Memory Management II

Virtual Memory

Virtual memory motivation

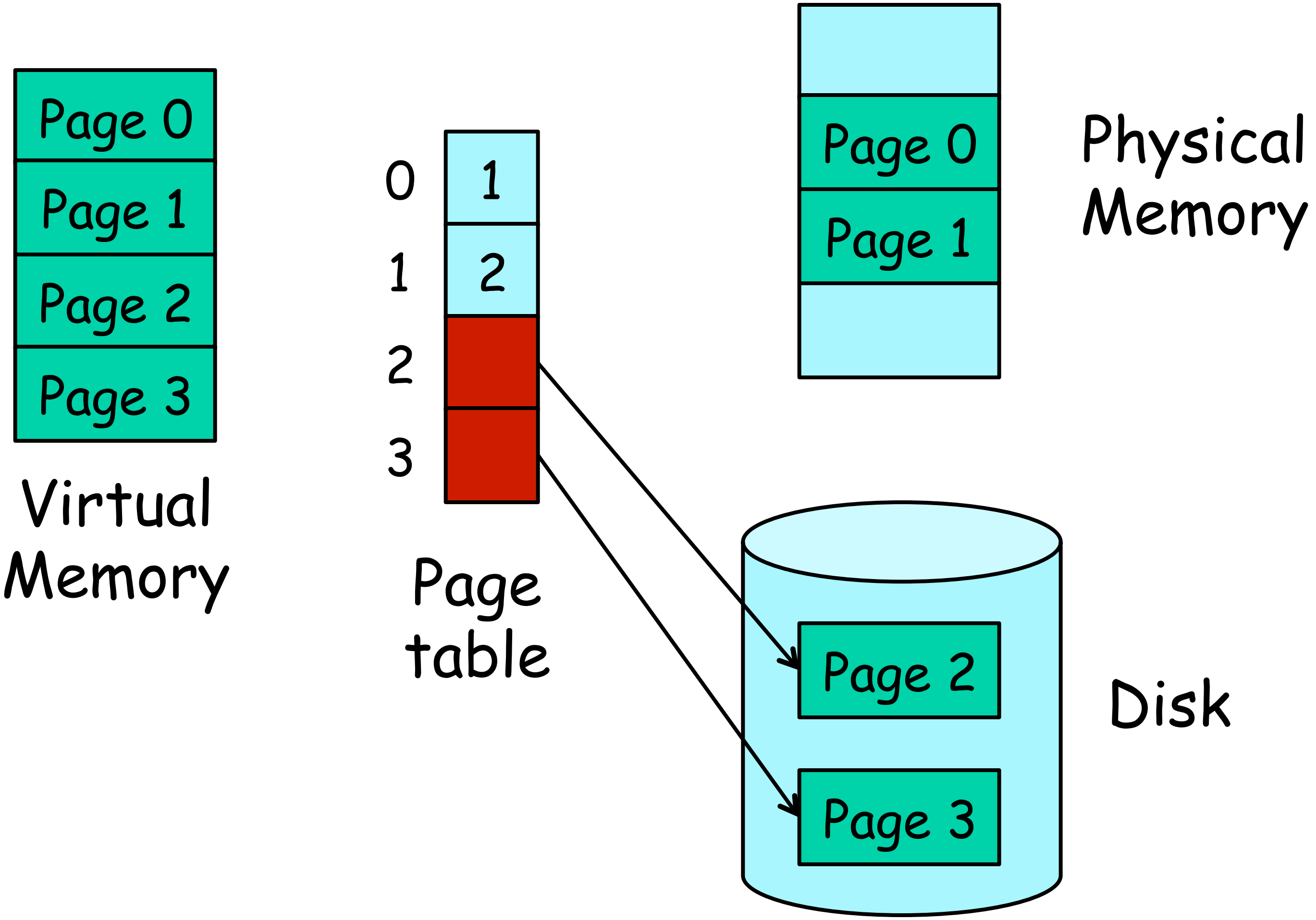
- Previous approach to memory management
    - Must completely load user process in memory
    - One large AS or too many AS ➔ out of memory
- Observation: locality of reference
    - Temporal: access memory location accessed just now
    - Spatial: access memory location adjacent to locations accessed just now
- Implication: process only needs a small part of address space at any moment!

Virtual memory idea

- OS and hardware produce illusion of disk as fast as main memory, or main memory as large as disk

- Process runs when not all pages are loaded in memory
  - Only keep referenced pages in main memory
  - Keep unreferenced pages on slower, cheaper backing store (disk)
  - Bring pages from disk to memory when necessary

