Virtual Memory

- What is virtual memory, and why do we need it?
- Demand paging
  - » Description
  - » Performance
- Page replacement: when it doesn't all fit into memory
  - » Algorithms
  - » Performance
- Allocating frames to processes
- Performance issues
  - » Thrashing
  - » Page size selection
  - » Writing efficient programs
- Virtual memory and segments

What is Virtual Memory?

- Virtual memory separates logical memory from physical memory
  - » Keep only the "active" code & data for a program in memory
  - » Keep the remainder of the pages on disk, swapping them in and out as necessary
  - » Allow a logical address space much larger than the available physical memory
  - » Allows more programs to run by keeping inactive pieces of code & data on disk
- Virtual memory can be used with
  - » Paging
  - » Segmentation

Demand Paging

- Simplest form of paging is <u>demand paging</u>: bring a page into memory only when it's actually referenced
  - » Requires less I/O (don't get pages until they're used)
  - » Requires less memory (not wasted on unused pages)
  - » More users (less memory per process)
  - » Faster response on process startup (no need to load entire program before running)
- On reference to page not in memory:
  - » If not in memory (but on disk), fetch into memory
  - » If invalid reference (dereferencing NULL pointer), abort process

Valid Bit in Page Table

- Associate a valid bit with each page table entry
  - 1 => page in memory
  - 0 => page not in memory
- Set all valid bits to 0 initially
- During address translation, check valid bit
  - 1 => translation proceeds normally
  - 0 => page fault exception (instruction doesn't finish)

frame #	valid bit
0x41f	1
0x241	1
0x03e	1
	0
0x12a	1
⋮	
	0
	0
0x3e0	1

How a Page Fault Works

- On reference to invalid page (valid == 0), cause an exception called a <u>page fault</u>
- During a page fault, OS must decide if reference is valid
  - » Use another bit from the page table entry (not the valid bit)
  - » Check the “frame number” to see if the page is on disk (for example, 0 == page not on disk either)
- OS allocates an empty page frame
- Read the page from disk into the just-allocated frame
- Modify the page table
  - » Insert the real frame number into the page table entry
  - » Change the valid bit from 0 to 1
- Restart the instruction
  - » Can be difficult with complex instructions!

What If There's No Free Frame?

- After a system has been running for some time, all frames will be allocated if there's no way to free them
  - » Exiting processes free their frames
  - » How can the OS claim frames from still-running processes?
- Page replacement
  - » Find a page in memory that's not in active use
  - » Swap it out (move it to disk)
  - » Mark the page table entry as invalid again
  - » A given page may be fetched into memory multiple times
- Page replacement algorithms
  - » Decide which page in memory to swap to disk
  - » Critical for good performance: OS wants to minimize page faults

Demand Paging Performance

- Assume the following numbers
  - » Page fault rate *p* (0 => no page faults)
  - » Page fault time *f*, composed of
    - – Exception overhead (~ 1-10 us)
    - – Time to swap the old page out (~ 10 ms)
    - – Time to swap the new page in (~ 10 ms)
    - – Instruction restart overhead (~ 1-10 us)
  - » Memory access time *t*
- Effective access time for memory is then:
  EAT = (1-p) * t + p * f

Demand Paging Performance: Example

- Basic performance numbers:
  - » Memory access time = 100 ns
  - » Disk access time = 10 ms
  - » Page being replaced is modified 40% of the time
    - – Only needs to be written to disk if it's modified
  - » Page fault overhead is 20 us (excluding disk I/O time)
  - » Page faults occur every 100,000 instructions
- Page fault time
  - » 10000 us * (1 + 40% * 1) + 20 us = 14020 us
- Effective access time
  - » EAT = p * 14020 + (1-p) * 0.100
  - » EAT = 10^{-5} * 14020 + (1- 10^{-5}) * 0.100 = 0.24 us = 240 ns

