

Memory Management – Swapping, Paging, and Virtual Memory

CS 111

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Operating System Principles

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How Much of Our Problem Have We Solved?

- We can use variable sized partitions
 - Cutting down on internal fragmentation
- We can move partitions around
 - Which helps coalescing be more effective
 - But segments still need contiguous chunks of memory
 - So external fragmentation is still a problem
- We still can't support more process data needs than we have physical memory

Outline

- Swapping
- Paging
- Virtual memory

Swapping

- What if we don't have enough RAM?
 - To handle all processes' memory needs
 - Perhaps even to handle one process
- Maybe we can keep some of their memory somewhere other than RAM
- Where?
- Maybe on a disk (hard or flash)
- Of course, you can't directly use code or data on a disk . . .

Swapping To Disk

- An obvious strategy to increase effective memory size
- When a process yields or is blocked, copy its memory to disk
- When it is scheduled, copy it back
- If we have relocation hardware, we can put the memory in different RAM locations
- Each process could see a memory space as big as the total amount of RAM

Downsides To Simple Swapping

- If we actually move everything out, the costs of a context switch are very high
 - Copy all of RAM out to disk
 - And then copy other stuff from disk to RAM
 - Before the newly scheduled process can do anything
- We're still limiting processes to the amount of RAM we actually have

Paging

- What is paging?
 - What problem does it solve?
 - How does it do so?
- Paged address translation
- Paging and fragmentation
- Paging memory management units

Segmentation Revisited

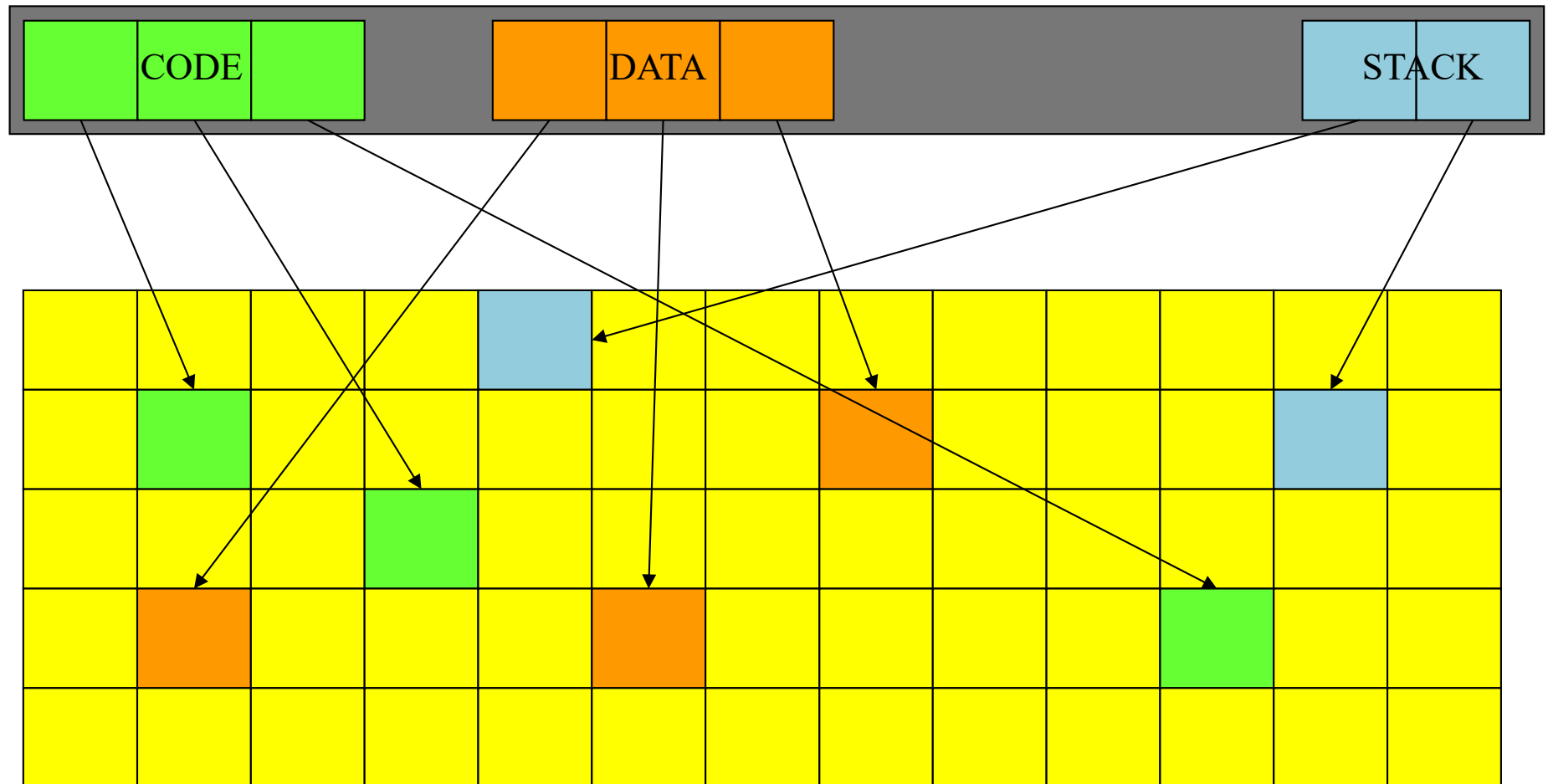
- Segment relocation solved the relocation problem for us
- It used base registers to compute a physical address from a virtual address
 - Allowing us to move data around in physical memory
 - By only updating the base register
- It did nothing about external fragmentation
 - Because segments are still required to be contiguous
- We need to eliminate the “contiguity requirement”