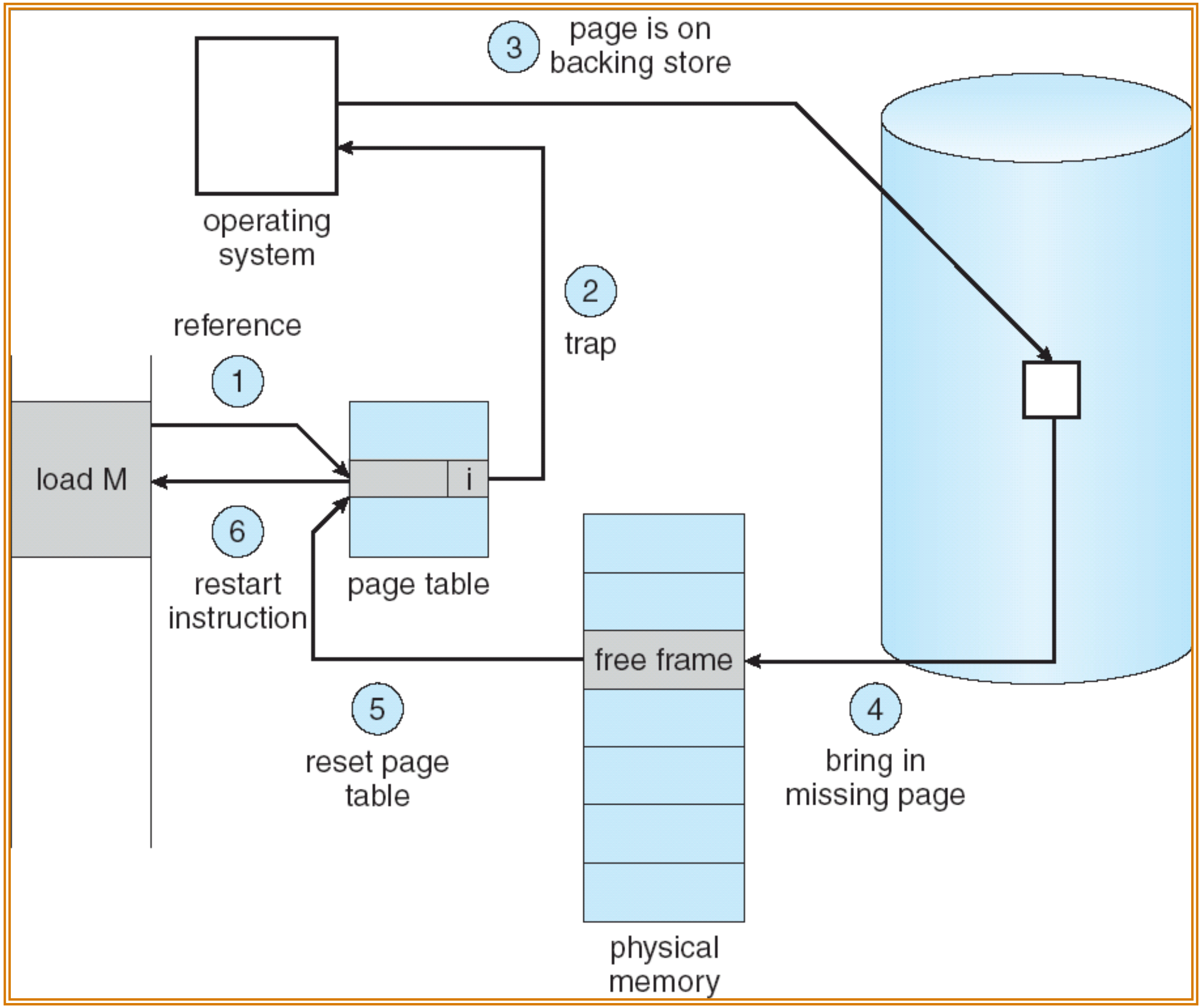
Virtual memory illustration



Detect reference to page on disk and recognize disk location of page

- Overload the present bit of page table entries
- If a page is on disk, clear present bit in corresponding page table entry and store disk location using remaining bits
- Page fault: if bit is cleared then referencing resulting in a trap into OS
- In OS page fault handler, check page table entry to detect if page fault is caused by reference to true invalid page or page on disk

Steps in handling a page fault



OS decisions

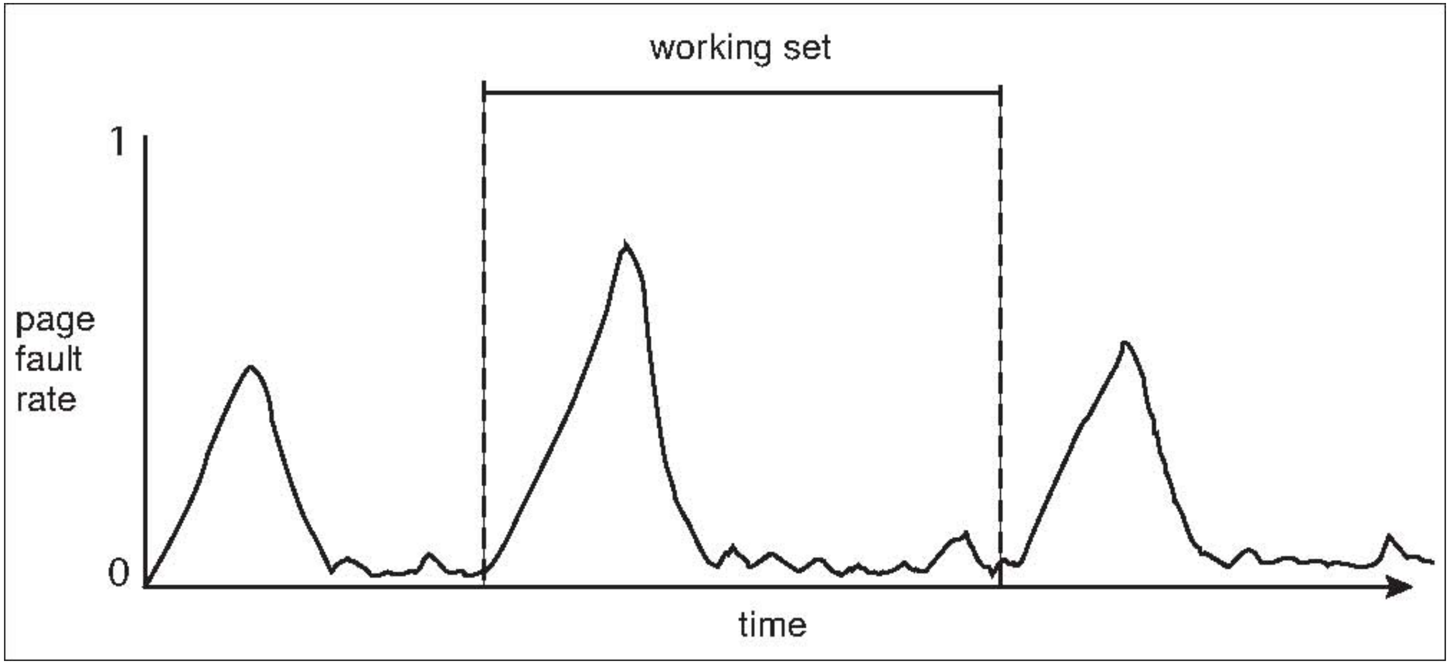
- Page selection
  - When to bring pages from disk to memory?
- Page replacement
  - When no free pages available, must select victim page in memory and throw it out to disk

Page selection algorithms

- Demand paging: load page on page fault
  - Start up process with no pages loaded
  - Wait until a page absolutely must be in memory
- Request paging: user specifies which pages are needed
  - Requires users to manage memory by hand
  - Users do not always know best
  - OS trusts users (e.g., one user can use up all memory)
- Prepaging: load page before it is referenced
  - When one page is referenced, bring in next one
  - Do not work well for all workloads
    - Difficult to predict future

Working set

- With pure demand paging:



- Pre-paging tries to smooth out bursts

Thrashing

- What if we need more pages regularly than we have?
  - Page fault to get page
  - Replace existing frame
  - But quickly need replaced frame back
- Leads to:
  - High page fault rate
  - Lots of I/O wait
  - Low CPU utilization
  - No useful work done
- **Thrashing**: system busy just swapping pages

Page replacement algorithms

- Optimal: throw out page that won't be used for longest time in future
- Random: throw out a random page
- FIFO: throw out page that was loaded in first
- LRU: throw out page that hasn't been used in longest time

