CSCE 313-200
Introduction to Computer Systems
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File System III

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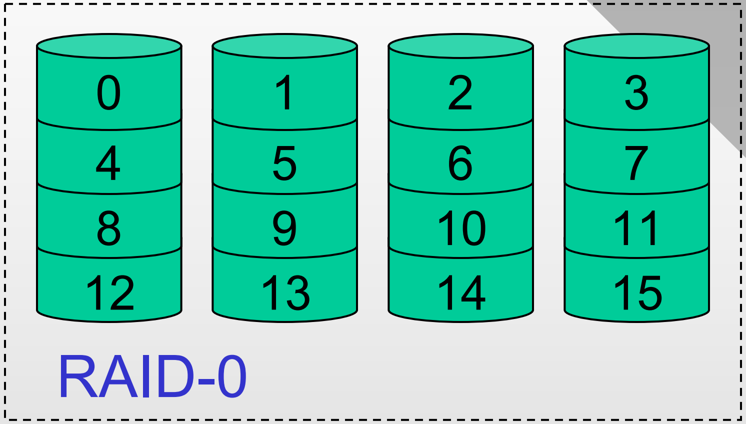
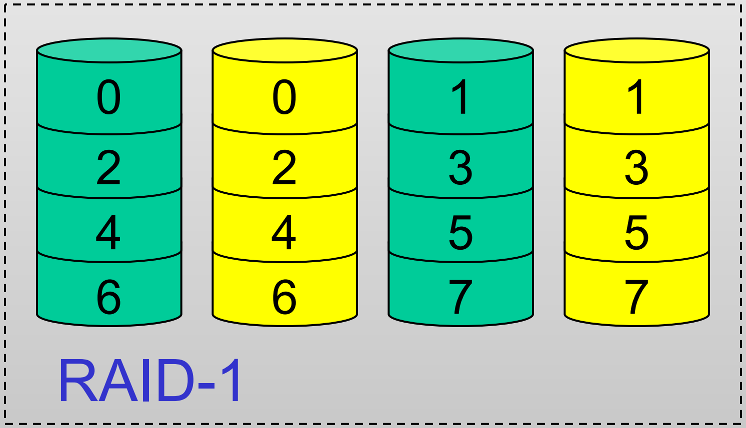
Chapter 11: Roadmap

11.1 I/O devices
11.2 I/O function
11.3 OS design issues
11.4 I/O buffering
11.5 Disk scheduling
11.6 RAID
11.7 Disk cache
11.8-11.10 Unix, Linux, Windows

RAID

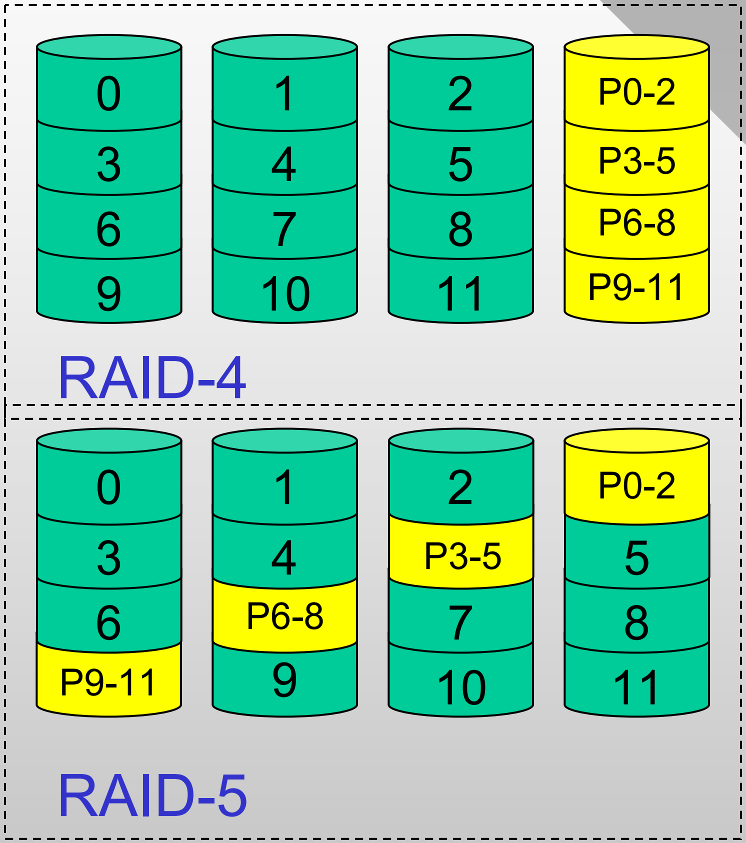
- Redundant Array of Inexpensive Disks (RAID)
  - Nowadays "I" is Independent
- RAID-0 (striping)
  - Non-redundant sequential writing to all disks
  - Goes in units of some fixed block size (e.g., 64 KB)
  - R/W speed N*S for N disks
  - Any failure renders array unusable, all data lost
- RAID-1 (mirroring)
  - One spare for each disk





