



Department of Physics,  
Computer Science & Engineering

CPSC 410 – Operating Systems I

# Virtualization: Virtual Memory

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Adapted from “CS 537 Introduction to Operating Systems”  
Arpaci-Dusseau

# Questions answered in this lecture:

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- How to run process when not enough physical memory?
- When should a page be moved from disk to memory?
- What page in memory should be replaced?
- How can the LRU page be approximated efficiently?

# Motivation

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OS goal: Support processes when not enough physical memory

- Single process with very large address space
- Multiple processes with combined address spaces

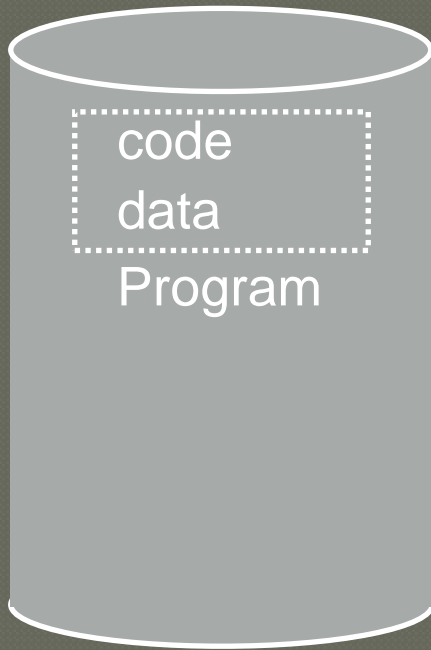
User code should be independent of amount of physical memory

- Correctness, if not performance

Virtual memory: OS provides illusion of more physical memory

Why does this work?

- Relies on key properties of user processes (workload) and machine architecture (hardware)



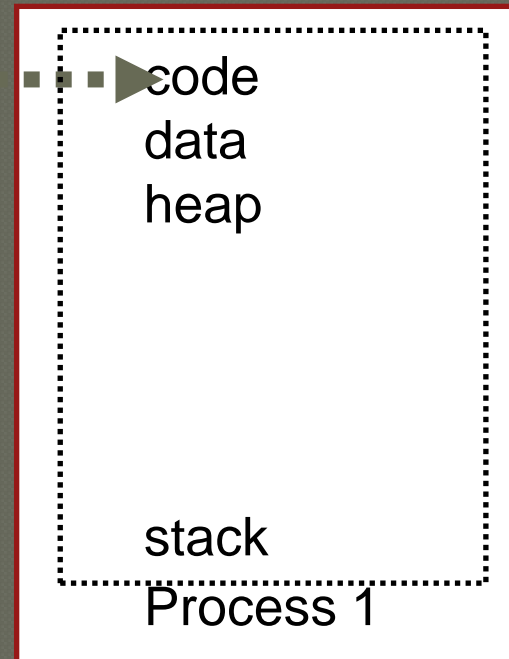
## Virtual Memory





create

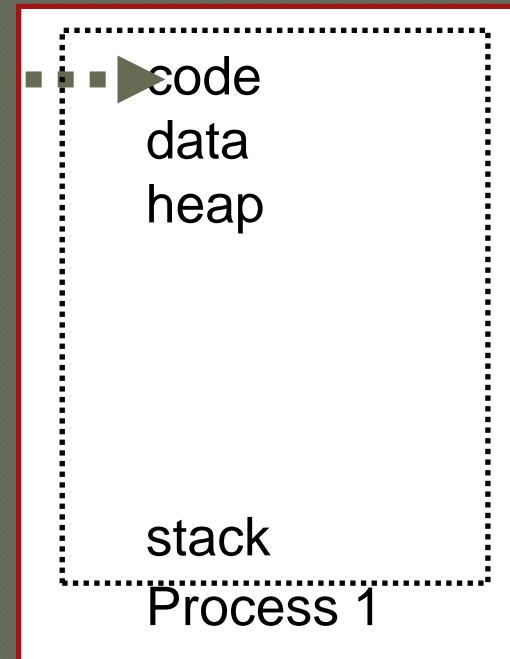
Virtual Memory



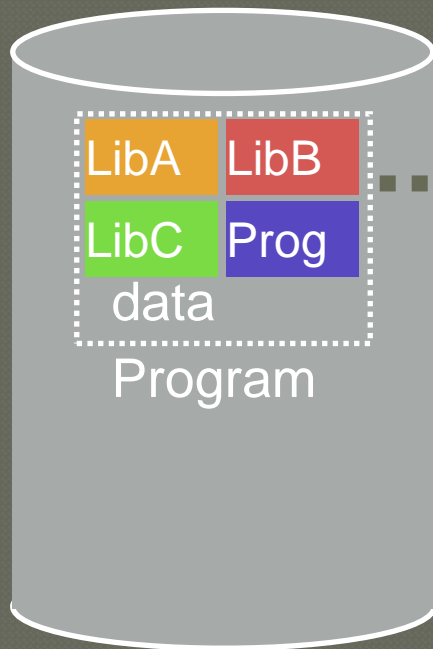


create

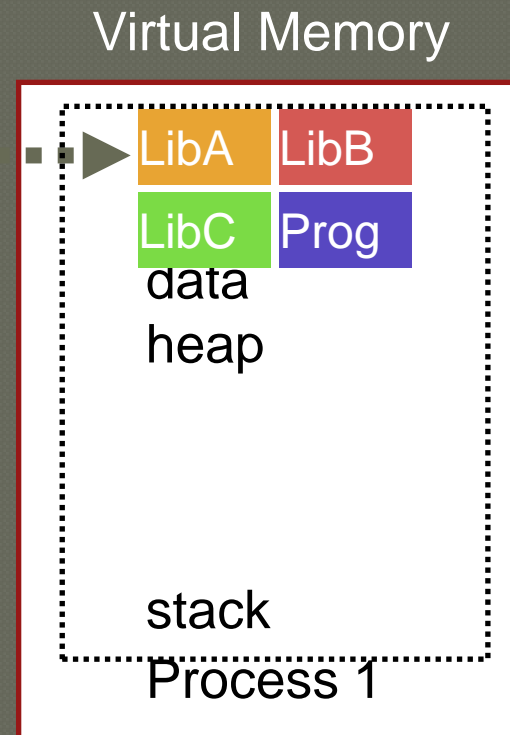
Virtual Memory



what's in code?

