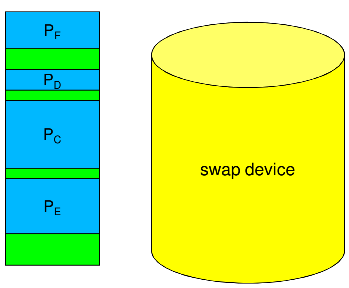
Memory Management

What to do when coalescing fails

- garbage collection is just another way to free
  - doesn't greatly help or hurt fragmentation
- ongoing activity can starve coalescing
  - chunks reallocated before neighbors become free
- we could stop accepting new allocations
  - convoy on memory manager would trash throughput
- we need a way to rearrange active memory
  - re-pack all processes in one end of memory
  - create one big chunk of free space at other end

Memory Compaction



The Need for Relocation

- Memory compaction moves a process
  - from where we originally loaded it to a new place
  - so we can compact the allocated memory
  - coalesce free space to cure external fragmentation
- But a program is full of addresses
  - conditional branches, subroutine calls
  - data addresses in the code, and in pointers
- We can't find/update all of these pointers
  - as we just saw with Garbage Collection

Why we swap

- make best use of a limited amount of memory
  - process can only execute if it is in memory
  - can't keep all processes in memory all the time
  - if it isn't READY, it doesn't need to be in memory
  - swap it out and make room for other processes
- improve CPU utilization
  - when there are no READY processes, CPU is idle
  - CPU idle time means reduced system throughput
  - more READY processes means better utilization

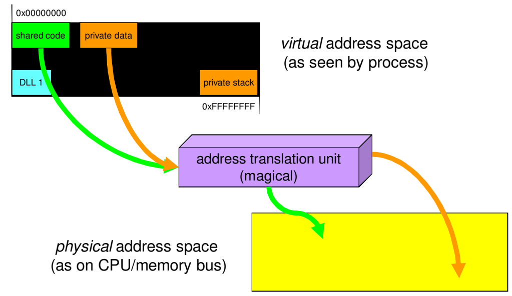
Pure Swapping

- each segment is contiguous
  - in memory, and on secondary storage
  - all in memory, or all on swap device
- swapping takes a great deal of time
  - transferring entire data (and text) segments
- swapping wastes a great deal of memory
  - processes seldom need the entire segment
- variable length memory/disk allocation
  - complex, expensive, external fragmentation

The Need for Dynamic Relocation

- there are a few reasons to move a process
  - needs a larger chunk of memory
  - swapped out, swapped back in to a new location
  - to compact fragmented free space
- all addresses in the program will be wrong
  - references in the code, pointers in the data
- it is not feasible to re-linkage edit the program
  - new pointers have been created during run-time

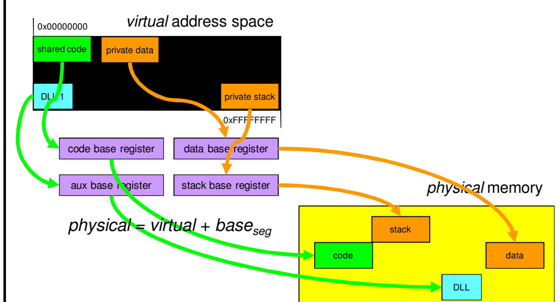
Virtual Address Translation



Segment Relocation

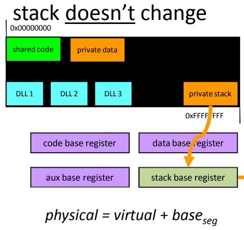
- a natural unit of allocation and relocation
  - process address space made up of segments
  - each segment is contiguous w/no holes
- CPU has segment base registers
  - point to (physical memory) base of each segment
  - CPU automatically relocates all references
- OS uses for virtual address translation
  - set base to region where segment is loaded
  - efficient: CPU can relocate every reference
  - transparent: any segment can move anywhere

