Vnodes

- **Every open file has an associated vnode struct**
- **All file system types (FFS, NFS, etc.) have vnodes**
  - `v_data` points to FS-specific data
  - Function pointers for operations (open/read/write/. . .)
- **When refcount → 0,** `inactive()` **called**
  - Does not "deallocate" vnode—caches it
  - Files can very efficiently be reopened before deallocation
  - `reclaim()` revokes vnode for another use

Name cache

- **Caches $\langle \textbf{dir}, \textbf{name} \rangle \rightarrow$ `vnode` translations**
  - Both positive and negative lookups cached
- **Need to invalidate all names for a `vnode` (mv dir)**
  - Each vnode has a "capability," also contained in cache
  - Bump 32-bit capability to flush cache efficiently
  - When counter wraps, invalidate all of name cache
- **Need to invalidate negative lookups when directory changed**
  - Bump capability

Buffer cache

- **Caches file blocks in memory**
  - Hash table maps $\langle$vnode, offset$\rangle$ $\rightarrow$ buffer
  - Freelists keep buffers not in use
- **Operations on buffers:**
  - `bread()` – fill buffer from underlying file
  - `breadn()` – like `bread()`, but start read ahead
  - `brelse()` – relinquish unmodified buffer
  - `bwrite()` – synchronously write data to disk
  - `bawrite()` – asynchronously write data to disk
  - `bdwrite()` – schedule delayed write

Write policies

- **When to use synchronous `bwrite()`?**
  - `fsync()` system call
  - Network file systems with synchronous writes
  - When cleaning reclaimed buffer
  - When order of disk writes matters
- **When to use `bdwrite()`?**
  - Buffer may be modified again
- **When to use `bawrite()`?**
  - Buffer full, might as well clean it

Buffer free lists

- **Locked – unused (for superblock?)**
- **LRU – (or can replace with different algorithm)**
- **Age**
  - Deleted files pushed onto front (reuse immediately)
  - Read-ahead blocks placed at end
- **Empty**
  - No physical memory

Algorithm: Optimal

- **Definition: Maximize #hits/#references**
  - Evict block that will be referenced furthest in the future
- **How to implement**
  - Gather trace of all references
  - Retroactively figure out what you should have done
- **Useful only as a point of comparison**
- **LRU used to approximate algorithm**
  - Most recently touched most likely to be touched soon
- **If you could implement Optimal, is it best?**
  - Best hit rate, but what about fairness?

Algorithm: FBR

- **Idea: Weight blocks by frequency of reference**
  - Count # of references
  - Evict blocks with lowest counts
- **Problem: Many short-spaced references, then none**
  - Don't bump count in "new" section of LRU queue
- **Problem: Evicted right as blocks leave new**
  - Only evict in "old" section of queue
- **Problem: Never evict blocks with high count**
  - Decay by half when total of counts reach some max

Algorithm: LRU-k

- **LRU based on kth most recent access**
- **Regular LRU is LRU-1**
- **LRU-2 works well in practice**
  - Great for walking indexed data structures
- **Computationally expensive**
  - Costs $\log N$ to manipulate buffer (with cache size N)

Algorithm: 2Q

- **Goal: Cheaper algorithm with benefits of LRU-2**
- **Idea: Keep 2 queues:**
  - A_1 for buffers accessed only once – FIFO
  - A_m for buffers accessed multiple times – LRU
- **Problem: Sizing A_1 vs. A_m is hard**
- **Solution: Ghost buffers**
  - Break A_1 into $A_{1\mathrm{in}}$ and $A_{1\mathrm{out}}$
  - $A_{1\mathrm{out}}$ doesn't actually contain buffered data

Algorithm: SEQ

- Detect sequential accesses
- Apply MRU to pages fetched by sequential access
- Does not detect looping behavior

EELRU

- **Idea: Ordinarily use simple LRU**
  - If many recently fetched pages being evicted, move to fallback algorithm.
- **Divide LRU queue into three regions**
  - LRU region – most recently accessed pages
  - early region – less recently accessed pages
  - late region – even less recently accessed pages
  - Use ghost buffers to track more buffers than memory size
- **Evict from head of early or head of late point, based on mathematical predictions**

Informed Prefetching & Caching [PGGSZ95]