- RAID-1 (cont'd)
  - R/W speed N*S/2
  - Tolerates single disk failure, may survive up to N/2 failures, but may also crash with just 2

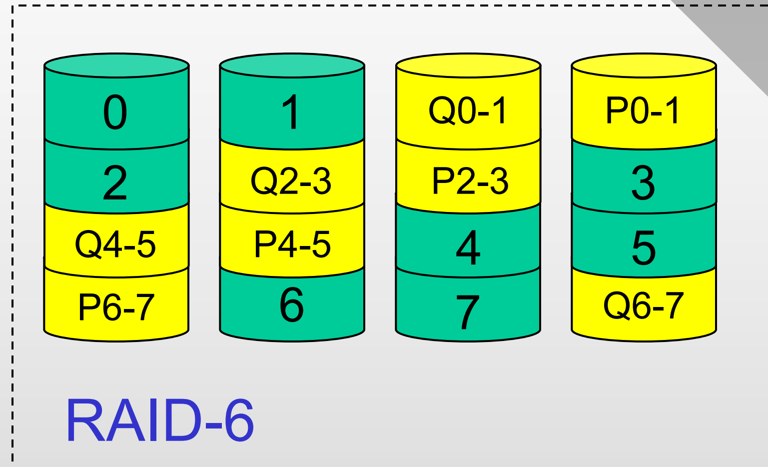
RAID

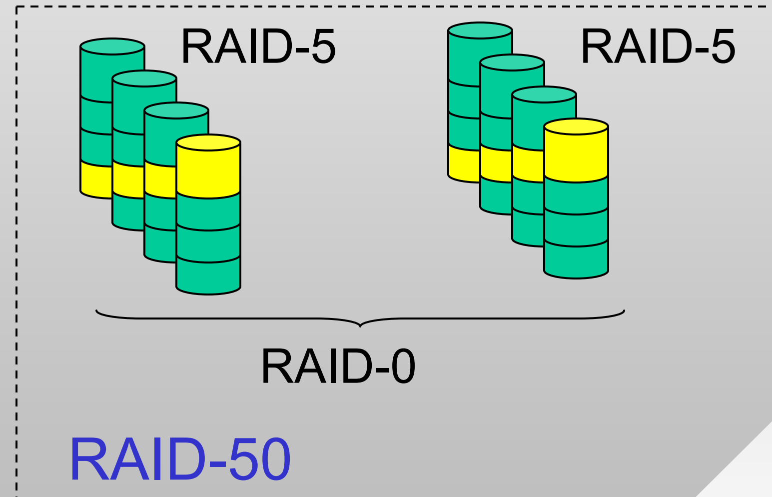


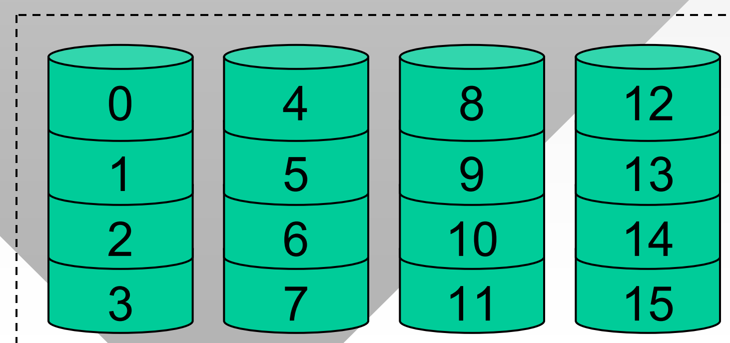
- RAID-2 and 3
  - Require synchronized disks
  - Not popular in practice
- All RAID levels 4+ compute block/stripe parity
  - Usually an XOR of all blocks
  - Failure of a disk allows recovery of block by XORing parity with remaining blocks
- RAID-4
  - Bottlenecks on parity disk (e.g., modification of blocks 2 and 6 cannot proceed in parallel)
- RAID-5
  - Parity split over all disks
  - Read speed S*(N-1)
  - Tolerates failure of any single disk, crashes if 2 or more fail concurrently