Page Replacement

- Modify page fault handler to include page replacement
  - » Prevents over-allocation of memory
  - » Centralizes code in one place
- Use *modified* (*dirty*) *bit* to keep track of changed pages
  - » Set bit to 0 each time page is swapped into memory
  - » Set bit to 1 each time page is written to
  - » Only swap to disk when page is “dirty” (dirty bit == 1)
- Store dirty bit in the page table entry
  - » TLB entries include the dirty bit and other bits used by paging
  - » Changes to status bits (such as dirty bit) occur only in TLB entry
  - » TLB entries written back to page table when the entry is replaced in the TLB

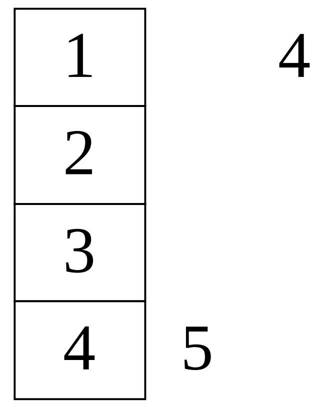
Page Replacement Algorithms

- A page replacement algorithm chooses the page to be swapped out of memory
- Goal: get the lowest page fault rate
  - Lower page fault rates mean better performance
  - Compare algorithm's page fault against "optimal" algorithm
- Evaluate the algorithm by running it on a particular sequence of memory (page) references
  - Compute the number of page faults on that sequence
  - Compare the page fault rate with other algorithms, including the optimal algorithm
- For these examples, we'll use the reference string
  1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5

Optimal Algorithm

- Optimal algorithm is the goal all other algorithms are measured against
- Rule: replace page that will not be used for the longest period of time
  - » Impossible to do in real OS - requires future knowledge
  - » Other algorithms attempt to figure out which page will be used furthest in the future, but may guess wrong
- Useful as a baseline for other algorithms' performance

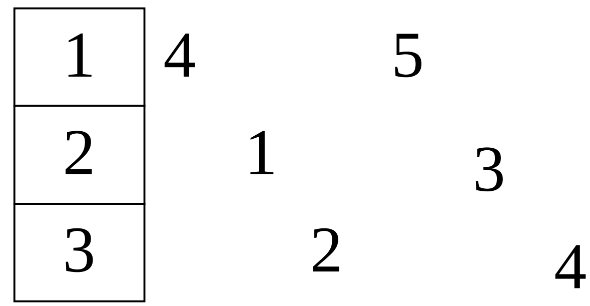
1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5



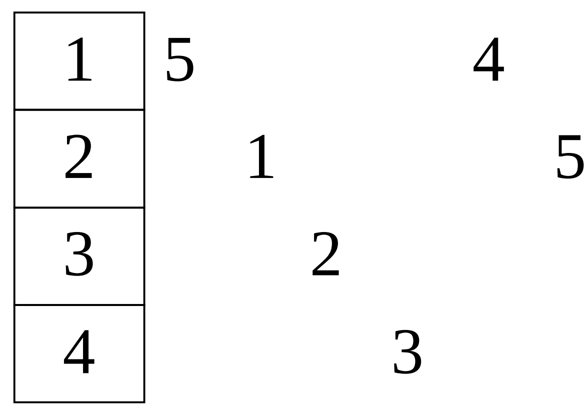
First-In-First-Out (FIFO) Algorithm

- Rule: replace the page that has been in memory the longest
- Simple to implement
  - » Keep a circular list of frames
  - » Update a pointer to the next frame to be replaced
- Belady's Anomaly: more frames can result in more (not fewer) page faults!
  - » May be present for FIFO replacement
  - » Can't be present for LRU replacement

1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5



9 page faults



10 page faults

Least Recently Used (LRU) Algorithm

- Rule: replace the page that was used least recently
- Implementation
  - » Keep a counter in each page table entry
  - » Copy the current clock into the PTE when a reference is made
  - » Search PTEs for the lowest clock value to find the page to replace
- Can be slow in real OS
  - » Searching through all those PTEs takes time!
  - » Updating PTEs with the current clock is slow

1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5

1				5
2				
3	5		4	
4		3		

Better LRU Implementation?

