Operating Systems
CSCI 3150

Lecture 12: Memory Management
Part III: Swapping

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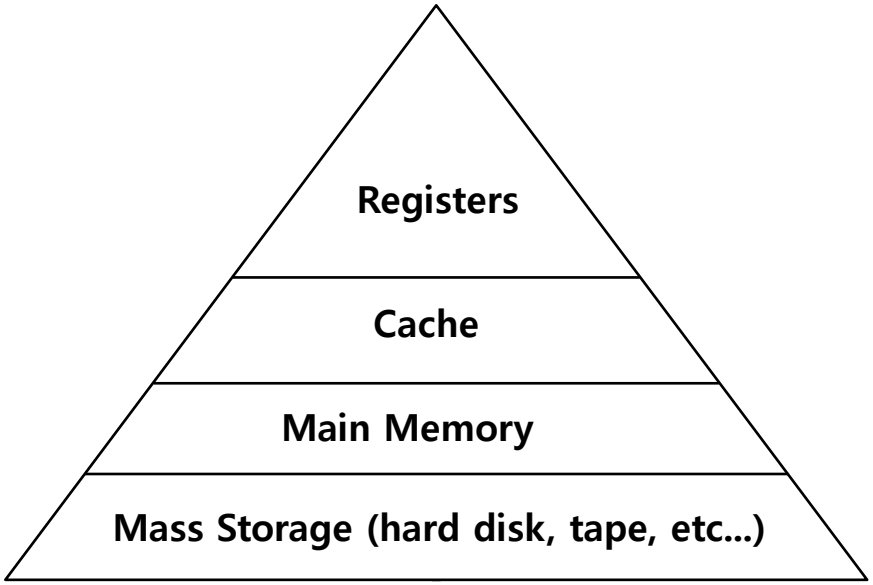
Overview

- Mechanisms
- Policies

Beyond Physical Memory: Mechanisms

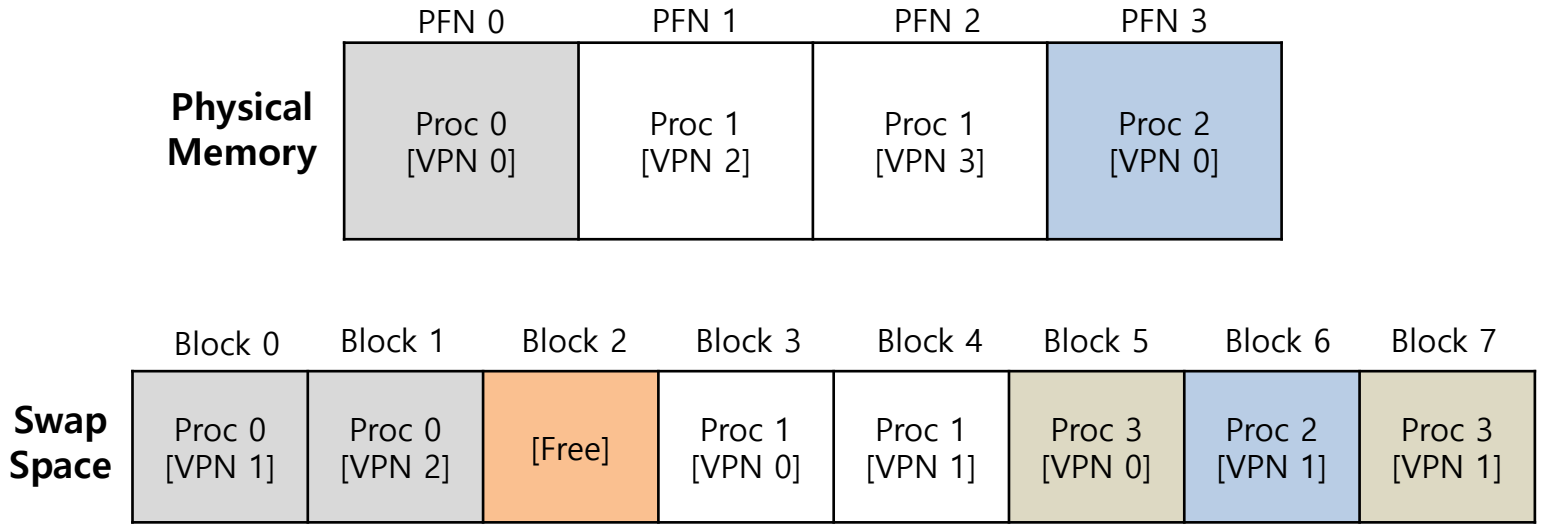
- Use part of disk as memory
  - OS needs a place to stash away portions of address space that currently aren't in great demand.
  - In modern systems, this role is usually served by a hard disk drive.



