COS 318: Operating Systems

Virtual Memory Paging

Jaswinder Pal Singh
Computer Science Department
Princeton University

(http://www.cs.princeton.edu/courses/cos318/)

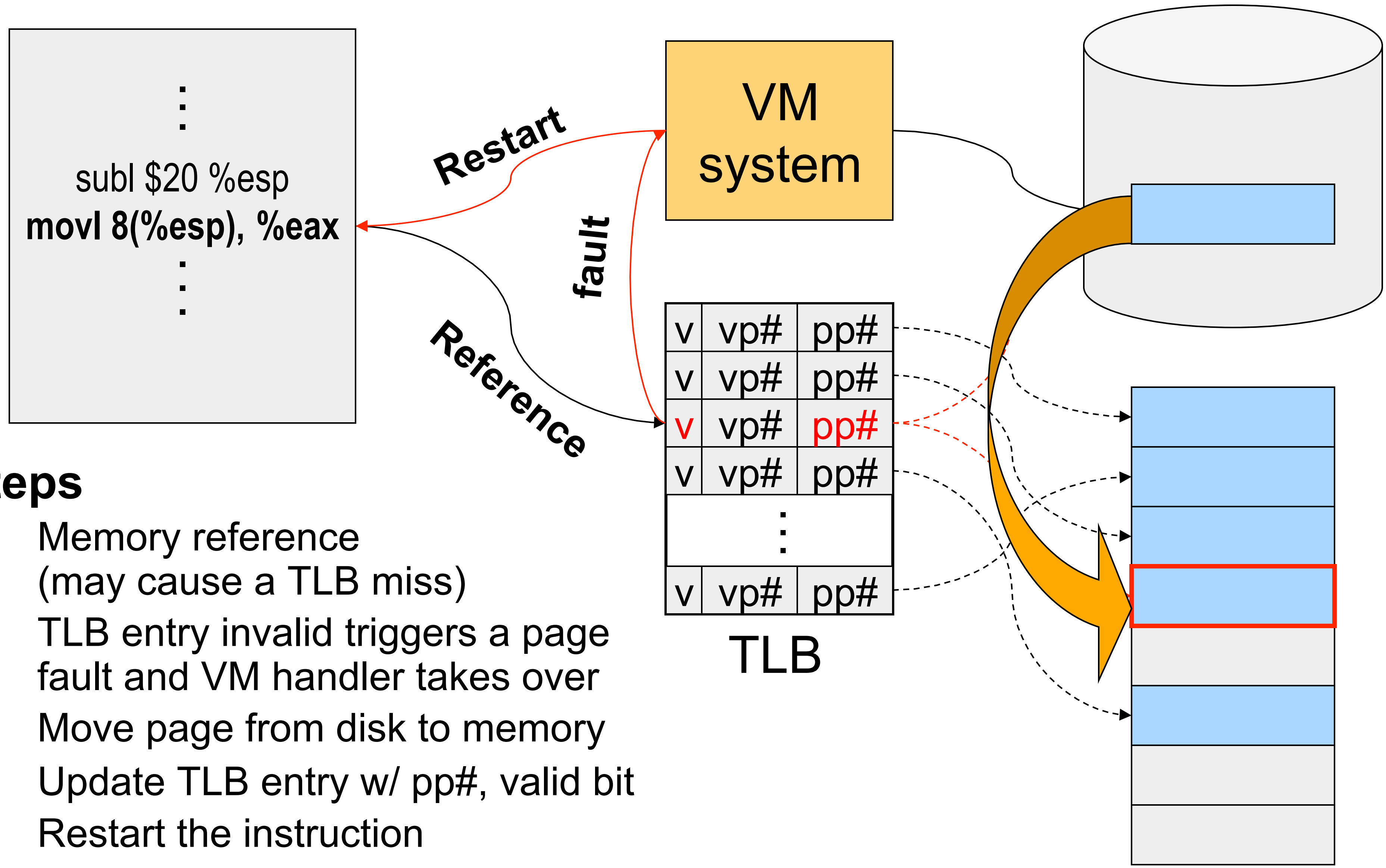
Today’s Topics

- Paging mechanism
- Page replacement algorithms

Virtual Memory Paging

- Simple world
  - Load entire process into memory. Run it. Exit.
- Problems
  - Slow (especially with big processes)
  - Wasteful of space (doesn't use all of its memory all the time)
- Solution
  - Demand paging: only bring in pages actually used
  - Paging: only keep frequently used pages in memory
- Mechanism:
  - Virtual memory maps some to physical pages, some to disk

