CS 134:
Operating Systems
Memory—Fun with Paging

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Overview

Page Faults
- Cost of Faults

Page Replacement
- Algorithms
- Easy Approaches
- Realistic Approaches

Optimizing Page Replacement
- Tweaking Clock
- “Pre-poning” Work

Working Sets
- Allocation Policies
- Thrashing

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Page Faults (cont.)

How long?

- Disk is slow
- 5–15 ms is a conservative guess
- Main memory takes 5–15 ns
- Page fault is about **1 million times slower** than a regular memory access
- Page faults must be rare! (Need locality!)

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A “Back of an Envelope Calculation”

How often are there page faults?

An example from a desktop machine:

- In 14 days
  - 378,110 page-ins
  - Average load < 4% $\rightarrow$ 12 hours actual compute time
  - 8.75 page faults per second *average*
- 1,000,000,000 memory accesses per second (a guess)
- 43,200,000,000,000 memory accesses in 12 hours
- 1 page-in every 114,252,466 memory accesses
- Using 5 ns for memory, 5 ms for disk:
  - $t_{\text{avg}} = (5,000,000 * 1 + 5 * 114,252,465)/114,252,466$
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Here’s the problem with t_{avg}: it’s spread over 14 days, including time when the desktop’s owner was asleep. It’s an *average*! So what if just 1% of those 378K page-ins happened last Monday morning when the owner started work? All of a sudden we’re spending $3781 \times 5\text{ms} = 18.905\text{sec}$ waiting for the machine to respond. And the reality is that many more than 1% of the page-ins happen when the owner is most actively using the machine. . .

Part of the problem is “cold start,” when a program is faulting itself in. We can improve that in several ways; for example we can pre-load the first page of instructions, perhaps the first page of each dynamic library. We can also detect sequential page accesses and prefetch future pages. Or going further, we can remember what happened last time the program ran and bring in those pages.

Page Faults (cont.)

Other kinds of page faults:

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- Copy-on-write memory—great for fork
- Lazy memory allocation
- Other tricks…

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What kind of other tricks? Well, for example, debugging and tracing; VM translation; buffer-overflow prevention.

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Page-Replacement Algorithms

Deciding which page to kick out is tricky
How to compare algorithms?

- Run them on a stream of page numbers corresponding to execution of a (hypothetical?) program

(We want to achieve the lowest page-fault rate, i.e., minimum t_{avg})

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00002f18 00002f1c 00002f20 00002f24
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The stream of page numbers for the above execution is

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Page-Replacement Policies

When you need to free up a frame, how do you choose?

Class Exercise

What are some *easy* strategies?

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Do this on the board with the class.

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Least Recently Used (LRU)

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Can it happen in real programs?

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Hardware maintains a “referenced” bit in the page table

- Set by hardware when page is accessed
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Use FIFO page replacement, but:

- If a page has its referenced bit set, clear it and move on to the next page

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CS34
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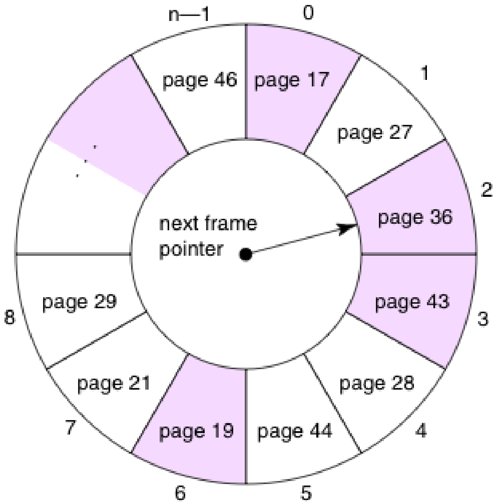
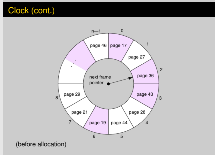
Clock (cont.)

