7.3 Operating System Issues

- *General Concerns*
- Representative Systems
- Copy on Write and Fork
- Backing Store Issues

Traditional OS Issues

- Fetch policy
- Placement policy
- Replacement policy

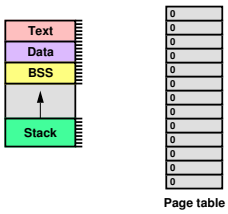
A Simple Paging Scheme

- *Fetch* policy
  - start process off with no pages in primary storage
  - bring in pages *on demand* (and only on demand)
    - this is known as *demand paging*
      - defer processing until you absolutely have to do it
      - why? because you may not have to process *at all*
      - *demand paging* is an instance of *Lazy Evaluation*, a powerful idea used in computer science
    - it's like http://www.flickclip.com/flicks/xmen1.html
      - watch the video from time index 10 to 15

A Simple Paging Scheme

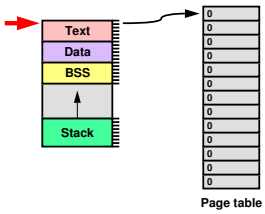
- *Placement* policy
  - unlike disk pages, it doesn't matter here - put the incoming page (from disk) in the first available physical page
    - page *frames* are used to keep track of physical pages
- *Replacement* policy
  - required if there is not enough *resource* to go around
  - e.g., replace the page that has been in primary storage the longest (FIFO policy, which can be bad)

Demand Paging



- After `exec()` is called, a page table is created with all entries having V=0

Demand Paging



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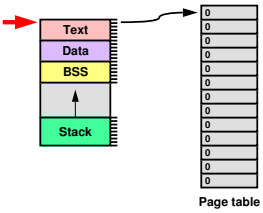

- After `exec()` is called, a page table is created with all entries having V=0
  - as the first instruction executes
    - since V=0, the hardware traps into the kernel

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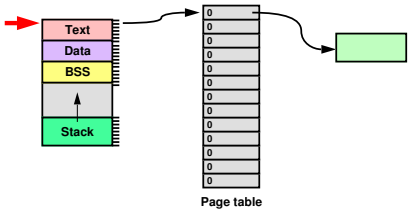

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  - as the first instruction executes
    - since V=0, the hardware traps into the kernel
    - the kernel *allocates a physical page* and copy the first 4KB of code into this page (allocate from where?)
      - point the corresponding page table entry to this page
      - update all necessary data structures

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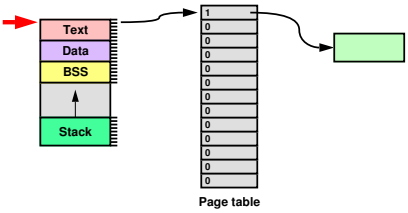

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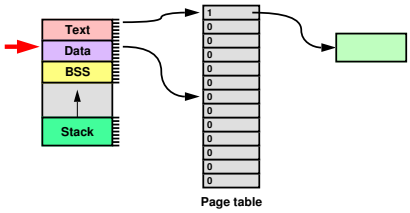
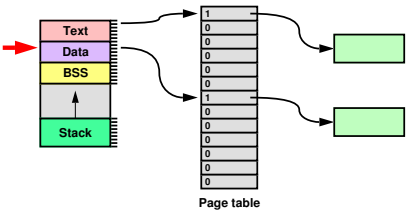
    - since V=0, the hardware traps into the kernel
    - the kernel *allocates a physical page* and copy the first 4KB of code into this page (allocate from where?)
      - point the corresponding page table entry to this page
      - update all necessary data structures
    - set V=1 and return from the trap

Demand Paging



- After `exec()` is called, a page table is created with all entries having V=0
  - as the program reference the data segment or access the stack

Demand Paging



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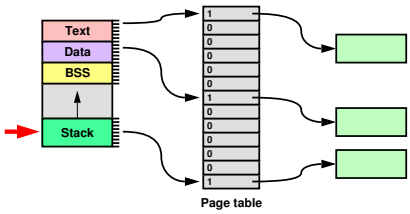
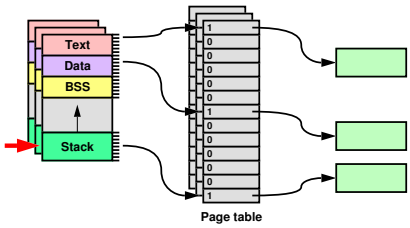
  - as the program reference the data segment or access the stack
    - similar things happen

Demand Paging



- After `exec()` is called, a page table is created with all entries having V=0
  - as the program reference the data segment or access the stack
    - similar things happen
    - although stack is a little different since it has to have a backing store

Demand Paging



- Remember, there are multiple processes and multiple page tables that the OS is servicing

Page Fault

- *Page Fault* (accessing a page with *V=0*)
  1) Trap occurs (due to a page fault)
  2) Find free physical page
  3) Write page out if no free physical page
  4) Fetch page
  5) Return from trap

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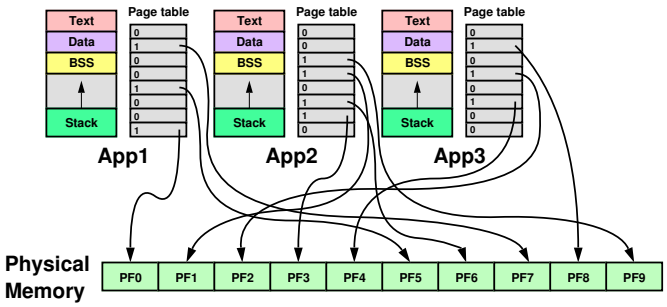
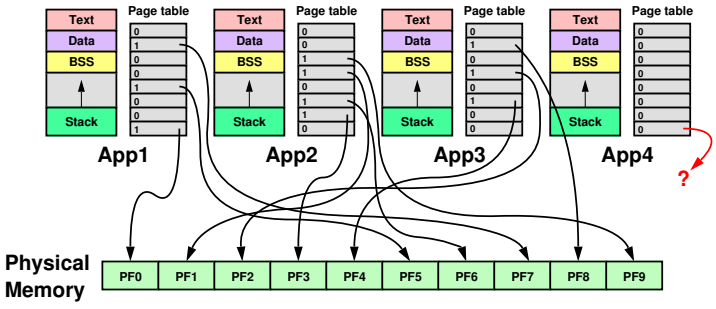
  4) Fetch page
  5) Return from trap
- Issues
  - in step (2), where and how do we find such a *free physical page*?
    - the Buddy System is used
      - return NULL if no free physical page is available
  - in step (3), where and how do we find a *physical page* to write out to disk?

Example

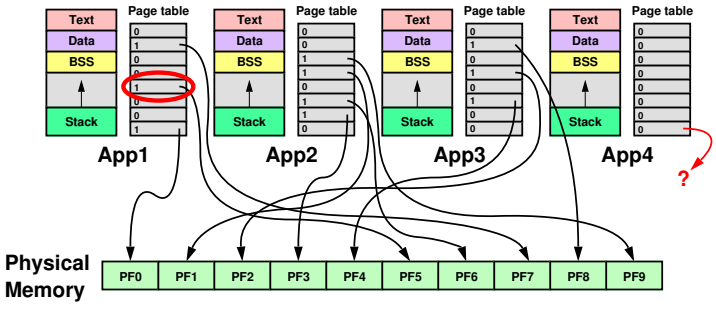


Example



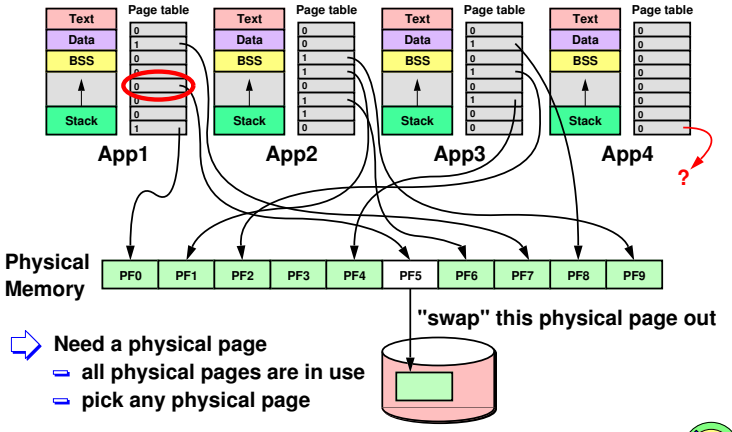
- Need a physical page
  - all physical pages are in use

Example



- Need a physical page
  - all physical pages are in use
  - pick any physical page