Segment Relocation

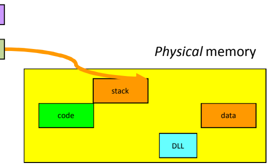


Moving a Segment

The virtual address of the stack doesn't change



Let's say we need to move the stack in physical memory



We just change the value in the stack base register

Privacy and Protection

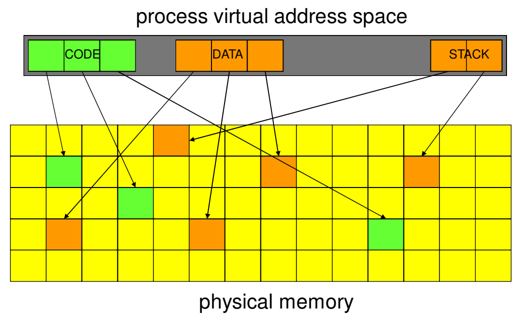
- confine process to its own address space
  - each segment also has a length/limit register
  - CPU verifies all offsets are within range
  - generates addressing exception if not
- protecting read-only segments
  - associate read/write access with each segment
  - CPU ensures integrity of read-only segments
- segmentation register update is privileged
  - only kernel-mode code can do this

Are Segments the Answer?

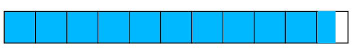
- a very natural unit of address space
  - variable length, contiguous data blobs
  - all-or-none with uniform r/w or r/o access
  - convenient/powerful virtual address abstraction
- but they are variable length
  - they require contiguous physical memory
  - ultimately leading to external fragmentation
  - requiring expensive swapping for compaction

… and in that moment he was enlightened …

paged address translation



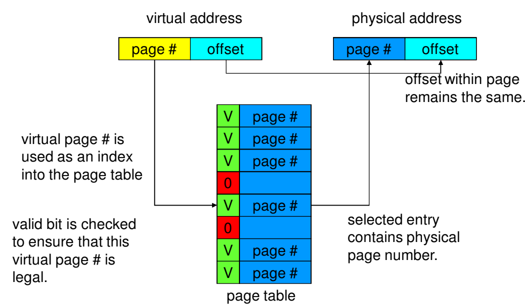
Paging and Fragmentation



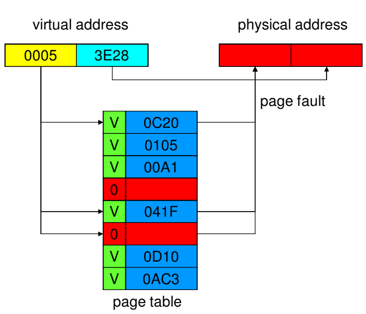
a segment is implemented as a set of virtual pages

- internal fragmentation
  - averages only ½ page (half of the last one)
- external fragmentation
  - completely non-existent (we never carve up pages)

Paging Memory Management Unit



Paging Relocation Examples



Swapping is Wasteful

- process does not use all its pages all the time
  - code and data both exhibit *reference locality*
  - some code/data may seldom be used
- keeping all pages in memory wastes space
  - more space/process = fewer processes in memory
- swapping them all in and out wastes time
  - longer transfers, longer waits for disk
- it arbitrarily limits the size of a process
  - process must be smaller than available memory

Loading Pages "On Demand"

- paging MMU supports *not present* pages
  - CPU access of *present* pages proceeds normally
- accessing *not present* page generates a trap
  - operating system can process this "*page fault*"
  - recognize that it is a request for another page
  - read that page in and resume process execution
- entire process needn't be in memory to run
  - start each process with a subset of its pages
  - load additional pages as program *demands* them

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Page Fault Handling

- initialize page table entries to *not present*
- CPU faults when invalid page is referenced
  1. trap forwarded to page fault handler
  2. determine which page, where it resides
  3. find and allocate a free page frame
  4. block process, schedule I/O to read page in
  5. update page table point at newly read-in page
  6. back up user-mode PC to retry failed instruction
  7. unblock process, return to user-mode
- Meanwhile, other processes can run

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Demand Paging – advantages

- improved system performance
  - fewer in-memory pages per process
  - more processes in primary memory
    - more parallelism, better throughput
    - better response time for processes already in memory
  - less time required to page processes in and out
  - less disk I/O means reduced queuing delays
- fewer limitations on process size
  - process can be larger than physical memory
  - process can have huge (sparse) virtual space

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Are Page Faults a Problem?

