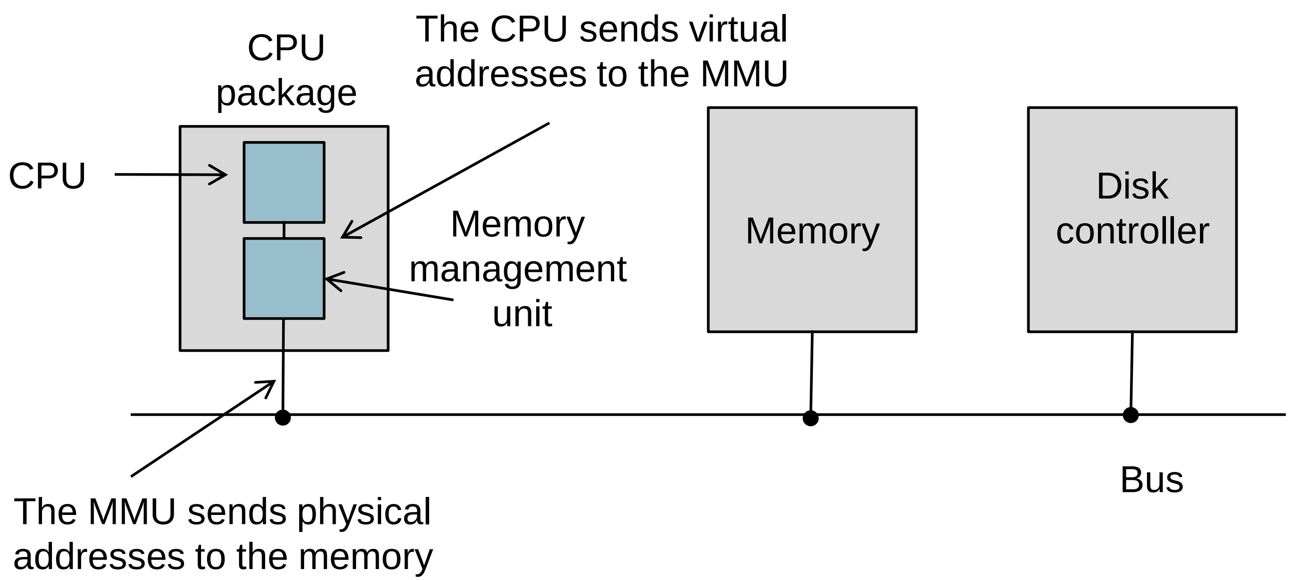
Virtual Memory

Today

- Virtual memory
- Page replacement algorithms
- Modeling page replacement algorithms

