

Memory Management: Paging and Virtual Memory

CS 111

Operating System Principles

Peter Reiher

Outline

- Paging
- Swapping and demand paging
- Virtual memory

Paging

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

Segmentation Revisited

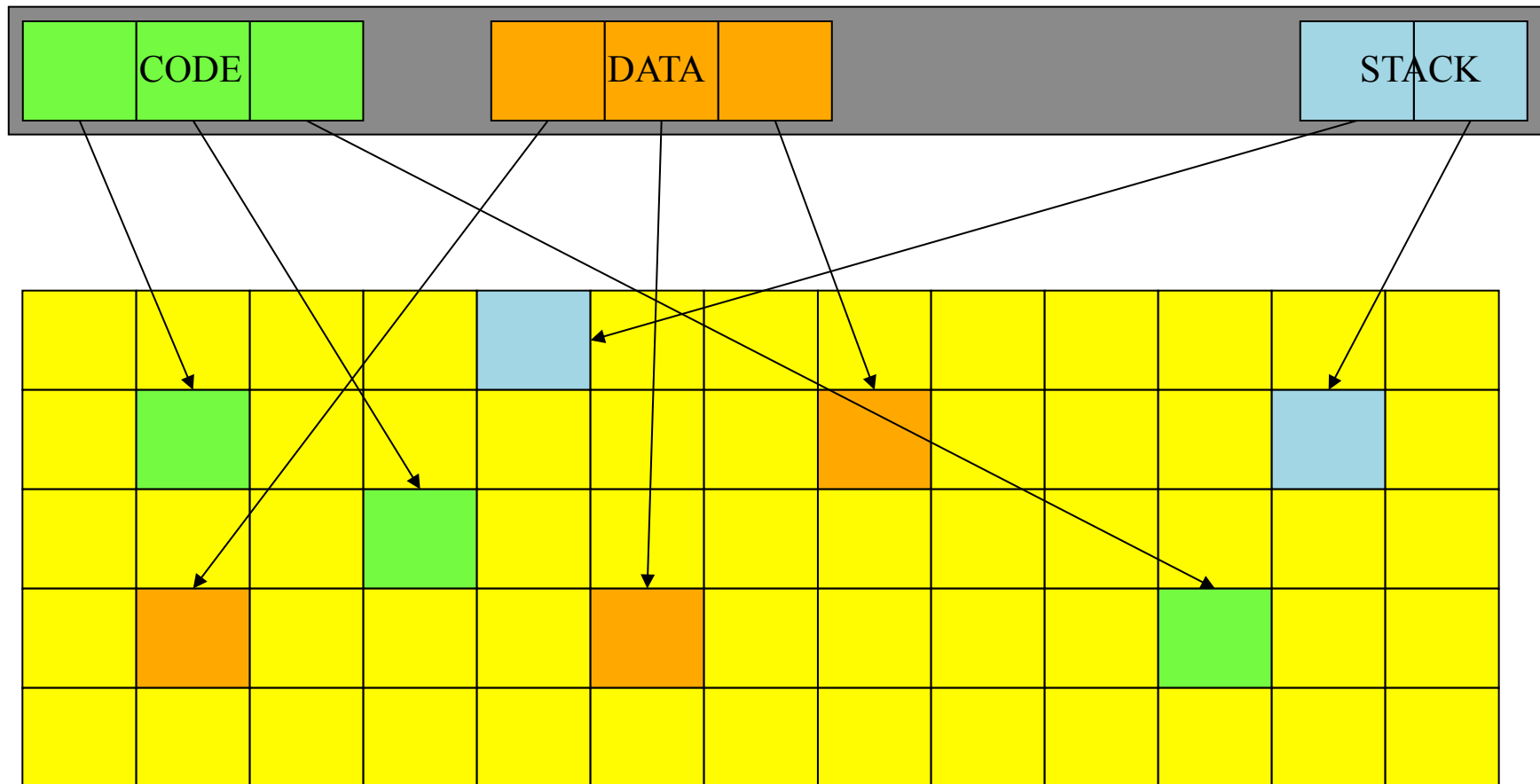
- Segment relocation solved the relocation problem for us
- It used base registers to compute a physical address from a virtual address
 - Allowing us to move data around in physical memory
 - By only updating the base register
- It did nothing about external fragmentation
 - Because segments are still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

