virtual memory 3

last time

mmap: mapping files into program memory

- shared (modify file) or copy-on-write (do not modify file)

process memory as a list of regions setup with mmap

page cache: memory as cache for (files, program data)

- cache because everything has place on disk/SSD
- hit: managed by CPU with page table
- miss: managed by OS

minimizing page cache misses: Belady's MIN

practical algorithms from working set assumption: LRU-like

accessed and dirty bits

on exam regrades (1)

yes, I wish we proofread the exam more carefully

- and, yes, I'm still trying to get better at foreclosing unexpected (to me) interpretations of questions

in some cases we accepted additional answers that weren't on the key

- e.g. multiple system calls to read file

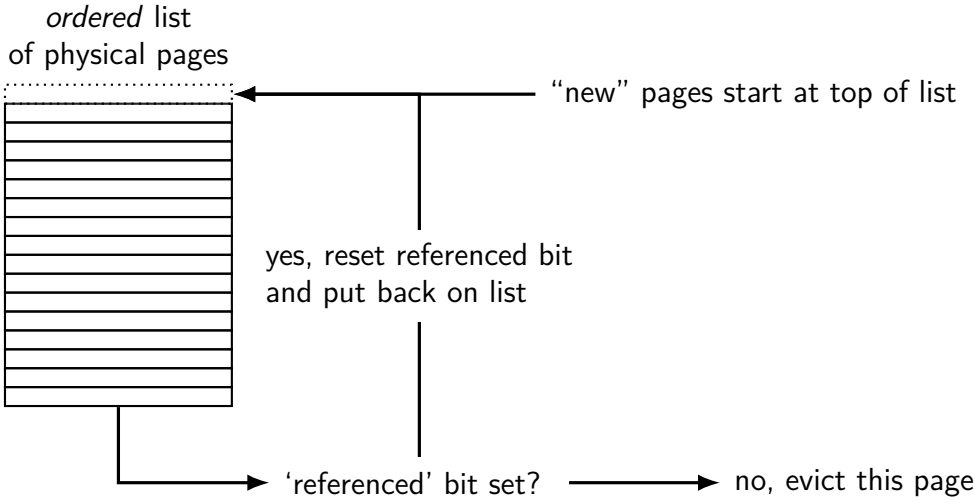
if you wrote comments regrading your interpretation of a question and think they weren't read or read carefully, please submit a regrade

on exam regrades (2)

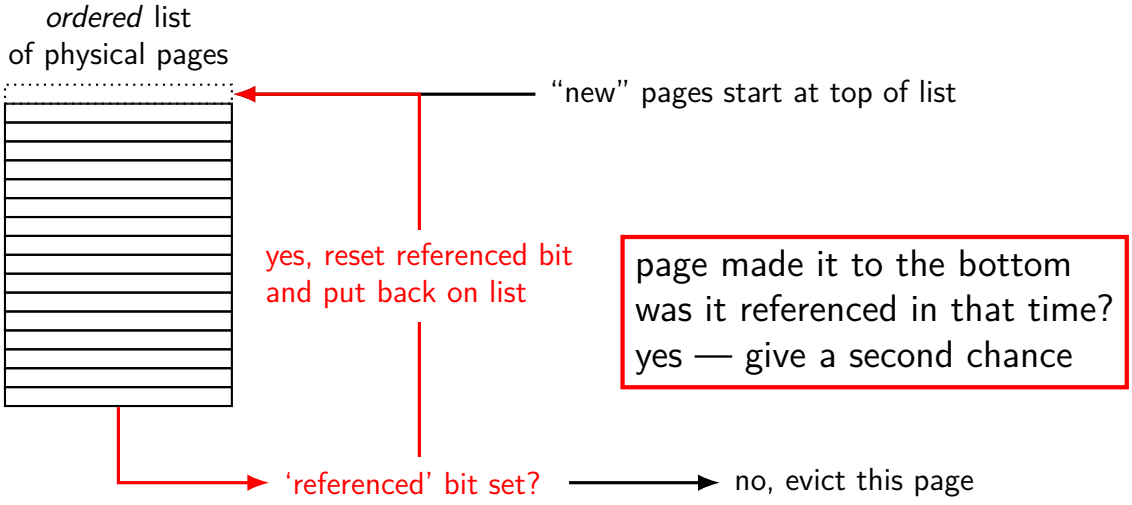
on the monitor question:

> it was pointed out to me that the key we graded with had a condition that caused pending non-videos to wait more often than necessary non-videos should have waited only when a pending video **and 4 non-videos running**
>
> ...can't just omit the pending condition: otherwise new non-video downloads can go in between when the video download is signalled and when it wakes up from the signal
>
> I believed I've scan through all the Q7s to find cases where we marked the fully correct answer wrong;

approximating LRU: second chance



approximating LRU: second chance



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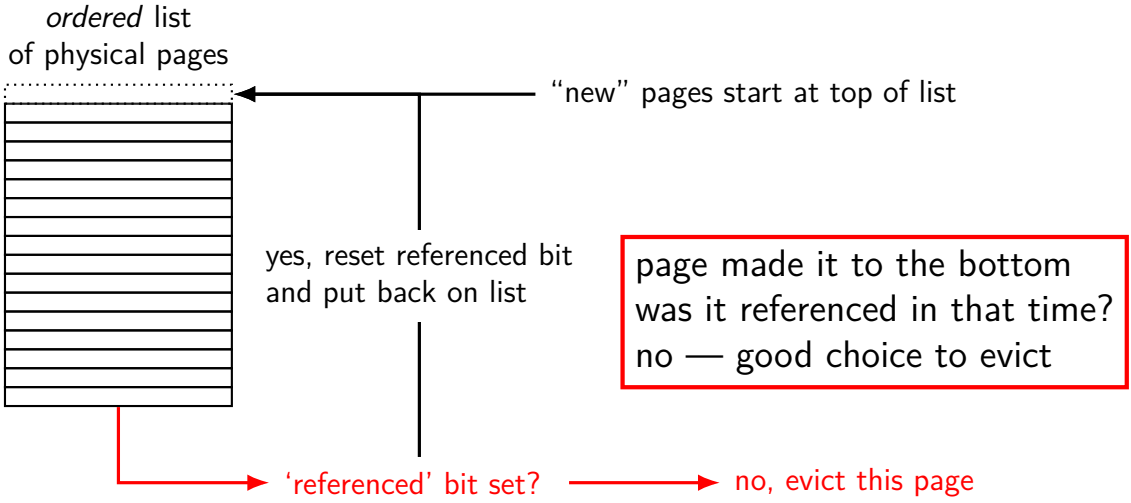


second chance example (1)

	A	B	C	D	—	—	—	B
1	A						D	
2		B						
3			C			C		
page list								
last added	*1R	*2R	*3R	1NR	2NR	3NR	*1R	1R
—	3NR	1R	2R	3R	1NR	2NR	3NR	3NR
end of list	2NR	3NR	1R	2R	3R	1NR	2NR	*2R

second chance example (1)

page 2 was at bottom of list
is not referenced
okay to use

							—	B
1	A						D	
2		B						
3			C			C		
page list								
last added	*1R	*2R	*3R	1NR	2NR	3NR	*1R	1R
—	3NR	1R	2R	3R	1NR	2NR	3NR	3NR
end of list	2NR	3NR	1R	2R	3R	1NR	2NR	*2R

second chance example (1)

	A	B	C	D	—	—	—	B
1	A						D	
2		B						
3			C			C		
page list								
last added	*1R	*2R	*3R	1NR	2NR	3NR	*1R	1R
—	3NR	1R	2R	3R	1NR	2NR	3NR	3NR
end of list	2NR	3NR	1R	2R	3R	1NR	2NR	*2R

second chance example (1)

page 1 was at bottom of list
reference — give second chance
moves to top of list
clear referenced bit

							—	B
1	A						D	
2		B						
3			C			C		
page list								
last added	*1R	*2R	*3R	1NR	2NR	3NR	*1R	1R
—	3NR	1R	2R	3R	1NR	2NR	3NR	3NR
end of list	2NR	3NR	1R	2R	3R	1NR	2NR	*2R

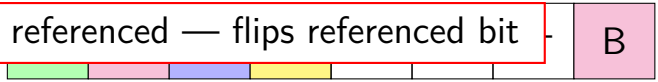
second chance example (1)

eventually page 1 gets to bottom of list again but now not referenced — use

1	A						D	
2		B						
3			C			C		
page list								
last added	*1R	*2R	*3R	1NR	2NR	3NR	*1R	1R
—	3NR	1R	2R	3R	1NR	2NR	3NR	3NR
end of list	2NR	3NR	1R	2R	3R	1NR	2NR	*2R

second chance example (1)

B referenced — flips referenced bit



1	A						D	
2		B						
3			C			C		
page list								
last added	*1R	*2R	*3R	1NR	2NR	3NR	*1R	1R
—	3NR	1R	2R	3R	1NR	2NR	3NR	3NR
end of list	2NR	3NR	1R	2R	3R	1NR	2NR	*2R

second chance example: exercise (1)

	A	B	C	D	—	—	—	B	A
1	A						D		
2		B							
3			C			C			
page list									
last added	*1R	*2R	*3R	1NR	2NR	3NR	*1R	1R	
—	3NR	1R	2R	3R	1NR	2NR	3NR	3NR	
end of list	2NR	3NR	1R	2R	3R	1NR	2NR	*2R	

exercise: What does this access to A replace? (D, B, or C?)
what is at end of list after? (PP 1, 2, or 3?)

second chance example: exercise (2)

	A	B	C	D	—	—	—	B	A	—	C
1	A						D				?
2		B									?
3			C			C				A	?
page list											
last added	*1R	*2R	*3R	1NR	2NR	3NR	*1R	1R	2NR	*3R	
—	3NR	1R	2R	3R	1NR	2NR	3NR	3NR	1R	2NR	
end of list	2NR	3NR	1R	2R	3R	1NR	2NR	*2R	3NR	1R	

second chance example: exercise (2)

	A	B	C	D	—	—	—	B	A	—	C
1	A						D				?
2		B									?
3			C			C				A	?
page list											
last added	*1R	*2R	*3R	1NR	2NR	3NR	*1R	1R	2NR	*3R	
—	3NR	1R	2R	3R	1NR	2NR	3NR	3NR	1R	2NR	
end of list	2NR	3NR	1R	2R	3R	1NR	2NR	*2R	3NR	1R	

exercise: What does this access to C replace? (D, B, or A?)
what is at end of list after? (PP 1, 2, or 3?)

second chance example (2)

	A	B	C	D	—	—	—	B	A	—	C	—
1	A						D					
2		B										C
3			C			C				A		
page list												
last added	*1R	*2R	*3R	1NR	2NR	3NR	*1R	1R	2NR	*3R	1NR	*2R
—	3NR	1R	2R	3R	1NR	2NR	3NR	3NR	1R	2NR	3R	1NR
end of list	2NR	3NR	1R	2R	3R	1NR	2NR	*2R	3NR	1R	2NR	3R

second chance cons

performs poorly with big memories...

may need to scan through lots of pages to find unaccessed

likely to count accesses from a long time ago

want some variation to tune its sensitivity

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performs poorly with big memories...