- Page faults should not affect correctness
  - after fault is handled, desired page is in RAM
  - process runs again, and can now use that page (assuming the OS properly saves/restores state)
- But programs might run <u>very</u> slowly
  - additional context switches waste available CPU
  - additional disk I/O wastes available throughput
  - processes are delayed waiting for needed pages
- We must minimize the number of page faults

Minimizing Number of Page Faults

- There are two ways:
  - keep the "right" pages in memory
  - give a process more pages of memory
- How do we keep "right" pages in memory?
  - we have no control over what pages we bring in
  - but we can decide which pages to evict
  - this is called "replacement strategy"
- How many pages does a process need?
  - that depends on which process and when
  - this is called the process' "working set"

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Belady's Optimal Algorithm

- Q: which page should we replace?
  A: the one we won't need for the longest time
- Why is this the right page?
  - it delays the next page fault as long as possible
  - minimum number of page faults per unit time
- How can we predict future references?
  - Belady cannot be implemented in a real system
  - but we can run implement it for test data streams
  - we can compare other algorithms against it

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Do we need an "Optimal" algorithm?

- Be very clear on what our goal is
  - we are not trying minimize the # of page faults
  - we are trying to minimize the cost of paging
- TANSTAAFL
  - we pay a price for every page fault
  - we also pay for every replacement decision
  - some decisions are more expensive than faults
  - we must do a cost/benefit analysis

Approximating Optimal Replacement

- note which pages have recently been used
  - use this data to predict future behavior
- Possible replacement algorithms
  - random, FIFO: straw-men ... forget them
- Least Recently Used
  - assert near future will be like recent past
    - programs do exhibit temporal and spatial locality
    - if we haven't used it recently, we probably won't soon
  - we don't have to be right 100% of the time
    - the more right we are, the more page faults we save

Why Programs Exhibit Locality

- Code locality
  - code in same routine is in same/adjacent page
  - loops iterate over the same code
  - a few routines are called repeatedly
  - intra-module calls are common
- Stack locality
  - activity focuses on this and adjacent call frames
- Data reference locality
  - this is common, but not assured

True LRU is hard to implement

- maintain this information in the MMU?
  - MMU notes the time, every time a page is referenced
  - maybe we can get a per-page read/written bit
- maintain this information in software?
  - mark all pages invalid, even if they are in memory
  - take a fault the first time each page is referenced
  - then mark this page valid for the rest of the time slice
- finding oldest page is prohibitively expensive
  - 16GB memory / 4K page = 4M pages to scan

Practical LRU surrogates

- must be cheap
  - can't cause additional page faults
  - avoid scanning the whole page table (it is big)
- clock algorithms ... a surrogate for LRU
  - organize all pages in a circular list
  - position around the list is a surrogate for age
  - progressive 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 page
    - if not, consider this page to be the least recently used

True Global LRU Replacement

reference	a	b	c	d	a	b	d	e	f	a	b	c	d	a	e	d

True LRU — loads 4, replacements 7

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

LRU Clock Algorithm

reference	a	b	c	d	a	b	d	e	f	a	b	c	d	a	e	d

LRU clock — loads 4, replacements 7

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	2	3	1	2	3	0	1	2	3

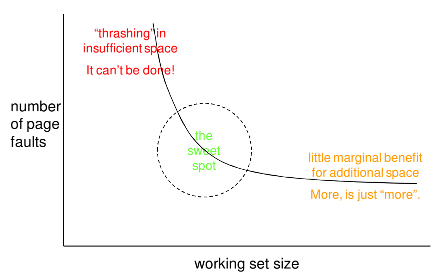
True LRU — loads 4, replacements 7

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

Working Sets – per process LRU

- Global LRU is probably a blunder
  - bad interaction with round-robin scheduling
  - better to give each process it's own page pool
  - do LRU replacement within that pool
- fixed # of pages per process is also 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 clearly want dynamic working sets

