CSE 560
Computer Systems Architecture

Virtual Memory

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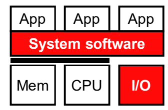
This Unit: Virtual Memory



- The operating system (OS)
  - A super-application
  - Hardware support for an OS
- Virtual memory
  - Page tables and address translation
  - TLBs and memory hierarchy issues

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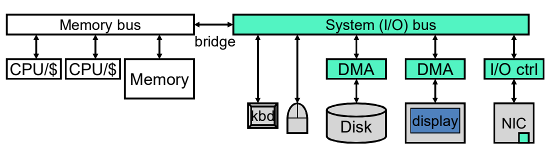
A Computer System: Hardware

CPUs and memories
- Connected by memory bus

I/O peripherals: storage, input, display, network, …
(NIC = Network Interface Controller)
- With separate or built-in DMA (direct memory access)
- Connected by **system bus** (which is connected to memory bus)



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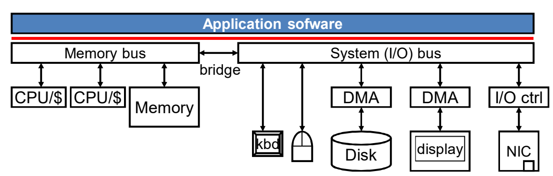
A Computer System: + App Software

- **Application software**: computer must do something



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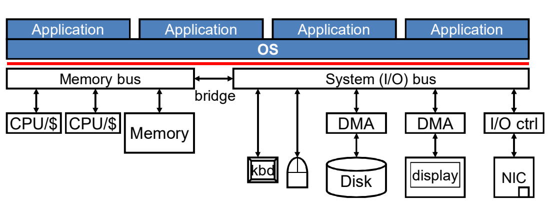
A Computer System: + OS

Operating System (OS): virtualizes hardware for apps
- **Abstraction**: provides **services** (*e.g.*, threads, files, *etc.*)
  + Simplifies app programming model, raw hardware is nasty
- **Isolation**: gives each app illusion of private CPU, memory, I/O
  + Simplifies app programming model
  + Increases hardware resource utilization



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Operating System (OS) and User Apps

- Sane system development requires a split

- **Operating System (OS)**: a super-privileged process
  - Manages hw resource allocation/revocation for all processes
  - Has direct access to resource allocation features
  - **Aware of:** many nasty hardware details, other processes
  - Talks directly to input/output devices (device driver software)

- **User-level apps**: ignorance is bliss
  - **Unaware of:** most nasty hardware details, other apps, OS
  - Explicitly denied access to resource allocation features

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System Calls

System Call: a user-level app "function call" to OS

- Leave description of what you want done in registers
- SYSCALL instruction (also called TRAP or INT)
  - User-level apps not allowed to invoke arbitrary OS code
  - Restricted set of legal OS addresses to jump to (**trap vector**)

1. Processor jumps to OS via trap vector (begin privileged mode)
2. OS performs operation
3. OS does a "return from system call" (end privileged mode)

Interrupts

Exceptions: synchronous, generated by running app
- *E.g.*, illegal instruction, divide by zero, *etc.*

Interrupts: asynchronous events generated externally
- *E.g.*, timer, I/O request/reply, *etc.*

Timer: programmable on-chip interrupt
- Initialize with some number of micro-seconds
- Timer counts down and interrupts when reaches 0

"Interrupt" handling: same mechanism for both
- "Interrupts" are on-chip signals/bits
  - Either internal (*e.g.*, timer, exceptions) or from I/O devices
- Processor continuously monitors interrupt status, when true…
- HW jumps to some preset address in OS code (interrupt vector)
- Like an asynchronous, non-programmatic SYSCALL

Virtualizing Processors

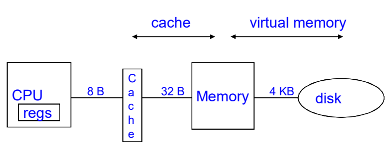
How do multiple apps (and OS) share the processors?
Goal: applications think there are an infinite # of processors

