CS162
Operating Systems and Systems Programming
Lecture 3

Concurrency: Processes, Threads, and Address Spaces

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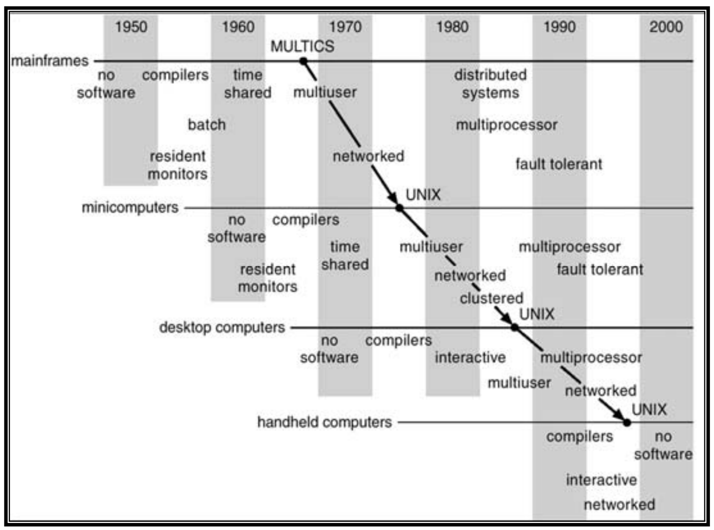
Review: History of OS

- Why Study?
  - To understand how user needs and hardware constraints influenced (and will influence) operating systems
- Several Distinct Phases:
  - Hardware Expensive, Humans Cheap
    - » Eniac, … Multics
  - Hardware Cheaper, Humans Expensive
    - » PCs, Workstations, Rise of GUIs
  - Hardware Really Cheap, Humans Really Expensive
    - » Ubiquitous devices, Widespread networking
- Rapid Change in Hardware Leads to changing OS
  - Batch ⇒ Multiprogramming ⇒ Timeshare ⇒ Graphical UI ⇒ Ubiquitous Devices ⇒ Cyberspace/Metaverse/??
  - Gradual Migration of Features into Smaller Machines
- Situation today is much like the late 60s
  - Small OS: 100K lines/Large: 10M lines (5M browser!)
  - 100-1000 people-years

Review: Migration of OS Concepts and Features

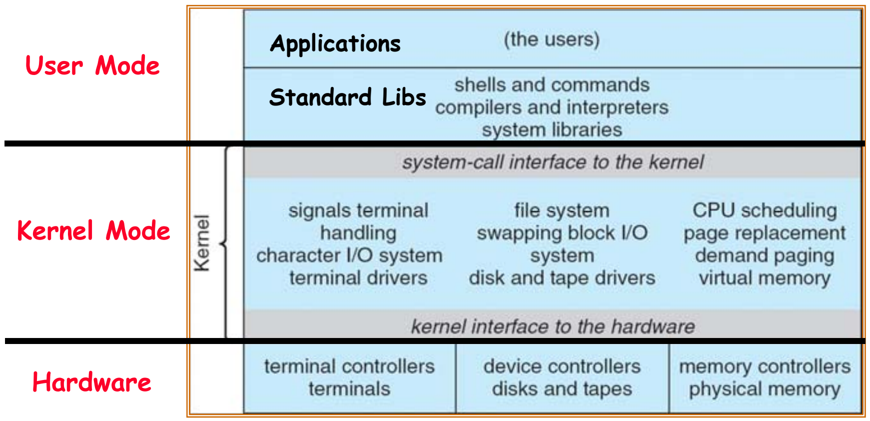


Goals for Today

- Finish discussion of OS structure
- How do we provide multiprogramming?
- What are Processes?
- How are they related to Threads and Address Spaces?

Note: Some slides and/or pictures in the following are adapted from slides ©2005 Silberschatz, Galvin, and Gagne. Many slides generated from my lecture notes by Kubiatowicz.

