Memory Management and Virtual Memory - 2

Some of the slides are adapted from Matt Welsh's.

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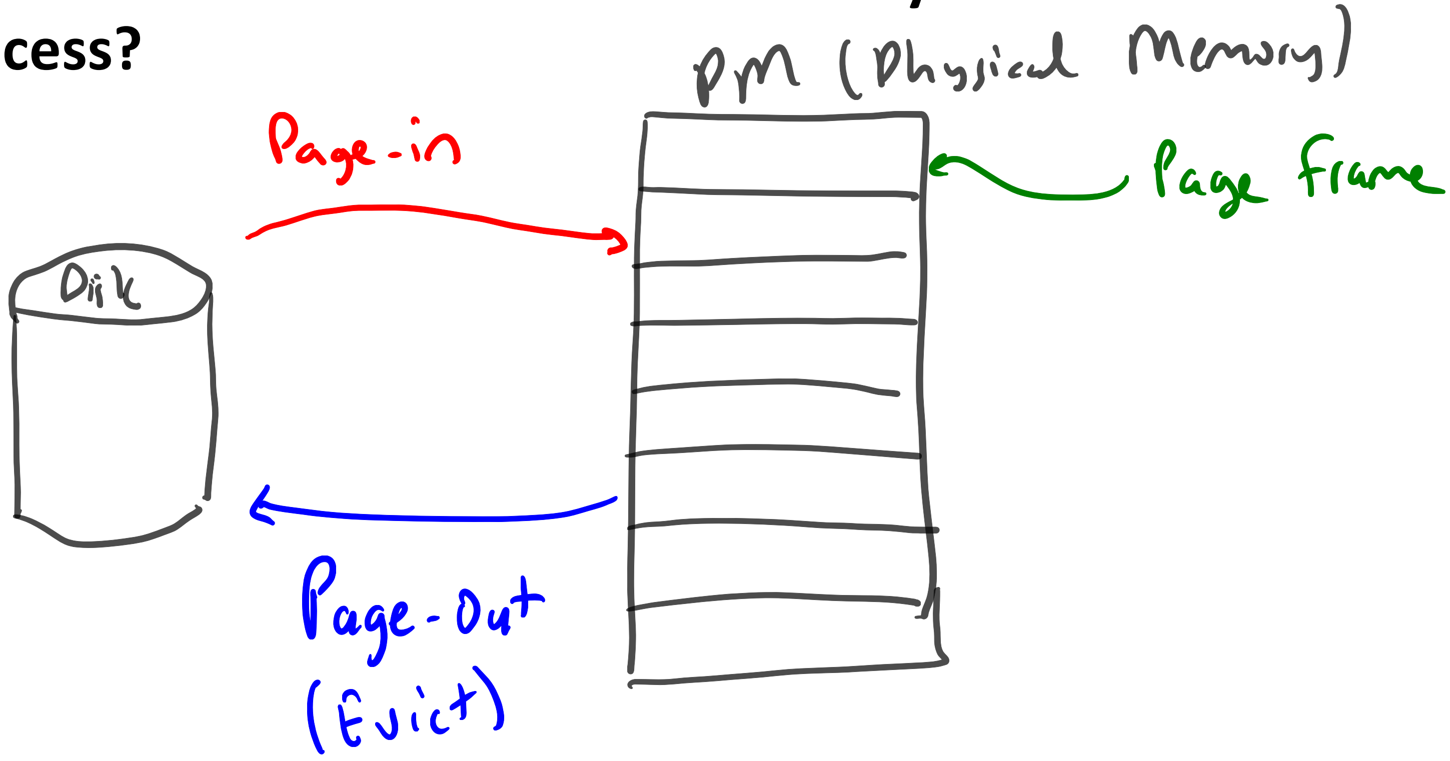
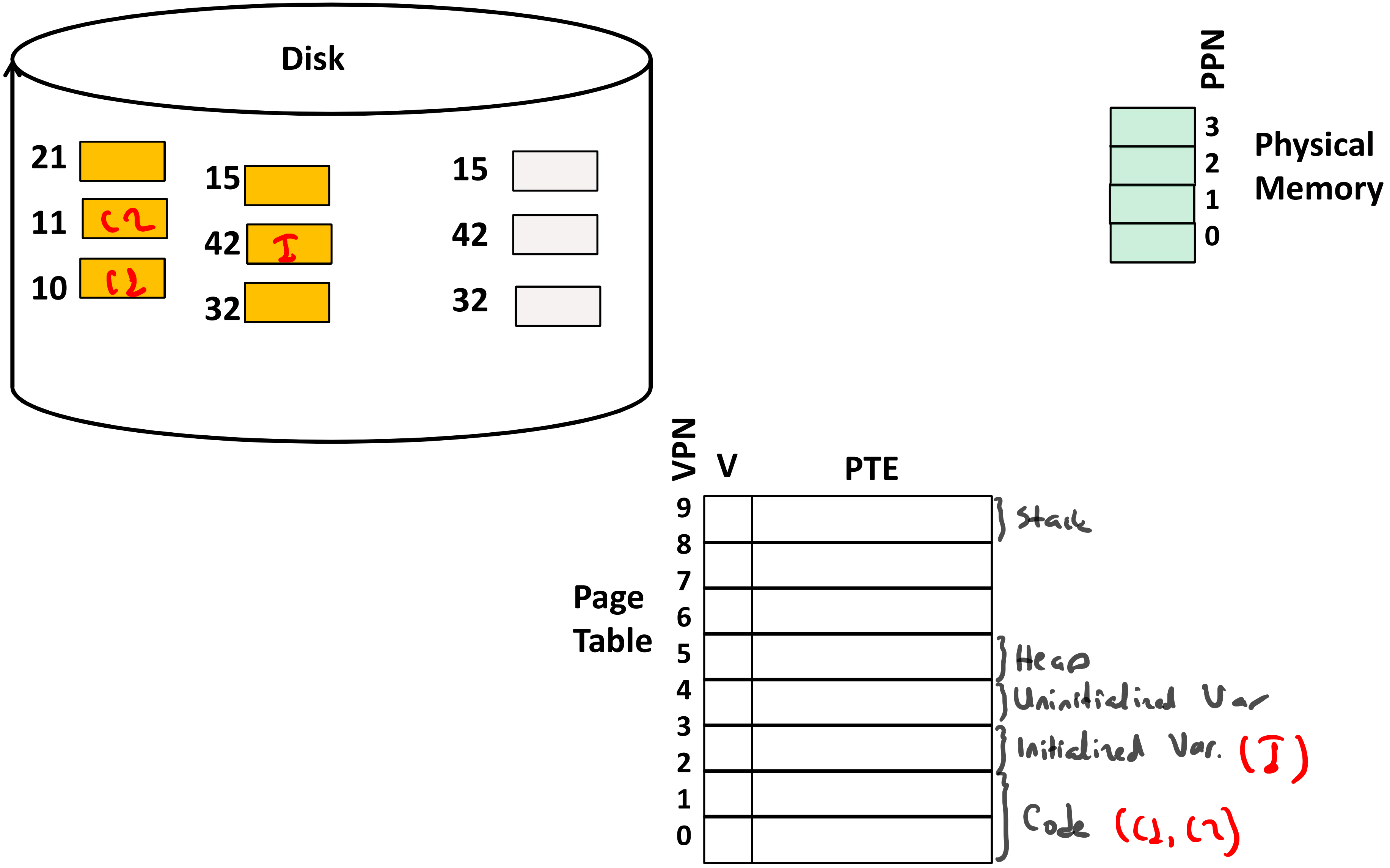
Some slides are from Silberschatz, and Gagne.

