CS 422/522 Design & Implementation of Operating Systems

Lecture 4: Memory Management & The Programming Interface

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This lecture

To support multiprogramming, we need "Protection"

- Kernel vs. user mode
- What is an address space?
- How to implement it?

Physical memory	**Abstraction: virtual memory**
No protection	Each program isolated from all others and from the OS
Limited size	Illusion of "infinite" memory
Sharing visible to programs	Transparent --- can't tell if memory is shared

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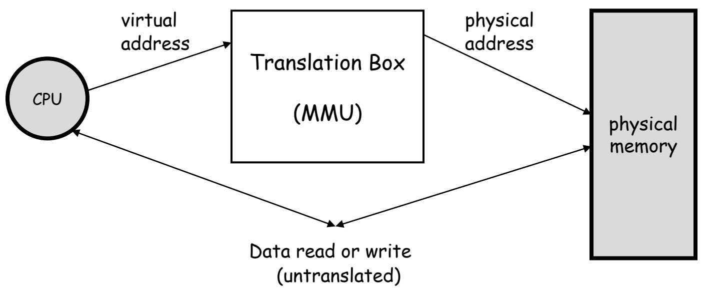
The big picture

- To support multiprogramming with protection, we need:
  - dual mode operations
  - translation between virtual address space and physical memory
- How to implement the translation?



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Address translation

- Goals
  - implicit translation on every memory reference
  - should be very fast
  - protected from user's faults
- Options
  - Base and Bounds
  - Segmentation
  - Paging
  - Multilevel translation
  - Paged page tables

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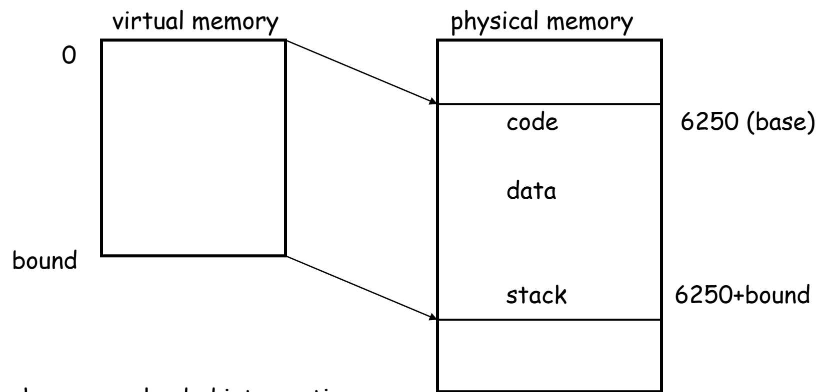
Base and Bounds



Each program loaded into contiguous regions of physical memory.
Hardware cost: 2 registers, adder, comparator.

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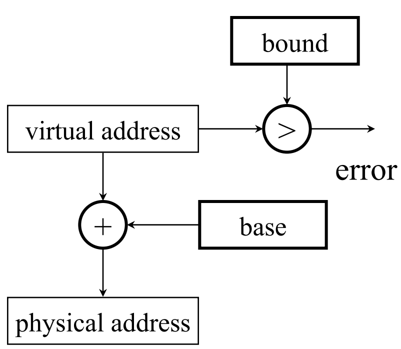
Base and Bounds (cont’ d)



- Built in Cray-1
- A program can only access physical memory in **[base, base+bound]**
- On a context switch: save/restore base, bound registers
- Pros: Simple
- Cons: fragmentation; hard to share (code but not data and stack); complex memory allocation

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Segmentation

- Motivation
  - separate the virtual address space into several segments so that we can share some of them if necessary
- A segment is a region of logically contiguous memory
- Main idea: generalize base and bounds by allowing a table of base&bound pairs

(assume 2 bit segment ID, 12 bit segment offset)

virtual segment #	physical segment start	segment size
code (00)	0x4000	0x700
data (01)	0	0x500
- (10)	0	0
stack (11)	0x2000	0x1000

