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

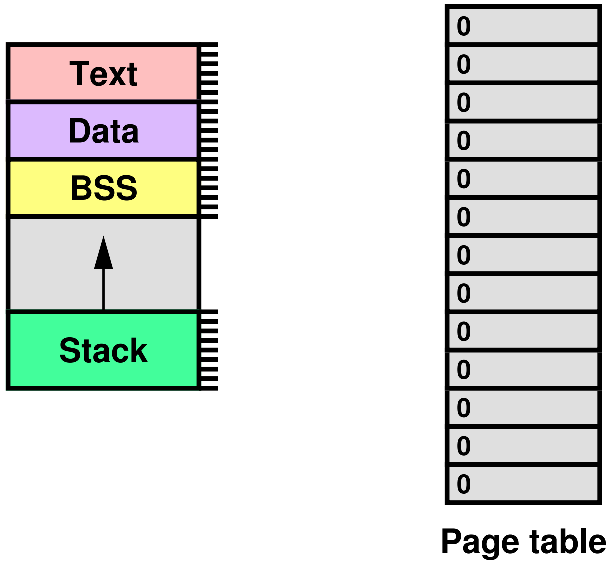
- *Fetch* policy
  - start process off with no pages in primary storage
  - bring in pages *on demand* (and only on demand)
    - this is known as *demand paging*
      - defer processing until you absolutely have to do it
      - why? because you may not have to process *at all*
      - *demand paging* 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**

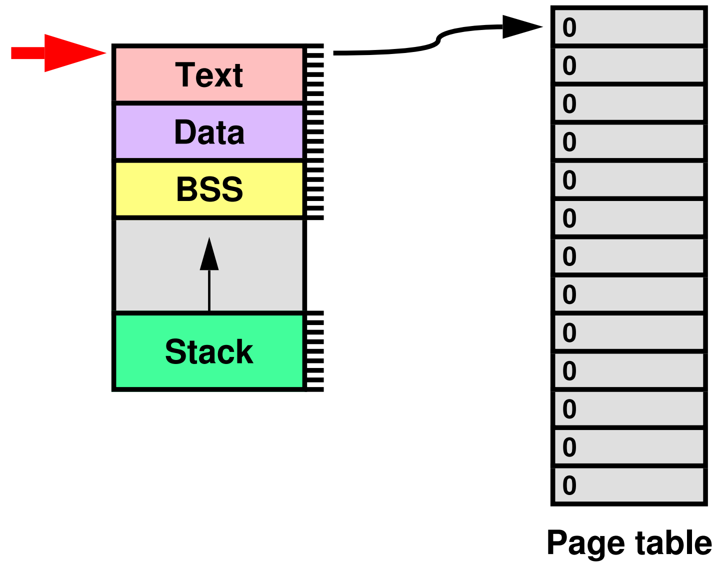
- ***Replacement*** **policy**
  - **required if there is not enough *resource* to go around**
  - **e.g., replace the page that has been in primary storage the longest (FIFO policy, which can be bad)**

Demand Paging



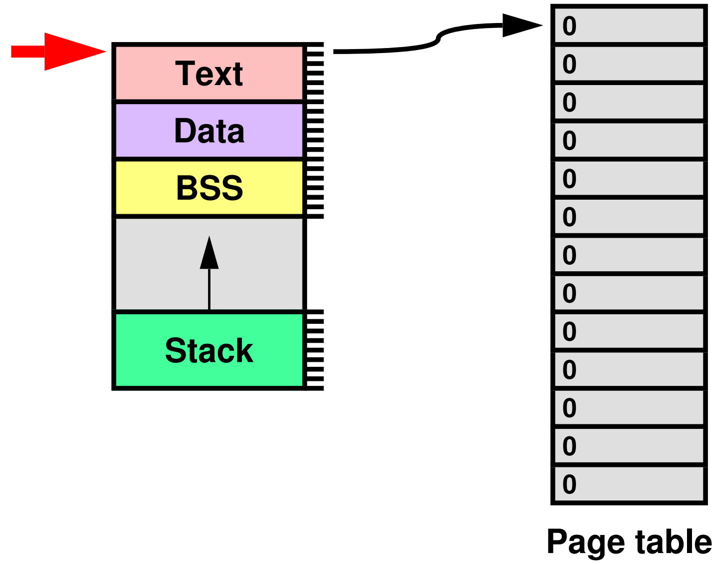
- After `exec()` is called, a page table is created with all entries having V=0

Demand Paging



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

Demand Paging



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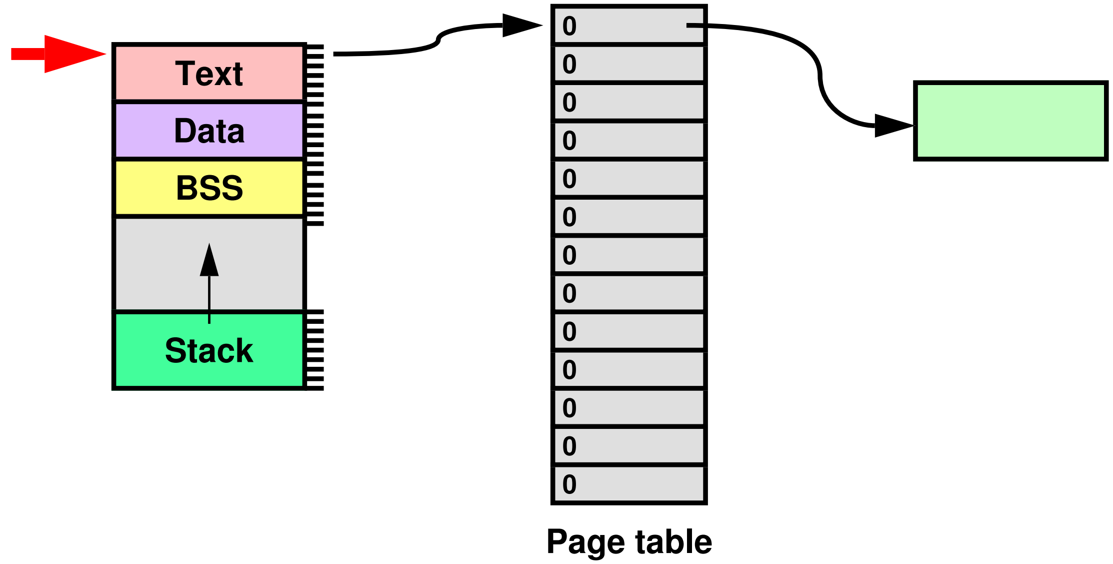
  - as the first instruction executes
    - since V=0, the hardware traps into the kernel