The Paging Approach

- Divide physical memory (RAM) into units of a single fixed size
 - A pretty small one, like 1-4K bytes or words
 - Typically called a *page frame*
- Treat the virtual address space in the same way
 - Call each virtual unit a *page*
- For each virtual address space page, store its data in one physical address page frame
 - Any page frame, not one specific to this page
- Use some magic per-page translation mechanism to convert virtual to physical pages

Paged Address Translation

process virtual address space



physical memory

Paging and Fragmentation

- A segment is implemented as a set of virtual pages



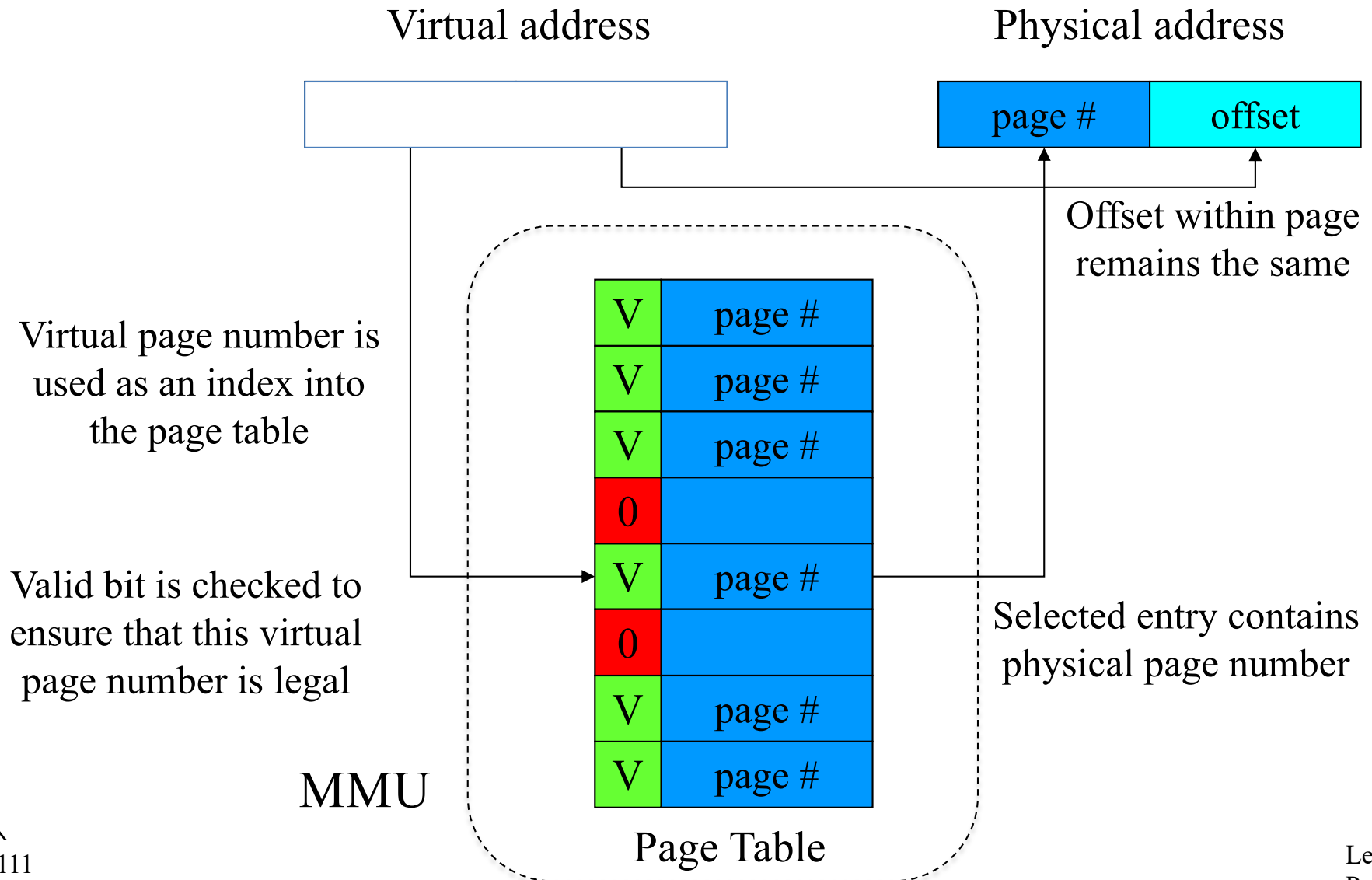
- Internal fragmentation
 - Averages only $\frac{1}{2}$ page (half of the last one)
- External fragmentation
 - Completely non-existent
 - We never carve up pages