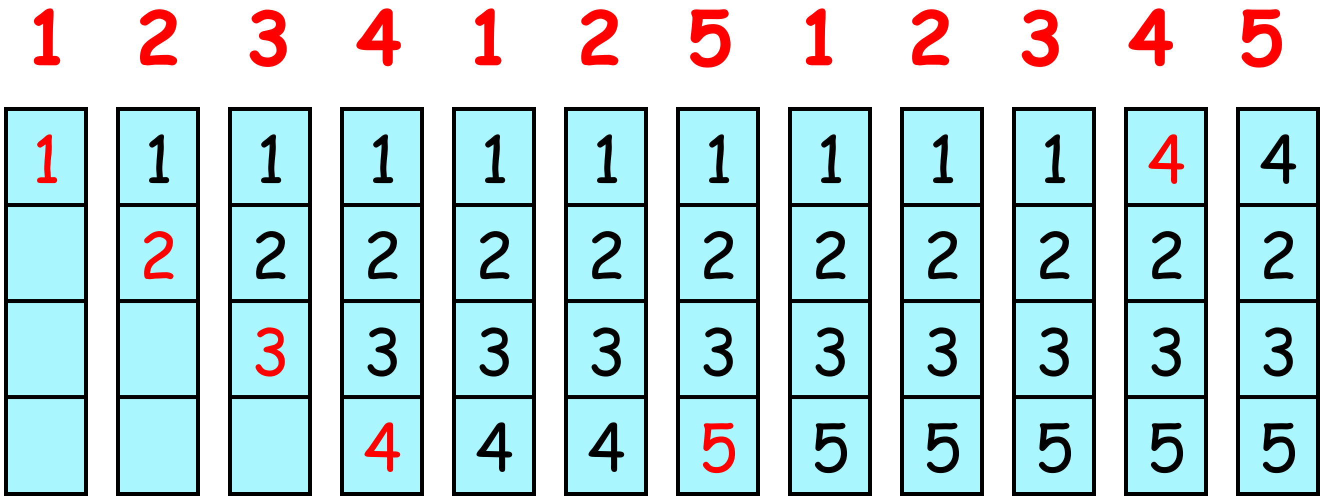
Evaluating page replacement algorithms

- Goal: fewest number of page faults
- A method: run algorithm on a particular string of memory references (reference string) and computing the number of page faults on that string
- In all our examples, the reference string is

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

Optimal algorithm

- Throw out page that won't be used for longest time in future



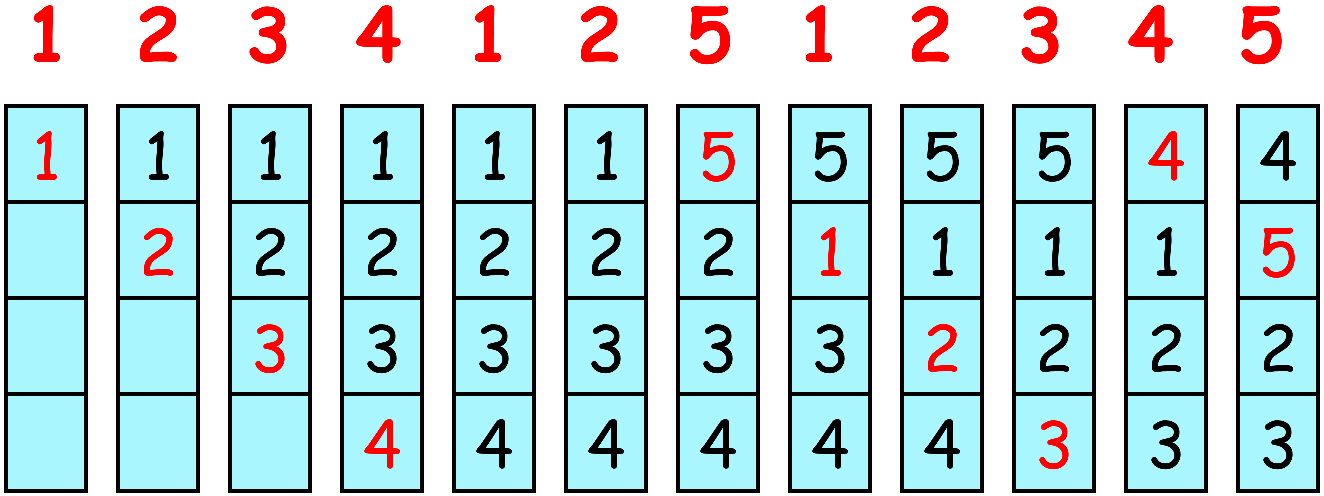
1	2	3	4	1	2	5	1	2	3	4	5
1	1	1	1	1	1	1	1	1	1	4	4
	2	2	2	2	2	2	2	2	2	2	2
		3	3	3	3	3	3	3	3	3	3
			4	4	4	5	5	5	5	5	5

6 page faults

Problem: difficult to predict future!

Fist-In-First-Out (FIFO) algorithm

- Throw out page that was loaded in first



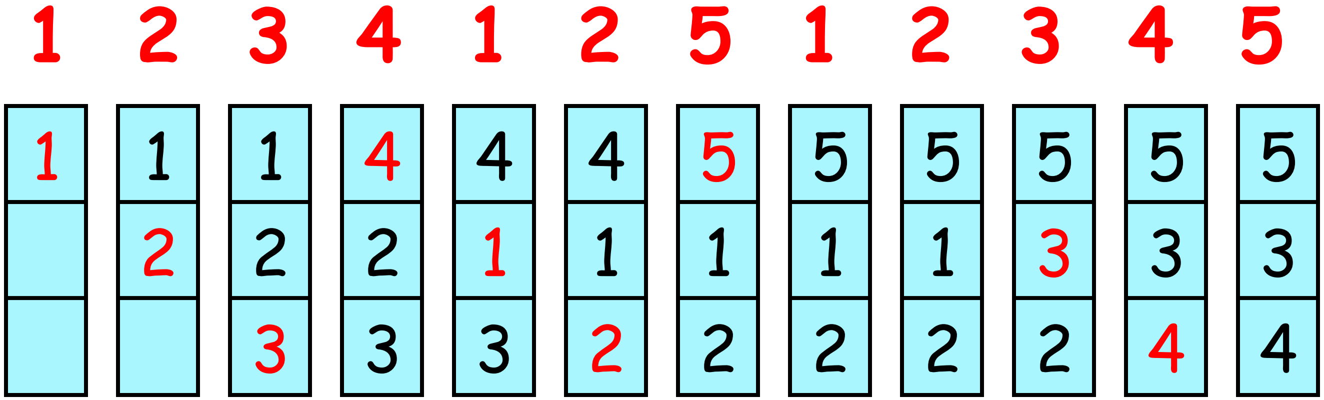
1	2	3	4	1	2	5	1	2	3	4	5
1	1	1	1	1	1	5	5	5	5	4	4
	2	2	2	2	2	2	1	1	1	1	5
		3	3	3	3	3	3	2	2	2	2
			4	4	4	4	4	4	3	3	3

10 page faults

Problem: ignores access patterns

Fist-In-First-Out (FIFO) algorithm (cont.)

