Virtual Memory

CSE 410, Spring 2004

Computer Systems

http://www.cs.washington.edu/education/courses/410/04sp/

Readings and References

- Reading
  - » Chapter 10 through 10.7.1, *Operating System Concepts*, Silberschatz, Galvin, and Gagne

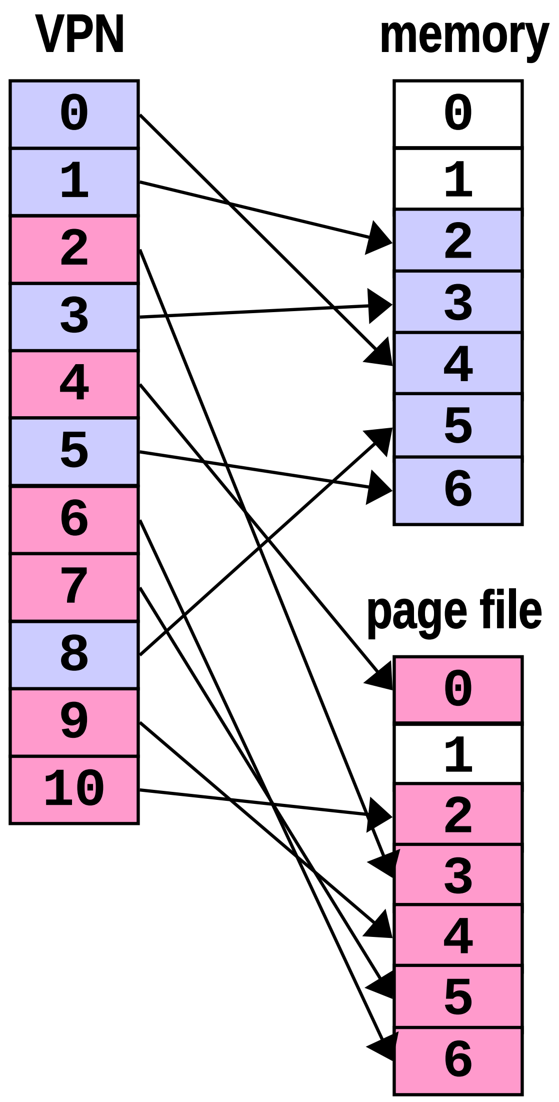
- Other References
  - » Chapter 7, *Inside Microsoft Windows 2000*, Third Edition, Solomon and Russinovich

Virtual Memory

- Virtual memory paging to disk
  - » manage memory as though we always had enough
  - » if more is needed, use disk as backup storage
- Demand Paging
  - » load program pages in to memory as needed
- Another level of the storage hierarchy
  - » Main memory is a cache
  - » Disk space is the backing store

Virtual Memory

- Page table entry can point to a PPN or a location on disk (offset into **page file**)
- A page on disk is swapped back in when it is referenced but is not actually present in main memory
  - » **page fault**