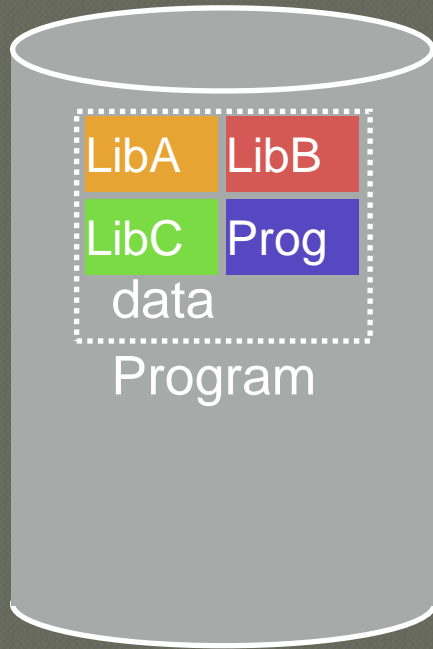


create



many large libraries, some  
of which are rarely/never used

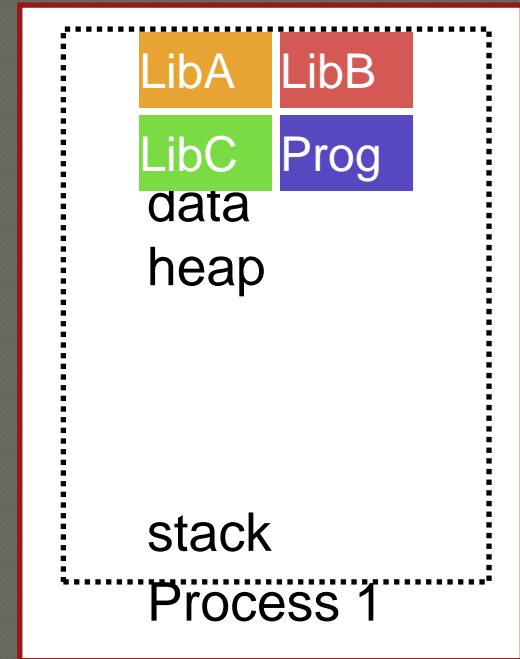
How to avoid wasting **physical pages** to back  
rarely used **virtual pages**?