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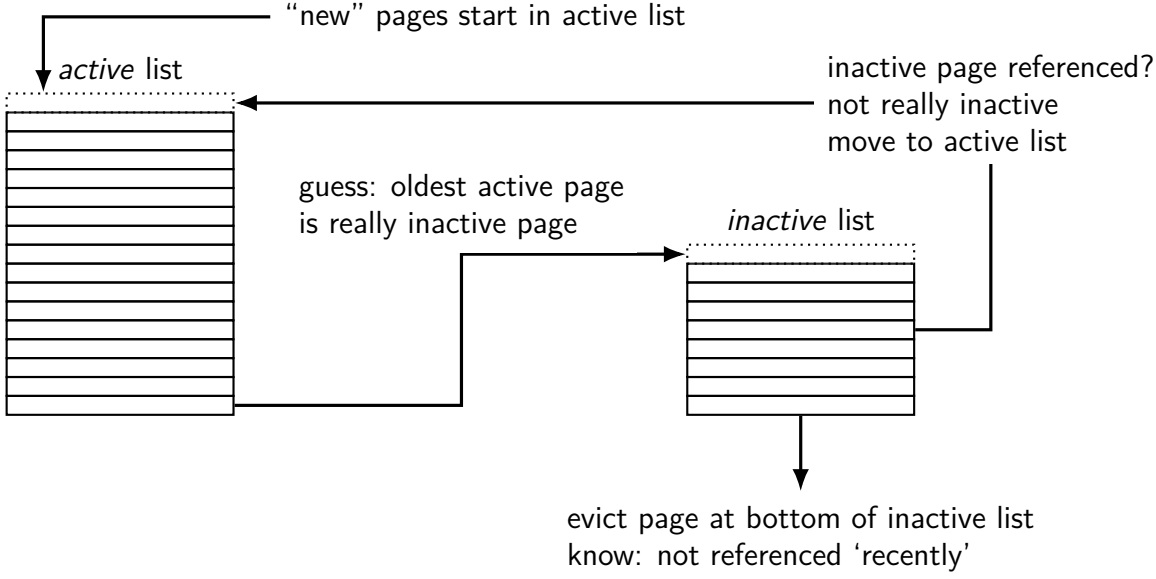
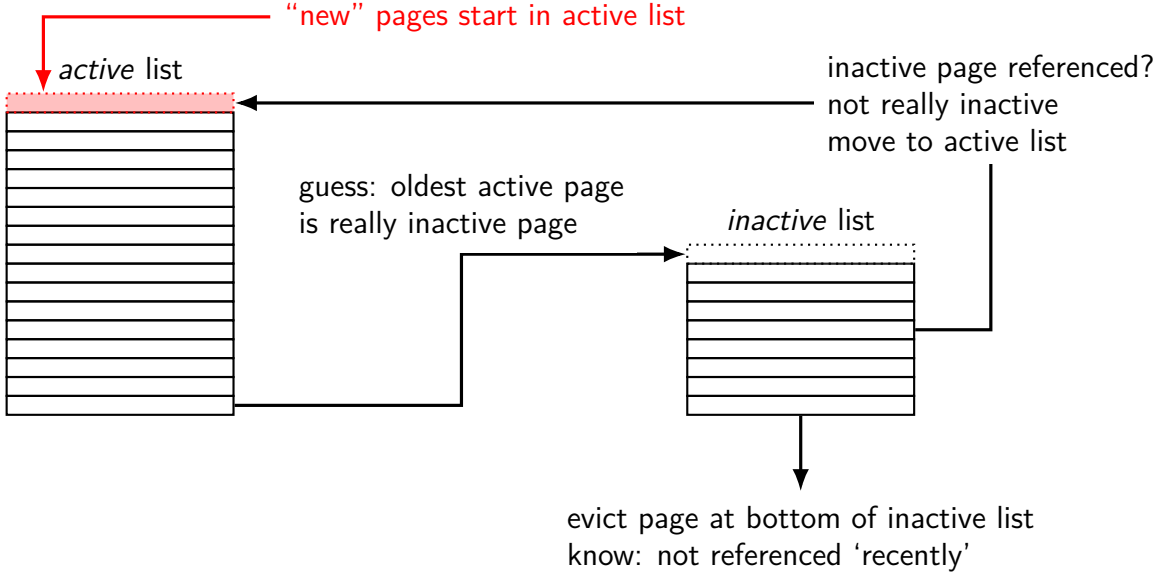
want some variation to tune its sensitivity

one idea: smaller list of pages to scan for accesses

approximating LRU: SEQ



approximating LRU: SEQ



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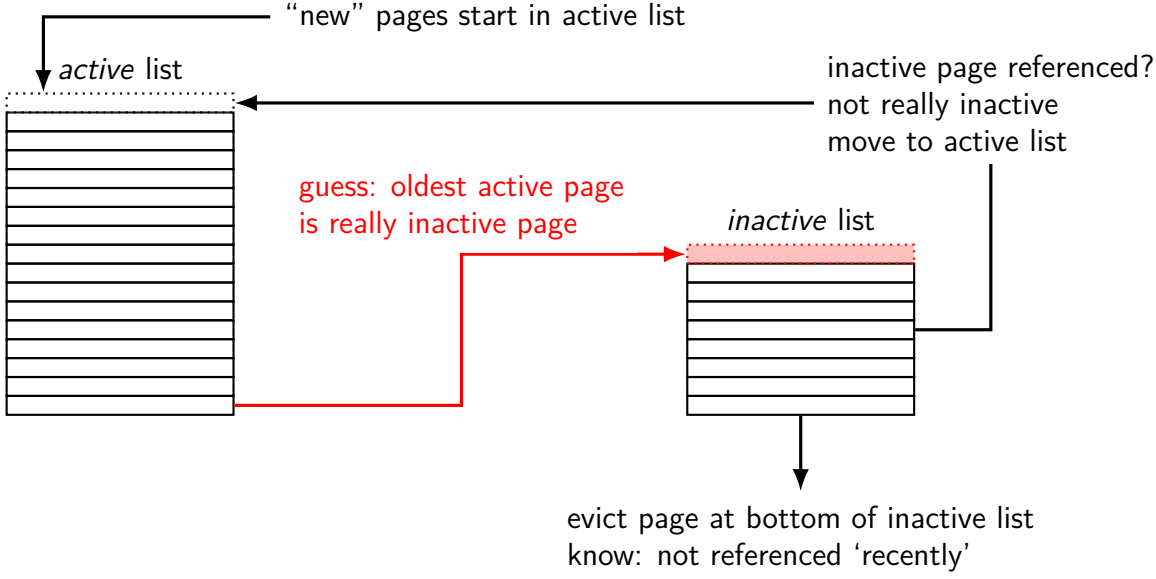

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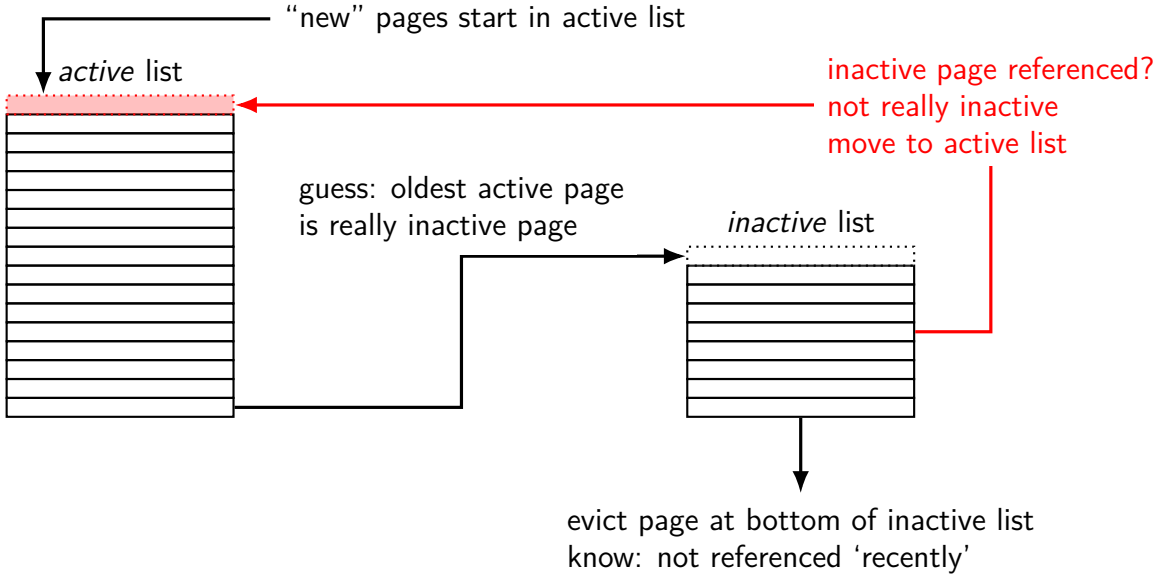

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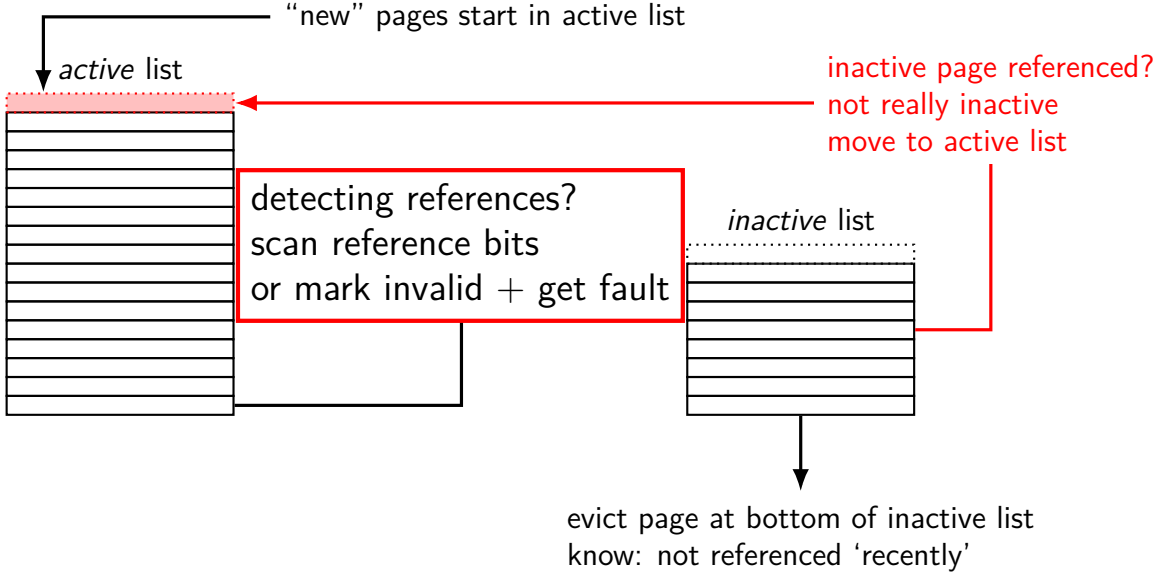

