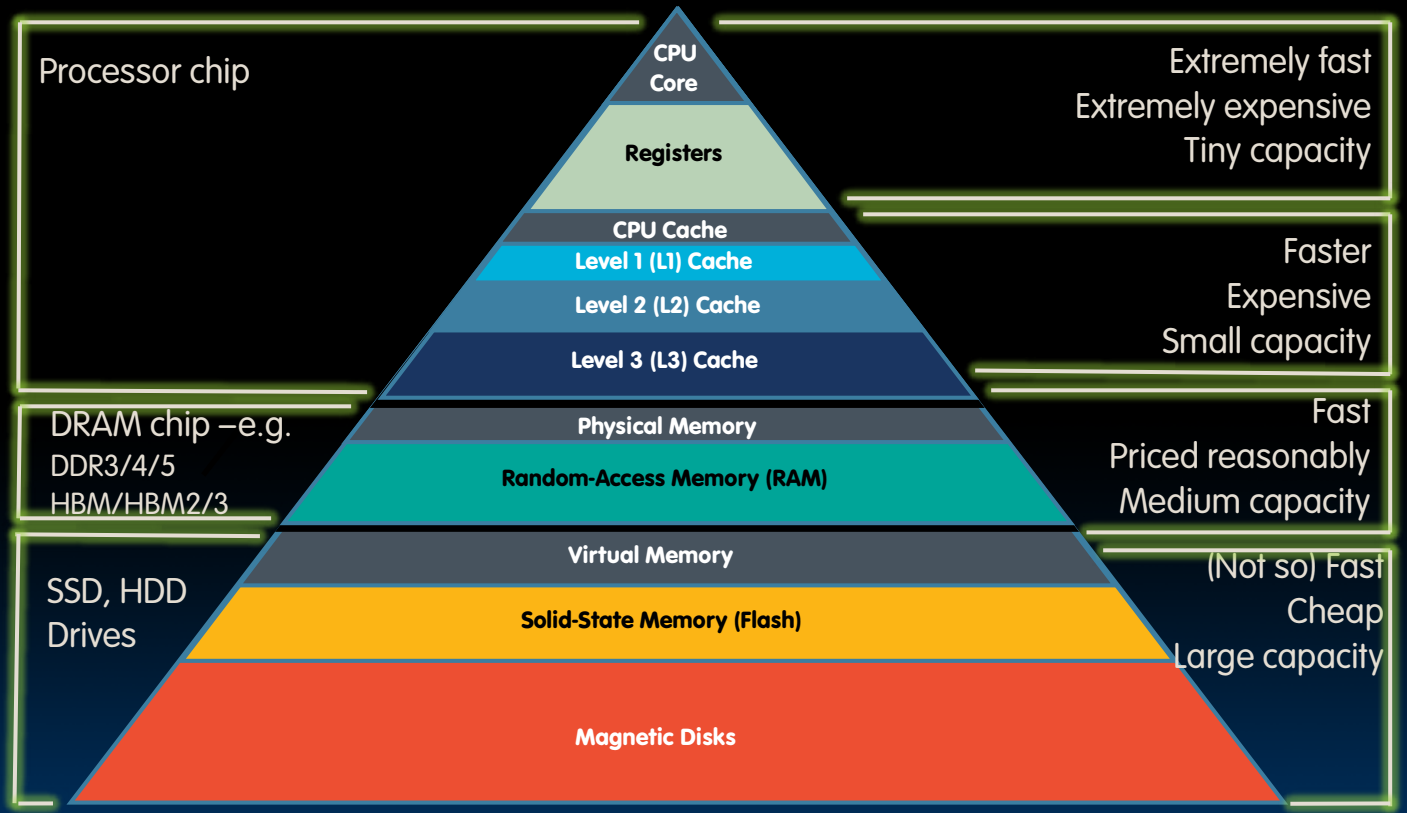
Virtual Memory Concepts

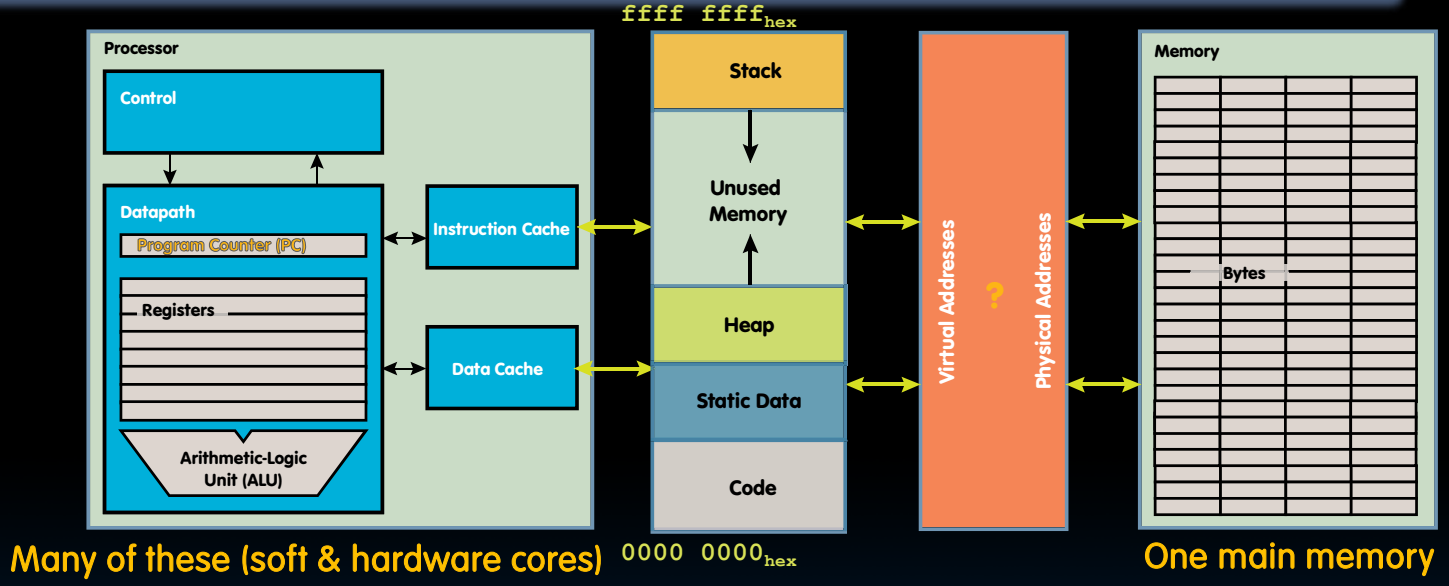
Virtual Memory

- Virtual memory - Next level in the memory hierarchy:
  - Provides program with illusion of a very large main memory: Working set of “pages” reside in main memory - others are on disk
  - Demand paging: Provides the ability to run programs larger than the primary memory (DRAM)
  - Hides differences between machine configurations
- Also allows OS to share memory, protect programs from each other
- Today, more important for protection than just another level of memory hierarchy
- Each process thinks it has all the memory to itself
- (Historically, it predates caches)