Review: UNIX System Structure



Microkernel Structure

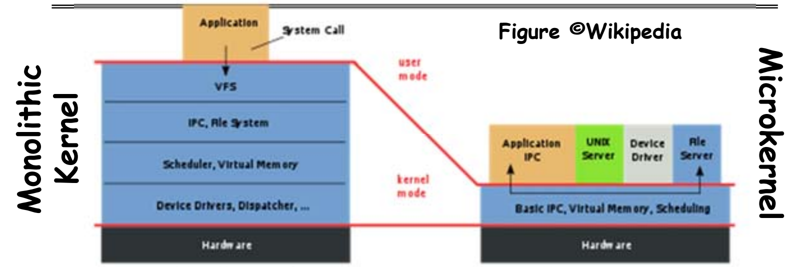
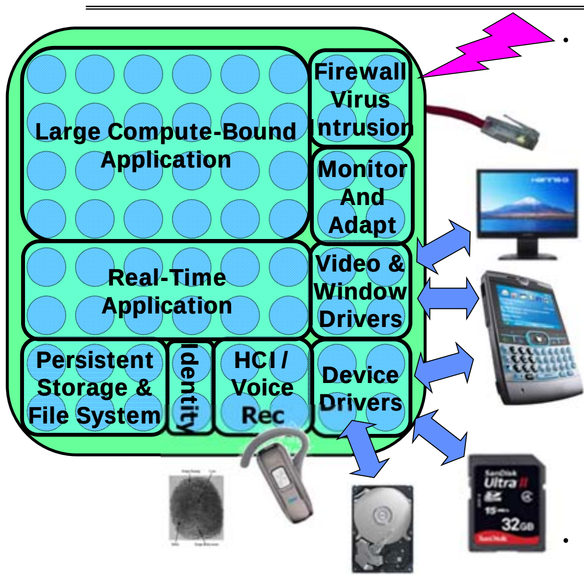


Figure ©Wikipedia

- Moves as much from the kernel into "*user*" space
  - Small core OS running at kernel level
  - OS Services built from many independent user-level processes
  - Communication between modules with message passing
- Benefits:
  - Easier to extend a microkernel
  - Easier to port OS to new architectures
  - More reliable (less code is running in kernel mode)
  - Fault Isolation (parts of kernel protected from other parts)
  - More secure
- Detriments:
  - Performance overhead severe for naïve implementation

Partition Based Structure for Multicore chips?



- Normal Components split into pieces
  - Device drivers (Security/Reliability)
  - Network Services (Performance)
    - » TCP/IP stack
    - » Firewall
    - » Virus Checking
    - » Intrusion Detection
  - Persistent Storage (Performance, Security, Reliability)
  - Monitoring services
    - » Performance counters
    - » Introspection
  - Identity/Environment services (Security)
    - » Biometric, GPS, Possession Tracking
- Applications Given Larger Partitions
  - Freedom to use resources arbitrarily

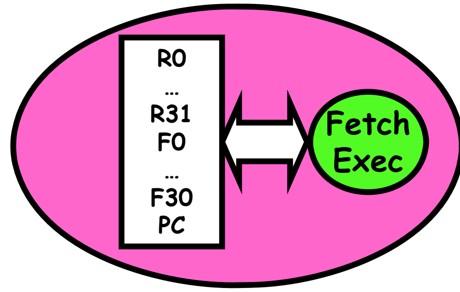
Concurrency

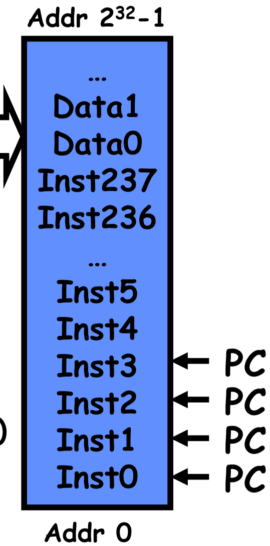
- "Thread" of execution
  - Independent Fetch/Decode/Execute loop
  - Operating in some Address space
- Uniprogramming: *one thread at a time*
  - MS/DOS, early Macintosh, Batch processing
  - Easier for operating system builder
  - Get rid concurrency by defining it away
  - Does this make sense for personal computers?
- Multiprogramming: *more than one thread at a time*
  - Multics, UNIX/Linux, OS/2, Windows NT/2000/XP, Mac OS X
  - Often called "multitasking", but multitasking has other meanings (talk about this later)
- ManyCore ⇒ Multiprogramming, right?