VM Paging Steps



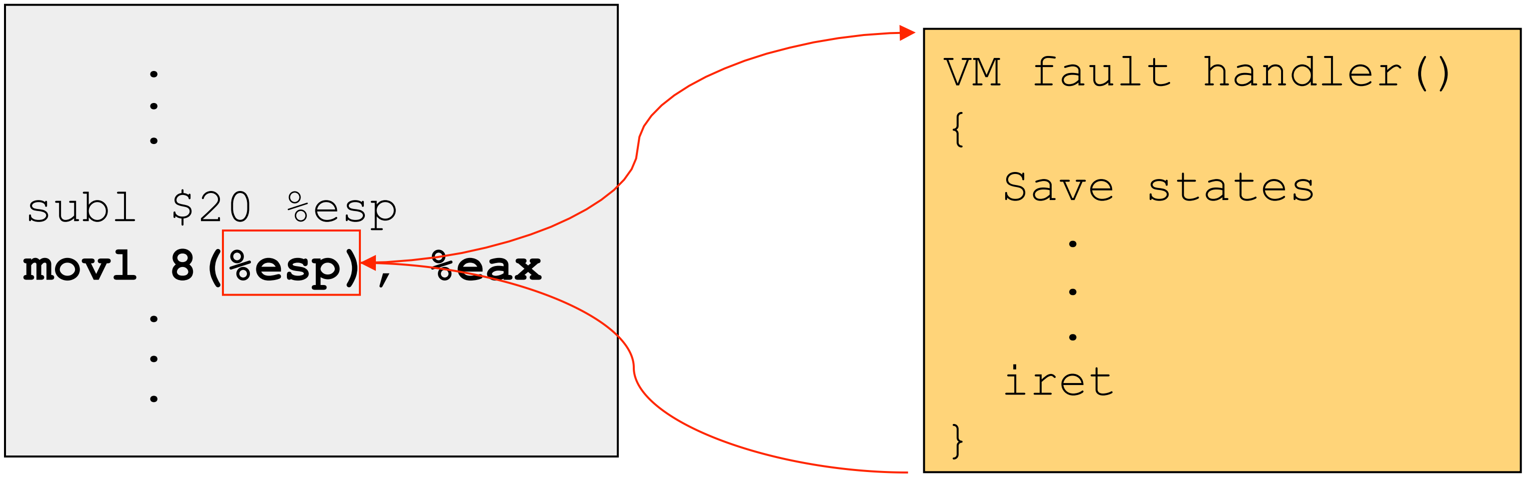
Steps

- Memory reference (may cause a TLB miss)
- TLB entry invalid triggers a page fault and VM handler takes over
- Move page from disk to memory
- Update TLB entry w/ pp#, valid bit
- Restart the instruction
- Memory reference again

Virtual Memory Issues

- How to switch a process after a fault?
  - Need to save state and resume
  - Is it the same as an interrupt?
- What to page in?
  - Just the faulting page or more?
  - Want to know the future…
- What to replace?
  - Cache (main memory) always too small, which page to replace?
  - Want to know the future...

How Does Page Fault Work?



- User program should not be aware of the page fault
- Fault may have happened in the middle of the instruction!
- Can we skip the faulting instruction?
- Is a faulting instruction always restartable?

What to Page In?