The Paging Approach

- Divide physical memory 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
- For each virtual address space page, store its data in one physical address page frame
- Use some magic per-page translation mechanism to convert virtual to physical pages

Paged Address Translation

process virtual address space



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

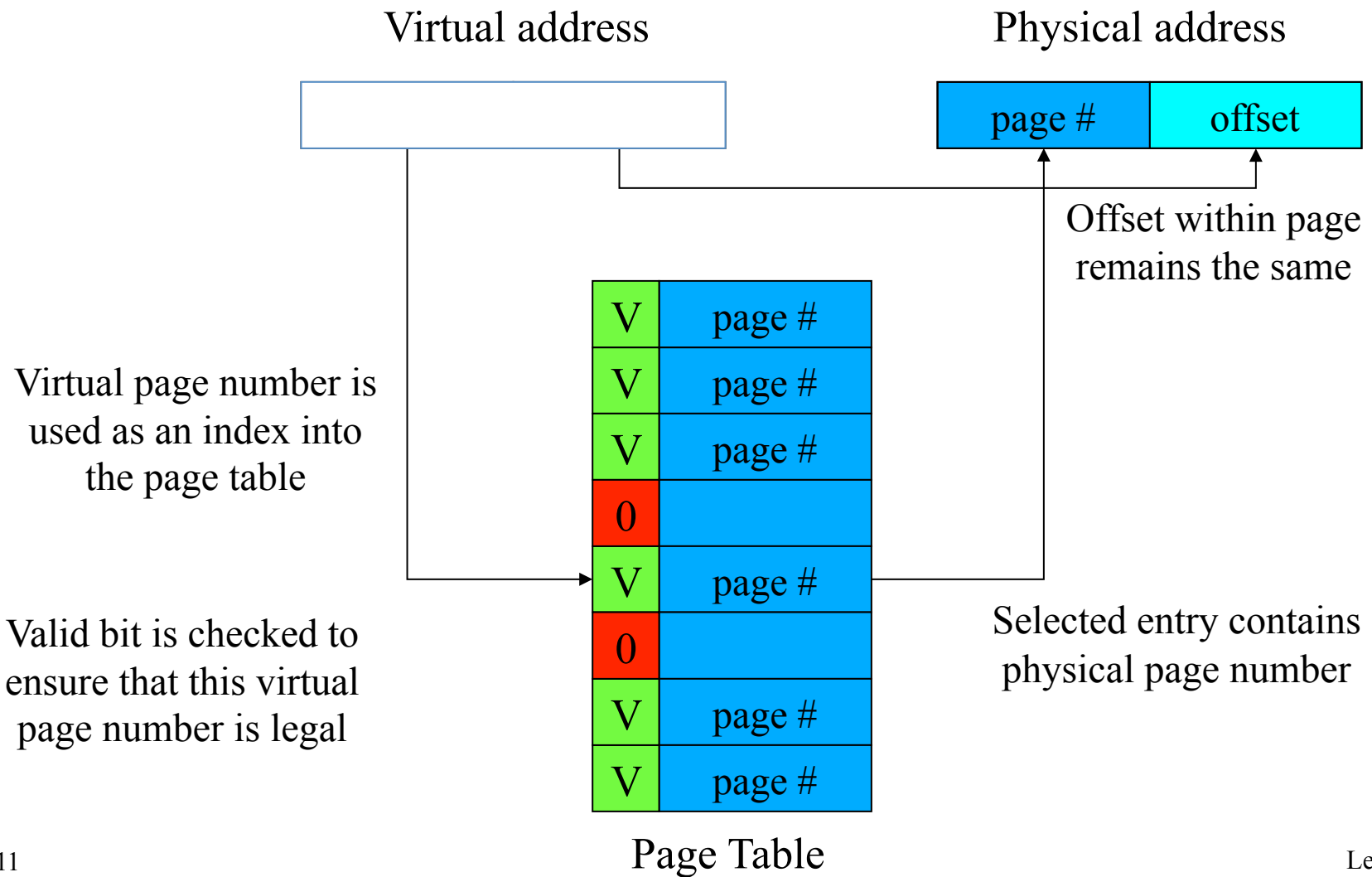
How Does This Compare To Segment Fragmentation?