Memory hierarchy in modern system

Swap Space

- Reserve some space on the disk for moving pages back and forth.
- OS needs to remember the swap space, in page-sized unit.



Physical Memory and Swap Space

Present Bit

- Add some machinery higher up in the system in order to support swapping the pages to and from the disk.
  - When the hardware looks in the PTE, it may find that the page is not present in physical memory.

Value	Meaning
1	page is present in physical memory
0	The page is not in memory but rather on disk.

Concepts

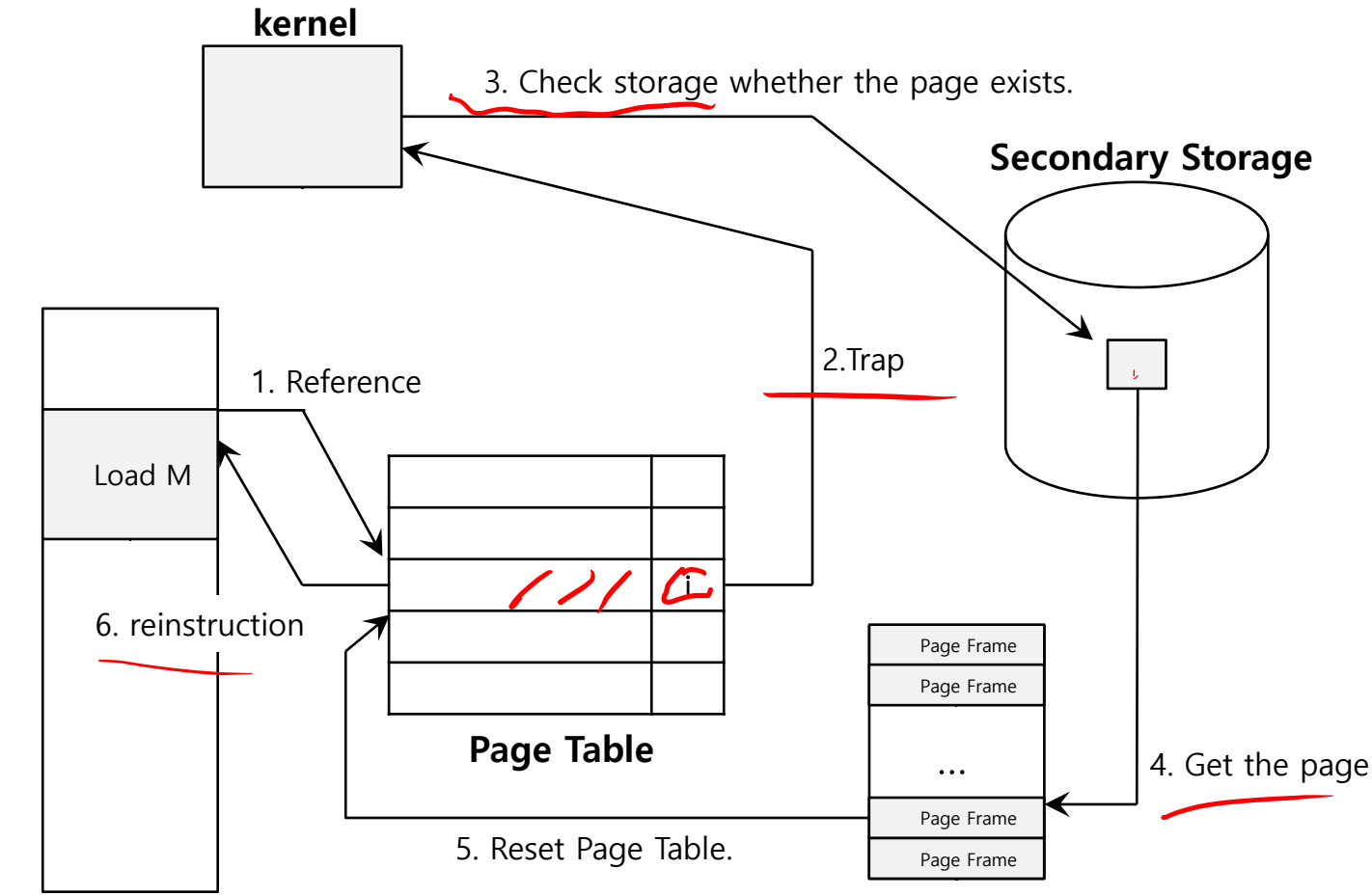
- Page fault
  - Accessing page that is not in physical memory.
  - If a page is not present and has been swapped to disk, the OS needs to swap the page back into memory in order to service the page fault.
- Page replacement
  - The OS likes to page out some pages to make room for the new ones it is about to bring in
  - The process of picking a page to evict (or replace) is known as page-replacement policy.