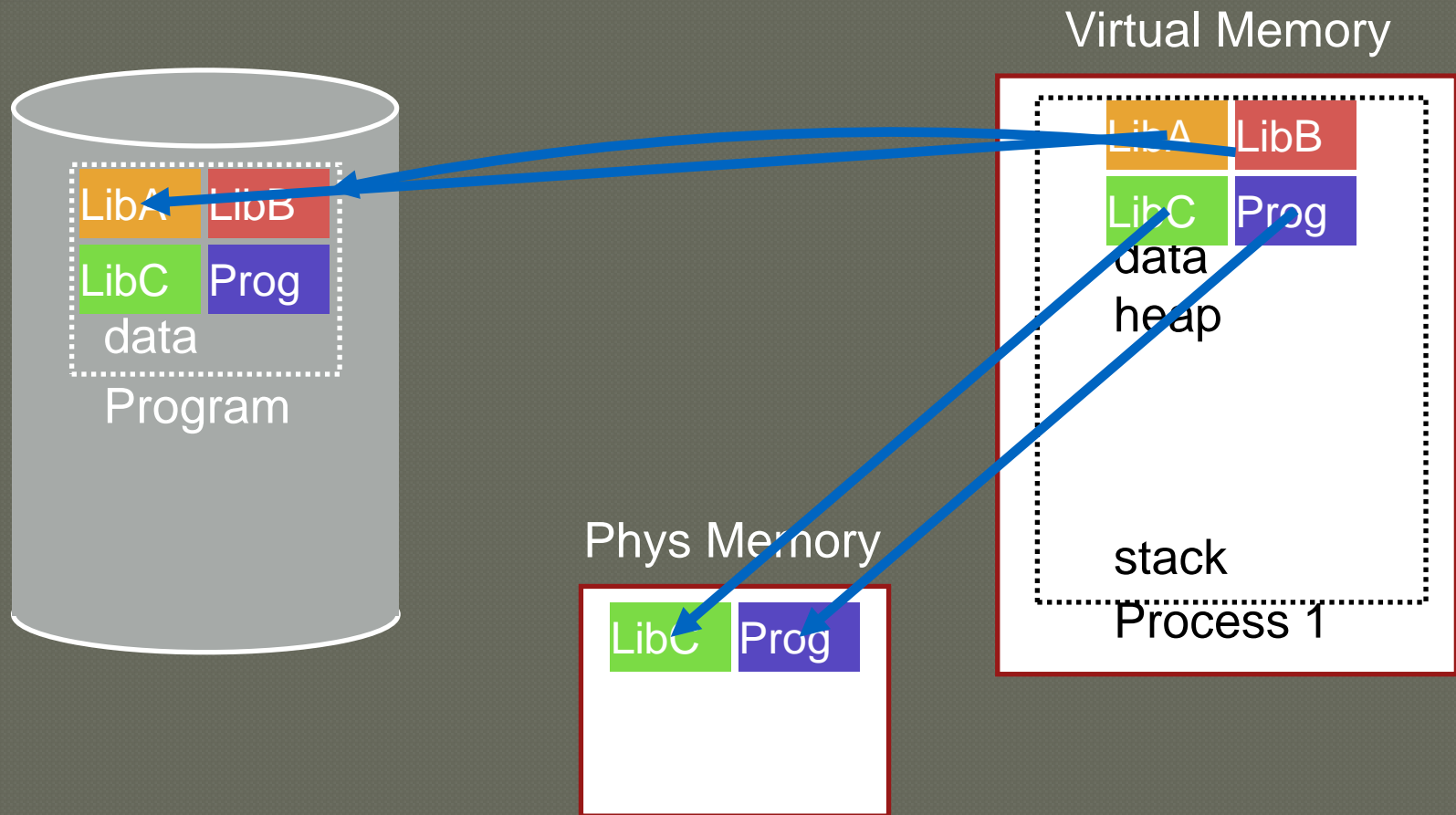
Phys Memory

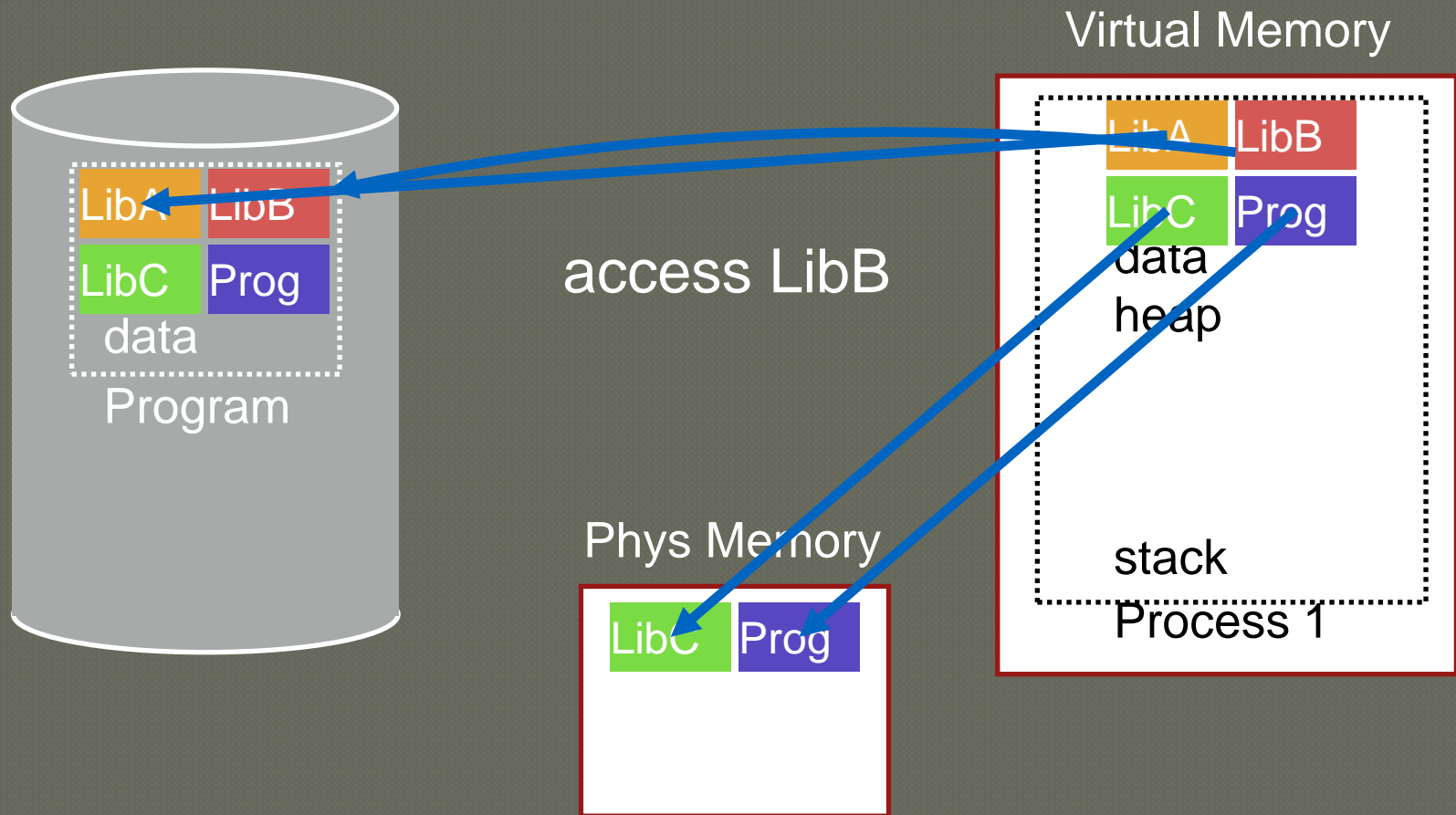


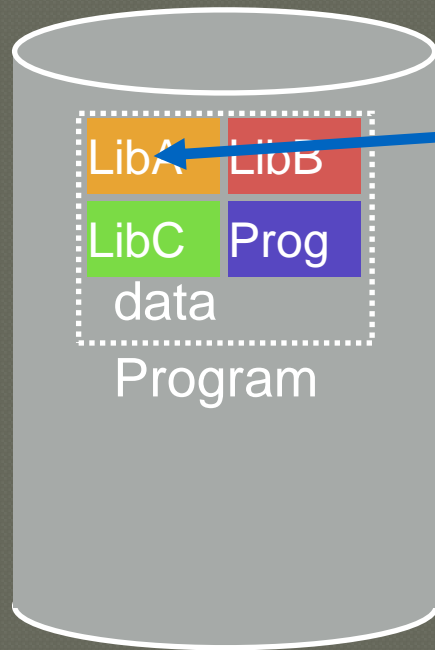
Virtual Memory



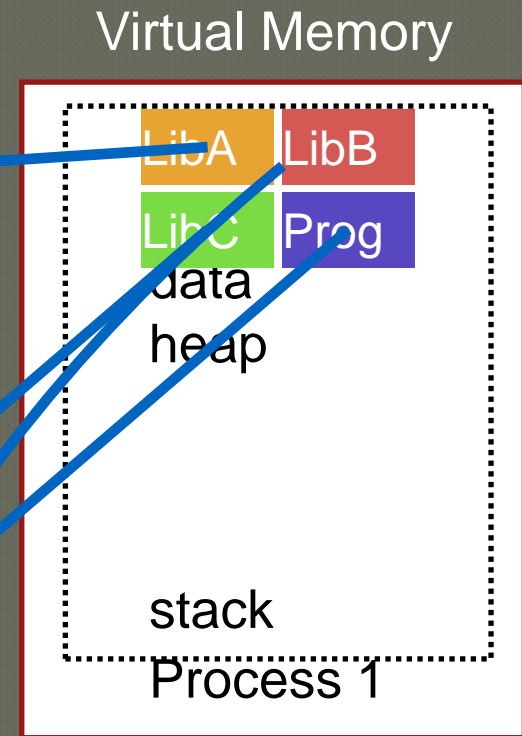
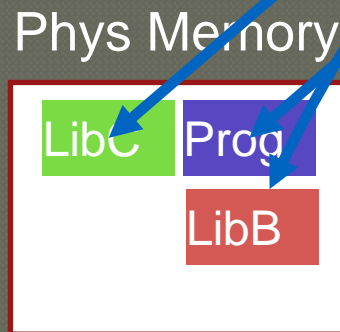


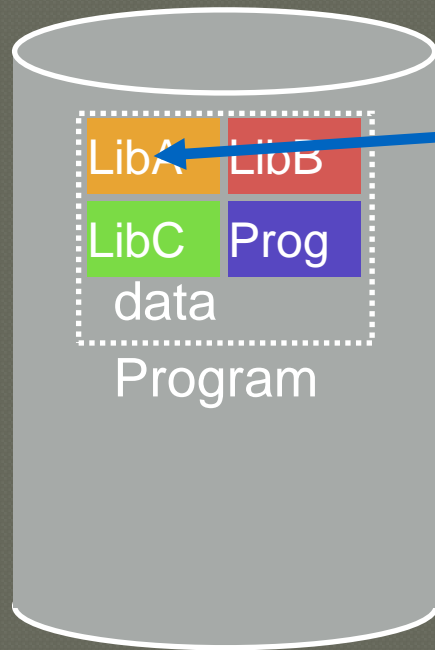






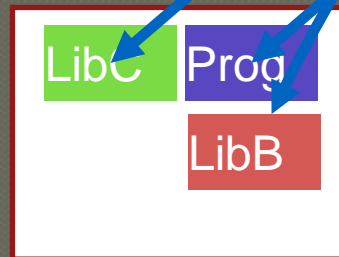
copy (or move)  
to RAM



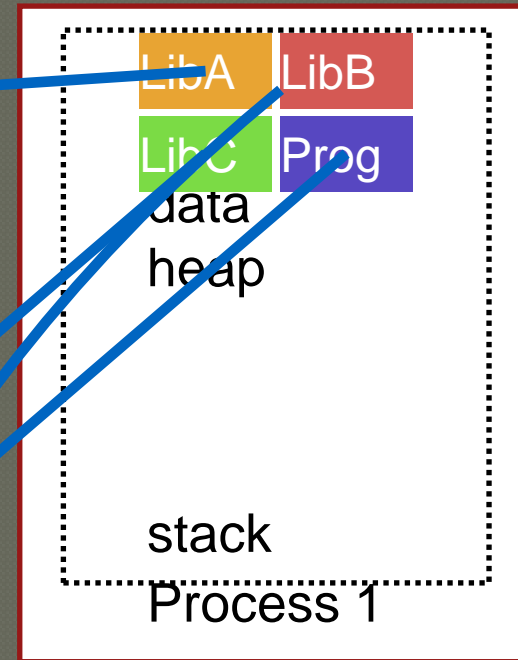


Called “**paging**” in

Phys Memory



