Memory Management

Goals of this Lecture

- Help you learn about:
  - The memory hierarchy
  - Spatial and temporal locality of reference
  - Caching, at multiple levels
  - Virtual memory
  - … and thereby …
  - How the hardware and OS give application pgms:
    - The illusion of a large contiguous address space
    - Protection against each other

Virtual memory is one of the most important concepts in systems programming

Motivation for Memory Hierarchy

- Faster storage technologies are more costly
  - Cost more money per byte
  - Have lower storage capacity
  - Require more power and generate more heat
- The gap between processing and memory is widening
  - Processors have been getting faster and faster
  - Main memory speed is not improving as dramatically
- Well-written programs tend to exhibit good locality
  - Across time: repeatedly referencing the same variables
  - Across space: often accessing other variables located nearby

Want the *speed* of fast storage at the *cost* and *capacity* of slow storage. Key idea: memory hierarchy!

Simple Three-Level Hierarchy

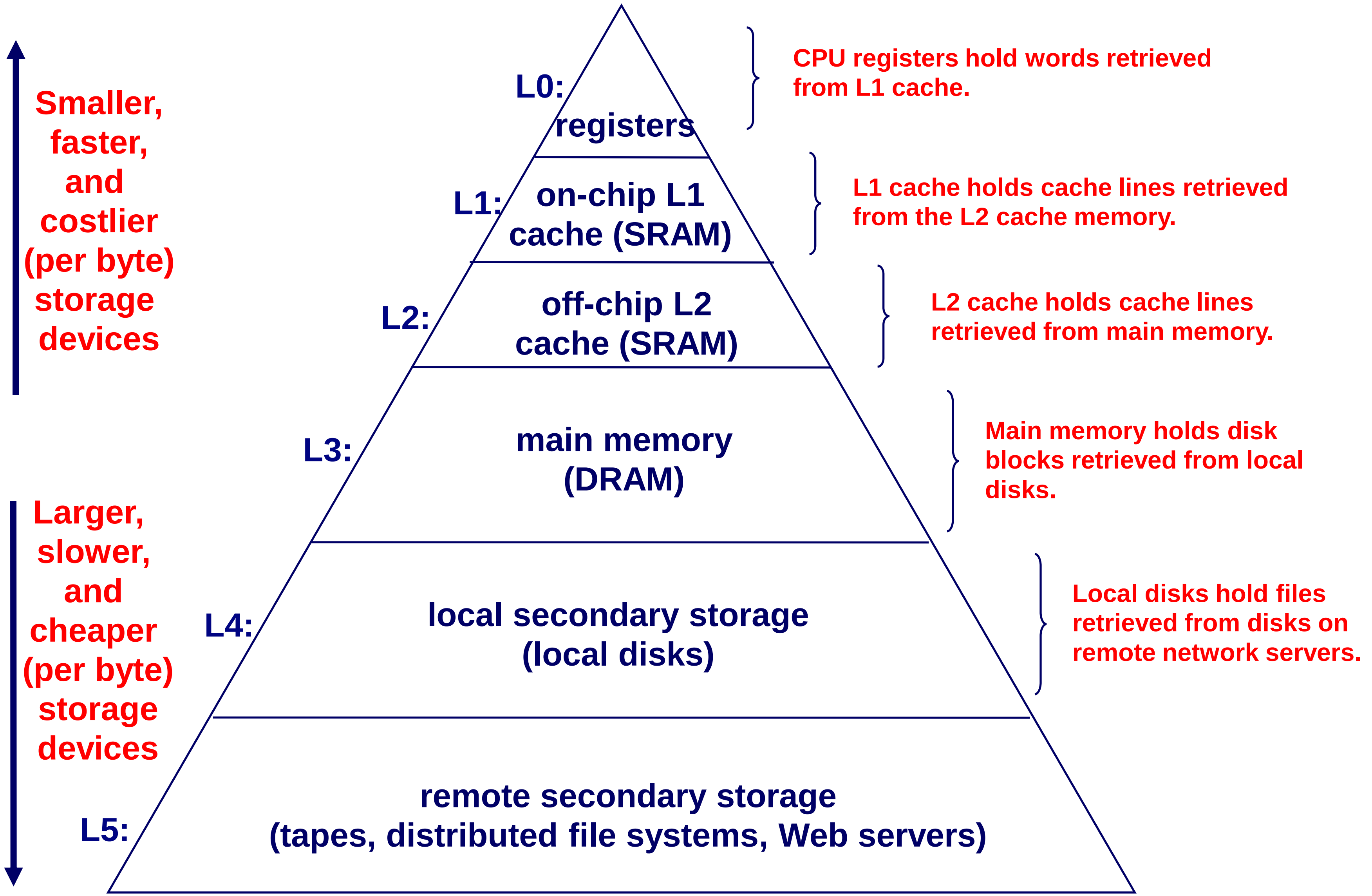
- Registers
  - Usually reside directly on the processor chip
  - Essentially no latency, referenced directly in instructions
  - Low capacity (e.g., 32-512 bytes)
- Main memory
  - Around 100 times slower than a clock cycle
  - Constant access time for any memory location
  - Modest capacity (e.g., 512 MB-2GB)
- Disk
  - Around 100,000 times slower than main memory
  - Faster when accessing many bytes in a row
  - High capacity (e.g., 200 GB)

Widening Processor/Memory Gap

- Gap in speed increasing from 1986 to 2000
  - CPU speed improved ~55% per year
  - Main memory speed improved only ~10% per year
- Main memory as major performance bottleneck
  - Many programs stall waiting for reads and writes to finish

- Changes in the memory hierarchy
  - Increasing the number of registers
    - 8 integer registers in the x86 vs. 128 in the Itanium
  - Adding caches between registers and main memory
    - On-chip level-1 cache and off-chip level-2 cache

An Example Memory Hierarchy



Locality of Reference

- Two kinds of locality
  - **Temporal locality**: recently referenced items are likely to be referenced in near future
  - **Spatial locality**: Items with nearby addresses tend to be referenced close together in time.