Example



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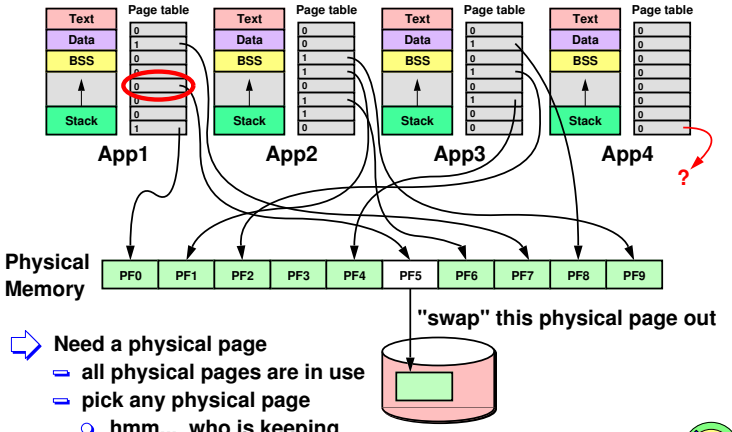
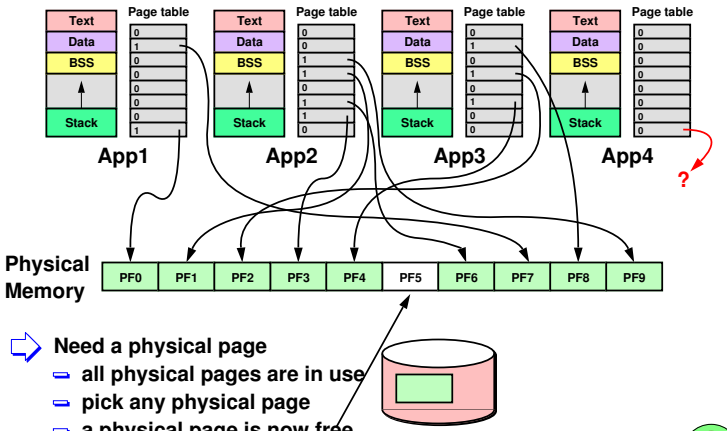


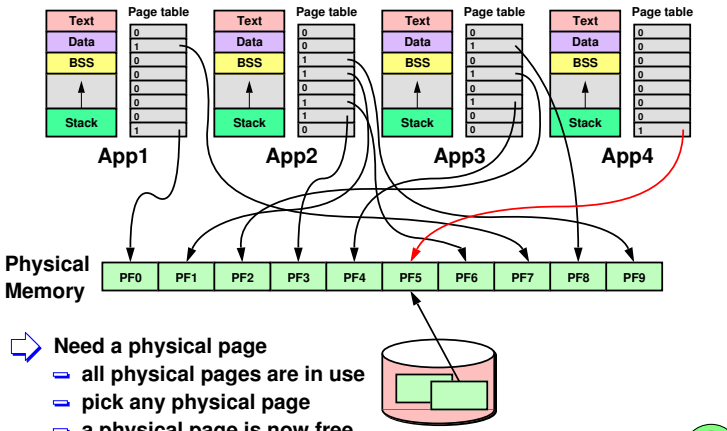
- Need a physical page
  - all physical pages are in use
  - pick any physical page
    - hmm... who is keeping track of where the physical page got copied to?

Example



- Need a physical page
  - all physical pages are in use
  - pick any physical page
  - a physical page is now free

Example

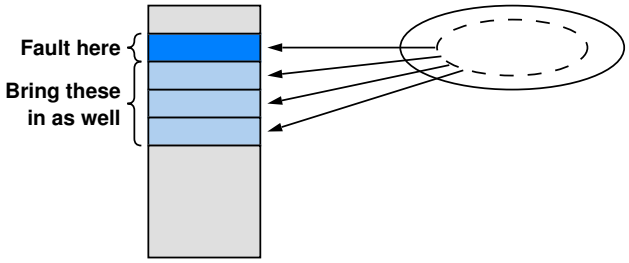


- Need a physical page
  - all physical pages are in use
  - pick any physical page
  - a physical page is now free
  - fetch page from disk and fix up page table

Performance

- *Page Fault* (accessing a page with *V=0*)
  1) Trap occurs (due to a page fault)
  2) Find free physical page
  3) Write page out if no free physical page
  4) Fetch page
  5) Return from trap
- A page fault can result in disk operations and slow down the application
  - do not want to wait for the disk!
  - need to reduce this latency
    - *prefetching*
    - *pageout daemon*

Improving the Fetch Policy

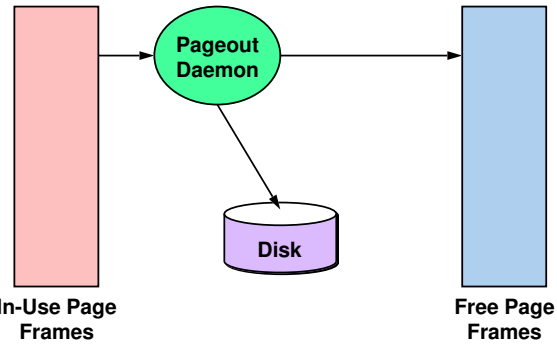


- This is *prefetching*, as we have seen before
  - accesses to pages is often sequential
  - gamble that this is worthwhile (since it takes up more memory)
- This improves step (4) on previous page
  - but it uses up physical memory faster
  - and what about steps (2) and (3)?

Improving the Replacement Policy

- When is replacement done?
  - doing it "on demand" causes excessive delays
    - so, "on-demand" is *not always* a good policy
  - should be performed as a separate, *concurrent* activity
    - use a thread *(*i.e., a *pageout deamon)* to continuously look for free pages
- Which pages are replaced?
  - FIFO policy is not good
  - want to replace those pages least likely to be referenced soon

The "Pageout Daemon"

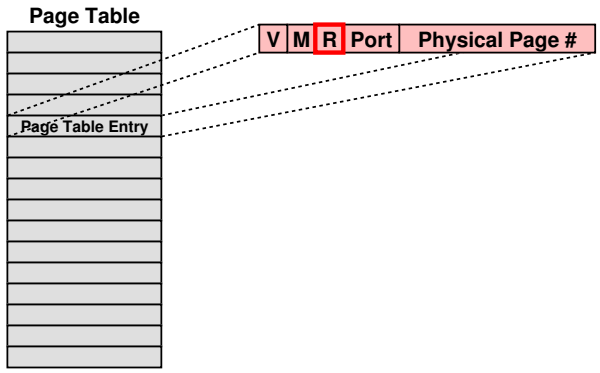


- *Page frames* are used to keep track of physical pages
- Can use *multiple* pageout daemons

Choosing the Page to Remove

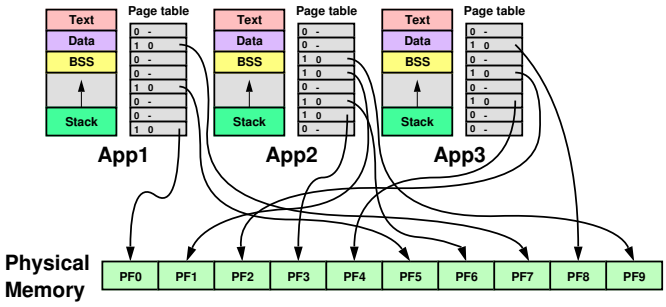
- If your DVD rack is full and you just bought a new DVD
  - which DVD would you remove from the rack to make room for the new DVD?
- Idealized policies:
  - FIFO (First-In-First-Out)
  - LRU (Least-Recently-Used)
  - LFU (Least-Frequently-Used)

Implementing LRU



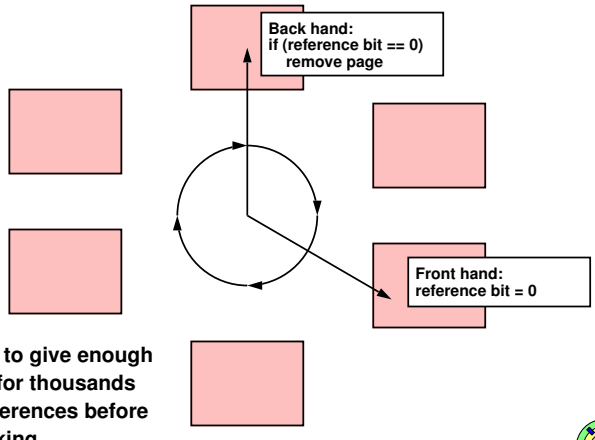
- To approximate LRU (a very coarse approximation), the *reference* bit in the page table entry is used

Using The Reference Bits



- Why would some pages referenced more often than other?
  - code?
  - stack?
  - depends on the application

Clock Algorithm



- Need to give enough time for thousands of references before checking

Global vs. Local Allocation

- Global allocation
  - all processes *compete* for page frames from a single pool
- Local allocation
  - each process has its own *private* pool of page frames
  - Windows does this
    - processes do not have to compete for the same pool of page frames

Thrashing

- Consider a system that has exactly two page frames:
  - process A has a page in frame 1
  - process B has a page in frame 2
- Process A references another page, causing a page fault
  - the page in frame 2 is removed from B and given to A
- Process B faults immediately; the page in frame 1 is given to B
- Process A resumes execution and faults again; the page in frame 1 is given back to A
- ...
  - neither processes makes progress

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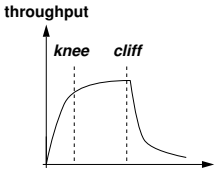
  - neither processes makes progress
- The problem
  - need 3 physical page frames, but only 2 are available