Virtual Memory



# Locality of Reference

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Leverage **locality of reference** within processes

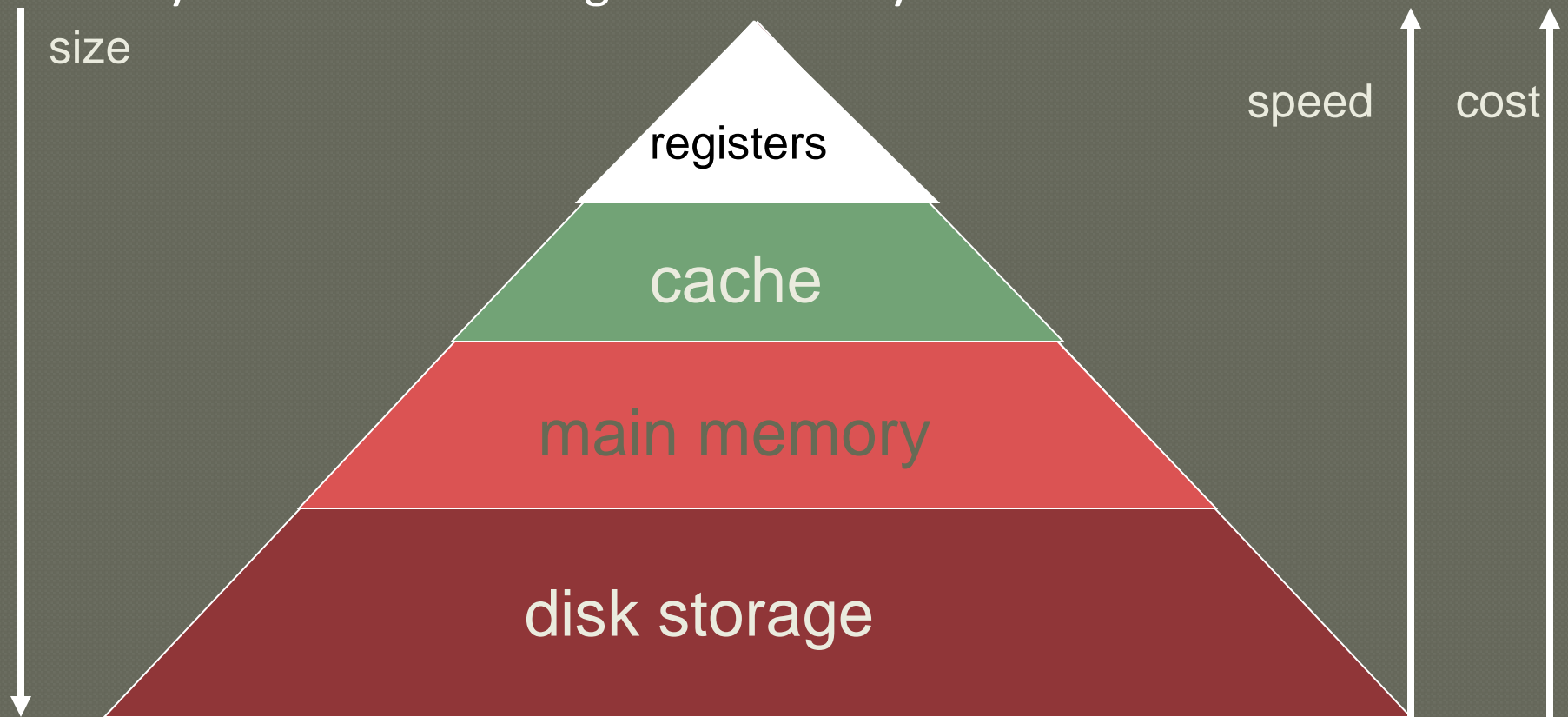
- **Spatial:** reference memory addresses **near** previously referenced addresses
- **Temporal:** reference memory addresses that have referenced in the past
- Processes spend majority of time in small portion of code
  - Estimate: 90% of time in 10% of code