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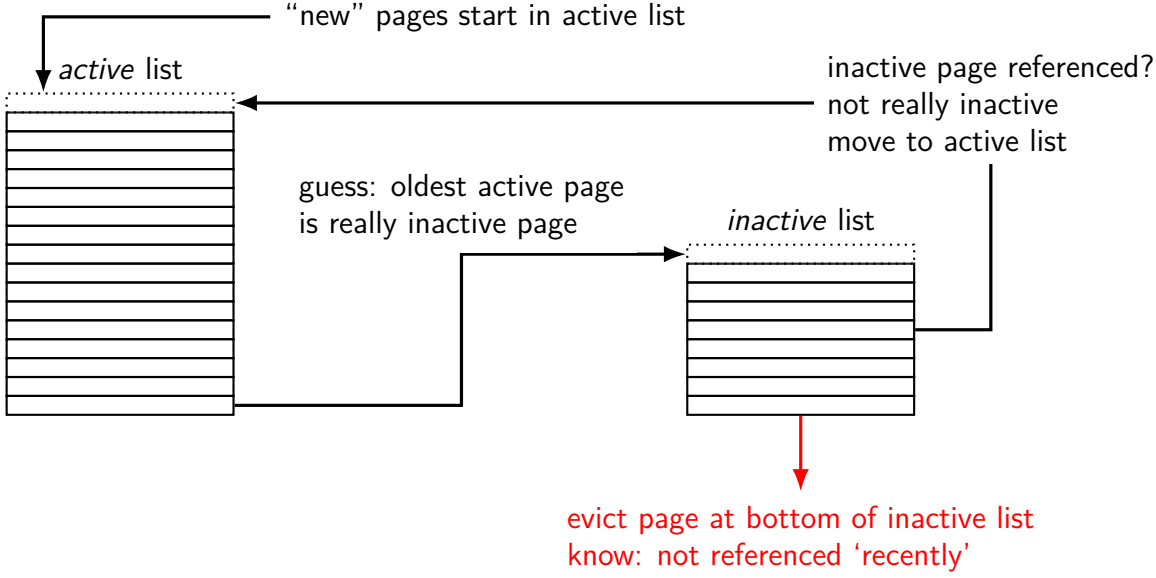

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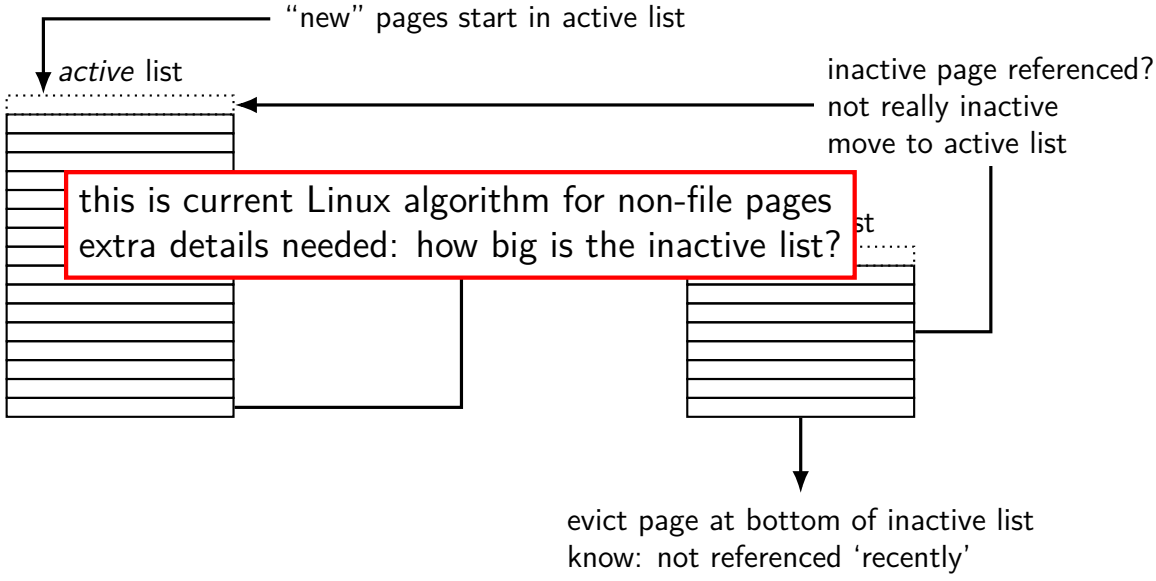
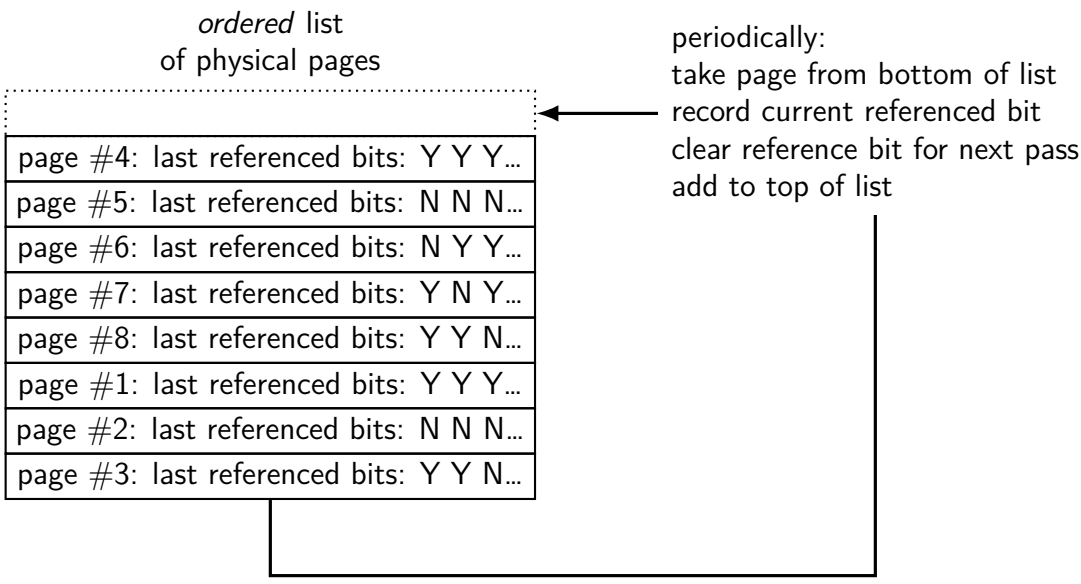
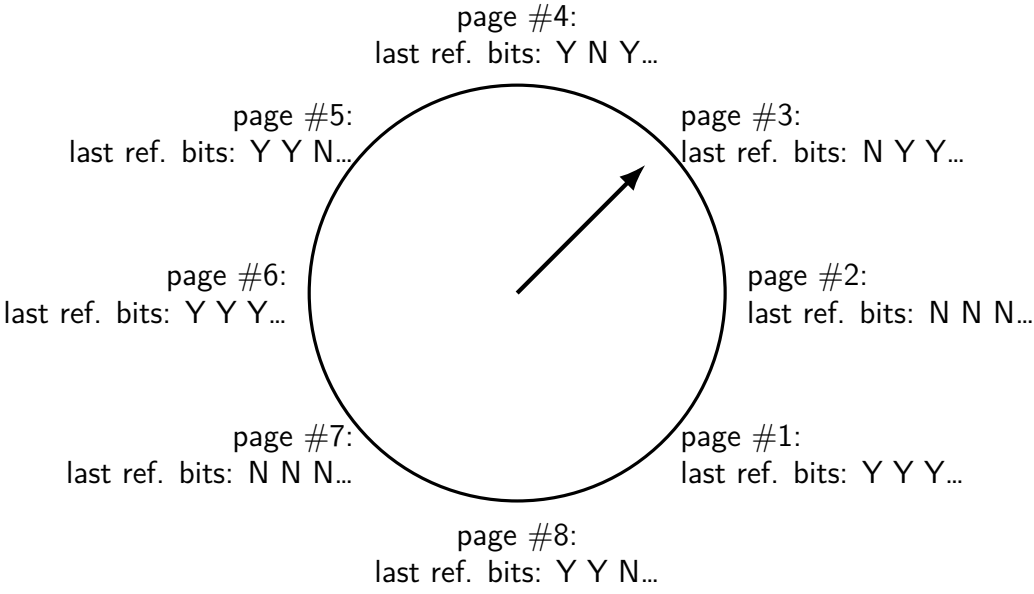


tracking usage: CLOCK (view 1)



tracking usage: CLOCK (view 2)



lazy replacement?

so far: don't do anything special until memory is full

only then is there a reason to writeback pages or evict pages

lazy replacement?

so far: don't do anything special until memory is full

only then is there a reason to writeback pages or evict pages

but real OSes are more proactive

non-lazy writeback

what happens when a computer loses power

how much data can you lose?

if we never run out of memory...all of it?

- no changed data written back

solution: track or scan for dirty pages and writeback

example goals:

- lose no more than 90 seconds of data
- force writeback at file close
- ...

non-lazy eviction

so far — allocating memory involves evicting pages

hopefully pages that haven't been used a long time anyways

non-lazy eviction

so far — allocating memory involves evicting pages

hopefully pages that haven't been used a long time anyways

alternative: evict earlier "in the background"

- "free": probably have some idle processor time anyways

allocation = remove already evicted page from linked list

- (instead of changing page tables, file cache info, etc.)

problems with LRU

question: when does LRU perform poorly?