- Consider this scenario:
 - Average requested allocation is 128K
 - For segmentation, 256K fixed size segments available
 - In the paging system, 4K pages
- For segmentation, average internal fragmentation is 50% (128K of 256K used)
- For paging?
 - Only the last page of an allocation is not full
 - On average, half of it is unused, or 2K
 - So 2K of 128K is wasted, or around 1.5%
- **Segmentation: 50% waste** • **Paging: 1.5% waste**

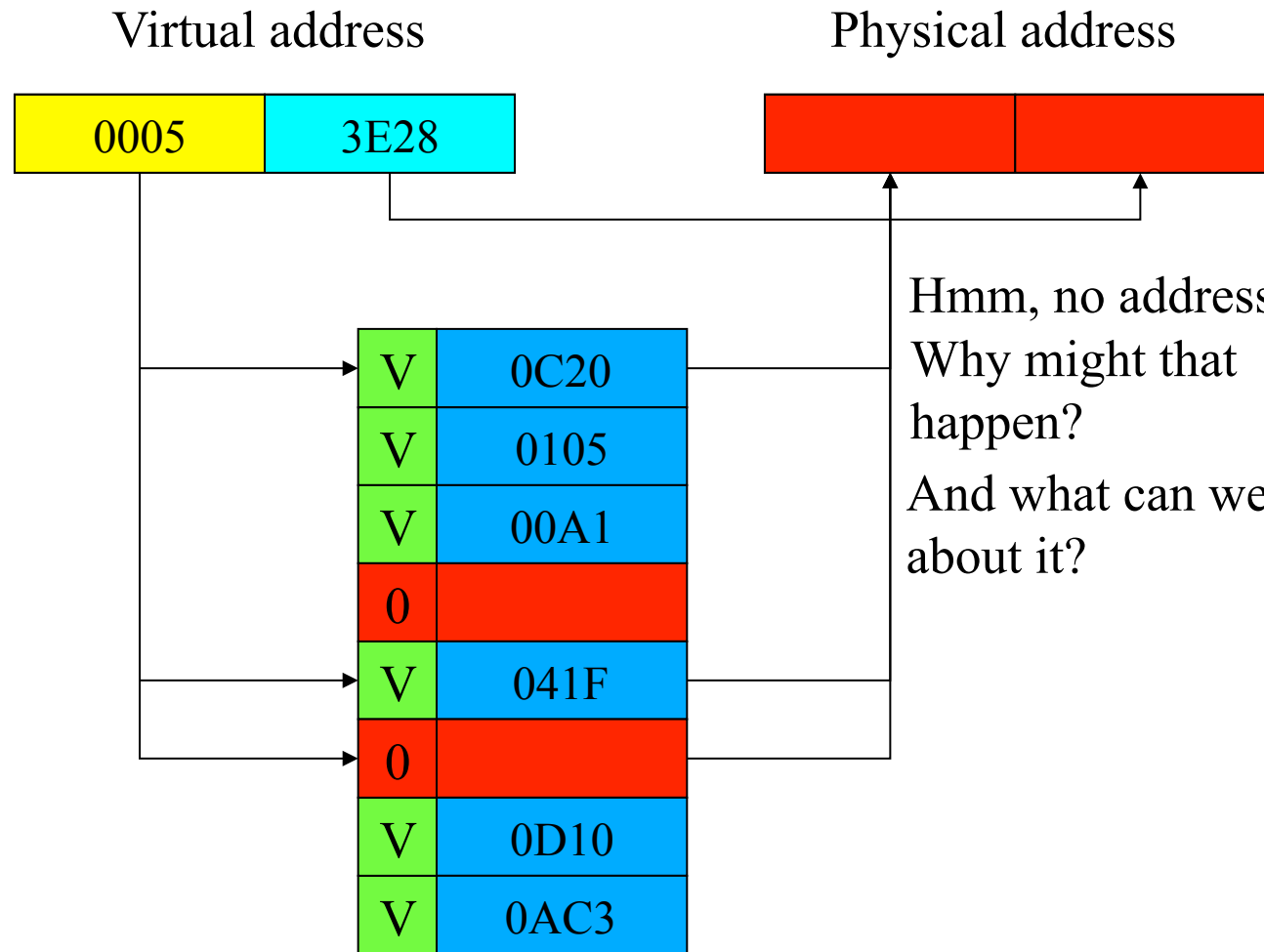
Providing the Magic Translation Mechanism

- On per page basis, we need to change a virtual address to a physical address
- 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 (Translation Lookaside Buffers, or TLB)
 - 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?