Tremendous
reduction in
fragmentation costs!

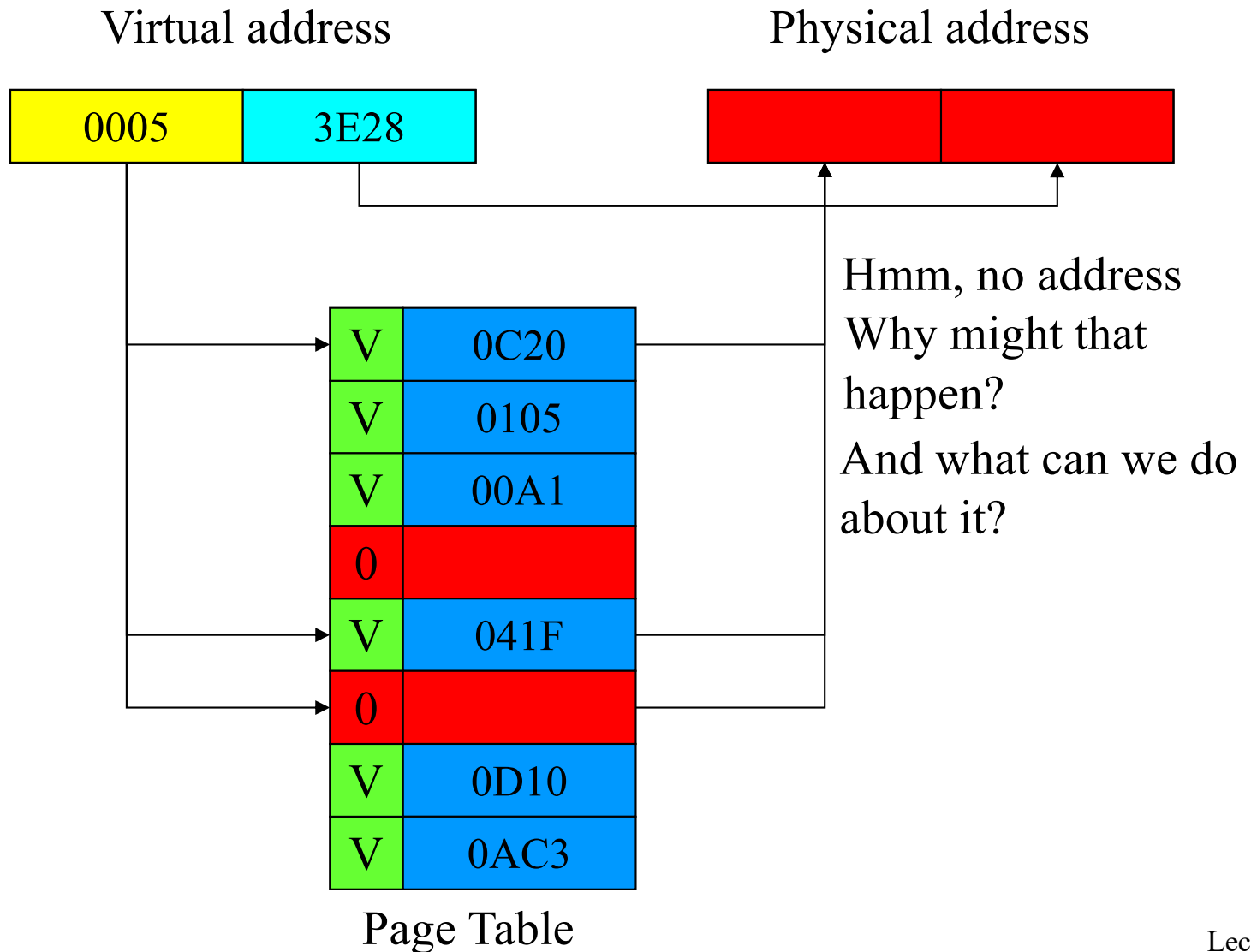
Providing the Magic Translation Mechanism

