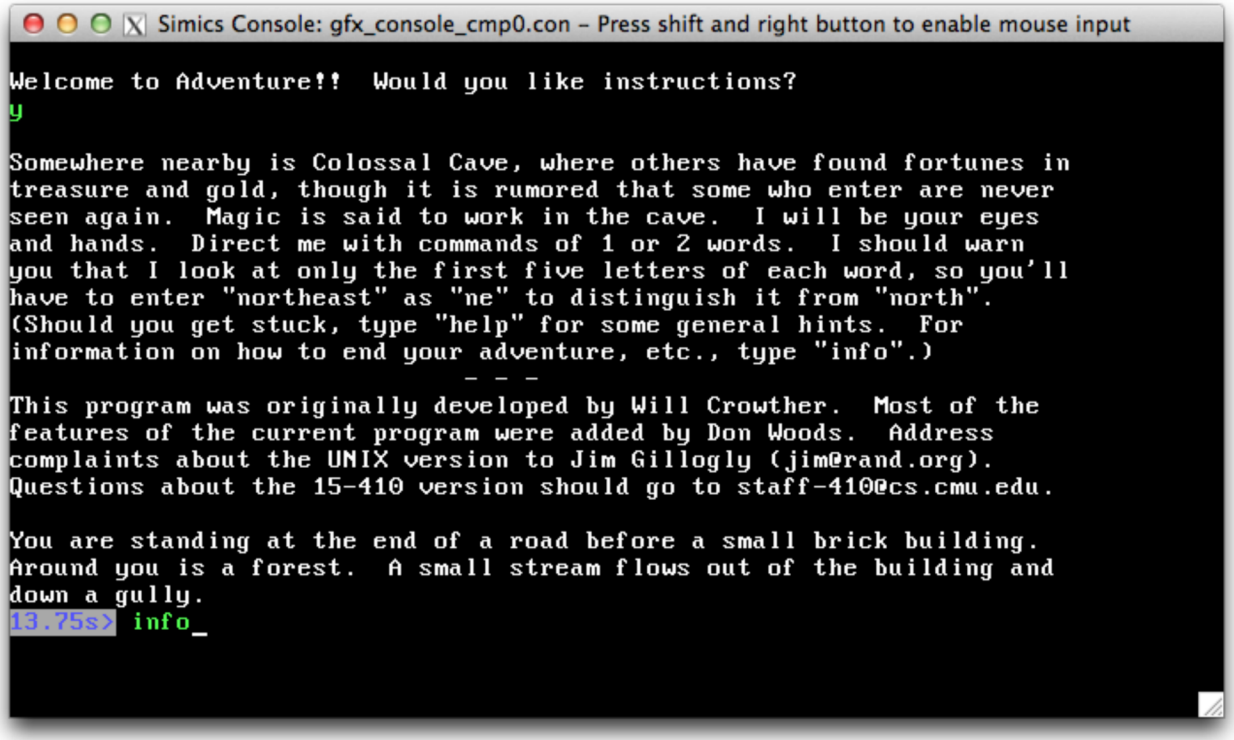
Project 1 Pieces



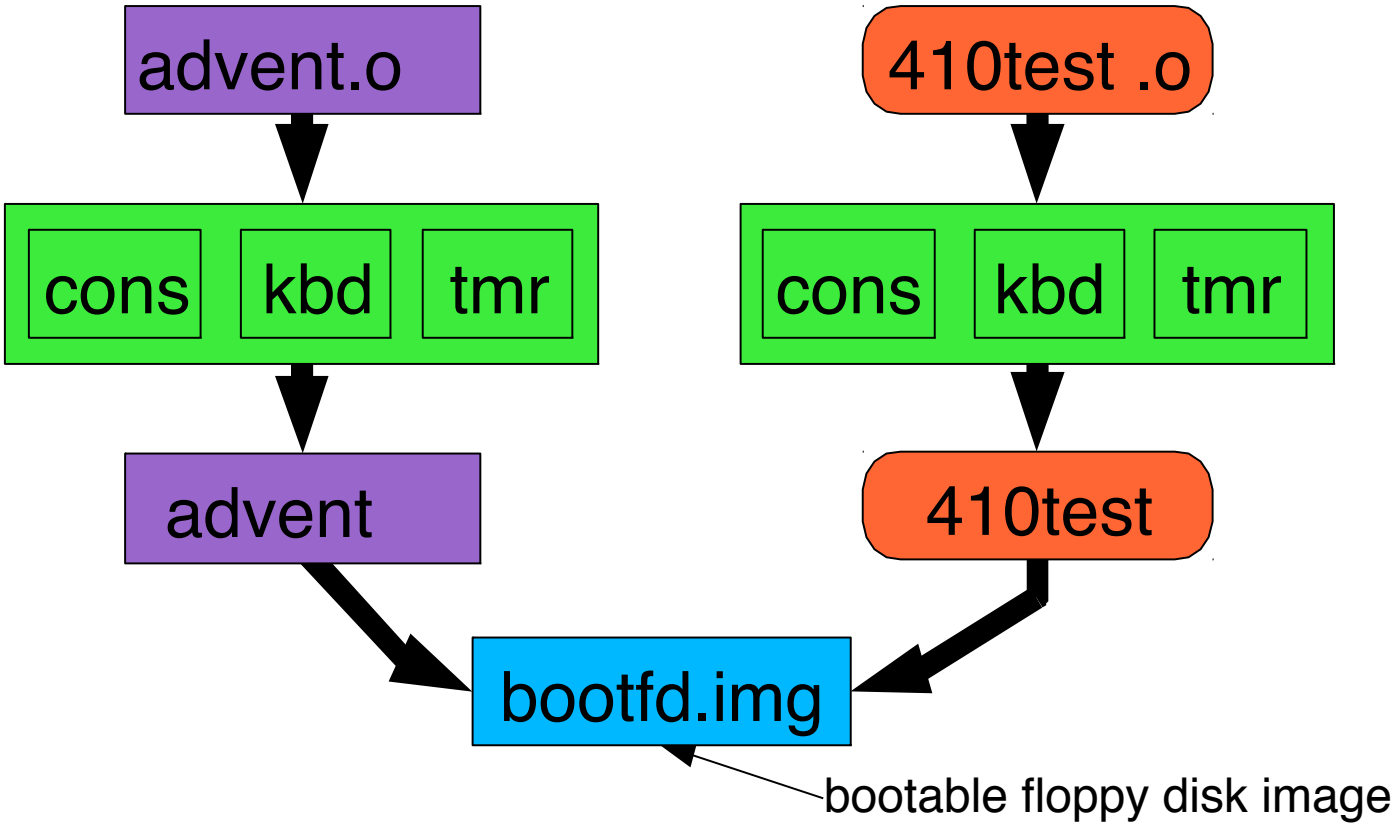
- You will build
  - A device-driver library
    - “console” (screen) driver
    - keyboard driver
    - timer driver
  - Test code to your taste
    - For historical reasons, this will be called “game.c”.
- We will provide
  - Underlying setup/utility code
  - A simple device-driver test program
  - A text-mode game!

Project 1 Pieces

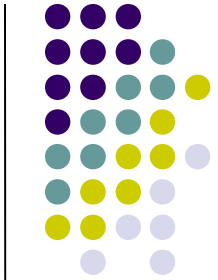
- The game we provide: “Adventure”



Project 1 Pieces

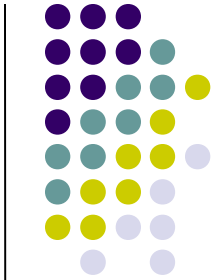


Summary



- Project 1 runs on ***bare hardware***
  - Not a machine-invisible language like ML or Java
  - Not a machine-portable language like C
  - Budget time for understanding this environment
- Project 1 runs on ***simulated*** bare hardware
  - You probably need more than printf() for debugging
  - Simics is not (exactly) gdb
  - Invest time to learn more than bare minimum

Summary



- Project 1 runs on bare ***PC*** hardware
  - As hardware goes, it's pretty irrational
  - ***Almost nothing*** works “how you would expect”
  - Those pesky bit-field diagrams do matter
  - Getting started is tough, so please don't delay.
- This isn't throwaway code
  - We will read it
  - You will use it for Project 3
  - So spend extra time to make it really great code!