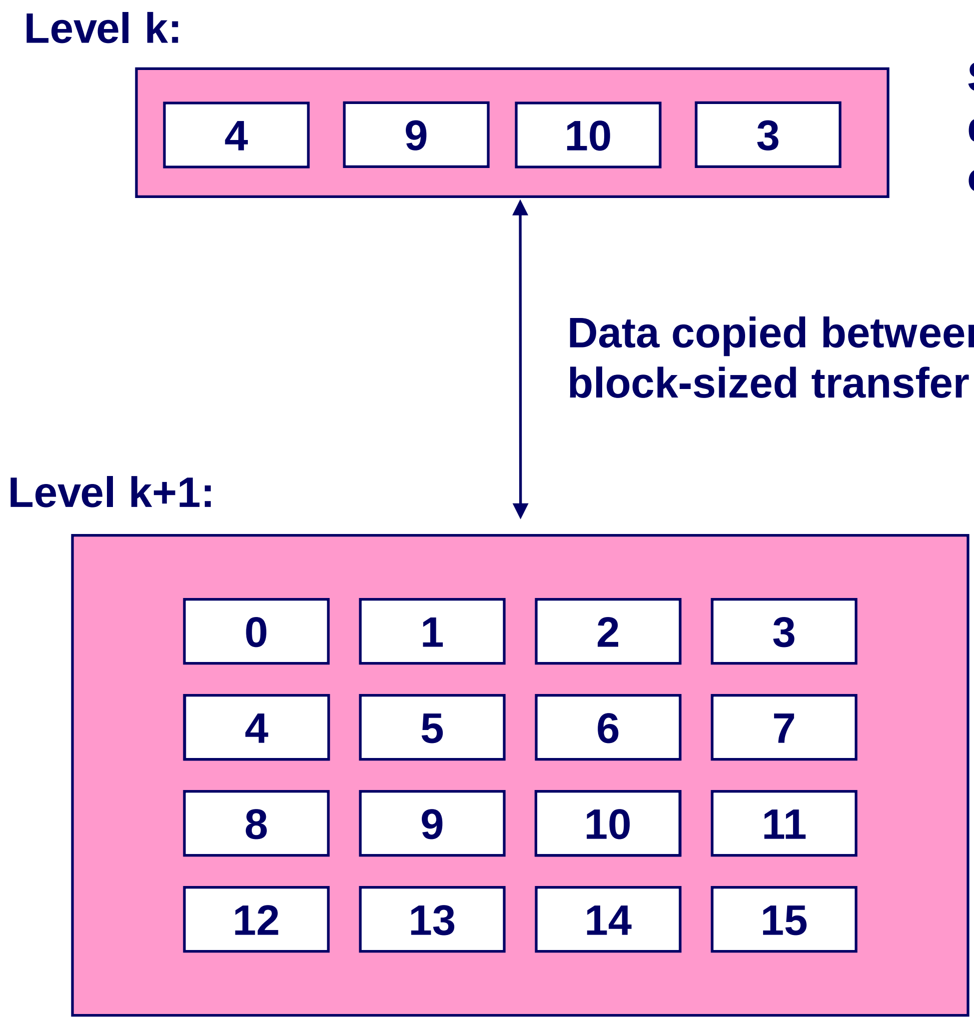
```
sum = 0;
for (i = 0; i < n; i++)
    sum += a[i];
return sum;
```

- Locality example
  - Program data
    - Temporal: the variable `sum`
    - Spatial: variable `a[i+1]` accessed soon after `a[i]`
  - Instructions
    - Temporal: cycle through the for-loop repeatedly
    - Spatial: reference instructions in sequence

Locality Makes Caching Effective

- Cache
  - Smaller, faster storage device that acts as a staging area
  - … for a *subset* of the data in a larger, slower device
- Caching and the memory hierarchy
  - Storage device at level k is a cache for level k+1
  - Registers as cache of L1/L2 cache and main memory
  - Main memory as a cache for the disk
  - Disk as a cache of files from remote storage
- Locality of access is the key
  - Most accesses satisfied by first few (faster) levels
  - Very few accesses go to the last few (slower) levels

Caching in a Memory Hierarchy



Smaller, faster, more expensive device at level k caches a subset of the blocks from level k+1

Data copied between levels in block-sized transfer units

Larger, slower, cheaper storage device at level k+1 is partitioned into blocks.