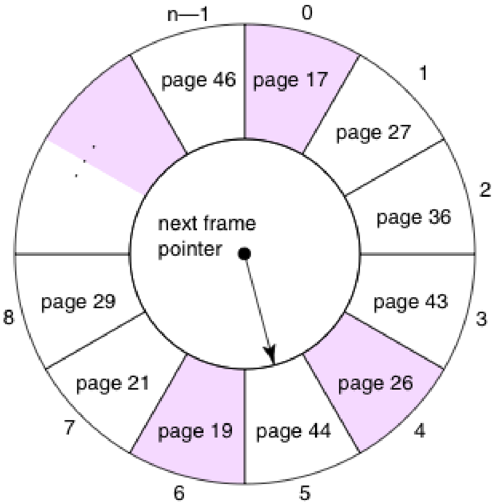


(before allocation)



Here, the magenta frames are ones that have been referenced. When there is a fault on virtual page 26 (poor choice of example, since it's hard to see 28/26 difference on the diagram), we clear the referenced bits on physical pages 2 and 3, then place virtual 26 into physical 4, setting its referenced bit, and advance the pointer to physical 5.

Clock (cont.)



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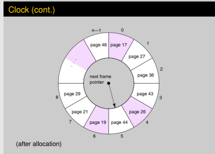
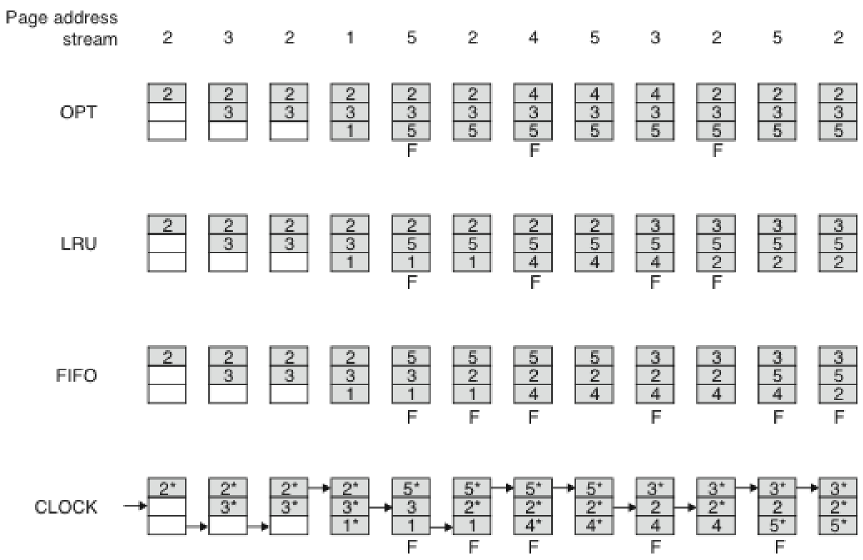
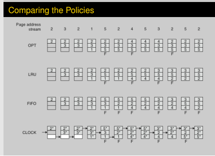


If there is another fault immediately, we'll put the new page in physical page 5, replacing virtual page 44.

Comparing the Policies





Spend some time on this slide.
An "F" under a column indicates that there was a fault. All algorithms are the same for the first four accesses, and all fault on the fifth access. Note that the first three faults aren't shown.
The last "F" under OPT could replace either virtual 4 or virtual 3.
On CLOCK, the fifth access finds all referenced bits set, so it chooses the page that was originally under the hand—after scanning every other page in the system! Fortunately, this is rare in real systems with thousands or even millions of pages.

Optimizations

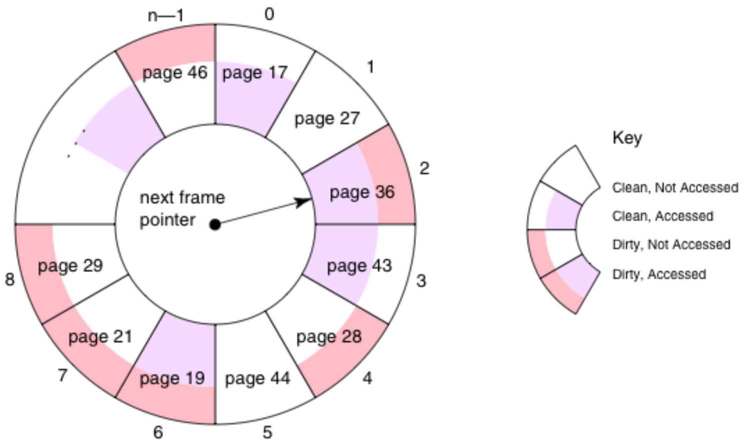
Why is page replacement slow?