- Page in the faulting page
  - Simplest, but each "page in" has substantial overhead
- Page in more pages each time
  - May reduce page faults if the additional pages are used
  - Waste space and time if they are not used
  - Real systems do some kind of prefetching
- Applications control what to page in
  - Some systems support for user-controlled prefetching
  - But, many applications do not always know

VM Page Replacement

- Things are not always available when you want them
  - It is possible that no unused page frame is available
  - VM needs to do page replacement
- On a page fault
  - If there is an unused frame, get it
  - **If no unused page frame available,**
    - **Choose a used page frame**
    - **If it has been modified, write it to disk**
    - **Invalidate its current PTE and TLB entry**
  - Load the new page from disk
  - Update the faulting PTE and remove its TLB entry
  - Restart the faulting instruction

Page Replacement

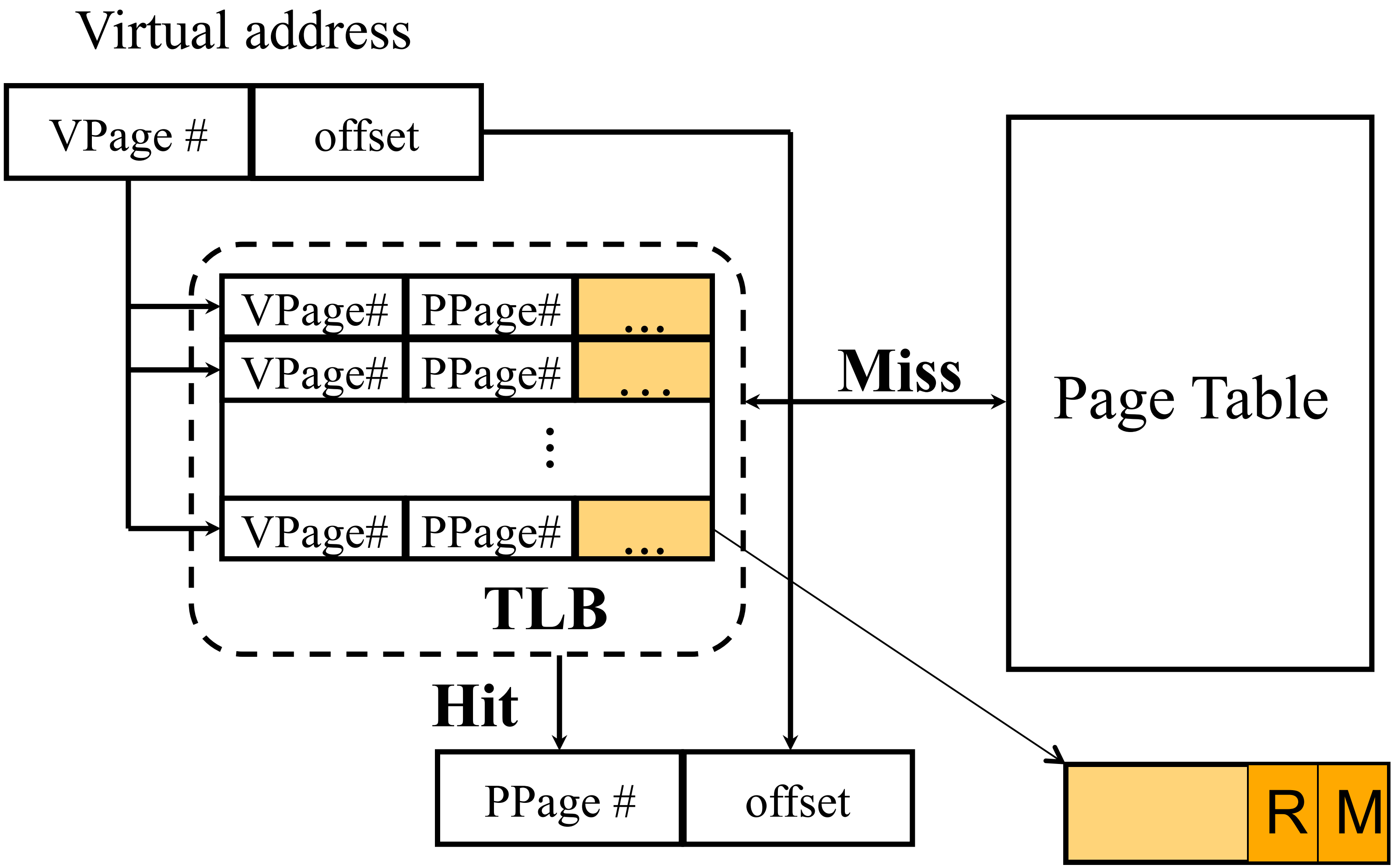
Which “Used” Page Frame To Replace?