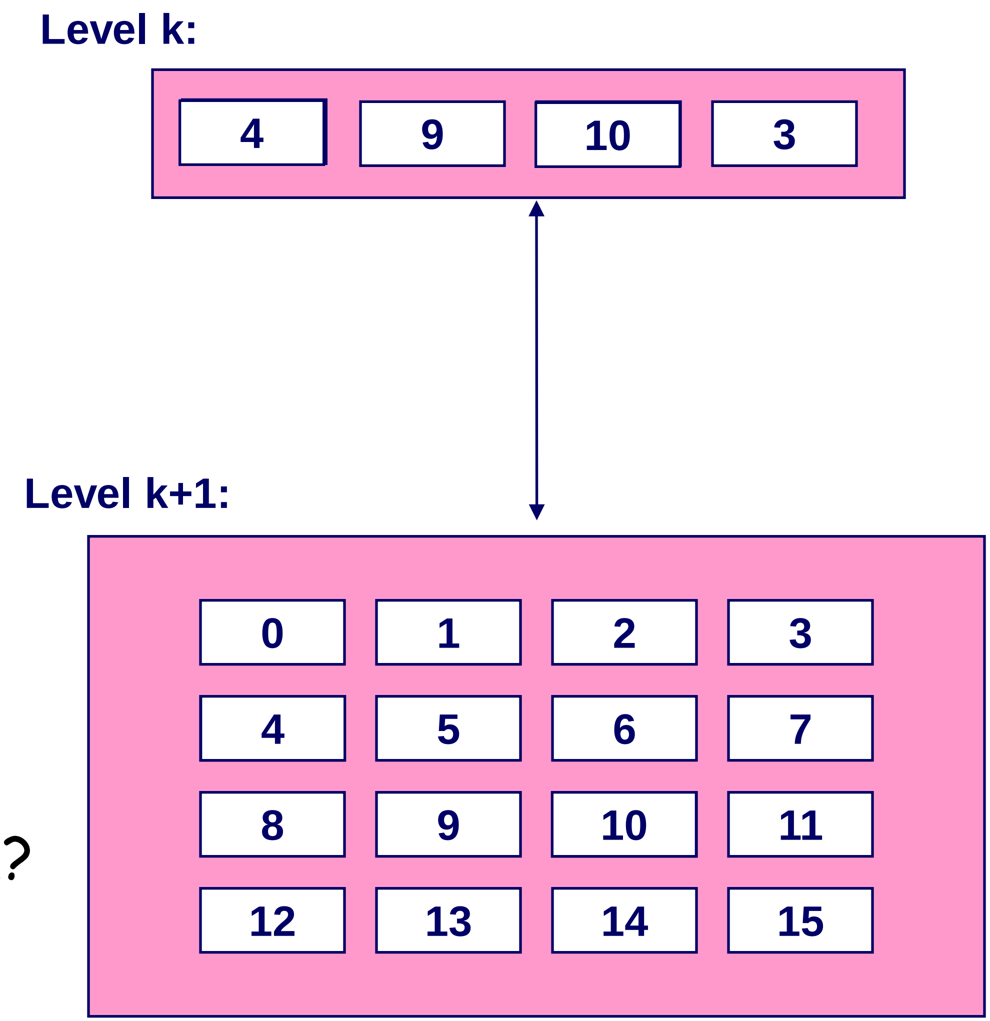
Cache Block Sizes

- Fixed vs. variable size
  - Fixed-sized blocks are easier to manage (common case)
  - Variable-sized blocks make more efficient use of storage
- Block size
  - Depends on access times at the level k+1 device
  - Larger block sizes further down in the hierarchy
  - E.g., disk seek times are slow, so disk pages are larger
- Examples
  - CPU registers: 4-byte words
  - L1/L2 cache: 32-byte blocks
  - Main memory: 4 KB pages
  - Disk: entire files

Cache Hit and Miss

- Cache hit
  - Program accesses a block available in the cache
  - Satisfy directly from cache
  - E.g., request for "10"
- Cache miss
  - Program accesses a block not available in the cache
  - Bring item into the cache
  - E.g., request for "13"

- Where to place the item?
- Which item to evict?



Three Kinds of Cache Misses

- Cold (compulsory) miss
  - Cold misses occur because the block hasn't been accessed before
  - E.g., first time a segment of code is executed
  - E.g., first time a particular array is referenced
- Capacity miss
  - Set of active cache blocks (the "working set") is larger than cache
  - E.g., manipulating a 1200-byte array within a 1000-byte cache
- Conflict miss
  - Some caches limit the locations where a block can be stored
  - E.g., block i must be placed in cache location (i mod 4)
  - Conflicts occur when multiple blocks map to the same location(s)
  - E.g., referencing blocks 0, 8, 0, 8, 0, 8, ... would miss every time

Cache Replacement

- Evicting a block from the cache
  - New block must be brought into the cache
  - Must choose a “victim” to evict
- Optimal eviction policy
  - Evict a block that is *never* accessed again
  - Evict the block accessed the *furthest in the future*
  - Impossible to implement without knowledge of the future
- Using the past to predict the future
  - Evict the “least recently used” (LRU) block
  - Assuming it is not likely to be used again soon
- But, LRU is often expensive to implement
  - Need to keep track of access times
  - So, simpler approximations of LRU are used

Who Manages the Cache?

- Registers
  - Cache of L1/L2 cache and main memory
  - Managed explicitly by the *compiler*
  - By determining which data are brought in and out of registers
  - Using relatively sophisticated code-analysis techniques
- L1/L2 cache
  - Cache of main memory
  - Managed by the *hardware*
  - Using relatively simple mechanisms (e.g., "i mod 4")
- **Main memory**
  - **Cache of the disk**
  - **Managed (in modern times) by the *operating system***
  - **Using relatively sophisticated mechanisms (e.g., LRU-like)**
  - **Since reading from disk is extremely time consuming**

Manual Allocation: Segmentation

- In the olden days (aka "before the mid 1950s")
  - Programmers incorporated storage allocation in their programs
  - … whenever the total information exceeded main memory
- Segmentation
  - Programmers would divide their programs into "segments"
  - Which would "overlay" (i.e., replace) one another in main memory
- Advantages
  - Programmers are intimately familiar with their code
  - And can optimize the layout of information in main memory
- Disadvantages
  - Immensely tedious and error-prone
  - Compromises the portability of the code

Automatic Allocation: Virtual Memory

- Give programmer the illusion of a very large memory
  - Large: 4 GB of memory with 32-bit addresses
  - Uniform: contiguous memory locations, from 0 to 2^{32}-1
- Independent of
  - The actual size of the main memory
  - The presence of any other processes sharing the computer

- Key idea #1: separate "address" from "physical location"
  - Virtual addresses: generated by the program
  - Memory locations: determined by the hardware and OS
- Key idea #2: caching
  - Swap virtual pages between main memory and the disk

One of the greatest ideas in computer systems!