Page Replacement

- How do we decide which pages to page-out (a.k.a kick out) of physical memory when memory is tight?

- How do we decide how much memory to allocate to a process?




Disk
21
11
C2
10
C1
15
42
I
32
15
42
32
PPN
3
2
1
0
Physical Memory
VPN
V
PTE
9
8
7
6
5
4
3
2
1
0
Page Table
Stack
Heap
Uninitialized Var
Initialized Var. (I)
Code (C1, C2)

Basic Page Replacement

- **How do we replace pages?**
  - Find the location of the desired page on disk
  - Find a free frame:
    - If there is a free frame, use it
    - If there is no free frame, use a page replacement algorithm to select a victim frame
  - Read the desired page into the (newly) free frame. Update the page and frame tables.
  - Restart the process

Evicting the best page

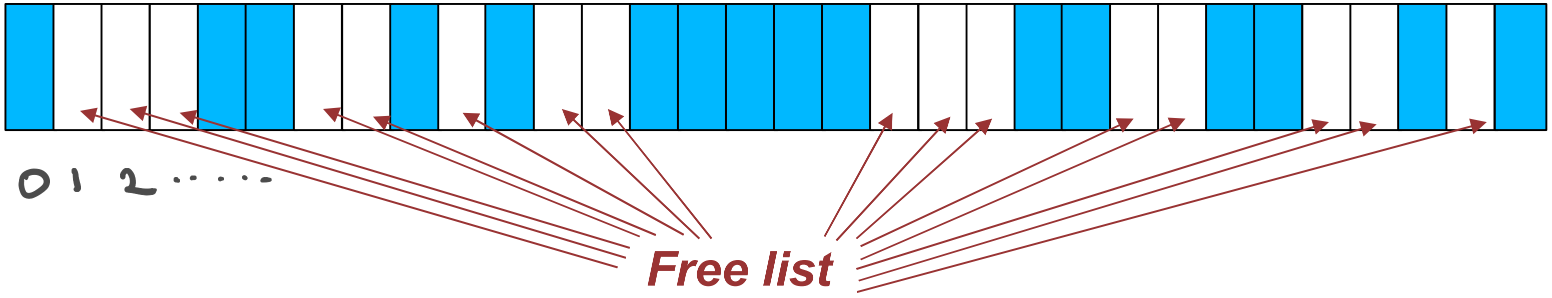
- **Goal of the page replacement algorithm:**
  - Reduce **page fault rate** by selecting the best page to evict
- **The “best” pages are those that will never be used again**
  - However, it's impossible to know in general whether a page will be touched
  - If you have information on future access patterns, it is possible to *prove* that evicting those pages that will be used the *furthest in the future* will *minimize* the page fault rate
- **What is the best algorithm for deciding the order to evict pages?**
  - Much attention has been paid to this problem.
  - Used to be a very hot research topic.
  - These days, widely considered solved (at least, solved well enough)

Locality

- **Exploiting locality**
  - **Temporal locality**: Memory accessed recently tends to be accessed again soon
  - **Spatial locality**: Memory locations *near* recently-accessed memory is likely to be referenced soon
- **Locality helps to reduce the frequency of paging**
  - Once something is in memory, it should be used many times
- **This depends on many things:**
  - The amount of locality and reference patterns in a program
  - The *page replacement policy*
  - The amount of physical memory and the *application footprint*

Page Replacement Basics

- **Most page replacement algorithms operate on some data structure that represents physical memory:**

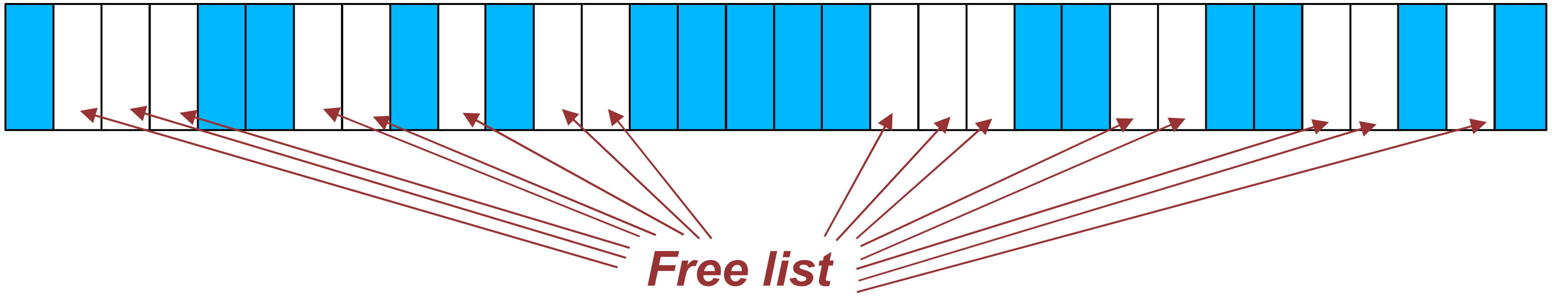


Free list

PPN 0 1 2 .....