- Random
- Optimal or MIN algorithm
- NRU (Not Recently Used)
- FIFO (First-In-First-Out)
- FIFO with second chance
- Clock
- LRU (Least Recently Used)
- NFU (Not Frequently Used)
- Aging (approximate LRU)
- Working Set
- WSClock

Optimal or MIN

- Algorithm:
  - Replace the page that won't be used for the longest time (Know all references in the future)
- Example
  - Reference string: [1] [2] [3] [4] 1 2 [5] 1 2 3 [4] 5
  - 4 page frames
  - 6 faults
- Pros
  - Optimal solution and can be used as an off-line analysis method
- Cons
  - No on-line implementation

Revisit TLB and Page Table



- Important bits for paging
  - **Reference**: Set when referencing a location in the page (can clear every so often, e.g. on clock interrupt)
  - **Modify**: Set when writing to a location in the page

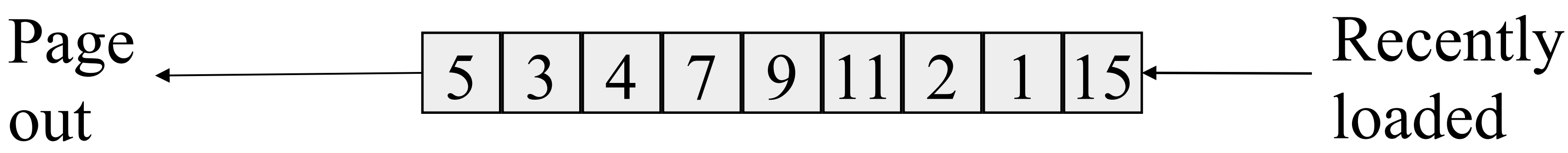
Not Recently Used (NRU)

- Algorithm
  - Randomly pick a page from the following (in this order)
    - Not referenced and not modified
    - Not referenced and modified
    - Referenced and not modified
    - Referenced and modified
  - Clear reference bits
- Example
  - 4 page frames
  - Reference string
  - 8 page faults

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

- Pros
  - Implementable
- Cons
  - Require scanning through reference bits and modified bits

First-In-First-Out (FIFO)



- Algorithm
  - Throw out the oldest page
- Example
  - 4 page frames
  - Reference string 1 2 3 4 1 2 5 1 2 3 4 5
  - 10 page faults
- Pros
  - Low-overhead implementation
- Cons
  - May replace the heavily used pages

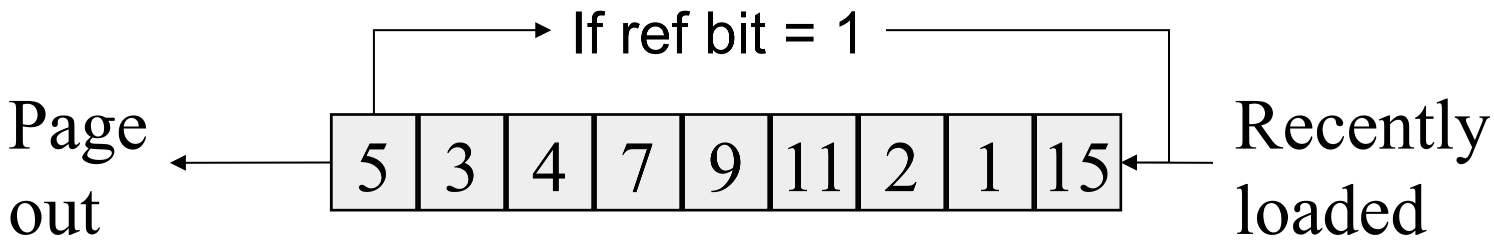
More Frames → Fewer Page Faults?