Demand Paging



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

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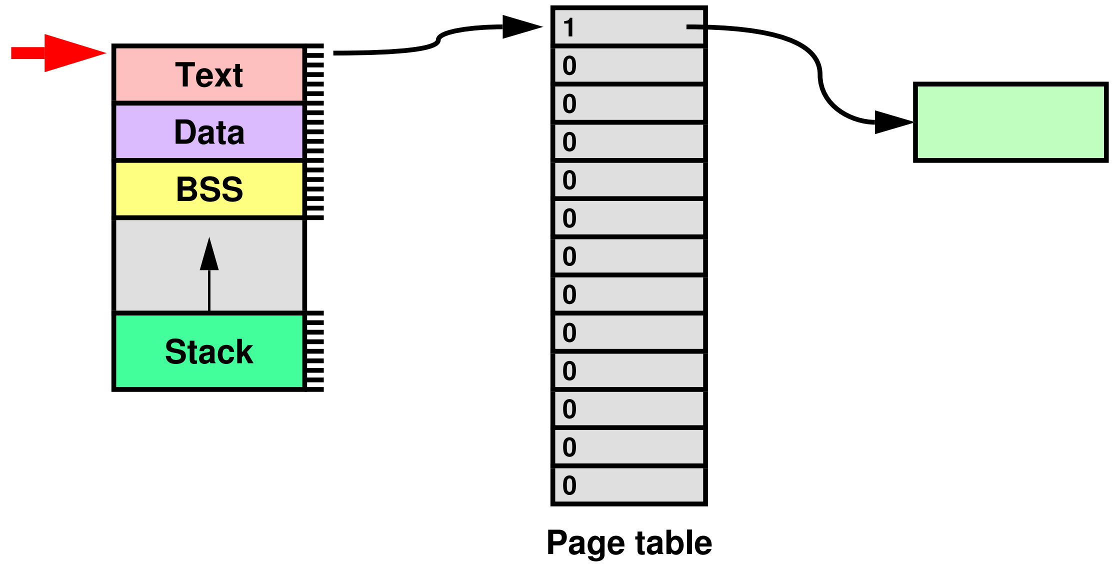

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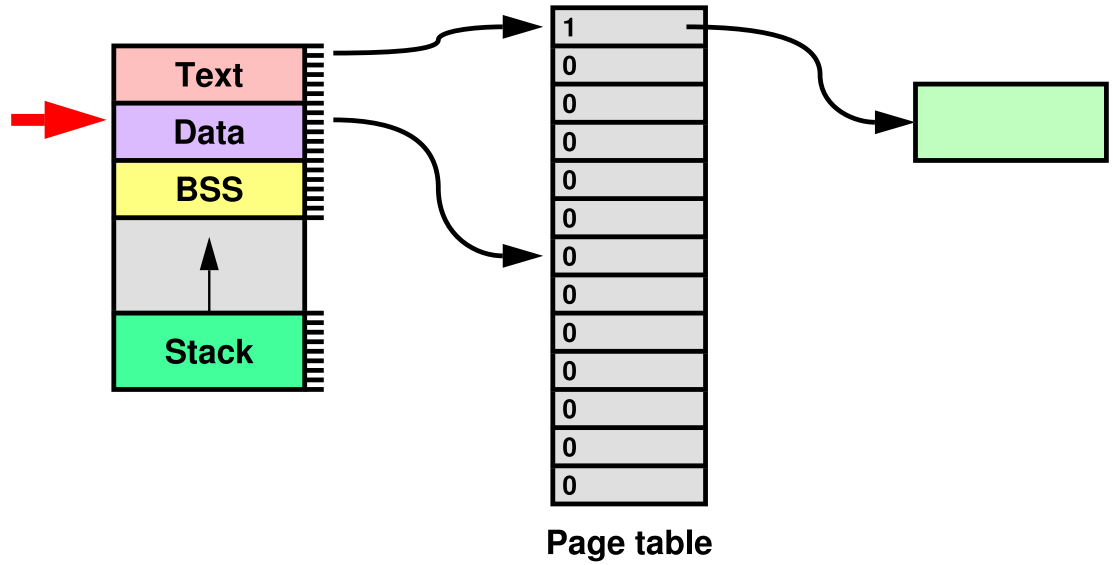
    - the kernel *allocates a physical page* and copy the first 4KB of code into this page (allocate from where?)
      - point the corresponding page table entry to this page
      - update all necessary data structures
    - set V=1 and return from the trap