Page Replacement Basics

- **Most page replacement algorithms operate on some data structure that represents physical memory:**



  - Might consist of a bitmap, one bit per physical page
  - Might be more involved, e.g., a reference count for each page (remember Shared memory/CoW?)
  - Free list consists of pages that are unallocated
- **Several ways of implementing this data structure**
  - Scan all process PTEs that correspond to mapped pages (valid bit == 1)
  - Keep separate linked list of physical pages
  - *Inverted page table*: One entry per physical page, each entry points to PTE

Free List

PM = 4GB = 2^{32}

Page Size = 1 KB = 2^{10}

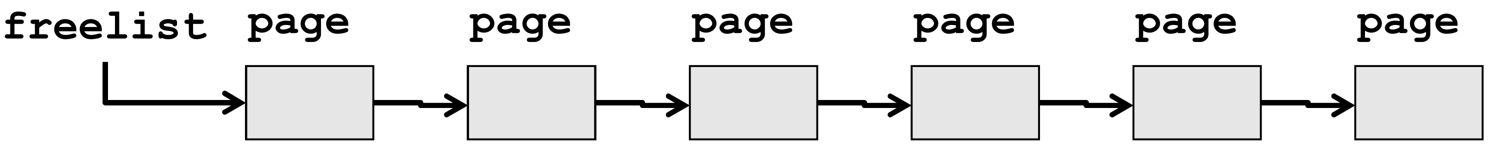
$\Rightarrow$ # of pages = 2^{22} = 4M pages

1 bit per page

1 byte per 8 pages $\Rightarrow \frac{2^{22}}{2^3} = 2^{19}$ = 512K

↳ Bitmap Size

- **Bitmap representation: n/8 bytes.**
  - i.e. 4GB = 4M pages requires 512KB
  - More information per frame required if page is not free. i.e. invalidate PTE's of address translation tables referring an evicted frame.
- **Linked list of `page` structures:**



  - Allocating a free page and inserting an evicted page is fast. Insert/remove from the head
  - Non-free page structures keep reference count, reference to task memory maps, file block info if loaded from a file, state and protection.

Algorithms: Random and FIFO

- **Random: Throw out a random page**
  - Obviously not the best scheme
  - Although very easy to implement!
- **FIFO: Throw out pages in the order that they were allocated**
  - Maintain a list of allocated pages
  - When the length of the list grows to cover all of physical memory, pop first page off list and allocate it
- **Why might FIFO be good?**
- **Why might FIFO not be so good?**

Algorithms: FIFO

- **FIFO: Throw out pages in the order that they were allocated**
  - Maintain a list of allocated pages
  - When the length of the list grows to cover all of physical memory, pop first page off list and allocate it
- **Why might FIFO be good?**
  - Maybe the page allocated very long ago isn't being used anymore
- **Why might FIFO not be so good?**
  - Doesn't consider spatial locality!
  - Suffers from *Belady's Anomaly*: Performance of an application might get *worse* as the size of physical memory *increases!!!*

Belady's Anomaly

time →

Access pattern	0	1	2	3	0	1	4	0	1	2	3	4
Physical memory (3 page frames)	0	0	0	1	2	3	0	0	0	1	4	4
		1	1	2	3	0	1	1	1	4	2	2
			2	3	0	1	4	4	4	2	3	3

9 page faults!

time →

Access pattern	0	1	2	3	0	1	4	0	1	2	3	4
Physical memory (4 page frames)	0	0	0	0	0	0	1	2	3	4	0	1
		1	1	1	1	1	2	3	4	0	1	2
			2	2	2	2	3	4	0	1	2	3
				3	3	3	4	0	1	2	3	4

10 page faults!

Algorithm: OPT (a.k.a MIN)

- **Evict page that won't be used for the longest time in the future**
  - Of course, this requires that we can foresee the future...
  - So OPT cannot be implemented!
- **This algorithm has the provably optimal performance**
  - Hence the name “OPT”
  - Also called “MIN” (for “minimal”)
- **OPT is useful as a “yardstick” to compare the performance of other (implementable) algorithms against**

Algorithm: Least Recently Used (LRU)

- **Evict the page that was used the longest time ago**
  - Keep track of when pages are referenced to make a better decision
  - Use past behavior to predict future behavior
    - LRU uses past information, while MIN uses future information
  - When does LRU work well, and when does it not?
- **Implementation**
  - Every time a page is accessed, record a *timestamp* of the access time
  - When choosing a page to evict, scan over all pages and throw out page with oldest timestamp
- **Problems with this implementation?**

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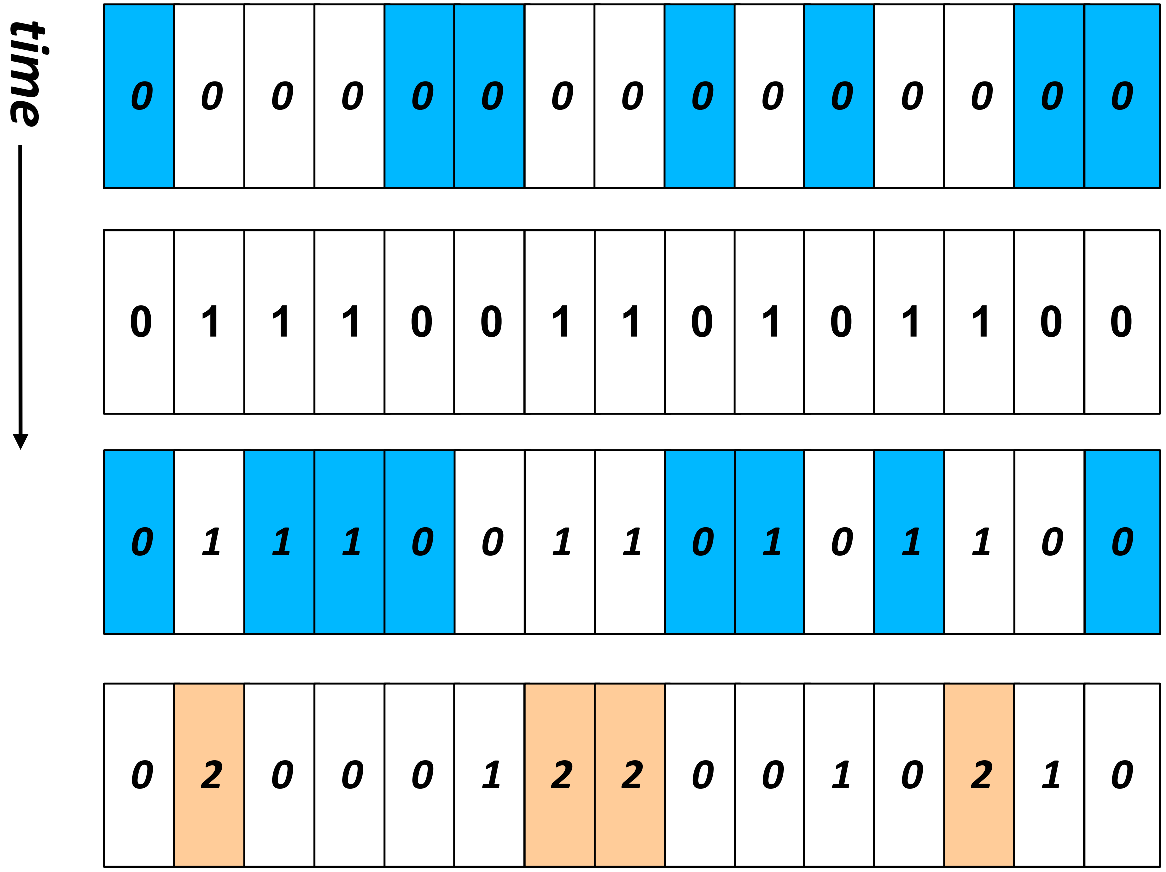
- **Problems with this implementation?**
  - 32-bit timestamp for each page would double the size of every PTE
  - Scanning all of the PTEs for the lowest timestamp would be slow