RAID

- RAID-6
  - Dual parity, read speed S*(N-2)
  - Tolerates failure of any 2 disks, crashes if 3 or more fail
  - On some cards, write speed 30% slower than RAID-5
- RAID-XY or X+Y
  - Several RAID-X arrays organized into a RAID-Y
- Windows also offers a spanned volume in software
  - Writes to one disk until full, then switches to the next →







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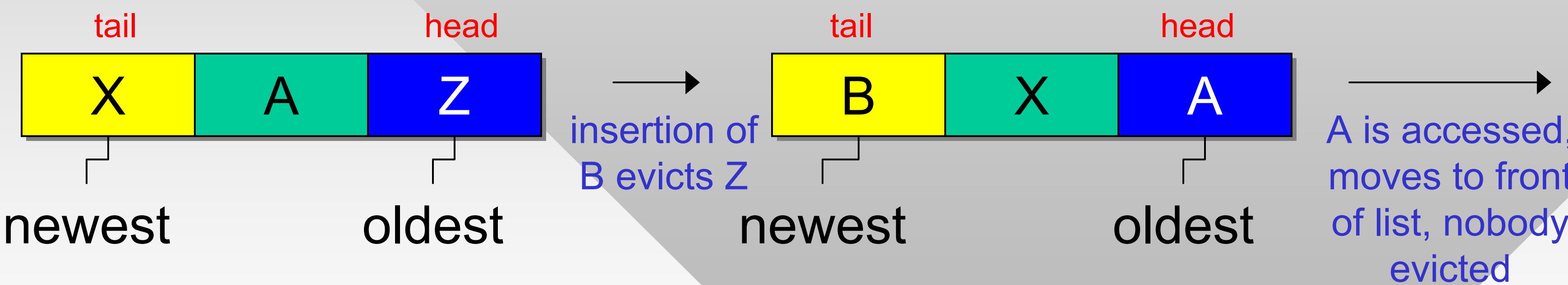
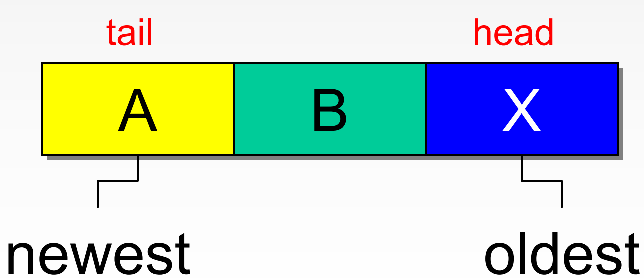
Disk Cache

- In caching, the main issue is achieving high hit rates
- Classical LRU (Least Recently Used)
  - Evict the item that hasn't been used the longest
- In practice, doubly-linked queue/list is enough
  - Most-recent items inserted at the tail, old evicted at the head