Great Idea #3: Principle of Locality / Memory Hierarchy



Virtual vs. Physical Addresses



- Processes use virtual addresses, e.g., 0 … 0xffff,ffff
  - Many processes, all using same (conflicting) addresses
- Memory uses physical addresses (also, e.g., 0 … 0xffff,ffff)
  - *Memory manager maps virtual to physical addresses*

Address Spaces

- Address space = set of addresses for all available memory locations
- Now, two kinds of memory addresses:
  - **Virtual Address Space**
    - Set of addresses that the user program knows about
  - **Physical Address Space**
    - Set of addresses that map to actual physical locations in memory
    - Hidden from user applications
- Memory manager maps (‘translates’) between these two address spaces

Bora's Laptop

```
bora@DESKTOP-QAB1DCR:~$ lscpu
Architecture:                    x86_64
CPU op-mode(s):                  32-bit, 64-bit
Byte Order:                      Little Endian
Address sizes:                   39 bits physical, 48 bits virtual
CPU(s):                          8
On-line CPU(s) list:             0-7
Thread(s) per core:              2
Core(s) per socket:              4
Socket(s):                       1
Vendor ID:                       GenuineIntel
CPU family:                      6
Model:                           126
Model name:                      Intel(R) Core(TM) i7-1065G7 CPU @ 1.30GHz
Stepping:                        5
CPU MHz:                         1497.604
BogoMIPS:                        2995.20
Hypervisor vendor:               Microsoft
Virtualization type:             full
L1d cache:                       192 KiB
L1i cache:                       128 KiB
L2 cache:                        2 MiB
L3 cache:                        8 MiB
```

Analogy

- Book title like virtual address
- Library of Congress call number like physical address
- Card catalogue like page table, mapping from book title to call #
- On card for book, in local library vs. in another branch like valid bit indicating in main memory vs. on disk (storage)
- On card, available for 2-hour in library use (vs. 2-week checkout) like access rights

Memory Hierarchy Requirements

- Allow multiple processes to simultaneously occupy memory and provide protection – don't let one program read/write memory from another

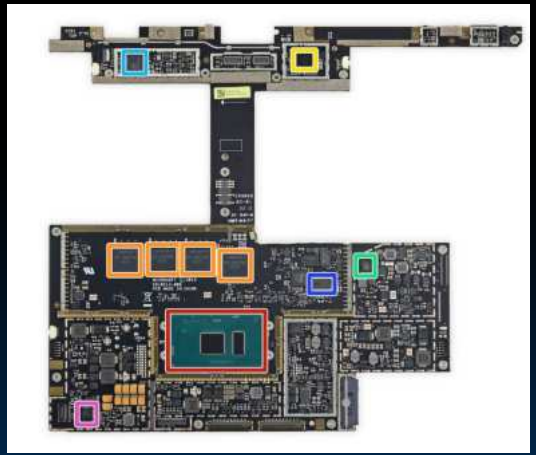
- Address space – give each program the illusion that it has its own private memory
  - Suppose code starts at address 0x40000000. But different processes have different code, both residing at the same address. So each program has a different view of memory.

Physical Memory and Storage

Memory

- Memory (DRAM)

Desktop/server



MS Surface Book

Apple A12 Bionic
(DRAM goes on top)

Volatile

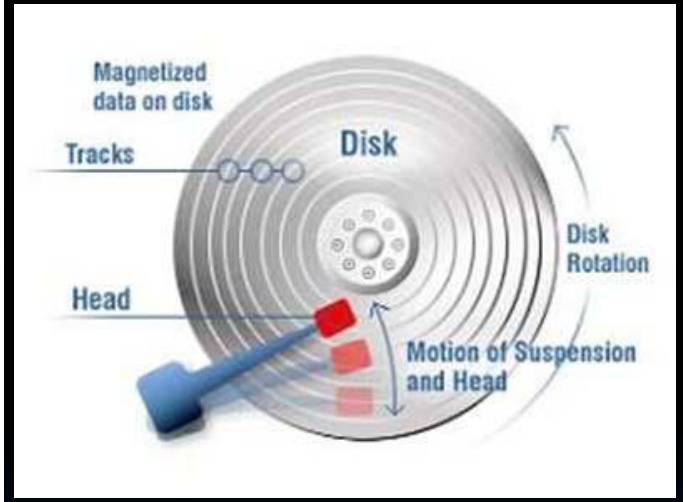
Latency to access first word: ~10ns
(~30-40 processor cycles)
Each successive (0.5ns – 1ns)
Each access brings 64 bits
Supports 'bursts'

Storage – "Disk"

Attached as a peripheral I/O device; Non-volatile

- SSD
  - Access: 40-100µs (~100k proc. cycles)
  - $0.05-0.5/GB
- HDD
  - Access: <5-10ms (10-20M proc. cycles)
  - $0.01-0.1/GB

Aside … Why are Disks So Slow?



- 10,000 rpm (revolutions per minute)
- 6 ms per revolution
- Average random access time: 3 ms (~10^7 processor cycles)

How Hard Drives Work?

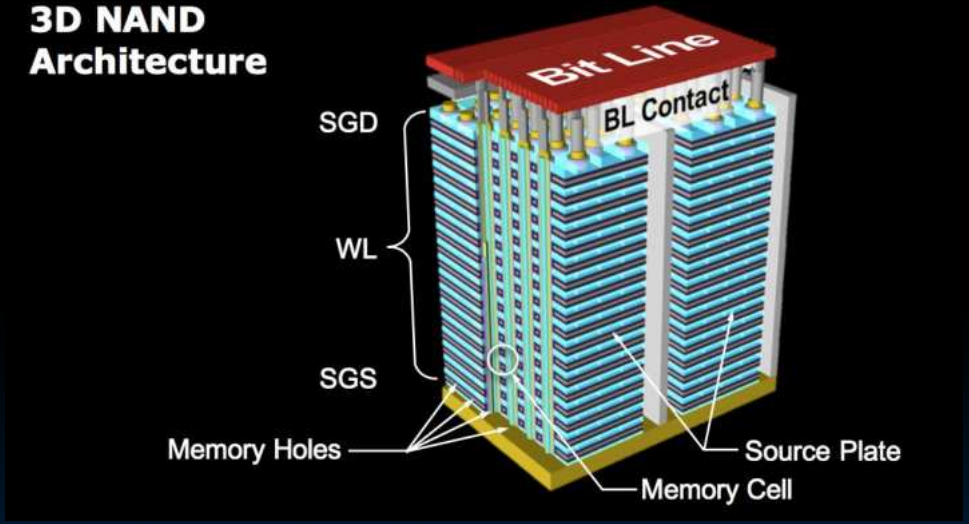
- Nick Parlante's https://cs.stanford.edu/people/nick/how-hard-drive-works/
  - Several YouTube videos as well

What About SSD?