Implication:

- Process only uses small amount of address space at any moment
- Only small amount of address space must be resident in physical memory

# Memory Hierarchy

Leverage **memory hierarchy** of machine architecture  
Each layer acts as “backing store” for layer above



# Virtual Memory Intuition

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Idea: OS keeps unreferenced pages on disk

- Slower, cheaper backing store than memory

Process can run when not all pages are loaded into main memory

OS and hardware cooperate to provide illusion of large disk as fast as main memory

- Same behavior as if all of address space in main memory
- Hopefully have similar performance

Requirements:

- OS must have **mechanism** to identify location of each page in address space → in memory or on disk
- OS must have **policy** for determining which pages live in memory and which on disk

# Virtual Address Space Mechanisms

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Each page in virtual address space maps to one of three locations:

- Physical main memory: Small, fast, expensive
- Disk (backing store): Large, slow, cheap
- Nothing (error): Free

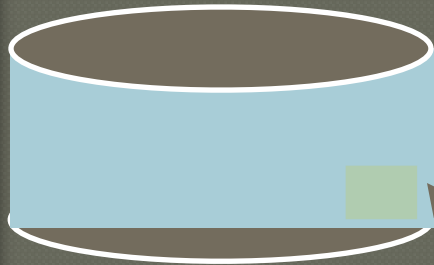
Extend page tables with an extra bit: present

- permissions (r/w), valid, present
- Page in memory: present bit set in PTE
- Page on disk: present bit cleared
  - PTE points to block on disk
  - Causes trap into OS when page is referenced
  - **Trap: page fault**

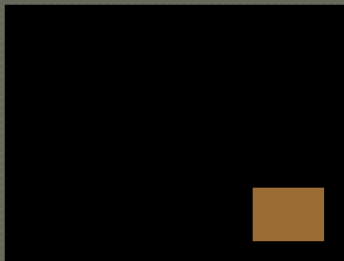


# Present Bit

Disk



Phys Memory



PFN	valid	prot	present
10	1	r-x	1
-	0	-	-
23	1	rw-	0
-	0	-	-
-	0	-	-
-	0	-	-
-	0	-	-
-	0	-	-
-	0	-	-
-	0	-	-
-	0	-	-
16	1	rw-	1
4	1	rw-	1

What if access vpn 0xb?

# Virtual Memory Mechanisms

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Hardware and OS cooperate to translate addresses

First, hardware checks TLB for virtual address

- if TLB hit, address translation is done; page in physical memory

If TLB miss...

- Hardware or OS walk page tables
- If PTE designates page is present, then page in physical memory

If page fault (i.e., present bit is cleared)

- Trap into OS (not handled by hardware)
- OS selects victim page in memory to replace
  - Write victim page out to disk if modified (add dirty bit to PTE)
- OS reads referenced page from disk into memory
- Page table is updated, present bit is set
- Process continues execution

## What should scheduler do?

# Mechanism for Continuing a Process

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## Continuing a process after a page fault is tricky

- Want page fault to be transparent to user
- Page fault may have occurred in middle of instruction
  - When instruction is being fetched
  - When data is being loaded or stored
- Requires hardware support
  - **precise interrupts**: stop CPU pipeline such that instructions before faulting instruction have completed, and those after can be restarted

## Complexity depends upon instruction set

- Can faulting instruction be restarted from beginning?
  - Example: `move +(SP), R2`
  - Must track side effects so hardware can undo

# Virtual Memory Policies

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Goal: Minimize number of page faults

- Page faults require milliseconds to handle (reading from disk)
- Implication: Plenty of time for OS to make good decision

OS has two decisions

- Page selection
  - **When** should a page (or pages) on disk be **brought into** memory?
- Page replacement
  - **Which** resident page (or pages) in memory should be **thrown out** to disk?

# Page Selection

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When should a page be brought from disk into memory?

**Demand paging:** Load page only when page fault occurs

- **Intuition:** Wait until page must absolutely be in memory
- When process starts: No pages are loaded in memory
- Problems: Pay cost of page fault for every newly accessed page

**Prepaging (anticipatory, prefetching):** Load page before referenced

- OS predicts future accesses (**oracle**) and brings pages into memory early
- Works well for some access patterns (e.g., sequential)
- Problems?