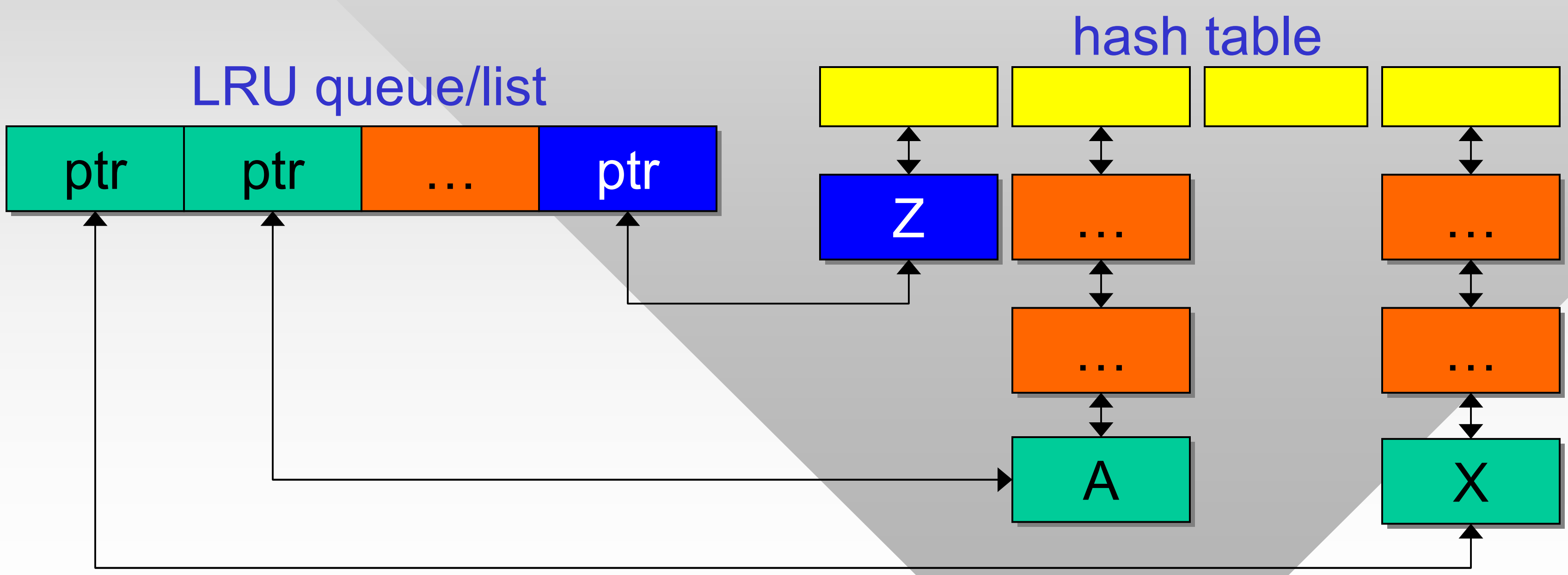




- How to quickly find accessed item in the queue?
  - Linear scanning is slow

Disk Cache

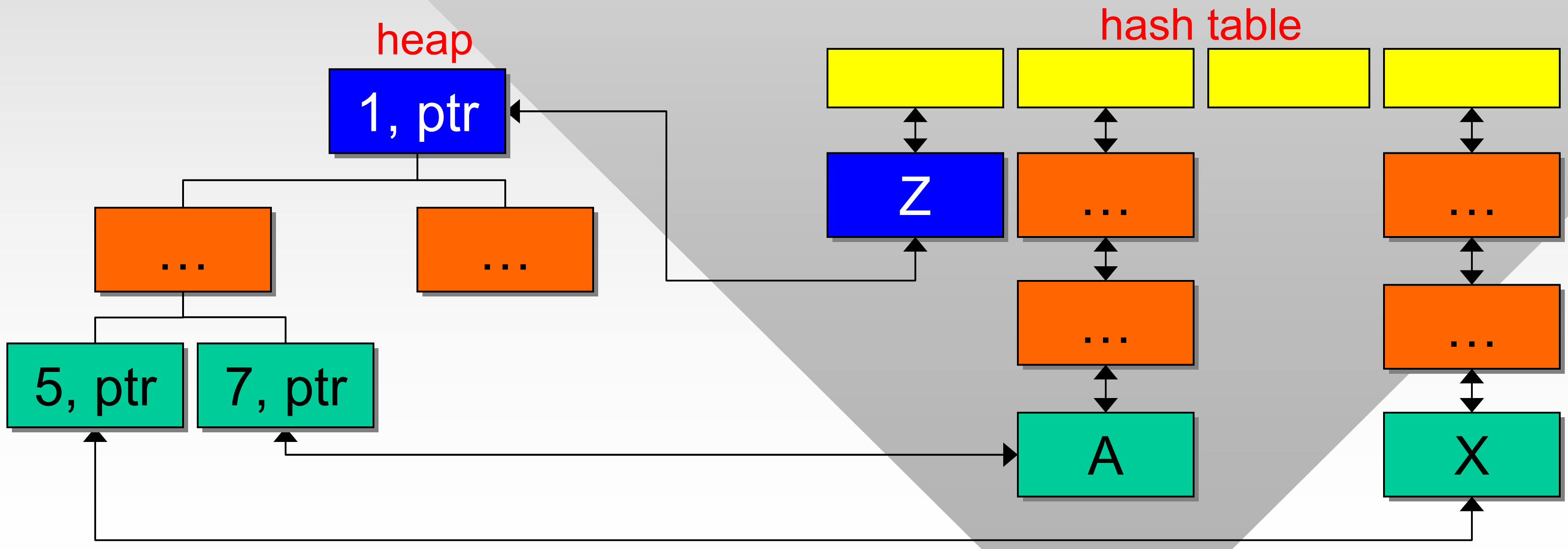
- Idea: maintain a hash table that stores a pointer to the item's location in the queue/list
- How to update the hash table during eviction?
  - Either look up item in hash table or store a reverse pointer