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 points to same physical page
 - Can be read-only or read/write sharing

So Is Paging Perfect?

- Pages are a very nice memory allocation unit
 - They eliminate internal and external fragmentation
 - They require a very simple but powerful MMU
- They are not a particularly natural unit of data
 - Programmers don't think in terms of pages
 - Programs are comprised of, and operate on, segments
 - Segments are the natural “chunks” of virtual address space
 - E.g., we map a new segment into the virtual address space
 - Each code, data, stack segment contains many pages

Paging and Segmentation

- We can use both segments and pages
- Programs request segments
 - Each code, data, stack segment contains many pages
- Requires two levels of memory management abstraction
 - A virtual address space is composed of segments
 - Relocation & swapping is done on a page basis
 - Segment based addressing, with page based relocation
- User processes see segments, paging is invisible

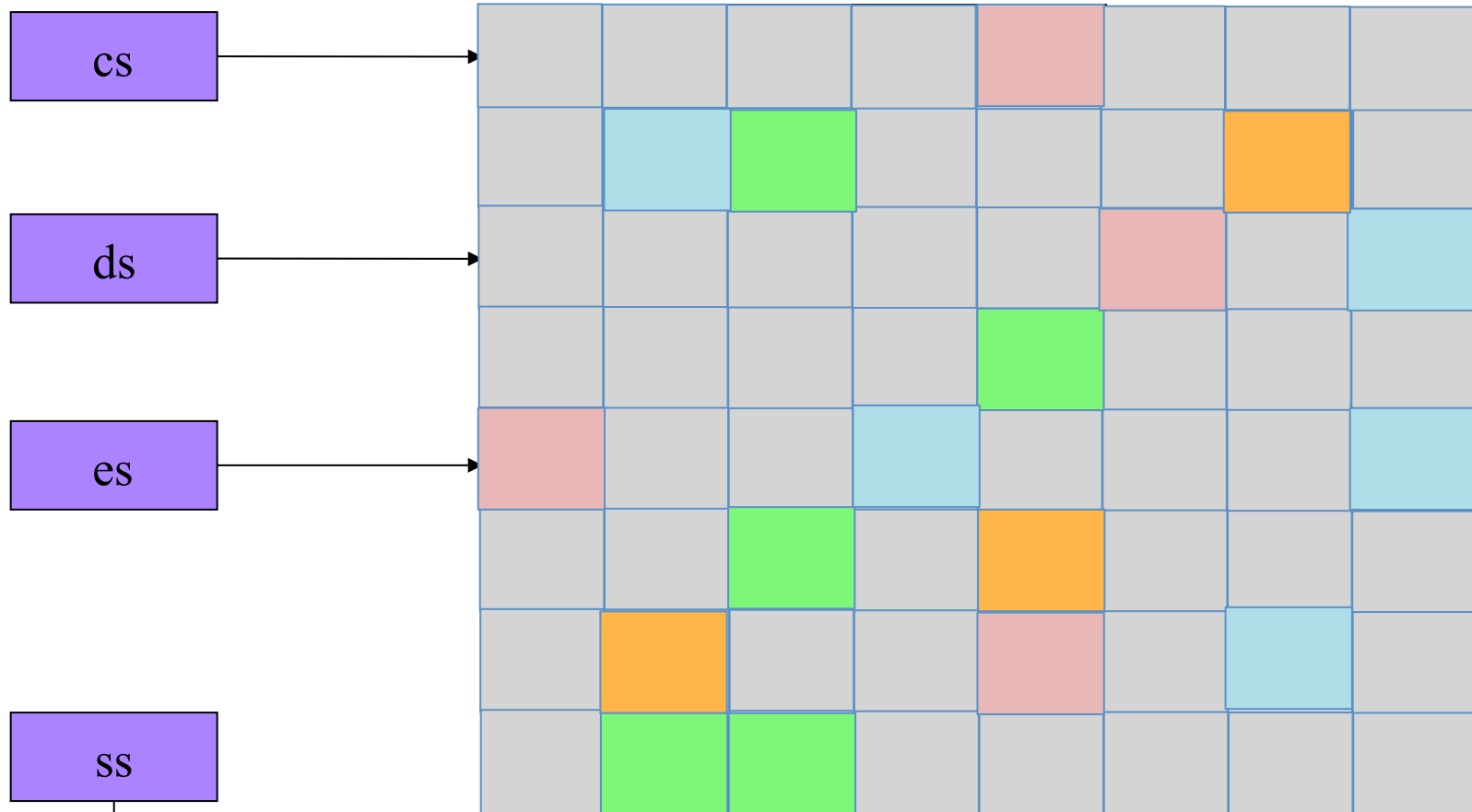
Relationships Between Segments and Pages