**Hints:** Combine above with user-supplied hints about page references

- User specifies: may need page in future, don't need this page anymore, or sequential access pattern, ...
- Example: `madvise()` in Unix

# Page Replacement

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Which page in main memory should be selected as victim?

- Write out victim page to disk if modified (dirty bit set)
- If victim page is not modified (clean), just discard

**OPT:** Replace page not used for longest time in future

- Advantages: Guaranteed to minimize number of page faults
- Disadvantages: Requires that OS predict the future; Not practical, but good for comparison

**FIFO:** Replace page that has been in memory the longest

- Intuition: First referenced long time ago, done with it now
- Advantages: Fair: All pages receive equal residency; Easy to implement (circular buffer)
- Disadvantage: Some pages may always be needed

**LRU:** Least-recently-used: Replace page not used for longest time in past

- Intuition: Use past to predict the future
- Advantages: With locality, LRU approximates OPT
- Disadvantages:
  - Harder to implement, must track which pages have been accessed
  - Does not handle all workloads well

# Page Replacement Example

Page reference string: ABCABDADBCB

	OPT	FIFO	LRU
ABC	<div></div> <div></div> <div></div>	<div></div> <div></div> <div></div>	<div></div> <div></div> <div></div>
A	<div></div> <div></div> <div></div>	<div></div> <div></div> <div></div>	<div></div> <div></div> <div></div>
B	<div></div> <div></div> <div></div>	<div></div> <div></div> <div></div>	<div></div> <div></div> <div></div>
D	<div></div> <div></div> <div></div>	<div></div> <div></div> <div></div>	<div></div> <div></div> <div></div>
A	<div></div> <div></div> <div></div>	<div></div> <div></div> <div></div>	<div></div> <div></div> <div></div>
D	<div></div> <div></div> <div></div>	<div></div> <div></div> <div></div>	<div></div> <div></div> <div></div>
B	<div></div> <div></div> <div></div>	<div></div> <div></div> <div></div>	<div></div> <div></div> <div></div>
C	<div></div> <div></div> <div></div>	<div></div> <div></div> <div></div>	<div></div> <div></div> <div></div>
B	<div></div> <div></div> <div></div>	<div></div> <div></div> <div></div>	<div></div> <div></div> <div></div>

Three pages  
of physical memory



# Page Replacement Comparison

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Add more physical memory, what happens to performance?

- LRU, OPT: Add more memory, guaranteed to have fewer (or same number of) page faults
  - Smaller memory sizes are guaranteed to contain a subset of larger memory sizes
  - Stack property: smaller cache always subset of bigger
- FIFO: Add more memory, usually have fewer page faults
  - Belady's anomaly: May actually have **more** page faults!



# Fifo Performance may Decrease!

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Consider access stream: ABCDABEABCDE

Consider physical memory size: 3 pages vs. 4 pages

How many misses with FIFO?

3 pages: 9 misses

4 pages: 10 misses

# Problems with LRU-based Replacement

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LRU does not consider frequency of accesses

- Is a page accessed **once** in the past equal to one accessed **N** times?
- Common workload problem:
  - Scan (sequential read, never used again) one large data region flushes memory

Solution: Track frequency of accesses to page

Pure LFU (Least-frequently-used) replacement

- Problem: LFU can never forget pages from the far past

Examples of other more sophisticated algorithms:

- LRU-K and 2Q: Combines recency and frequency attributes
- Expensive to implement, LRU-2 used in databases

# Implementing LRU

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## Software Perfect LRU

- OS maintains ordered list of physical pages by reference time
- When page is referenced: Move page to front of list
- When need victim: Pick page at back of list
- Trade-off: Slow on memory reference, fast on replacement

## Hardware Perfect LRU

- Associate timestamp register with each page
- When page is referenced: Store system clock in register
- When need victim: Scan through registers to find oldest clock
- Trade-off: Fast on memory reference, slow on replacement (especially as size of memory grows)

## In practice, do not implement Perfect LRU

- LRU is an approximation anyway, so approximate more
- Goal: Find an old page, but not necessarily the very oldest

# Clock Algorithm

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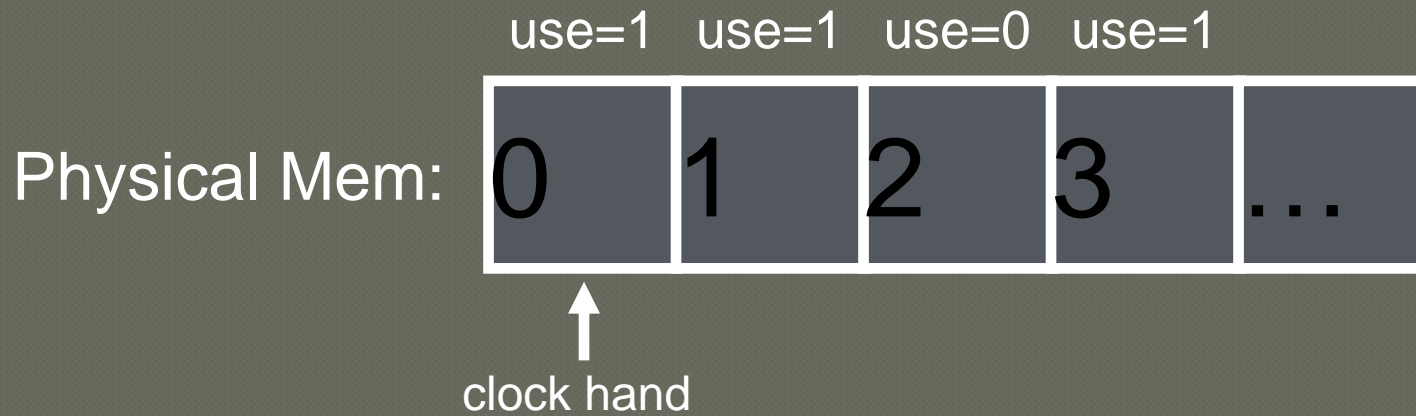
## Hardware