no need to store items in both hash table and LRU queue

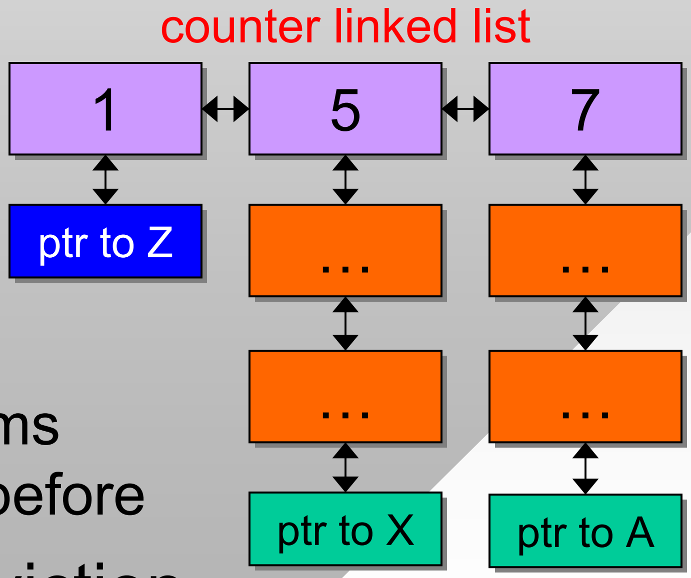
Disk Cache

- Age and frequency of usage may not be related
  - More accurate method may be LFU (Least Frequently Used)
  - Assign counter C to items, how often it has been accessed
  - Sort items by C, evict the one with the smallest counter
- Requires a min-heap ordered by access counters



Disk Cache

- LFU complexity
  - O(1) for cache hit, logN for reinsertion (existing item)
  - O(1) for cache miss, logN for eviction (new item)
- Could also use a balanced binary search tree
  - Left-most child is always evicted
- Another approach: organize counters into doubly-linked list
  - Each counter has a list of nodes that tie for their value of C
  - Nodes contain pointers to actual items which are part of the hash table as before
- Constant-time access/insertion/eviction