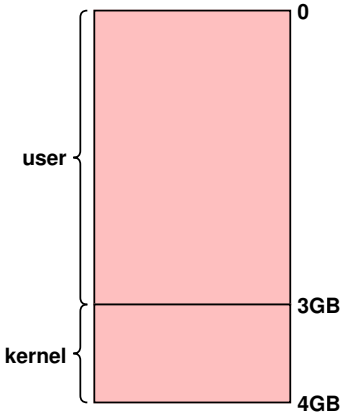
The Working-Set Principle

- To deal with thrashing, the idea of *Working-Set* can be used
  - although it may be difficult to implement exactly
- The set of pages being used by a program (the working set) is relatively small and changes slowly with time
  - *WS(P,T)* is the set of *pages* used by process P over time period T
- Over time period T, P should be given |WS(P,T)| page frames
  - if space isn't available, then P should not run and should be *swapped out*
- If the sum of the working-set of all processes is less than the total amount of available physical memory
  - then thrashing cannot occur
  - using *Local Allocation* is a way to *reduce the chance* of *thrashing*

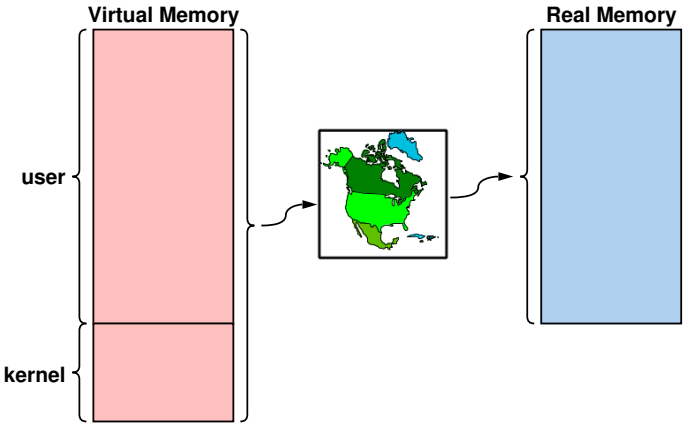
7.3 Operating System Issues

- General Concerns
- *Representative Systems*
- Copy on Write and Fork
- Backing Store Issues

Linux Intel x86 VM Layout



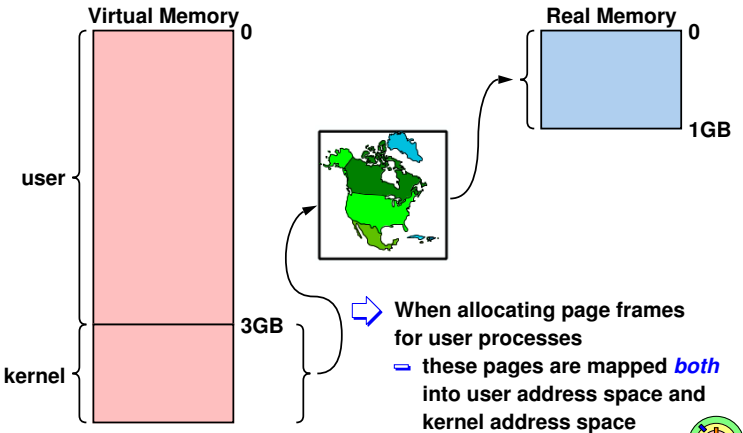
Real Memory



Memory Allocation

- User
  - virtual allocation
    - fork
    - pthread_create
    - exec
    - brk
    - mmap
  - real allocation
    - (not done)
- OS kernel
  - virtual allocation
    - fork, etc.
    - kernel data structures
  - real allocation
    - page faults
    - kernel data structures
      - e.g., page tables

Example: 1GB Of Real Memory



- When allocating page frames for user processes
  - these pages are mapped *both* into user address space and kernel address space

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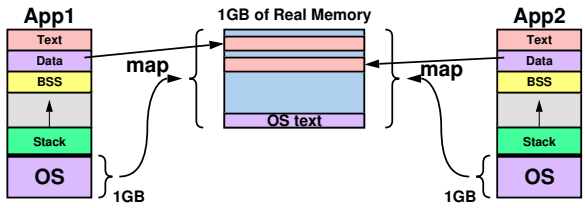
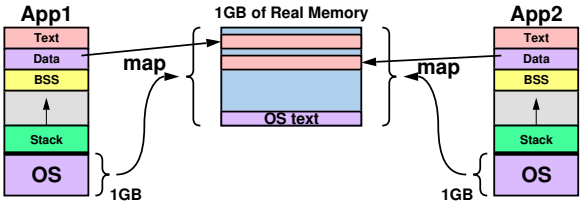


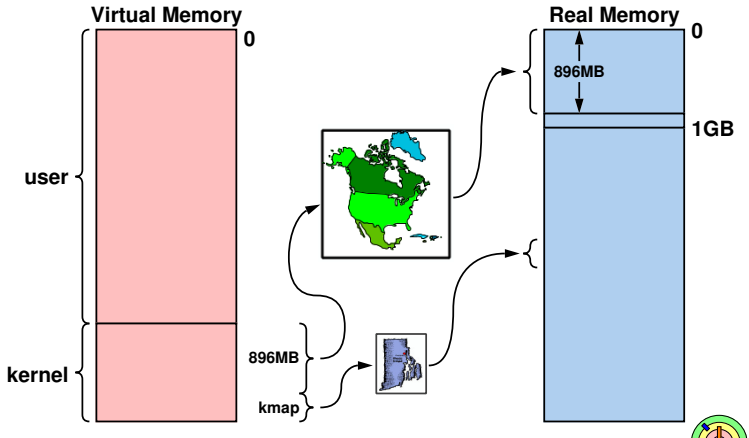
- When you switch from one process to another
  - OS code and OS data stay where they were
  - top 1/4 of page tables of all processes are *mapped identically*!
    - the kernel does *not* need its own page table!
- If you only have 1GB of physical memory
  - OS can read every piece of "user memory" easily (directly)
- *Every physical address* can have *two virtual addresses*
  - one for the kernel and one for a user process

Example: 1GB Of Real Memory



- HW: read `pt_init()` in "`kernel/mm/pagetable.c`" of `weenix`
  - kernel text, data, and bss starts at virtual address `0xc0000000`
  - then comes kernel's *page directory table* (4KB+4KB)
  - then comes kernel's *page tables* (4KB each)
  - understand how *memory map* is setup for the *kernel*
  - understand that the *kernel*, just like user processes, can only use *virtual addresses*!
- Although `weenix` only has about 16MB of usable physical memory

Lots of Real Memory



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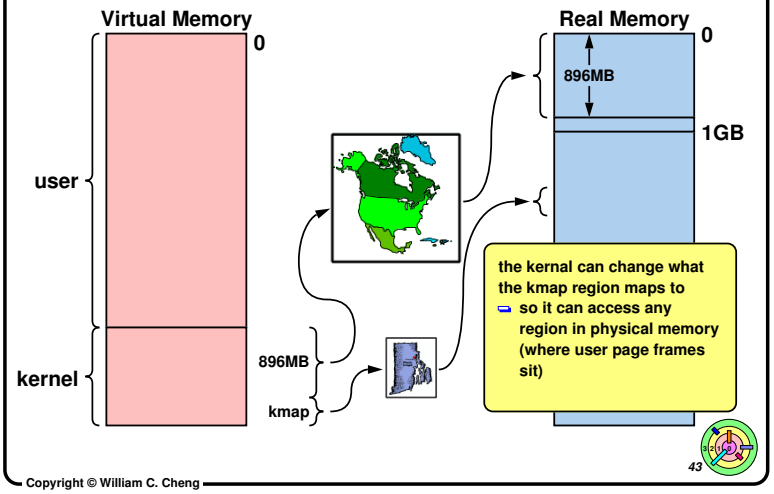
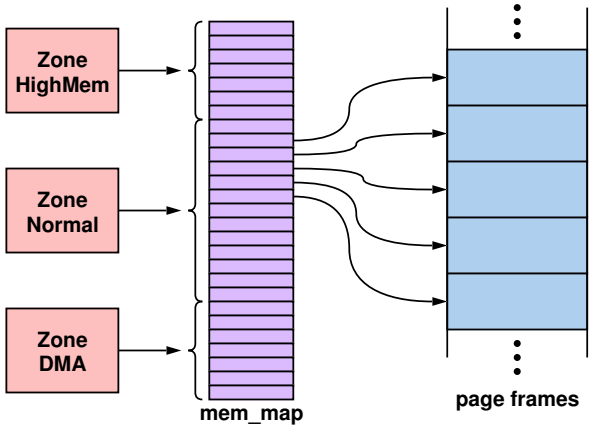


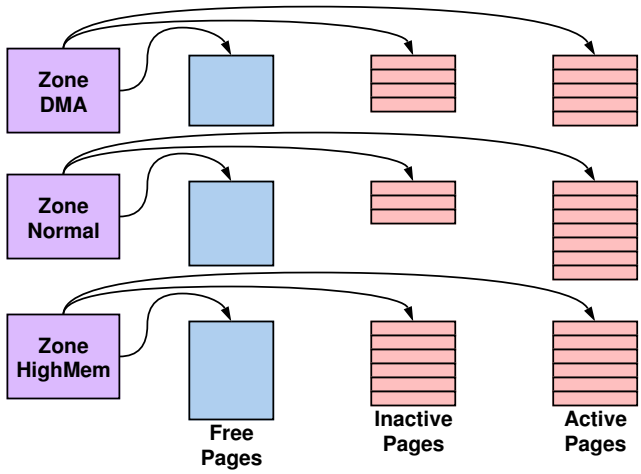
Mem_map and Zones

- Linux divides *physical memory* into 3 zones
  - *DMA zone:* locations $< 2^{24}$
    - `0x00000000` to `0x00ffffff`
    - many DMA devices can only handle 24-bit address
  - *Normal zone:* locations $\geq 2^{24}$ and $< 2^{30} - 2^{27}$
    - `0x01000000` to `0x37ffffff`
    - OS data structures must reside in this range
    - user pages *may* be in this range
  - *HighMem zone:* locations $\geq 2^{30} - 2^{27}$
    - `0x40000000` to `0xffffffff`
    - *strictly* for user pages