- Consider the following with 4 page frames
  - Algorithm: FIFO replacement
  - Reference string: [1] [2] [3] [4] 1 2 [5] [1] [2] [3] [4] [5]
  - 10 page faults

- Same string with 3 page frames
  - Algorithm: FIFO replacement
  - Reference string: [1] [2] [3] [4] [1] [2] [5] 1 2 [3] [4] 5
  - **9 page faults!**

- This is so called "Belady's anomaly" (Belady, Nelson, Shedler 1969)

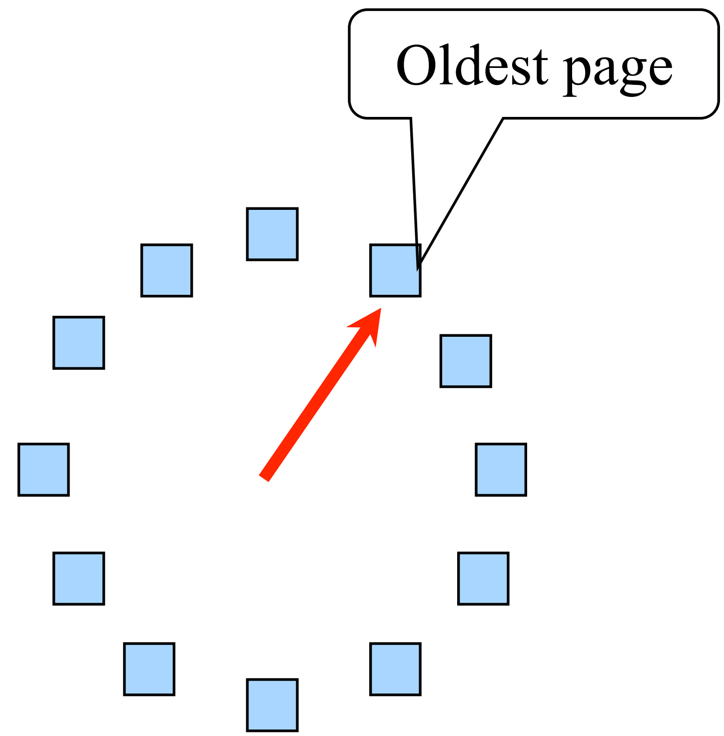
FIFO with 2nd Chance



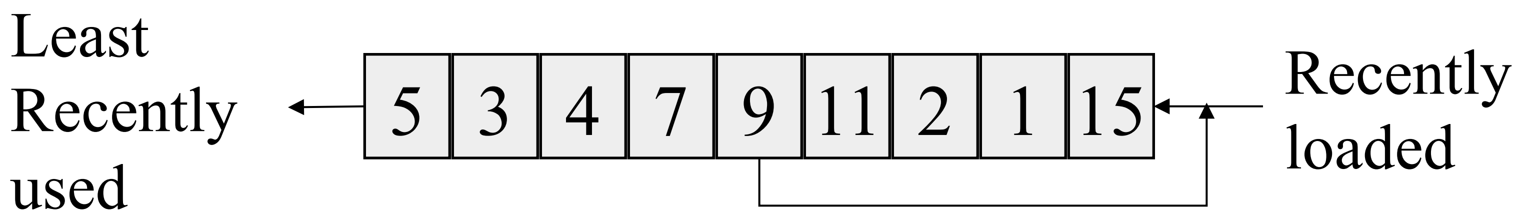
- Algorithm
  - Check the reference-bit of the oldest page
  - If it is 0, then replace it
  - If it is 1, clear the reference bit, put the page to the end of the list, and continue searching
  - Looking for an old page not referenced in current clock interval, for example
- Example
  - 4 page frames
  - Reference string: 1 2 3 4 1 2 5 1 2 3 4 5
  - 8 page faults
- Pros
  - Simple to implement
- Cons
  - The worst case may take a long time

Clock

- FIFO clock algorithm
  - Hand points to the oldest page
  - On a page fault, follow the hand to inspect pages
- Second chance
  - If the reference bit is 1, set it to 0 and advance the hand
  - If the reference bit is 0, use it for replacement
- Compare with the FIFO with 2nd chance
  - What's the difference?
- What if memory is very large
  - Take a long time to go around?