Demand Paging



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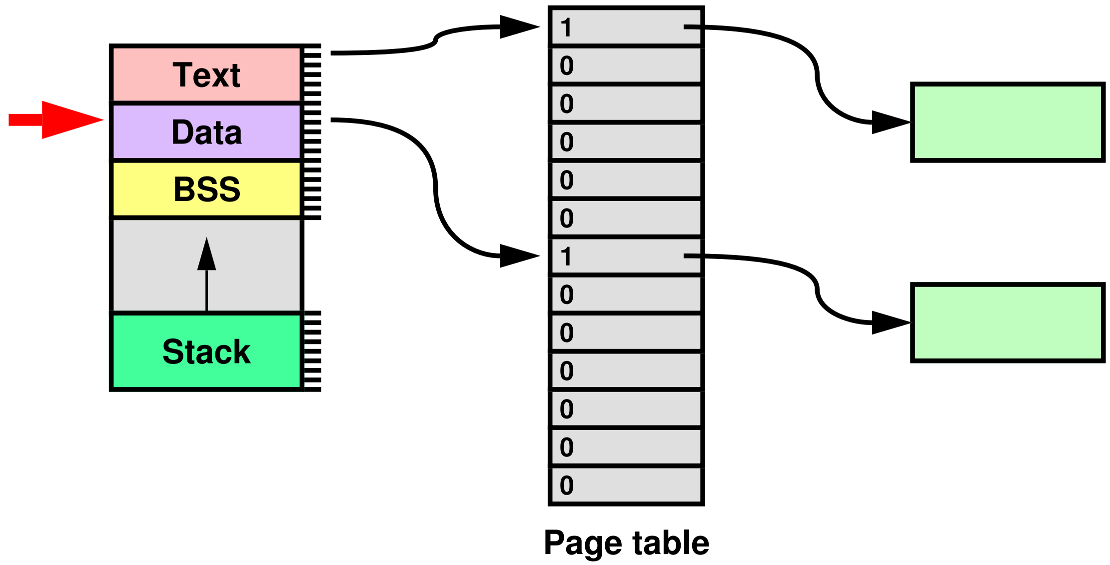

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    - similar things happen

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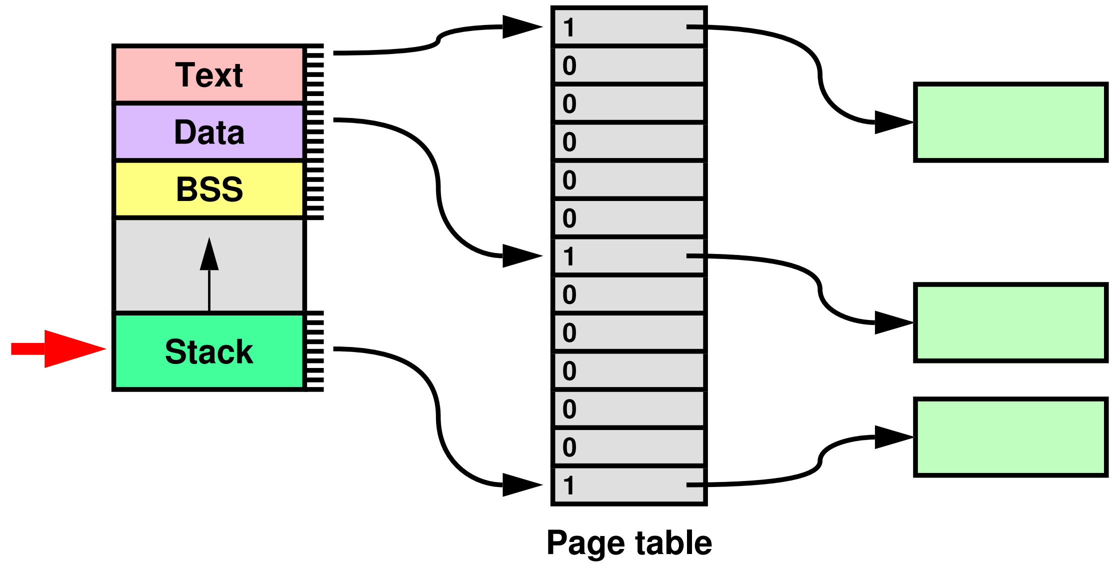
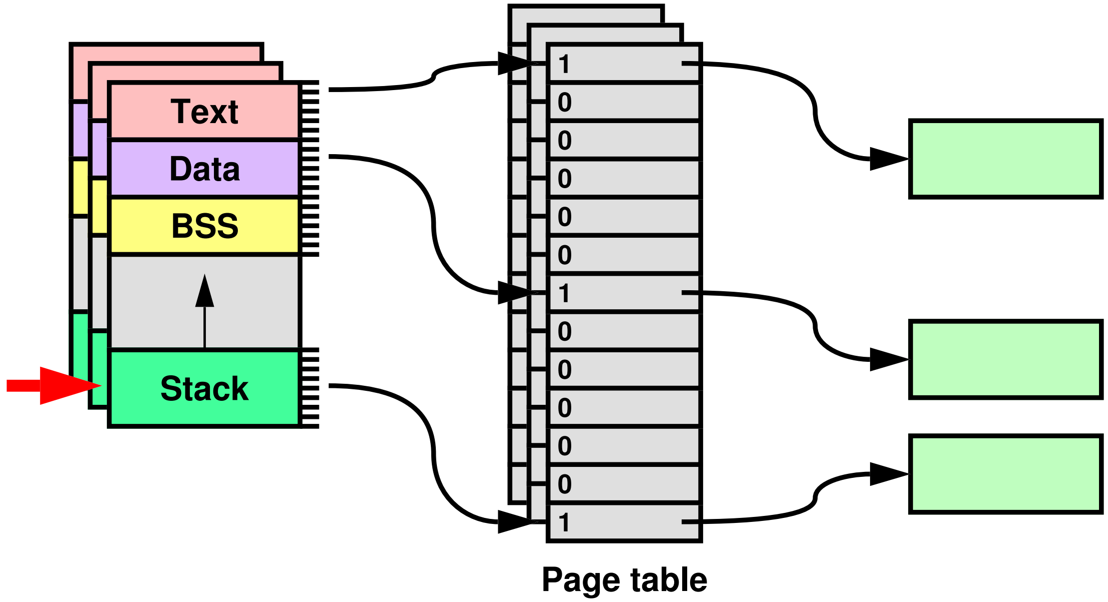
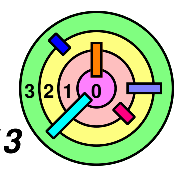