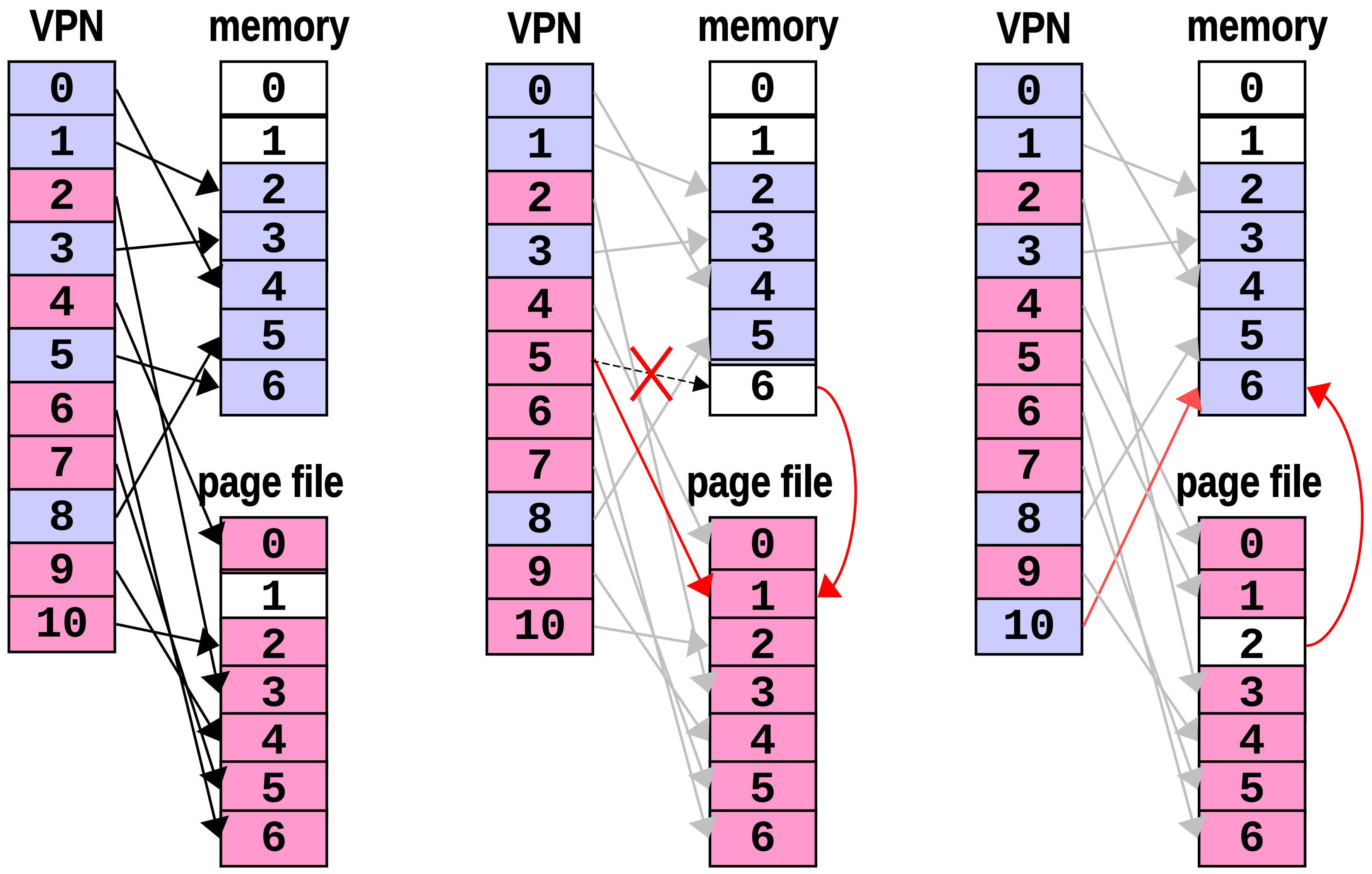
Demand Paging

- As a program runs, the memory pages that it needs may or may not be in memory when it needs them
  - » if in memory, execution proceeds
  - » if not in memory, page is read in from disk and stored in memory
- If desired address is not in memory, the result is a page fault

A reference to memory location X

- MMU: Is X's VPN in the Translation Lookaside Buffer?
  - » Yes => get data from cache or memory. **Done.**
  - » No => Trap to OS to load X's VPN/PPN into the TLB
- OS: Is X's page actually in physical memory?
  - » Yes => replace a TLB entry with X's VPN/PPN. Return control to original thread and restart instruction. **Done.**
  - » No => must load the page from disk
- OS: replace a current page in memory with X's page from disk
  - » pick a page to replace, write it back to disk if dirty
  - » load X's page from disk into physical memory
  - » Replace the TLB entry with X's VPN/PPN.
  - » Return control to original thread and restart instruction. **Done!**

Page Fault Example



Reference to **VPN 10** causes a **page fault** because it is not in memory.

PPN 6 has not been used recently. **Write** it to the page file.

Read VPN 10 from the page file into physical memory at **PPN 6**.