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only reading things once

repeated scans of large amounts of data

problems with LRU

question: when does LRU perform poorly?

only reading things once

repeated scans of large amounts of data

both common access patterns for files

CLOCK-Pro: special casing for one-use pages

by default, Linux tries to handle scanning of files

- one read of file data — e.g. play a video, load file into memory

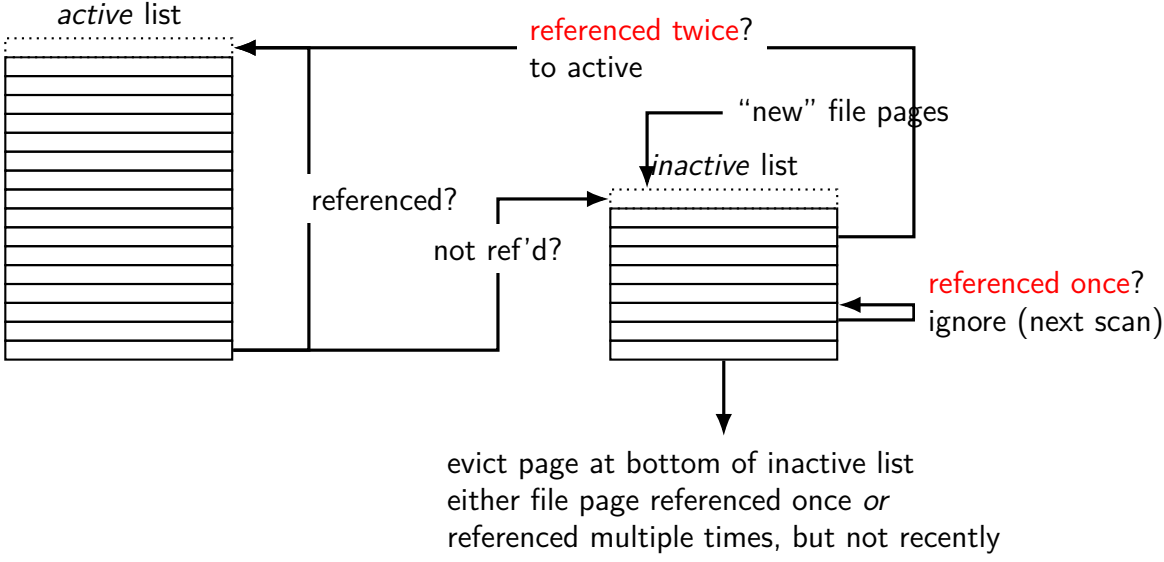
basic idea: don't consider pages active until the second access

single scans of file won't "pollute" cache

without this change: reading large files slows down other programs

- recently read part of large file steals space from active programs

CLOCK-Pro: special casing for one-use pages



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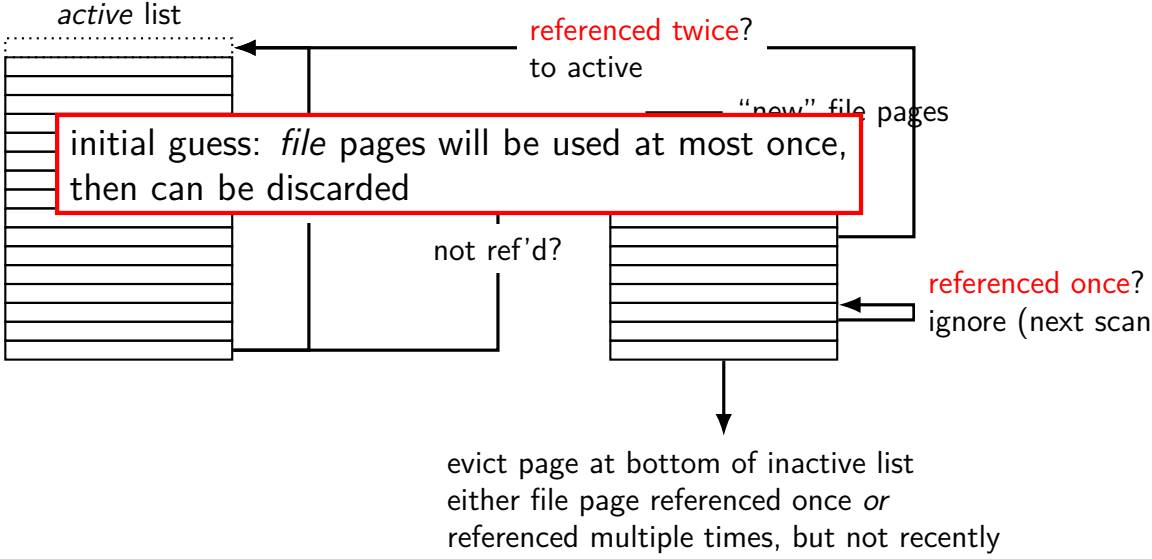

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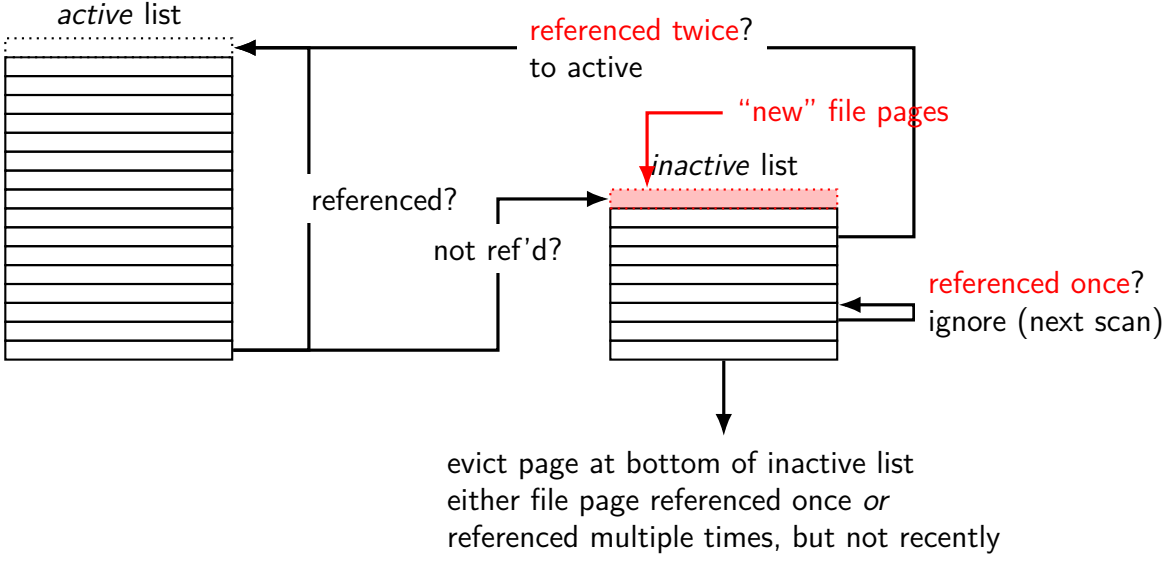

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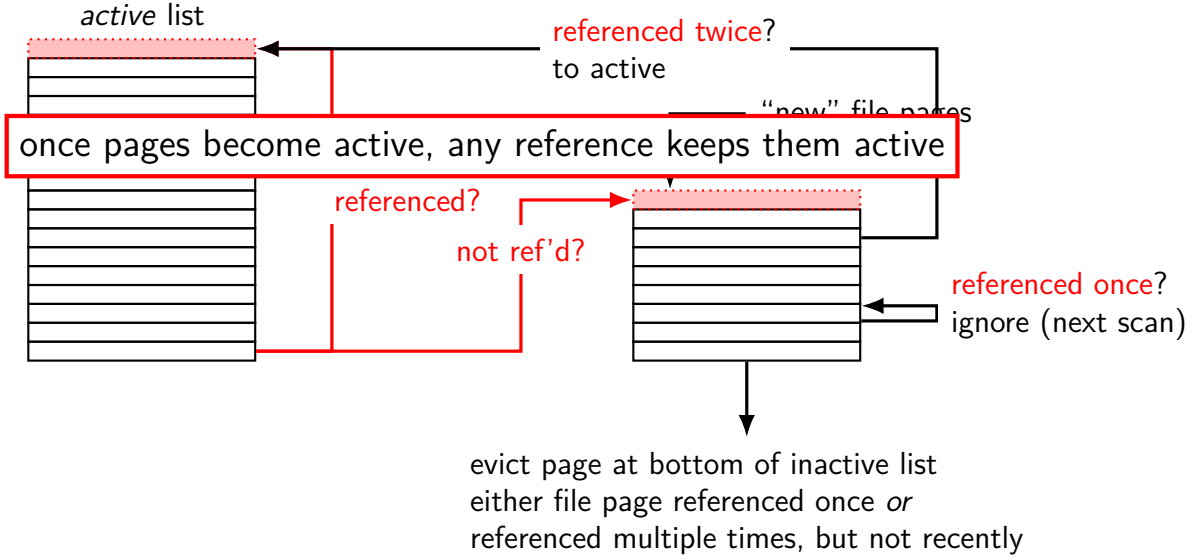

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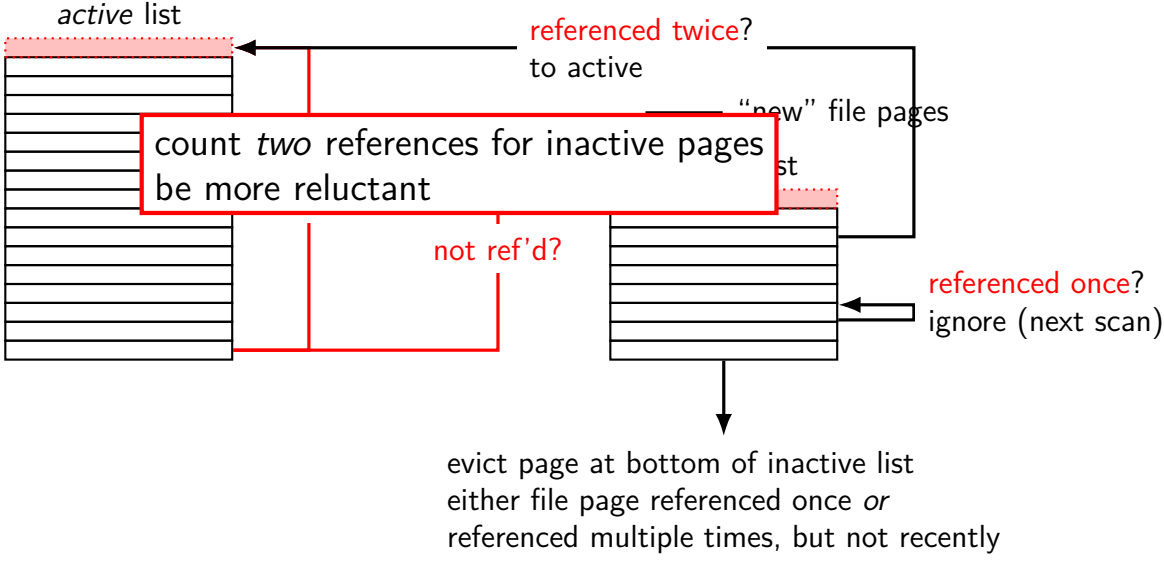