The Basic Problem of Concurrency

- The basic problem of concurrency involves resources:
  - Hardware: single CPU, single DRAM, single I/O devices
  - Multiprogramming API: users think they have exclusive access to shared resources
- OS Has to coordinate all activity
  - Multiple users, I/O interrupts, …
  - How can it keep all these things straight?
- Basic Idea: Use Virtual Machine abstraction
  - Decompose hard problem into simpler ones
  - Abstract the notion of an executing program
  - Then, worry about multiplexing these abstract machines
- Dijkstra did this for the "THE system"
  - Few thousand lines vs 1 million lines in OS 360 (1K bugs)

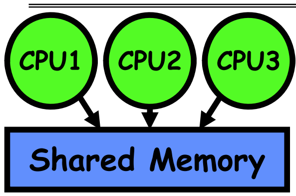
Recall (61C): What happens during execution?

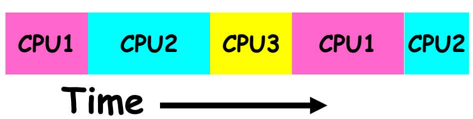




- Execution sequence:
  - Fetch Instruction at PC
  - Decode
  - Execute (possibly using registers)
  - Write results to registers/mem
  - PC = Next Instruction(PC)
  - Repeat

How can we give the illusion of multiple processors?





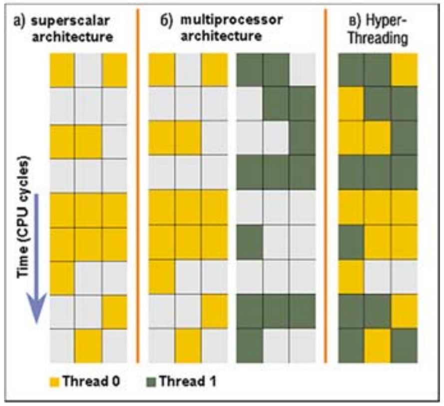
- Assume a single processor. How do we provide the illusion of multiple processors?
  - Multiplex in time!
- Each virtual "CPU" needs a structure to hold:
  - Program Counter (PC), Stack Pointer (SP)
  - Registers (Integer, Floating point, others…?)
- How switch from one CPU to the next?
  - Save PC, SP, and registers in current state block
  - Load PC, SP, and registers from new state block
- What triggers switch?
  - Timer, voluntary yield, I/O, other things

Properties of this simple multiprogramming technique

- All virtual CPUs share same non-CPU resources
  - I/O devices the same
  - Memory the same
- Consequence of sharing:
  - Each thread can access the data of every other thread (good for sharing, bad for protection)
  - Threads can share instructions (good for sharing, bad for protection)
  - Can threads overwrite OS functions?
- This (unprotected) model common in:
  - Embedded applications
  - Windows 3.1/Machintosh (switch only with yield)
  - Windows 95—ME? (switch with both yield and timer)

Modern Technique: SMT/Hyperthreading

- Hardware technique
  - Exploit natural properties of superscalar processors to provide illusion of multiple processors
  - Higher utilization of processor resources
- Can schedule each thread as if were separate CPU
  - However, not linear speedup!
  - If have multiprocessor, should schedule each processor first



- Original technique called "Simultaneous Multithreading"
  - See http://www.cs.washington.edu/research/smt/
  - Alpha, SPARC, Pentium 4 ("Hyperthreading"), Power 5

Administrivia

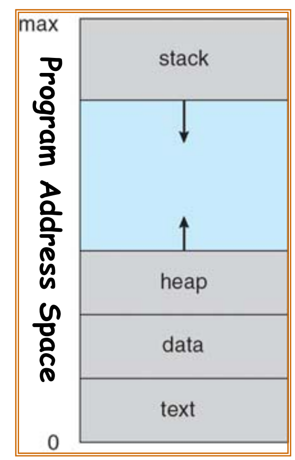
- Waitlist: Cleared of all non-majors and grad students
  - 2 students added to class this morning
  - Waitlist has 7 EECS juniors on it in case missing students have dropped
- Section signup successful!
  - Our sections seem to be pretty balanced
  - Missing 6-8 students. Look at the Group/Section Assignments link to see what section you have and if your are missing!
    - » If you are not in group, will assume you are dropping class
  - Have one three-person group in Section 3
    - » Should be no three-person groups!
    - » Does someone need a group and can make Section 3?
- Reader: ready in a couple of days
  - Probably by Friday: I'll put an announcement on Website
- Tuesday: Start Project 1
  - Go to Nachos page and start reading up
  - Note that all the Nachos code will be printed in your reader (Available soon…)

How to protect threads from one another?