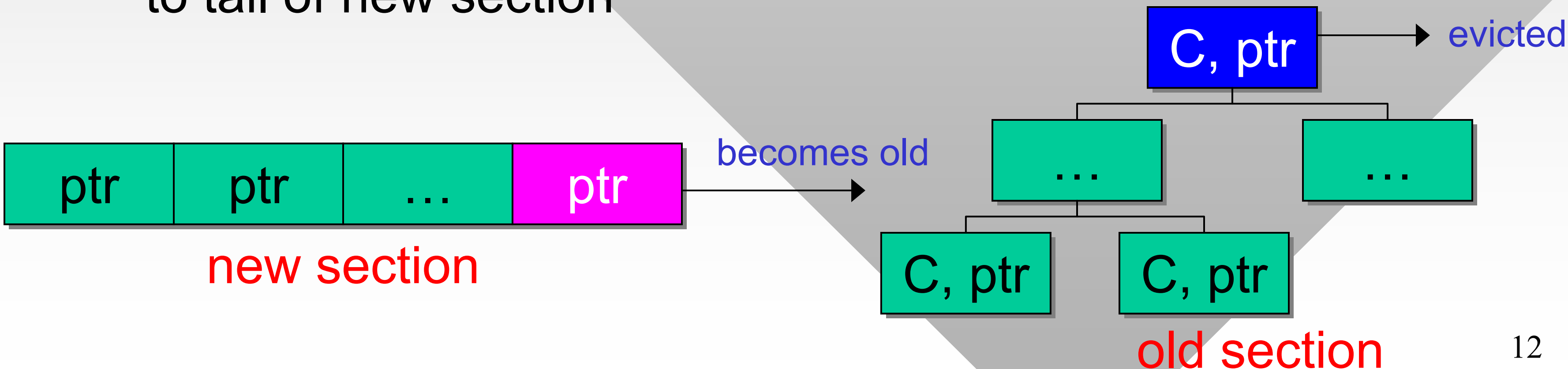


Disk Cache

- Problem #1: LFU is biased against new items, which it may evict immediately after insertion
  - As an improvement, evict every K cache requests and use LRU within each linked list of nodes that have the same C
- Problem #2: items with large counters stay virtually forever in the cache
  - Suppose an item gets 1M initial hits due to locality, but is never needed again
  - It will not get evicted until C = 1M is the *smallest* counter in the heap/list
- Goal: prevent fresh items from being immediately evicted and discount the importance of back-to-back access

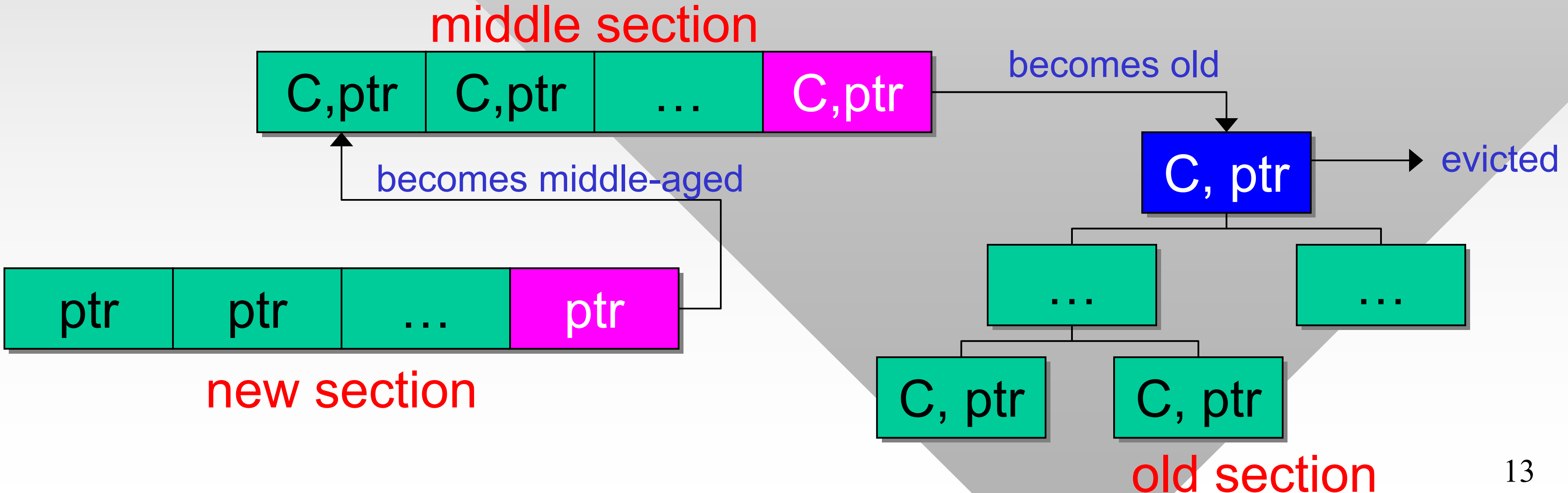
Disk Cache

- Hybrid LRU-LFU methods
  - Attempt to register only long-term usage
- New section is similar to LRU
  - Items move to the tail on access, counters unchanged
  - Eviction moves from the head to the *old section*
- Old section is similar to LFU, sorted by counter
  - Hits increment C and move item to tail of new section