- Address problems with previous LRU implementation
  - » Searching for frame to replace is slow (requires scan of all PTEs)
  - » Updating PTE with current clock can be slow w/o hardware help
- Use a doubly-linked list of page numbers, where pages at top of list have been used recently
  - » Move page to top of list when it's referenced
  - » No search for replacement
  - » May be slow: 6 pointers changed on page reference
- Better still: combine the two methods
  - » Use clock for entries in TLB
  - » Update list in memory only when PTE is replaced in TLB

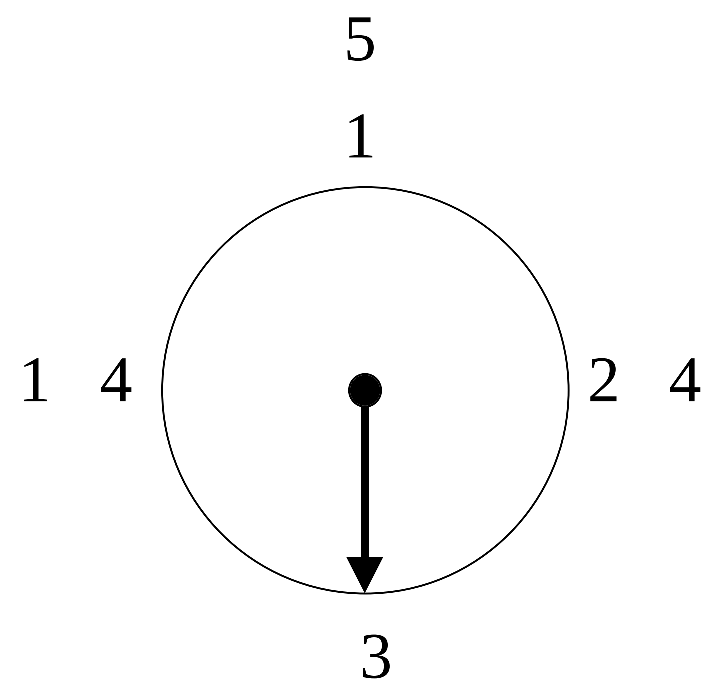
Approximating LRU

- Problem: LRU can be slow and needs hardware help
- Use a reference bit in each PTE
  - » Reference bit initially set to 0
  - » Reference bit set to 1 when page is referenced
  - » Replace a page with bit set to 0 if such a page exists
    - – May not be the least recently used
- Use the reference bit to approximate LRU
  - » Second chance replacement
  - » Clock algorithm

Clock Algorithm

- Keep a circular list of page frames in memory
- Keep a pointer to a location in the circular list
- Rule:
  ```
  while (not done) {
    if (ref bit == 1) {
      replace this frame
    } else {
      set ref bit = 0
      leave page in memory &
      advance to next frame
    }
  }
  ```
- Set ref bit = 1 when page is referenced

1, 2, 3, 4, 5, 3, 2, 5, 1,5, 4



Page Replacement in Unix

- Problem with clock algorithm: slow replacement (dirty page must be written out before new page brought in)
- Keep a circular list of frames as with clock algorithm
  - » Go through list of frames at a fixed rate
    - – If frame's reference bit is 0
      - Write it to disk (if dirty) and clear the dirty bit
      - Place it into a pool of "available" pages & set valid bit in PTE to 0
    - – If frame's reference bit is 1, set the bit to 0
- On a page fault
  - » Search available pool for the desired page - if found, mark PTE as valid and remove page from available pool
  - » If not found, replace any page in available pool with page fetched from disk

Counting-Based Algorithms

- Keep a counter of the number of references that have been made to each page
- LFU algorithm: replace page with the smallest count
- MFU algorithm: replace page with largest count, since page with smallest count may have just been brought in and will be used more in the future
- Problem: counts can only increase
- Solution: periodically go through PTEs and reduce counters
  - » Set counters back to 0
  - » Reduce counters by a factor of *n*