- Made with transistors
- Nothing mechanical that turns
- Like “Ginormous” register file
  - Does not ”forget” when power is off (non-volatile)
- Fast access to all locations, regardless of address
- Still much slower than register, DRAM
  - Read/write blocks, not bytes
  - Potential reliability issues
- Some unusual requirements:
  - Can’t erase single bits – only entire blocks

Flash Memory

- 3D array of bit cells (up to 256 layers!)

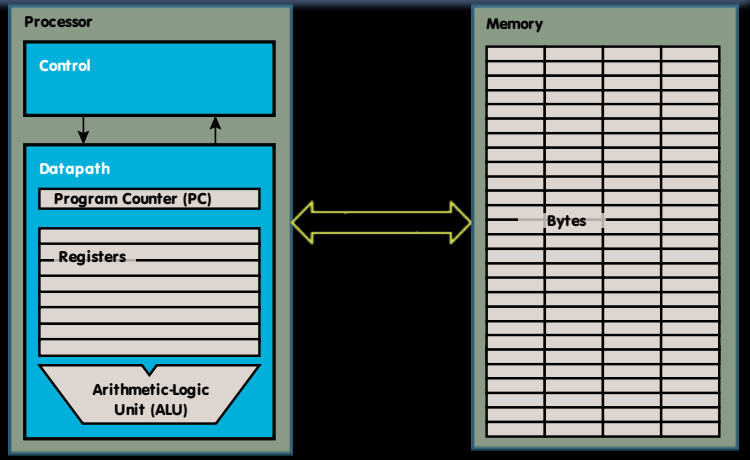


Western Digital/Semiengineering

Memory Manager

Virtual Memory

- In a ‘bare metal’ system (w/o OS), addresses issued with loads/stores are real physical addresses

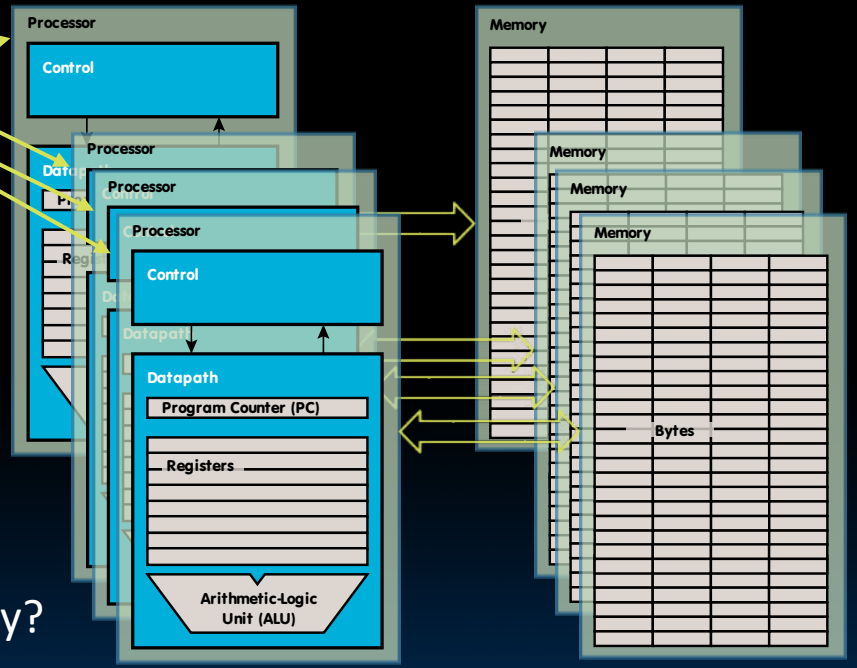


  - In this mode, any process can issue any address, therefore can access any part of memory, even areas which it doesn’t own
    - Ex: The OS data structures
  - We should send all addresses through a mechanism that the OS controls, before they make it out to DRAM - a translation mechanism
    - Check that process has permission to access a particular part of memory

Virtual Memory

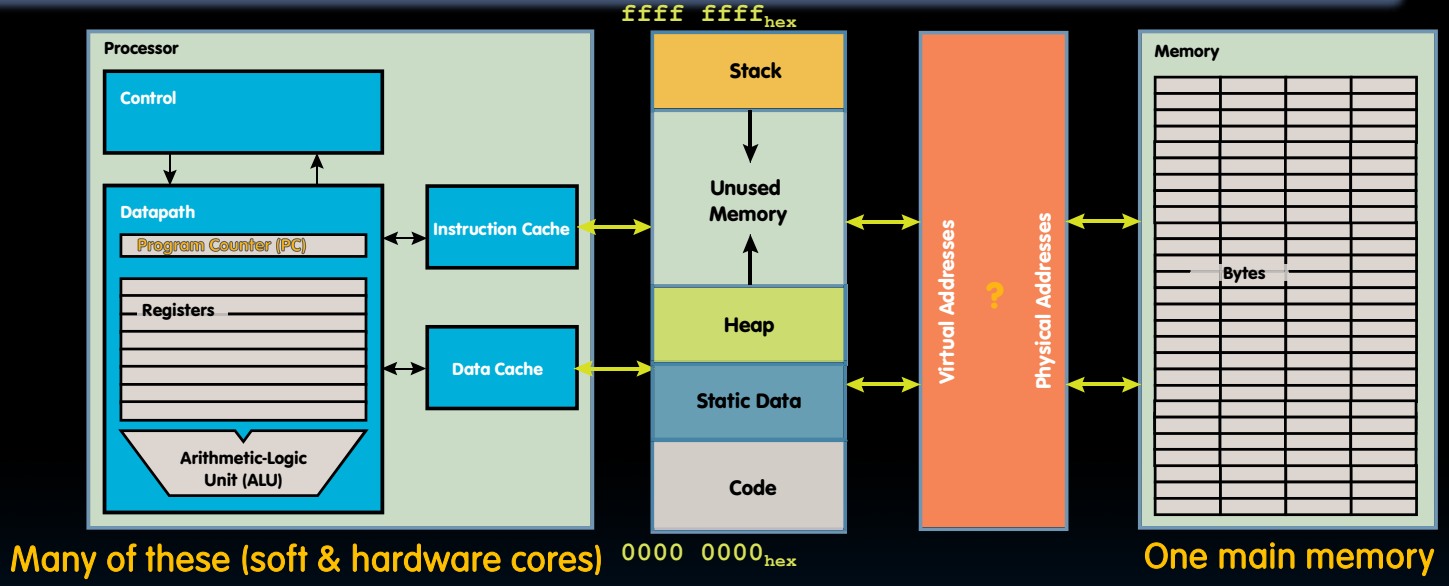
100+ Processes, managed by OS

```
0:04.34 /usr/libexec/UserEventAgent (Aqua)
0:10.60 /usr/sbin/distnoted agent
0:09.11 /usr/sbin/cfprefsd agent
0:04.71 /usr/sbin/usernoted
0:02.35 /usr/libexec/nsurlsessiond
0:28.68 /System/Library/PrivateFrameworks/Calend
0:04.36 /System/Library/PrivateFrameworks/GameCe
0:01.90 /System/Library/CoreServices/cloudphotos
0:49.72 /usr/libexec/secinitd
0:01.66 /System/Library/PrivateFrameworks/TCC.fr
0:12.68 /System/Library/Frameworks/Accounts.fram
0:09.56 /usr/libexec/SafariCloudHistoryPushAgent
0:00.27 /System/Library/PrivateFrameworks/CallHi
0:00.74 /System/Library/CoreServices/mapspushd
0:00.79 /usr/libexec/fmfd
```