Mem_map and Zones



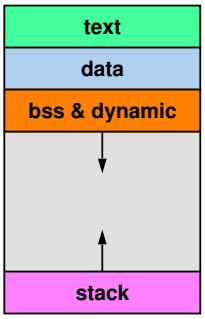
Page Lists



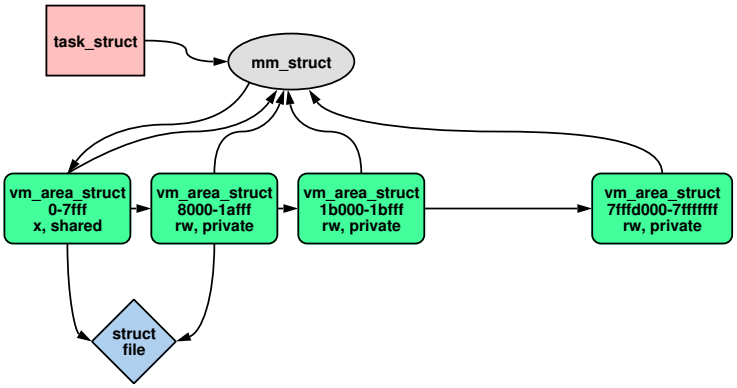
Page Lists

- Each zone's page frames are divided into three lists
  - *free list*
    - not used
    - *buddy system* to maintain
    - contiguous in real addresses implies contiguous in virtual address
  - *inactive*
    - picked out by *clock algorithm* as *not recently used*
    - dirty/modified
  - *active*
    - picked out by *clock algorithm* as *recently used*

Simple User Address Space

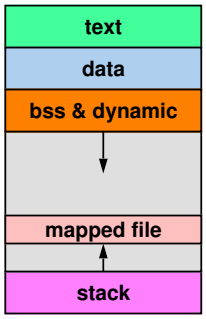


Address-Space Representation (Somewhat Simplified)

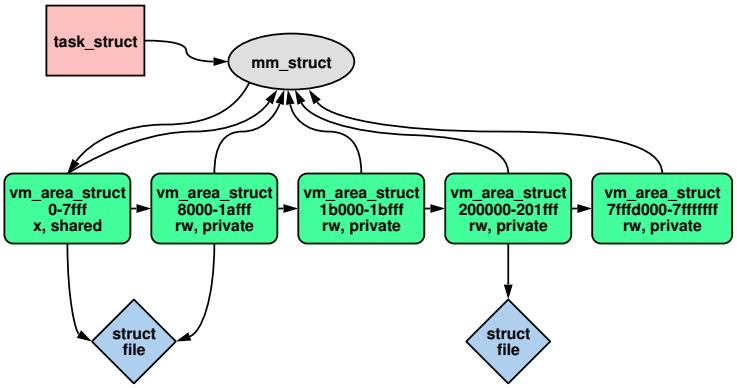


- `vm_area_struct` is what we used to call `as_region`

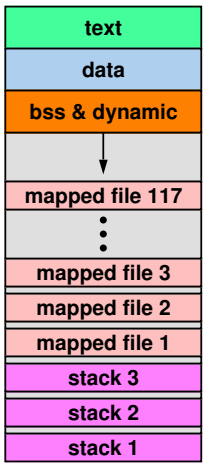
Adding a Mapped File



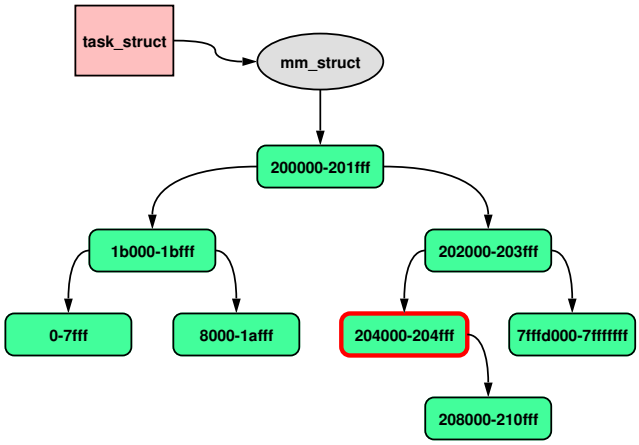
Address-Space Representation: More Areas



Adding More Stuff



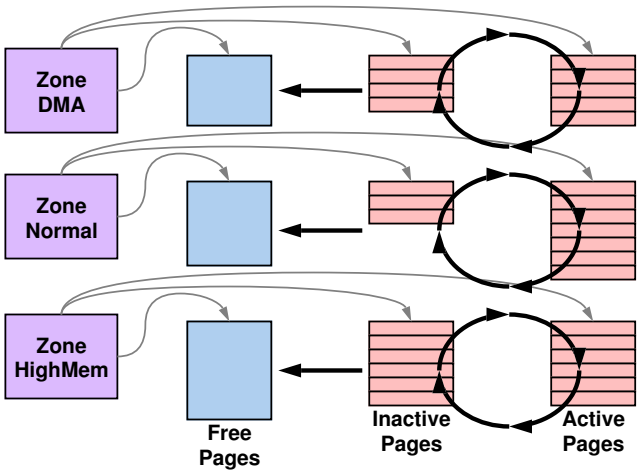
Address-Space Representation: Reality



Linux Page Management

- Replacement
  - two-handed clock algorithm
  - applied to zones in sequence
  - essentially global in scope

Page Scanning



Important Linux VM Data Structures Summary

- For each process, *PCB* contains
  - *Memory Map* (i.e., that's how the address space is represented)
    - maps *virtual* memory segments
    - keeps track of *Backing Store* (which file the data come from)
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  3) *unmap* this page from the corresponding *page table*
  4) free the page frame

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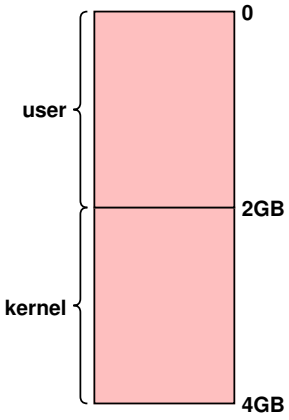
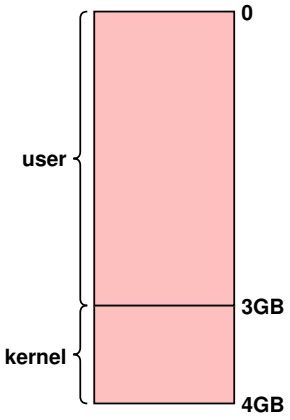
Windows x86 Layout

- Two choices

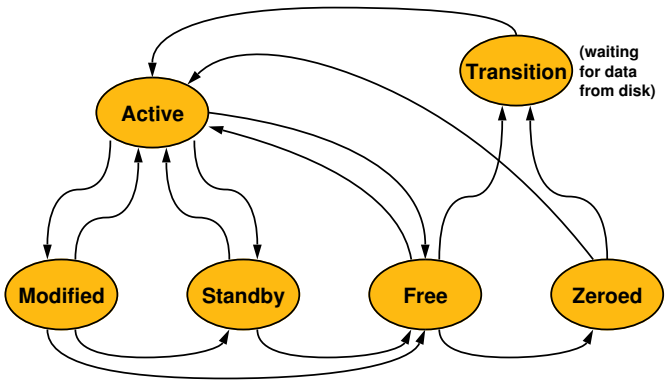




Windows Paging Strategy Highlights

- All processes guaranteed a "working set"
  - lower bound on page frames
  - you can get "cannot start a process because there is not enough memory" message
- Competition for additional page frames
- "Balance-set" manager thread maintains working sets
  - one-handed clock algorithm
- *Swapper* thread swaps out idle processes (inactive for 15 seconds)
  - first kernel stacks
  - then working set
  - very different from Linux
- Some of kernel memory is *paged*
  - page faults are possible
    - makes more physical memory available
    - must "*lock down*" page frames for page fault handler

Windows Page-Frame States



7.3 Operating System Issues

- General Concerns
- Representative Systems
- *Copy on Write and Fork*
- Backing Store Issues

Unix and Virtual Memory: The `fork()`/`exec()` Problem

- Naive implementation:
  - `fork()` actually makes a copy of the parent's address space for the child
  - child executes a few instructions (setting up file descriptors, etc.)
  - child calls `exec()`
  - result: a lot of time wasted copying the address space, though very little of the copy is actually used