Virtual Memory & Memory Caches

- Physical memory can be thought of as a cache of the page file
- Many of the same concepts we learned with memory caches apply to virtual memory
  - » both work because of locality
  - » dirty bits prevent pages from always being written back
- Some implementation aspects are different
  - » Virtual Memory is usually fully associative with complex replacement algorithms because a page fault is so expensive (at least one disk read is required)

Replacement Algorithms

- FIFO - First In, First Out
  - » throw out the oldest page
  - » often throws out frequently used pages
- RANDOM - toss a random page
  - » works okay, but not good enough
- OPT - toss the one you won’t need
  - » pick page that won't be used for the longest time
  - » provably optimal, but impossible to implement

Approximations to OPT

- LRU - Least Recently Used
  - » remember temporal locality?
    - if we have used a page recently, we probably will use it again in the near future
  - » LRU is hard to implement exactly since there is significant record keeping overhead
- CLOCK - approximation of LRU
  - » and LRU is an approximation of OPT

Perfect LRU

- Least Recently Used
  - » timestamp <u>each</u> page on <u>every</u> reference
  - » on page fault, find oldest page
  - » can keep a queue ordered by time of reference
    - but that requires updating the queue <u>every</u> reference
  - » too much overhead per memory reference

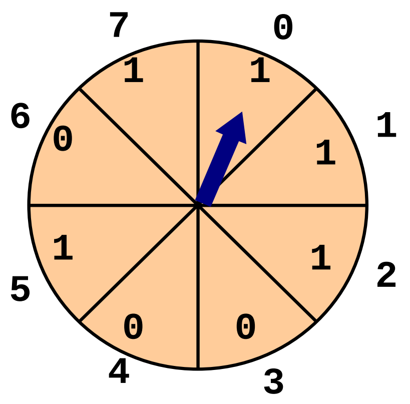
LRU Approximation: Clock

- Clock algorithm
  - » replace an old page, not necessarily the oldest page
- Keep a reference bit for every physical page
  - » memory hardware sets the bit on every reference
  - » bit isn't set => page not used since bit last cleared
- Maintain a "next victim" pointer
  - » can think of it as a clock hand, iterating over the collection of physical pages

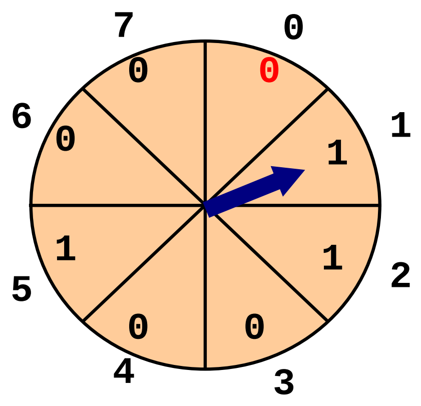
Tick, tick, ...

- On page fault (we need to replace somebody)
  - » advance the victim pointer to the next page
  - » check state of the reference bit
  - » If set, clear the bit and go to next page
    - this page has been used since the last time we looked. Clear the usage indicator and move on.
  - » If not set, select this page as the victim
    - this page has not been used since we last looked
    - replace it with a new page from disk

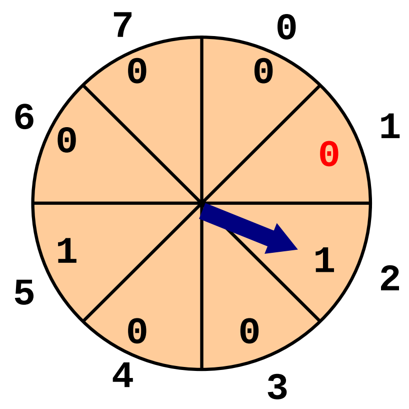
Find a victim



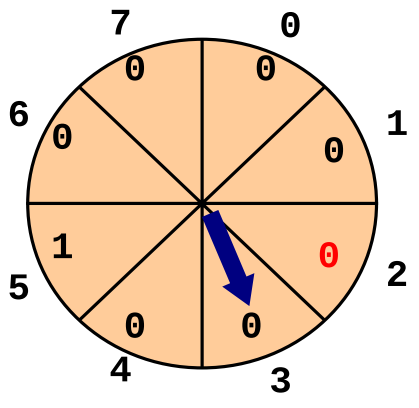
advance; **PPN 0** has been **used**; clear and advance