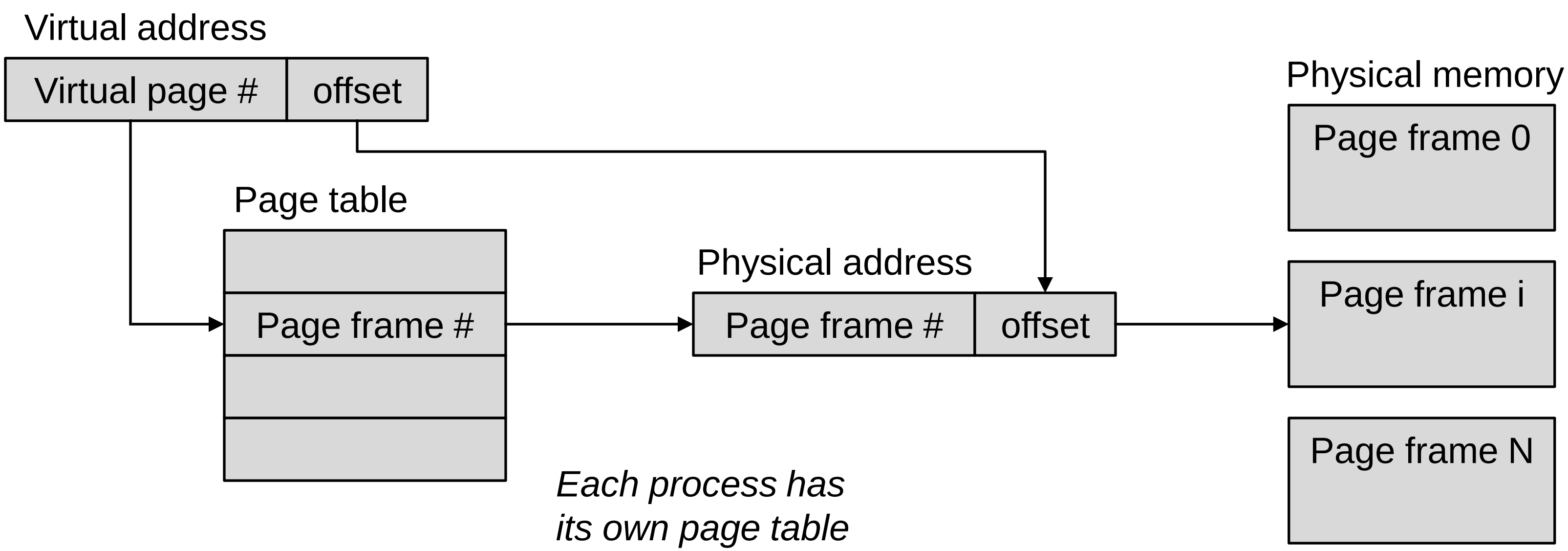
Reminder: virtual memory with paging

- Hide the complexity – let the OS do the job
- Virtual address space split into pages
- Physical memory split into page frames
- Page & page frames = size (512B … 64KB)
- Map pages into page frames
  - Doing the translation – OS + MMU



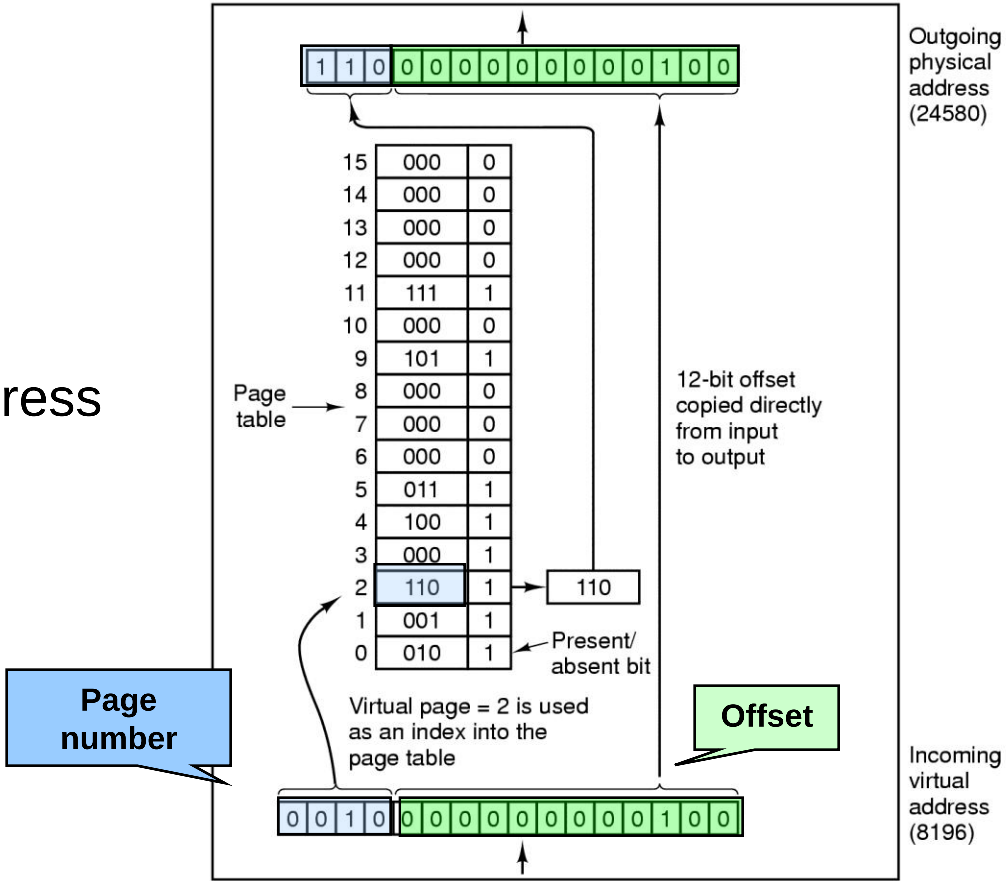
Address translation with paging

- Virtual to physical address
  - Two parts – virtual page number and offset
  - Virtual page number – index into a page table
  - Page table maps virtual pages to page frames
    - Managed by the OS
    - One entry per page in virtual address space
  - Physical address – page number and offset