Making Good Use of Memory and Disk

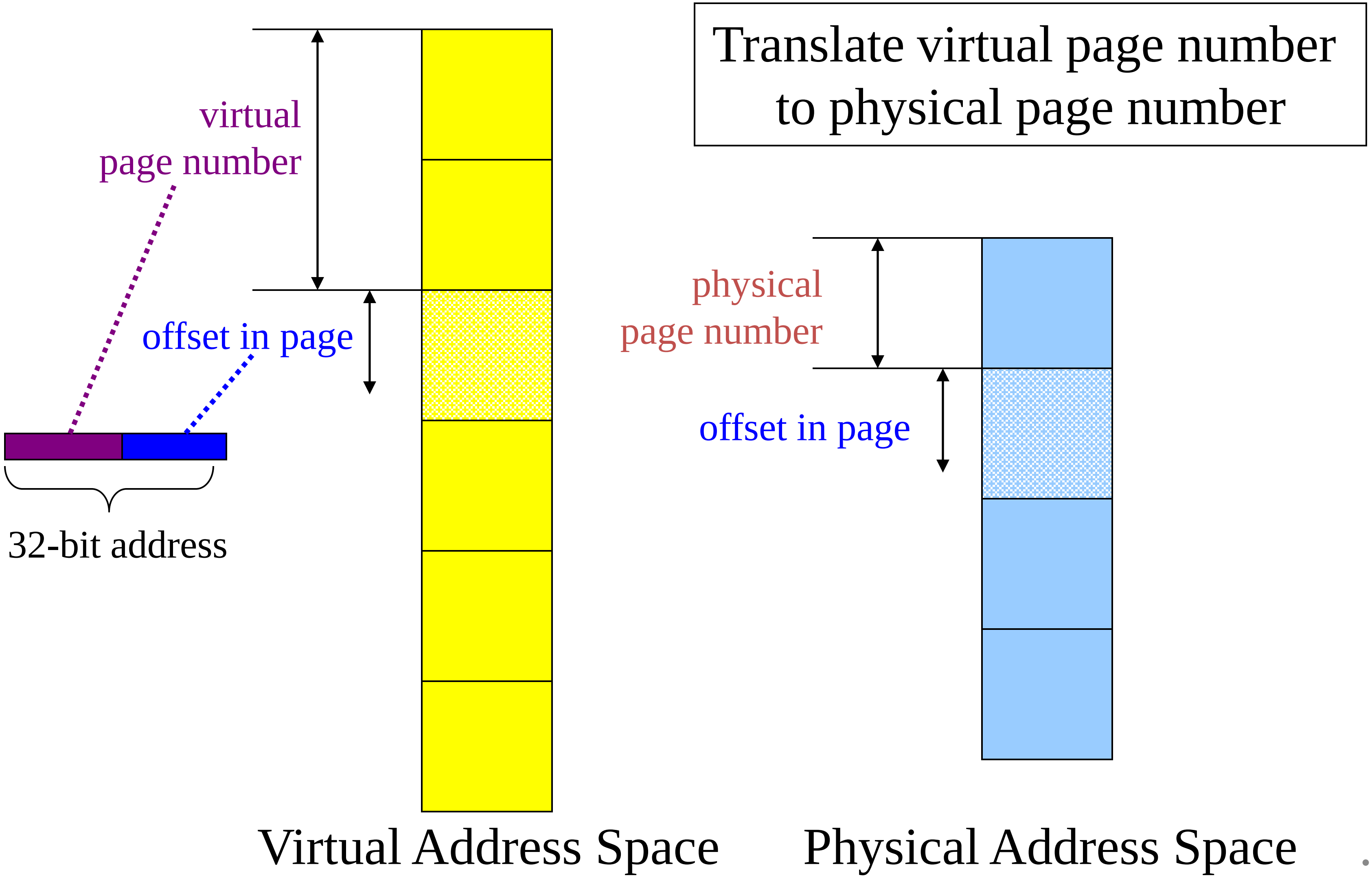
- Good use of the disk
  - Read and write data in large "pages"
  - … to amortize the cost of "seeking" on the disk
  - E.g., page size of 4 KB
- Good use of main memory
  - Even though the address space is large
  - … programs usually access only small portions at a time
  - Keep the "working set" in main memory
    - Demand paging: only bring in a page when needed
    - Page replacement: selecting good page to swap out
- Goal: avoid thrashing
  - Continually swapping between memory and disk

Virtual Address for a Process

- Virtual page number
  - Number of the page in the virtual address space
  - Extracted from the upper bits of the (virtual) address
  - … and then mapped to a physical page number
- Offset in a page
  - Number of the byte within the page
  - Extracted from the lower bits of the (virtual) address
  - … and then used as offset from start of physical page

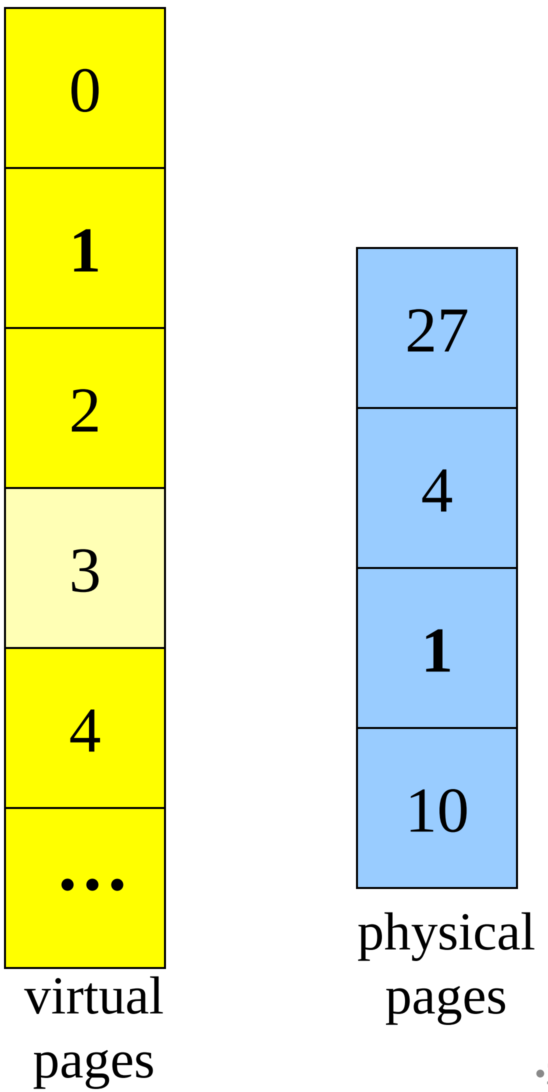
- Example: 4 KB pages
  - 20-bit page number: 2^{20} virtual pages
  - 12-bit offset: bytes 0 to 2^{12}-1