- On per page basis, we need to change a virtual address to a physical address
 - On every memory reference
- Needs to be fast
 - So we'll use hardware
- The Memory Management Unit (MMU)
 - A piece of hardware designed to perform the magic quickly

Paging and MMUs



Some Examples



The MMU Hardware

- MMUs used to sit between the CPU and bus
 - Now they are typically integrated into the CPU
- What about the page tables?
 - Originally implemented in special fast registers
 - But there's a problem with that today
 - If we have 4K pages, and a 64 Gbyte memory, how many pages are there?
 - $2^{36}/2^{12} = 2^{24}$
 - Or 16 M of pages
 - We can't afford 16 M of fast registers

Handling Big Page Tables

- 16 M entries in a page table means we can't use registers
- So now they are stored in normal memory
- But we can't afford 2 bus cycles for each memory access
 - One to look up the page table entry
 - One to get the actual data
- So we have a very fast set of MMU registers used as a cache
 - Which means we need to worry about hit ratios, cache invalidation, and other nasty issues
 - TANSTAAFL

The MMU and Multiple Processes

- There are several processes running
- Each needs a set of pages
- We can put any page anywhere
- But if they need, in total, more pages than we've physically got,
 - Something's got to go
- How do we handle these ongoing paging requirements?

Where Do We Keep Extra Pages?

- We have more pages than RAM page frames
- So some of them must be somewhere other than RAM
- Where else do we have the ability to store data?
- How about on our flash drive?
- In paged system, typically some pages are kept on persistent memory device
- But code can only access a page in RAM . . .

Ongoing MMU Operations

- What if the current process adds or removes pages?
 - Directly update active page table in memory
 - Privileged instruction to flush (stale) cached entries
- What if we switch from one process to another?
 - Maintain separate page tables for each process
 - Privileged instruction loads pointer to new page table
 - A reload instruction flushes previously cached entries
- How to share pages between multiple processes?
 - Make each page table point to same physical page
 - Can be read-only or read/write sharing

Demand Paging

- If we can't keep all our pages in RAM, some are out on disk
- But we can't directly use them on disk
- So which ones do we put out on disk?
- And how do we get them back if it turns out we need to use them?
- Demand paging is the modern approach to that problem

What Is Demand Paging?