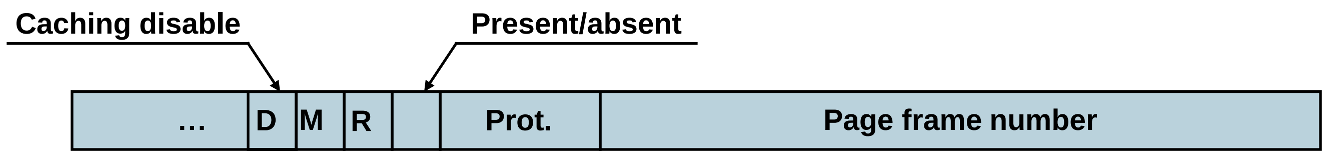
Details of the MMU work

- MMU with 16 4KB pages
- Page # (first 4 bits) index into page table
- If not there
  - Page fault
- Else
  - Output register +
  - 12 bit offset →
  - 15 bit physical address



Page table entry

- An opportunity – there's a PTE lookup per memory reference, what else can we do with it?
- Looking at the details



  – Page frame number – the most important field
  – Protection – 1 bit for R&W or R or 3 bits for RWX
  – Present/absent bit
    • Says whether or not the virtual address is used
  – Modified (M): dirty bit
    • Set when a write to the page has occurred
  – Referenced (R): Has it being used?
  – To ensure we are not reading from cache (D)
    • Key for pages that map onto device registers rather than memory

Page replacement algorithms

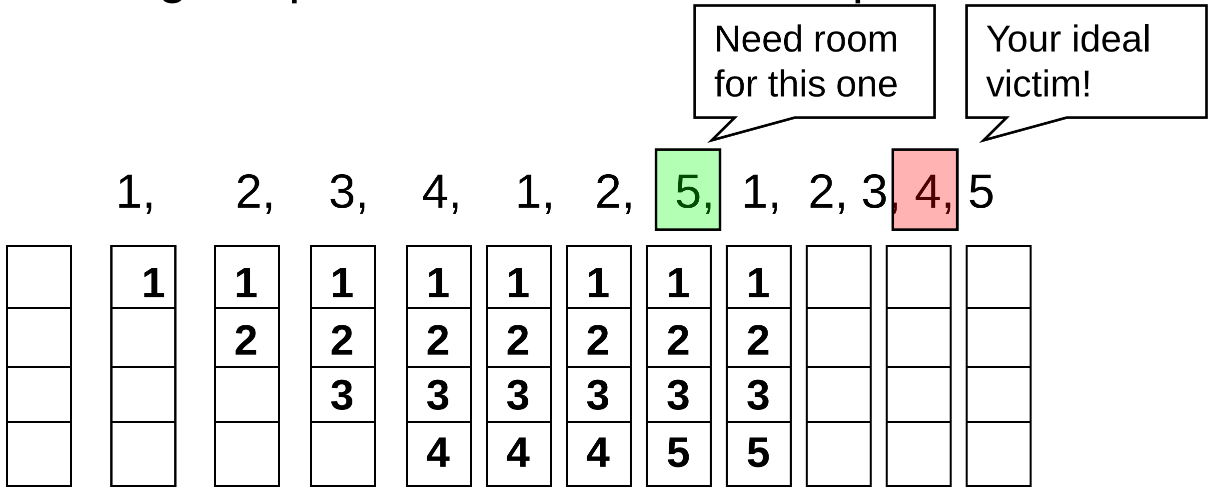
- OS uses main memory as (page) cache
  - If only load *when* reference – demand paging
- Page fault – cache miss
  - Need room for new page? Page replacement algorithm
  - What's your best candidate for removal?
    - The one you will never touch again – duh!
- What do you do with victim page?
  - A modified page must first be saved
  - An unmodified one just overwritten
  - Better not to choose an often used page
    - It will probably need to be brought back in soon

How can any of this work?!?!