When to Perform Page Replacement

- Lazy approach…
  - OS waits until memory is full to start replacing pages.
  - This is clearly unrealistic… Do not procrastinate!
- Swap Daemon, Page Daemon
  - When there are fewer than LW (low watermark) pages available, a background thread that is responsible for freeing memory runs.
  - The thread evicts pages until there are HW (high watermark) pages available.

Page Fault Control Flow

- PTE used for data such as the PFN of the page for a disk address.



When the OS receives a page fault, it looks in the PTE and issues the request to disk.

Page Fault Control Flow – Hardware

```
1:       VPN = (VirtualAddress & VPN_MASK) >> SHIFT
2:       (Success, TlbEntry) = TLB_Lookup(VPN)
3:       if (Success == True) // TLB Hit
4:          if (CanAccess(TlbEntry.ProtectBits) == True)
5:                Offset = VirtualAddress & OFFSET_MASK
6:                PhysAddr = (TlbEntry.PFN << SHIFT) | Offset
7:                Register = AccessMemory(PhysAddr)
8:          else RaiseException(PROTECTION_FAULT)
9:       else // TLB Miss
10:         PTEAddr = PTBR + (VPN * sizeof(PTE))
11:         PTE = AccessMemory(PTEAddr)
12:         if (PTE.Valid == False)
13:               RaiseException(SEGMENTATION_FAULT)
14:         else
15:            if (CanAccess(PTE.ProtectBits) == False)
16:               RaiseException(PROTECTION_FAULT)
17:            else if (PTE.Present == True)
18:               // assuming hardware-managed TLB
19:               TLB_Insert(VPN, PTE.PFN, PTE.ProtectBits)
20:               RetryInstruction()
21:            else if (PTE.Present == False)
22:               RaiseException(PAGE_FAULT)
```

Page Fault Control Flow – Software

```
1:        PFN = FindFreePhysicalPage()
2:        if (PFN == -1) // no free page found
3:                PFN = EvictPage() // run replacement algorithm
4:        DiskRead(PTE.DiskAddr, pfn) // sleep (waiting for I/O)
5:        PTE.present = True // update page table with present
6:        PTE.PFN = PFN // bit and translation (PFN)
7:        RetryInstruction() // retry instruction
```

- The OS must find a physical frame for the soon-be-faulted-in page to reside within.
- If there is no such page, waiting for the replacement algorithm to run

Summary

- Swapping: making the part of disk as memory
- Present bit required

22. Swapping: Policies

Goal of Cache Management

- To minimize cache misses
- To improve *average memory access time (AMAT)*

$T_M \ll T_D$

$$AMAT = (P_{Hit} * T_M) + (P_{Miss} * T_D)$$

Notation	Meaning
T_M	The cost of accessing memory
T_D	The cost of accessing disk
P_{Hit}	The probability of finding the data item in the cache(a hit)
P_{Miss}	The probability of not finding the data in the cache(a miss)

The Optimal Replacement Policy

- Lead to the fewest number of misses overall.
  - Replace the page that will be accessed furthest in the future.
  - Result in the fewest possible cache misses.
- Serve only as a comparison point, to know how close we are to perfection.

Tracing the Optimal Policy

Reference Row

0 1 2 0 1 3 0 3 1 2 1

Access	Hit/Miss?	Evict	Resulting Cache State
0	Miss		0
1	Miss		0,1
2	Miss		0,1,2
0	Hit		0,1,2
1	Hit		0,1,2
3	Miss	2	0,1,3
0	Hit		0,1,3
3	Hit		0,1,3
1	Hit		0,1,3
2	Miss	3	0,1,2
1	Hit		0,1,2

Hit rate is $\frac{Hits}{Hits+Misses} = \mathbf{54.6\%}$

Future is unknown!