Solution: time-share the resource
- Trigger a **context switch** at a regular interval (~1ms)
  - **Pre-emptive**: app doesn't yield CPU, OS forcibly takes it
    - + Stops greedy apps from starving others
- **Architected state**: PC, registers
  - Save and restore them on context switches
  - Memory state?
- **Non-architected state**: caches, predictor tables, *etc.*
  - Ignore or flush
- Operating System responsible for handling context switching
  - Hardware support is just a timer interrupt

Motivations for Virtual Memory

- **Use Physical DRAM as a Cache for the Disk**
  - Address space of a process can exceed physical memory size
  - Sum of address spaces of multiple processes can exceed physical memory
- **Simplify Memory Management**
  - Multiple processes resident in main memory
    - Each process with its own address space
  - Only "active" code and data is actually in memory
    - Allocate more memory to process as needed
- **Provide Protection**
  - One process can't interfere with another
    - because they operate in different address spaces
  - User process cannot access privileged information
    - different sections of address spaces have different permissions

Levels in Memory Hierarchy



	Register	Cache	Memory	Disk Memory
size:	32 B	32 KB-4MB	1024 MB	100 GB
speed:	1 ns	2 ns	30 ns	8 ms
$/Mbyte:		$125/MB	$0.20/MB	$0.001/MB
line size:	8 B	32 B	4 KB	

larger, slower, cheaper →

Virtualizing Main Memory

How do multiple apps (and the OS) share main memory?
Goal: each application thinks it has private memory

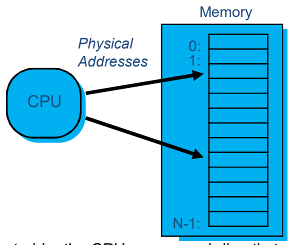
App's insn/data footprint > main memory ?
- **Requires main memory to act like a cache**
  - With disk as next level in memory hierarchy (slow)
  - Write-back, write-allocate, large blocks or "pages"

Solution:
- Part #1: treat memory as a "cache"
- Part #2: add a level of indirection (address translation)

Parameter	I$/D$	L2	Main Memory
t_{hit}	2ns	10ns	**30ns**
t_{miss}	**10ns**	**30ns**	**10ms (10M ns)**
Capacity	8–64KB	128KB–2MB	**64MB–64GB**
Block size	16–32B	32–256B	**4+KB**
Assoc./Repl.	1–4, NMRU	4–16, NMRU	**Full, "working set"**

A System with Physical Memory Only

Examples:
- most Cray machines, early PCs, many embedded systems, etc.



Addresses generated by the CPU correspond directly to bytes in physical memory

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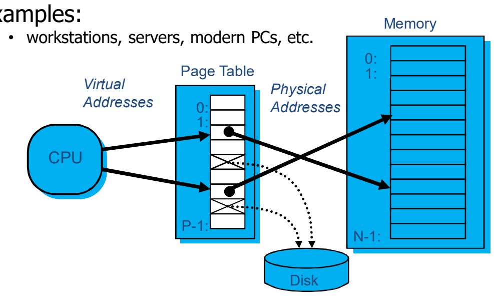
A System with Virtual Memory

Examples:
- workstations, servers, modern PCs, etc.



Address Translation: Hardware converts virtual addresses to physical addresses via OS-managed lookup table (page table)

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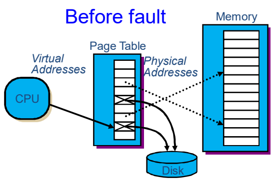
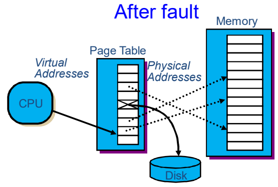
Page Faults (like "Cache Misses")

- What if an object is on disk rather than in memory?
  - Page table entry indicates virtual address not in memory
  - OS exception handler invoked to move data from disk into memory
    - current process suspends, others can resume
    - OS has full control over placement, etc.