Approximating LRU: Additional-Reference-Bits

- **Use the PTE reference bit and a small counter per page**
  - (Use a counter of, say, 2 or 3 bits in size, and store it in the PTE)
- **Periodically (say every 100 msec), scan all physical pages in the system**
  - If the page has not been accessed (PTE reference bit == 0), **increment (or shift right)** the counter
  - If the page has been accessed (reference bit == 1), **set counter to zero (or shift right)**
  - **Clear** the PTE reference bit in either case!
- **Counter will contain the number of scans since the last reference to this page.**
  - PTE that contains the highest counter value is the least recently used
  - So, **evict the page with the highest counter**

LRU example



0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	1	1	1	0	0	1	1	0	1	0	1	1	0	0
0	1	1	1	0	0	1	1	0	1	0	1	1	0	0
0	2	0	0	0	1	2	2	0	0	1	0	2	1	0

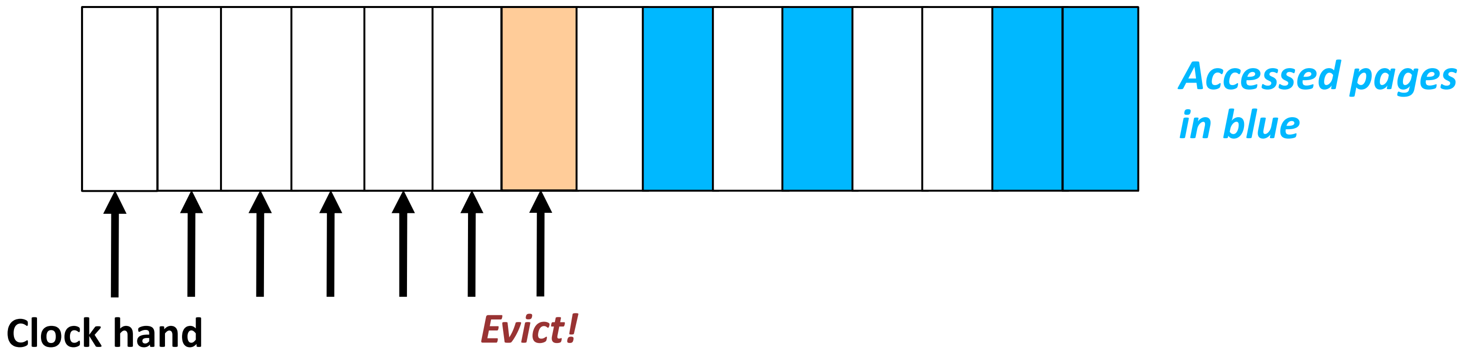
Accessed pages in blue

Increment counter for untouched pages

These pages have the highest counter value and can be evicted.

Algorithm: LRU Second-chance (Clock)

- **LRU requires searching for the page with the highest last-ref count**
  - Can do this with a sorted list or a second pass to look for the highest value
- **Simpler technique: Second-chance algorithm**
  - “Clock hand” scans over all physical pages in the system
    - Clock hand loops around to beginning of memory when it gets to end
  - If PTE reference bit == 1, **clear bit** and **advance hand to give it a second-chance**
  - If PTE reference bit == 0, **evict** this page
    - No need for a counter in the PTE!



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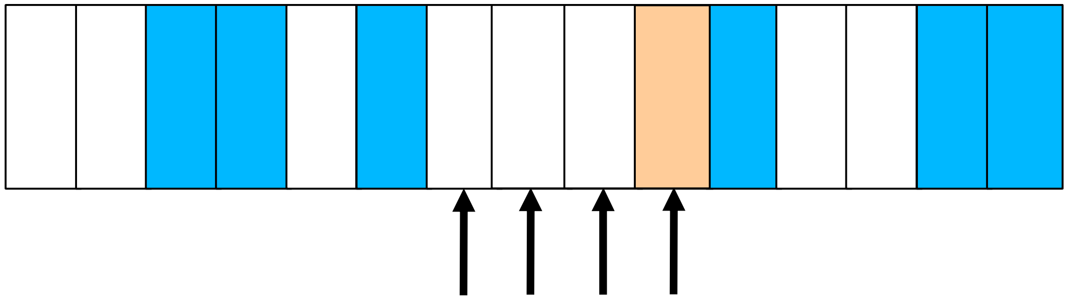


Accessed pages in blue

Clock hand **Evict!**

Algorithm: LRU Second-chance (Clock)

- **This is a lot like LRU, but operates in an iterative fashion**
  - To find a page to evict, just start scanning from current clock hand position
  - What happens if all pages have ref bits set to 1?
  - What is the *minimum* “age” of a page that has the ref bit set to 0?
- **Slight variant -- “nth chance clock”**
  - Only evict page if hand has swept by N times
  - Increment per-page counter each time hand passes and ref bit is 0
  - Evict a page if counter >= N
  - Counter cleared to 0 each time page is used

