CSCE 451/851
Operating Systems Principles

Page Replacement Algorithms

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Virtual Memory Management
Fundamental issues

- Placement strategy
- Replacement strategies
- Load control strategies

Example: *Demand paging*

» No placement strategy required *per se*
» Load control: load pages only when faults occur
» Replacement: ...

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Page Replacement Algorithms
Concept

- Typically $\Sigma_i |VAS_i|$ >> *Physical Memory*
- With demand paging, physical memory fills quickly
- So when a process faults & memory is full, some page must be swapped out

  (So handling a page fault now requires ***2*** disk accesses not 1!)
- Which page should be replaced?
  - » *Local replacement* — replace a page of the faulting process
  - » *Global replacement* — possibly replace the page of another process

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Page Replacement Algorithms
Evaluation methodology

- Record a *trace* of pages accessed by a process
  - » Example: (Virtual) address trace...

    (3,0), (1,9), (4,1), (2,1), (5,3), (2,0), (1,9), (2,4), (3,1), (4,8)
  - » ... generates page trace

    3, 1, 4, 2, 5, 2, 1, 2, 3, 4 (represented as *c*, *a*, *d*, *b*, *e*, *b*, *a*, *b*, *c*, *d*)
- Simulate the behavior of a page replacement algorithm on the trace & record the number of page faults generated
  - » *fewer faults == better performance*

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Local Page Replacement
FIFO replacement

- Simple to implement
  - » A single pointer suffices
- Performance with 4 page frames:

Page Trace

Time		0	1	2	3	4	5	6	7	8	9	10
Requests			*c*	*a*	*d*	*b*	*e*	*b*	*a*	*b*	*c*	*d*
Page Frames	0	*a*	*a*	*a*	*a*	*a*	***e***	*e*	*e*	*e*	*e*	***d***
	1	*b*	*b*	*b*	*b*	*b*	*b*	*b*	***a***	*a*	*a*	*a*
	2	*c*	*c*	*c*	*c*	*c*	*c*	*c*	*c*	***b***	*b*	*b*
	3	*d*	*d*	*d*	*d*	*d*	*d*	*d*	*d*	*d*	***c***	*c*
Faults							•		•	•	•	•

Optimal Page Replacement
Clairvoyant replacement

- Replace the page that won't be needed for the longest time in the future

Time		0	1	2	3	4	5	6	7	8	9	10
Requests			*c*	*a*	*d*	*b*	*e*	*b*	*a*	*b*	*c*	*d*
Page Frames	0	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*	***d***
	1	*b*	*b*	*b*	*b*	*b*	*b*	*b*	*b*	*b*	*b*	*b*
	2	*c*	*c*	*c*	*c*	*c*	*c*	*c*	*c*	*c*	*c*	*c*
	3	*d*	*d*	*d*	*d*	*d*	***e***	*e*	*e*	*e*	*e*	*e*
Faults							•					•
Time page needed next						*a* = 7 *b* = 6 *c* = 9 *d* = 10						*a* = 15 *b* = 11 *c* = 13 *d* = 14

Least Recently Used Replacement
"Back to the future"

- Replace the page that hasn't been referenced for the longest time
  - » Use the recent past as a predictor of the future

Time		0	1	2	3	4	5	6	7	8	9	10
Requests			*c*	*a*	*d*	*b*	*e*	*b*	*a*	*b*	*c*	*d*
Page Frames	0	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*
	1	*b*	*b*	*b*	*b*	*b*	*b*	*b*	*b*	*b*	*b*	*b*
	2	*c*	*c*	*c*	*c*	*c*	***e***	*e*	*e*	*e*	*e*	***d***
	3	*d*	*d*	*d*	*d*	*d*	*d*	*d*	*d*	*d*	***c***	*c*
Faults							•				•	•
Time page last used						*a* = 2 *b* = 4 *c* = 1 *d* = 3				*a* = 7 *b* = 8 *e* = 5 *d* = 3	*a* = 7 *b* = 8 *e* = 5 *c* = 9	