Disk Cache

- Research suggests that the LFU (old) section is still biased against new blocks, evicts them right away
- Solution: create a middle section to build up counters
  - On hits, middle-aged items increment counters and move to the tail of new section
  - When item is old, its C should reflect its long-term usage

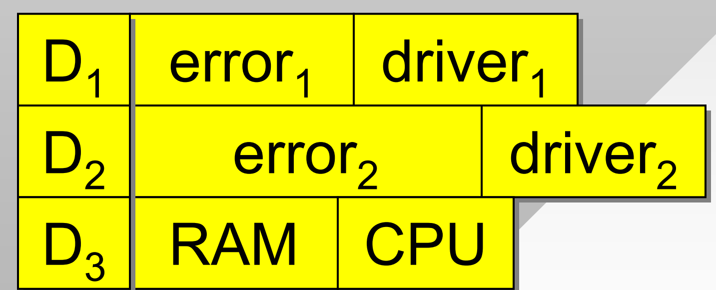


Chapter 12: Roadmap

- 12.1 Overview
- 12.2 File organization
- 12.3 Directories
- 12.4 Sharing
- 12.5 Record blocking
- 12.6 Secondary storage
- 12.7 File security
- 12.8-12.10 Unix, Linux, Windows

File Organization

- As before, a file is just a bunch of bytes
- Our next task is to figure out how to organize these bytes within the file to enable ease of operation
  - Mostly concerned here with data lookup and retrieval
- Assume data is split into items/records
  - Each record has multiple fields (e.g., name, age, SSN)
- 1) Pile is the most general
  - Records dumped into file as they become available to the program, in no particular order, \n separator
  - Different records may have different length or # of fields, typically read by humans
  - e.g., Unix syslog file into which all kernel modules write



File Organization

- 2) Sequential file (sorted or unsorted)
  - One field in each record is the key, everything else is value
  - Search for a given key or range

SSN_1	$salary_1$	age_1
SSN_2	$salary_2$	age_2

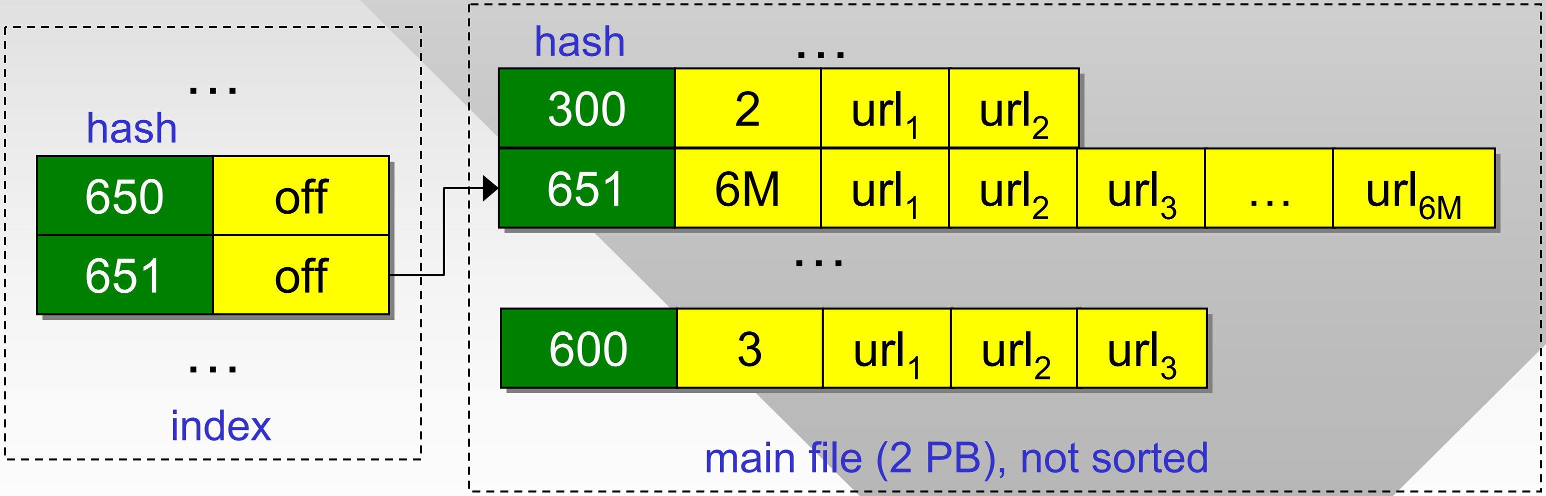
- Fixed-size fields
  - E.g., payroll database with all fields padded to same size