A Simple Policy: FIFO

- Pages were placed in a queue when they enter the system.
- When a replacement occurs, the page on the head of the queue (the "**first-in**" page) is evicted.
  - Simple to implement
  - Agnostic to the importance of pages

Tracing the FIFO Policy

Reference Row

0 1 2 0 1 3 0 3 1 2 1

Access	Hit/Miss?	Evict	Resulting Cache State
0	Miss		0
1	Miss		0,1
2	Miss		0,1,2
0	Hit		0,1,2
1	Hit		0,1,2
3	Miss	0	1,2,3
0	Miss	1	2,3,0
3	Hit		2,3,0
1	Miss		3,0,1
2	Miss	3	0,1,2
1	Hit		0,1,2

Hit rate is $\frac{Hits}{Hits+Misses} = \mathbf{36.4\%}$

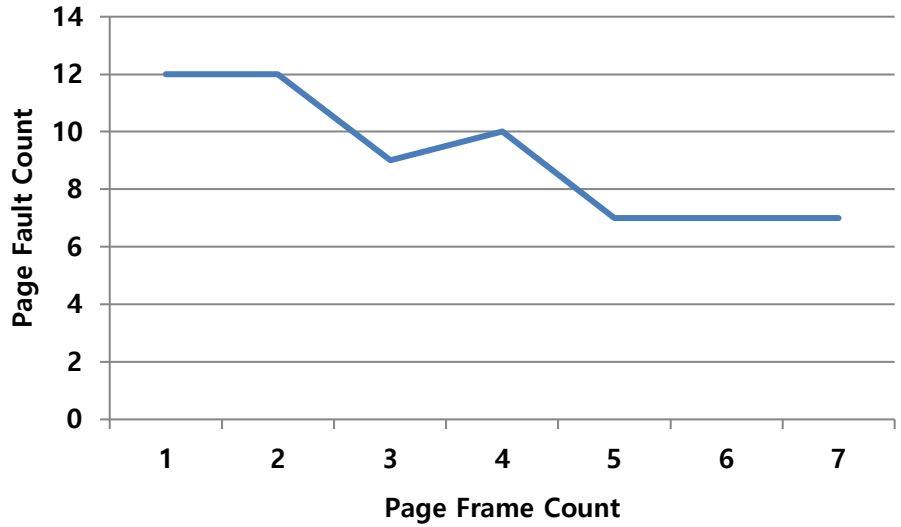
Even though page 0 had been accessed a number of times, FIFO still kicks it out.

Belady's Anomaly

- We would expect the cache hit rate to increase when the cache gets larger. But in this case, with FIFO, it gets worse.

Reference Row

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



Another Simple Policy: Random

- Picks a random page to replace under memory pressure.
  - It doesn't really try to be too intelligent in picking which page to evict
  - Random does depends entirely upon how lucky Random gets in its choice.

Access	Hit/Miss?	Evict	Resulting Cache State
0	Miss		0
1	Miss		0,1
2	Miss		0,1,2
0	Hit		0,1,2
1	Hit		0,1,2
3	Miss	0	1,2,3
0	Miss	1	2,3,0
3	Hit		2,3,0
1	Miss	3	2,0,1
2	Hit		2,0,1
1	Hit		2,0,1

Using History

- Learn on the past and use **history**.
  - Two types of historical information.

Historical Information	Meaning	Algorithms
Recency	The more recently a page has been accessed, the more likely it will be accessed again	LRU
Frequency	If a page has been accessed many times, It should not be replaced as it clearly has some value	LFU

Using History: LRU

- Replace the least-recently-used page.