- A process doesn't actually need all its pages in memory to run
- It only needs those it actually references
- So, why bother loading up all the pages when a process is scheduled to run?
- And, perhaps, why get rid of all of a process' pages when it yields?
- Move pages onto and off of disk “on demand”

How To Make Demand Paging Work

- The MMU must support “not present” pages
 - Generates an exception when they are referenced
 - OS can bring in the requested page and retry the faulted reference
- Entire process needn't be in memory to start running
 - Start each process with a subset of its pages
 - Load additional pages as program demands them
- The big challenge will be performance

Achieving Good Performance for Demand Paging

- Demand paging will perform poorly if most memory references require disk access
 - Worse than swapping in all the pages at once, maybe
- So we need to be sure most don't
- How?
- By ensuring that the page holding the next memory reference is already there
 - Almost always

Demand Paging and Locality of Reference

- How can we predict what pages we need in memory?
 - Since they'd better be there when we ask
- Primarily, rely on *locality of reference*
 - Put simply, the next address you ask for is likely to be close to the last address you asked for
- Do programs typically display locality of reference?
- Fortunately, yes!

Why is Locality of Reference Usually Present?

- Code usually executes sequences of consecutive or nearby instructions
 - Most branches tend to be relatively short distances (into code in the same routine)
- We typically need access to things in the current or previous stack frame
- Many heap references to recently allocated structures
 - E.g., creating or processing a message
- No guarantees, but all three types of memory are likely to show locality of reference

Page Faults

- Page tables no longer necessarily contain pointers to RAM page frames
- In some cases, the pages are not in RAM, at the moment
 - They're out on disk (hard or flash)
- When a program requests an address from such a page, what do we do?
- Generate a *page fault*
 - Which is intended to tell the system to go get it
 - A type of exception

A Page Fault Example

Virtual address

0005	3E28
------	------

Physical address

--	--

V	0C20
V	0105
V	00A1
0	
V	041F
0	
V	0D10
V	0AC3

Page Table

Hmm, no address
Why might that
happen?
PAGE FAULT!

Now what . . . ?

Handling a Page Fault

- Initialize page table entries to “not present”
- CPU faults if “not present” page is referenced
 - Fault enters kernel, just like any other exception
 - Forwarded to page fault handler
 - Determine which page is required, where it resides
 - Schedule I/O to fetch it, then block the process
 - Make page table entry point to newly read-in page
 - Back up user-mode PC to retry failed instruction
 - Return to user-mode and try again
- Meanwhile, other processes can run

Page Faults Don't Impact Correctness

- Page faults only slow a process down
- After a fault is handled, the desired page is in RAM
- And the process runs again and can use it
 - Based on the OS ability to save process state and restore it
- Programs never crash because of page faults
- But they might be very slow if there are too many

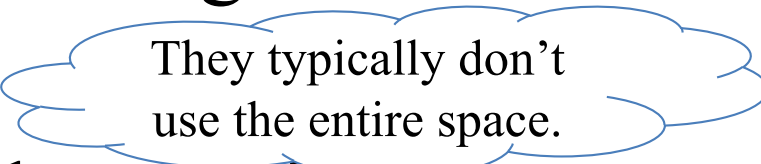
Demand Paging Performance

- Page faults may block processes
- Overhead (fault handling, paging in and out)
 - Process is blocked while we are reading in pages
 - Delaying execution and consuming cycles
 - Directly proportional to the number of page faults
- Key is having the “right” pages in memory
 - Right pages -> few faults, little paging activity
 - Wrong pages -> many faults, much paging
- We can't control which pages we read in
 - Key to performance is choosing which to kick out

Virtual Memory

- A generalization of what demand paging allows
- A form of memory where the system provides a useful abstraction
 - A very large quantity of memory
 - For each process
 - All directly accessible via normal addressing
 - At a speed approaching that of actual RAM
- The state of the art in modern memory abstractions

The Basic Concept

- Give each process an address space of immense size
 - Perhaps as big as word size allows
 - Or half that big . . .
- Allow processes to request segments within that space
 - • •
- Use dynamic paging and swapping to support the abstraction
- The key issue is how to create the abstraction when you don't have that much real memory

The Key VM Technology: Replacement Algorithms

- The goal is to have each page already in memory when a process accesses it
- We can't know ahead of time what pages will be accessed
- We rely on locality of access
 - In particular, to determine which pages to move out of memory and onto disk
- If we make wise choices, the pages we need in memory will still be there

The Basics of Page Replacement

- We keep some set of all pages in memory
 - As many as will fit
 - Probably not all belonging to a single process
- Under some circumstances, we need to replace one of them with another page that's on disk
 - E.g., when we have a page fault
- Paging hardware and MMU translation allows us to choose any page for ejection to disk
- Which one of them should go?