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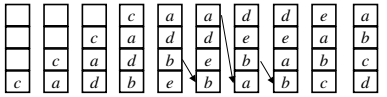
Least Recently Used Replacement
Implementation

- Maintain a "stack" of recently used pages

Time		0	1	2	3	4	5	6	7	8	9	10
Requests			*c*	*a*	*d*	*b*	*e*	*b*	*a*	*b*	*c*	*d*
Page Frames	0	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*
	1	*b*	*b*	*b*	*b*	*b*	*b*	*b*	*b*	*b*	*b*	*b*
	2	*c*	*c*	*c*	*c*	*c*	***e***	*e*	*e*	*e*	*e*	***d***
	3	*d*	*d*	*d*	*d*	*d*	*d*	*d*	*d*	*d*	***c***	*c*
Faults							•				•	•

LRU Page Stack



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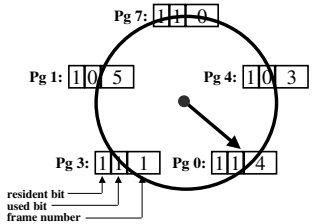
Approximate *LRU* Replacement
The *Clock* algorithm

- Maintain a circular list of pages resident in memory
  - » Use a *clock* (or *used*) bit to track how often a page is accessed — bit set whenever a page is referenced
- Clock sweeps over pages looking for one with used bit = 0
  - » Replaces pages that haven't been referenced for one complete revolution of the clock




```
func Clock_Replacement
begin
  while (page not found for replacement) do
    if (used bit for current page = 0) then
       replace current page
    else
       reset used bit
    end if
    advance clock pointer
  end while
end Clock_Replacement
```

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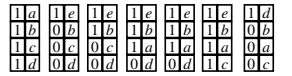
Clock Page Replacement
Example

Time	0	1	2	3	4	5	6	7	8	9	10
Requests		*c*	*a*	*d*	*b*	*e*	*b*	*a*	*b*	*c*	*d*
Page Frames 0	*a*	*a*	*a*	*a*	*a*	***e***	*e*	*e*	*e*	*e*	***d***
Page Frames 1	*b*	*b*	*b*	*b*	*b*	*b*	*b*	*b*	*b*	*b*	*b*
Page Frames 2	*c*	*c*	*c*	*c*	*c*	(*c*)	*c*	***a***	*a*	*a*	*a*
Page Frames 3	*d*	*d*	*d*	*d*	*d*	*d*	*d*	*d*	*d*	***c***	*c*
Faults						•		•		•	•

Page table entries for resident pages:



The LRU page

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Performance of Page Replacement Algorithms

- Least recently used
  - » Ages pages based on when they were last used
- FIFO
  - » Ages pages based on when they're brought into memory

The principle of locality

- 90% of the execution of a program is sequential
- Most interative constructs consist of a relatively small number of instructions
- When processing large data structures, the dominant cost is sequential processing on individual structure elements

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Belady's Anomaly
More memory ≠ Better performance!

FIFO Replacement

Time		0	1	2	3	4	5	6	7	8	9	10	11	12
Requests			*a*	*b*	*c*	*d*	*a*	*b*	*e*	*a*	*b*	*c*	*d*	*e*
Page Frames	0	*a*	*a*	*a*	*a*	***d***	*d*	*d*	***e***	*e*	*e*	*e*	*e*	*e*
	1	*b*	*b*	*b*	*b*	*b*	***a***	*a*	*a*	*a*	*a*	***c***	*c*	*c*
	2	*c*	*c*	*c*	*c*	*c*	*c*	***b***	*b*	*b*	*b*	*b*	***d***	*d*
Faults						•	•	•	•			•	•	