- A segment is a named collection of pages
- Operations on segments:
 - Create/open/destroy
 - Map/unmap segment to/from process
 - Find physical page number of virtual page n
- Connection between paging & segmentation
 - Segment mapping implemented with page mapping
 - Page faulting uses segments to find requested page

Segmentation on Top of Paging

Segment base registers

Process ~~physical~~ address space



Swapping

- Segmented paging allows us to have non-contiguous allocations
- But it still limits us to the size of physical RAM
- How can we avoid that?
- By keeping some segments somewhere else
- Where?
- Maybe on a disk

Swapping Segments To Disk

- An obvious strategy to increase effective memory size
- When a process yields, copy its segments to disk
- When it is scheduled, copy them back
- Paged segments mean we need not put any of this data in the same place as before yielding
- Each process could see a memory space as big as the total amount of RAM

Downsides To Segment 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

Demand Paging

- What is paging?
 - What problem does it solve?
 - How does it do so?
- Locality of reference
- Page faults and performance issues

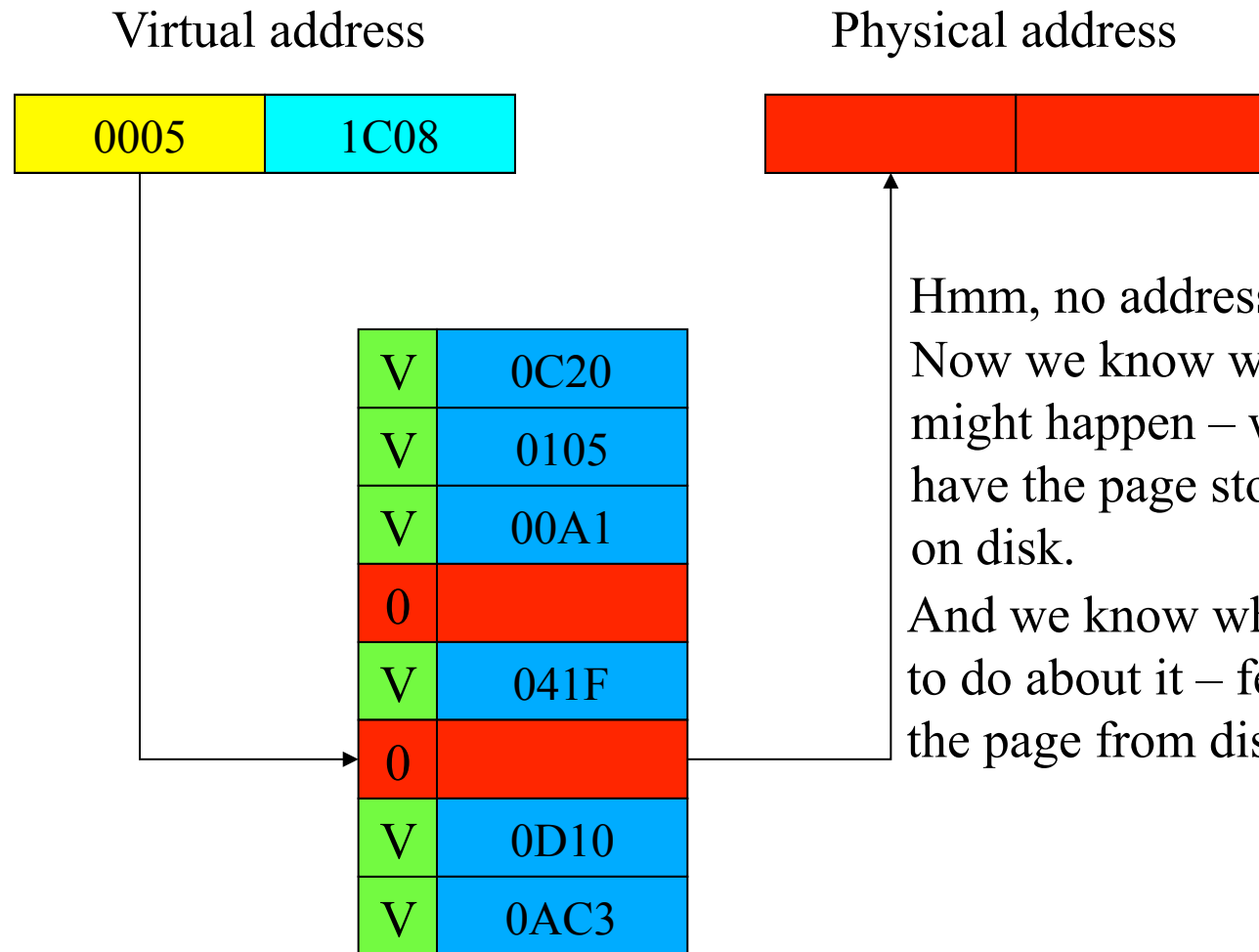
What Is Demand Paging?