- 100's of processes
  - OS multiplexes these over available cores
- But what about memory?
  - There is only one!
  - We cannot just "save" its contents in a context switch …

Review: Virtual vs. Physical Addresses



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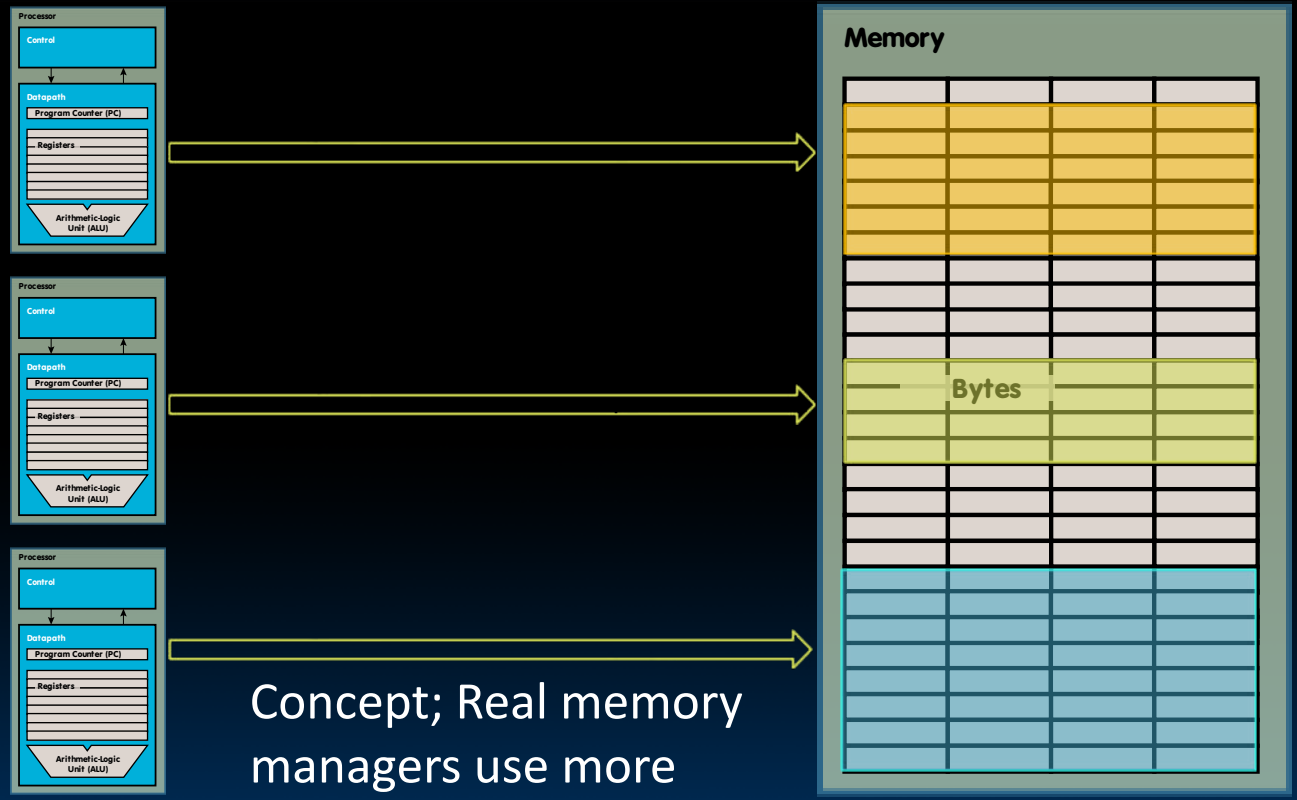
Conceptual Memory Manager



Concept; Real memory managers use more complex mappings

Responsibilities of Memory Manager

1) Map virtual to physical addresses
2) Protection:
   - Isolate memory between processes
   - Each process gets dedicate ”private” memory
   - Errors in one program won’t corrupt memory of other program
   - Prevent user programs from messing with OS’s memory
3) Swap memory to disk
   - Give illusion of larger memory by storing some content on disk
   - Disk is usually much larger and slower than DRAM
     - Use “clever” caching strategies