- After `exec()` is called, a page table is created with all entries having V=0
  - as the program reference the data segment or access the stack
    - similar things happen
    - although stack is a little different since it has to have a backing store

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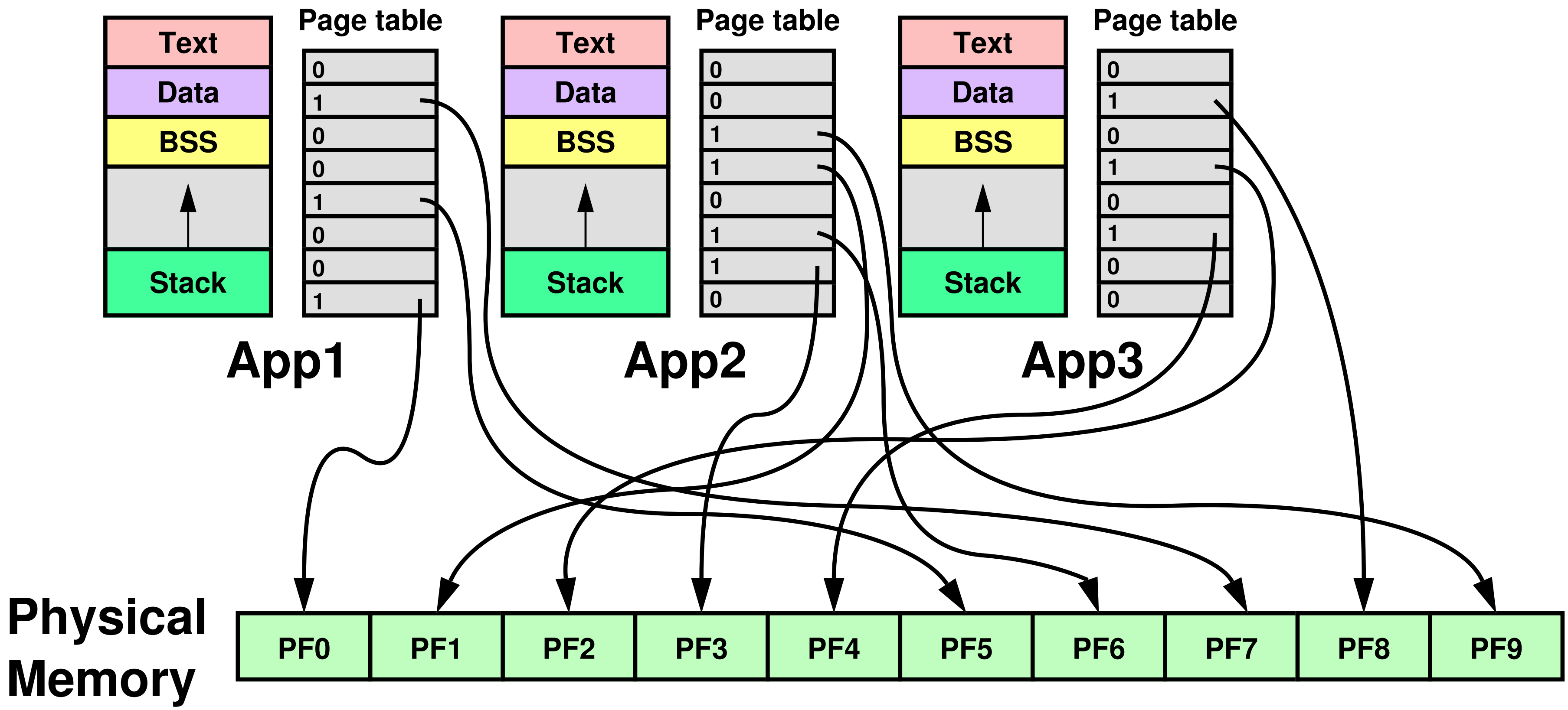
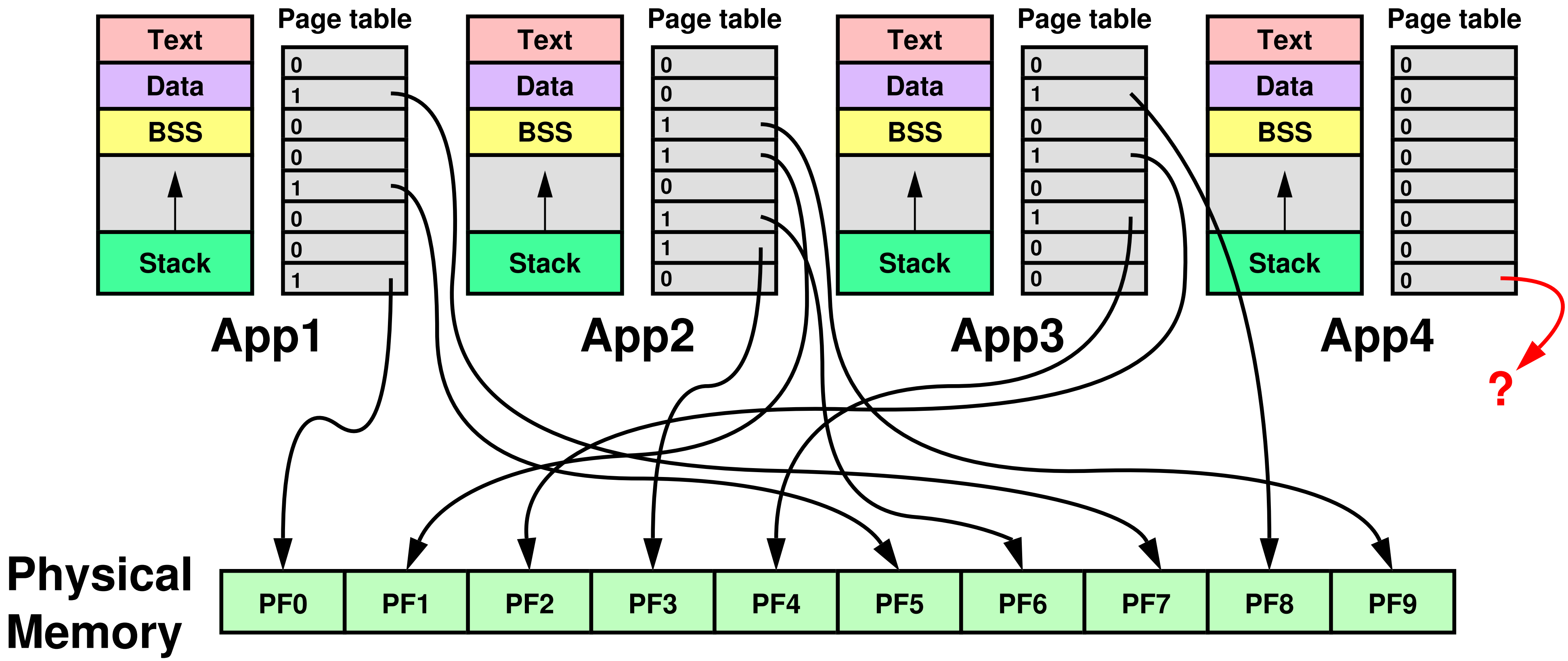
- Issues
  - in step (2), where and how do we find such a ***free physical page***?
    - the Buddy System is used
      - return NULL if no free physical page is available
  - in step (3), where and how do we find a ***physical page*** to write out to disk?