- 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 a fault/trap when they are referenced
 - OS can bring in 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

Returning to Our Paging Example



Hmm, no address
Now we know why it
might happen – we
have the page stored
on disk.
And we know what
to do about it – fetch
the page from disk!

Achieving Good Performance for Demand Paging

- Demand paging will perform poorly if most memory references require disk access
 - Worse than bringing in all the pages at once, maybe
- So we need to be sure most references 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 which 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!

Instruction Locality of Reference

- Code usually executes sequences of consecutive instructions
- Most branches tend to be relatively short distances (into code in the same routine)
- Even routine calls tend to come in clusters
 - E.g., we'll do a bunch of file I/O, then we'll do a bunch of list operations

Stack Locality of Reference

- Obvious locality here
- We typically need access to things in the current stack frame
 - Either the most recently created one
 - Or one we just returned to from another call
- Since the frames usually aren't huge, obvious locality here

Heap Data Locality of Reference

- Many data references to recently allocated buffers or structures
 - E.g., creating or processing a message
- Also common to do a great deal of processing using one data structure
 - Before using another
- But more chances for non-local behavior than with code or the stack

Page Faults

- Page tables no longer necessarily contain pointers to pages of RAM
- In some cases, the pages are not in RAM, at the moment
 - They're out on disk
- 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

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 trap
 - 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 point at 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

Pages and Secondary Storage

- When not in memory, pages live on secondary storage
 - Typically a disk
 - In an area called “swap space”
- How do we manage swap space?
 - As a pool of variable length partitions?
 - Allocate a contiguous region for each process
 - As a random collection of pages?
 - Just use a bit-map to keep track of which are free
 - As a file system?
 - Create a file per process (or segment)
 - File offsets correspond to virtual address offsets

Swap Space and Segments

- Should the swap space be organized somehow by segments?
- A paging MMU eliminates need to store consecutive virtual pages in contiguous physical pages
- But locality of reference suggests pages in segments are likely to be used together
- Disk pays a big performance penalty particularly for spreading operations across multiple cylinders
- Well-clustered allocation may lead to more efficient I/O when we are moving pages in and out
- Organizing swap by segments can help

Demand Paging Performance

- Page faults may result in shorter time slices
 - Standard overhead/response-time tradeoff
- 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 what 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 your hardware's word size allows
- 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 what 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 possible pages in memory
 - Perhaps not all belonging to the current 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

Do We Require Optimal Algorithms?