`vfork()`

- Don't make a copy of the address space for the child; instead, give the address space to the child
  - the parent is suspended until the child returns it
- The child executes a few instructions, then does an exec
  - as part of the exec, the address space is handed back to the parent
- Advantages
  - very efficient
- Disadvantages
  - works only if child does an exec
  - child must not intentionally or accidentically modify the address space

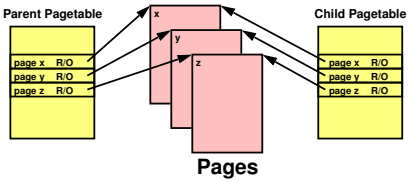
A Better `fork()`

- Parent and child share the pages comprising their address spaces
  - if either party attempts to modify a page, the modifying process gets a copy of just that page
- Principle of *Lazy Evaluation* at work
  - try to put things off as long as possible if you don't have to do them now
    - if it needs to be done now, you don't really have a choice
  - if you wait long enough, it might turn out that you don't have to do them at all
- Advantages
  - semantically equivalent to the original `fork()`
  - usually faster than the original `fork()`
- Disadvantages
  - slower than `vfork()`

Copy on Write and `fork()`

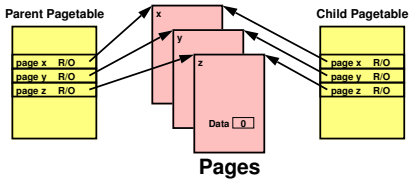
- Given that demand paging is the way to go, we need to use *copy-on-write*
  - a process gets a *private* copy of the page after a thread in the process performs a *write* for the *first time*
    - if a virtual memory segment is *R/W* and *privately mapped*, then we need to perform copy-on-write
  - *copy-on-write* must work with `fork()`
    - what are the complications?

Private Mapping - Copy on Write Occurs after `fork()`



- Parent and child process share pages, all marked *read-only* at first
  - to initalize the child's page table, just use `memcpy()` to copy the entire page table from the parent

Private Mapping - Copy on Write Occurs after `fork()`



Data = 17;

- Parent and child process share pages, all marked *read-only* at first
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    - this is another reason for a *page fault*

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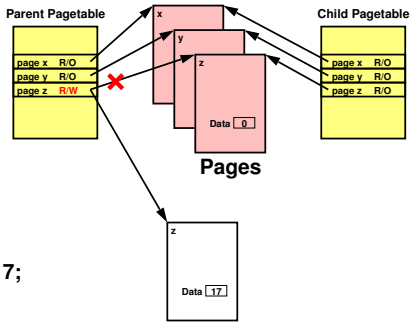

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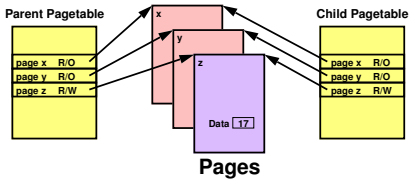
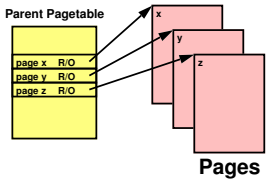
Share-Mapped Files



Data = 17;

- For *shared* mapping, changes are writting into the shared page
  - please note that the information about whether a page is *shared* or *private* is *not* inside the page table
    - it is kept in a kernel data structure

Private Mapping - Copy on Write Occurs before `fork()`



- For *private* mapping, *copy on write*

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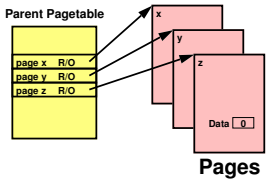

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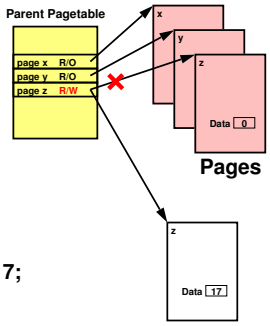
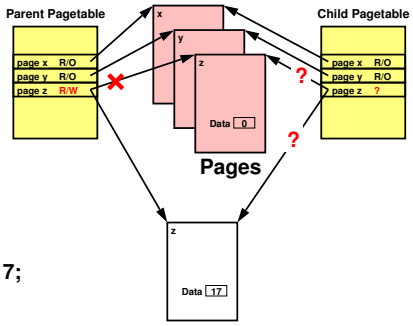


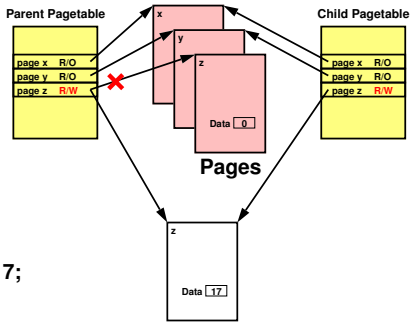
- For *private* mapping, *copy on write*

A Private-Mapped File Changes



- Complication: what if the page is modified before `fork()`?
  - should child process' page be marked "modified"?
    - some of child's pages are initialized from files and some are initialized from the parent's address space

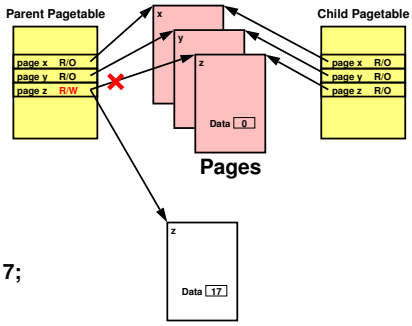
A Private-Mapped File Changes



Data = 17;

- Complication: what if the page is modified before `fork()`?
  - `memcpy()` the parent's page table is wrong: what if the parent modify the page further?
    - child should not see these changes

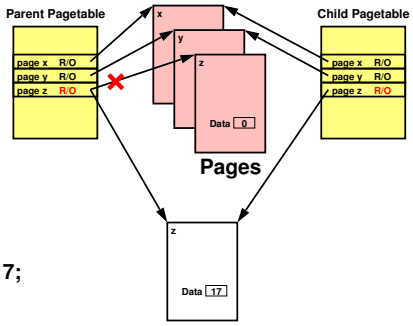
A Private-Mapped File Changes



Data = 17;

- Complication: what if the page is modified before `fork()`?
  - this is also wrong
    - child process should see 17 in Data on page z

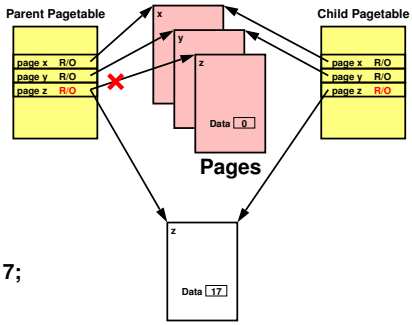
A Private-Mapped File Changes



Data = 17;

- Complication: what if the page is modified before `fork()`?
  - this seems to be the correct solution
    - i.e., copy PTEs from parent and start copy-on-write on all private pages

A Private-Mapped File Changes

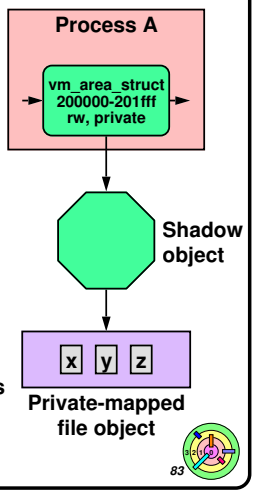


Data = 17;

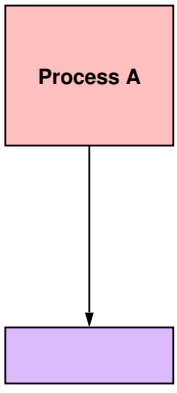
- Complication: what if the page is modified before `fork()`?
  - but what if now the parent or the child calls `fork()`?
    - afterwards, another process calls `fork()` again, etc.?
    - cannot use PTEs to keep track

Copy-on-write & Fork

- *Shadow Objects*
  - indirection
  - keep track of pages that were *originally copy-on-write* but have been *modified*
- A page in a memory map, into which an object was mapped *private* (e.g., data region), has an associated *shadow object*
  - if the page is "referenced in the shadow object" (or "associated with a shadow object"), it has been modified
  - otherwise, the page is associated with the *original* object (file or even a "zero/anonymous" objects)
  - x, y, z on the right are pages / page frames
- *Shadow object* tells you *where to copy from* when you need to perform *copy-on-write*

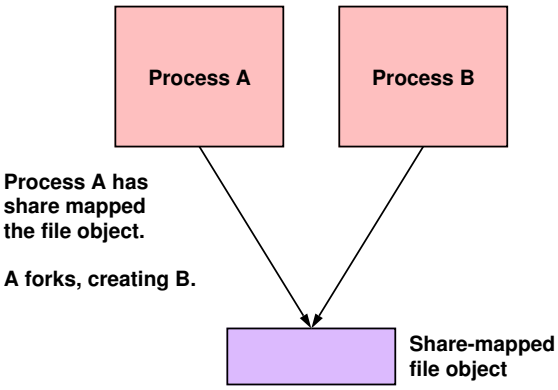


Share Mapping (1)

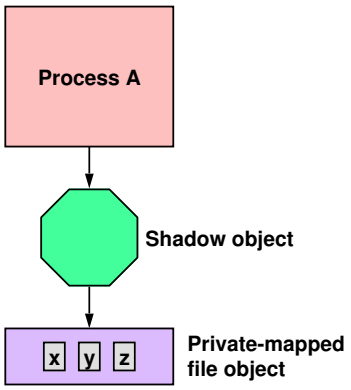


Process A has share mapped the file object.

