Virtual Memory I

CSE 351 Winter 2018

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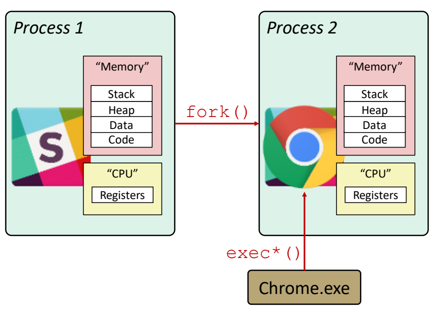
Administrative

- Homework 4 due tonight
- Lab 4 due next Wednesday (2/28)

Creating New Processes & Programs



`exit`: Ending a process

- `void exit(int status)`
  - Exits a process
    - Status code: 0 is used for a normal exit, nonzero for abnormal exit

Zombies

- When a process terminates, it still consumes system resources
  - Various tables maintained by OS
  - Called a "zombie" (a living corpse, half alive and half dead)
- *Reaping* is performed by parent on terminated child
  - Parent is given exit status information and kernel then deletes zombie child process
- What if parent doesn't reap?
  - If any parent terminates without reaping a child, then the orphaned child will be reaped by `init` process (pid == 1)
    - **Note:** on more recent Linux systems, `init` has been renamed `systemd`
  - In long-running processes (e.g. shells, servers) we need *explicit* reaping

`wait`: Synchronizing with Children

- `int wait(int *child_status)`
  - Suspends current process (*i.e.* the parent) until one of its children terminates
  - Return value is the PID of the child process that terminated
    - *On successful return, the child process is reaped*
  - If `child_status != NULL`, then the `*child_status` value indicates why the child process terminated
    - Special macros for interpreting this status – see **`man wait(2)`**
- **Note:** If parent process has multiple children, `wait` will return when *any* of the children terminates
  - `waitpid` can be used to wait on a specific child process

Process Management Summary

- `fork` makes two copies of the same process (parent & child)
  - Returns different values to the two processes
- `exec*` replaces current process from file (new program)
  - Two-process program:
    - First `fork()`
    - **if** (pid == 0) { /* *child code* */ } **else** { /* *parent code* */ }
  - Two different programs:
    - First `fork()`
    - **if** (pid == 0) { execv(…) } **else** { /* *parent code* */ }
- `wait` or `waitpid` used to synchronize parent/child execution and to reap child process

Summary

- Processes
  - At any given time, system has multiple active processes
  - On a one-CPU system, only one can execute at a time, but each process appears to have total control of the processor
  - OS periodically "context switches" between active processes
    - Implemented using *exceptional control flow*
- Process management
  - `fork`: one call, two returns
  - `execve`: one call, usually no return
  - `wait` or `waitpid`: synchronization
  - `exit`: one call, no return

Roadmap

C:

```
car *c = malloc(sizeof(car));
c->miles = 100;
c->gals = 17;
float mpg = get_mpg(c);
free(c);
```

Java:

```
Car c = new Car();
c.setMiles(100);
c.setGals(17);
float mpg =
    c.getMPG();
```

Memory & data
Integers & floats
x86 assembly
Procedures & stacks
Executables
Arrays & structs
Memory & caches
Processes
Virtual memory
Memory allocation
Java vs. C

Assembly language:

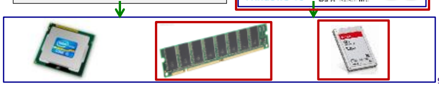
```
get_mpg:
    pushq   %rbp
    movq    %rsp, %rbp
    ...
    popq    %rbp
    ret
```

OS:

Machine code:

```
0111010000011000
100011010000010000000010
1000100111000010
110000011111101000011111
```

Computer system:



Virtual Memory (VM*)

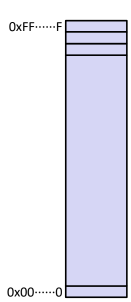
- **Overview and motivation**
- **VM as a tool for caching**
- Address translation
- VM as a tool for memory management
- VM as a tool for memory protection

Warning: Virtual memory is pretty complex, but crucial for understanding how processes work and for debugging performance