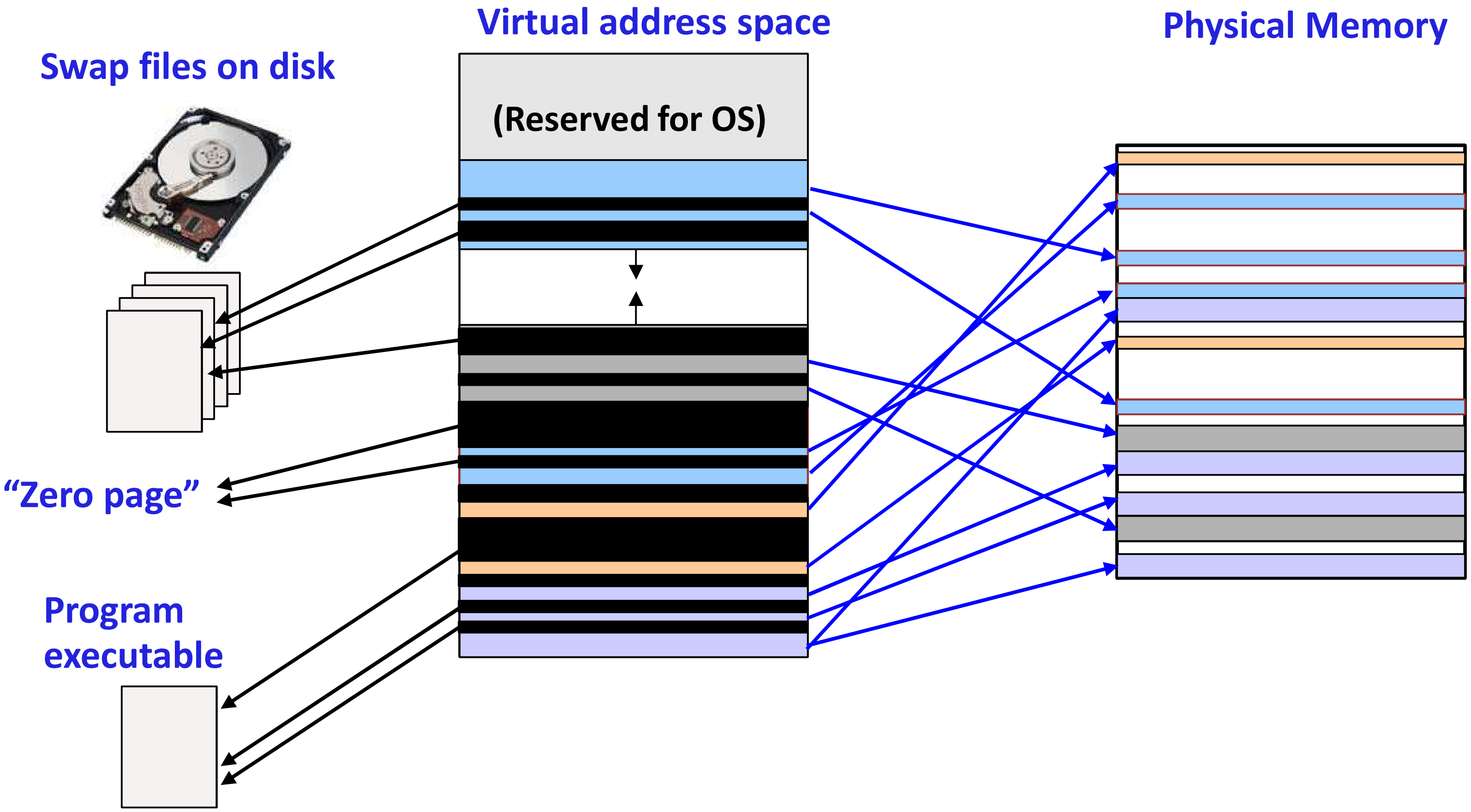
Algorithm: LRU Enhanced Second-chance (Clock)

- **Be even smarter: Consider the R(eference) bit and the M(odified) bit as an ordered pair to classify pages into four classes**
  - **(0,0)** : Neither recently used not modified – best page to replace
  - **(0,1)** : Not recently used but modified – not quite as good, since the page has to be written out before replacement
  - **(1,0)** : recently used but clean – probably will be used again
  - **(1,1)** :recently used and modified – probably will be used again and the page will be need to be written out before it can be replaced

- **We may need to scan the circular queue several times.**
- **The number of required I/O's reduced.**

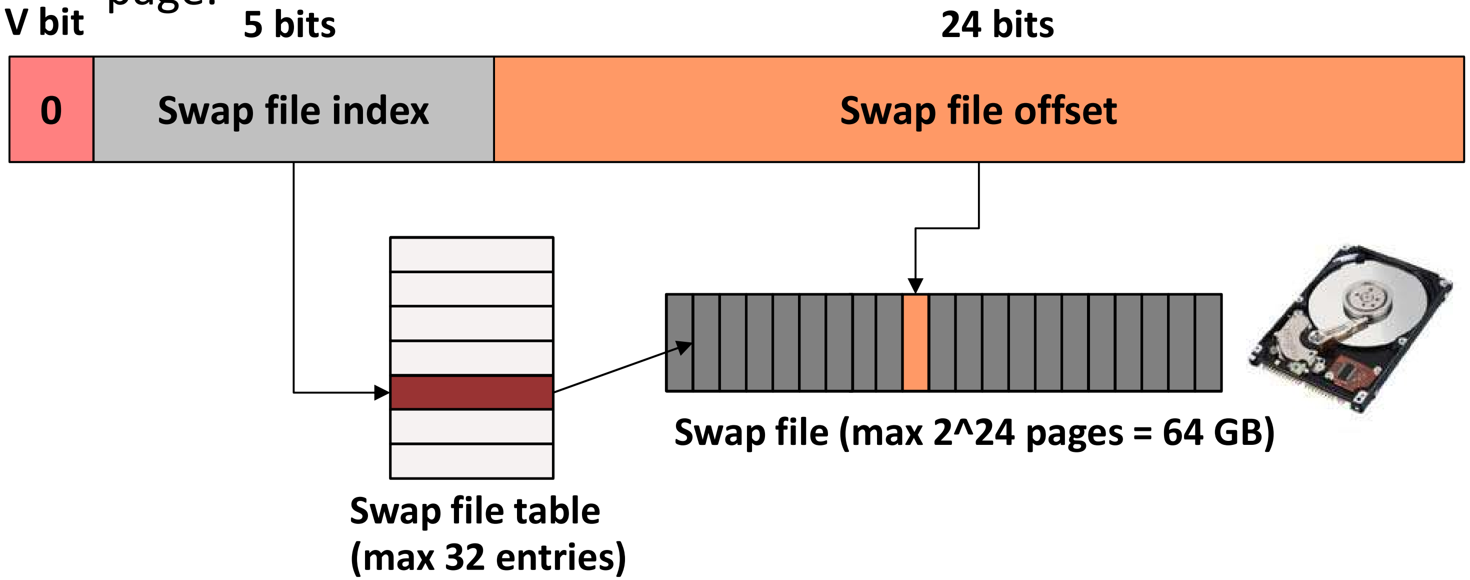
Swap Files

- **What happens to the page that we choose to evict?**
  - Depends on what kind of page it is and what state it's in!
- **OS maintains one or more swap files or partitions on disk**
  - Special data format for storing pages that have been swapped out