Paged Memory

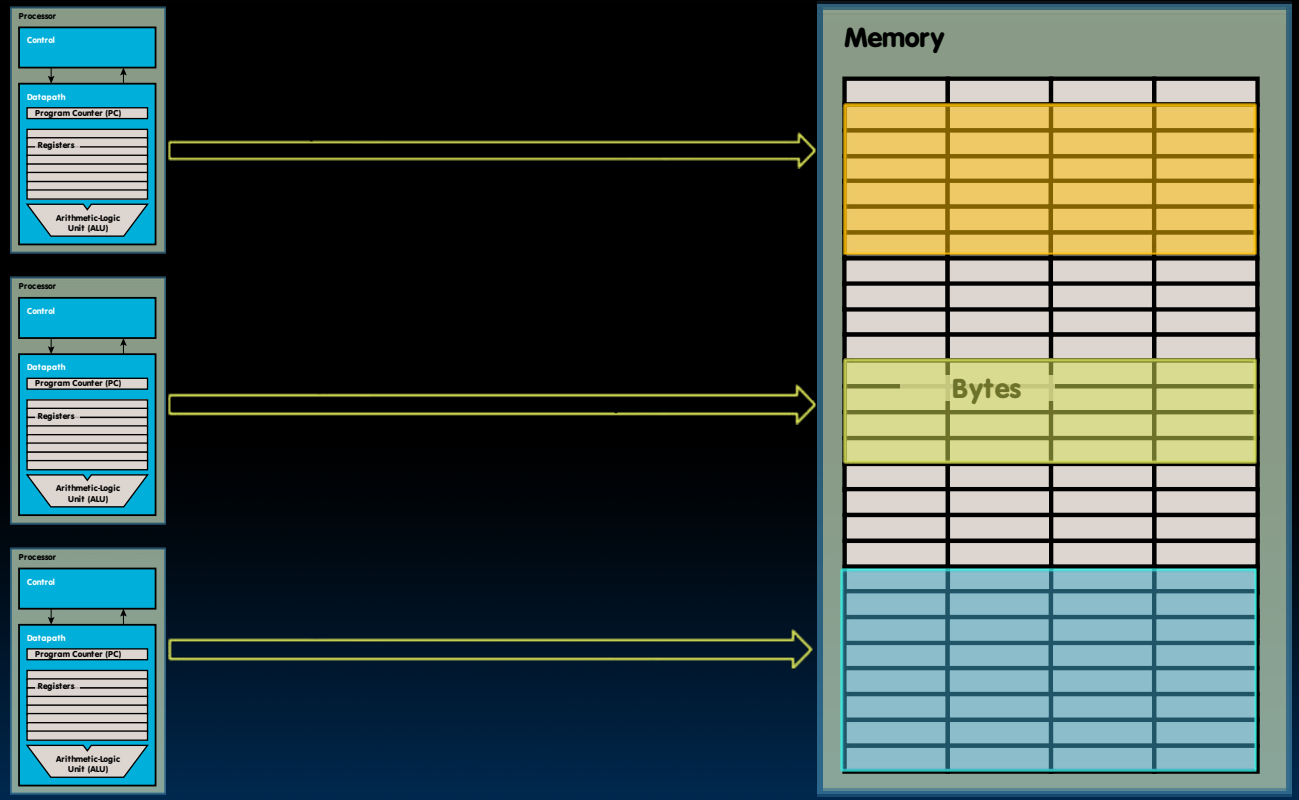
Memory Manager and Paged Memory

- Concept of “paged memory” dominates
  - Physical memory (DRAM) is broken into pages
  - Typical page size: 4 KiB+ (on modern OSs)
    - Need 12 bits to address 4KiB

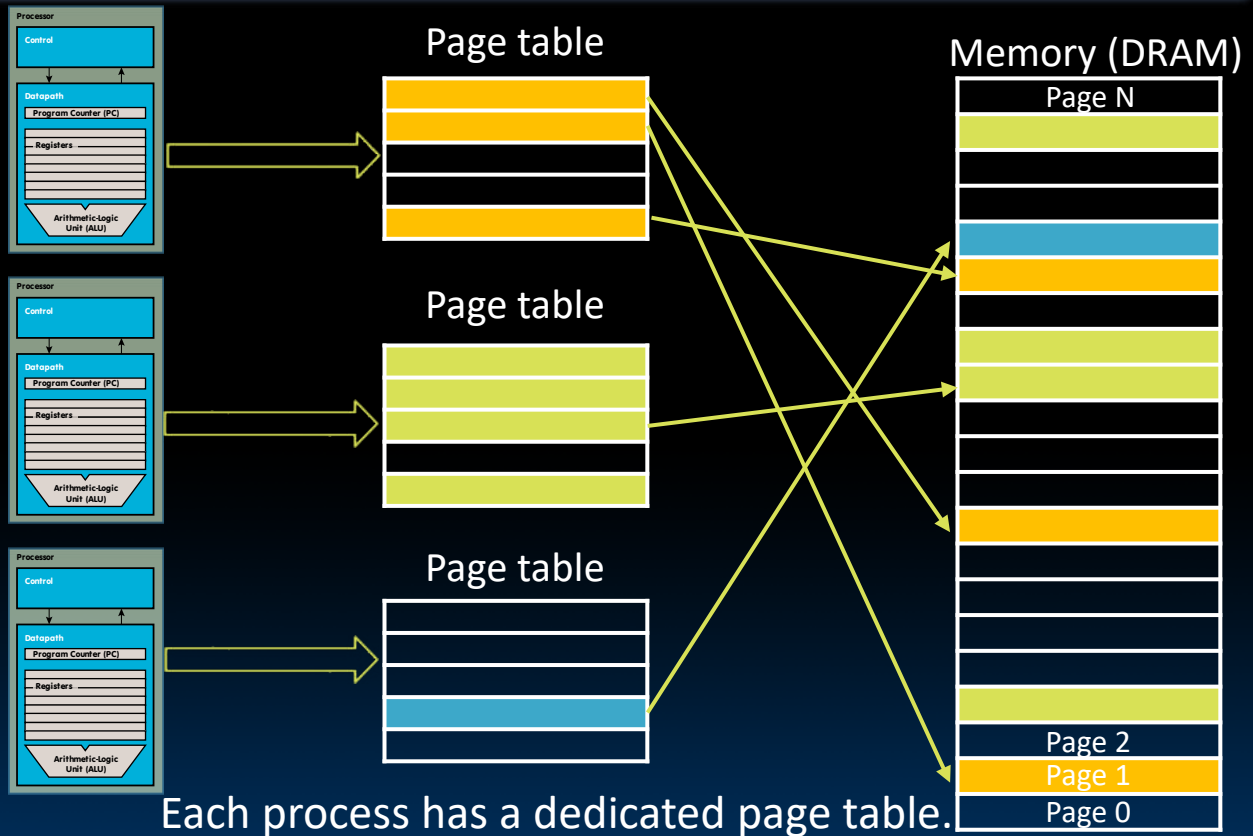
Virtual address (e.g., 32 Bits)

page number (e.g., 20 Bits)	offset (e.g., 12 Bits)