**Not to be confused with "Virtual Machine" which is a whole other thing.*

Memory as we know it so far… is *virtual!*

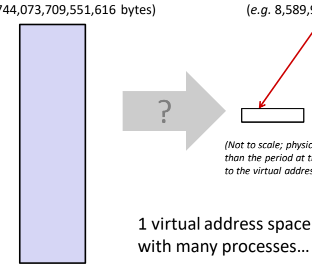
- Programs refer to virtual memory addresses
  - `movq (%rdi),%rax`
  - Conceptually memory is just a very large array of bytes
  - System provides private address space to each process
- Allocation: Compiler and run-time system
  - Where different program objects should be stored
  - All allocation within single virtual address space
- But…
  - We *probably* don't have 2^w bytes of physical memory
  - We *certainly* don't have 2^w bytes of physical memory ***for every process***
  - Processes should not interfere with one another
    - Except in certain cases where they want to share code or data



Problem 1: How Does Everything Fit?

64-bit virtual addresses can address several exabytes (18,446,744,073,709,551,616 bytes)

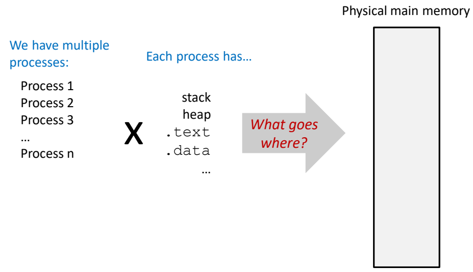
Physical main memory offers a few gigabytes (*e.g.* 8,589,934,592 bytes)



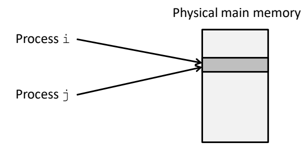
(Not to scale; physical memory would be smaller than the period at the end of this sentence compared to the virtual address space.)

1 virtual address space per process, with many processes…

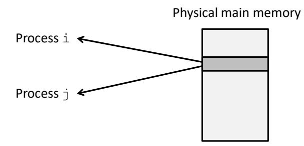
Problem 2: Memory Management



Problem 3: How To Protect



Problem 4: How To Share?

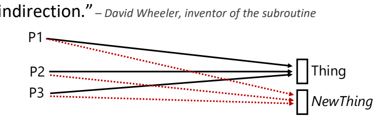


How can we solve these problems?

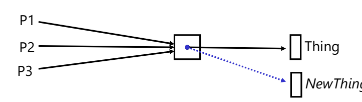
1) Fitting a huge address space into a tiny physical memory
2) Managing the address spaces of multiple processes
3) Protecting processes from stepping on each other's memory
4) Allowing processes to share common parts of memory

Indirection

- "Any problem in computer science can be solved by adding another level of indirection." *– David Wheeler, inventor of the subroutine*
- Without Indirection



- With Indirection

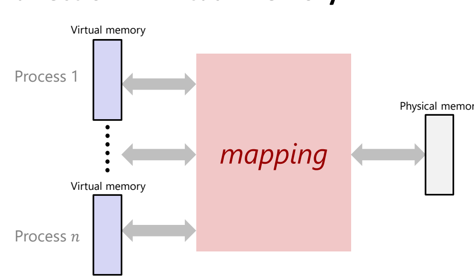


What if I want to move Thing?

Indirection

- *Indirection*: The ability to reference something using a name, reference, or container instead of the value itself. A flexible mapping between a name and a thing allows changing the thing without notifying holders of the name.
  - Adds some work (now have to look up 2 things instead of 1)
  - But don't have to track all uses of name/address (single source!)
- Examples:
  - **Phone system:** cell phone number portability
  - **Domain Name Service (DNS):** translation from name to IP address
  - **Call centers:** route calls to available operators, etc.
  - **Dynamic Host Configuration Protocol (DHCP):** local network address assignment

Indirection in Virtual Memory



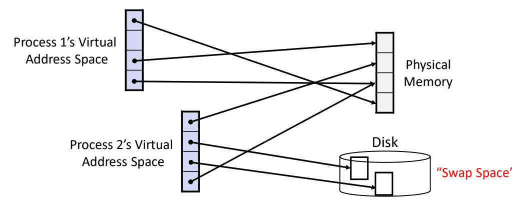
- Each process gets its own private virtual address space
- Solves the previous problems!