Swap Files

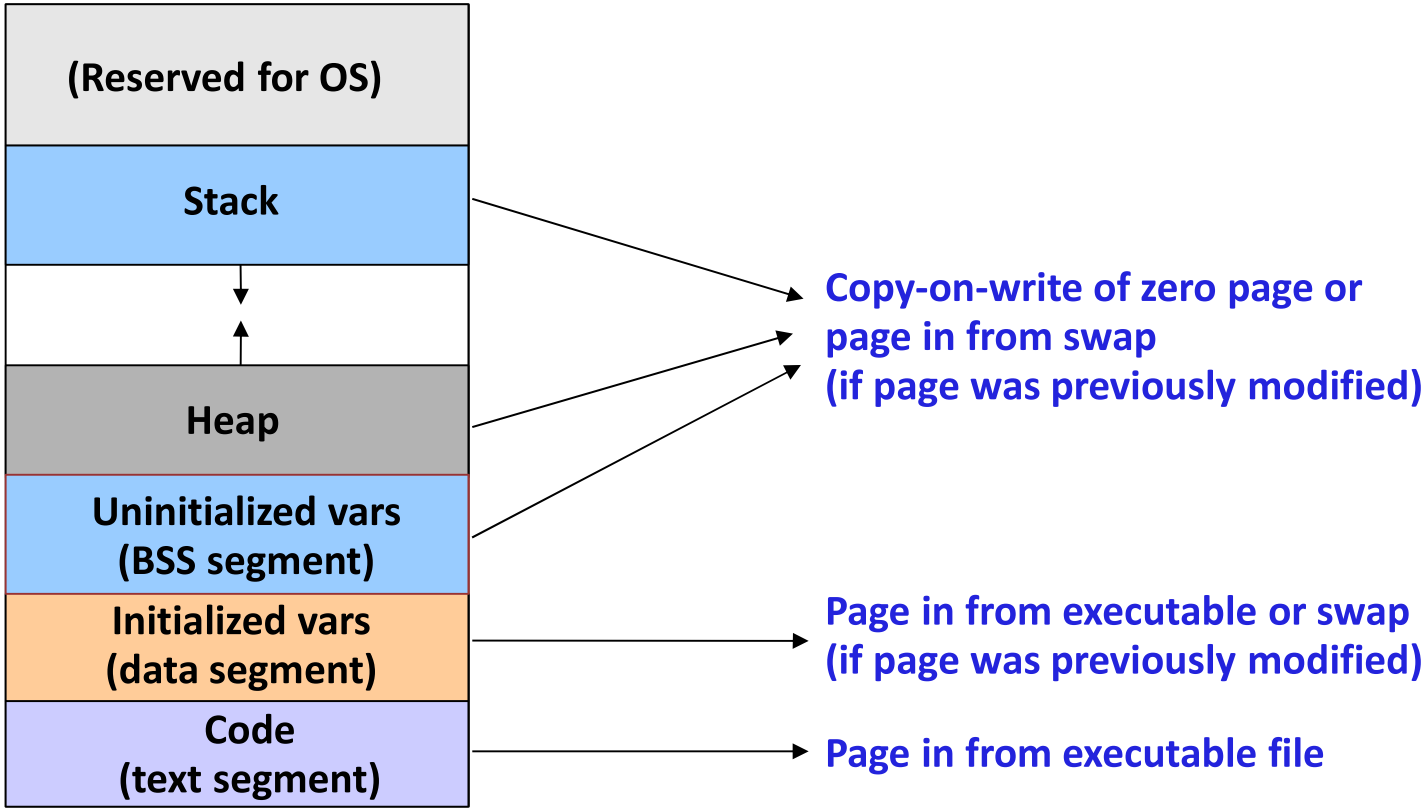
- **How do we keep track of where things are on disk?**
  - Recall PTE format
  - When V bit is 0, can recycle the PFN field to remember something about the page.



- **But … not all pages are swapped in from swap files!**
  - What about executables?
  - Or “zero pages”?
  - How do we deal with these file types?

VM map structure

- **OS keeps a “map” of the layout of the process address space.**
  - This is separate from the page tables.
  - In fact, the VM map is used by the OS to lay out the page tables.
- **This map can indicate where to find pages that are not in memory**
  - e.g., the disk file ID and the offset into the file.



(Reserved for OS)

Stack

Heap

Uninitialized vars (BSS segment)

Initialized vars (data segment)

Code (text segment)

Copy-on-write of zero page or page in from swap (if page was previously modified)

Page in from executable or swap (if page was previously modified)

Page in from executable file

Page Eviction

- **How we evict a page depends on its type.**
- **Code page:**
  - Just remove it from memory – can recover it from the executable file on disk!
- **Unmodified (*clean*) data page:**
  - If the page has previously been swapped to disk, just remove it from memory
    - Assuming that page's backing store on disk has not been overwritten
  - If the page has never been swapped to disk, allocate new swap space and write the page to it
  - Exception: unmodified zero page – no need to write out to swap at all!
- **Modified (*dirty*) data page:**
  - If the page has previously been swapped to disk, write page out to the swap space
  - If the page has never been swapped to disk, allocate new swap space and write the page to it

Physical Frame Allocation

- **How do we allocate physical memory across multiple processes?**
  - What if Process A needs to evict a page from Process B?
  - How do we ensure fairness?
  - How do we avoid having one process hogging the entire memory of the system?
- **Local replacement algorithms**
  - Per-process limit on the physical memory usage of each process
  - When a process reaches its limit, it evicts pages *from itself*
- ***Global-replacement algorithms***
  - *Physical size of processes can grow and shrink over time*
  - *Allow processes to evict pages from other processes*
- ***Note that one process' paging can impact performance of entire system!***
  - *One process that does a lot of paging will induce more disk I/O*

Working Set

- **A process's *working set* is the set of pages that it currently “needs”**
- ***Definition:***
  - WS(P, t, w) = the set of pages that process P accessed in the time interval [t-w, t]
  - “w” is usually counted in terms of number of page references
    - A page is in WS if it was referenced in the last w page references
- ***Working set changes over the lifetime of the process***
  - Periods of high locality exhibit **smaller** working set
  - Periods of low locality exhibit **larger** working set
- ***Basic idea: Give process enough memory for its working set***
  - If WS is larger than physical memory allocated to process, it will tend to swap
  - If WS is smaller than memory allocated to process, it's wasteful
  - This amount of memory grows and shrinks over time

Estimating the working set

- **How do we determine the working set?**
- **Simple approach: modified clock algorithm**
  - Sweep the clock hand at fixed time intervals
  - Record how many seconds since last page reference
  - All pages referenced in last T seconds are in the working set
- **Now that we know the working set, how do we allocate memory?**
  - If working sets for all processes fit in physical memory, done!
  - Otherwise, reduce memory allocation of larger processes
    - Idea: Big processes will swap anyway, so let the small jobs run unencumbered
  - Very similar to shortest-job-first scheduling: give smaller processes better chance of fitting in memory
- **How do we decide the working set time limit T?**
  - If T is too large, very few processes will fit in memory
  - If T is too small, system will spend more time swapping
    - Which is better?