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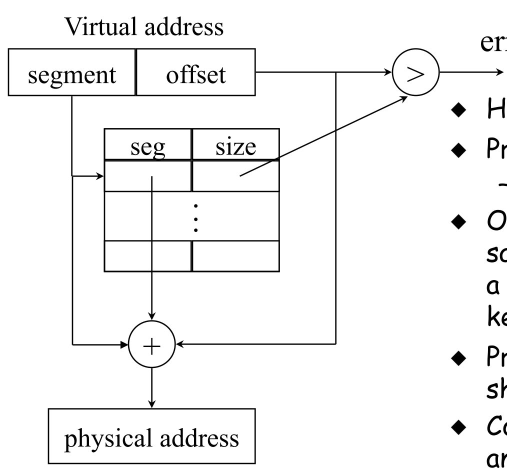
Segmentation (cont' d)



- Have a table of (seg, size)
- Protection: each entry has
  - (nil,read,write)
- On a context switch: save/restore the table or a pointer to the table in kernel memory
- Pros: efficient, easy to share
- Cons: complex management and fragmentation within a segment

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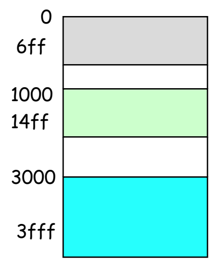
Segmentation example

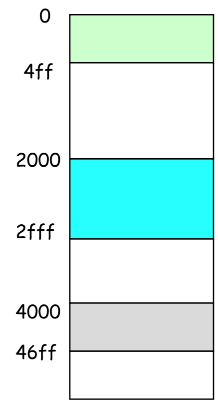
(assume 2 bit segment ID, 12 bit segment offset)

v-segment #		p-segment start	segment size
code	(00)	0x4000	0x700
data	(01)	0	0x500
-	(10)	0	0
stack	(11)	0x2000	0x1000

virtual memory



physical memory



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Segmentation example (cont’ d)

Virtual memory for `strlen(x)`

Main:	240	store 1108, r2
	244	store pc+8, r31
	248	jump 360
	24c	
	…	
strlen:	360	loadbyte (r2), r3
	…	
	420	jump (r31)
	…	
x:	1108	a b c \0
	…	

physical memory for `strlen(x)`

x:	108	a b c \0
	…	
Main:	4240	store 1108, r2
	4244	store pc+8, r31
	4248	jump 360
	424c	
	…	
strlen:	4360	loadbyte (r2), r3
	…	
	4420	jump (r31)
	…	

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Paging

- Motivations
  - both branch bounds and segmentation still require fancy memory management (e.g., first fit, best fit, re-shuffling to coalesce free fragments if no single free space is big enough for a new segment)
  - can we find something simple and easy
- Solution
  - allocate physical memory in terms of fixed size chunks of memory, or **pages**.
  - Simpler because it allows use of a bitmap

    00111110000001100 --- each bit represents one page of physical memory

    1 means allocated, 0 means unallocated

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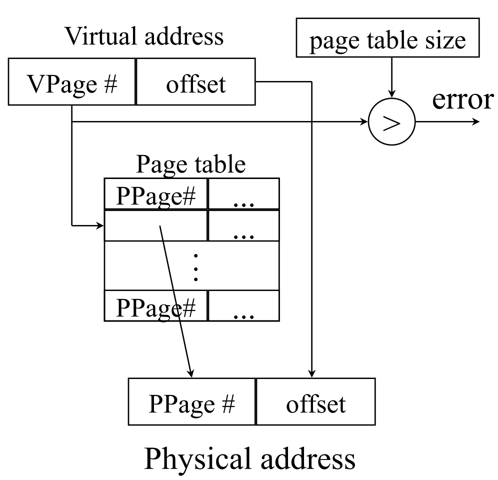
Paging (cont' d)



- Use a page table to translate
- Various bits in each entry
- Context switch: similar to the segmentation scheme
- What should be the page size?
- Pros: simple allocation, easy to share
- Cons: big page table and cannot deal with internal fragmentation easily