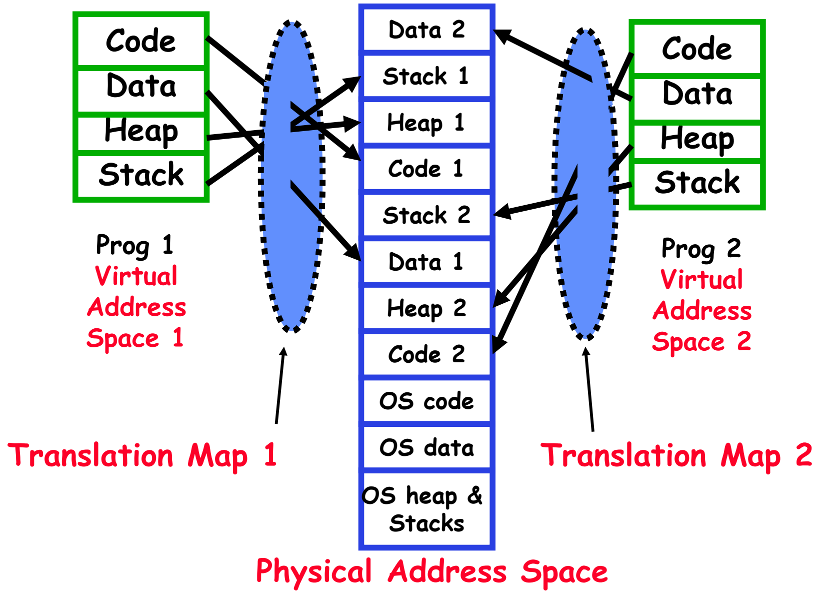
- Need three important things:
  1. Protection of memory
     - » Every task does not have access to all memory
  2. Protection of I/O devices
     - » Every task does not have access to every device
  3. Protection of Access to Processor: Preemptive switching from task to task
     - » Use of timer
     - » Must not be possible to disable timer from usercode

Recall: Program's Address Space

- Address space ⇒ the set of accessible addresses + state associated with them:
  - For a 32-bit processor there are 2^{32} = 4 billion addresses
- What happens when you read or write to an address?
  - Perhaps Nothing
  - Perhaps acts like regular memory
  - Perhaps ignores writes
  - Perhaps causes I/O operation
    - » (Memory-mapped I/O)
  - Perhaps causes exception (fault)



Providing Illusion of Separate Address Space: Load new Translation Map on Switch

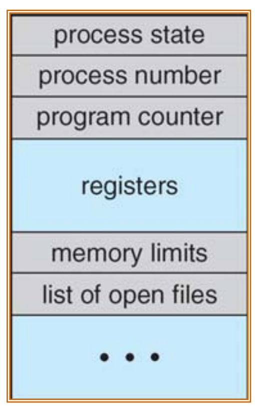


Traditional UNIX Process

- Process: *Operating system abstraction to represent what is needed to run a single program*
  - Often called a "HeavyWeight Process"
  - Formally: a single, sequential stream of execution in its *own* address space
- Two parts:
  - Sequential Program Execution Stream
    - » Code executed as a *single, sequential* stream of execution
    - » Includes State of CPU registers
  - Protected Resources:
    - » Main Memory State (contents of Address Space)
    - » I/O state (i.e. file descriptors)
- Important: There is no concurrency in a heavyweight process

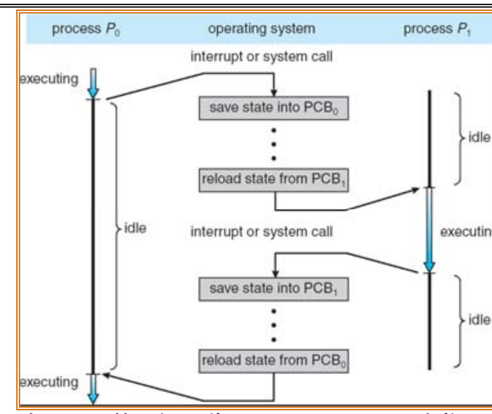
How do we multiplex processes?