Review: Conceptual Memory Manager



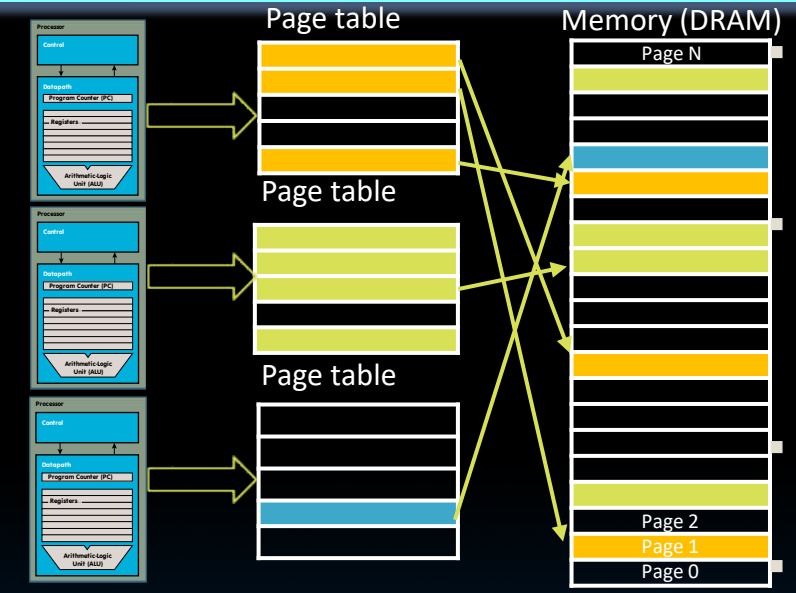
Paged Memory



Each process has a dedicated page table.

Physical memory non-consecutive.

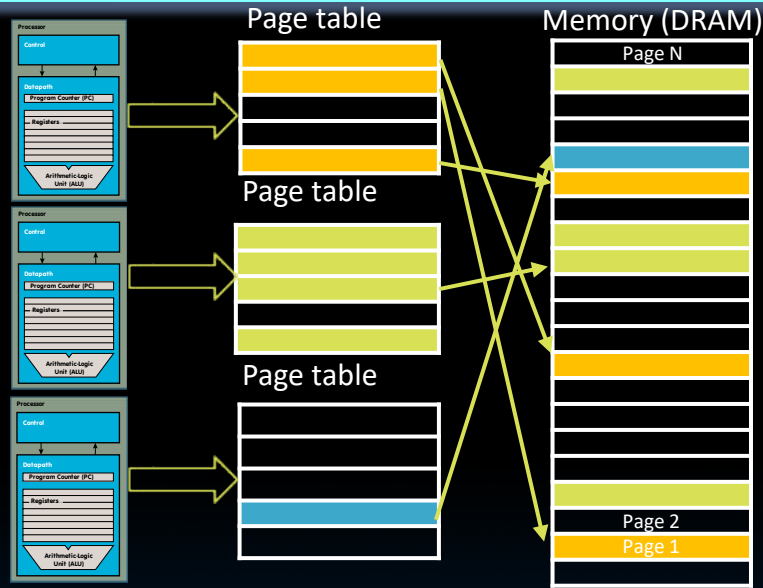
Paged Memory Address Translation



- OS keeps track of which process is active
  - Chooses correct page table
- Memory manager extracts page number from virtual address
  - e.g. just top 20 bits
- Looks up page address in page table
- Computes physical memory address from sum of
  - Page address and
  - Offset (from virtual address)

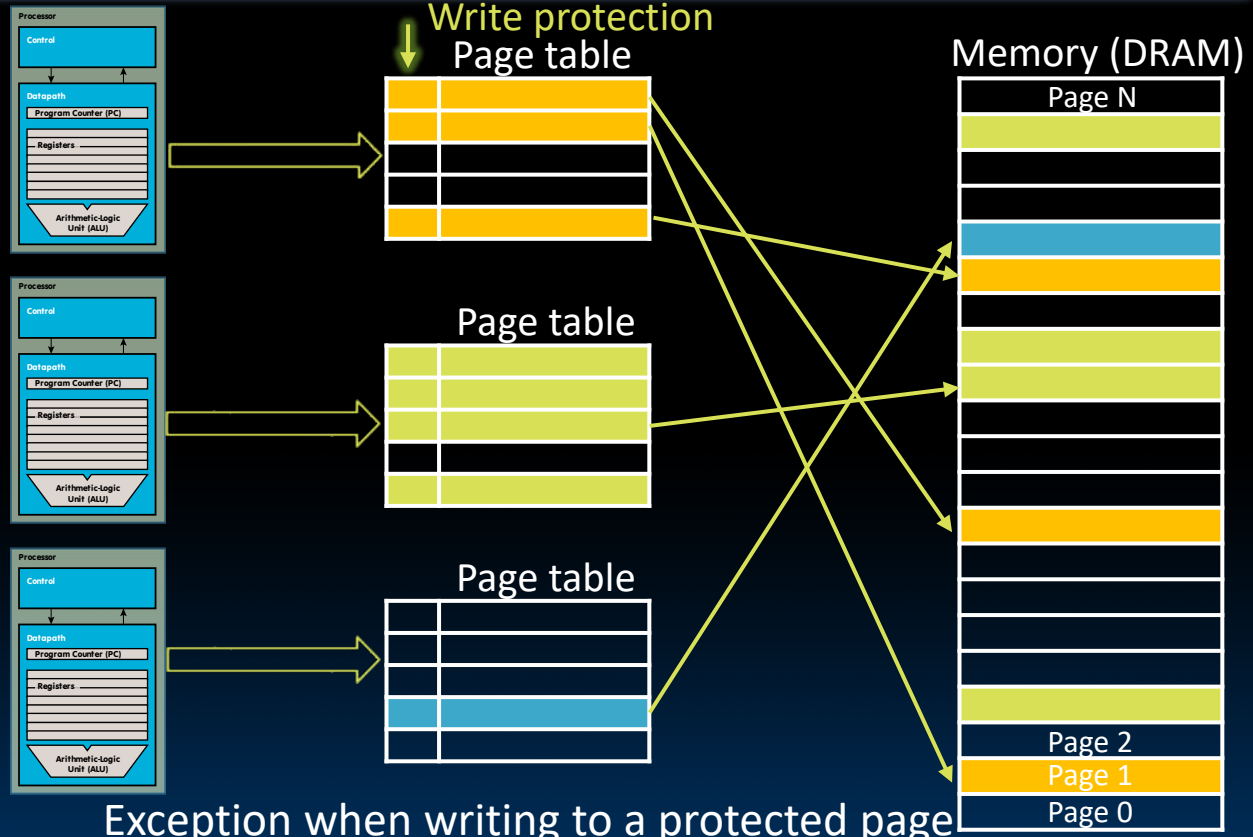
Physical addresses may (but do not have to) have more or fewer bits than virtual addresses

Protection



- Assigning different pages in DRAM to processes also keeps them from accessing each others memory
  - Isolation
  - Page tables handled by OS (in supervisory mode)
- Sharing is also possible
  - OS may assign same physical page to several processes