Virtual Memory for a Process



Page Table to Manage the Cache

- Current location of each virtual page
  - Physical page number, or
  - Disk address (or null if unallocated)
- Example
  - Page 0: at location xx on disk
  - Page 1: at physical page 2
  - Page 3: not yet allocated
- Page "hit" handled by hardware
  - Compute the physical address
    - Map virtual page # to physical page #
    - Concatenate with offset in page
  - Read or write from main memory
    - Using the physical address
- Page "miss" triggers an exception…



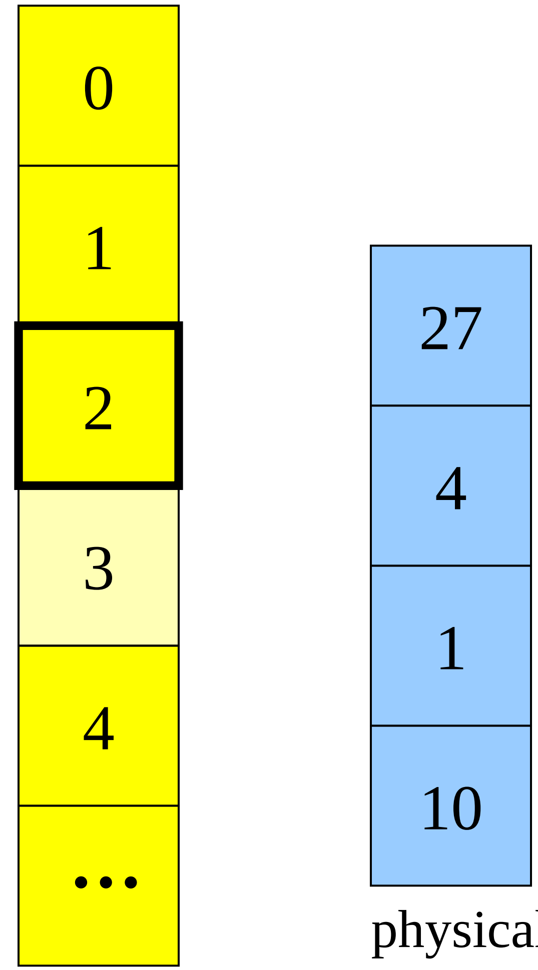
“Miss” Triggers Page Fault

- Accessing page not in main memory

	V	Physical or disk address
0	0	xx
1	1	2
2	**0**	**yy**
3	0	null
4	1	1
		…

```
movl  0002104, %eax
```

Virtual page #2 at location yy on disk!