- Not absolutely
- What's the consequence of the algorithm 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

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
- Least recently used is the best algorithm, lacking a true oracle

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
 - The computer science equivalent to the “*unseen hand*”

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

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				!				f				d			!
frame 1		b				!				a				!		
frame 2			c					e				c				
frame 3				d			!				b					e

Loads 4
Replacements 7

Maintaining Information for LRU

- Can we keep it in the MMU?
 - MMU notes the time whenever a page is referenced
 - MMU translation must be blindingly fast
 - Getting/storing time on every fetch would be very expensive
 - At best they will maintain a *read* and a *written* bit per page
- Can we maintain this information in software?
 - Mark all pages invalid, even if they are in memory
 - Take a fault first time each page is referenced, note the time
 - Then mark this page valid for the rest of the time slice
 - Causing page faults to reduce the number of page faults???
- We need a cheap software surrogate for LRU
 - No extra page faults
 - Can't scan entire list each time, since it's big

Clock Algorithms

- A surrogate for LRU
- Organize all pages in a circular list
- MMU sets a reference bit for the page on access
- Scan whenever we need another page
 - For each page, ask MMU if page has been referenced
 - If so, reset the reference bit in the MMU & skip this page
 - 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 pos	0	1	2	3	0	0	0	0	0	1	2	3	0	1	2	3

loads 4, replacements 7

True LRU

frame 0	a				a											d
frame 1		b												a		
frame 2			c				e					c				
frame 3				d		d				b					e	

Loads 4

Replacements 7

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 is a bargain!

Page Replacement and Multiprogramming

- We don't want to clear out all the page frames on each context switch
- 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 gets in, lots of page faults