Optimizations

Why is page replacement slow?

One of the big costs is writing dirty pages. That's especially bad because it may mean seeking to the swap space to write, then somewhere else to read.

An Improved Clock



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CS34
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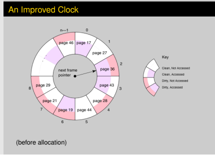

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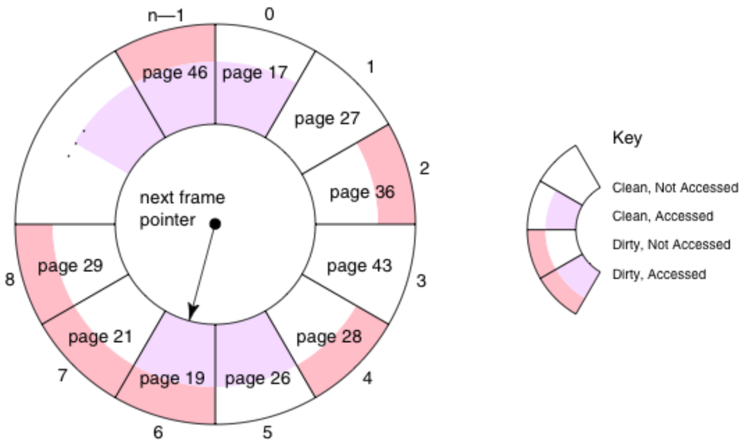

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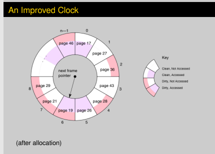

Here, we've skipped over virtual page 28 (physical 4) because it's dirty, and instead we've replaced physical 6. That saves us the disk write—but if we keep going in this mode, eventually all pages will be dirty, not accessed. We'll come back to that point in a moment.

More Clock

How quickly does the hand go around?

Why is that an issue?

More Clock
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Why is that an issue?

It's an issue because the notion of "recently used" depends on how fast you go around. Adding memory has an effect; so does adding other programs.

Two-Handed Clock

Have two clock hands, separated by fixed amount:

- Leading hand clears referenced bit
- Lagging hand frees unreferenced pages
- “Recently used” now depends only on distance between hands

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Page Buffering

Try to do some work *ahead of time*—keep a list of “free” pages

- Find a page that doesn’t appear to be being used
- Write it to disk if dirty
- Free it if clean
- Can be implemented with queue of “ready to free” pages
  - Can reprieve page from queue if it gets referenced

Even FIFO page replacement is workable with page buffering.

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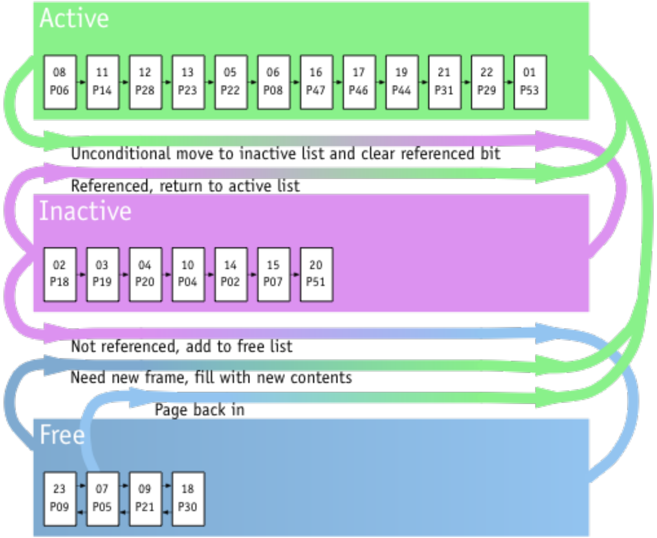
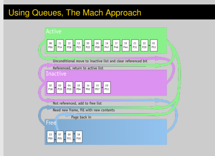
Using Queues, The Mach Approach





This is a practical implementation of a buffering algorithm.
Only dirty pages can be reactivated, because otherwise the OS has lost track of "what they really are."

Attempts to keep 2/3 of pages active, 1/3 inactive, 5% in free list.

Enough Frames?