- Results with 3 physical pages



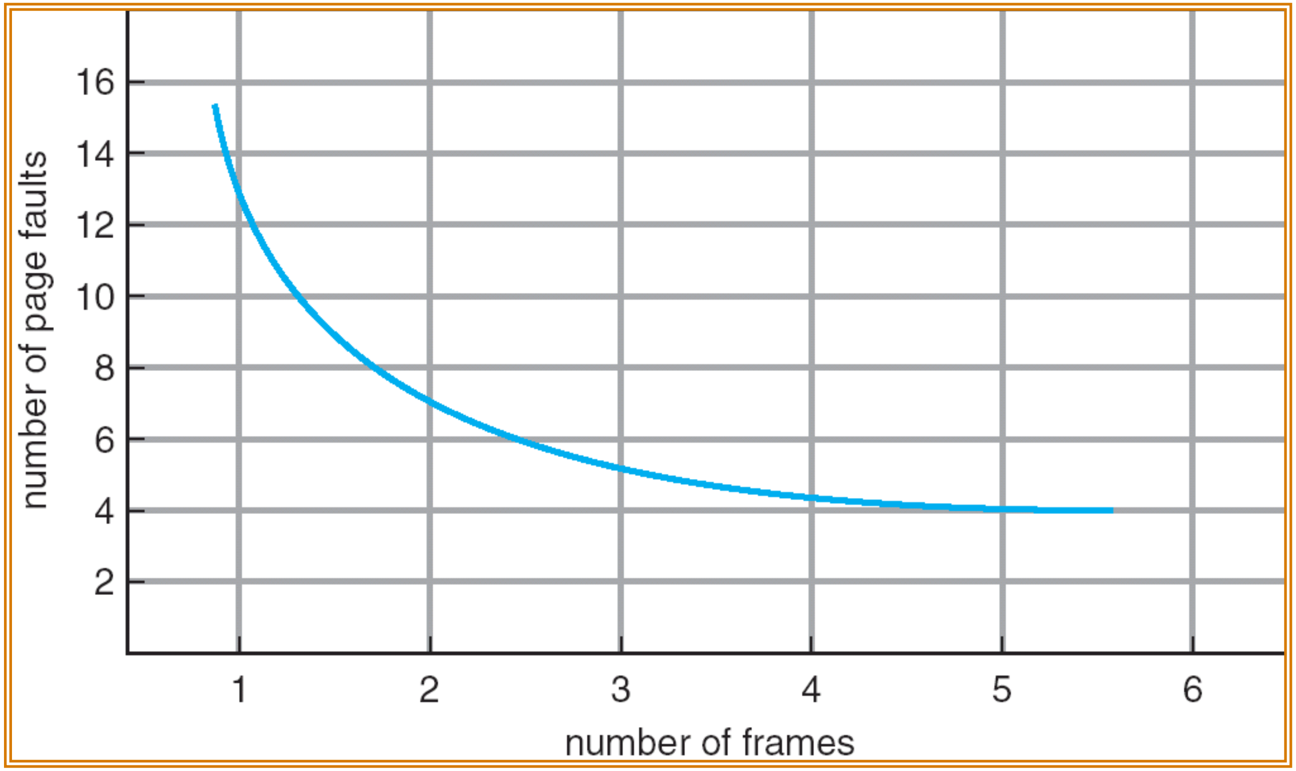
1	2	3	4	1	2	5	1	2	3	4	5
1	1	1	4	4	4	5	5	5	5	5	5
	2	2	2	1	1	1	1	1	3	3	3
		3	3	3	2	2	2	2	2	4	4

9 page faults

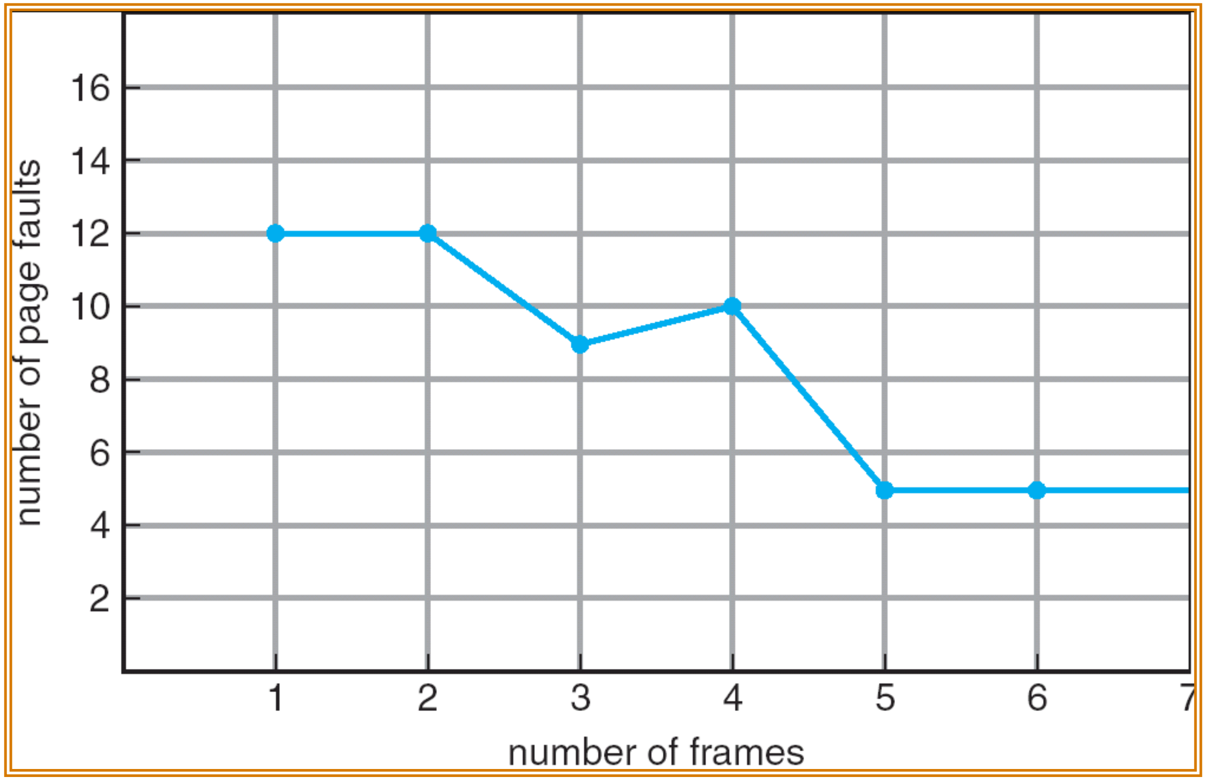
Problem: fewer physical pages → fewer faults!