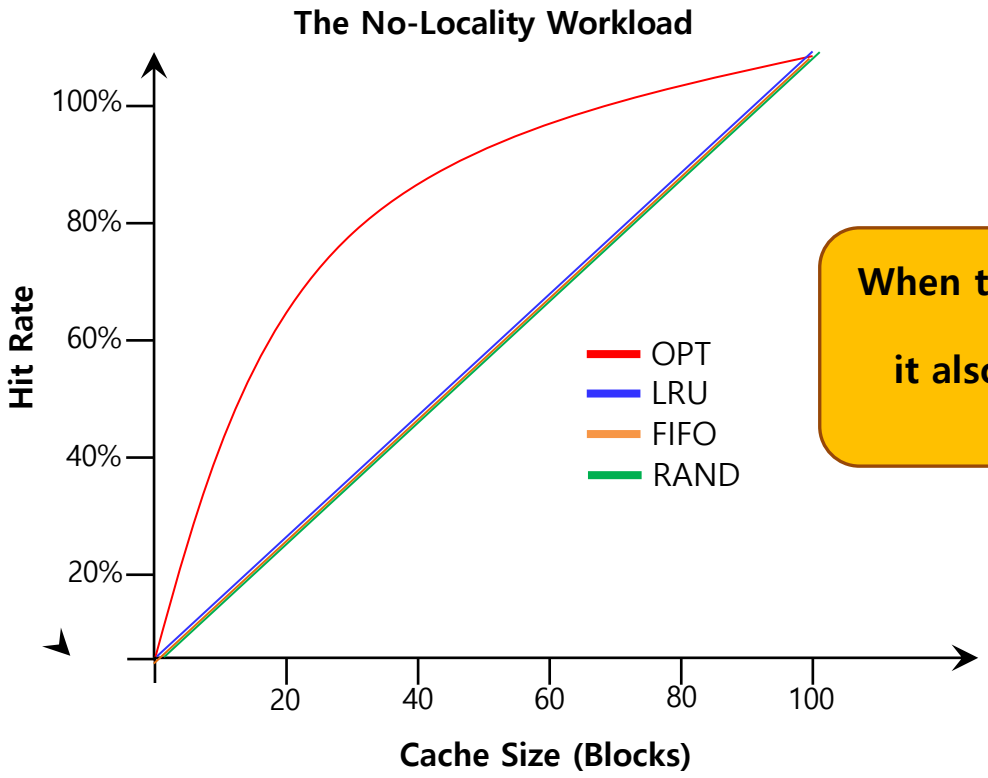
Reference Row

0 1 2 0 1 3 0 3 1 2 1

Access	Hit/Miss?	Evict	Resulting Cache State
0	Miss		0
1	Miss		0,1
2	Miss		0,1,2
0	Hit		1,2,0
1	Hit		2,0,1
3	Miss	2	0,1,3
0	Hit		1,3,0
3	Hit		1,0,3
1	Hit		0,3,1
2	Miss	0	3,1,2
1	Hit		3,2,1

Workload Example : The No-Locality Workload

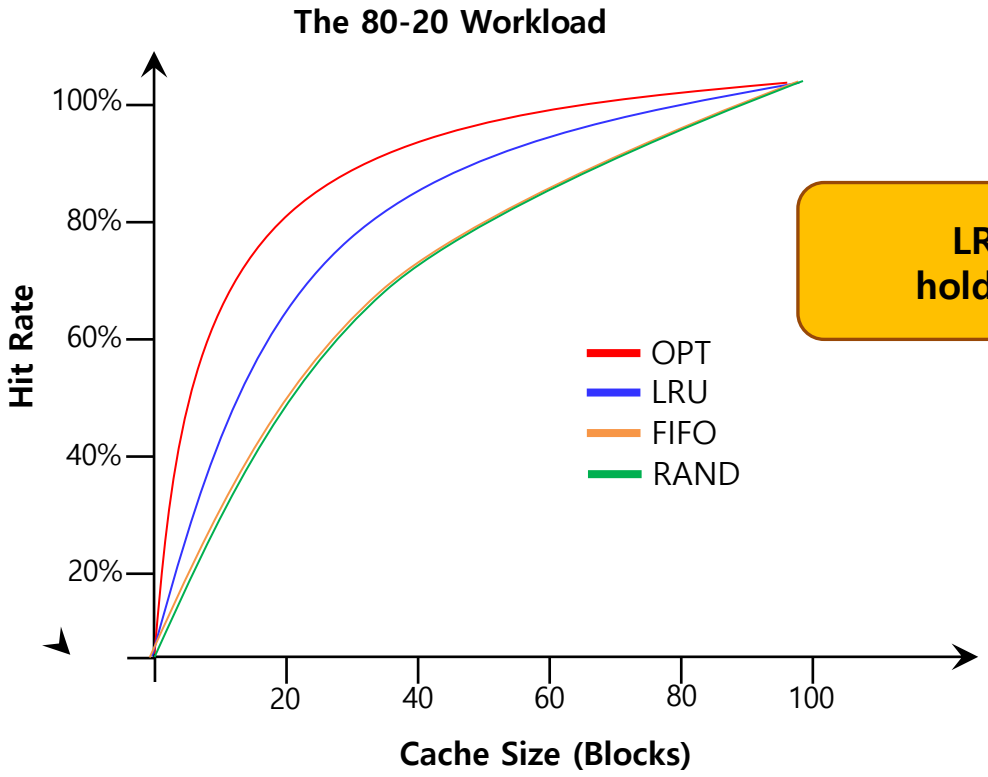
- Each reference is to a random page in a set of 100 pages
  - Workload has 100 accesses over time.
  - Choosing the next page to refer to at random