Allocating Frames to Processes

- Each process needs a minimum number of pages
  - » A single instruction might access more than one page
  - » Example:
    VAX instruction add.w 70000(r1), 70000(r2), 70000(r3)
    - – Instruction might span 2 pages
    - – Each operand might span 2 pages
    - – Total page faults = 2 + 3 * 2 = 8 page faults!
  - » System must make sure that a process can execute such an instruction if necessary
- Two basic allocation schemes:
  - » Fixed allocation
  - » Priority allocation

Fixed Allocation of Frames

- Equal allocation: allocate frames to processes evenly
  - » If there are 256 frames and 8 processes, allocate 32 frames per process
- Proportional allocation: allocate frames according to the size of the process (bigger process => more frames)
  - » Add up the total number of frames required by all running processes
  - » Divide by the total number of available frames for paging
  - » Divide each process's total frames by the result to compute the total allocation for that process (but allocate minimum #)
  - » Example: p1 -> 100 frames, p2 -> 20 frames, p3 -> 40 frames
    40 frames available
    p1 gets 100*40/(100+40+20) = 25 frames
    p2 gets 20 * 40/160 = 5 frames
    p3 gets 40*40/160 = 10 frames

Priority Allocation of Frames

- Allocate frames to processes proportionally using priorities rather than fixed allocation (size)
  - » Priority = number of recent page faults
  - » Priority = more “important” process
- If process Pi generates a page fault
  - » Select one of its own frames for replacement
  - » Select a frame from a process with a lower priority

Local vs. Global Frame Allocation

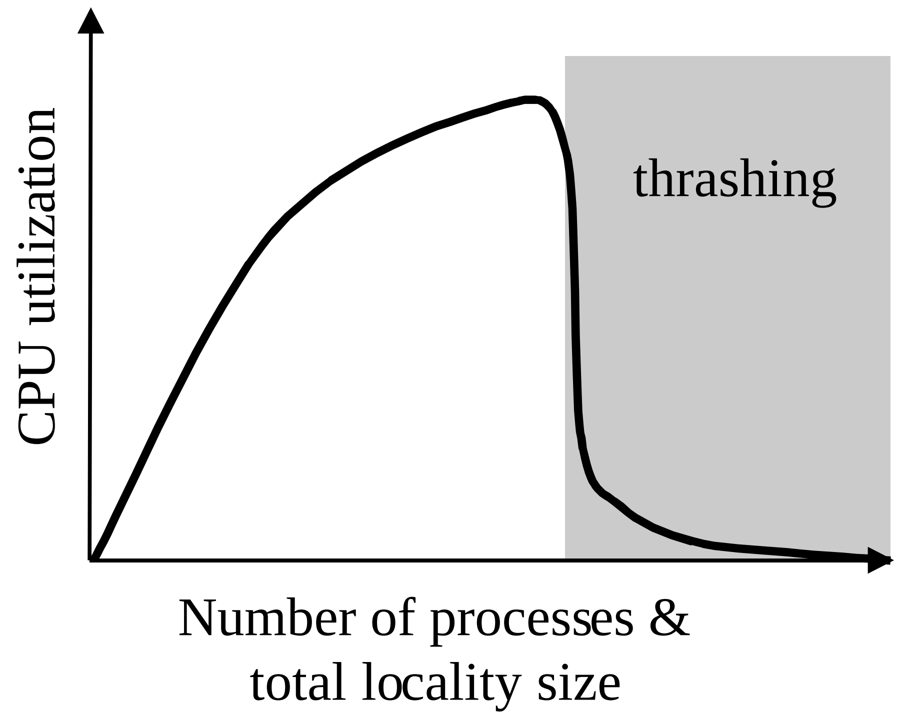
- Local replacement
  - » Replacement algorithm is run only on frames allocated to the process
  - » More “suitable” frames in other processes are ignored
  - » Easier bookkeeping
  - » Penalizes processes that behave poorly (too many page faults)
- Global replacement
  - » Replacement algorithm run over entire set of frames in all processes
  - » Can be slower than local replacement
  - » Usually leads to globally better behavior
  - » Individual processes may be slowed down unnecessarily