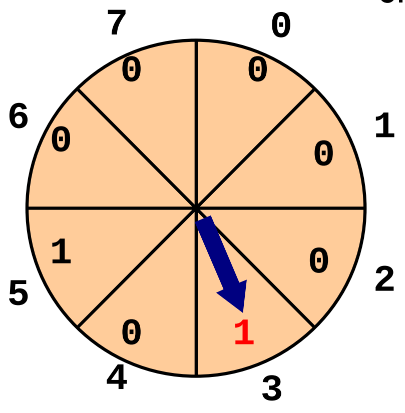
PPN 1 has been **used**; clear and advance



PPN 2 has been **used**; clear and advance



PPN 3 has been **not** been used; replace and set use bit

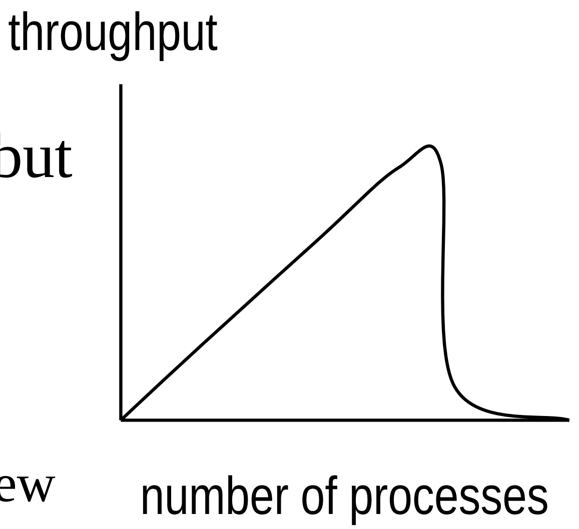


Clock Questions

- Will Clock always find a page to replace?
  - » at worst it will clear all the reference bits, finally coming around to the oldest page
- If the hand is moving slowly?
  - » not many page faults
- If the hand is moving quickly?
  - » many page faults
  - » lots of reference bits set

Thrashing

- **Thrashing** occurs when pages are tossed out, but are needed again right away
  - » listen to the hard drive grind
- Example: a program touches 50 pages often but there are only 40 physical pages in system
- What happens to performance?
  - » enough memory 2 **ns**/ref (most refs hit in cache)
  - » not enough memory 2 **ms**/ref (page faults every few instructions)
- Very common with shared machines



Thrashing Solutions

- If one job causes thrashing
  - » rewrite program to have better locality of reference
- If multiple jobs cause thrashing
  - » only run as many processes as can fit in memory
- Big red button
  - » swap out some memory hogs entirely
- Buy more memory

Working Set

- The working set of a process is the set of pages that it is actually using
  - » set of pages a job has used in the last T seconds
  - » usually much smaller than the amount it might use
- If working set fits in memory process won't thrash
- Why do we adjust the working set size?
  - » too big => inefficient because programs keep pages in memory that they are not using very often
  - » too small => thrashing results because programs are losing pages that they are about to use

Appendix

Windows 2000 Example

Win2K Memory Management

- Win2K Pro/Server/DataCenter
  - » can manage 4 to 64GB physical memory
  - » Virtual address is 2GB user, 2GB system
- Some services of memory manager
  - » allocate / free virtual memory
  - » share memory between processes
  - » map large files into memory
  - » lock pages in memory

W2K Working Set

- Subset of virtual pages resident in physical memory is the current working set
- W2K allows working set to grow
  - » demand paging causes read from disk
  - » reads in clusters of pages on a fault - 8 pages for code, 4 pages for data
- Working set is trimmed as necessary
  - » using version of the clock algorithm