When the cache is large enough to fit the entire workload, it also doesn't matter which policy you use.

Workload Example : The 80-20 Workload

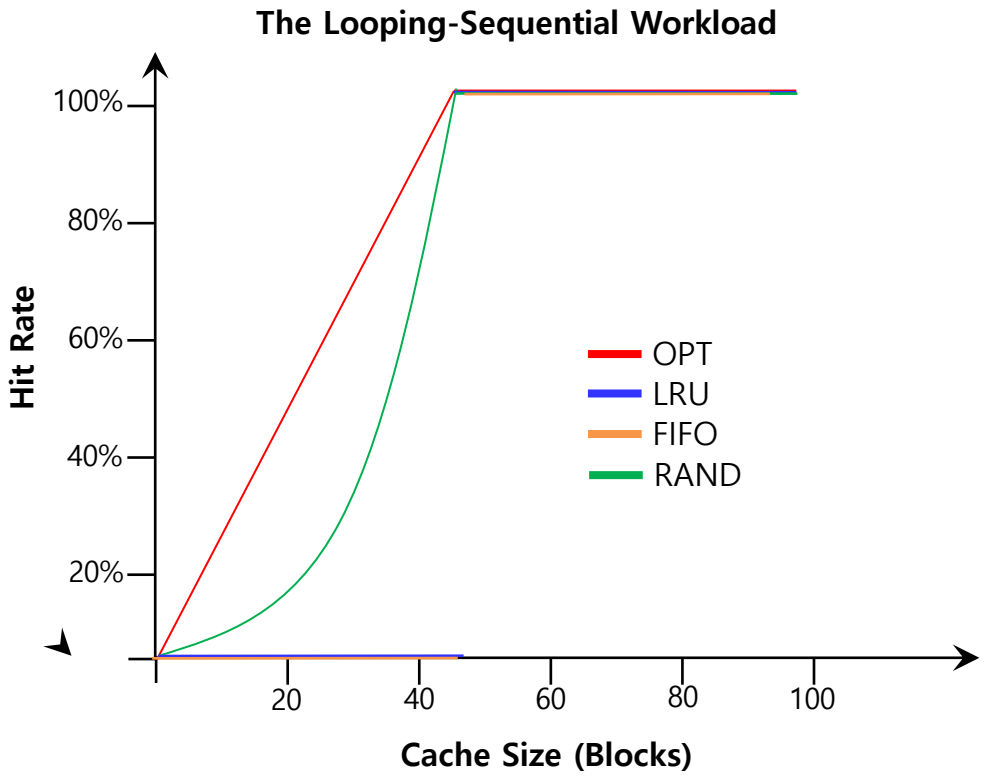
- Exhibits locality: 80% of the reference are made to 20% of the page
- The remaining 20% of the reference are made to the remaining 80% of the pages.



LRU is more likely to hold onto the hot pages.

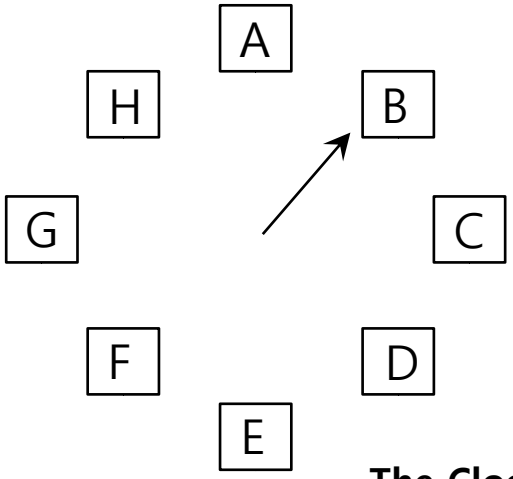
Workload Example : The Looping Sequential

- Refer to 50 pages in sequence.
  - Starting at 0, then 1, … up to page 49, and then we loop, repeating those accesses, for total of 10,000 accesses to 50 unique pages.