The Optimal Replacement Algorithm

- Replace the page that will be next referenced furthest in the future
- Why is this the right page?
 - It delays the next page fault as long as possible
 - Fewer page faults per unit time = lower overhead
- A slight problem:
 - We would need an *oracle* to know which page this algorithm calls for
 - And we don't have one

Oracles are systems that perfectly predict the future.

Do We Require Optimal Algorithms?

- Not absolutely
- What's the consequence being wrong?
 - We take an extra page fault that we shouldn't have
 - Which is a performance penalty, not a program correctness penalty
 - Often an acceptable tradeoff
- The more often we're right, the fewer page faults we take
- For traces, we can run the optimal algorithm, comparing it to what we use when live

Approximating the Optimal

- Rely on locality of reference
- Note which pages have recently been used
 - Perhaps with extra bits in the page tables
 - Updated when the page is accessed
- Use this data to predict future behavior
- If locality of reference holds, the pages we accessed recently will be accessed again soon

Candidate Replacement Algorithms

- Random, FIFO
 - These are dogs, forget ‘em
- Least Frequently Used
 - Sounds better, but it really isn’t
- Least Recently Used
 - Assert that near future will be like the recent past
 - If we haven’t used a page recently, we probably won’t use it soon
 - How to actually implement LRU?

Naïve LRU

- Each time a page is accessed, record the time
- When you need to eject a page, look at all timestamps for pages in memory
- Choose the one with the oldest timestamp
- Will require us to store timestamps somewhere
- And to search all timestamps every time we need to eject a page

With 64 Gbytes of RAM and 4K pages, 16 megabytes of timestamps – sounds expensive.

True LRU Page Replacement

Reference stream

a	b	c	d	a	b	d	e	f	a	b	c	d	a	e	d
---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---

Page table using true LRU

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
frame 0	a 0				a 4				f 8				d 12			d 15
frame 1		b 1				b 5				a 9				a 13		
frame 2			c 2					e 7				c 11				
frame 3				d 3			d 6				b 10				e 14	

Loads 4
Replacements 7

Maintaining Information for LRU

- Can we keep it in the MMU?
 - MMU would note the time whenever a page is referenced
 - But MMU translation must be blindingly fast
 - Getting/storing time on every fetch would be very expensive
 - At best MMU will maintain a *read* and a *written* bit per page
- Can we maintain this information in software?
 - Complicated and time consuming
 - If we maintain real timestamps, multiple overhead instructions for each real memory reference
- We need a cheap software surrogate for LRU
 - No extra instructions per memory reference
 - Mustn't cause extra page faults
 - Can't scan entire list each time on replacement, since it's big

Clock Algorithms

Remember
guess pointers
from Next Fit
algorithm?

- A surrogate for LRU
- Organize all page frames in a circular list
- MMU sets a reference bit for the frame on access
- Scan whenever we need another page
 - For each frame, ask MMU if frame's reference bit is set
 - If so, clear the reference bit in the MMU & skip this frame
 - If not, consider this page to be the least recently used
 - Next search starts from this position, not head of list
- Use position in the scan as a surrogate for age
- No extra page faults, usually scan only a few pages

Clock Algorithm Page Replacement

Reference Stream

a	b	c	d	a	b	d	e	f	a	b	c	d	a	e	d
---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---

LRU clock

0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15

frame 0

a				!	!	!	!	f				d			!
---	--	--	--	---	---	---	---	---	--	--	--	---	--	--	---

frame 1

	b				!	!	!		a				!	!	
--	---	--	--	--	---	---	---	--	---	--	--	--	---	---	--

frame 2

		c					e			b				e	
--	--	---	--	--	--	--	---	--	--	---	--	--	--	---	--

frame 3

			d			!	!	!			c				
--	--	--	---	--	--	---	---	---	--	--	---	--	--	--	--

clock

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

pos

loads 4, replacements 7

True LRU

frame 0

a				a
---	--	--	--	---

frame 1

	b			
--	---	--	--	--

frame 2

		c		
--	--	---	--	--

frame 3

			d	
--	--	--	---	--

Loads 4

Replacements 7

		d
--	--	---

a		
---	--	--

		c
--	--	---

	b	
--	---	--

		e
--	--	---

Comparing True LRU To Clock Algorithm

- Same number of loads and replacements
 - But didn't replace the same pages
- What, if anything, does that mean?
- Both are just approximations to the optimal
- If LRU clock's decisions are 98% as good as true LRU
 - And can be done for 1% of the cost (in hardware and cycles)