Thrashing in Virtual Memory

- Not “enough” pages leads to very high page fault rates
  - » Low CPU utilization - CPU always waiting for pages from disk
  - » Potential OS problems
    - – OS sees low CPU utilization
    - – OS adds another process to better utilize CPU
    - – Thrashing gets even worse as there are more processes fighting over too little memory
- Thrashing describes a process (or system) that spends all of its time swapping pages in and out
- How few is “too few” pages for a process?

Characterizing Thrashing

- Paging works because of locality
  - » Locality is the pages "currently" in use by a process
  - » Process moves from one locality to another
  - » Localities may overlap
- Thrashing occurs when the current localities for all processes don't fit into physical memory
  - » CPU utilization drops
  - » I/O rate increases



Avoiding Thrashing: Working Sets

- Working set is the group of pages "currently" in use by a given process
  - » "Currently" means the page was accessed within the past *n* instructions by this process
  - » The *n* instruction window is called the working set window
- WSS_i (P_i's working set) is all of the pages accessed in the most recent *n* instructions
  - » If window is too small, it won't encompass the current locality
  - » If window is too large, it will encompass several localities and possibly waste space
  - » If window is infinitely large, it will include the whole program
- Goal: keep the sum of the sizes of WSS_i below the total available physical memory
- If all WSS_i won't fit into memory, suspend a process

Calculating Working Set Size

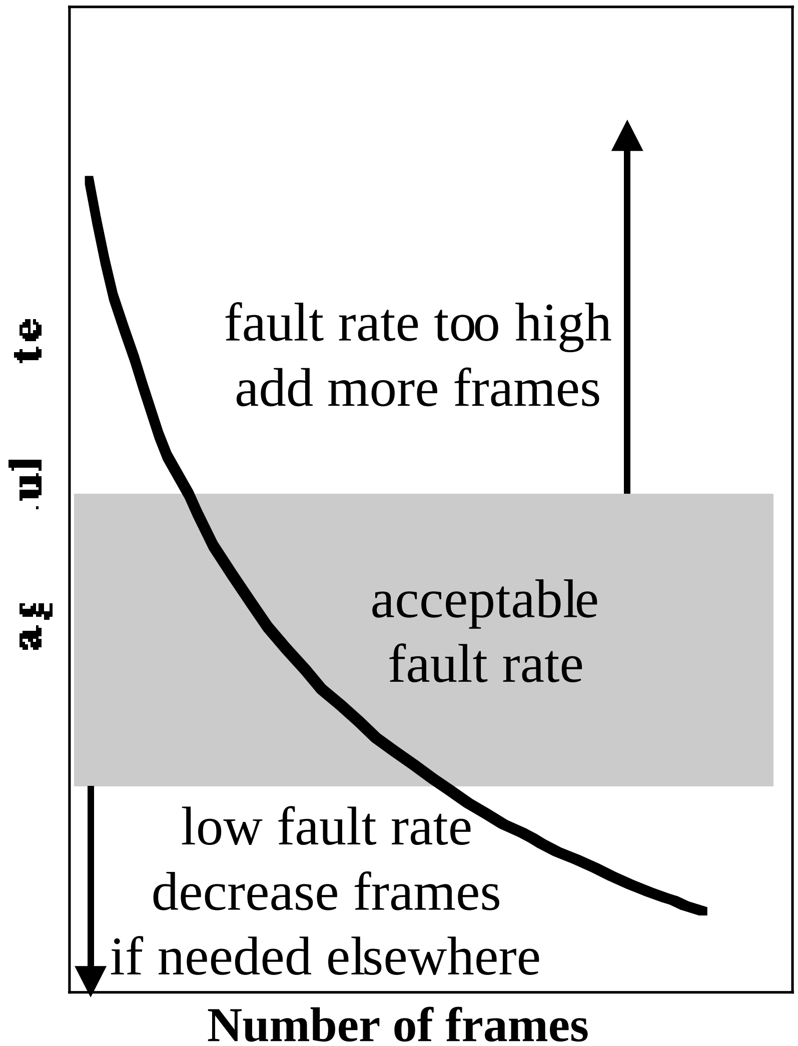
- Exact calculation of working set size is difficult
- Approximate calculation with an interval timer, reference bit per page, and history of reference bits for all pages
  - » Current reference bit set to 1 on page reference
  - » History (values at previous interrupts) also stored in PTE
- For example, working set window is 100,000 instructions
  - » Timer interrupts every 100,000 instructions
  - » For each page in the process
    - – Shift history bits left by 1 position
    - – Insert the value of the current reference bit
    - – Set the current reference bit to 0
  - » If any history bits are 1, page is in current working set