Page Fault Frequency

- **Dynamically tune memory size of process based on # page faults**
- **Monitor page fault rate for each process (faults per sec)**
- **If page fault rate above threshold, give process more memory**
  - Should cause process to fault less
  - Doesn't always work!
    - Recall Belady's Anomaly
- **If page fault rate below threshold, reduce memory allocation**

When to Evict/Page-Out Pages

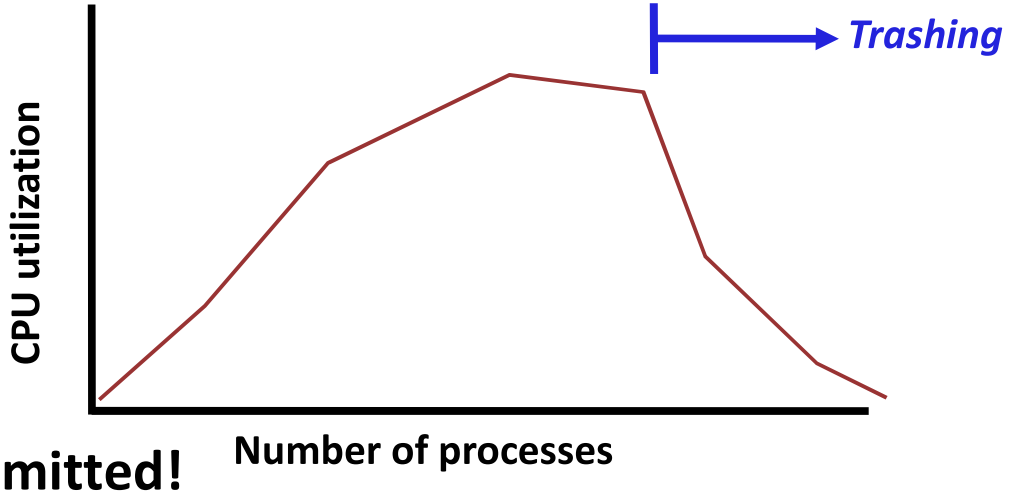
- **On page fault, when a free page is required**
  - In a loaded system most requests need replacement algorithm to work.
  - When replacement requires I/O, task needs to sleep.
  - Performance of tasks reduces, replacement time is added.
- **Solution: Page Daemon (or swap daemon)**
  - Watches system free memory. Start replacing pages as free memory drops below a threshold.
  - Maintains a pool of free memory all the time so tasks requiring a new page can find a new page instantly.
  - It sleeps when there is plenty of memory. Adaptively wake ups more often and replaces more pages as system is low on memory.
  - In extreme cases, it starts replacing whole memory of tasks (trashing)

Paging and swapping

- **However, on heavily-loaded systems, memory can fill up**
- **To achieve good system performance, must move "inactive" pages out to disk**
        - If we didn't do this, what options would the system have if memory is full???
    - What constitutes an "inactive" page?
    - How do we choose the right set of pages to copy out to disk?
    - How do we decide when to move a page back into memory?
- **Swapping**
    - Usually refers to moving the memory for an entire process out to disk
    - This effectively puts the process to sleep until OS decides to swap it back in
- **Paging out/in**
    - Refers to moving individual pages out to disk (and back)
    - We often use the terms "paging out" and "swapping" interchangeably

Trashing

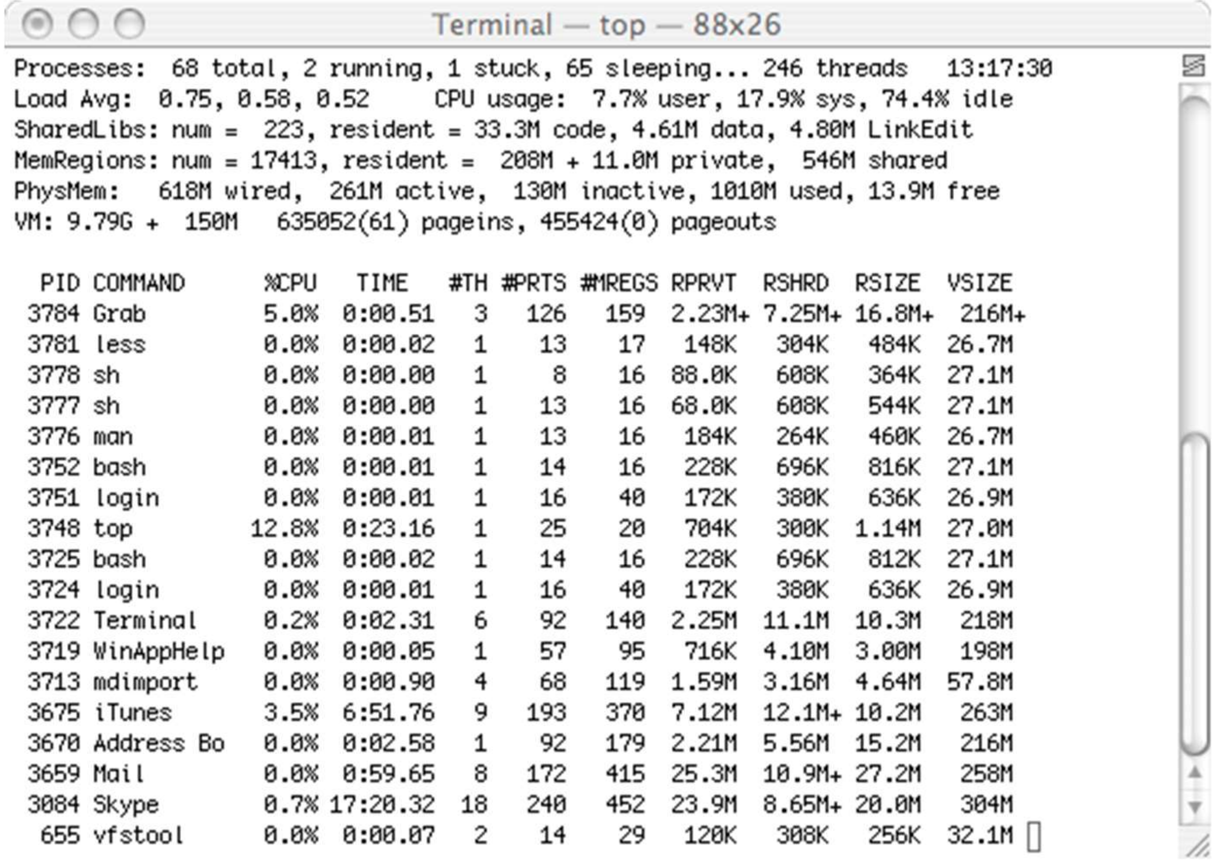
- **As system becomes more loaded, spends more of its time paging**
  - Eventually, no useful work gets done!



- **System is overcommitted!**
  - If the system has too little memory, the page replacement algorithm doesn't matter
- **Solutions?**
  - Change scheduling priorities to “slow down” processes that are thrashing
  - Identify process that are hogging the system and kill them?
    - Is thrashing a problem on systems with only one user?