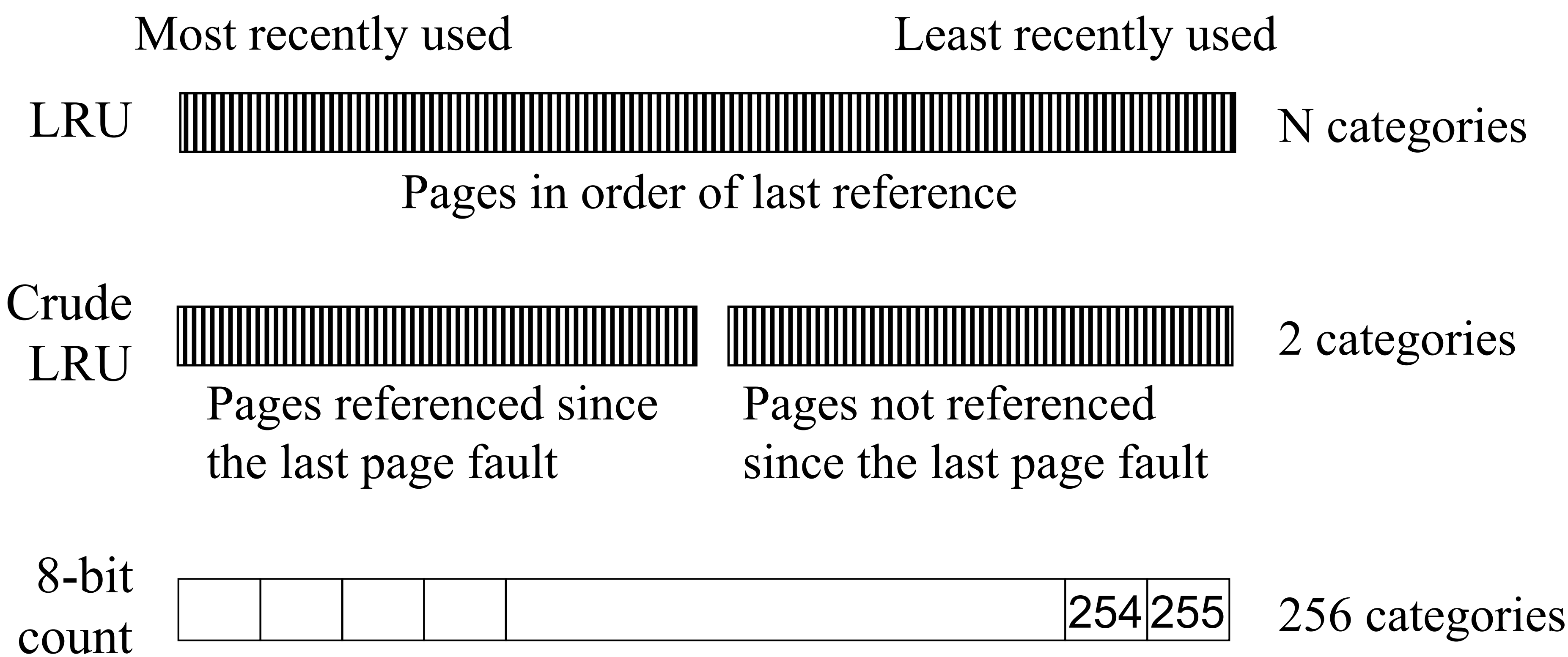
Least Recently Used



- Algorithm
  - Replace page that hasn't been used for the longest time
    - Order the pages by time of reference
    - Timestamp for each referenced page
- Example
  - 4 page frames
  - Reference string: 1 2 3 4 1 2 5 1 2 3 4 5
  - 8 page faults
- Pros
  - Good to approximate MIN
- Cons
  - Difficult to implement