Approximating LRU: Clock Algorithm

- Require hardware support: **use bit**
  - Whenever a page is referenced, the use bit is set by hardware to 1.
  - Hardware never clears the bit, though; that is the responsibility of the OS
- Clock Algorithm
  - All pages of the system arranges in a circular list.
  - A clock hand points to a page to begin with.
  - The algorithm continues until it finds a use bit that is set to 0.

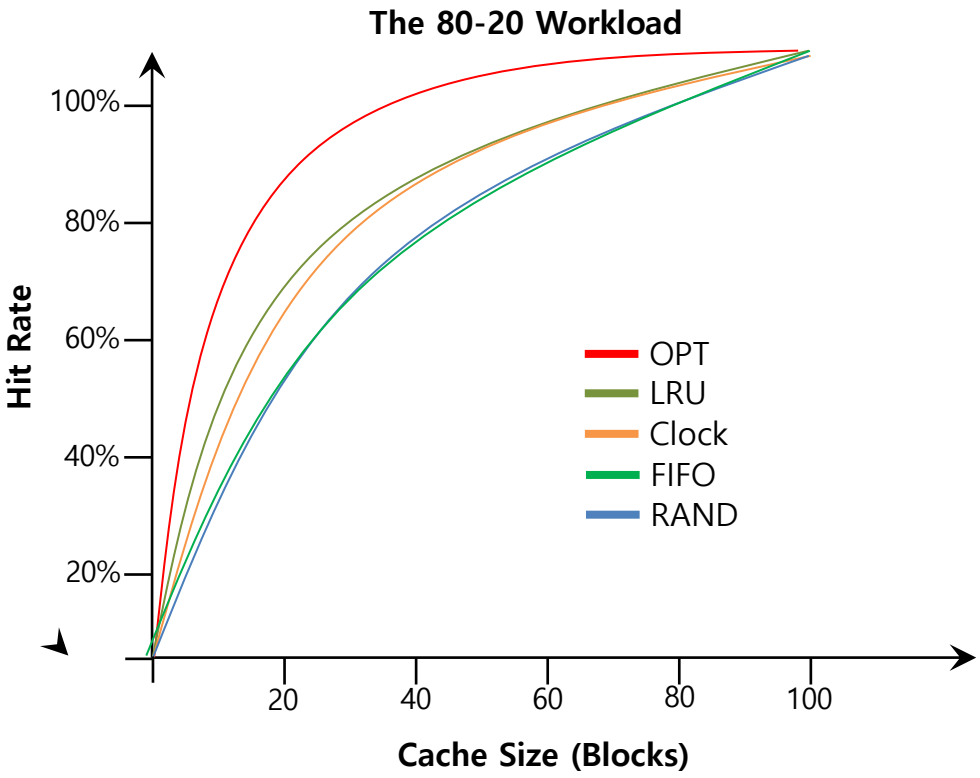


Use bit	Meaning
0	Evict the page
1	Clear **use bit** and advance hand

The Clock page replacement algorithm

Workload with Clock Algorithm

- Clock algorithm doesn't do as well as perfect LRU; it does better then approach that don't consider history at all.

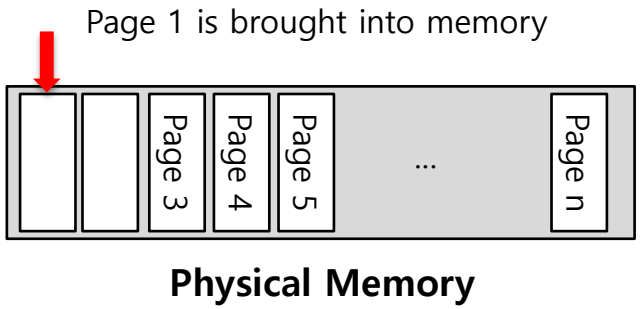


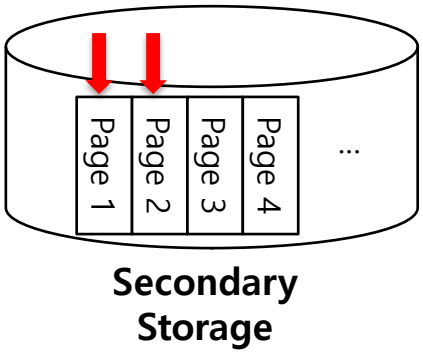
Considering Dirty Pages

- The hardware includes a **modified bit** (a.k.a **dirty bit**)
  - Page has been **modified** and is thus **dirty**, it must be written back to disk to evict it.
  - Page has not been modified; the eviction is free.