belady anomaly

Ideal curve of # of page faults v.s. # of physical pages

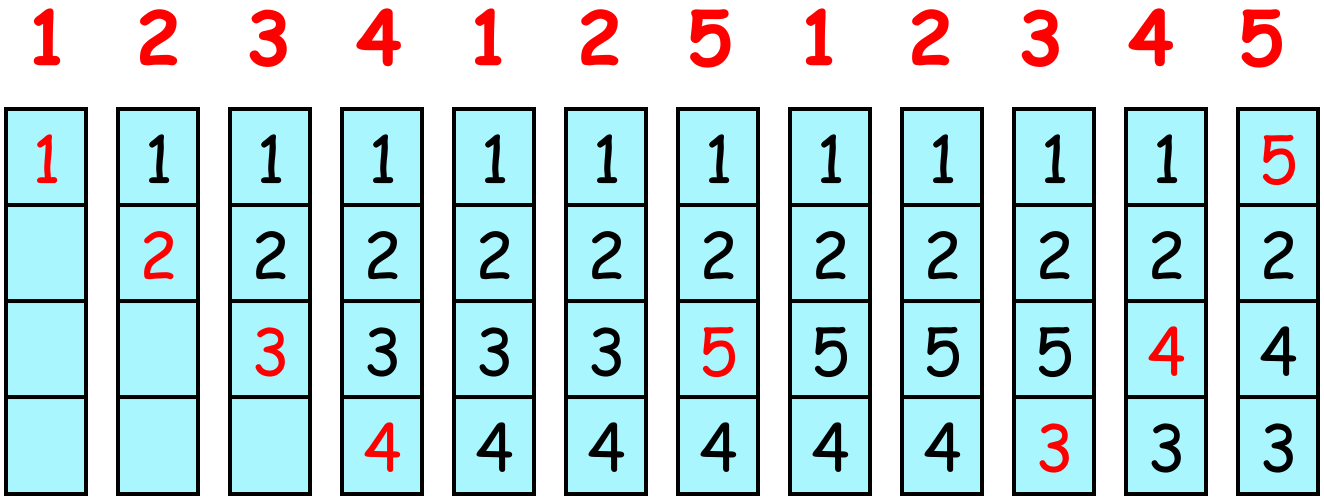


FIFO illustrating belady's anomaly



Least-Recently-Used (LRU) algorithm

- Throw out page that hasn't been used in longest time. Can use FIFO to break ties



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

8 page faults

Advantage: with locality, LRU approximates Optimal

Implementing LRU: hardware

- A counter for each page
- Every time page is referenced, save system clock into the counter of the page
- Page replacement: scan through pages to find the one with the oldest clock
- Problem: have to search all pages/counters!

Implementing LRU: software

- A doubly linked list of pages
- Every time page is referenced, move it to the front of the list
- Page replacement: remove the page from back of list
  - Avoid scanning of all pages
- Problem: too expensive
  - Requires 6 pointer updates for each page reference
  - High contention on multiprocessor

LRU: concept vs. reality

- LRU is considered to be a reasonably good algorithm
- Problem is in implementing it efficiently
  - Hardware implementation: counter per page, copied per memory reference, have to search pages on page replacement to find oldest
  - Software implementation: no search, but pointer swap on each memory reference, high contention
- In practice, settle for efficient approximate LRU
  - Find a not recently accessed page, but not necessarily the least recently accessed
  - LRU is approximation anyway, so approximate more