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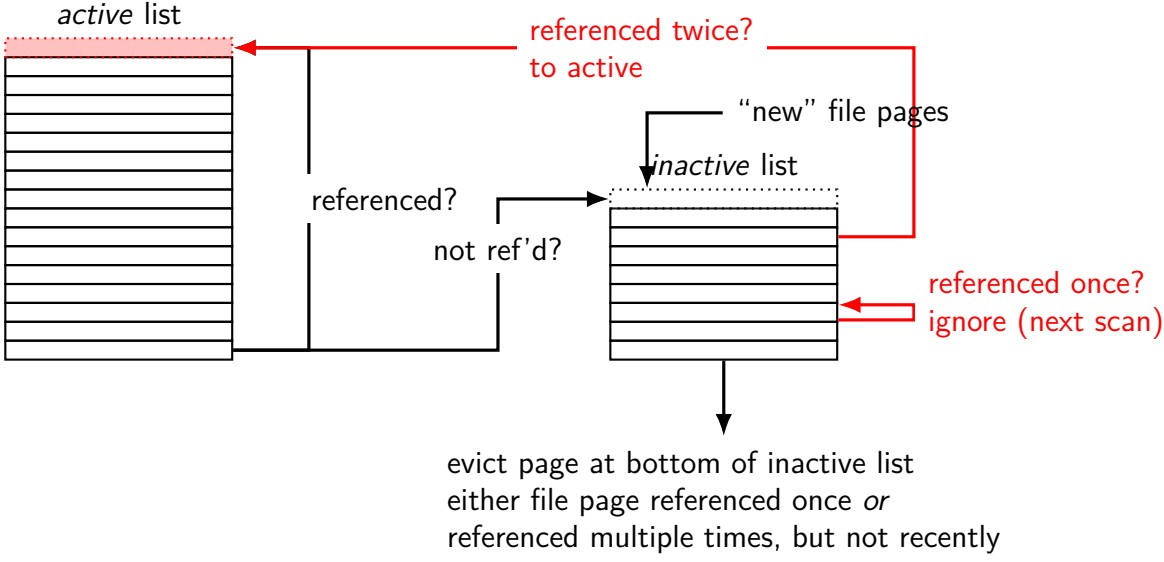

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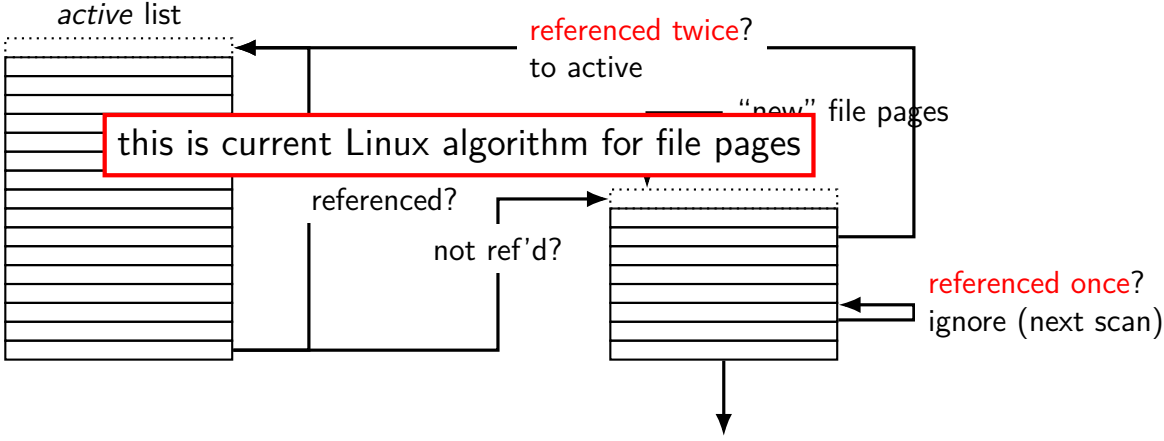


default Linux page replacement summary

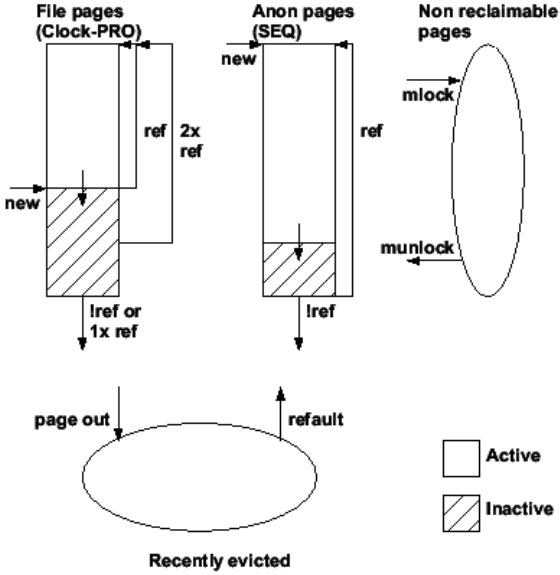


Figure: https://linux-mm.org/PageReplacementDesign

default Linux page replacement summary

identify *inactive* pages — guess: not going to be accessed soon

- file pages which haven't been accessed more than once, or
- any pages which haven't been accessed recently

some minimum threshold of inactive pages

- add to inactive list in background
- detecting references — scan referenced bits
- (I thought Linux marked as invalid — but wrong: not on x86)
- detect enough references — move to active

oldest inactive page still not used $\rightarrow$ evict that one

- otherwise: give it a second chance

being proactive

previous assumption: load on demand

why is something loaded?

- page fault
- maybe because application starts

can we do better?

readahead

program accesses page 4 of a file, page 5, page 6. What's next?

readahead

program accesses page 4 of a file, page 5, page 6. What's next?

page 7 — idea: guess this

on page fault, does it look like contiguous accesses?

called readahead

readahead heuristics

exercise: devise an algorithm to detect to do readahead.

- how to detect the reading pattern?
- when to start reads?
- how much to readahead?
- what state to keep?

Linux readahead heuristics — how much

how much to readahead?

Linux heuristic: count number of cached pages from before

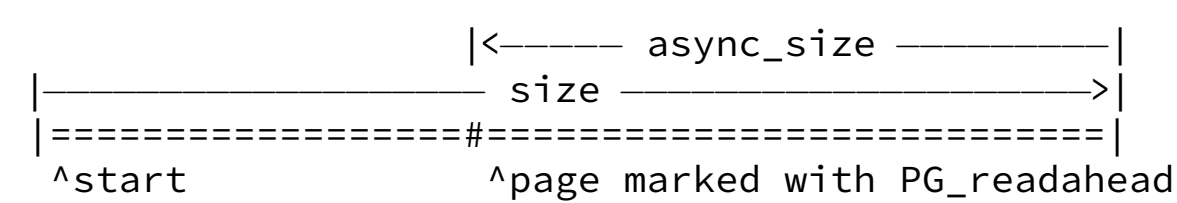
guess we should read about that many more
(plus minimum/maximum to avoid extremes)

goal: readahead more when applications are using file more

goal: don't readahead as much with low memory

Linux readahead heuristics — when

track “readahead windows” — pages read because of guess:



when `async_size` pages left, read next chunk

marked page = detect reads to this page

- one option: make page temporary invalid

idea: keep up with application, but not too far ahead

ASCII art figure: comments of Linux readahead code

thrashing

what if there's just not enough space?

- for program data, files currently being accessed

always reading things from disk

causes performance collapse — disk is really slow

known as thrashing

‘fair’ page replacement

so far: page replacement about least recently used

what about sharing fairly between users?

sharing fairly?

process A

4MB of stack+code, 16MB of heap
shared cached 24MB file X

process B

4MB of stack+code, 16MB of heap
shared cached 24MB file X

process C

4MB of stack+code, 4MB of heap
cached 32MB file Y

process D+E

4MB of stack+code (each), 70MB of heap (each)
but all heap + most of code is shared copy-on-write

accounting pages

shared pages make it difficult to count memory usage

Linux *cgroups* accounting (mostly): last touch

- count shared file pages for the process that last 'used' them
- ...as detected by page fault for page

Linux cgroup limits

Linux “control groups” of processes

can set memory limits for group of proceses:

low limit: don’t ‘steal’ pages when group uses less than this

- always take pages someone is using (unless no choice)

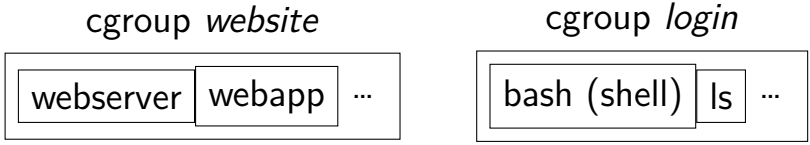
high limit: never let group use more than this

- replace pages from this group before anything else

...

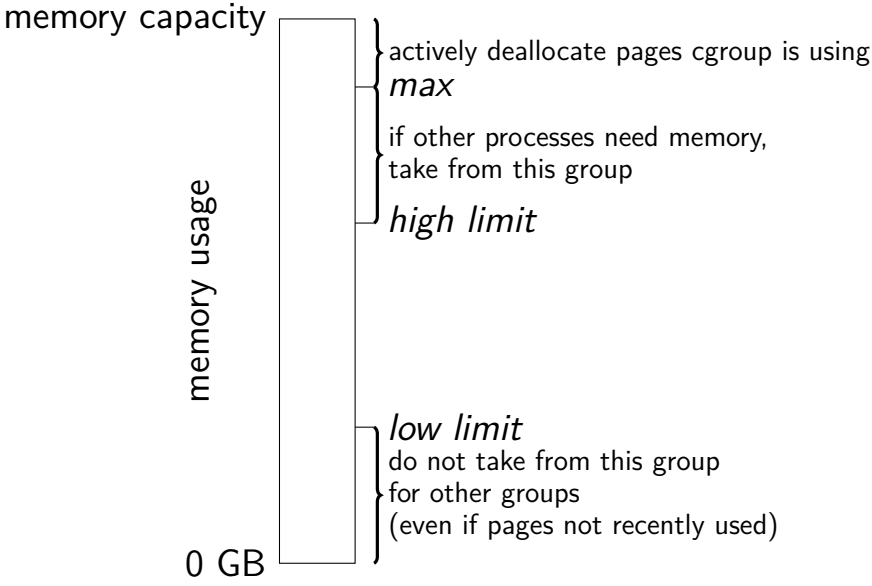
Linux cgroups

Linux mechanism: seperate processes into groups:



can set memory and CPU and ...shares for each group

Linux cgroup memory limits



page cache/replacement summary

program memory + files — swapped to disk, cached in memory

mostly, assume working set model

- keep (hopefully) small active set in memory
- least recently used variants

special cases for non-LRU-friendly patterns (e.g. scans)