***It's a
bargain!***

Page Replacement and Multiprogramming

- We don't want to clear out all the page frames on each context switch
 - When switched-out process runs again, we don't want a bunch of page faults
- How do we deal with sharing page frames?
- Possible choices:
 - Single global pool
 - Fixed allocation of page frames per process
 - Working set-based page frame allocations

Single Global Page Frame Pool

- Treat the entire set of page frames as a shared resource
- Approximate LRU for the entire set
- Replace whichever process' page is LRU
- Probably a mistake
 - Bad interaction with round-robin scheduling
 - The guy who was last in the scheduling queue will find all his pages swapped out
 - And not because he isn't using them
 - When he's scheduled, lots of page faults

Per-Process Page Frame Pools

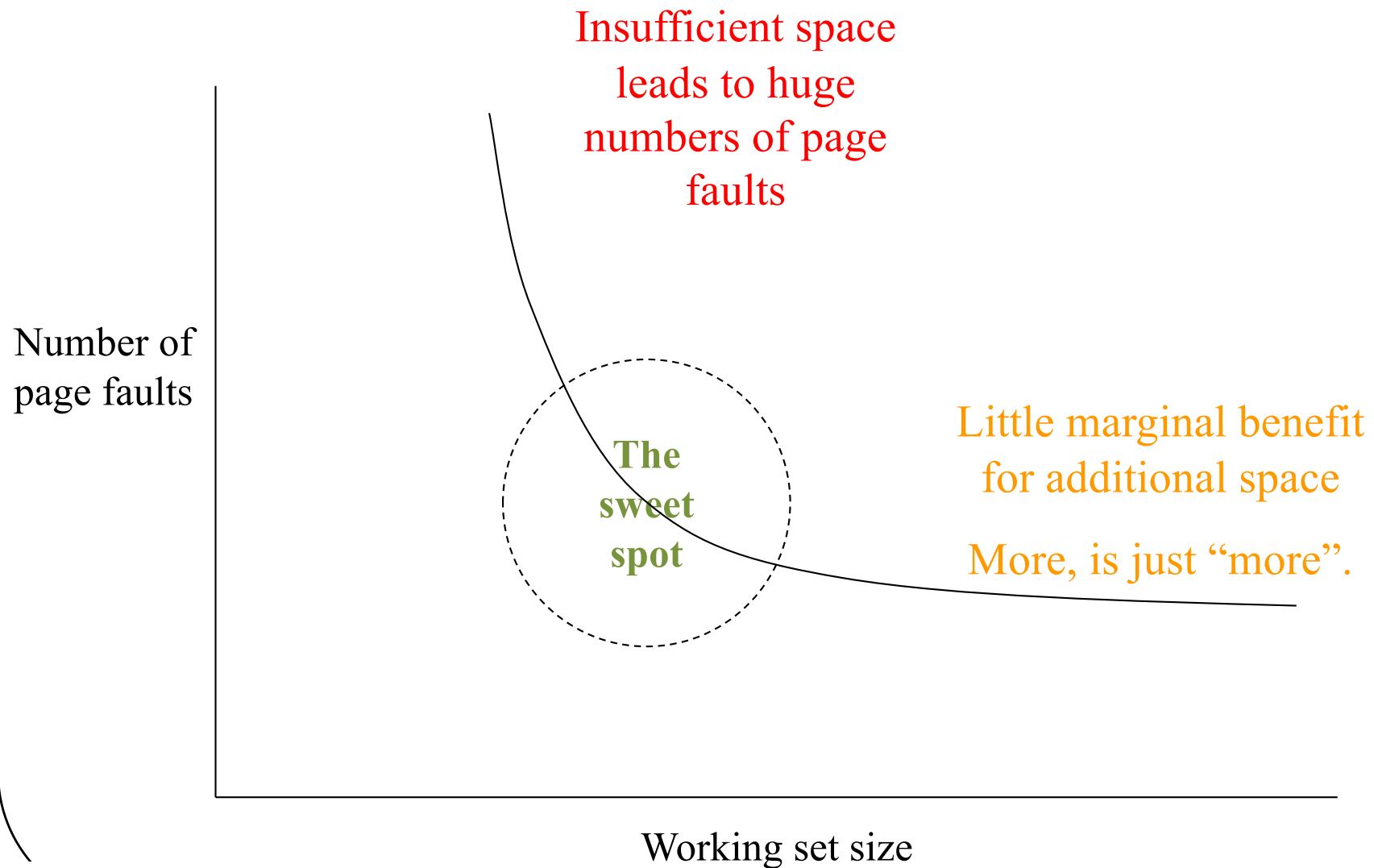
- Set aside some number of page frames for each running process
 - Use an LRU approximation separately for each
- How many page frames per process?
- Fixed number of frames per process is bad
 - Different processes exhibit different locality
 - Which pages are needed changes over time
 - Number of pages needed changes over time
 - Much like different natural scheduling intervals
- We need a dynamic customized allocation