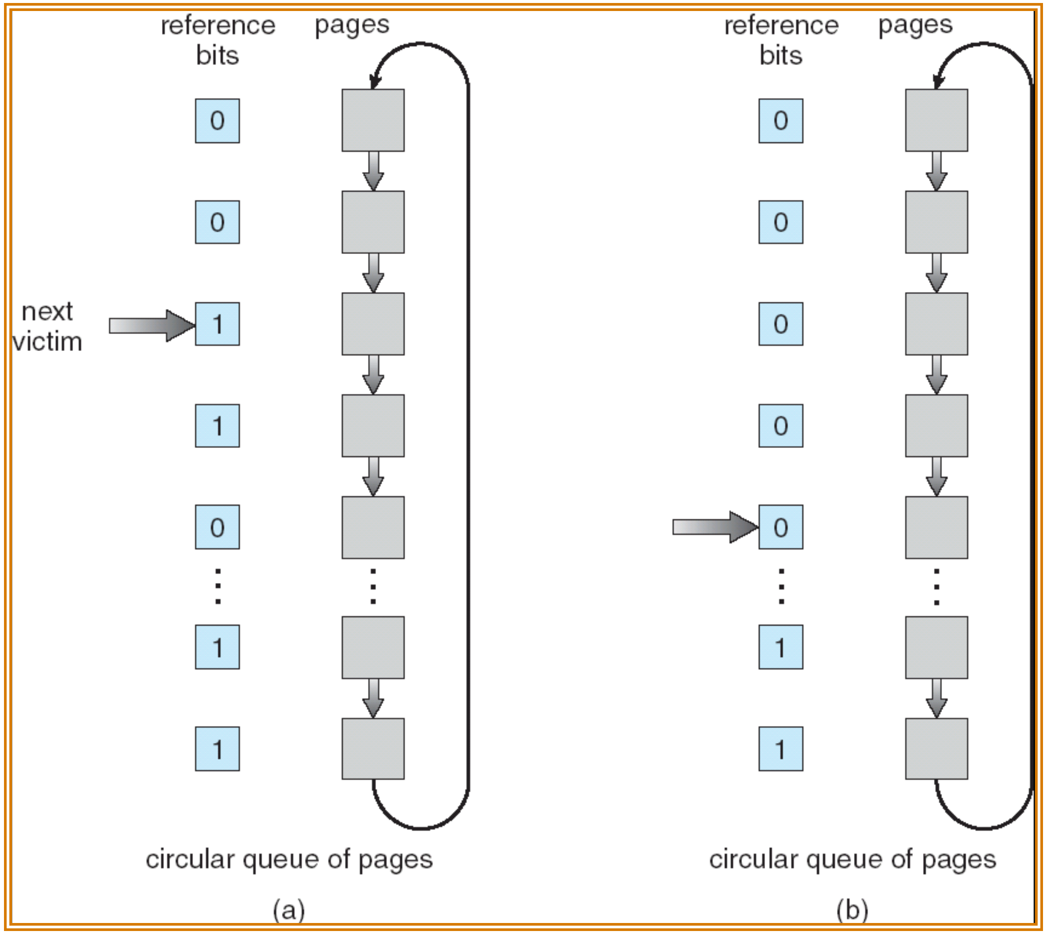
Clock (second-chance) algorithm

- Goal: remove a page that has not been referenced recently
  - good LRU-approximate algorithm
- Idea
  - A reference bit per page
  - Memory reference: hardware sets bit to 1
  - Page replacement: OS finds a page with reference bit cleared
  - OS traverses all pages, clearing bits over time

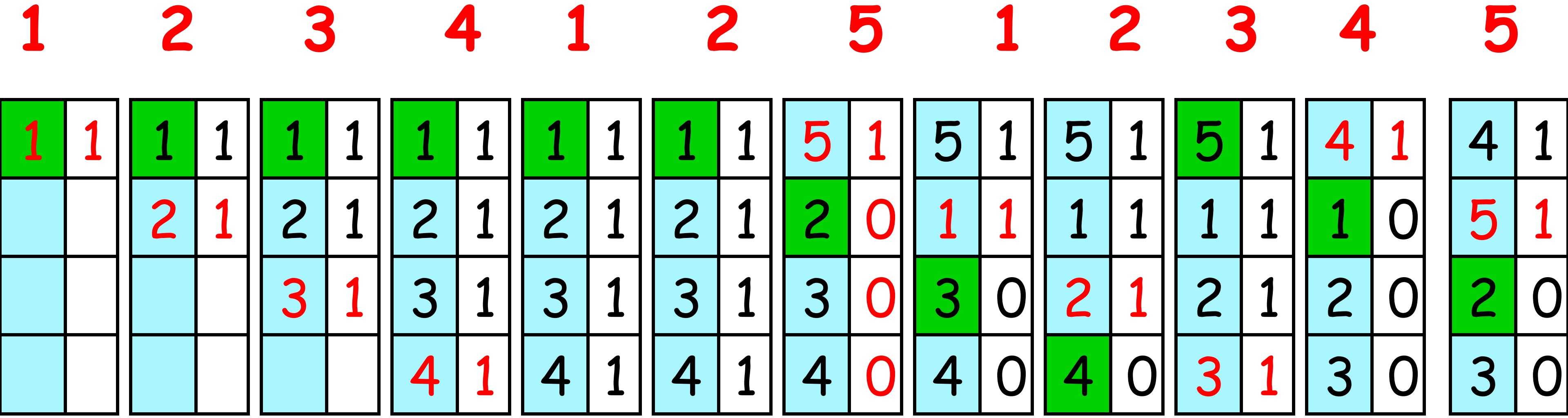
Clock algorithm implementation

- Combining FIFO with LRU: *give the victim page that FIFO selects a* second chance
- Keep pages in a circular list = clock
- Pointer to next victim = clock hand
- To replace a page, OS examines the page pointed to by hand
  - If ref bit == 1, clear, advance hand
  - Else return current page as victim

A single step in Clock algorithm



Clock algorithm example



1	2	3	4	1	2	5	1	2	3	4	5
1 1	1 1	1 1	1 1	1 1	1 1	5 1	5 1	5 1	5 1	4 1	4 1
	2 1	2 1	2 1	2 1	2 1	2 0	1 1	1 1	1 1	1 0	5 1
		3 1	3 1	3 1	3 1	3 0	3 0	2 1	2 1	2 0	2 0
			4 1	4 1	4 1	4 0	4 0	4 0	3 1	3 0	3 0

10 page faults

Advantage: simple to implement!

Clock algorithm extension

- Problem of clock algorithm: does not differentiate dirty v.s. clean pages

- Dirty page: pages that have been modified and need to be written back to disk
  - More expensive to replace dirty than clean pages
  - One extra disk write (about 5 ms)

Clock algorithm extension (cont.)

- Use dirty bit to give preference to dirty pages
- On page reference
  - Read: hardware sets reference bit
  - Write: hardware sets dirty bit
- Page replacement
  - reference = 0, dirty = 0 → **victim page**
  - reference = 0, dirty = 1 → **skip** (don't change)
  - reference = 1, dirty = 0 → reference = 0, dirty = 0
  - reference = 1, dirty = 1 → reference = 0, dirty = 1
  - advance hand, repeat
  - If no victim page found, run swap daemon to flush unreferenced dirty pages to the disk, repeat

Summary of page replacement algorithms

- Optimal: throw out page that won't be used for longest time in future
  - Best algorithm if we can predict future
  - Good for comparison, but not practical
- Random: throw out a random page
  - Easy to implement
  - Works surprisingly well. Why? Avoid worst case
  - Cons: random
- FIFO: throw out page that was loaded in first
  - Easy to implement
  - Fair: all pages receive equal residency
  - Ignore access pattern
- LRU: throw out page that hasn't been used in longest time
  - Past predicts future
  - With locality: approximates Optimal
  - Simple approximate LRU algorithms exist (Clock)

Current trends in memory management

- Virtual memory is less critical now
  - Personal computer v.s. time-sharing machines
  - Memory is cheap ➔ Larger physical memory
- Virtual to physical translation is still useful
  - "All problems in computer science can be solved using another level of indirection" David Wheeler
- Larger page sizes (even multiple page sizes)
  - Better TLB coverage
  - Smaller page tables, less page to manage
  - Internal fragmentation: not a big problem
- Larger virtual address space
  - 64-bit address space
  - Sparse address spaces
- File I/O using the virtual memory system
  - Memory mapped I/O: `mmap()`

Backup Slides

Dynamic allocation issue: fragmentation

- Fragment: small trunk of free memory ("holes"), too small for future allocation requests
  - External fragment: visible to system
  - Internal fragment: visible to process (e.g. if allocate at some granularity)
- Goal
  - Reduce number of holes
  - Keep holes large
- Stack fragmentation vs heap fragmentation

Typical heap implementation

- Data structure: free list
  - Chains free blocks together
- Allocation
  - Choose block large enough for request
  - Update free list
- Free
  - Add block back to list
  - Merge adjacent free blocks