Write Protection

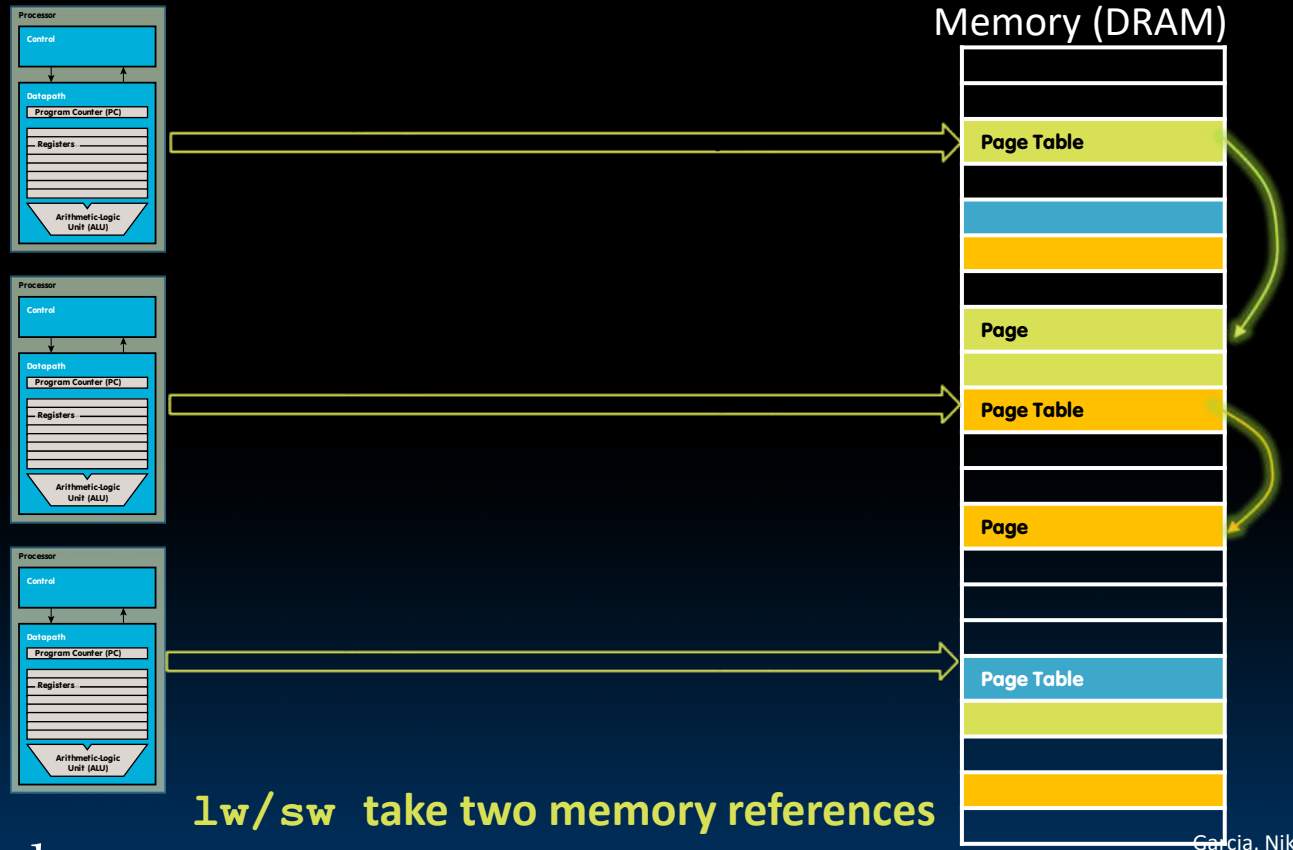


Exception when writing to a protected page (e.g. program code)

Where Do Page Tables Reside?

- E.g., 32-Bit virtual address, 4-KiB pages
  - Single page table size:
    - 4×2^{20} Bytes = 4-MiB
    - 0.1% of 4-GiB memory
    - But much too large for a cache!
- Store page tables in memory (DRAM)
  - Two (slow) memory accesses per **`lw/sw`** on cache miss
  - How could we minimize the performance penalty?
    - Transfer blocks (not words) between DRAM and processor cache
      - Exploit spatial locality
    - Use a cache for frequently used page table entries …