Benefits of sharing pages

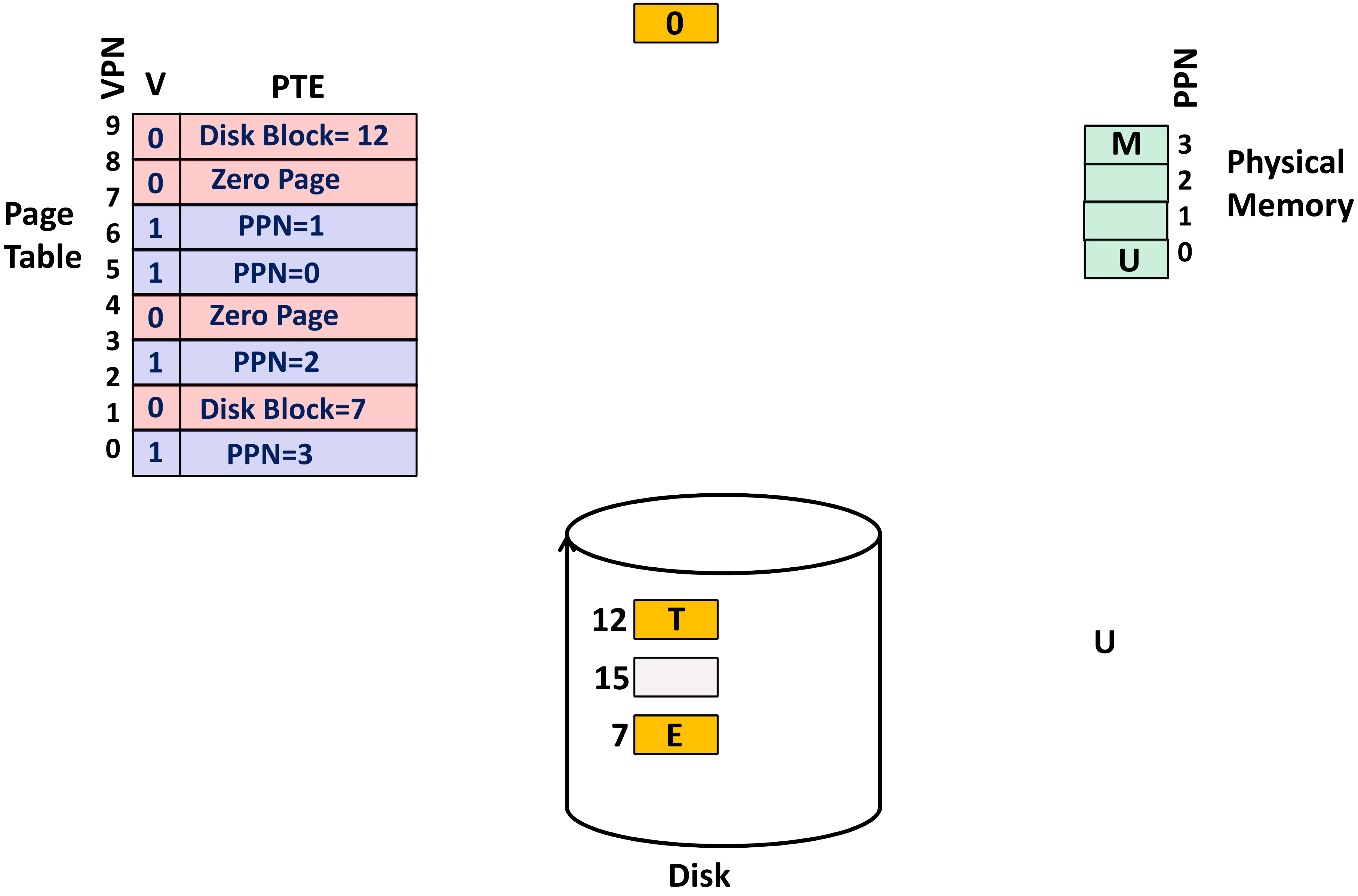
- **How much memory savings do we get from sharing pages across identical processes?**
  - A lot! Use the “top” command...



```
Processes:  68 total, 2 running, 1 stuck, 65 sleeping... 246 threads   13:17:30
Load Avg:  0.75, 0.58, 0.52     CPU usage:  7.7% user, 17.9% sys, 74.4% idle
SharedLibs: num =  223, resident = 33.3M code, 4.61M data, 4.80M LinkEdit
MemRegions: num = 17413, resident =  208M + 11.0M private,  546M shared
PhysMem:   618M wired,  261M active,  130M inactive, 1010M used, 13.9M free
VM: 9.79G +  150M   635052(61) pageins, 455424(0) pageouts

  PID COMMAND      %CPU   TIME   #TH #PRTS #MREGS RPRVT  RSHRD  RSIZE  VSIZE
 3784 Grab         5.0%  0:00.51   3   126   159  2.23M+ 7.25M+ 16.8M+  216M+
 3781 less         0.0%  0:00.02   1    13    17   148K   304K   484K  26.7M
 3778 sh           0.0%  0:00.00   1     8    16  88.0K   608K   364K  27.1M
 3777 sh           0.0%  0:00.00   1    13    16  68.0K   608K   544K  27.1M
 3776 man          0.0%  0:00.01   1    13    16   184K   264K   460K  26.7M
 3752 bash         0.0%  0:00.01   1    14    16   228K   696K   816K  27.1M
 3751 login        0.0%  0:00.01   1    16    40   172K   380K   636K  26.9M
 3748 top         12.8%  0:23.16   1    25    20   704K   300K  1.14M  27.0M
 3725 bash         0.0%  0:00.02   1    14    16   228K   696K   812K  27.1M
 3724 login        0.0%  0:00.01   1    16    40   172K   380K   636K  26.9M
 3722 Terminal     0.2%  0:02.31   6    92   140  2.25M  11.1M  10.3M   218M
 3719 WinAppHelp   0.0%  0:00.05   1    57    95   716K  4.10M  3.00M   198M
 3713 mdimport     0.0%  0:00.90   4    68   119  1.59M  3.16M  4.64M  57.8M
 3675 iTunes       3.5%  6:51.76   9   193   370  7.12M  12.1M+ 10.2M   263M
 3670 Address Bo   0.0%  0:02.58   1    92   179  2.21M  5.56M  15.2M   216M
 3659 Mail         0.0%  0:59.65   8   172   415  25.3M  10.9M+ 27.2M   258M
 3084 Skype        0.7% 17:20.32  18   240   452  23.9M  8.65M+ 20.0M   304M
  655 vfstool      0.0%  0:00.07   2    14    29   120K   308K   256K  32.1M
```

Page Replacement



0

Page Table

VPN	V	PTE
9	0	Disk Block= 12
8	0	Zero Page
7		
6	1	PPN=1
5	1	PPN=0
4	0	Zero Page
3		
2	1	PPN=2
1	0	Disk Block=7
0	1	PPN=3

Physical Memory

	PPN
M	3
	2
	1
U	0

U

Disk

12	T
15	
7	E