Approximation of LRU

- Use CPU ticks
  - For each memory reference, store the ticks in its PTE
  - Find the page with minimal ticks value to replace
- Use a smaller counter



Aging: Not Frequently Used (NFU)

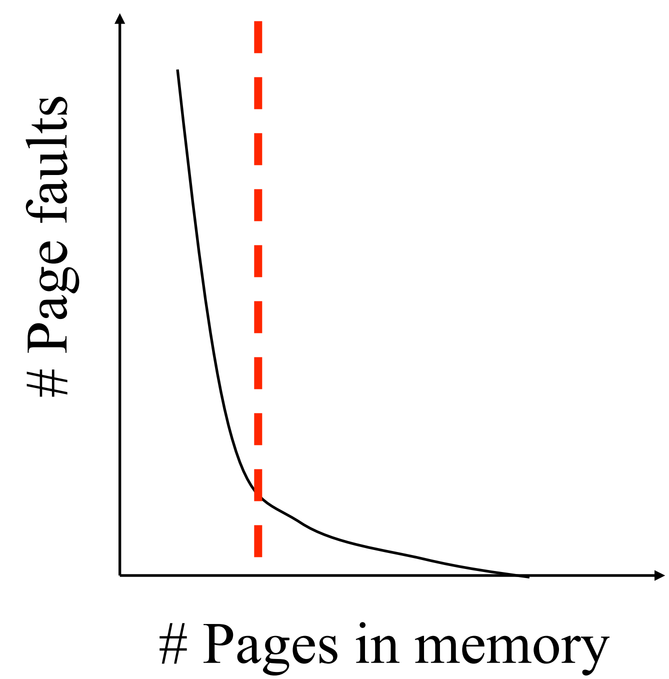
- Algorithm
  - Shift reference bits into counters
  - Pick the page with the smallest counter to replace

00000000	00000000	10000000	01000000	10100000
00000000	10000000	01000000	10100000	01010000
10000000	11000000	11100000	01110000	00111000
00000000	00000000	00000000	10000000	01000000

- Old example
  - 4 page frames
  - Reference string: 1 2 3 4 1 2 5 1 2 3 4 5
  - 8 page faults
- Main difference between NFU and LRU?
  - NFU has a short history (counter length)
- How many bits are enough?
  - In practice 8 bits are quite good

Program Behavior (Denning 1968)

- 80/20 rule
  - > 80% memory references are within <20% of memory space
  - > 80% memory references are made by < 20% of code
- Spatial locality
  - Neighbors are likely to be accessed
- Temporal locality
  - The same page is likely to be accessed again in the near future



Working Set

- Main idea (Denning 1968, 1970)
  - Define a working set as the set of pages in the most recent K page references
  - Keep the working set in memory will reduce page faults significantly
- Approximate working set
  - The set of pages of a process used in the last T seconds
- An algorithm
  - On a page fault, scan through all pages of the process
  - If the reference bit is 1, record the current time for the page
  - If the reference bit is 0, check the "time of last use,"
    - If the page has not been used within T, replace the page
    - Otherwise, go to the next
  - Add the faulting page to the working set

WSClock

- Follow the clock hand
- If the reference bit is 1
  - Set reference bit to 0
  - Set the current time for the page
  - Advance the clock hand
- If the reference bit is 0, check "time of last use"
  - If the page has been used within δ, go to the next
  - If the page has not been used within δ and modify bit is 1
    - Schedule the page for page out and go to the next
  - If the page has not been used within δ and modify bit is 0
    - Replace this page

Replacement Algorithms

- The algorithms
  - Random
  - Optimal or MIN algorithm
  - NRU (Not Recently Used)
  - FIFO (First-In-First-Out)
  - FIFO with second chance
  - Clock
  - LRU (Least Recently Used)
  - NFU (Not Frequently Used)
  - Aging (approximate LRU)
  - Working Set
  - WSClock
- Which are your top two?

Summary

- VM paging
  - Page fault handler
  - What to page in
  - What to page out
- LRU is good but difficult to implement
- Clock (FIFO with 2nd hand) is considered a good practical solution
- Working set concept is important