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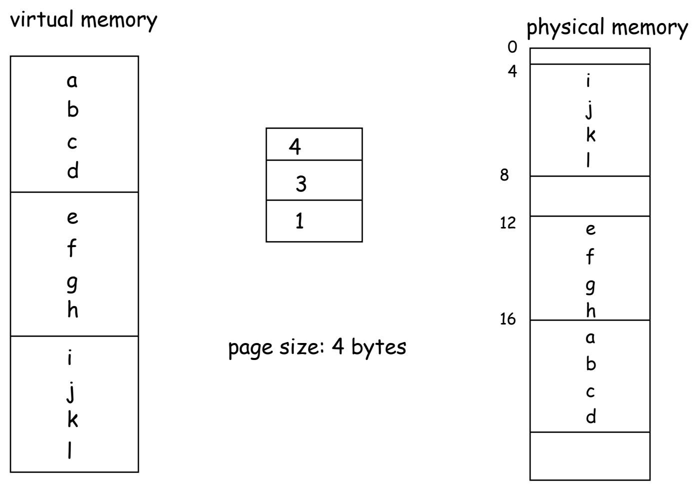
Paging example



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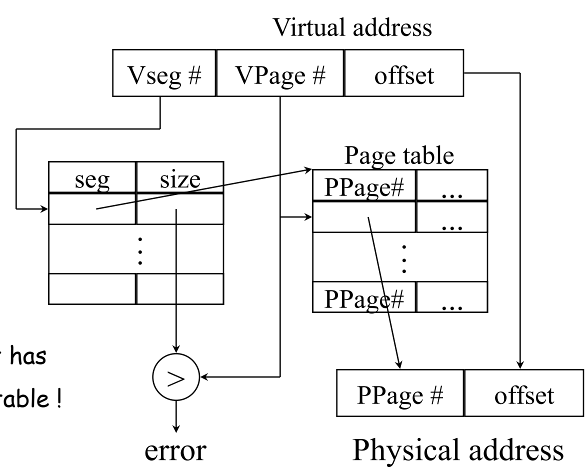
Segmentation with paging



Each segment has its own page table !

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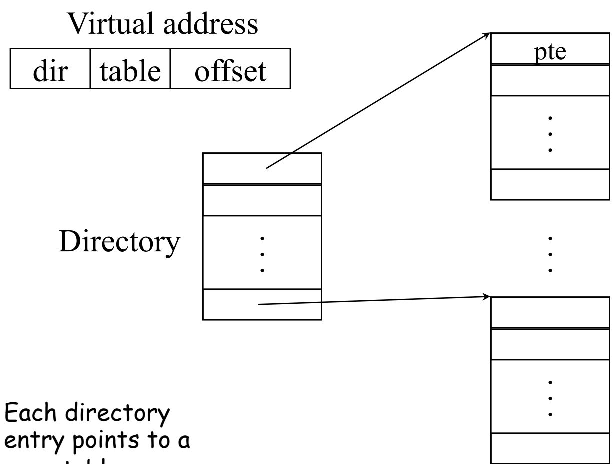
Two-level paging



Each directory entry points to a page table

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Two-level paging example

- A logical address (on 32-bit machine with 4K page size) is divided into:
  - a page number consisting of 20 bits.
  - a page offset consisting of 12 bits.
- Since the page table is paged, the page number is further divided into:
  - a 10-bit page number.
  - a 10-bit page offset.
- Thus, a logical address is as follows:

page number		page offset
p_i	p_2	d
10	10	12

where p_i is an index into the outer page table, and p_2 is the displacement within the page of the outer page table.

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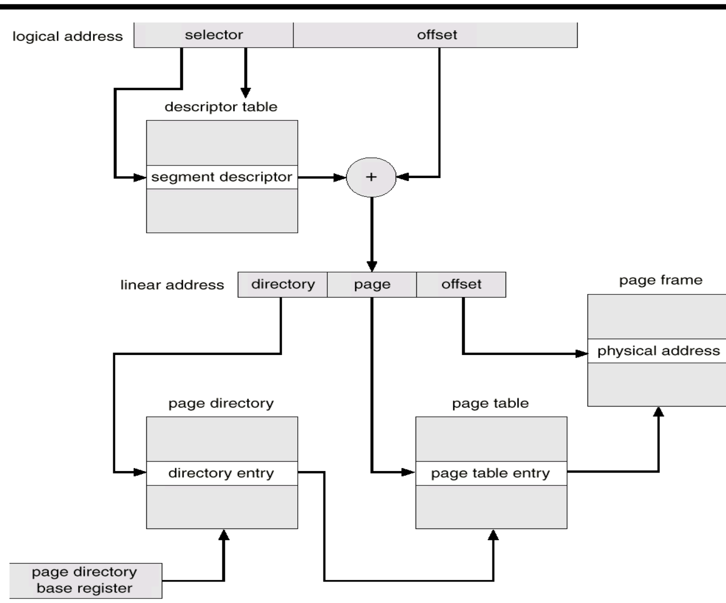
Segmentation with paging – Intel 386