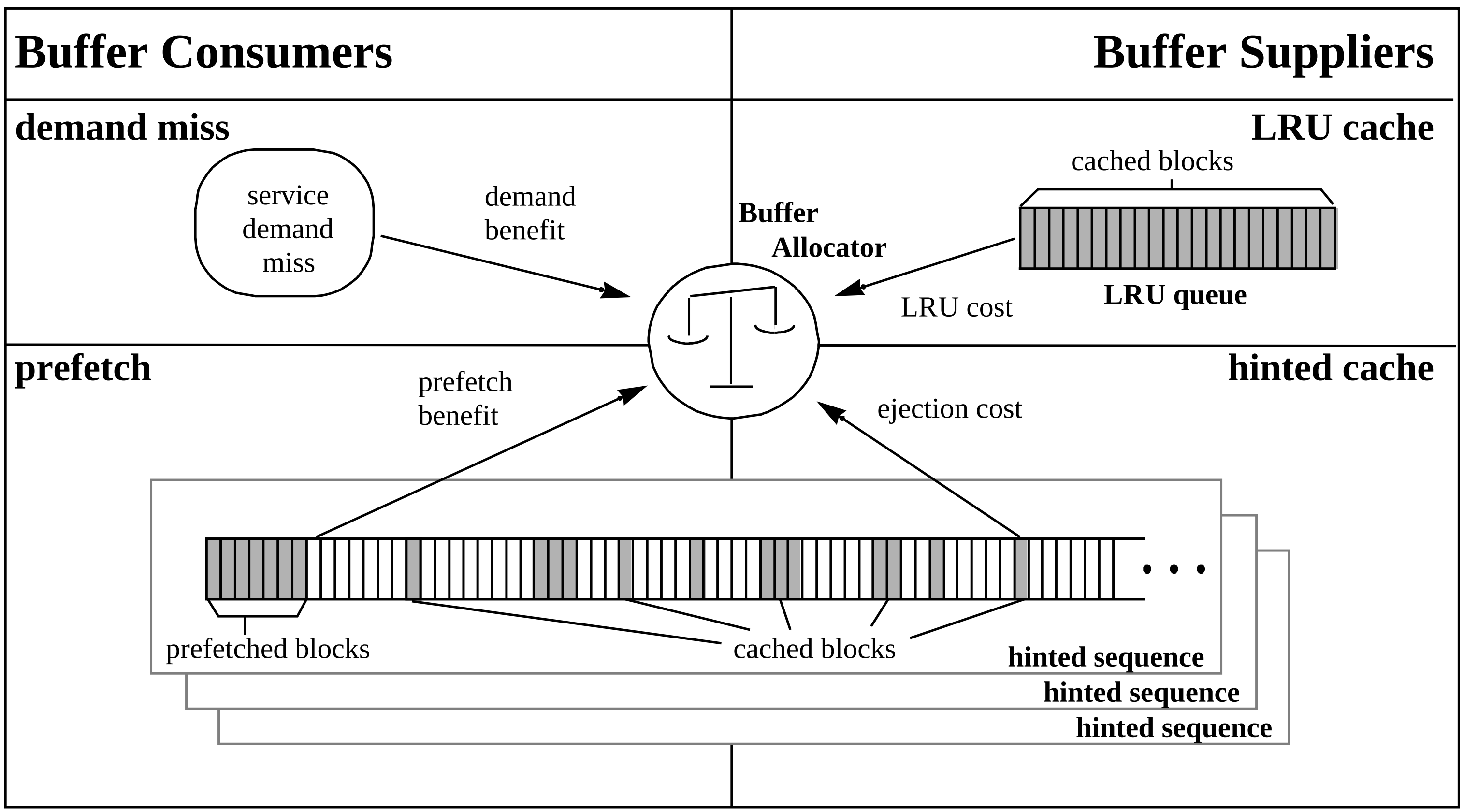
- **Idea: Improve I/O performance by giving OS hints**
- **What is a *hint* in computer systems?**
  - Information that may improve performance
  - Does not have to be true (will not affect correctness)
  - Does not have to be heeded by system
- **Two kinds of hints: Advice & Disclosure**
  - *Advice*—suggested policy, e.g., “use MRU for this file”
  - *Disclosure*–gives notice of how App. will use OS interface, e.g., “App. will read file 4 times”
- **Which is a better: Advice or disclosure?**

Advantages of disclosure

- **Remains correct when environment changes**
  - Increases portability of application to different hardware
- **Gives OS more info $\Longrightarrow$ More robust**
  - OS may not be able to follow every process's advice
    e.g., not enough buffers to prefetch everything
  - Disclosure allows OS to optimize for actual resources
- **Hints uses same abstractions as later operations**
  - I.e., specified with fd/offsets, not inode/buffers
  - Better modularity

Disclosure interface

- **Added disclosure ioctl call w. two arguments**
  - *File specifier*: File descriptor or file name
  - *Pattern specifier*: Whole file, or list of ⟨offset,len⟩ pairs
- **OS weighs needs/resources of hints vs. demand**



Using speculative execution [CG99]

- **Disclosure requires programmer to insert hints**
- **Idea: Automatically generate hints with spec. exec.**
  - Application stalls waiting for a read
  - Spawn another thread, and continue executing w/o data
  - Issue prefetches for any further accesses
- **Preventing side effects in speculative thread**
  - Disallow all system calls except fstat (& sbrk)
  - Catch signals in case of errors like divide-by-zero
  - Implement software copy-on-write—Make two copies of application text segment, instrument one for CoW
- **Results: 20-70% improvement on many apps**