- The current state of process held in a process control block (PCB):
  - This is a "snapshot" of the execution and protection environment
  - Only one PCB active at a time
- Give out CPU time to different processes (Scheduling):
  - Only one process "running" at a time
  - Give more time to important processes
- Give pieces of resources to different processes (Protection):
  - Controlled access to non-CPU resources
  - Sample mechanisms:
    - » Memory Mapping: Give each process their own address space
    - » Kernel/User duality: Arbitrary multiplexing of I/O through system calls



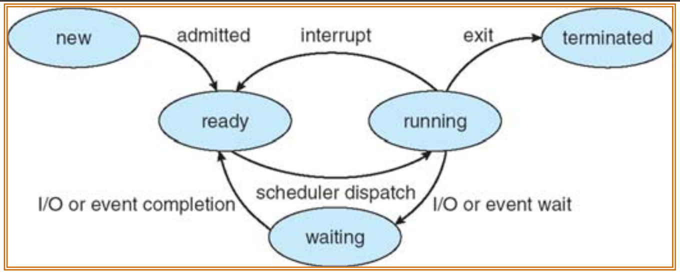
Process Control Block

CPU Switch From Process to Process



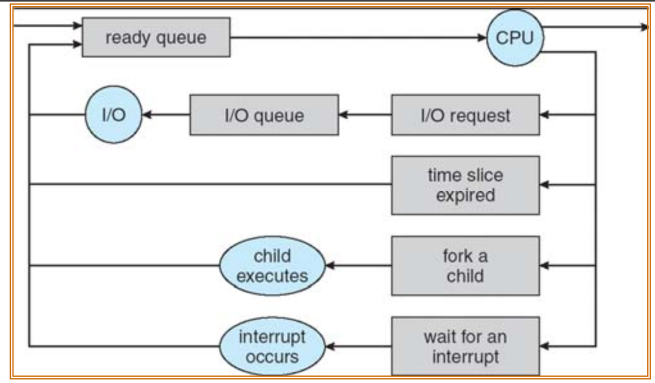
- This is also called a "context switch"
- Code executed in kernel above is overhead
  - Overhead sets minimum practical switching time
  - Less overhead with SMT/hyperthreading, but… contention for resources instead

Diagram of Process State



- As a process executes, it changes *state*
  - new: The process is being created
  - ready: The process is waiting to run
  - running: Instructions are being executed
  - waiting: Process waiting for some event to occur
  - terminated: The process has finished execution

Process Scheduling

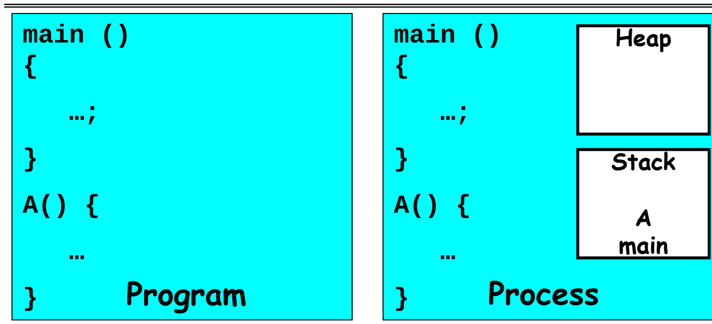


- PCBs move from queue to queue as they change state
  - Decisions about which order to remove from queues are Scheduling decisions
  - Many algorithms possible (few weeks from now)

What does it take to create a process?