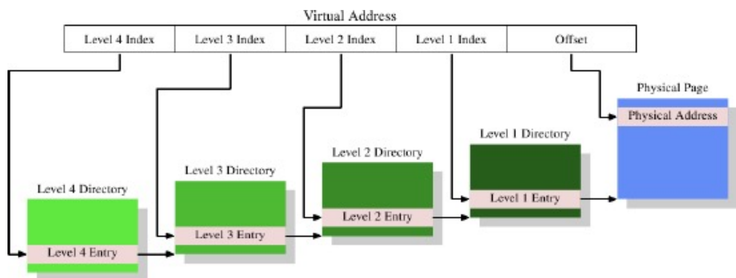
- As shown in the following diagram, the Intel 386 uses segmentation with paging for memory management with a two-level paging scheme.

Intel 30386 address translation



How many PTEs do we need ?

- Worst case for 32-bit address machine
  - # of processes × 2^{20} (if page size is 4096 bytes)
- What about 64-bit address machine?
  - # of processes × 2^{52}



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Summary: virtual memory mapping

- What?
  - separate the programmer's view of memory from the system's view
- How?
  - translate every memory operation using table (page table, segment table).
  - Speed: cache frequently used translations
- Result?
  - each user has a private address space
  - programs run independently of actual physical memory addresses used, and actual memory size
  - protection: check that they only access their own memory

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Summary (cont'd)

- Goal: multiprogramming with protection + illusion of "infinite" memory
- Today's lecture so far:
  - HW-based approach for protection: dual mode operation + address space
  - Address translation: virtual address -> physical address
- Future topics
  - how to make address translation faster? use cache (TLB)
  - demand paged virtual memory
- The rest of today's lecture:
  - The programming interface

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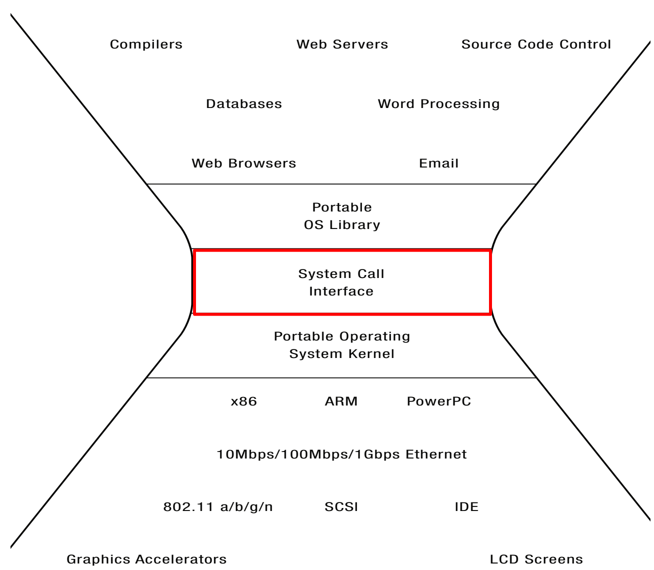
The programming interface



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Abstraction: process & file system

- **Problem**
  - Multiple CPU cores, many I/O devices and lots of interrupts
  - Users feel they have machine to themselves
- **Answer**
  - Decompose hard problems into simple ones
  - Deal with one at a time
  - **Process is such a unit (reflecting something dynamic)**
  - **File system is another high-level abstraction (for "data")**
- **Future**
  - How processes differ from threads? What is a process really?
  - Generalizing "processes" to "containers" & "virtual machines"

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Simplest process

- Sequential execution
  - No concurrency inside a process
  - Everything happens sequentially
  - Some coordination may be required
- Process state
  - Registers
  - Main memory
  - I/O devices
    - File system
    - Communication ports