Page Table Stored in Memory



`lw/sw` take two memory references

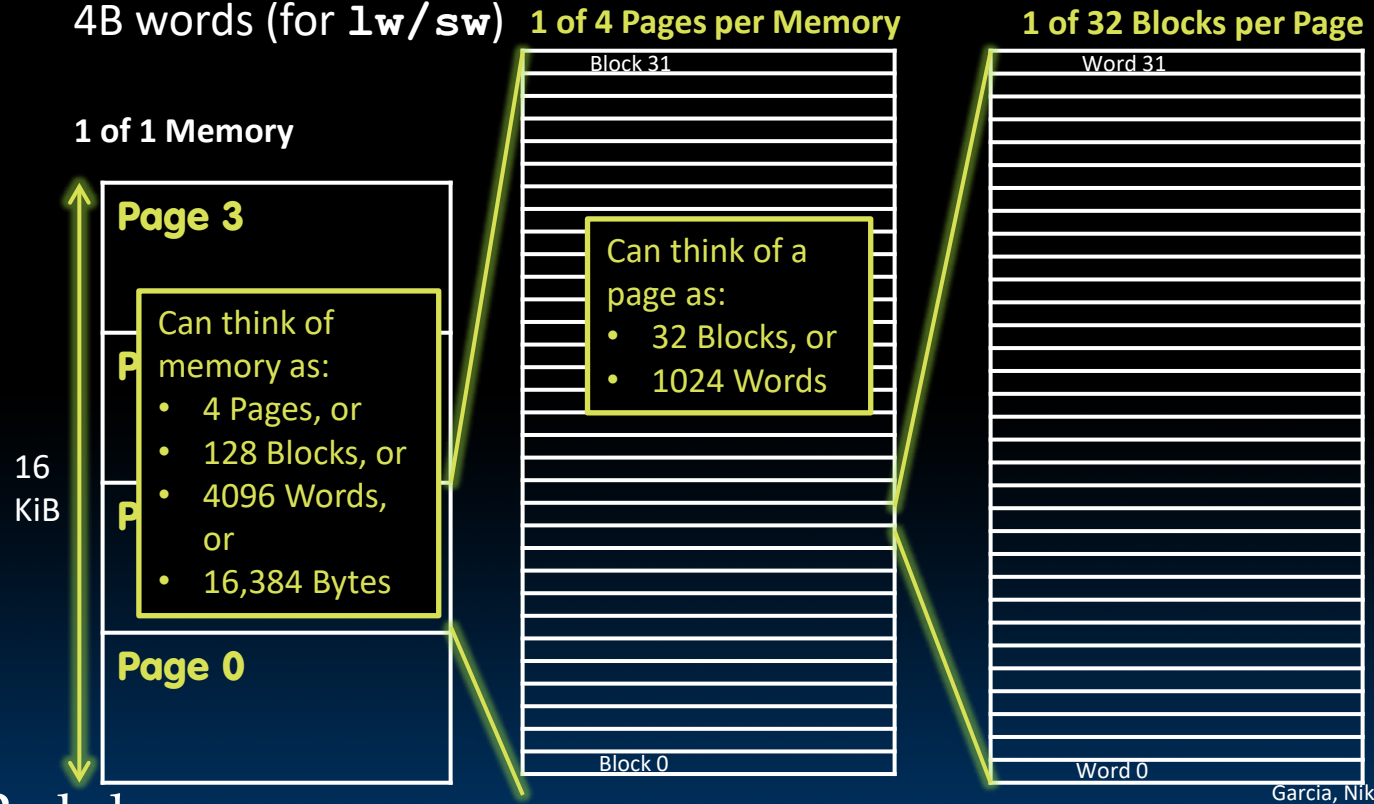
Page Faults

Blocks vs. Pages

- In caches, we dealt with individual *blocks*
  - Usually ~64B on modern systems
- In VM, we deal with individual *pages*
  - Usually ~4 KiB on modern systems
- Common point of confusion:
  - Bytes,
  - Words,
  - Blocks,
  - Pages
    - Are all just different ways of looking at memory!

Bytes, Words, Blocks, Pages

E.g.: 16 KiB DRAM, 4 KiB Pages (for VM), 128 B blocks (for caches), 4B words (for `lw/sw`)



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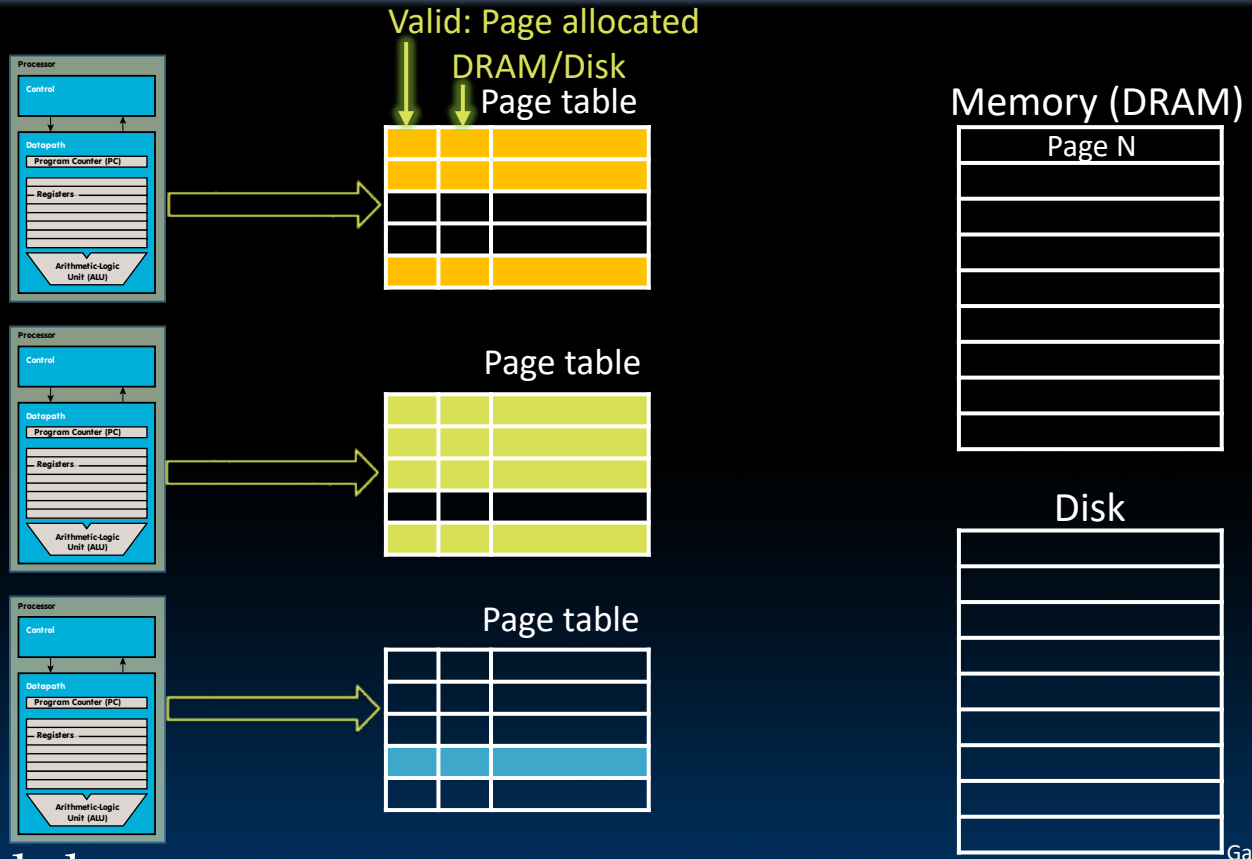

Memory Access

- Check page table entry:
  - Valid?
    - Yes, valid → In DRAM?
      - Yes, in DRAM: read/write data
      - No, on disk: allocate new page in DRAM
        - If out of memory, evict a page from DRAM
        - Store evicted page to disk
        - Read page from disk into memory
        - Read/write data
    - Not Valid
      - allocate new page in DRAM
        - If out of memory, evict a page
        - Read/write data

Page fault
OS intervention

Page Fault

- Page faults are treated as exceptions
  - Page fault handler (yet another function of the interrupt/trap handler) does the page table updates and initiates transfers
  - Updates status bits
- (If page needs to be swapped from disk, perform context switch)
- Following the page fault, the instruction is re-executed

Remember: Out of Memory

```c
int main(void) {
    const int G = 1024*1024*1024;
    for (int n=0; ;n++) {
        char *p = malloc(G*sizeof(char));
        if (p == NULL) {
            fprintf(stderr,
                    "failed to allocate > %g TiBytes\n", n/1000.0);
            return 1;  // abort program
        }
        // no free, keep allocating until out of memory
    }
}
```

```
$ gcc OutOfMemory.c; ./a.out
failed to allocate > 131 TiBytes
```

Write-Through or Write-Back?

- DRAM acts like “cache” for disk
  - Should writes go directly to disk (write-through)?
  - Or only when page is evicted?

- Which option do you propose?