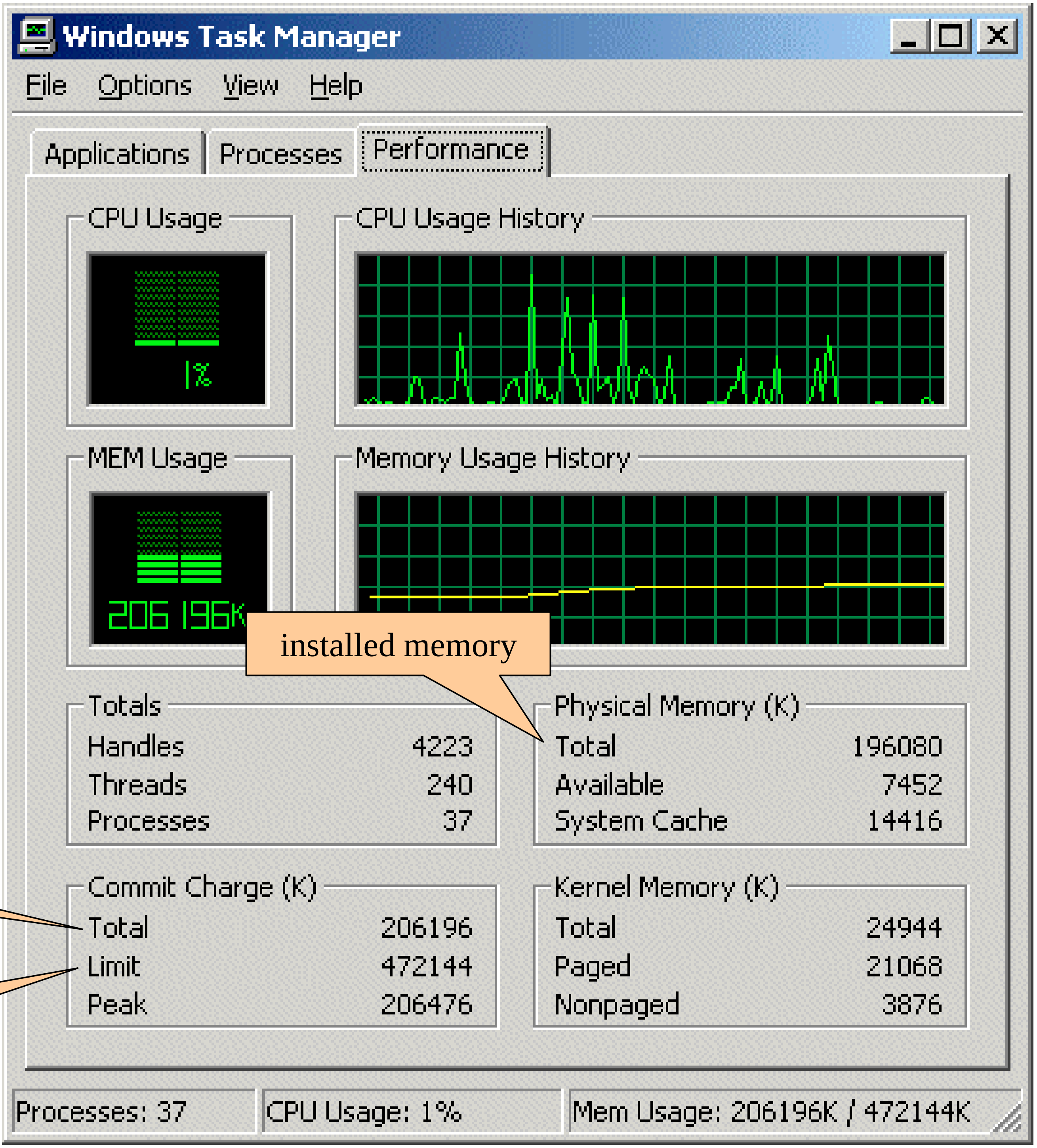
Managing allocations

- A process <u>reserves</u> address space
  - » tell the OS that we will need this memory space
  - » OS builds Virtual Address Descriptors but does not build page tables
- then <u>commits</u> pages in the address space
  - » room exists for the pages in memory or on disk
  - » OS builds page table for committed page when a page fault occurs

Example: Stack Allocation

- Stack area is reserved when thread starts
  - » generally 1MB, although this can be changed at thread creation or with a linker switch
  - » Just one page of 4KB is committed
  - » the following page is marked PAGE_GUARD
  - » if page fault, then one more page is committed and the stack is allowed to grow another 4KB until it happens again

Total committed memory greater than installed physical memory



Totals

Handles	4223
Threads	240
Processes	37

Physical Memory (K)

Total	196080
Available	7452
System Cache	14416

Commit Charge (K)