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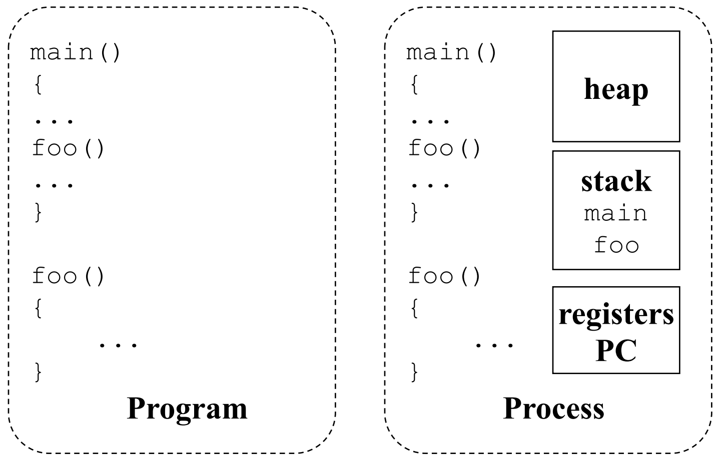
Program vs. process



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Program vs. process (cont'd)

- Process > program
  - Program is just part of process state
  - Example: many users can run the same program (but different processes)
- Process < program
  - A program can invoke more than one process
  - Example: cc starts up cpp, cc1, cc2, as, ld (each are programs themselves)

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Process control block (PCB)

- Process management info
  - State
    - Ready: ready to run
    - Running: currently running
    - Blocked: waiting for resources
  - Registers, EFLAGS, and other CPU state
  - Stack, code and data segment
  - Parents, etc
- Memory management info
  - Segments, page table, stats, etc
- I/O and file management
  - Communication ports, directories, file descriptors, etc.
- How OS takes care of processes
  - Resource allocation and process state transition

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Primitives of processes

- Creation and termination
  - Exec, Fork, Wait, Kill
- Signals
  - Action, Return, Handler
- Operations
  - Block, Yield
- Synchronization
  - We will talk about this later

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Make a process

- Creation
  - Load code and data into memory
  - Create an empty call stack
  - Initialize state to same as after a process switch
  - Make the process ready to run

- Clone
  - Stop current process and save state
  - Make copy of current code, data, stack and OS state
  - Make the process ready to run

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UNIX process management

- UNIX fork – system call to create a copy of the current process, and start it running
  - No arguments!

- UNIX exec – system call to change the program being run by the current process

- UNIX wait – system call to wait for a process to finish

- UNIX signal – system call to send a notification to another process

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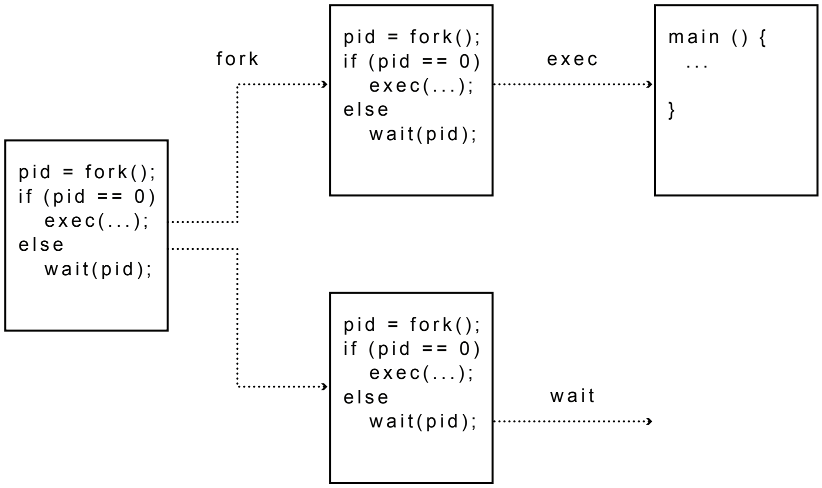
UNIX process management



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Question: What does this code print?

```
int child_pid = fork();

if (child_pid == 0) {           // I'm the child process
   printf("I am process #%d\n", getpid());
   return 0;
} else {                        // I'm the parent process
   printf("I am parent of process #%d\n", child_pid);
   return 0;
}
```