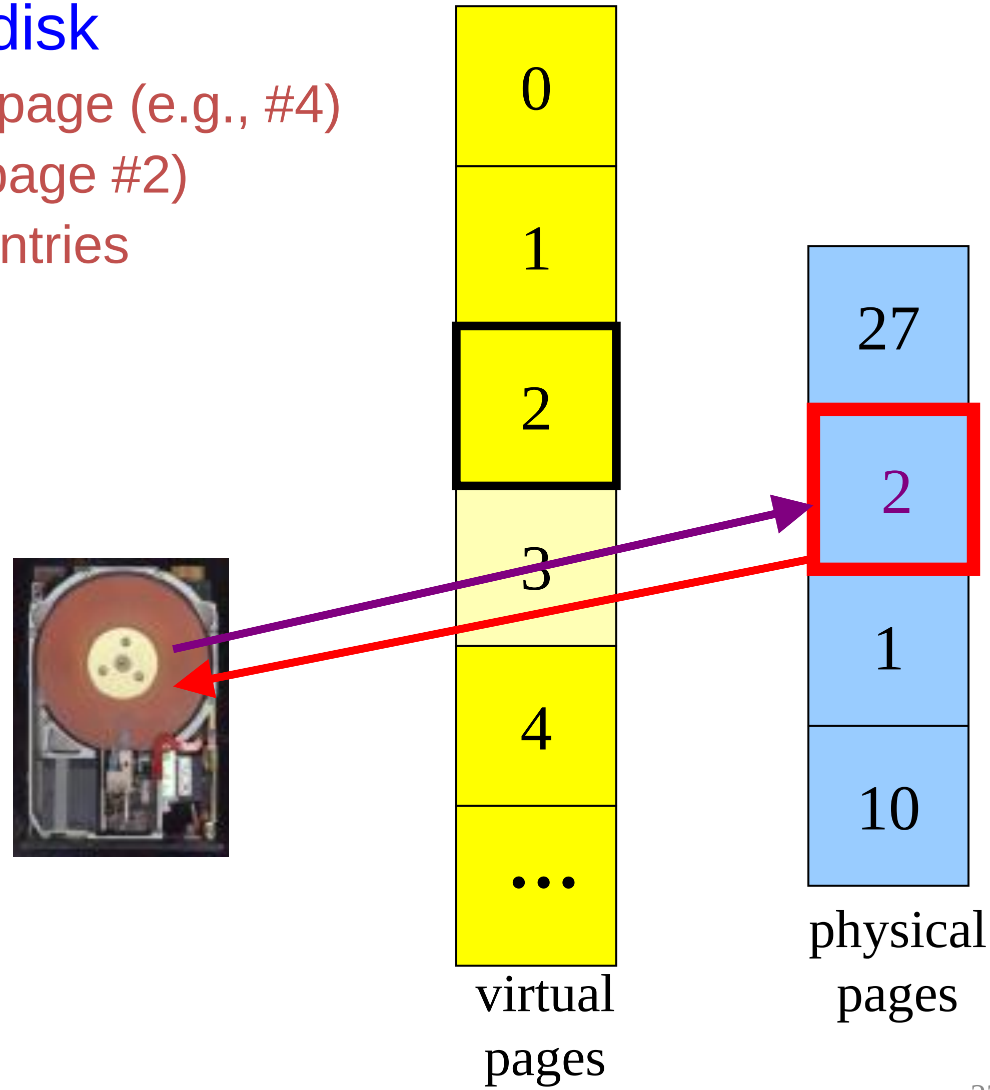
virtual pages

physical pages

OS Handles the Page Fault

- Bringing page in from disk
  - If needed, swap out old page (e.g., #4)
  - Bring in the new page (page #2)
  - Update the page table entries

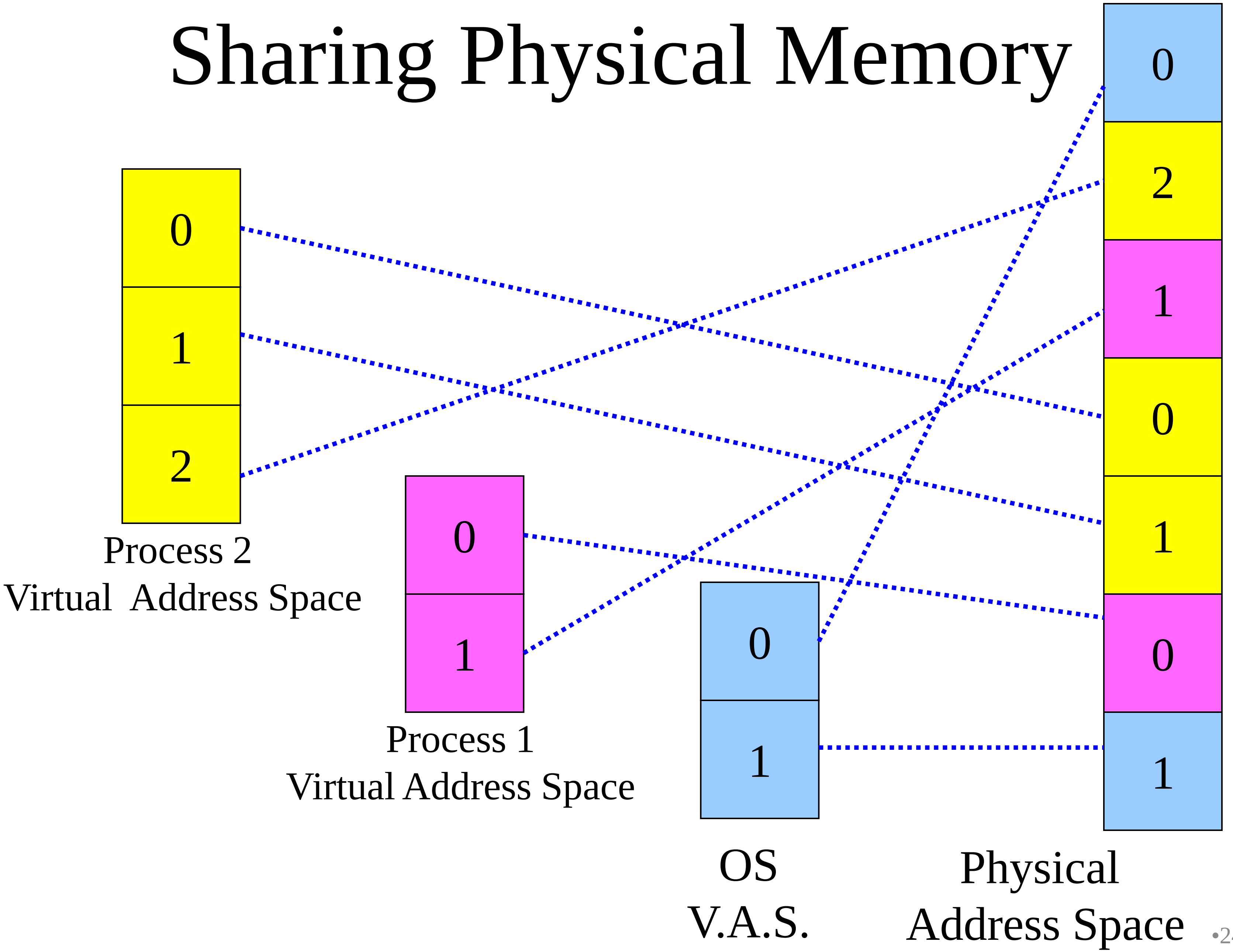
	V	Physical or disk address
0	0	xx
1	1	2
2	~~0~~ 1	~~yy~~ 1
3	0	null
4	~~1~~ 0	~~1~~ zz
		…