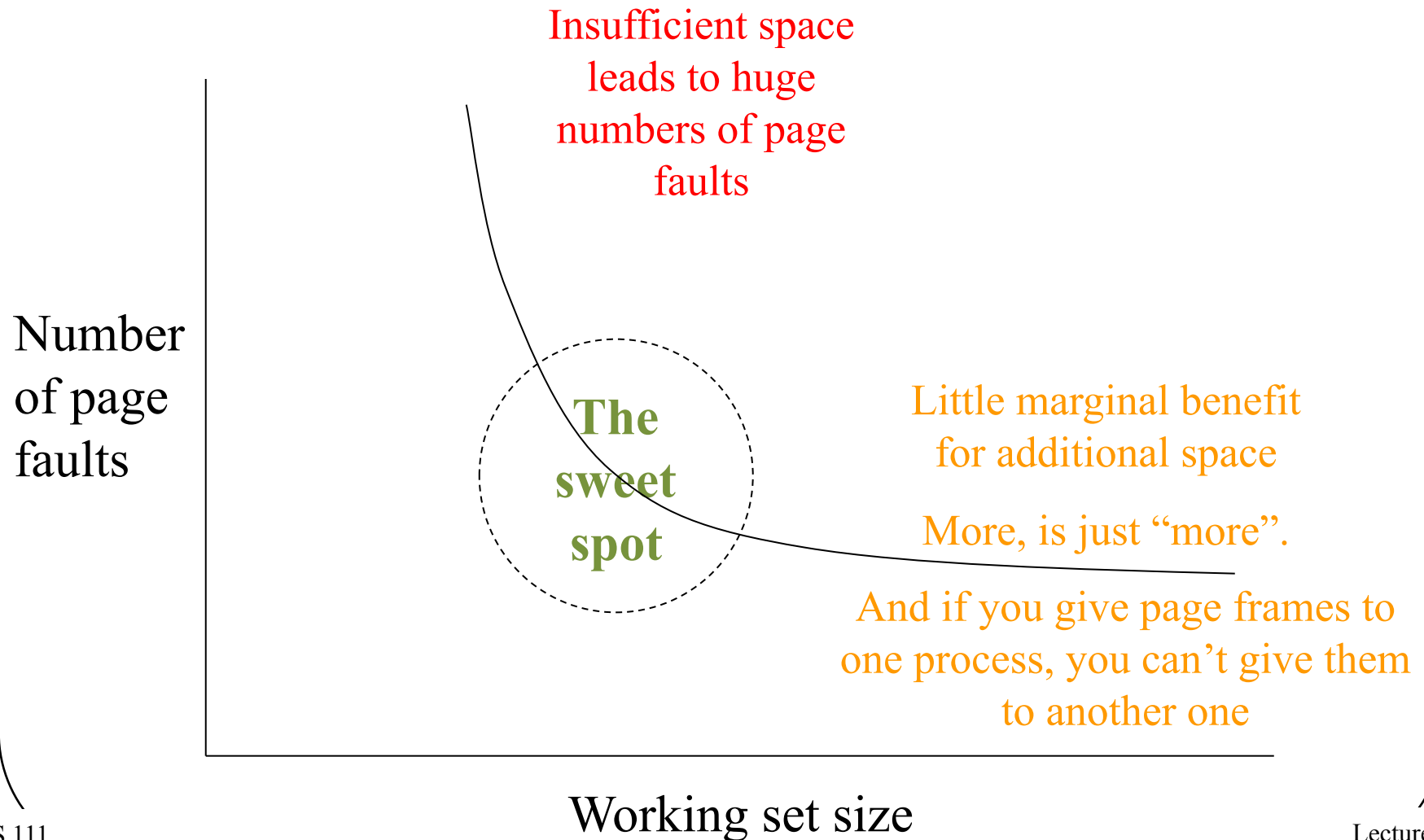
Per-Process Page Frame Pools

- 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 pages 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

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 pages?
 - Needed pages will replace one another continuously
 - This is called *thrashing*
- 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
 - Track last use time for each page, for owning process
 - Steal page least recently used (by its owner)
 - Approximately, for cost reasons
 - Processes that need more pages tend to get more
 - Processes that don't use their pages tend to lose them

Working Set Clock Algorithm

page frame	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
referenced	0	1	0	1	1	0	0	0	0	1	0	0	1	1	0
process	P ₀	P ₀	P ₁	P ₂	P ₂	P ₁	P ₁	P ₀	P ₂	P ₀	P ₁	P ₂	P ₀	P ₁	P ₂
last ref	15	51	69	65	80	15	75	33	72	54	23	25	45	25	47



Clock pointer

current execution times

P₀ = 55

P₁ = 75

P₂ = 80

t = 15

P₀ gets a fault

page 6 was just referenced

clear ref bit, update time

page 7 is (55-33=22) ms old

P₀ replaces his own page

Stealing a Page

Page
frame

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

referenced

0	1	0	1	1	0	0	0	0	0	0	0	1	1	0
---	---	---	---	---	---	---	---	---	---	---	---	---	---	---

process

P ₀	P ₀	P ₁	P ₂	P ₂	P ₁	P ₁	P ₀	P ₂	P ₀	P ₀	P ₂	P ₀	P ₁	P ₂
----------------	----------------	----------------	----------------	----------------	----------------	----------------	----------------	----------------	----------------	----------------	----------------	----------------	----------------	----------------

last ref

15	51	69	65	80	15	75	33	72	54		25	45	25	47
----	----	----	----	----	----	----	----	----	----	--	----	----	----	----

Clock pointer



current execution times

P₀ = 55

P₁ = 75

P₂ = 80

t = 25

P₀ has been experiencing
too many page faults
recently

P₀ gets a fault

page 6 was just referenced
page 7 is (55-33=22) ms old
page 8 is (80-72=8) ms old
page 9 is (55-54=1) ms old
page 10 is (75-23=52) ms old

P₀ steals this page from P₁

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 memory
 - We will thrash unless we do something
- We cannot squeeze working set sizes
 - This will also cause thrashing
- We can reduce the number of competing processes
 - Swap some of the ready processes out
 - To ensure enough memory for the rest to run
- We can round-robin who is in and out

Pre-Loading

- What happens when process comes in from disk?
- Pure swapping
 - All pages present before process is run, no page faults
- Pure demand paging
 - Pages are only brought in as needed
 - Fewer pages per process, more processes in memory
- What if we pre-loaded the last working set?
 - Far fewer pages to be read in than swapping
 - *Probably* the same disk reads as pure demand paging
 - Far fewer initial page faults than pure demand paging

Clean Vs. Dirty Pages

- Consider a page, recently brought 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 a 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 swapped out of memory, 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 swap 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 scheduler 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

• An outgoing equivalent of pre-loading