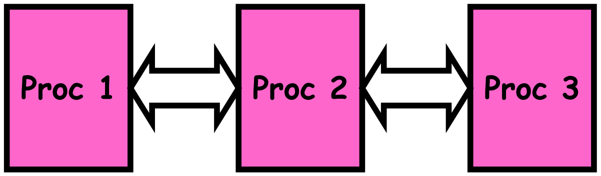
- Must construct new PCB
  - Inexpensive
- Must set up new page tables for address space
  - More expensive
- Copy data from parent process? (Unix `fork()`)
  - Semantics of Unix `fork()` are that the child process gets a complete copy of the parent memory and I/O state
  - Originally *very* expensive
  - Much less expensive with "copy on write"
- Copy I/O state (file handles, etc)
  - Medium expense

Process =? Program



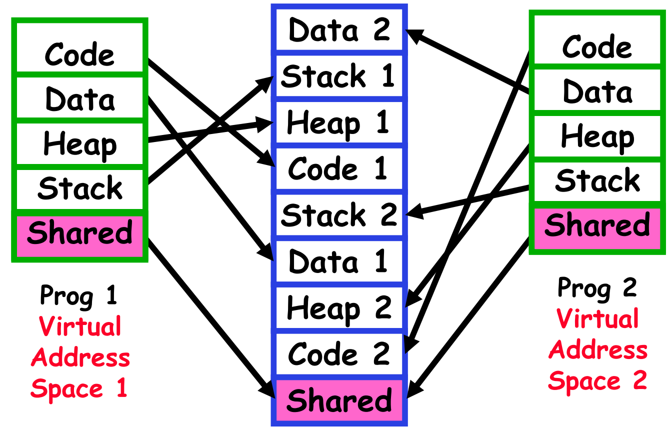
- More to a process than just a program:
  - Program is just part of the process state
  - I run emacs on lectures.txt, you run it on homework.java – Same program, different processes
- Less to a process than a program:
  - A program can invoke more than one process
  - cc starts up cpp, cc1, cc2, as, and ld

Multiple Processes Collaborate on a Task



- High Creation/memory Overhead
- (Relatively) High Context-Switch Overhead
- Need Communication mechanism:
  - Separate Address Spaces Isolates Processes
  - Shared-Memory Mapping
    - » Accomplished by mapping addresses to common DRAM
    - » Read and Write through memory
  - Message Passing
    - » `send()` and `receive()` messages
    - » Works across network

Shared Memory Communication



- Communication occurs by "simply" reading/writing to shared address page
  - Really low overhead communication
  - Introduces complex synchronization problems

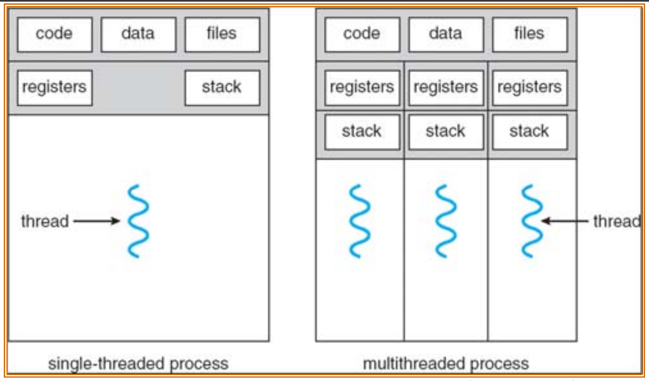
Inter-process Communication (IPC)

- Mechanism for processes to communicate and to synchronize their actions
- Message system – processes communicate with each other without resorting to shared variables
- IPC facility provides two operations:
  - `send(`*message*`)` – message size fixed or variable
  - `receive(`*message*`)`
- If *P* and *Q* wish to communicate, they need to:
  - establish a *communication link* between them
  - exchange messages via send/receive
- Implementation of communication link
  - physical (e.g., shared memory, hardware bus, systcall/trap)
  - logical (e.g., logical properties)

Modern "Lightweight" Process with Threads

- Thread: *a sequential execution stream within process* (Sometimes called a "Lightweight process")
  - Process still contains a single Address Space
  - No protection between threads
- Multithreading: *a single program made up of a number of different concurrent activities*
  - Sometimes called multitasking, as in Ada…
- Why separate the concept of a thread from that of a process?
  - Discuss the "thread" part of a process (concurrency)
  - Separate from the "address space" (Protection)
  - Heavyweight Process ≡ Process with one thread

Single and Multithreaded Processes



- Threads encapsulate concurrency: "Active" component
- Address spaces encapsulate protection: "Passive" part
  - Keeps buggy program from trashing the system
- Why have multiple threads per address space?