Example

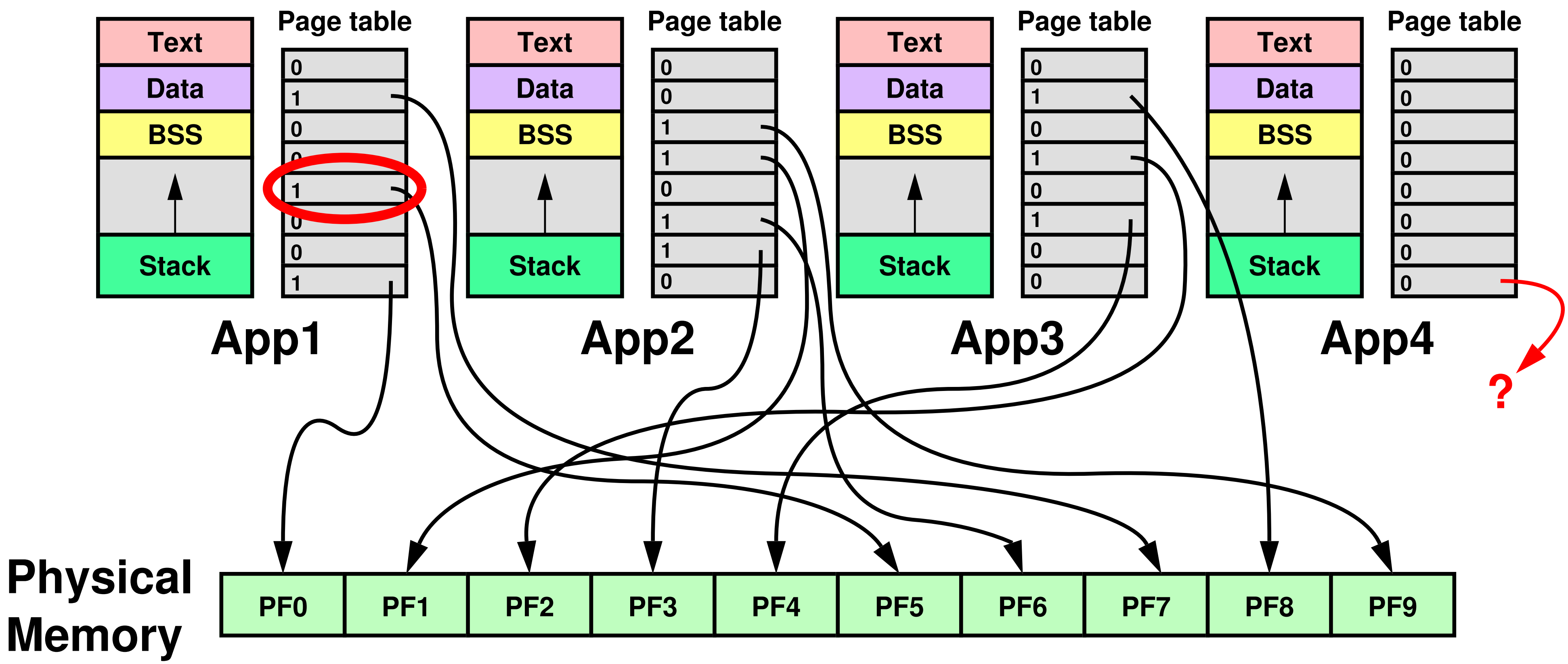

Text
Data
BSS
Stack
Page table
0
1
0
0
1
0
0
1
App1
Text
Data
BSS
Stack
Page table
0
0
1
1
0
1
1
0
App2
Text
Data
BSS
Stack
Page table
0
1
0
1
0
1
0
0
App3
Physical Memory
PF0
PF1
PF2
PF3
PF4
PF5
PF6
PF7
PF8
PF9

Example



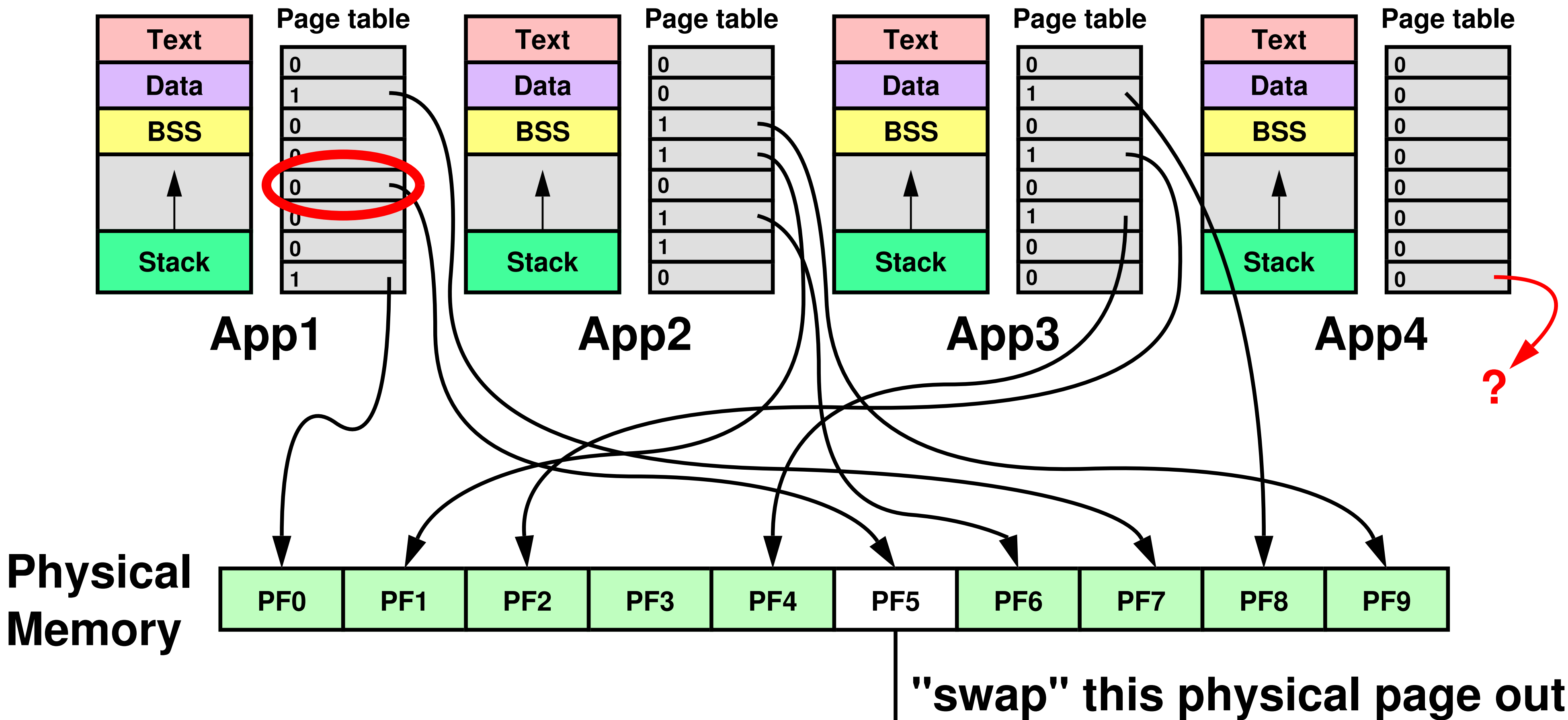
- Need a physical page
  - all physical pages are in use