- Keep use (or reference) bit for each page frame
- When page is referenced: set use bit

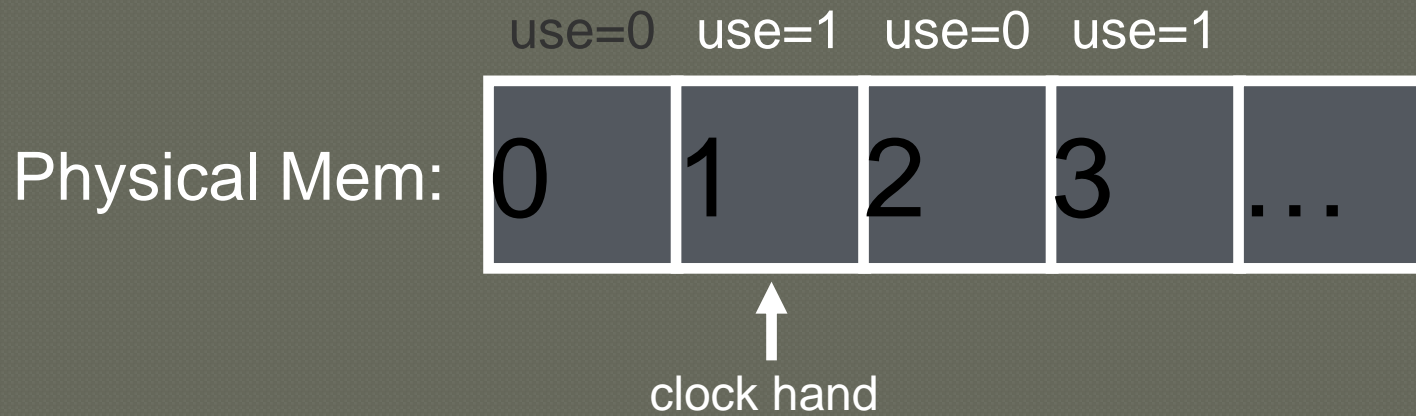
## Operating System

- Page replacement: Look for page with use bit cleared (has not been referenced for awhile)
- Implementation:
  - Keep pointer to last examined page frame
  - Traverse pages in circular buffer
  - Clear use bits as search
  - Stop when find page with already cleared use bit, replace this page