Total	206196
Limit	472144
Peak	206476

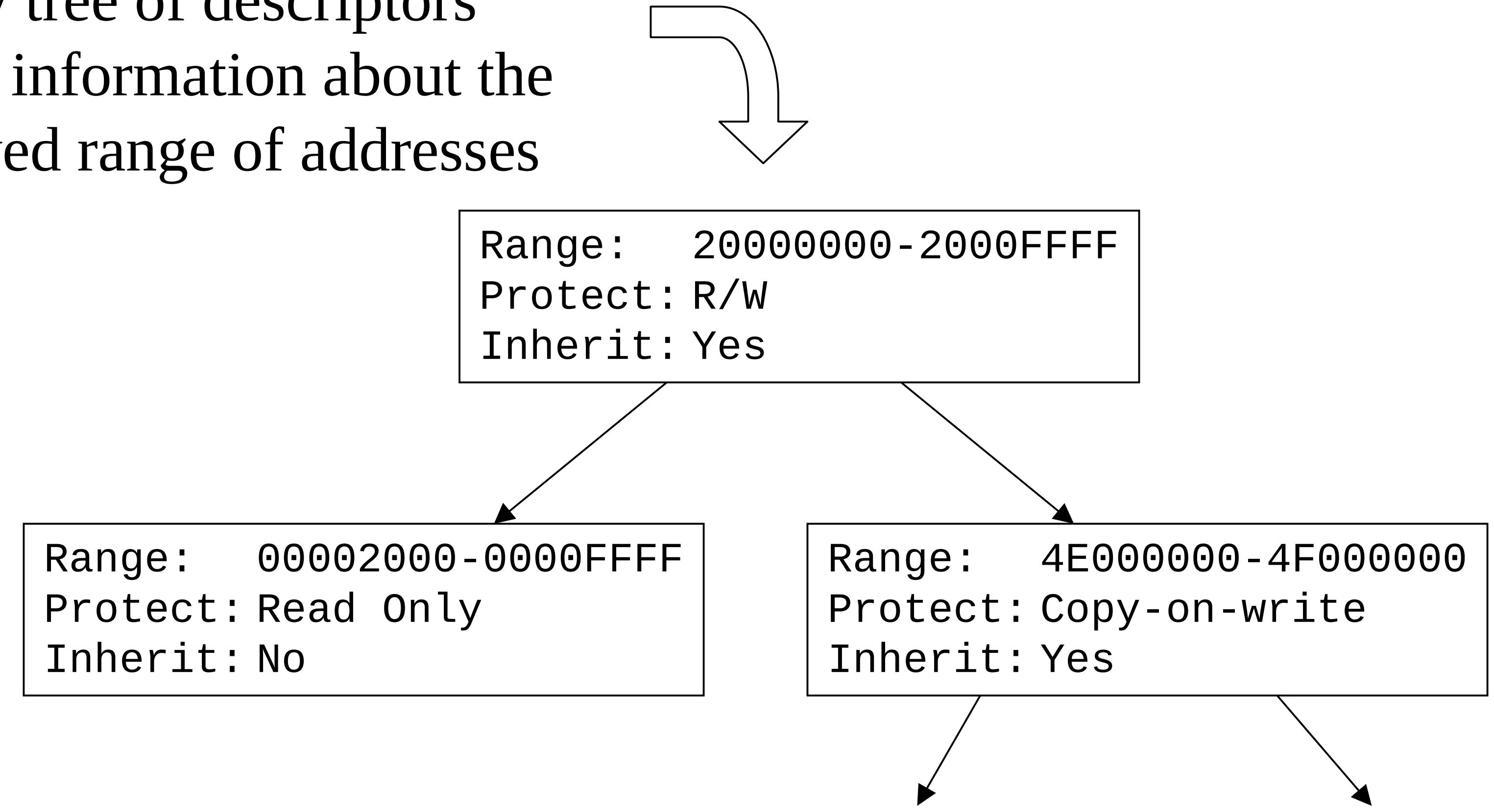
Kernel Memory (K)