- Locality
  - Temporal locality – location recently referenced tend to be referenced again soon
  - Spatial locality – locations near recently referenced are more likely to be referenced soon
- Locality means paging could be infrequent
  - Once you brought a page in, you’ll use it many times
  - Some issues that may play against you
    - Degree of locality of application
    - Page replacement policy and application reference pattern
    - Amount of physical memory and application footprint

Optimal algorithm (Belady's algorithm)

- For now, assume a process pages against itself, using a fixed number of page frames
- Best page to replace – the one you'll never need again
  - Replace page needed at the farthest point in future
  - Optimal but unrealizable
- Estimate by …
  - Logging page use on previous runs of process
  - Although impractical, useful for comparison



Not recently used (NRU) algorithm

- Each page has *Reference* and *Modified* bits
  - Set when page is referenced, modified
  - R bit set means recently referenced, so you must clear it every now and then
- Pages are classified

How can this occur?

R	M	Class
0	0	Not referenced, not modified (0,0 → 0)
0	1	Not referenced, modified (0,1 → 1)
1	0	Referenced, but not modified (1,0 → 2)
1	1	Referenced and modified (1,1 → 3)

- NRU removes page at random
  - from lowest numbered, non-empty class
- Easy to understand, relatively efficient to implement and sort-of OK performance

FIFO algorithm

- Maintain a linked list of all pages – in order of arrival
- Victim is first page of list
  - Maybe the oldest page will not be used again …
- Disadvantage
  - But maybe it will – the fact is, you have no idea!
  - Increasing physical memory *might* increase page faults (Belady's anomaly)

A, B, C, D, A, B, E, A, B, C, D, E

	A	B	C	D	A	B	E	E	E	C	D	D
		A	B	C	D	A	B	B	B	E	C	C
			A	B	C	D	A	A	A	B	E	E

Second chance algorithm

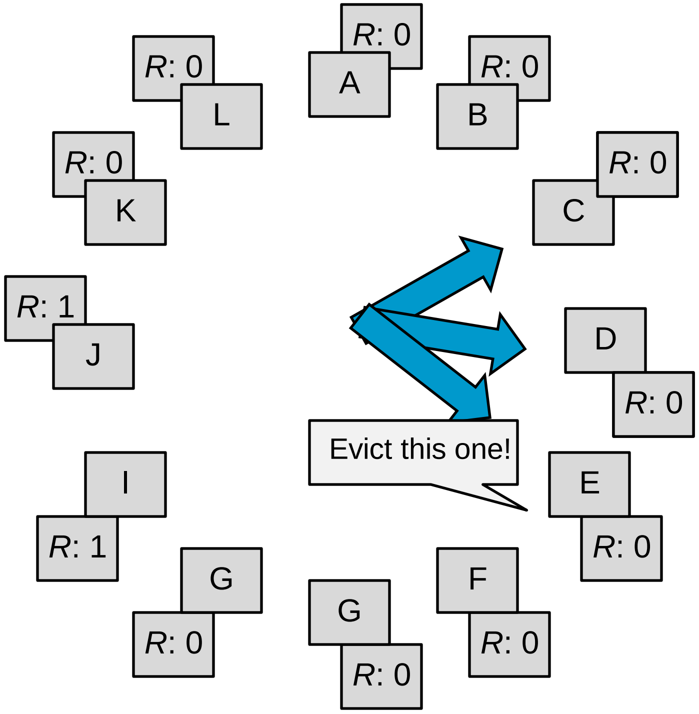
- Simple modification of FIFO
  - Avoid throwing out a heavily used page – look at the R bit
- Operation of second chance
  - Pages sorted in FIFO order
  - If page has been used, give it another chance – move it to the end of the list of pages, clear R and update its timestamp
  - Page list if fault occurs at time 20, A has R bit set (time is loading time)

	Page	Time	R
Most recently loaded	H	18	X
	G	15	X
	F	14	X
	E	12	X
	D	8	X
	C	7	X
	B	3	0
Oldest page	**A**	**0**	**1**