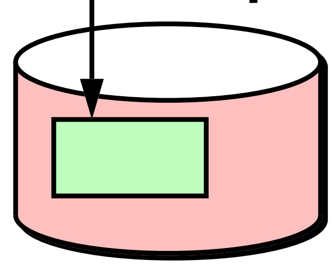
Example



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

Example





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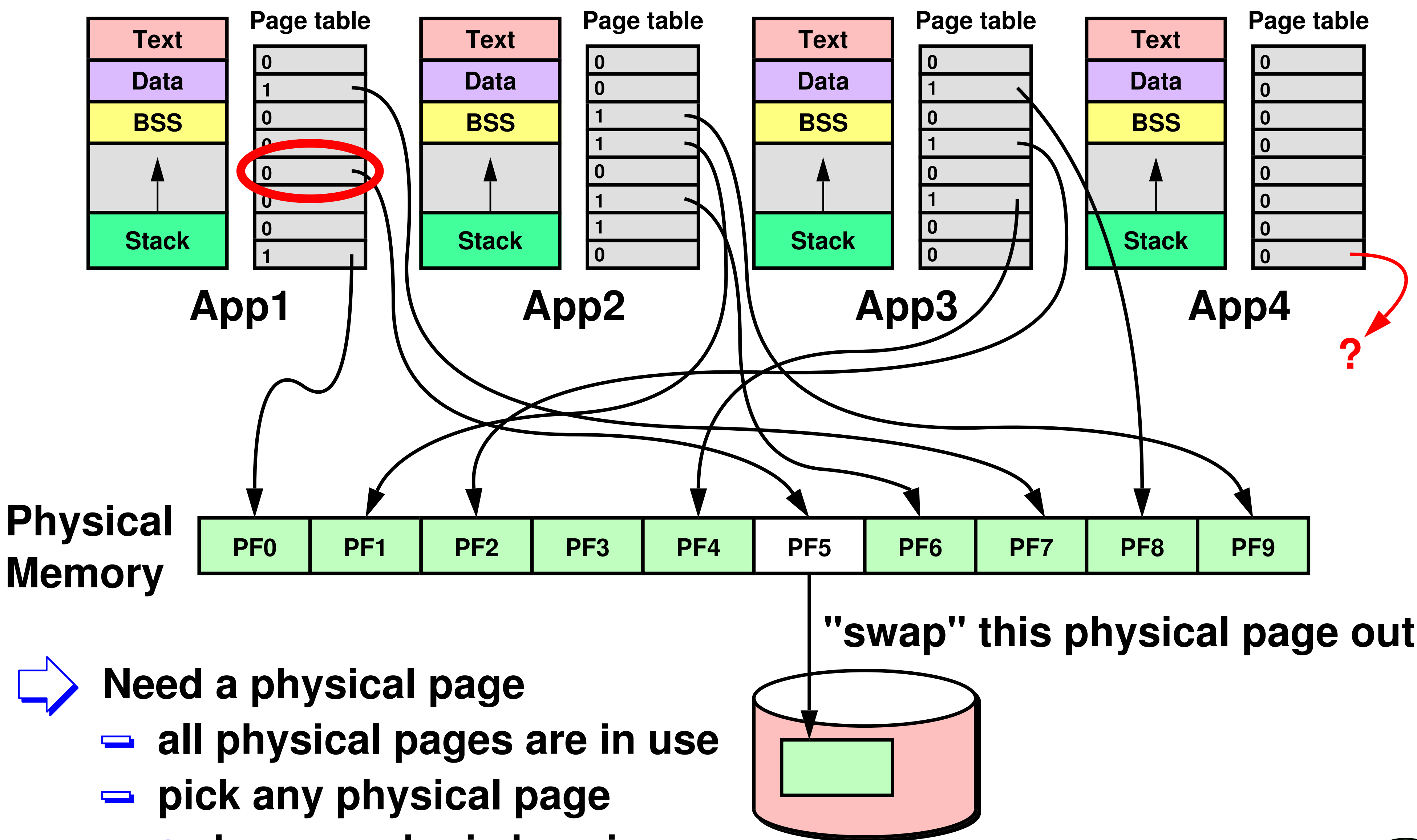
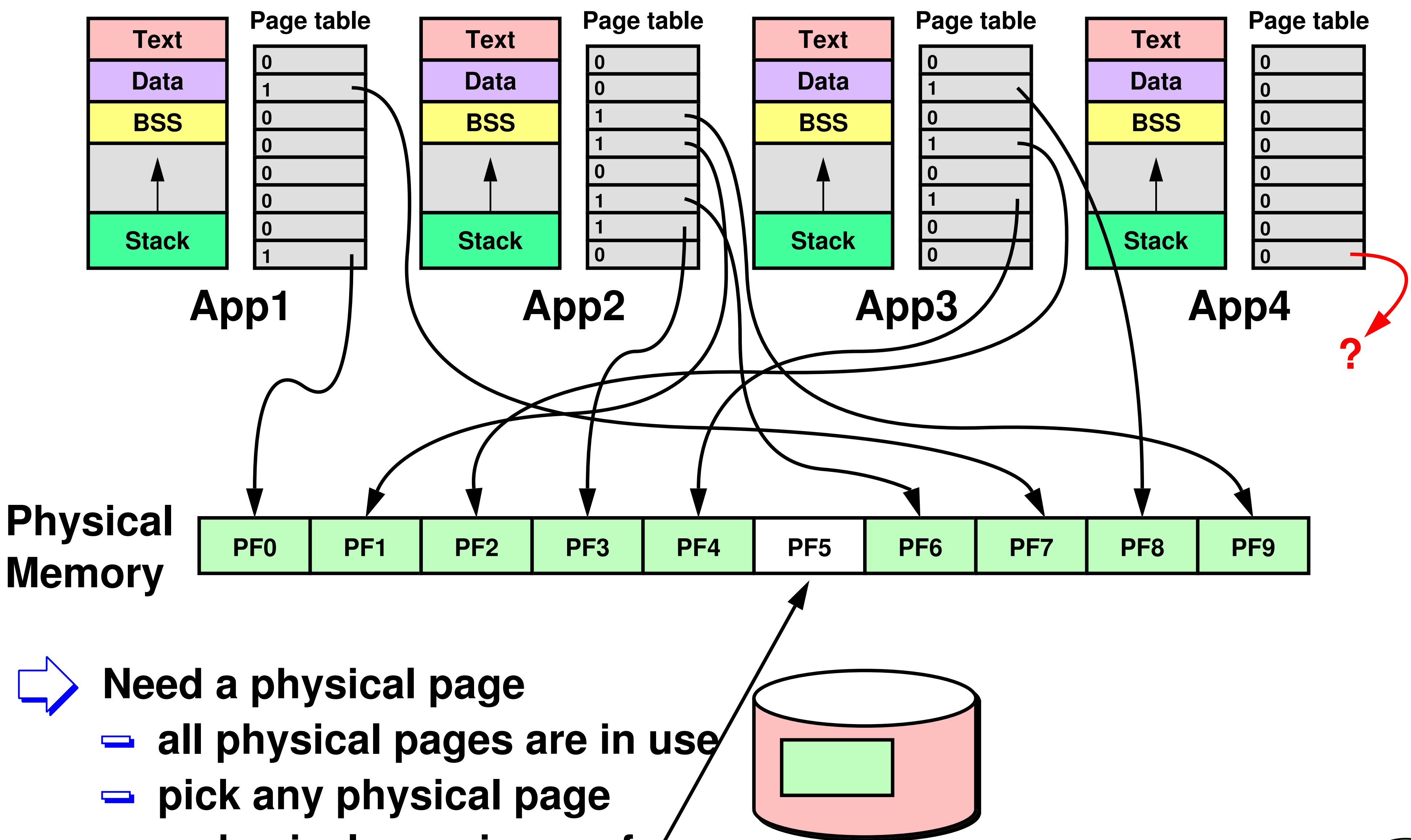