Share Mapping (2)



Private Mapping (1)



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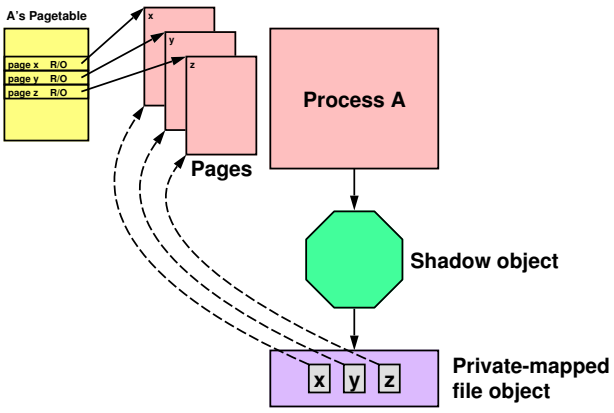

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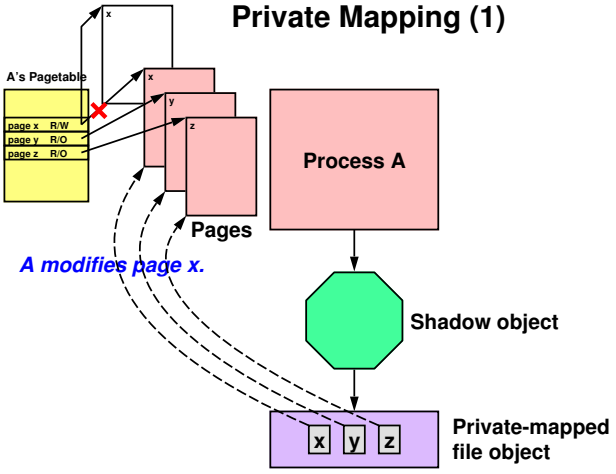

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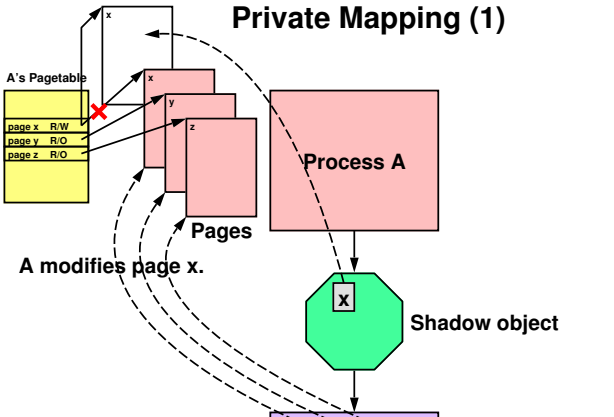

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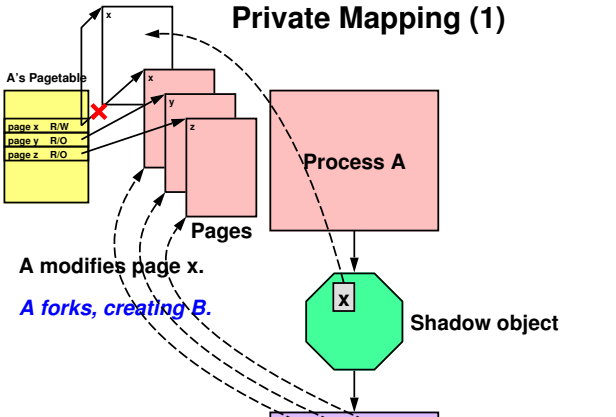
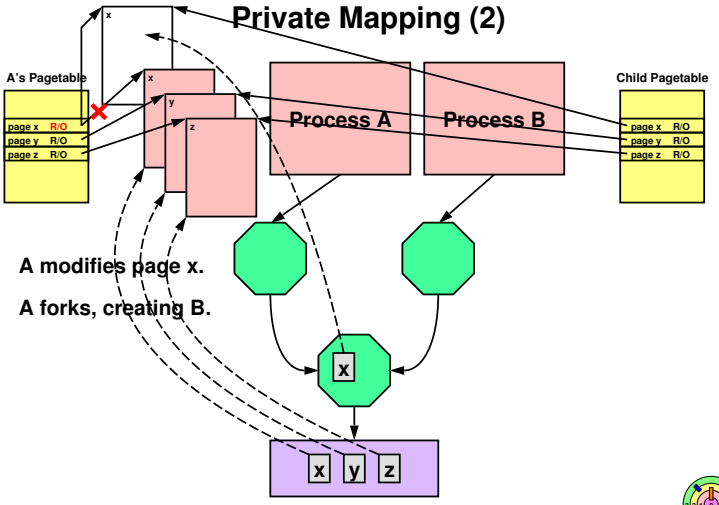


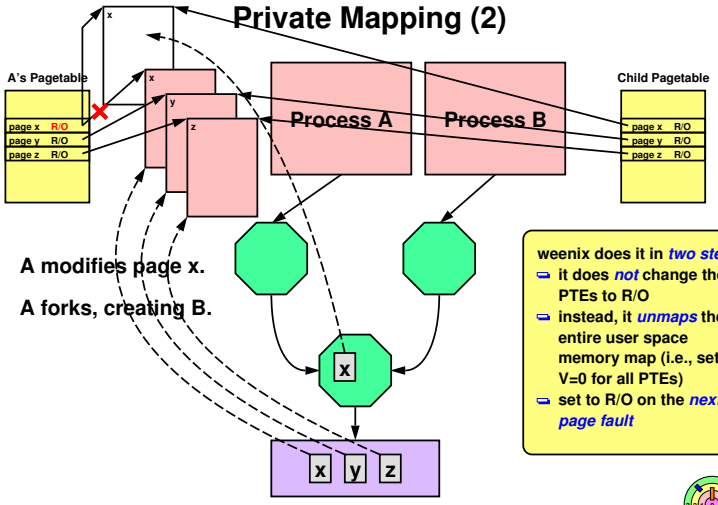
Private Mapping (2)



A modifies page x.

A forks, creating B.

Private Mapping (2)



A modifies page x.

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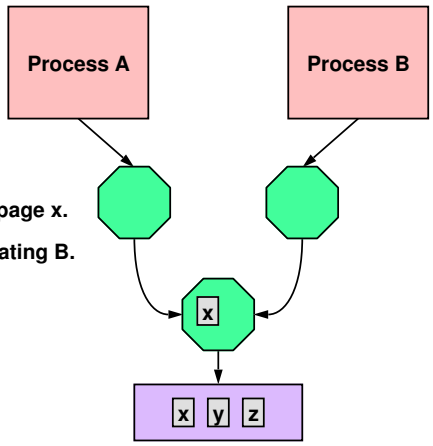
weenix does it in *two steps*
- it does *not* change these PTEs to R/O
- instead, it *unmaps* the entire user space memory map (i.e., sets V=0 for all PTEs)
- set to R/O on the *next page fault*

Private Mapping (2)



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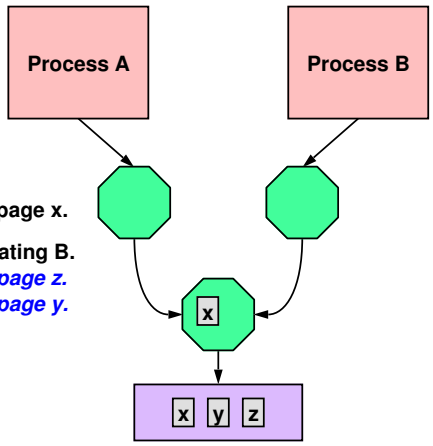
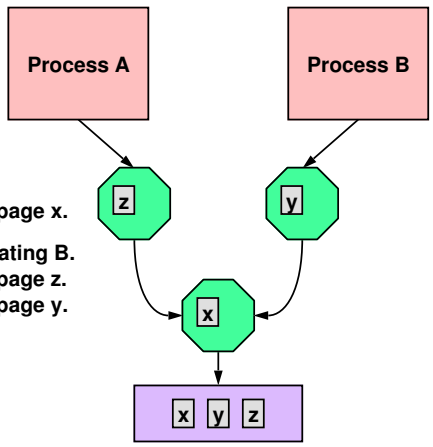


A modifies page x.

A forks, creating B.
A modifies page z.
B modifies page y.

Private Mapping (2)



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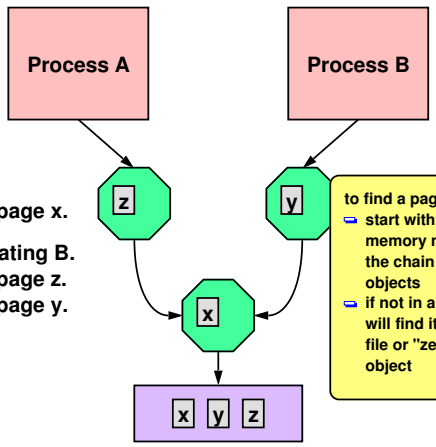
Private Mapping (2)

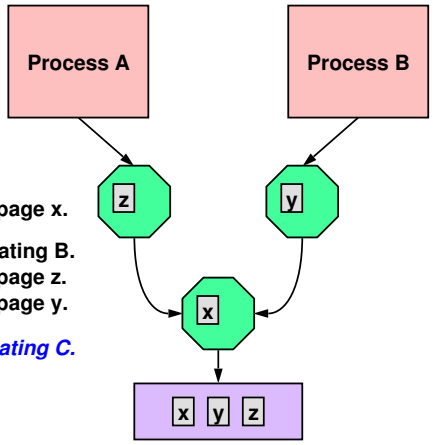


A modifies page x.