Working Sets

- Give each running process an allocation of page frames matched to its needs
- How do we know what its needs are?
- Use *working sets*
- Set of pages used by a process in a fixed length sampling window in the immediate past¹
- Allocate enough page frames to hold each process' working set
- Each process runs replacement within its own set

¹This definition paraphrased from Peter Denning's definition

The Natural Working Set Size



Optimal Working Sets

- What is optimal working set for a process?
 - Number of pages needed during next time slice
- What if we run the process in fewer frames?
 - Needed pages will replace one another continuously
 - Process will run very slowly
- How can we know what working set size is?
 - By observing the process' behavior
- Which pages should be in the working-set?
 - No need to guess, the process will fault for them

Implementing Working Sets

- Manage the working set size
 - Assign page frames to each in-memory process
 - Processes page against themselves in working set
 - Observe paging behavior (faults per unit time)
 - Adjust number of assigned page frames accordingly
- *Page stealing* algorithms to adjust working sets
 - E.g., Working Set-Clock
 - Track last use time for each page, for owning process
 - Find page (approximately) least recently used (by its owner)
 - Processes that need more pages tend to get more
 - Processes that don't use their pages tend to lose them

Thrashing

- Working set size characterizes each process
 - How many pages it needs to run for τ milliseconds
- What if we don't have enough memory?
 - Sum of working sets exceeds available page frames
 - No one will have enough pages in memory
 - Whenever anything runs, it will grab a page from someone else
 - So they'll get a page fault soon after they start running
- This behavior is called *thrashing*
- When systems thrash, all processes run slow
- Generally continues till system takes action

Preventing Thrashing

- We usually cannot add more memory
- We cannot squeeze working set sizes
 - This will also cause thrashing
- We can reduce number of competing processes
 - Swap some of the ready processes out
 - To ensure enough memory for the rest to run
- Swapped-out processes won't run for quite a while
- But we can round-robin which are in and which are out

Clean Vs. Dirty Pages

- Consider a page, recently paged in from disk
 - There are two copies, one on disk, one in memory
- If the in-memory copy has not been modified, there is still an identical valid copy on disk
 - The in-memory copy is said to be “clean”
 - Clean pages can be replaced without writing them back to disk
- If the in-memory copy has been modified, the copy on disk is no longer up-to-date
 - The in-memory copy is said to be “dirty”
 - If paged out of memory, it must be written to disk

Dirty Pages and Page Replacement

- Clean pages can be replaced at any time
 - The copy on disk is already up to date
- Dirty pages must be written to disk before the frame can be reused
 - A slow operation we don't want to wait for
- Could only kick out clean pages
 - But that would limit flexibility
- How to avoid being hamstrung by too many dirty page frames in memory?

Pre-Emptive Page Laundering

- Clean pages give memory manager flexibility
 - Many pages that can, if necessary, be replaced
- We can increase flexibility by converting dirty pages to clean ones
- Ongoing background write-out of dirty pages
 - Find and write out all dirty, non-running pages
 - No point in writing out a page that is actively in use
 - On assumption we will eventually have to page out
 - Make them clean again, available for replacement

Conclusion

- Paging allows us to use RAM more efficiently
 - More processes runnable
- Virtual memory provides a good abstraction for programmers
 - But typically requires demand paging to work
- Key technology for VM is page replacement
- Working set approaches allow us to minimize page faults