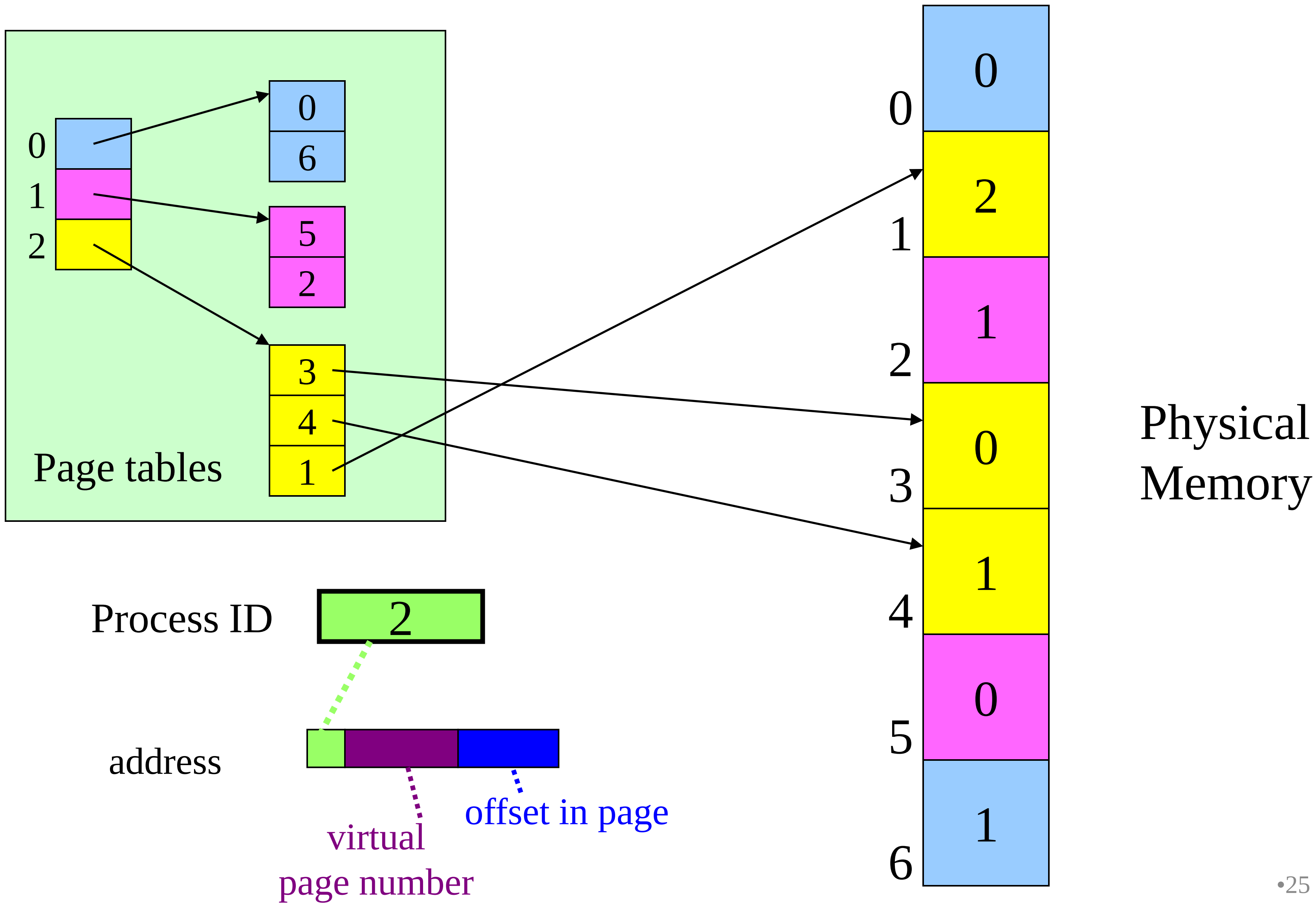
VM as a Tool for Memory Protection

- Memory protection
  - Prevent process from unauthorized reading or writing of memory
- User process should not be able to
  - Modify the read-only text section in its own address space
  - Read or write operating-system code and data structures
  - Read or write the private memory of other processes
- Hardware support
  - Permission bits in page-table entries (e.g., read-only)
  - Separate identifier for each process (i.e., process-id)
  - Switching between *unprivileged* mode (for user processes) and *privileged* mode (for the operating system)