Examples of multithreaded programs

- Embedded systems
  - Elevators, Planes, Medical systems, Wristwatches
  - Single Program, concurrent operations
- Most modern OS kernels
  - Internally concurrent because have to deal with concurrent requests by multiple users
  - But no protection needed within kernel
- Database Servers
  - Access to shared data by many concurrent users
  - Also background utility processing must be done

Examples of multithreaded programs (con't)

- Network Servers
  - Concurrent requests from network
  - Again, single program, multiple concurrent operations
  - File server, Web server, and airline reservation systems
- Parallel Programming (More than one physical CPU)
  - Split program into multiple threads for parallelism
  - This is called Multiprocessing

- Some multiprocessors are actually uniprogrammed:
  - Multiple threads in one address space but one program at a time

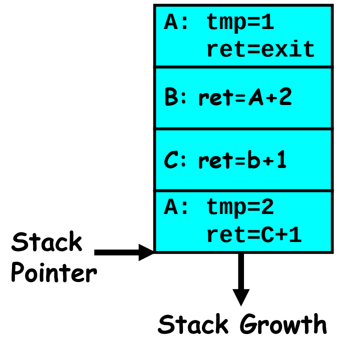
Thread State

- State shared by all threads in process/addr space
  - Contents of memory (global variables, heap)
  - I/O state (file system, network connections, etc)
- State "private" to each thread
  - Kept in TCB ≡ Thread Control Block
  - CPU registers (including, program counter)
  - Execution stack – what is this?

- Execution Stack
  - Parameters, Temporary variables
  - return PCs are kept while called procedures are executing

Execution Stack Example

```
A(int tmp) {
  if (tmp<2)
    B();
  printf(tmp);
}
B() {
  C();
}
C() {
  A(2);
}
A(1);
```



- Stack holds temporary results
- Permits recursive execution
- Crucial to modern languages

Classification

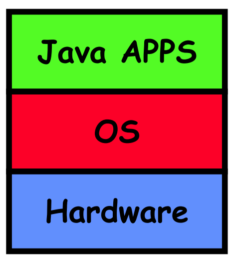
# threads Per AS: / # of addr spaces:	One	Many
One	MS/DOS, early Macintosh	Traditional UNIX
Many	Embedded systems (Geoworks, VxWorks, JavaOS,etc) JavaOS, Pilot(PC)	Mach, OS/2, Linux Windows 9x??? Win NT to XP, Solaris, HP-UX, OS X

- Real operating systems have either
  - One or many address spaces
  - One or many threads per address space
- Did Windows 95/98/ME have real memory protection?
  - No: Users could overwrite process tables/System DLLs

Example: Implementation Java OS

- Many threads, one Address Space
- Why another OS?
  - Recommended Minimum memory sizes:
    - » UNIX + X Windows: 32MB
    - » Windows 98: 16-32MB
    - » Windows NT: 32-64MB
    - » Windows 2000/XP: 64-128MB
  - What if we want a cheap network point-of-sale computer?
    - » Say need 1000 terminals
    - » Want < 8MB
- What language to write this OS in?
  - C/C++/ASM? Not terribly high-level. Hard to debug.
  - Java/Lisp? Not quite sufficient – need direct access to HW/memory management

Java OS Structure



Summary

- Processes have two parts
  - Threads (Concurrency)
  - Address Spaces (Protection)
- Concurrency accomplished by multiplexing CPU Time:
  - Unloading current thread (PC, registers)
  - Loading new thread (PC, registers)
  - Such context switching may be voluntary (`yield()`, I/O operations) or involuntary (timer, other interrupts)
- Protection accomplished restricting access:
  - Memory mapping isolates processes from each other
  - Dual-mode for isolating I/O, other resources
- Book talks about processes
  - When this concerns concurrency, really talking about thread portion of a process
  - When this concerns protection, talking about address space portion of a process