Issues With Working Sets

- Method for calculating working set has problems
  - May not be completely accurate
  - May be somewhat slow
- Interrupt more often
  - Better accuracy
  - Slower
- Keep more history bits
  - Better accuracy
  - More space required
- Use clock-based methods (discussed earlier) to approximate working set algorithms
- Use page-fault frequency to figure out working set size

Using Page Fault Frequency

- Each process has an acceptable page fault rate
  - » If actual rate is higher, add more frames
  - » If actual rate is lower, remove frames
- Don't remove frames unless other processes need them!
  - » Low page fault rate is good!
  - » Allow processes to keep pages until they're needed elsewhere



Prefetching Pages

- Demand paging is good, but may result in excessive delay
  - » User must wait while process fetches needed pages
  - » Solution: fetch pages *before* they're needed
- Prefetch pages that may be needed soon
  - » Pages near the current page (1-2 pages ahead or behind)
  - » Pages the program says it will need soon
- Advantage: less delay seen by process & user (need pages already in memory)
- Disadvantage: may replace useful pages with pages that will never be used

Selecting a Page Size

- Consider many issues when selecting a page size
  - » May not be a single “optimal” page size
  - » Tradeoffs between different factors
- Fragmentation
  - + Smaller pages have less internal fragmentation
- Page table size
  - + Larger pages require smaller page tables
- I/O overhead
  - + Larger pages have less I/O overhead per byte
  - + Smaller pages require less I/O for a single page fault
- Locality
  - + Larger pages require fewer fetches for a given locality
  - + Smaller pages include less “inactive” memory

User Programs and Virtual Memory

- Program code interacts with virtual memory system
  - » Interaction hidden from user
  - » Performance problems *not* hidden!
- Program to add two 2-D arrays together
  - » Arrays stored in C order
  - » Page size is 4 KB
  - » Only 2 data frames available to process
- Loop order makes a *huge* difference in performance!

```
int X[1024][1024], Y[1024][1024];
```

```
for (j=0; j<1024; j++) {
  for (k=0; k<1024; k++) {
    X[j][k] += Y[j][k];
  }
}
```

X: 1024 page faults
Y: 1024 page faults

```
for (k=0; k<1024; k++) {
  for (j=0; j<1024; j++) {
    X[j][k] += Y[j][k];
  }
}
```

X: 1024 x 1024 page faults
Y: 1024 x 1024 page faults

Demand Segmentation

- Some systems can support segments but not paging
  - » Trap when unloaded segment is accessed
  - » No address translation for paging
- Use methods similar to those used in paging
  - » Valid bit in segment descriptor to indicate a segment loaded into memory
  - » Segment fault if segment not in memory
    - – Segment loaded into memory (space found by looking through list of memory holes)
    - – Segment table updated to show valid segment
  - » Deallocate segments no longer in use