A forks, creating B.
A modifies page z.
B modifies page y.

to find a page to *copy from*
- start with the process' memory map and follow the chain of shadow objects
- if not in a shadow object, will find it in the mapped file or "zero/anonymous" object

Private Mapping (2)

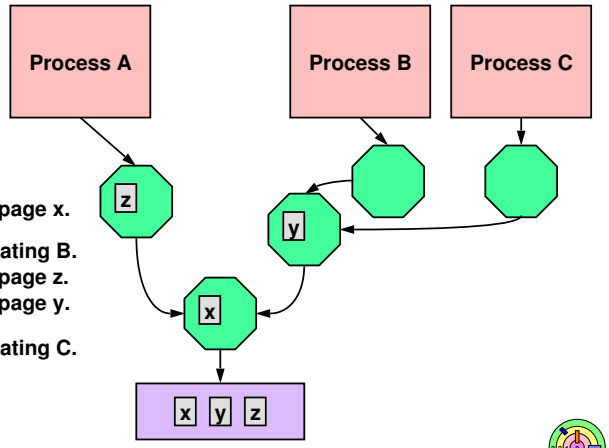


A modifies page x.

A forks, creating B.
A modifies page z.
B modifies page y.

B forks, creating C.

Private Mapping (3)



A modifies page x.

A forks, creating B.
A modifies page z.
B modifies page y.

B forks, creating C.

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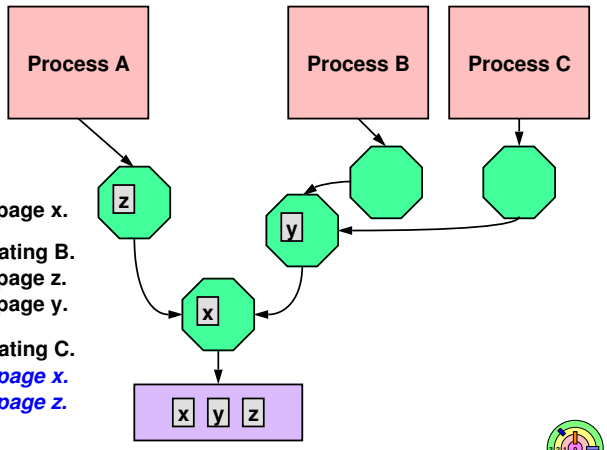
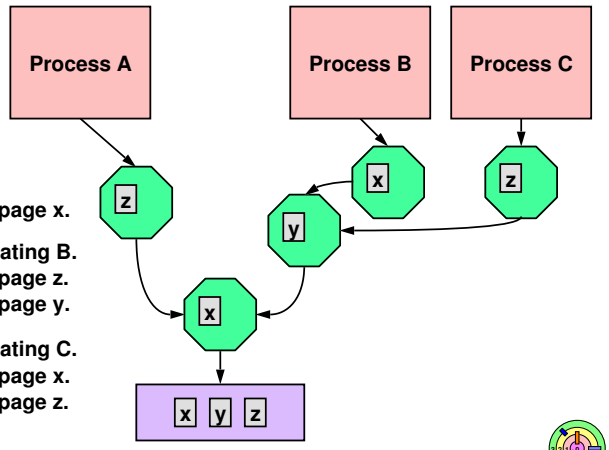


A modifies page x.

A forks, creating B.
A modifies page z.
B modifies page y.

B forks, creating C.
B modifies page x.
C modifies page z.

Private Mapping (3)



A modifies page x.

A forks, creating B.
A modifies page z.
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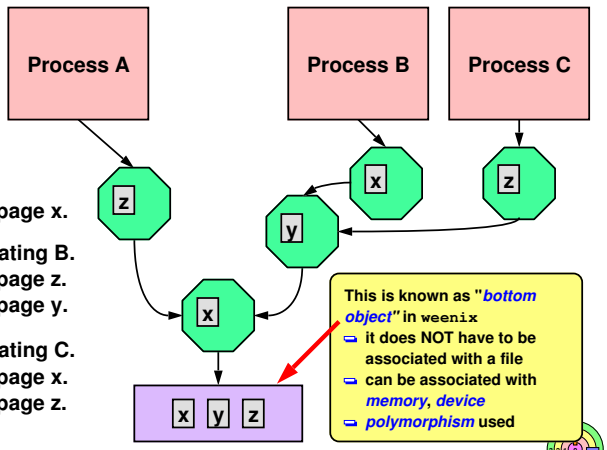
B forks, creating C.
B modifies page x.
C modifies page z.

Private Mapping (3)

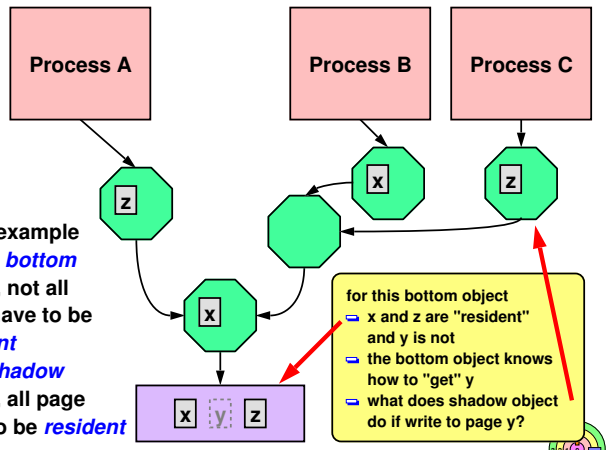


A modifies page x.

A forks, creating B.
A modifies page z.
B modifies page y.

B forks, creating C.
B modifies page x.
C modifies page z.

Private Mapping (3)

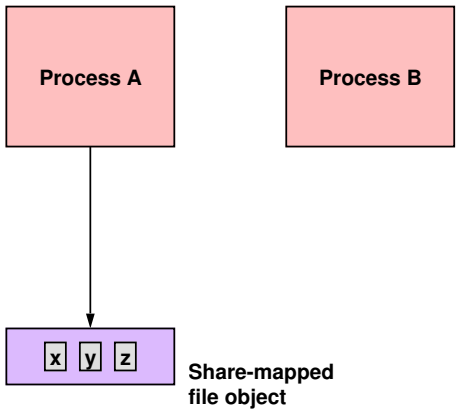


- a slightly different example
  - for the *bottom object*, not all page have to be *resident*
  - for a *shadow object*, all page have to be *resident*

Virtual Copy

- Local RPC
  - "copy" arguments from one process to another
  - assume arguments are page-aligned and page-sized
  - map pages into both caller and callee, copy-on-write
    - works in most cases, except when the page corresponds to a shared memory-mapped file
      - in this case, the sender does not have a shadow object!

Share and Private Mapping



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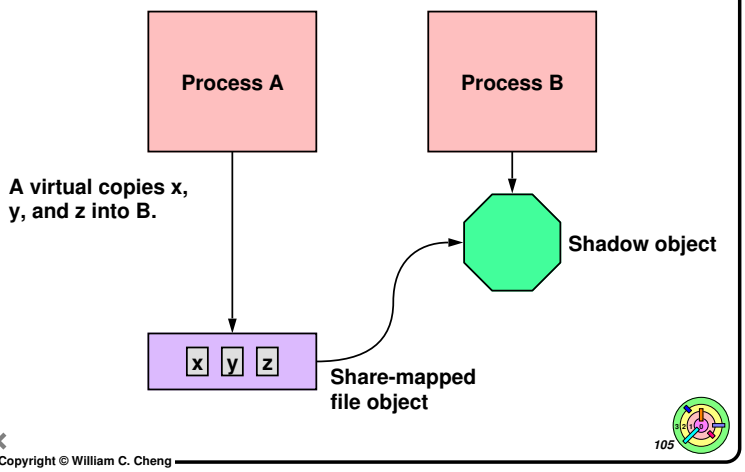
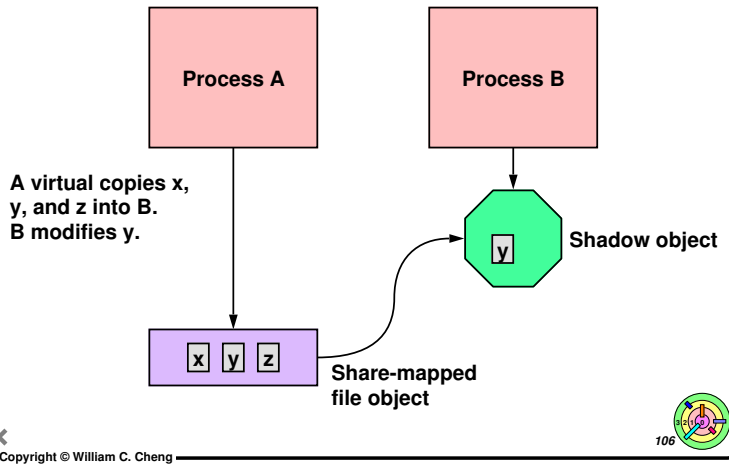