Total	24944
Paged	21068
Nonpaged	3876

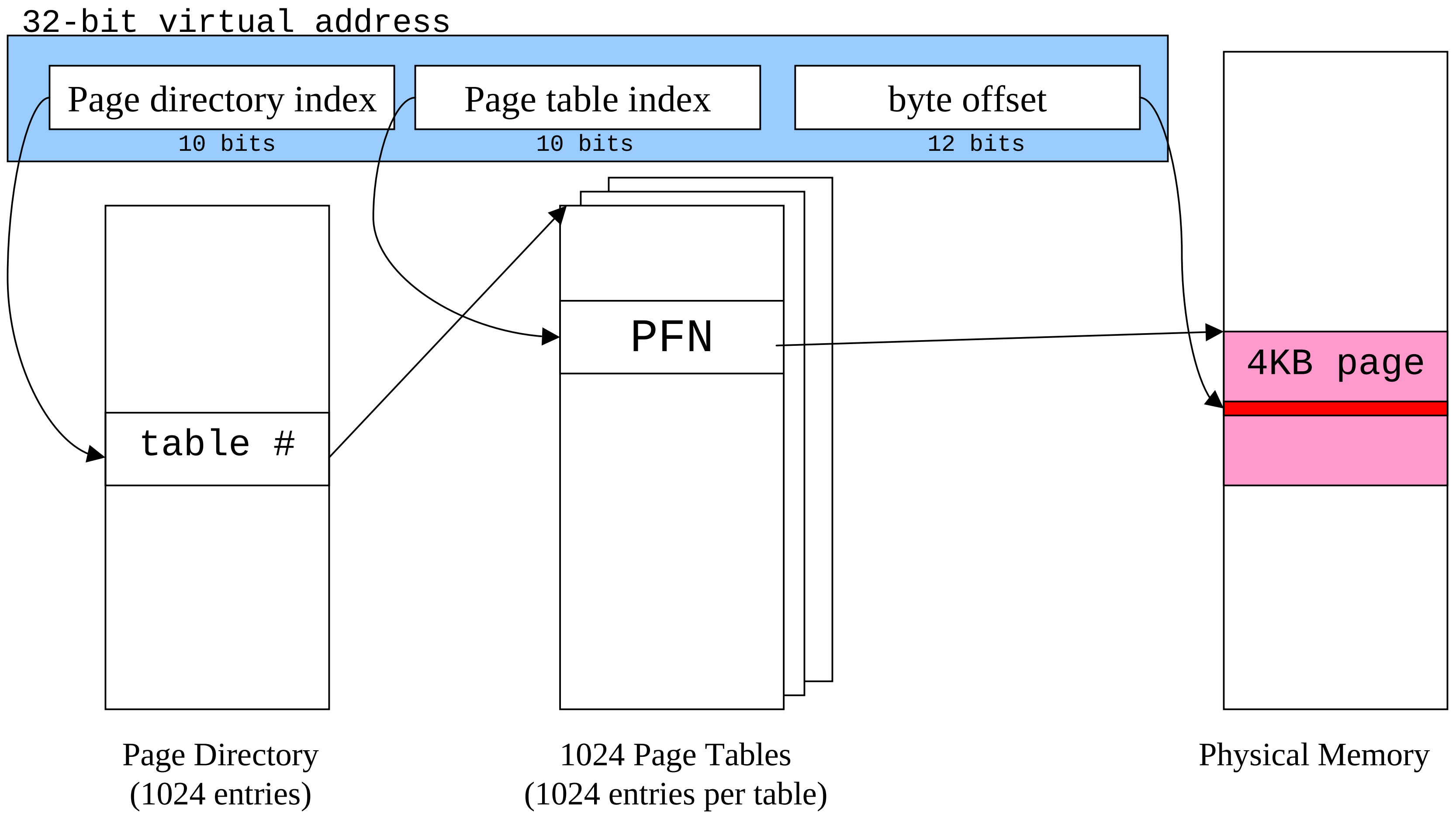
Processes: 37 CPU Usage: 1% Mem Usage: 206196K / 472144K

Virtual Address Descriptors

binary tree of descriptors stores information about the reserved range of addresses