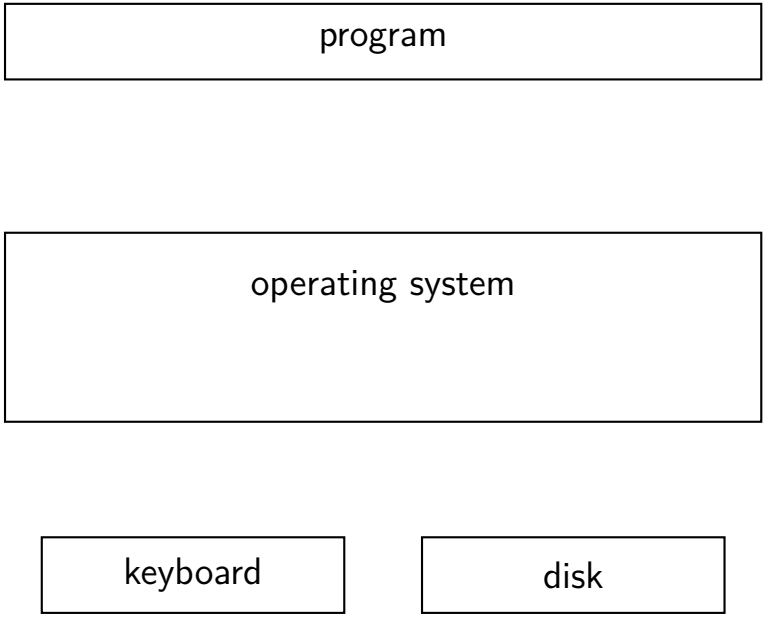
- maybe more we haven't discussed?

being proactive (writeback when idle, readahead, pool of pre-evicted pages)

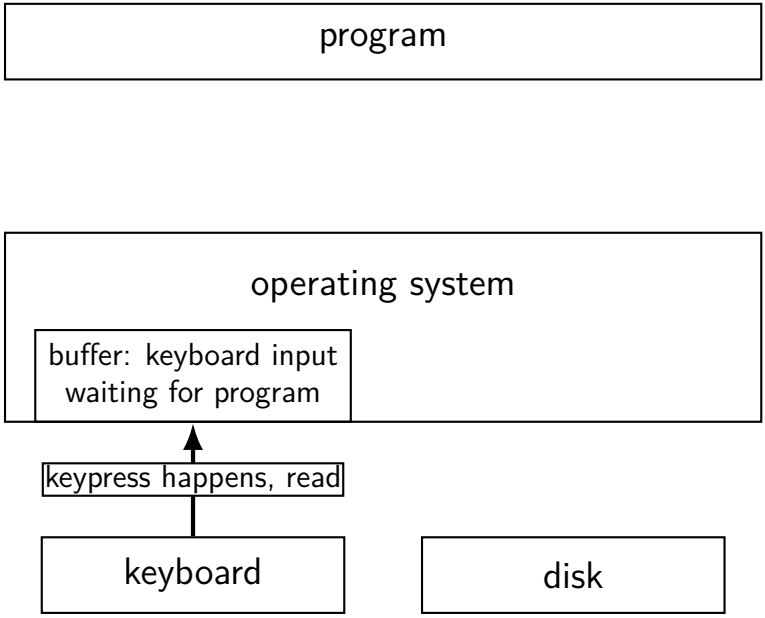
handling non-miss-rate goals

- fair replacement: limit active memory per user?
- probably more we haven't discussed here? optimizing throughput? fair throughput between users?

recall: kernel buffering (reads)



recall: kernel buffering (reads)



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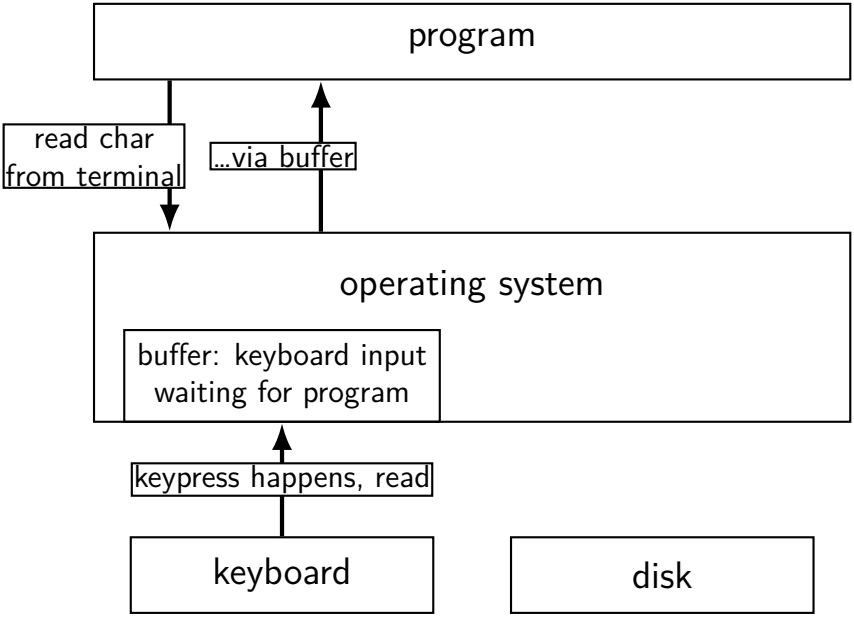

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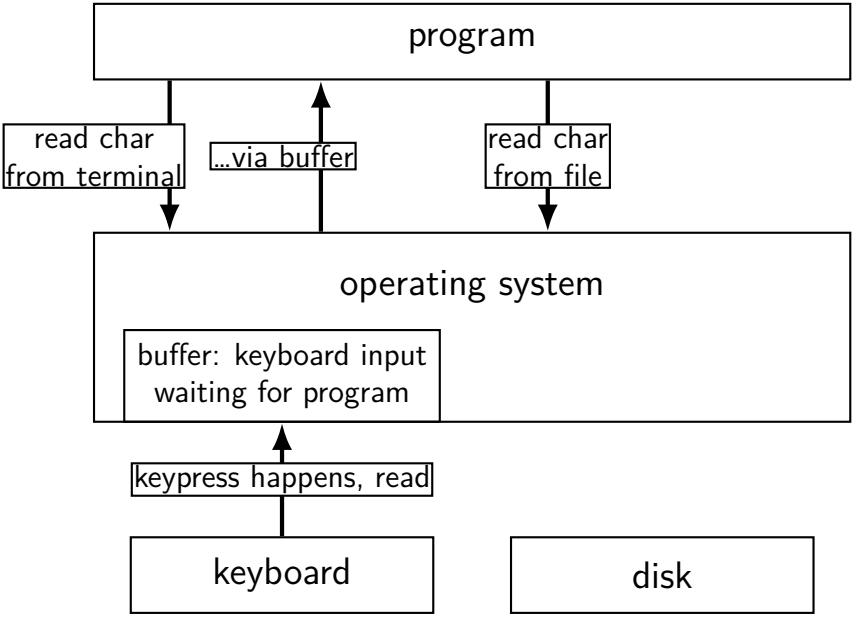

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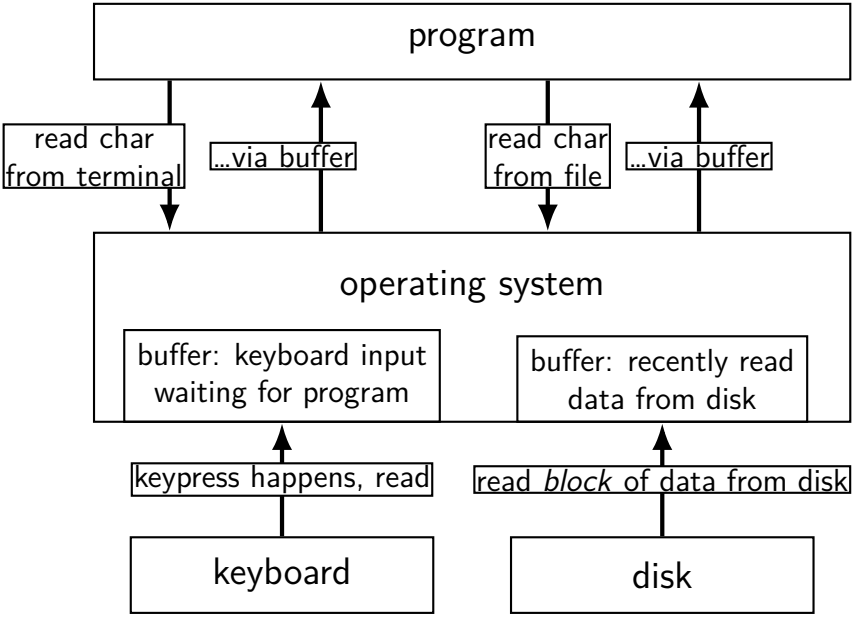

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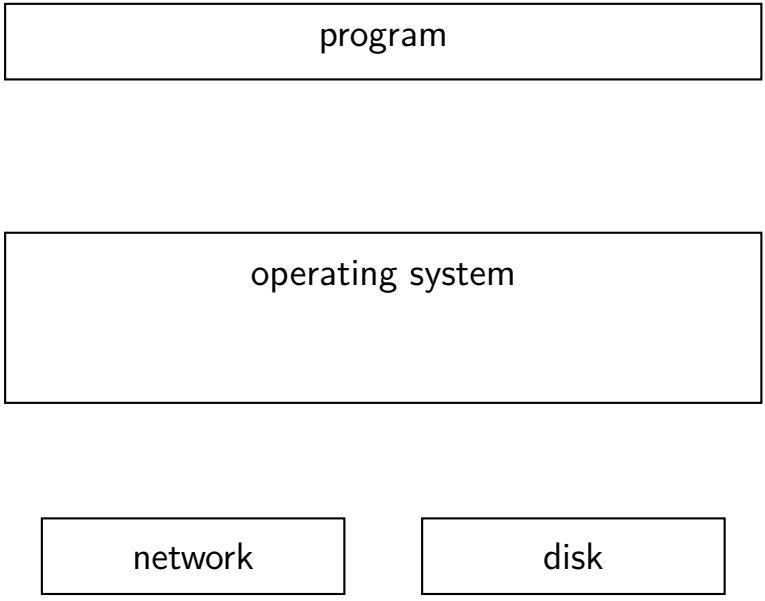