# Clock: Look For a Page



# Clock: Look For a Page



# Clock: Look For a Page



# Clock: Look For a Page



evict **page 2** because it has not been recently used



# Clock: Look For a Page



**page 0** is accessed...

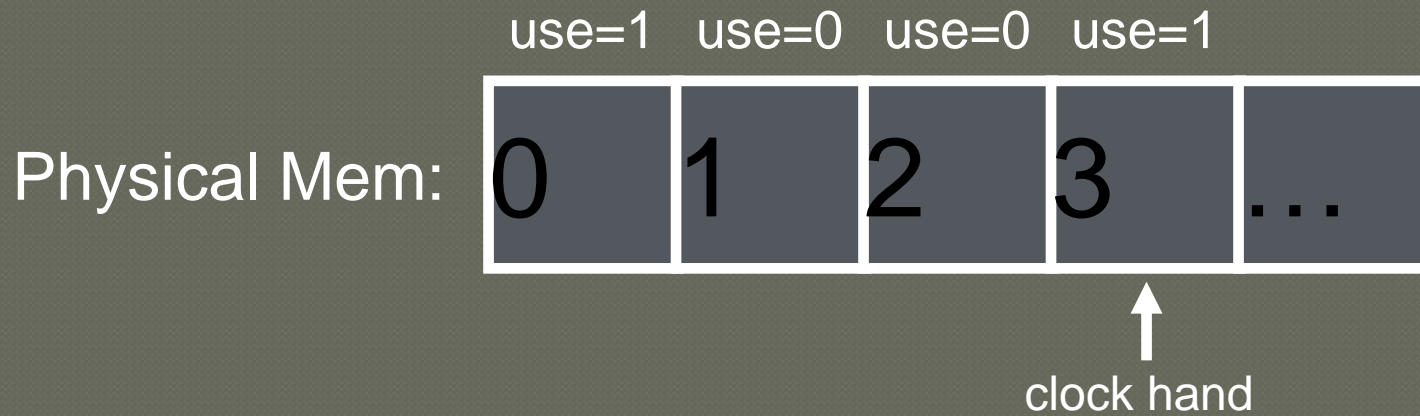
# Clock: Look For a Page



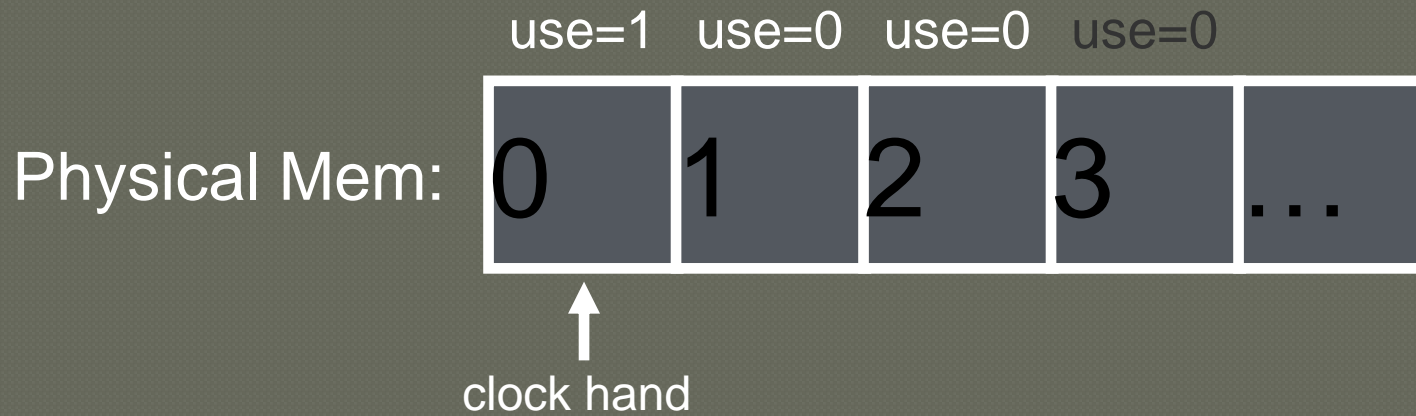
# Clock: Look For a Page



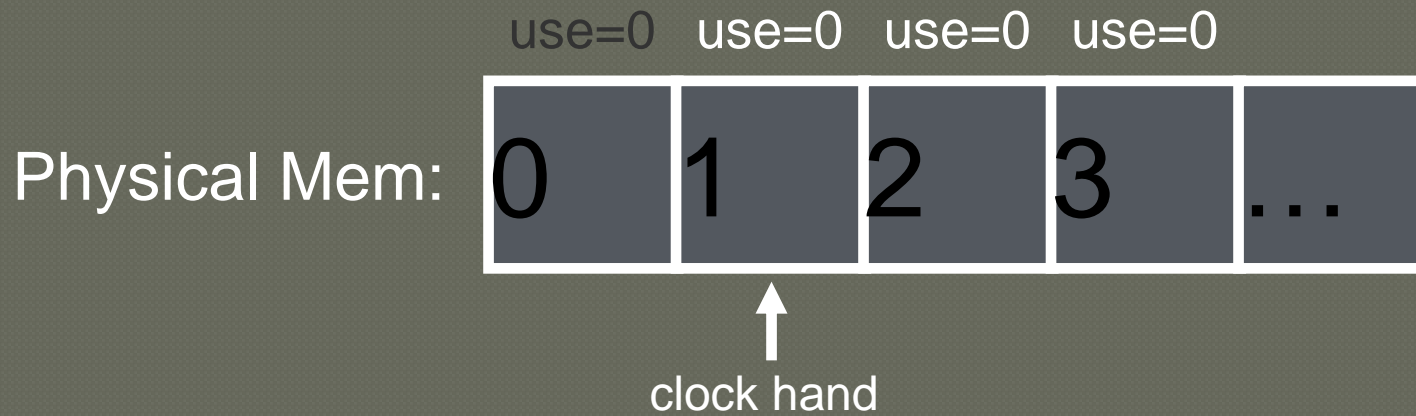
# Clock: Look For a Page



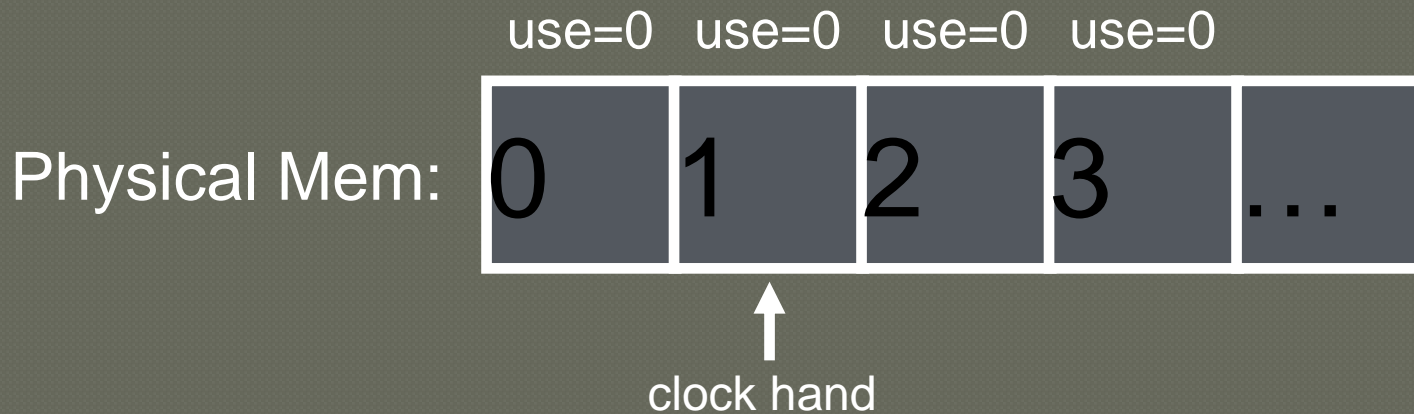
# Clock: Look For a Page



# Clock: Look For a Page



# Clock: Look For a Page



evict **page 1** because it has not been recently used

# Clock Extensions

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## Replace multiple pages at once

- Intuition:  
Expensive to run replacement algorithm and to write single block to disk
- Find multiple victims each time and track free list

## Add software counter (“chance”)

- Intuition: Better ability to differentiate across pages (how much they are being accessed)
- Increment software counter if use bit is 0
- Replace when chance exceeds some specified limit

## Use dirty bit to give preference to dirty pages

- Intuition: More expensive to replace dirty pages
  - Dirty pages must be written to disk, clean pages do not
- Replace pages that have use bit and dirty bit cleared



# What if no Hardware Support?

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What can the OS do if hardware does not have use bit (or dirty bit)?

- Can the OS “emulate” these bits?

Leading question:

- How can the OS get control (i.e., generate a trap) every time use bit should be set? (i.e., when a page is accessed?)

# Conclusions

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Illusion of virtual memory:

Processes can run when sum of virtual address spaces  $>$  amount of physical memory

Mechanism:

- Extend page table entry with “present” bit
- OS handles page faults (or page misses) by reading in desired page from disk

Policy:

- Page selection – demand paging, prefetching, hints
- Page replacement – OPT, FIFO, LRU, others

Implementations (clock) perform approximation of LRU