"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 try to run process in fewer pages?
  - needed pages 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

- managed 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 (WS-Clock) algorithms
  - track last use time for each page, for owning process
  - find page 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

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 ptr

current execution times: $P_0 = 55$ | $P_1 = 75$ | $P_2 = 80$ **t = 15**

P_0 gets a fault
- page 6 was just referenced
  - clear ref bit, update time
- page 7 is (55-33=22) ms old
  - P_0 replaces his own page

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	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 ptr

current execution times $P_0 = 55$ $P_1 = 75$ $P_2 = 80$ **t = 25**

P_0 gets a fault
page 6 was just referenced
page 7 is (55-33=22) ms old
P_0 replaces his own page

P_0 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
P_0 steals this page from P_1

Thrashing Prevention

- 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 our working sets exceeds available memory
- we cannot squeeze working set sizes
  – this will result in thrashing
- reduce number of competing processes
  – swap some of the ready processes out
  – to ensure enough memory for the rest to run
- we can round-robbin who is in and out

Pre-loading – a page/swap hybrid

- what happens when process swaps in
- 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-load 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 and Dirty Pages

- consider a page, recently paged in from disk
  – there are two copies, on 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"
  – we can replace page without writing it 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 we write it out to disk, it becomes "clean" again

preemptive page laundering

- clean pages can be replaced at any time
  – copy on disk is already up to date
  – clean pages give flexibility to memory scheduler
  – many pages that can, if necessary, be replaced
- 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
- this is the outgoing equivalent of pre-loading

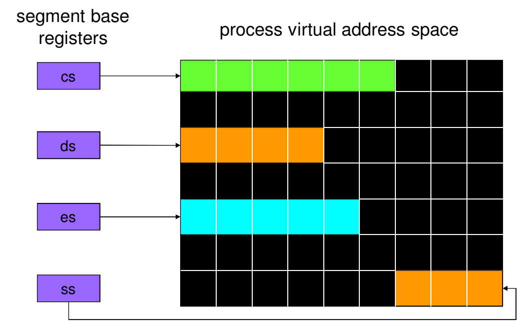
Copy on Write

- *fork(2)* is a very expensive operation
  – we must copy all private data/stack pages
  – sadly most will be discarded by next *exec(2)*
- assume child will not update most pages
  – share all private pages, mark them *copy on write*
  – change them to be read-only for parent and child
  – on write-page fault, make a copy of that page
  – on exec, remaining pages become private again
- *copy on write* is a common optimization

paging and segmentation

- pages are a very nice memory allocation unit
  - they eliminate internal and external fragmentation
  - they admit of a very simple and powerful MMU
- they are not a particularly natural unit of data
  - 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
- two levels of memory management abstraction
  - a virtual address space is comprised of segments
  - relocation & swapping is done on a page basis
  - segment base addressing, with page based relocation
- user processes see segments, paging is invisible

segmentation on top of paging



Segments – collections of pages

- a segment is a named collection of pages
  - each page has a home on secondary storage
- 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 w/page mapping
  - page faulting uses segments to find requested page

Managing Secondary Storage

- where do pages live when not in memory?
  - we swap them out to secondary storage (disk)
  - how do we manage our 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

Paging and Shared Segments

- shared memory, executables and DLLs
- created/managed as mappable segments
  - one copy mapped into multiple processes
  - demand paging same as with any other pages
  - 2ndary home may be in a file system
- shared pages don't fit working set model
  - may not be associated with just one process
  - global LRU may be more appropriate
  - shared pages often need/get special handling