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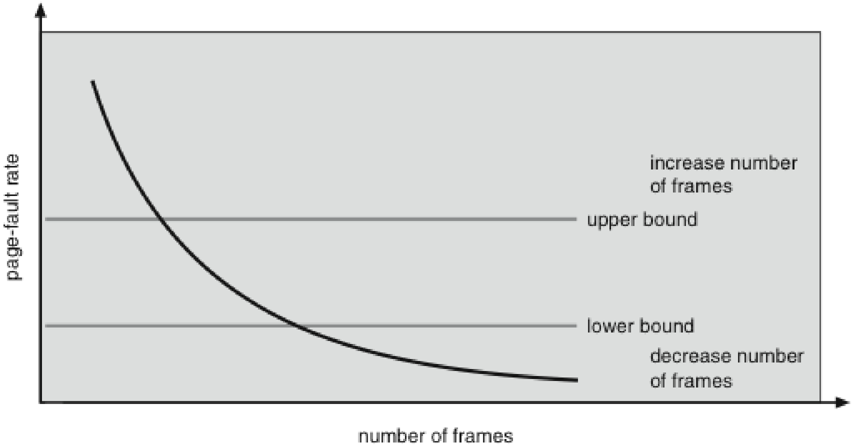
Working Sets

With fewer pages, page fault rate rises.

- If a process “almost always” page faults, it needs more frames
- If a process “almost never” page faults, it has spare frames



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CS34
└Working Sets
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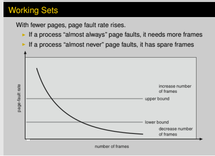

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Formal definition is "pages referenced in last *k* accesses." Close approximation is "pages referenced in last *n* ms." Note that this is pretty close to what the CLOCK algorithm does, except that other processes can interfere. Which leads to. . .

Local vs. Global

Whose pages do we take?

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Frame Allocation Policies

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- Each process needs a bare minimum number of pages (set by hardware characteristics of machine)
- Frames need to be shared out *fairly* between processes

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Local, Fixed Frame Allocation

Give each of the n processes $1/n$ of the available frames

- Each process can only take frames from itself

Class Exercise

What do you think?

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Class Exercise
What do you think?

- Some processes use a lot of VM, but don't access it often
- Some processes use a little VM, but access it often
- Not fair

Global, Variable Allocation

Just take the “best” (e.g., LRU) page, no matter which process it belongs to. . .

Class Exercise

Is this policy fair?

If not, why not?

Global, Variable Allocation

Just take the “best” (e.g., LRU) page, no matter which process it belongs to. . .

Class Exercise

Is this policy fair?

If not, why not?

Local, Variable Allocation

Each program has a frame allocation

- Use *working set* measurements to adjust frame allocation from time to time.
- Each process can only take frames from itself.

Class Exercise

What's wrong with this policy?

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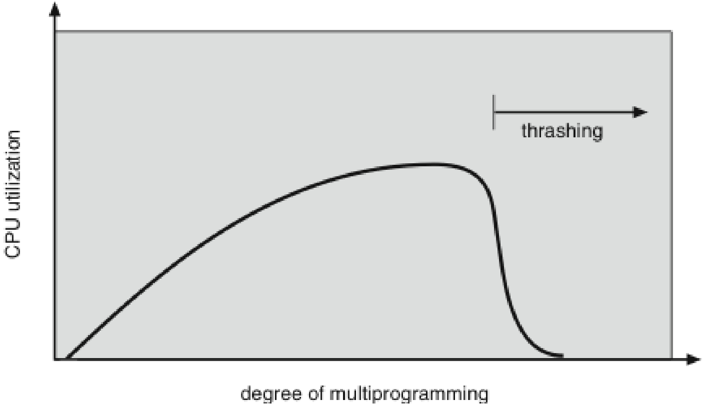
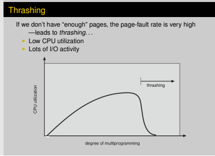
Thrashing

If we don't have "enough" pages, the page-fault rate is very high —leads to *thrashing*. . .

- Low CPU utilization
- Lots of I/O activity





Thrashing

Under local replacement policy, only problem process is affected (usually)

- Can detect and swap out until can give bigger working set
- If can't give big enough, might want to kill. . .

Under global replacement policy, whole machine can be brought to its knees!

. . . But even under local policy, disk can become so busy that no other work gets done!

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