Page	Time	R
A	**20**	**0**
H	18	X
G	15	X
F	14	X
E	12	X
D	8	X
C	7	X
B	3	0

Clock algorithm

- Second chance is reasonable but inefficient
  - Quit moving pages around – move a pointer?
- Same as Second chance but for implementation
  - Keep all pages in a circular list, as a clock, with the hand pointing to the oldest page
  - When page fault
    - Look at page pointed at by hand
      - If R = 0, evict page
      - If R = 1. clear R & move hand



Least recently used (LRU) algorithm

- Pages used recently will used again soon
  - Throw out page unused for longest time
  - Idea: past experience is a decent predictor of future behavior
    - LRU looks at the past, Belady's wants to look at the future
    - *How is LRU different from FIFO?*
- Must keep a linked list of pages
  - Most recently used at front, least at rear
  - Update this list every memory reference!!
    - Too expensive in memory bandwidth, algorithm execution time, etc
- Alternatively keep counter in page table entry
  - Equipped hardware with a counter, incremented after each instruction
  - After each reference, update PTE for the referenced page with value of the counter
  - Choose page with lowest value counter

A second HW LRU implementation

- Use a matrix – *n* page frames – *n x n* matrix
- Page *k* is reference
  - Set all bits of row *k* to 1
  - Set all bits of column *k* to 0
- Page of lowest row is LRU

0,1,2,3,2,1,0,3,2

0	1	2	3	
0	0	0	0	0
0	0	0	0	1
0	0	0	0	2
0	0	0	0	3

0	1	2	3	
0	1	1	1	0
0	0	0	0	1
0	0	0	0	2
0	0	0	0	3

0	1	2	3	
0	0	1	1	0
1	0	1	1	1
0	0	0	0	2
0	0	0	0	3

0	1	2	3	
0	0	0	1	0
1	0	0	1	1
1	1	0	1	2
0	0	0	0	3

0	1	2	3	
0	0	0	0	0
1	0	0	0	1
1	1	0	0	2
1	1	1	0	3

0	1	2	3	
0	0	0	0	0
1	0	0	0	1
1	1	0	1	2
1	1	0	0	3

0	1	2	3	
0	0	0	0	0
1	0	1	1	1
1	0	0	1	2
1	0	0	0	3

0	1	2	3	
0	1	1	1	0
0	0	1	1	1
0	0	0	1	2
0	0	0	0	3

0	1	2	3	
0	1	1	0	0
0	0	1	0	1
0	0	0	0	2
1	1	1	0	3

0	1	2	3	
0	0	1	0	0
0	0	1	0	1
1	0	1	1	2
1	0	1	0	3

… 1,0,3,2

Simulating LRU in software

- Not Frequently Used
  - Software counter associated with each page
  - At clock interrupt – add R to counter for each page
  - Problem - it never forgets!
- Better – Aging
  - Push R from the left, drop bit on the right
  - How is this *not* LRU? One bit per tick & a finite number of bits per counter

		R		R	
0	0 0 0 0 0 0 0 0	1	1 0 0 0 0 0 0 0	1	1 1 0 0 0 0 0 0
1	0 0 0 0 0 0 0 0	0	0 0 0 0 0 0 0 0	1	1 0 0 0 0 0 0 0
2	0 0 0 0 0 0 0 0	1	1 0 0 0 0 0 0 0	0	0 1 0 0 0 0 0 0
3	0 0 0 0 0 0 0 0	0	0 0 0 0 0 0 0 0	0	0 0 0 0 0 0 0 0
4	0 0 0 0 0 0 0 0	1	1 0 0 0 0 0 0 0	1	1 1 0 0 0 0 0 0
5	0 0 0 0 0 0 0 0	1	1 0 0 0 0 0 0 0	0	0 1 0 0 0 0 0 0