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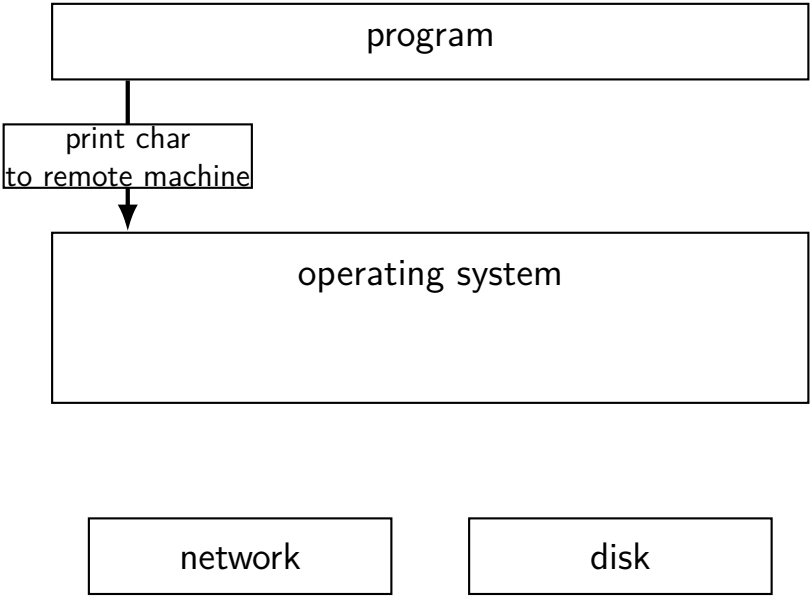

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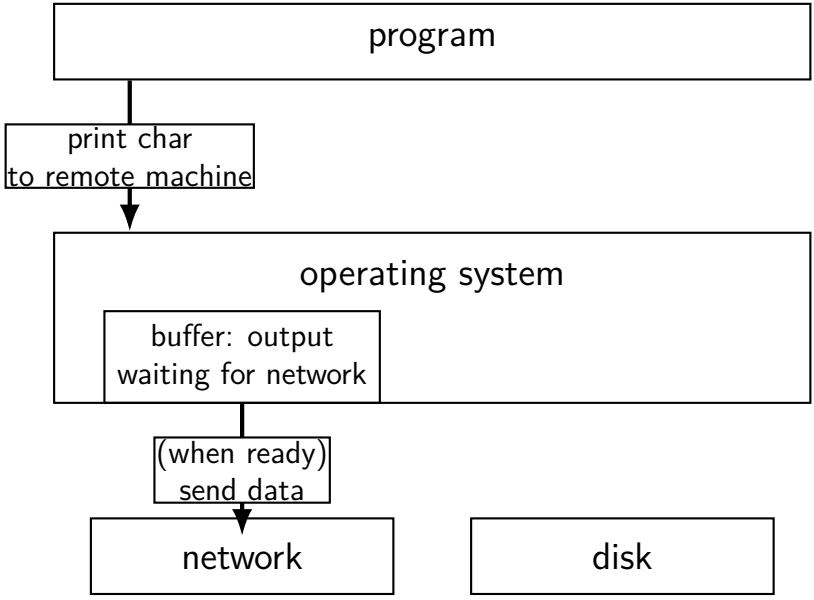
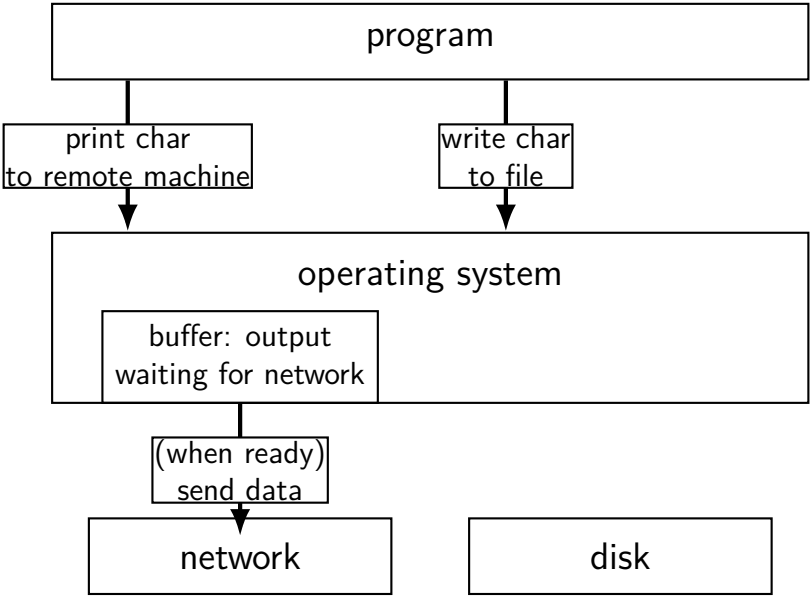
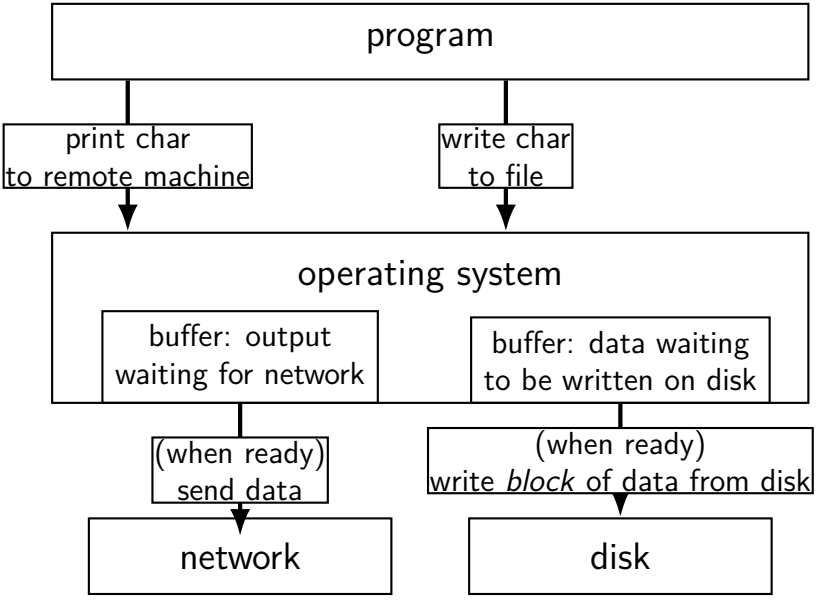


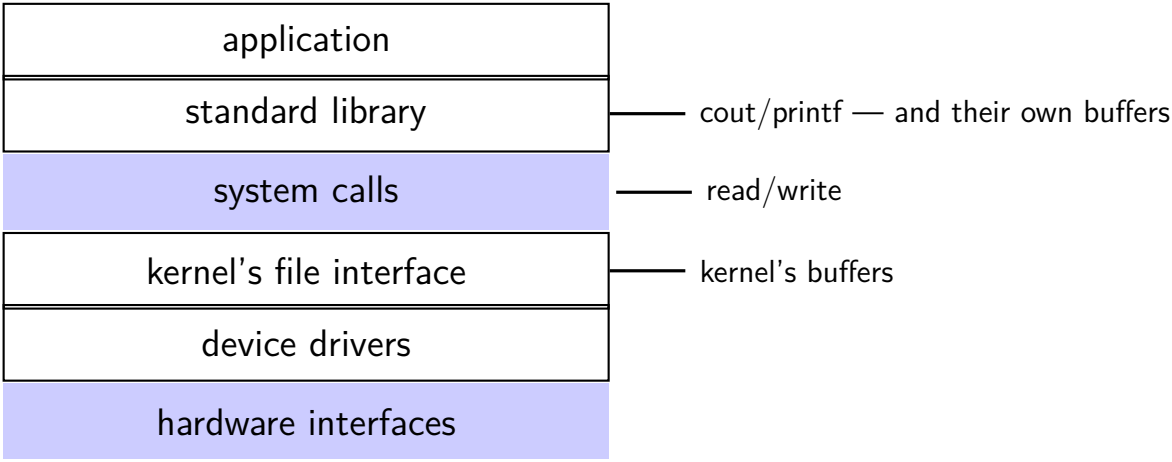
recall: kernel buffering (writes)



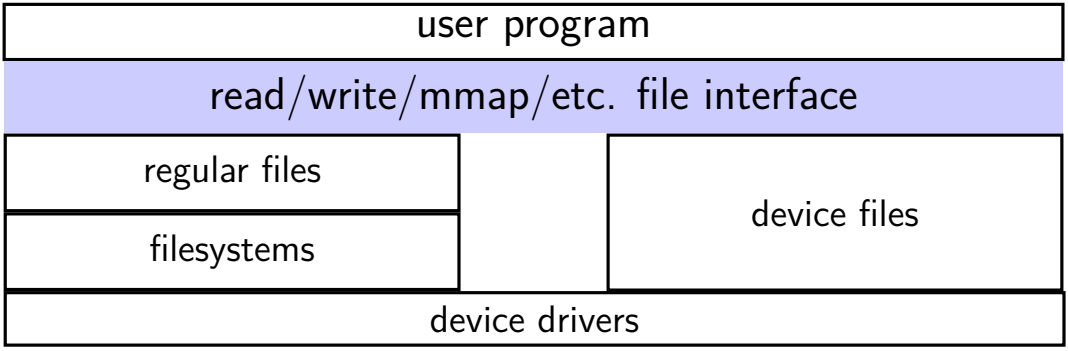
recall: kernel buffering (writes)



recall: layering



ways to talk to I/O devices



devices as files

talking to device? open/read/write/close

typically similar interface within the kernel

device driver implements the file interface

example device files from a Linux desktop

`/dev/snd/pcmC0D0p` — audio playback

configure, then write audio data

`/dev/sda`, `/dev/sdb` — SATA-based SSD and hard drive

usually access via filesystem, but can mmap/read/write directly

`/dev/input/event3`, `/dev/input/event10` — mouse and keyboard

can read list of keypress/mouse movement/etc. events

`/dev/dri/renderD128` — builtin graphics

DRI = direct rendering infrastructure

devices: extra operations?

read/write/mmap not enough?