$node_1$	deg_1	$list_1$
$node_2$	deg_2	$list_2$

- Variable-size fields
  - E.g., graph (key = nodeID, value = degree + adjacency list)
- If sorted by key
  - If fixed-size values, binary search to find records
  - If variable-size, need unambiguous record separators
  - Painful to add elements as resorting the file is expensive

File Organization

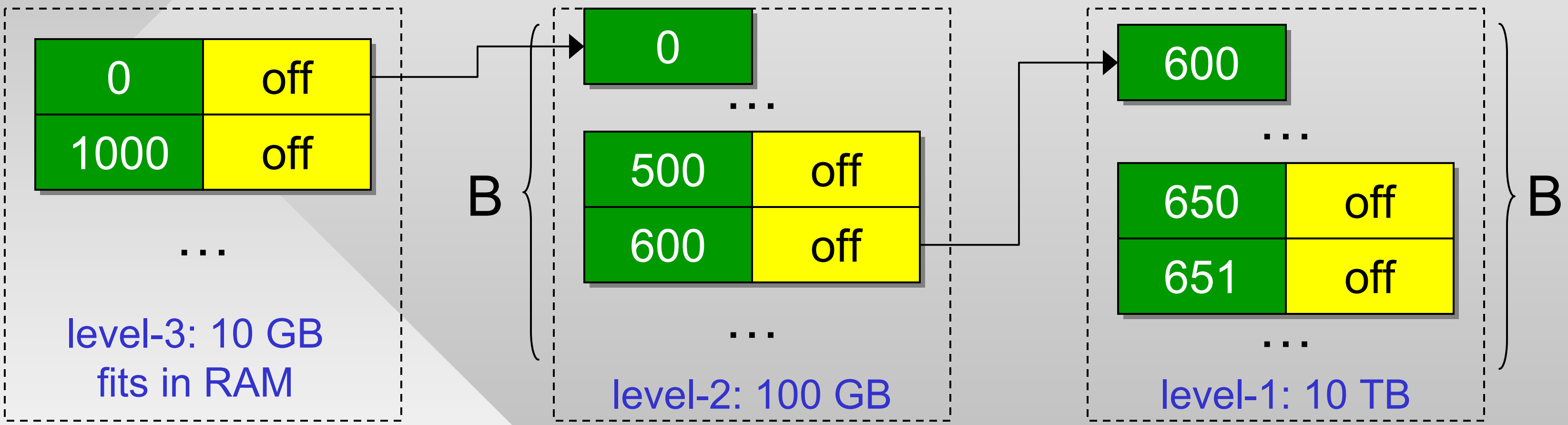
- 3) Indexed Sequential
  - File structure that has the main file with data (usually huge) and a separate file containing the index for keys
- Suppose the main file is Google's word→URL mapping
  - Query maps hashes of words to pages with them



- Binary search on the index, find offset in main file

File Organization

- If index is too big to fit in RAM and binary search is inefficient, a k-level index is possible



- Assume level-1 index size F, read I/O block size B
  - Binary search needs $\log_2(F/B)$ seeks
  - On the other hand, k-level index needs k-1 seeks
- F = 10 TB file, B = 1 MB block size $\rightarrow$ 23 seeks, while multi-index above does it in k-1 = 2 seeks

File Organization

- 4) Indexed
  - Separate index for every possible field, allows database-like operations on fields
- Main challenge for indexed files is keeping the index updated when it doesn't fit in RAM
- 5) Hashed file
  - Treat file contents as RAM, hash items directly to some offset

```
uint64 N;           // hash table size
// preallocate file of size N * sizeof(item)
void Hash (Item x) {
    off = HashFunction (x.key) % N;
    file.Seek (off * sizeof(Item));
    file.Write (&x, sizeof(Item));
}
```

- What to do with collisions?