Page Frames	0	*a*	*a*	*a*	*a*	*a*	***e***	*e*	*e*	*e*	*e*	*e*	***d***	*d*
	1	*b*	*b*	*b*	*b*	*b*	*b*	*b*	*b*	***a***	*a*	*a*	*a*	***e***
	2	*c*	*c*	*c*	*c*	*c*	*c*	*c*	*c*	*c*	***b***	*b*	*b*	*b*
	3		***d***	*d*	*d*	*d*	*d*	*d*	*d*	*d*	*d*	***c***	*c*	*c*
Faults			•				•			•	•	•	•	•

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Explicitly Using Locality
The working set model of page replacement

- Assume recently referenced pages are likely to be referenced again soon...
- ... and only keep those pages recently referenced in memory (called *the working set*)
  - » pages may be removed even when no page fault occurs
  - » number of frames allocated to a process will vary over time
- A process is allowed to execute only if its working set fits into memory
  - » implicit load control

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Working Set Page Replacement
Implementation

- Keep track of the last τ references
  - » The pages referenced during the last τ memory accesses are the working set
  - » τ is called the *window size*
- Example: working set computation, $\tau = 4$ references:

	Time	0	1	2	3	4	5	6	7	8	9	10
	Requests		*c*	*c*	*d*	*b*	*c*	*e*	*c*	*e*	*a*	*d*
Pages in Memory	Page *a*	$p_{t=0}$	•	•	•	-	-	-	-	-	•	•
	Page *b*	-	-	-	-	•	•	•	•	-	-	-
	Page *c*	-	•	•	•	•	•	•	•	•	•	•
	Page *d*	$p_{t=-1}$	•	•	•	•	•	•	-	-	-	•
	Page *e*	$p_{t=-2}$	•	-	-	-	-	•	•	•	•	•
	Faults		•			•		•			•	•

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Optimal Page Replacement
For processes with a variable number of frames

- *VMIN* — Replace a page that is not referenced in the *next* τ accesses
- Example: $\tau = 4$

	Time	0	1	2	3	4	5	6	7	8	9	10
	Requests		*c*	*c*	*d*	*b*	*c*	*e*	*c*	*e*	*a*	*d*
Pages in Memory	Page *a*	•$_{t=0}$	-	-	-	-	-	-	-	-	•	-
	Page *b*	-	-	-	-	•	-	-	-	-	-	-
	Page *c*	-	•	•	•	•	•	•	•	-	-	-
	Page *d*	•$_{t=-4}$	•	•	•	-	-	-	-	-	-	•
	Page *e*	-	-	-	-	-	-	•	•	•	-	-
	Faults		•			•		•			•	•

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Page-Fault-Frequency Page Replacement
An alternate working set computation

- Explicitly attempt to minimize page faults
  - » When page fault frequency is high — *increase working set*
  - » When page fault frequency is low — *decrease working set*
- Algorithm:
  - » Keep track of the rate at which faults occur
    - ❖ Record the time, t_{last}, of the last page fault
  - » If the time between page faults is "large" then reduce working set
    - ❖ If $t_{current} - t_{last} > \tau$, then remove from memory all pages not referenced in $[t_{last}, t_{current}]$
  - » If the time between page faults is "small" then increase working set
    - ❖ If $t_{current} - t_{last} \leq \tau$, then add faulting page to the working set

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Page-Fault-Frequency Page Replacement
Example, window size = 2

- If $t_{current} - t_{last} > 2$, remove pages not referenced in $[t_{last}, t_{current}]$ from the working set
- If $t_{current} - t_{last} \leq 2$, add faulting page to the working set

	Time	0	1	2	3	4	5	6	7	8	9	10
	Requests		*c*	*c*	*d*	*b*	*c*	*e*	*c*	*e*	*a*	*d*
Pages in Memory	Page *a*	•	•	•	•	-	-	-	-	-	•	•
	Page *b*	-	-	-	-	•	•	•	•	•	-	-
	Page *c*	-	•	•	•	•	•	•	•	•	•	•
	Page *d*	•	•	•	•	•	•	•	•	•	-	•
	Page *e*	•	•	•	•	-	-	•	•	•	•	•
	Faults		•			•		•			•	•
	$t_{cur} - t_{last}$					3		2			3	1

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