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Implementing UNIX fork & exec

- Steps to implement UNIX fork
  - Create and initialize the process control block (PCB) in the kernel
  - Create a new address space
  - Initialize the address space with a copy of the entire contents of the address space of the parent
  - Inherit the execution context of the parent (e.g., any open files)
  - Inform the scheduler that the new process is ready to run
- Steps to implement UNIX exec
  - Load the program into the current address space
  - Copy arguments into memory in the address space
  - Initialize the hardware context to start execution at ``start''

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Process context switch

- Save a context (everything that a process may damage)
  - All registers (general purpose and floating point)
  - All co-processor state
  - Save all memory to disk?
  - What about cache and TLB stuff?

Very machine dependent !

- Start a context
  - Does the reverse
- Challenges
  - OS code must save state without changing any state
  - How to run without touching any registers?
    * CISC machines have a special instruction to save and restore all registers on stack
    * RISC: reserve registers for kernel or have way to carefully save one and then continue

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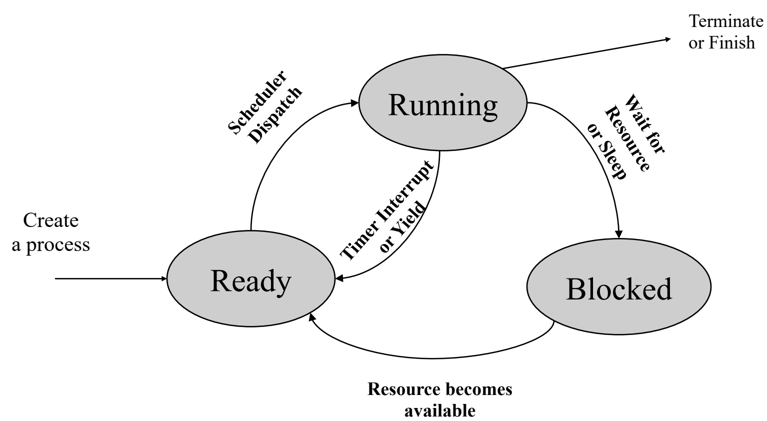
Process state transition



Running: executing now
Ready: waiting for CPU
Blocked: waiting for I/O or lock

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Which ready process to pick?

0 ready processes: run idle loop
1 ready process: easy!
> 1: what to do?

- FIFO?
  - put threads on back of list, pull them off from front
  - (nachos does this: schedule.cc)
- Pick random? (could result in starvation)
- Priority?
  - give some threads a better shot at the CPU

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Scheduling policies

- Scheduling issues
  - fairness: don't starve process
  - prioritize: more important first
  - deadlines: must do by time 'x' (car brakes)
  - optimization: some schedules >> faster than others
- No universal policy:
  - many variables, can't maximize them all
  - conflicting goals
    - **more important jobs vs starving others**
    - **I want my job to run first, you want yours.**
- Given some policy, how to get control ?

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How to get control?

- Traps: events generated by current process
  - system calls
  - errors (illegal instructions)
  - page faults
- Interrupts: events external to the process
  - I/O interrupt
  - timer interrupt (every 100 milliseconds or so)
- Process perspective:
  - explicit: process yields processor to another
  - implicit: causes an expensive blocking event, gets switched

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UNIX I/O --- a key innovation ("files")

- Uniformity
  - All operations on all files, devices use the same set of system calls: open, close, read, write
- Open before use
  - Open returns a handle (file descriptor) for use in later calls on the file
- Byte-oriented
- Kernel-buffered reads/writes
- Explicit close
  - To garbage collect the open file descriptor
- Pipes (for interprocess communication → a kernel buffer with two file descriptors, one for reading, one for writing)

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UNIX file system interface

- UNIX file open is a Swiss Army knife:
  - Open the file, return file descriptor
  - Options:
    * If file doesn't exist, return an error
    * If file doesn't exist, create file and open it
    * If file does exist, return an error
    * If file does exist, open file
    * If file exists but isn't empty, nix it then open
    * If file exists but isn't empty, return an error
    * …

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