Two-level Page Tables



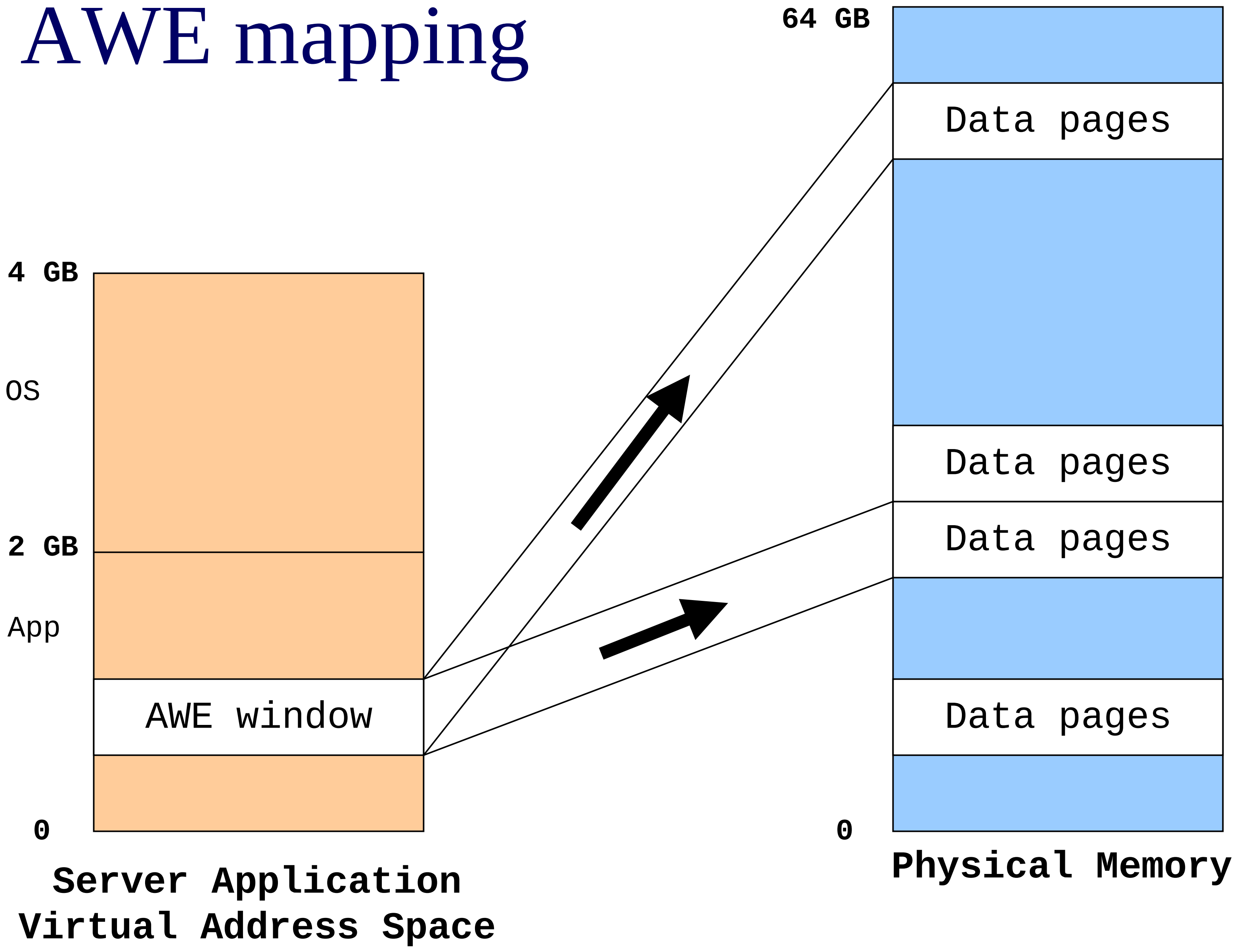
Shared Memory

- “Section Objects” or file mapping objects
- Map portion of address space to common physical pages
    » generally backed up with paging to disk
- page file backed - shared memory
- data file backed - memory mapped file, can be shared

Address Windowing Extensions

- What do you do when 2GB is too small?
- Allocate huge chunks of physical memory
- Designate some virtual pages that are a window into that physical memory
- Remap the virtual pages to point to different parts of the physical memory as needed
- Useful for large database applications, etc

AWE mapping


64 GB
Data pages
4 GB
OS
Data pages
2 GB
Data pages
App
AWE window
Data pages
0
0
Physical Memory
Server Application
Virtual Address Space