Heap allocation strategies

- Best fit
  - Search the whole list on each allocation
  - Choose the smallest block that can satisfy request
  - Can stop search if exact match found

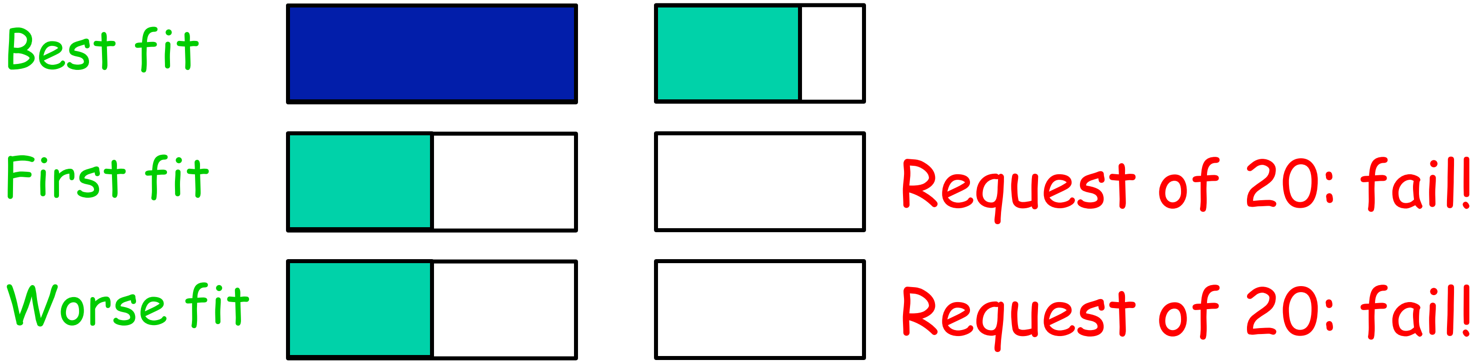
- First fit
  - Choose first block that can satisfy request

- Worst fit
  - Choose largest block (most leftover space)

Which is better?

Example

- Free space: 2 blocks, size 20 and 15
- Workload 1: allocation requests: 10 then 20



Best fit

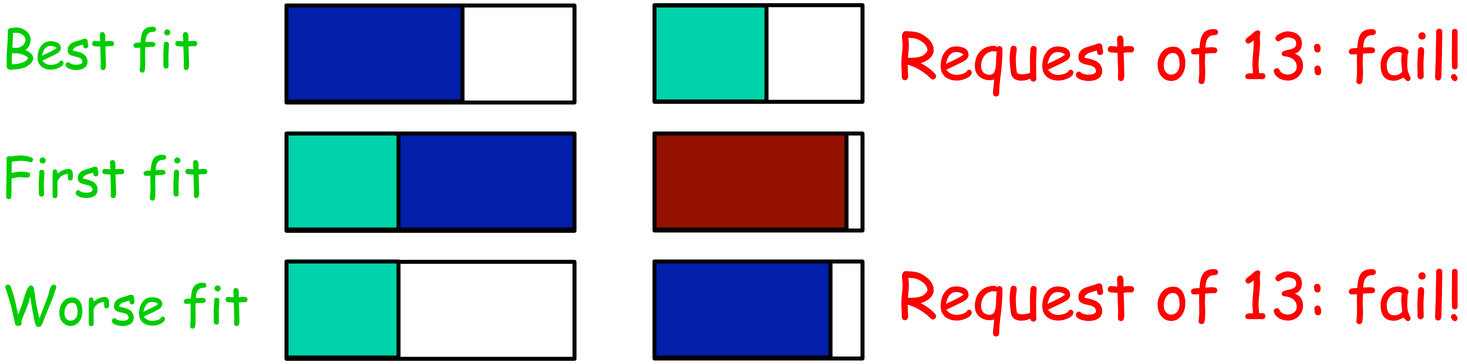
First fit

Request of 20: fail!

Worse fit

Request of 20: fail!

- Workload 2: allocation requests: 8, 12, then 13



Best fit

Request of 13: fail!

First fit

Worse fit

Request of 13: fail!

Comparison of allocation strategies

- Best fit
  - Tends to leave very large holes and very small holes
  - Disadvantage: very small holes may be useless
- First fit:
  - Tends to leave "average" size holes
  - Advantage: faster than best fit
- Worst fit:
  - Simulation shows that worst fit is worst in terms of storage utilization

Buddy allocator motivation

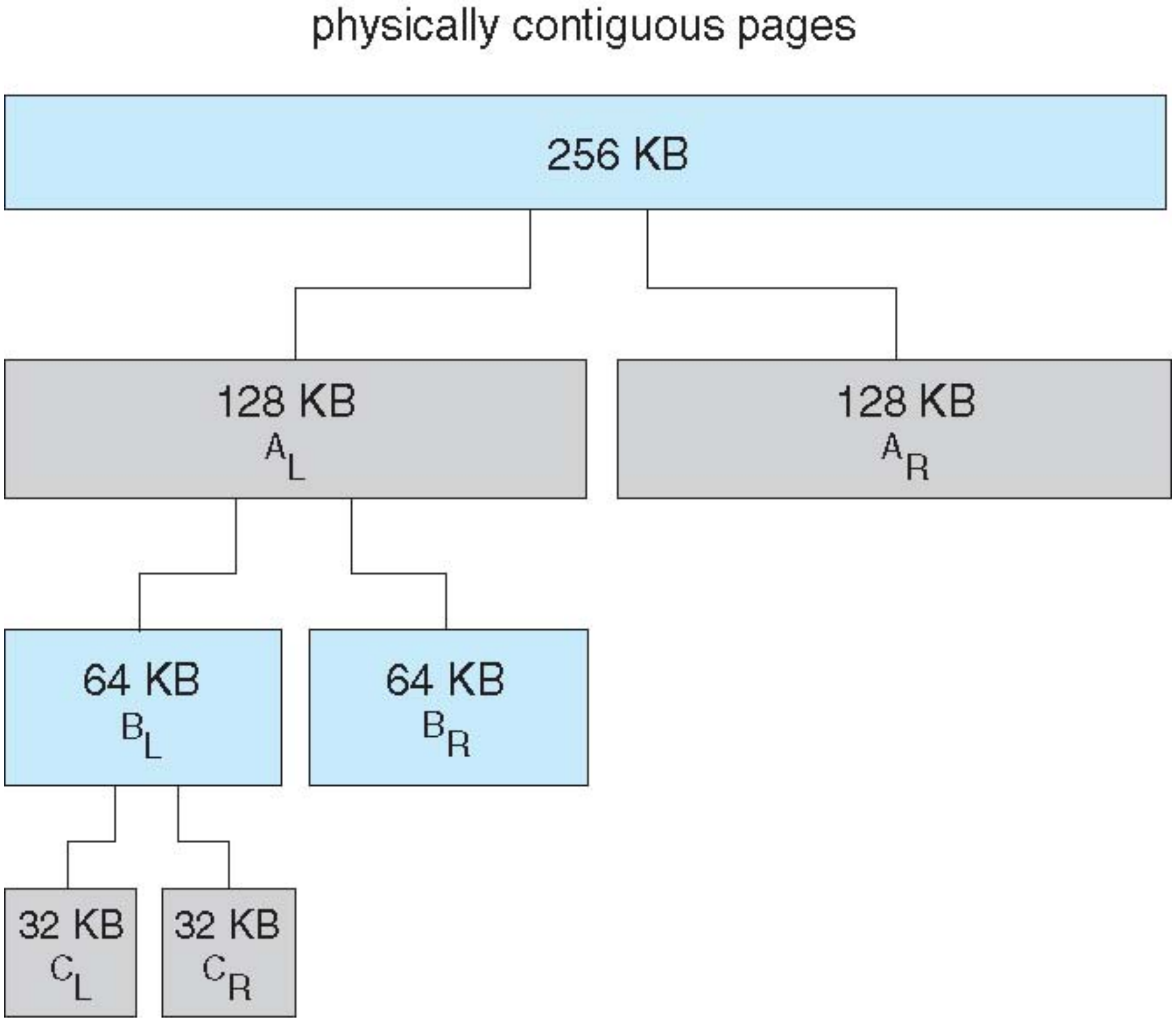
- Allocation requests: frequently 2^n
  - E.g., allocation physical pages in FreeBSD and Linux
  - Generic allocation strategies: overly generic
- Fast search (allocate) and merge (free)
  - Avoid iterating through entire free list
- Avoid external fragmentation for req of 2^n; keep free pages contiguous