Working set

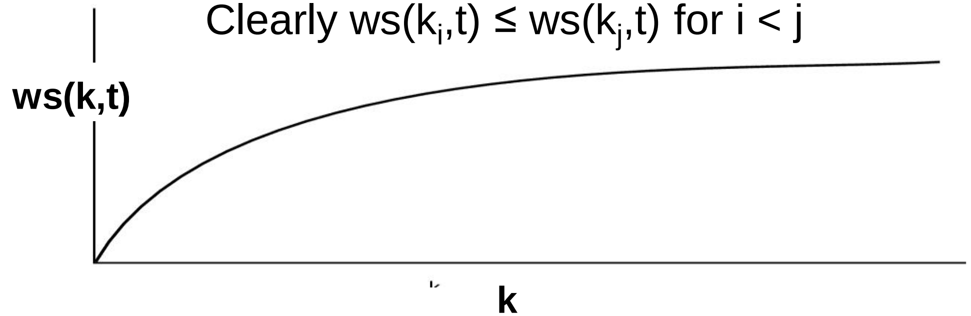
- Most programs show *locality of reference*
  - *O*ver a short time, just a few common pages
- Working set
  - Models the dynamic locality of a process' memory usage
  - i.e. the set of pages currently needed by a process
- Intuitively, working set must be in memory, otherwise you'll experience heavy faulting (thrashing)
  - What does it mean 'how much memory does program x need?" – what is program x average/worst-case working set size?

Working set

- Demand paging
  – Simplest strategy, load page when needed
- Can you do better knowing a process WS?
  – How could you use this to reduce turnaround time? *Prepaging*
- Working set definition
  – *ws(k,t) = {pages p such that p was referenced in the k most recent memory references}* (*k* is WS window size)

What bounds ws(k, t) as you increase k?

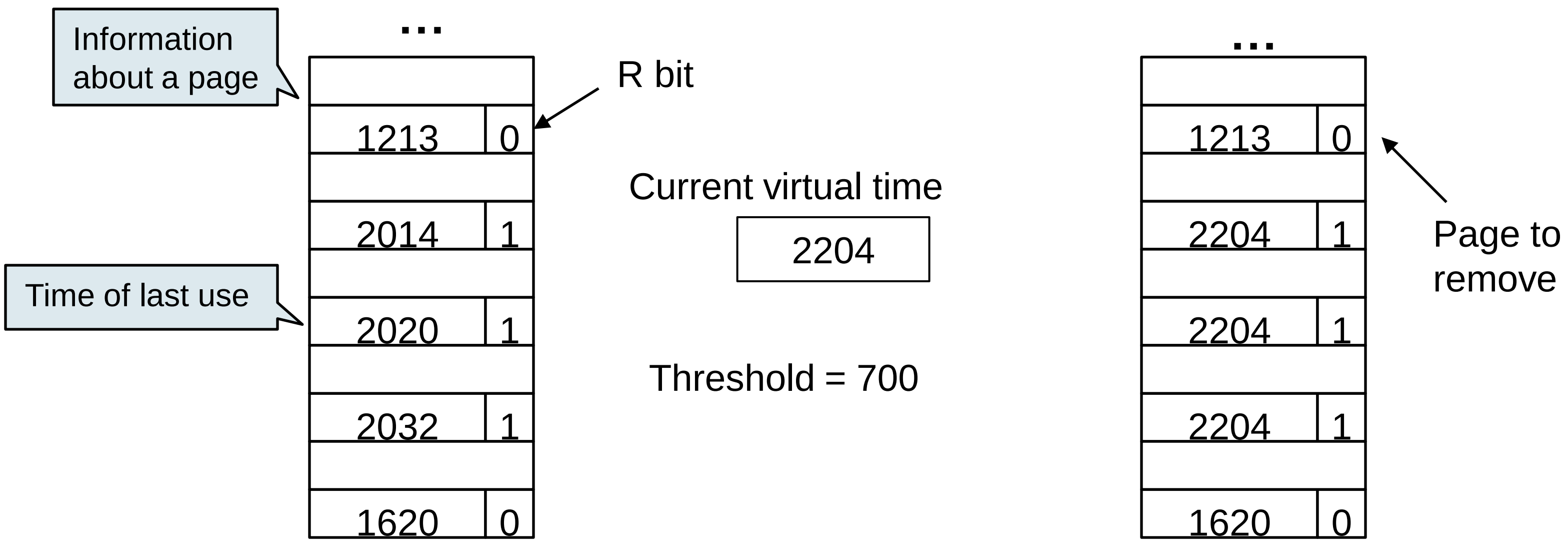
Clearly $ws(k_i,t) \le ws(k_j,t)$ for $i < j$