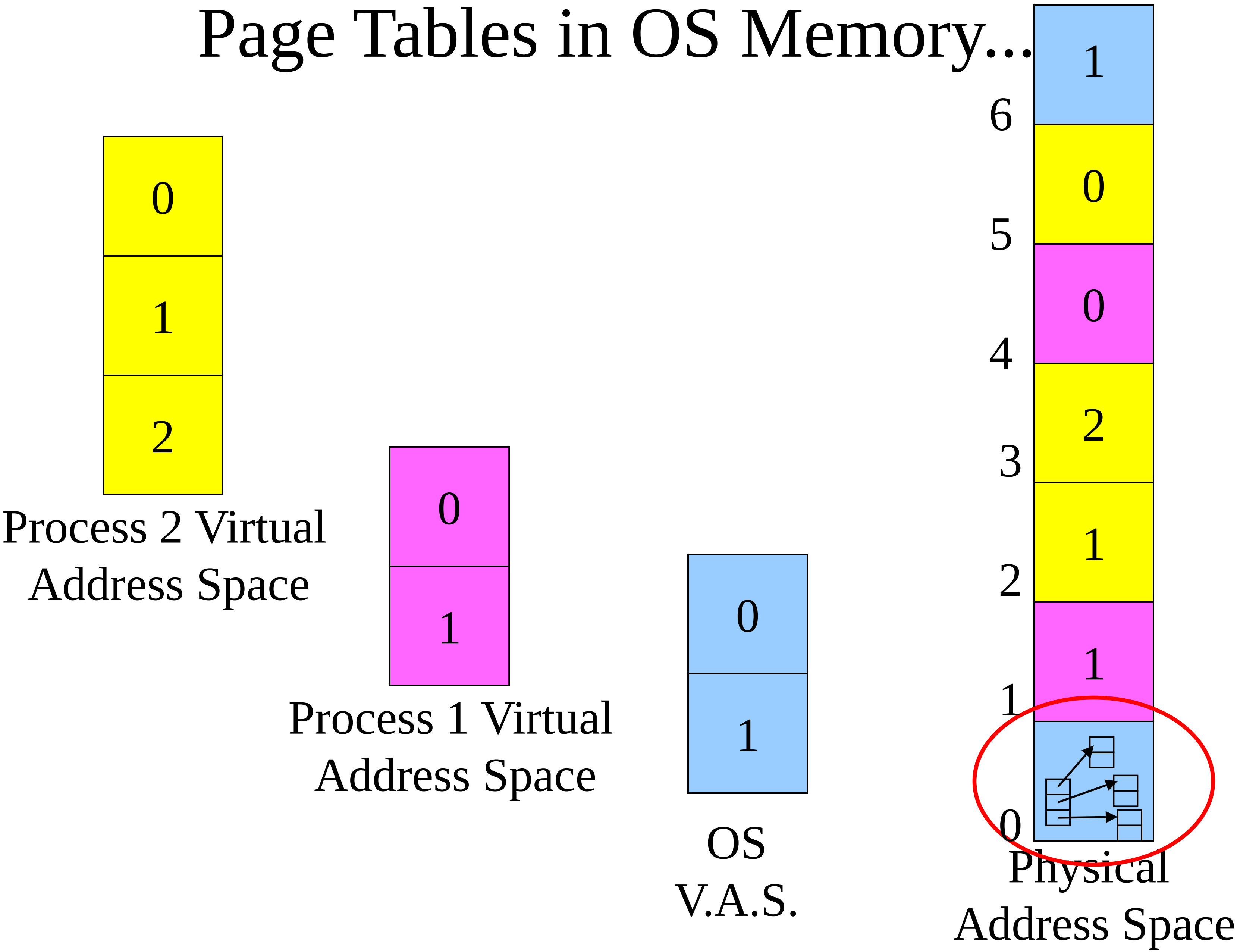
Sharing Physical Memory



Process-ID and Page Table Entries



Page Tables in OS Memory…



Measuring the Memory Usage

Virtual memory usage
Physical memory usage ("resident set size")
CPU time used by this process so far

```
% ps l
F  UID   PID  PPID PRI   VSZ   RSS STAT  TIME COMMAND
0  115  7264  7262  17  4716  1400  SN   0:00 -csh
0  115  7290  7264  17 15380 10940  SN   5:52 emacs
0  115  3283  7264  23  2864   812  RN   0:00 ps l
```

Unix

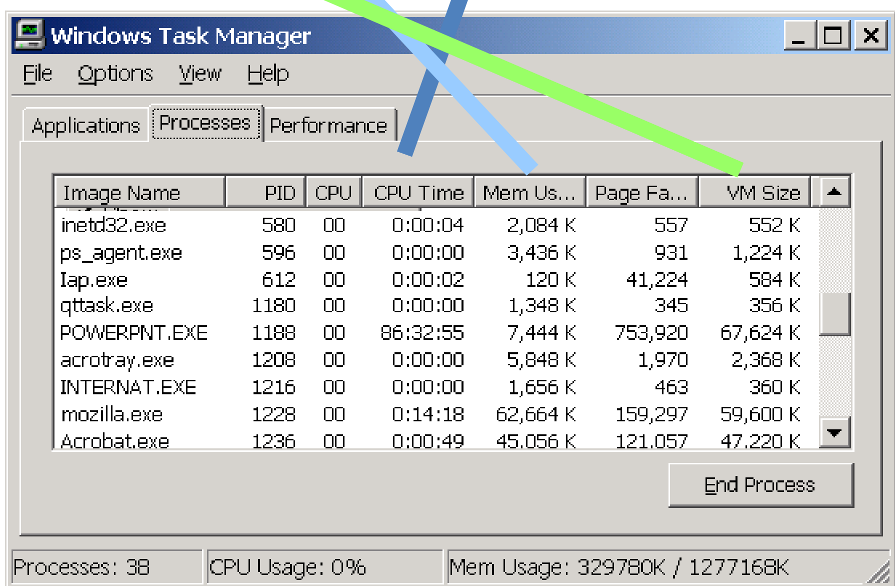


Image Name	PID	CPU	CPU Time	Mem Us...	Page Fa...	VM Size
inetd32.exe	580	00	0:00:04	2,084 K	557	552 K
ps_agent.exe	596	00	0:00:00	3,436 K	931	1,224 K
Iap.exe	612	00	0:00:02	120 K	41,224	584 K
qttask.exe	1180	00	0:00:00	1,348 K	345	356 K
POWERPNT.EXE	1188	00	86:32:55	7,444 K	753,920	67,624 K
acrotray.exe	1208	00	0:00:00	5,848 K	1,970	2,368 K
INTERNAT.EXE	1216	00	0:00:00	1,656 K	463	360 K
mozilla.exe	1228	00	0:14:18	62,664 K	159,297	59,600 K
Acrobat.exe	1236	00	0:00:49	45,056 K	121,057	47,220 K

Windows

VM as a Tool for Memory Management

- Simplifying linking
  - Same memory layout for each process
    - E.g., text section always starts at **`0x08048000`**
    - E.g., stack always grows down from **`0x0bffffff`**
  - Linker can be independent of physical location of code
- Simplifying sharing
  - User processes can share some code and data
    - E.g., single physical copy of stdio library code (like printf)
  - Mapped in to the virtual address space of each process
- Simplifying memory allocation
  - User processes can request additional memory from the heap
    - E.g., using **`malloc()`** to allocate, and **`free()`** to deallocate
  - OS allocates *contiguous* virtual pages…
    - … and scatters them *anywhere* in physical memory

Summary

- Memory hierarchy
  - Memory devices of different speed, size, and cost
  - Registers, on-chip cache, off-chip cache, main memory, disk, tape
  - Locality of memory accesses making caching effective
- Virtual memory
  - Separate virtual address space for each process
  - Provides caching, memory protection, and memory management
  - Implemented via cooperation of the address-translation hardware and the OS (when page faults occur)

- In **Dynamic Memory Management** lectures:
  - Dynamic memory allocation on the heap
  - Management by user-space software (e.g., **`malloc()`** and **`free()`**)