Share and Private Mapping



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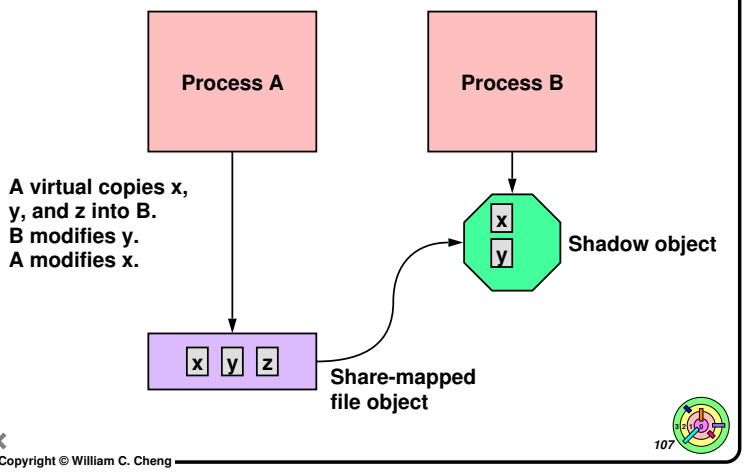

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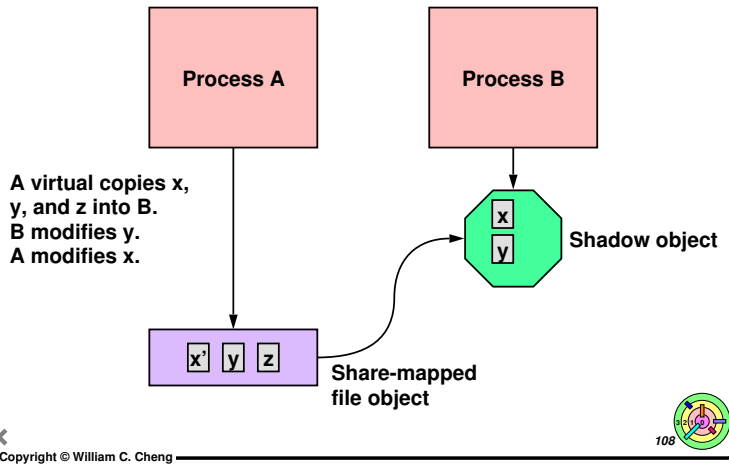
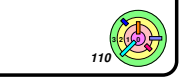


Shadow Objects Summary

- Why go through all this trouble?
  - because we want to implement *copy-on-write* together with `fork()`
    - *a variable* (such as `Data` a few slides back) can exist in *many* different physical pages *simultaneously*
      - each contains a different *version* of this variable
- To manage this mess, `weenix` uses the idea of Shadow Objects
  - what is the "idea" of Shadow Objects?
    - organize a tree of shadow objects using an *inverted tree* data structure
      - where the root is the *bottom object*
    - the rule of finding the physical page frame that contains the global variable in question for a particular process
      - traversing shadow object pointers on the inverted tree
    - when and how to perform *copy-on-write*
  - you have to implement what's described on these slides



Memory Management Objects in `weenix`

- In `weenix`, an *mmobj* is used to manage *page frames*
  - types of *mmobj* in kernel assignments are:
    - there's one that lives *inside a vnode* (`vn->vn_mmobj`)
    - a *shadow object* is an mmobj
    - an *anonymous object* (meaning not associated with a file and not a shadow object) is an mmobj
  - a `vmarea` is supported by one of these 3 mmobjs

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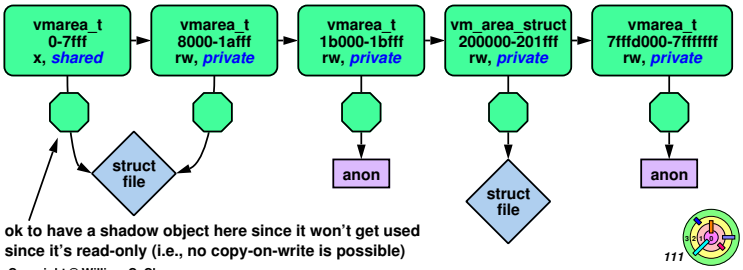
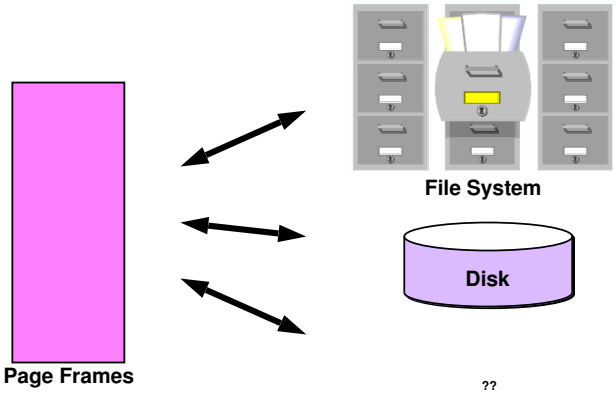


ok to have a shadow object here since it won't get used since it's read-only (i.e., no copy-on-write is possible)

7.3 Operating System Issues

- General Concerns
- Representative Systems
- Copy on Write and Fork
- *Backing Store Issues*

The Backing Store



Backing Up Pages (1)

- *Read-only* mapping of a file (e.g. text)
  - pages come from the file, but, since they are never modified, they never need to be written back
- Read-write *shared* mapping of a file (e.g. via `mmap()` system call)
  - pages come from the file, modified pages are written back to the file
- `weenix` supports this type of "backing store"

Backing Up Pages (2)

- Read-write *private* mapping of a file (e.g. the data section as well as memory mapped private by the `mmap()` system call)
  - pages come from the file, but *modified pages*, associated with *shadow objects*, must be backed up in *swap space*
- Anonymous memory (e.g. bss, stack, and shared memory)
  - pages are created as *zero fill on demand;* they must be backed up in *swap space*
    - *modified pages* of these, associated with *shadow objects*, must be backed up in *swap space*
- `weenix` does *not* support this type of backing store
  - need to prevent the pageout daemon to free up these pages accidentically
    - simply move them out of the pageout daemon's way

Swap Space

- Space management possibilities
  - radical-*conservative* approach: *eager evaluation* (or pre-allocation)
    - backing-store space is allocated when virtual memory is allocated
    - page outs always succeed
    - might need to have much more backing store than needed
  - radical-*liberal* approach: *lazy evaluation*
    - backing-store space is allocated only when needed
    - page outs could fail because of no space
    - can get by with minimal backing-store space

Swap Space

- Space management possibilities
  - mixed approach: e.g., reserve stack space for a thread in Windows
    - the address space for the thread stack is first *"reserved"*
      - no backing store actually created, but space is reserved so no other thread can use the reserved space
    - when part of this address space is used, it's *"committed"* (backing store is actually allocated)
- For things like `malloc()` and allocation of address space for privately-mapped files
  - by default, done with eager evaluation in Windows and most Unix/Linux systems
  - both systems provide means for lazy evaluation as well

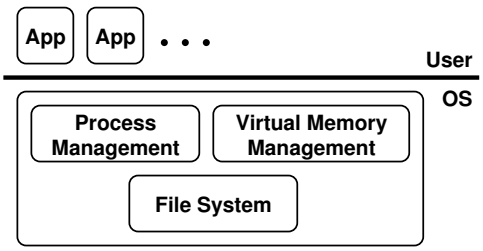
Space Allocation in Linux

- Total memory = primary + swap space
- System-wide parameter: overcommit_memory
  - three possibilities
    - maybe (default)
    - always
    - never
- mmap has MAP_NORESERVE flag
  - don't worry about over-committing

Space Allocation in Windows

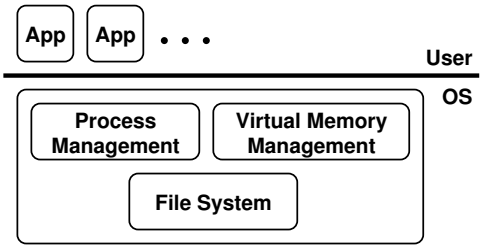
- Space reservation
  - allocation of virtual memory
- Space commitment
  - reservation of physical resources
    - paging space + physical memory
- `MapViewOfFile` (sort of like `mmap`)
  - no over-commitment
- Thread creation
  - creator specifies both reservation and commitment for stack pages

Summary



- The subsystems are inter-related
  - file systems uses threads managed by the process subsystem
  - file systems uses buffer cache (managed by the memory subsystem)
  - memory subsystem uses threads to do background work
  - process subsystem keeps track of data structures related to files and virtual memory on behalf of processes

Summary



- To make sure you understand the big picuture
  - think of everything that happens in these subsystems when you type "ls" into a console
- Kernel 3 is where everything comes together
  - although we are already using a kernel memory map in earlier assignments (see `pt_init()`)