Before fault



After fault



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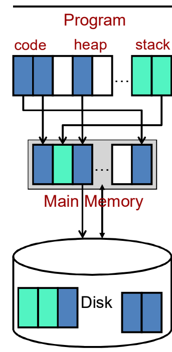
Virtual Memory (VM)



- Programs use **virtual addresses (VA)**
  - $0\ldots2^N-1$
  - VA size also referred to as machine size
  - *E.g.*, 32-bit (embedded) or 64-bit (server)
- Memory uses **physical addresses (PA)**
  - $0\ldots2^M-1$ (typically $M<N$, especially if $N=64$)
  - 2^M is most physical memory machine supports
- VA→PA at **page** granularity (VP→PP)
  - By "system" (OS + HW)
  - Mapping need not preserve contiguity
  - VP need not be mapped to any PP
  - Unmapped VPs live on disk (swap)

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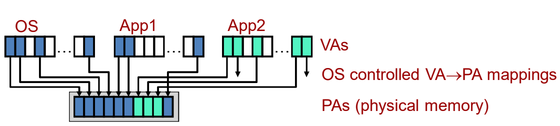
Virtual Memory (VM)

Virtual Memory (VM):
- Level of indirection
- Application generated addresses are **virtual addresses (VAs)**
  - Each process ***thinks*** it has its own 2^N bytes of address space
- Memory accessed using **physical addresses (PAs)**
- VAs translated to PAs at some coarse granularity
- OS controls VA to PA mapping for itself and all other processes
- Logically: translation performed before every insn fetch, load, store
- Physically: hardware acceleration removes translation overhead



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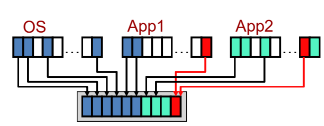
Uses of Virtual Memory

- **Isolation** and **Multi-programming (Memory Management)**
  - Each app thinks it has 2^N B of memory that starts @ 0
  - Apps can't read/write each other's memory
    - Can't even address the other program's memory!
- **Protection**
  - Each page has read/write/execute permission set by OS
  - Enforced by hardware
- **Inter-process communication**
  - Map same physical pages into multiple virtual address spaces
  - Or share files via the UNIX `mmap()` call



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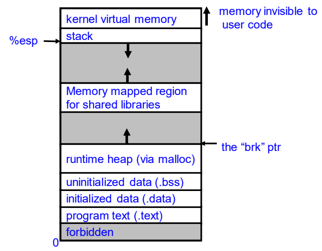
Memory Management

- Multiple processes can reside in physical memory.
- How do we resolve address conflicts?
  - what if two processes access something at the same address?

Linux/x86 process memory image



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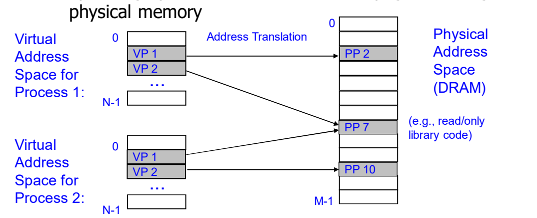
Solution: Separate Virt. Addr. Spaces

- Virtual and physical address spaces divided into equal-sized blocks
  - blocks are called "pages" (both virtual and physical)
- Each process has its own virtual address space
  - operating system controls how virtual pages as assigned to physical memory



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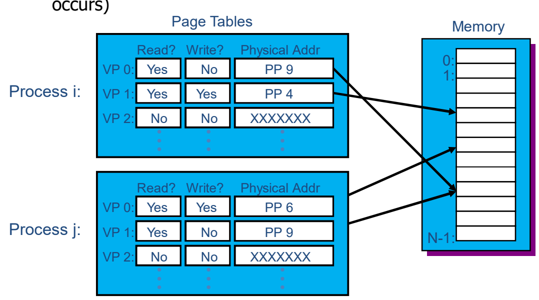
Protection

- Page table entry contains access rights information
  - hardware enforces this protection (trap into OS if violation occurs)



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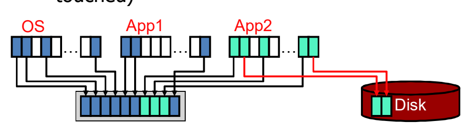
Virtual Memory: The Basics

- Programs use **virtual addresses (VA)**
  - VA size (N) aka machine size (e.g., Core 2 Duo: 48-bit)
- Memory uses **physical addresses (PA)**
  - PA size (M) typically M<N, especially if N=64
  - 2^M is most physical memory machine supports
- VA→PA at **page** granularity (VP→PP)
  - Mapping need not preserve contiguity
  - VP need not be mapped to any PP
  - Unmapped VPs live on disk (swap) or nowhere (if not yet touched)



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