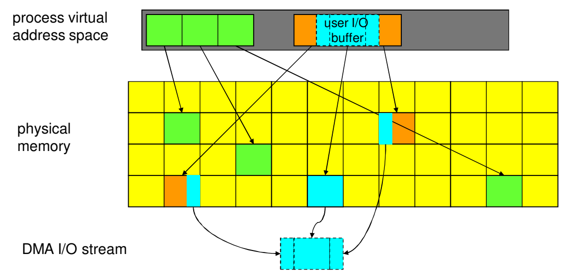
Virtual Memory and I/O

- user I/O requests use virtual buffer address
  - how can a device controller find that data
- kernel can copy data into physical buffers
  - accessing user data through standard mechanisms
- kernel may translate virtual to physical
  - give device the corresponding physical address
- CPU may include an I/O MMU
  - use page tables to translate virt addrs to phys
  - all DMA I/O references go through the I/O MMU

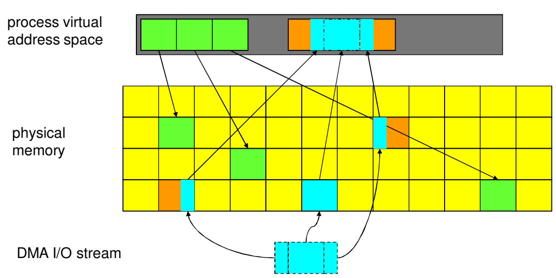
Scatter/Gather I/O

- many controllers support DMA transfers
  - entire transfer must be contiguous in physical memory
- user buffers are in paged virtual memory
  - user buffer may be spread all over physical memory
  - *scatter*: read from device to multiple pages
  - *gather*: writing from multiple pages to device
- same three basic approaches apply
  - copy all user data into contiguous physical buffer
  - split logical req into chain-scheduled page requests
  - I/O MMU may automatically handle scatter/gather

"gather" writes from paged memory



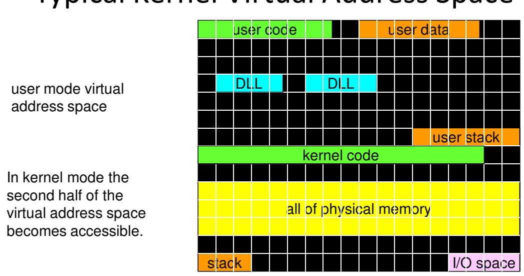
"scatter" reads into paged memory



Kernel Space vs. User Space

- user space
  - multiple segments: code, data, stack, DLLs
  - segments are allocated in one-page units
  - data space managed as heap by user-mode code
- Kernel space (may be virtual or physical)
  - also includes all system code and data structures
  - also includes mapped I/O space
- physical memory divided into two classes
  - most managed as pages, for use by processes
  - some managed as storage heap for kernel allocation

Typical Kernel Virtual Address Space



Not to Scale

(density is greatly exaggerated)

Moving Data between Kernel/User

- kernel often needs to access user data
  - to access system call parameters
  - to perform read and write system calls
- kernel may run in a virtual address space
  - which includes current process' address space
- special instructions for cross-space access
  - e.g. "move from previous data"
- kernel may execute w/physical addresses
  - software translation of user-space addresses

Assignments

- For next Lecture
  - Introduction to IPC
  - send(2), recv(2), named pipes, mmap(2)
  - Arpaci C25, 26, 27-27.2
  - user-mode threads
- Project
  - try to get P1B working before lab
  - order your BeagleBone

Supplementary Slides

implementing a paging MMU

- MMUs used to sit between the CPU and bus
  - now they are typically integrated into the CPU
- page tables
  - originally implemented in special fast registers
  - now, w/larger address spaces, stored in memory
  - entries cached in very fast registers as they are used
    - which makes cache invalidation an issue
- optional features
  - read/write access control, referenced/dirty bits
  - separate page tables for each processor mode

updating a paging MMU

- adding/removing pages for current process
  - directly update active page table in memory
  - privileged instruction to flush (stale) cached entries
- switching from one process to another
  - maintain separate page tables for each process
  - privileged instruction loads pointer to new page table
  - reload instruction flushes previously cached entries
- sharing pages between multiple processes
  - make each page table point to same physical page
  - can be read-only or read/write sharing

Discussion Slides