Address Spaces

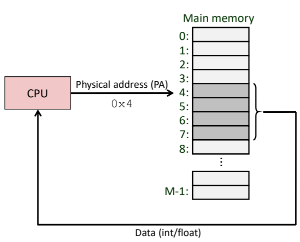
- Virtual address space: Set of $N = 2^n$ virtual addr
  - {0, 1, 2, 3, …, N-1}
- Physical address space: Set of $M = 2^m$ physical addr
  - {0, 1, 2, 3, …, M-1}
- Every byte in main memory has:
  - one physical address (PA)
  - zero, one, *or more* virtual addresses (VAs)

Mapping

- A virtual address (VA) can be mapped to either physical memory or disk
  - Unused VAs may not have a mapping
  - VAs from *different* processes may map to same location in memory/disk

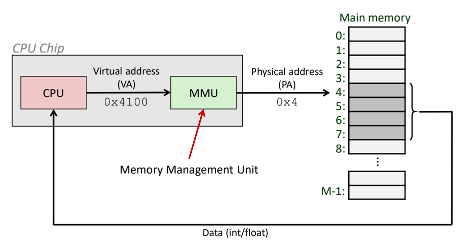


A System Using Physical Addressing



- Used in "simple" systems with (usually) just one process:
  - Embedded microcontrollers in devices like cars, elevators, and digital picture frames

A System Using Virtual Addressing



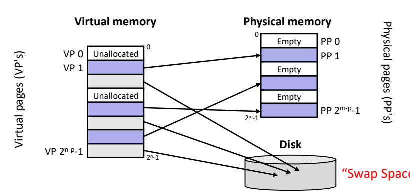
- Physical addresses are *completely invisible to programs*
  - Used in all modern desktops, laptops, servers, smartphones…
  - One of the great ideas in computer science

Why Virtual Memory (VM)?

- Efficient use of limited main memory (RAM)
  - Use RAM as a cache for the parts of a virtual address space
    - Some non-cached parts stored on disk
    - Some (unallocated) non-cached parts stored nowhere
  - Keep only active areas of virtual address space in memory
    - Transfer data back and forth as needed
- Simplifies memory management for programmers
  - Each process "gets" the same full, private linear address space
- Isolates address spaces (protection)
  - One process can't interfere with another's memory
    - They operate in *different address spaces*
  - User process cannot access privileged information
    - Different sections of address spaces have different permissions

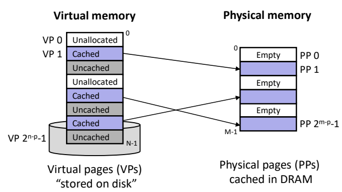
VM and the Memory Hierarchy

- Think of virtual memory as array of $N = 2^n$ contiguous bytes
- *Pages* of virtual memory are usually stored in physical memory, but sometimes spill to disk
  - Pages are another unit of aligned memory (size is $P = 2^p$ bytes)
  - Each virtual page can be stored in *any* physical page (no fragmentation!)



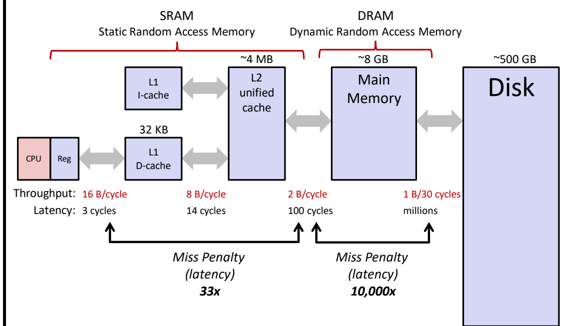
or: Virtual Memory as DRAM Cache for Disk

- Think of virtual memory as an array of $N = 2^n$ contiguous bytes stored *on a disk*
- Then physical main memory is used as a *cache* for the virtual memory array
  - These "cache blocks" are called *pages* (size is $P = 2^p$ bytes)



Memory Hierarchy: Core 2 Duo

Not drawn to scale



Virtual Memory Design Consequences

- Large page size: typically 4-8 KB or 2-4 MB
  - *Can* be up to 1 GB (for "Big Data" apps on big computers)
  - Compared with 64-byte cache blocks
- Fully associative
  - Any virtual page can be placed in any physical page
  - Requires a "large" mapping function – different from CPU caches
- Highly sophisticated, expensive replacement algorithms in OS
  - Too complicated and open-ended to be implemented in hardware
- *Write-back* rather than *write-through*
  - *Really* don't want to write to disk every time we modify something in memory
  - Some things may never end up on disk (*e.g.* stack for short-lived process)

Why does VM work on RAM/disk?