- audio output device — set format of audio? headphones plugged in?
- terminal — whether to echo back what user types?
- CD/DVD — open the disk tray? is a disk present?
- ...

extra POSIX file descriptor operations:

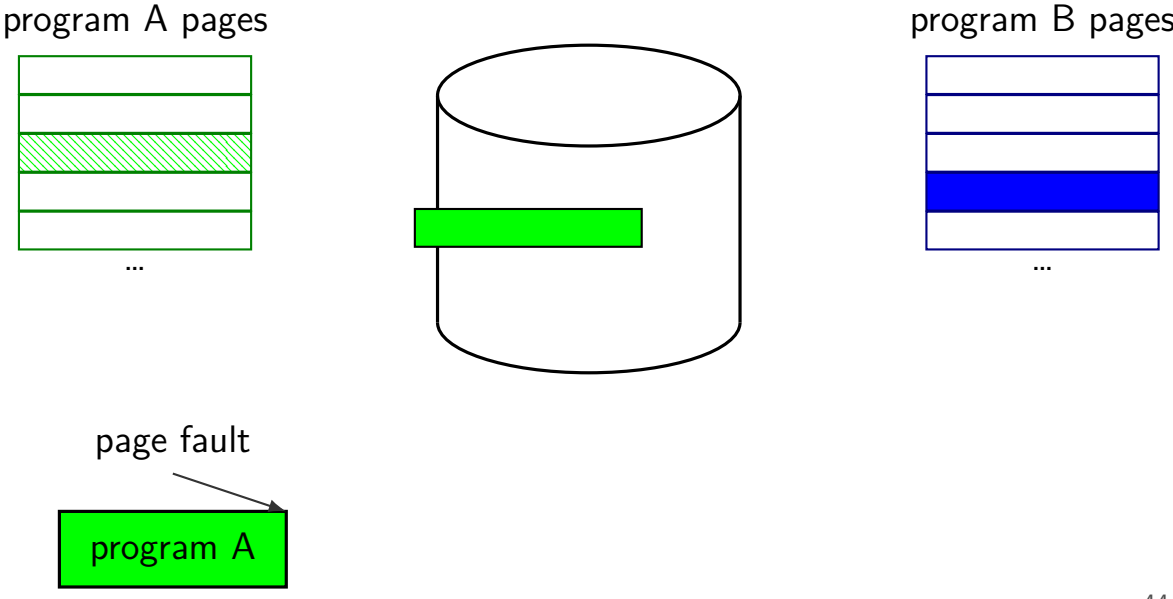
- ioctl (general I/O control) — device driver-specific interface
- tcsetattr (for terminal settings)
- fcntl
- ...

also possibly extra device files for same device:

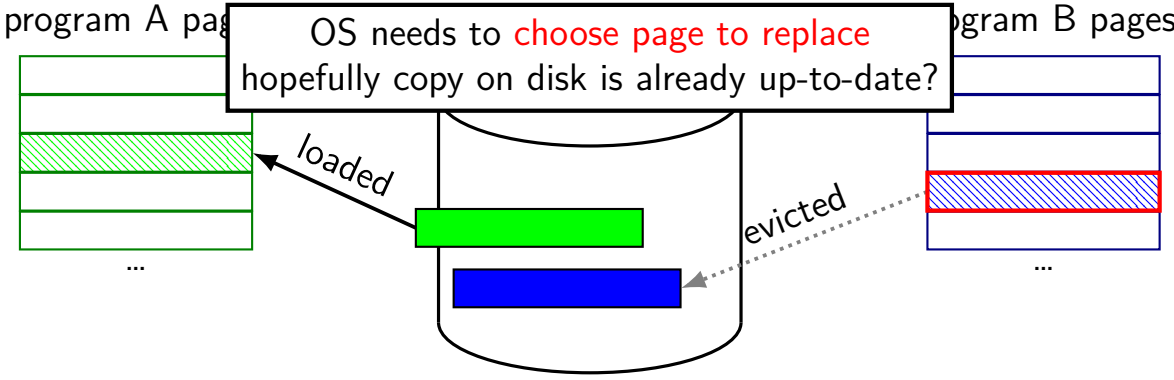
- `/dev/snd/controlC0` to configure audio settings for `/dev/snd/pcmC0D0p`, `/dev/snd/pcmC0D10p`, ...

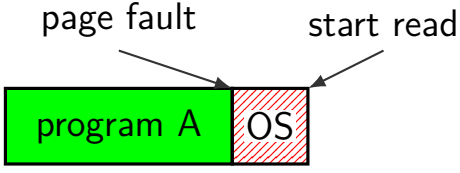
backup slides

swapping timeline

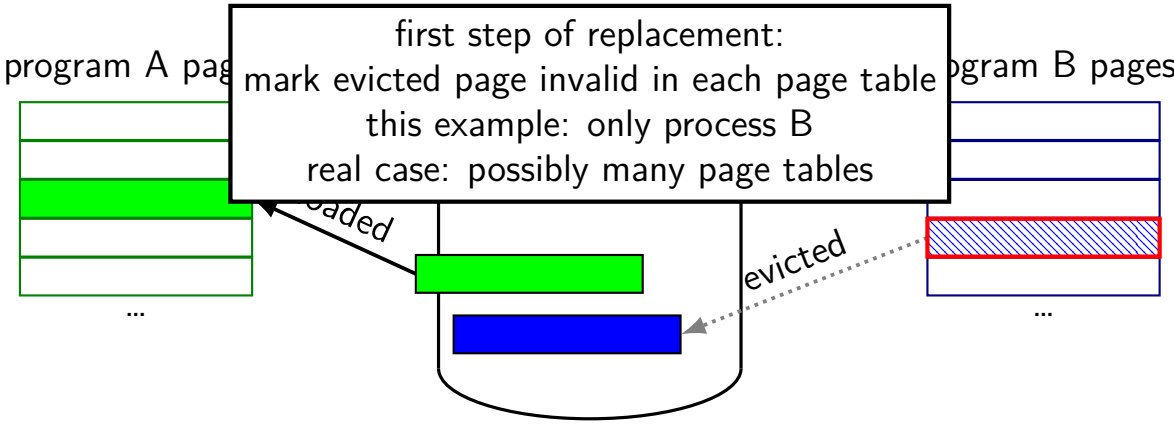


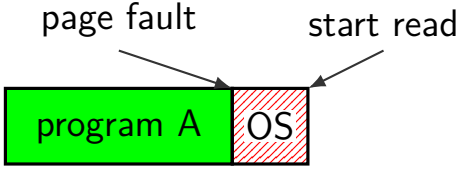
swapping timeline



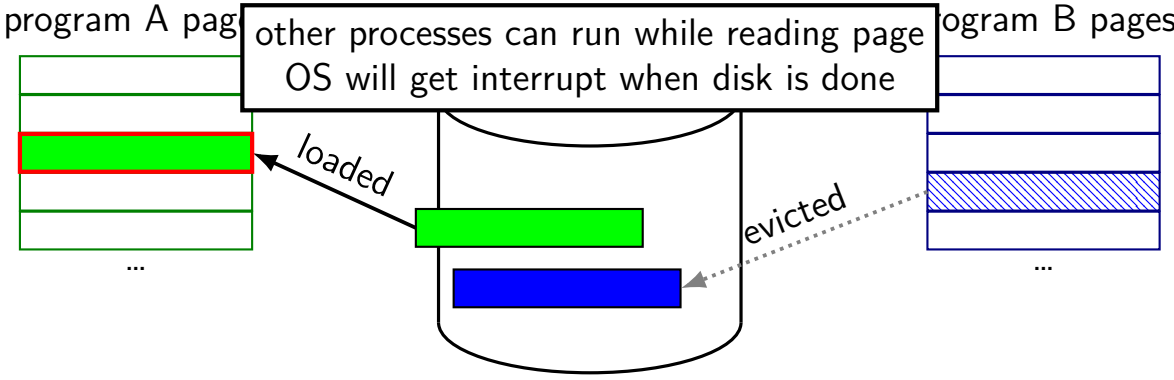


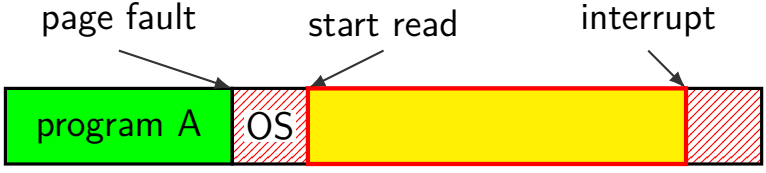
swapping timeline



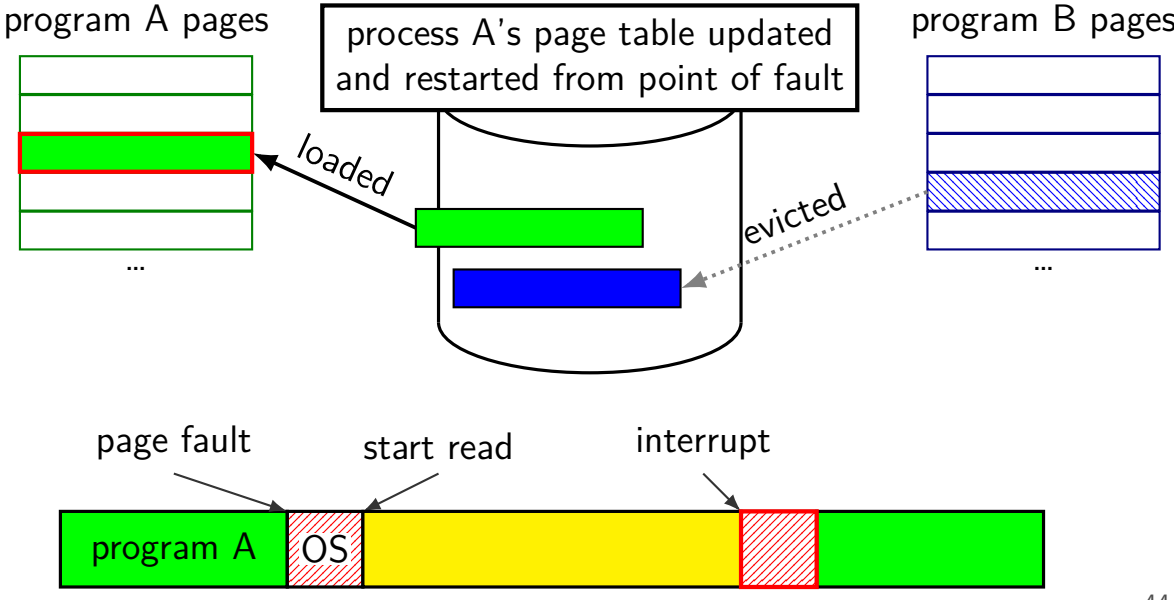


swapping timeline





swapping timeline



POSIX: everything is a file

the file: one interface for

- devices (terminals, printers, ...)
- regular files on disk
- networking (sockets)
- local interprocess communication (pipes, sockets)

basic operations: open(), read(), write(), close()

the file interface

open before use

- setup, access control happens here

byte-oriented

- real device isn't? operating system needs to hide that

explicit close

the file interface

open before use

- setup, access control happens here

byte-oriented

- real device isn't? operating system needs to hide that

explicit close