  – A more operational definition – instead of k reference pages, t msec of execution time

Working set algorithm

- Working set and page replacement
  - Victim – a page *not* in the working set
- At each clock interrupt – scan the page table
  - R = 1? Write Current Virtual Time (CVT) into *Time of Last Use*
  - R = 0? CVT – *Time of Last Use > Threshold ? out!* else see if there's some other page and evict oldest (w/ R=0)
  - If all are in the working set (all R = 1), random, preferably clean

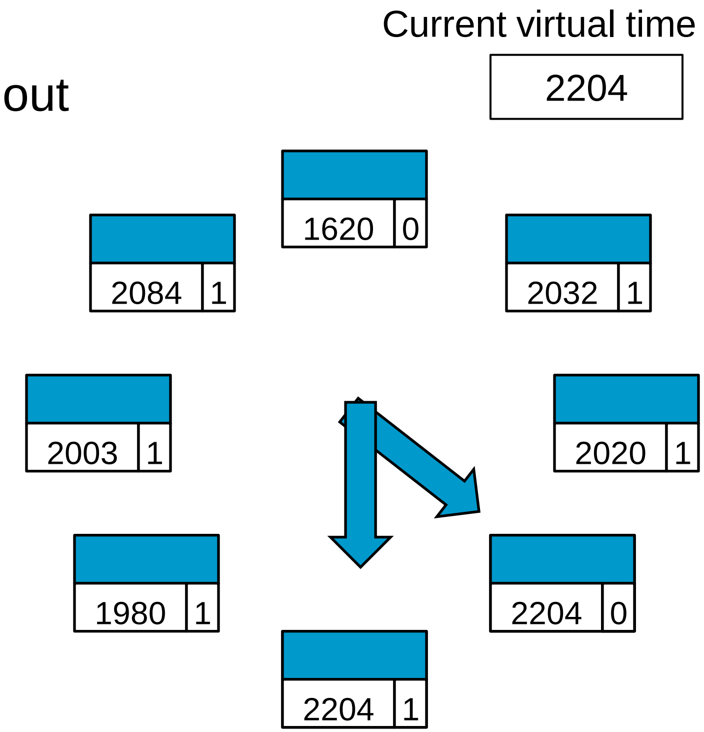


WSClock algorithm

- Problem with WS algorithm – Scans the whole table
- Instead, scan only what you need to find a victim
- Combine clock & working set
  - If R = 1, unset it
  - If R = 0, if age > T and page clean, out
  - If dirty, schedule write and check next one
  - If loop around,

    There's 1+ write scheduled – you'll have a clean page soon

    There's none, pick any one



R = 0 & 2204 – 1213 > T

Cleaning policy

- To avoid having to write pages out when needed – paging daemon
  - Periodically inspects state of memory
  - Keep enough pages free
  - If we need the page before it's overwritten – reclaim it!
- Two hands for better performance (BSD)
  - First one clears R, second checks it
  - If hands are kept close, only heavily used pages have a chance
  - If back is just ahead of front hand (359 degrees), original clock
  - Two key parameters, adjusted at runtime
    - Scanrate – rate at which hands move through the list
    - Handspread – gap between them

Design issues – global vs. local policy

- When you need a page frame, pick a victim from
  – Among your own resident pages – Local
  – Among all pages – Global
- Local algorithms
  – Basically every process gets a fixed % of memory
- Global algorithms
  – Dynamically allocate frames among processes
  – Better, especially if working set size changes at runtime
  – How many page frames per process?
    • Start with basic set & react to Page Fault Frequency (PFF)
- Most replacement algorithms can work both ways except for those based on working set

Why not working set based algorithms?

Load control

- Despite good designs, system may still thrash
  - Sum of working sets > physical memory
- Page Fault Frequency (PFF) indicates that
  - Some processes need more memory
  - but no process needs less
- Way out: Swapping
  - So yes, even with paging you still need swapping
  - Reduce number of processes competing for memory
  - ~ two-level scheduling – careful with which process to swap out (there's more than just paging to worry about!)

  What would you like of the remaining processes?

Next time …

- We'll now consider design & implementation issues for paging systems
  - Things you want/need to pay attention for good performance