- Avoids disk accesses because of *locality*
  - Same reason that L1 / L2 / L3 caches work
- The set of virtual pages that a program is "actively" accessing at any point in time is called its *working set*
  - If (*working set of one process ≤ physical memory*):
    - Good performance for one process (after compulsory misses)
  - If (*working sets of all processes > physical memory*):
    - ***Thrashing:*** Performance meltdown where pages are swapped between memory and disk continuously (CPU always waiting or paging)
    - This is why your computer can feel faster when you add RAM

Virtual Memory (VM)

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- **Address translation**
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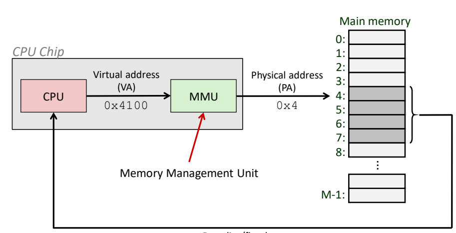
Address Translation

How do we perform the virtual → physical address translation?



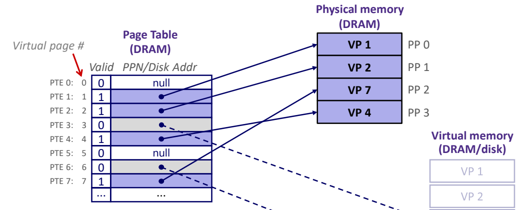
Address Translation: Page Tables

- CPU-generated address can be split into:

  n-bit address: | Virtual Page Number | Page Offset |

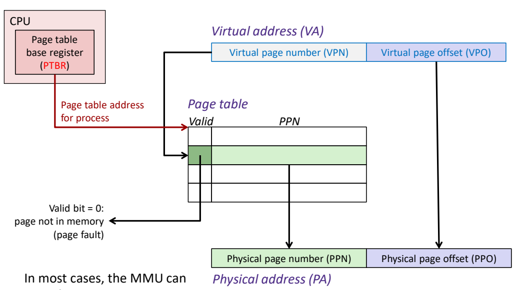
  - Request is Virtual Address (VA), want Physical Address (PA)
  - Note that Physical Offset = Virtual Offset (page-aligned)
- Use lookup table that we call the *page table* (PT)
  - Replace Virtual Page Number (VPN) for Physical Page Number (PPN) to generate Physical Address
  - Index PT using VPN: page table entry (PTE) stores the PPN plus management bits (*e.g.* Valid, Dirty, access rights)
  - Has an entry for *every* virtual page – why?

Page Table Diagram



- Page tables stored in physical memory
  - Too big to fit elsewhere – managed by MMU & OS
- How many page tables in the system?
  - *One per process*

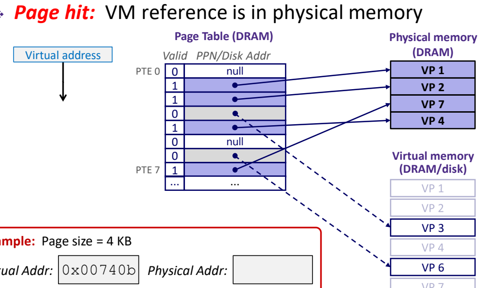
Page Table Address Translation



In most cases, the MMU can perform this translation without software assistance

Page Hit

- ***Page hit:*** VM reference is in physical memory



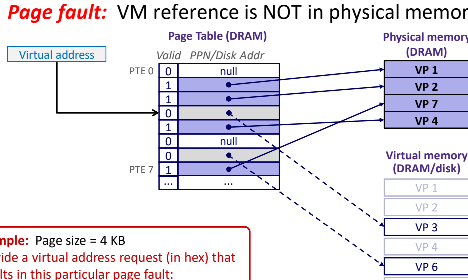
Example: Page size = 4 KB

Virtual Addr: `0x00740b` *Physical Addr:*

VPN: *PPN:*

Page Fault

- ***Page fault:*** VM reference is NOT in physical memory



Example: Page size = 4 KB
Provide a virtual address request (in hex) that results in this particular page fault:

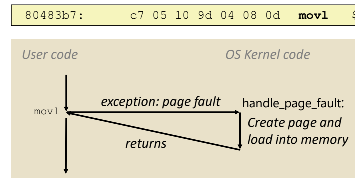
Virtual Addr:

Page Fault Exception

- User writes to memory location
- That portion (page) of user's memory is currently on disk

```
int a[1000];
int main ()
{
    a[500] = 13;
}
```

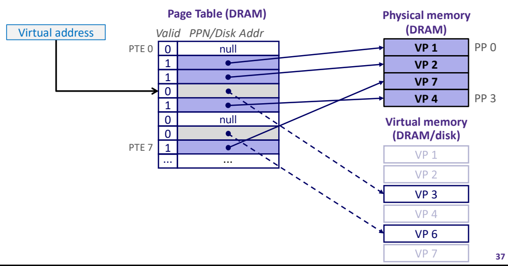
```
80483b7:    c7 05 10 9d 04 08 0d    movl    $0xd,0x8049d10
```



- Page fault handler must load page into physical memory
- Returns to faulting instruction: `mov` is executed again!
  - Successful on second try

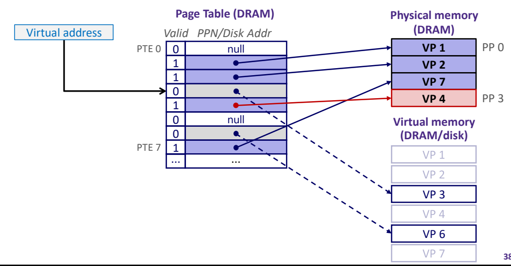
Handling a Page Fault

- Page miss causes page fault (an exception)



Handling a Page Fault

- Page miss causes page fault (an exception)
- Page fault handler selects a *victim* to be evicted (here VP 4)



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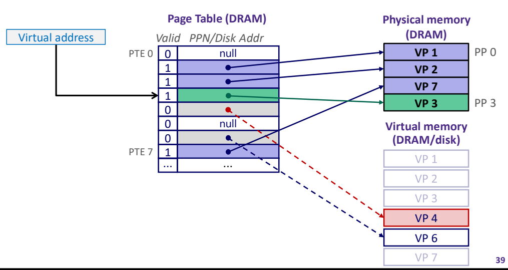
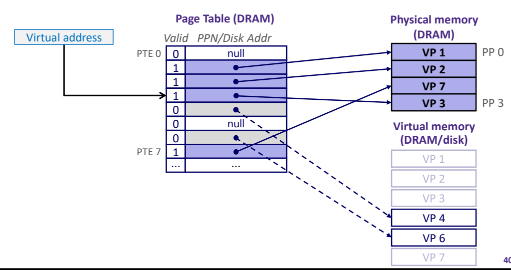


Handling a Page Fault

- Page miss causes page fault (an exception)
- Page fault handler selects a *victim* to be evicted (here VP 4)
- Offending instruction is restarted: page hit!



Peer Instruction Question

- How many bits wide are the following fields?
  - 16 KB pages
  - 48-bit virtual addresses
  - 16 GB physical memory

	VPN	PPN
(A)	34	24
(B)	32	18
(C)	30	20
(D)	34	20

Summary

- Virtual memory provides:
  - Ability to use limited memory (RAM) across multiple processes
  - Illusion of contiguous virtual address space for each process
  - Protection and sharing amongst processes
- Indirection via address mapping by page tables
  - Part of memory management unit and stored in memory
  - Use virtual page number as index into lookup table that holds physical page number, disk address, or NULL (unallocated page)
  - On page fault, throw exception and move page from swap space (disk) to main memory