Real: used in FreeBSD and Linux

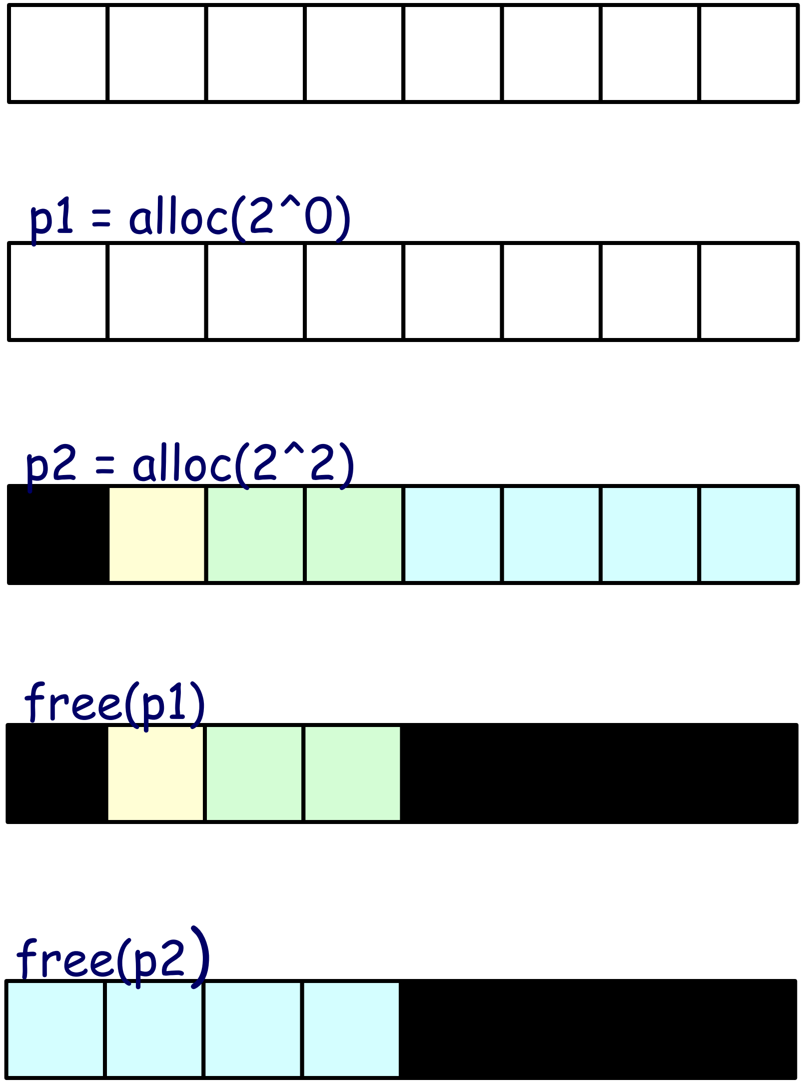
Buddy allocator implementation

- Allocation restrictions: 2^k, 0<= k <= N
- Data structure
  - N free lists of blocks of size 2^0, 2^1, …, 2^N
- Allocation of 2^k:
  - Search free lists (k, k+1, k+2, …) for appropriate size
    - Recursively divide larger blocks until reach block of correct size
    - Insert "buddy" blocks into free lists
- Free
  - Recursively coalesce block with buddy if buddy free

Buddy allocator illustration



Buddy allocation example



freelist[3] = {0}

p1 = alloc(2^0)

freelist[0] = {1}, freelist[1] = {2}

freelist[2] = {4}

p2 = alloc(2^2)

freelist[0] = {1}, freelist[1] = {2}

free(p1)

freelist[2] = {0}

free(p2)

freelist[3] = {0}

Legend:

Black: allocated.

Other color: on freelist of that color.

freelist[3] = free list for blocks of 2^3 pages.

Pros and cons of buddy allocator

- Advantages
  - Fast and simple compared to general dynamic memory allocation
  - Avoid external fragmentation by keeping free physical pages contiguous

- Disadvantages
  - Internal fragmentation
    - Allocation of block of k pages when k != 2^n

Slab allocator

- Motivation:
  - Frequent (de)allocationof certain kernel objects
    - E.g., file struct, inode, …
  - Other allocators: overly general; assume variable size
- Slab: cache of "slots"
  - Slot size = object size
  - Free memory management = bitmap
  - Allocate: set bit and return slot
  - Free: clear bit
- Real: used in FreeBSD and Linux, implemented on top of buddy page allocator, for objects smaller than a page

Slab allocator illustration