Prefetching

- The OS guesses that a page is about to be used, and thus bring it in ahead of time.

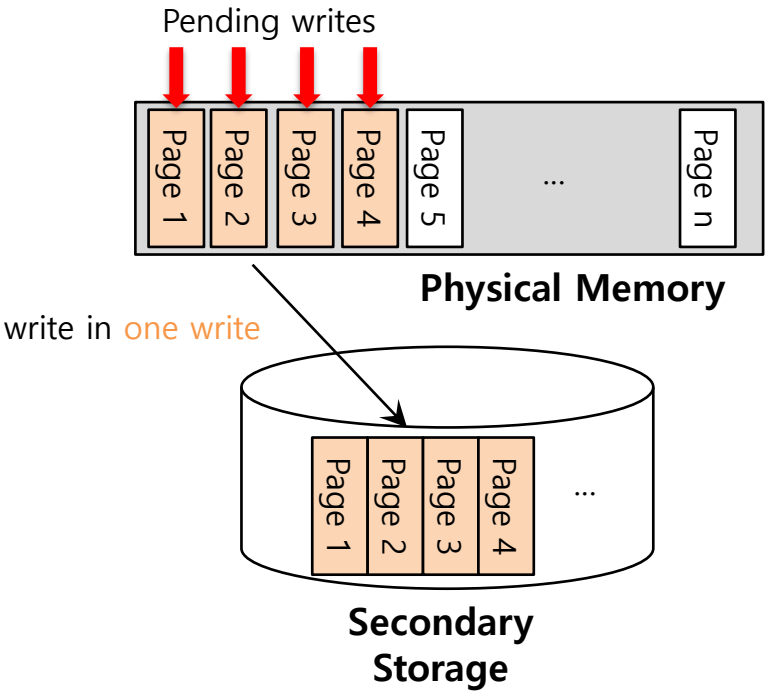




Page 2 likely soon be accessed and
thus should be brought into memory too

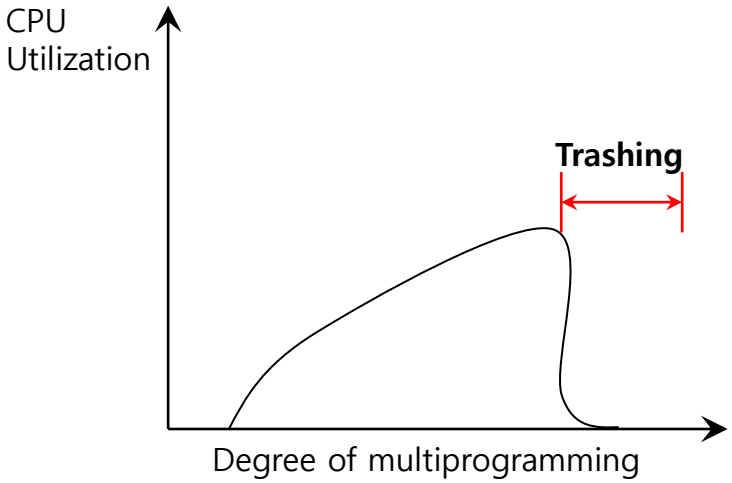
Clustering, Grouping

- Collect a number of pending writes together in memory and write them to disk in one write.
  - Perform a **single large write** more efficiently than **many small ones**.



Thrashing

- Memory is oversubscribed and the memory demands of the set of running processes exceeds the available physical memory.
  - Decide not to run a subset of processes.
  - Reduced set of processes working sets fit in memory.



Summary

- Swapping: use part of disk as memory
- Page replacement (page/swap out, page/swap in)
  - LRU, LFU, Random, FIFO
- Approximation to LRU: Clock
- Batching the disk IO
  - Clustering
  - Grouping
  - Prefetching