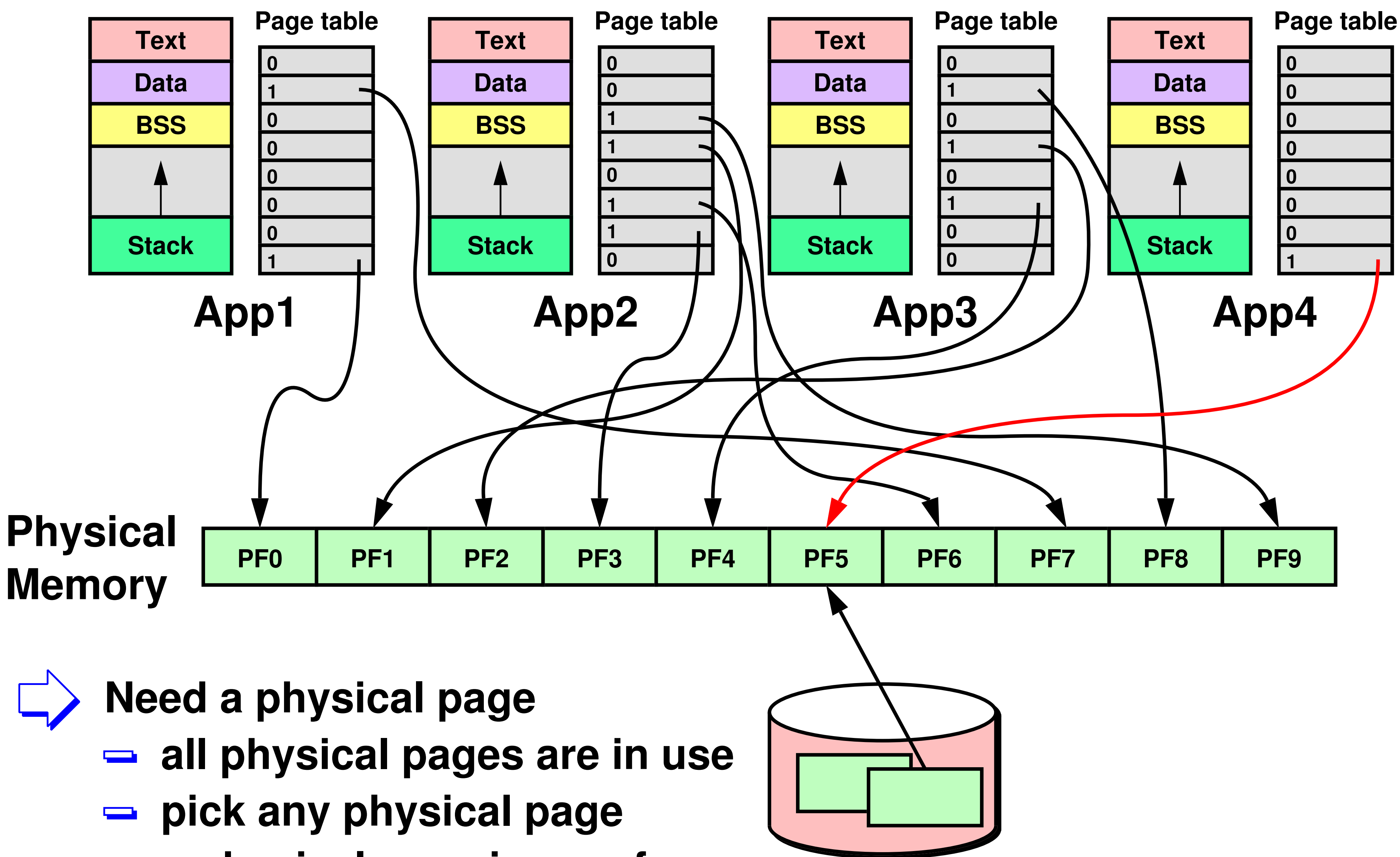
- Need a physical page
  - all physical pages are in use
  - pick any physical page
    - hmm... who is keeping track of where the physical page got copied to?

Example



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

Example



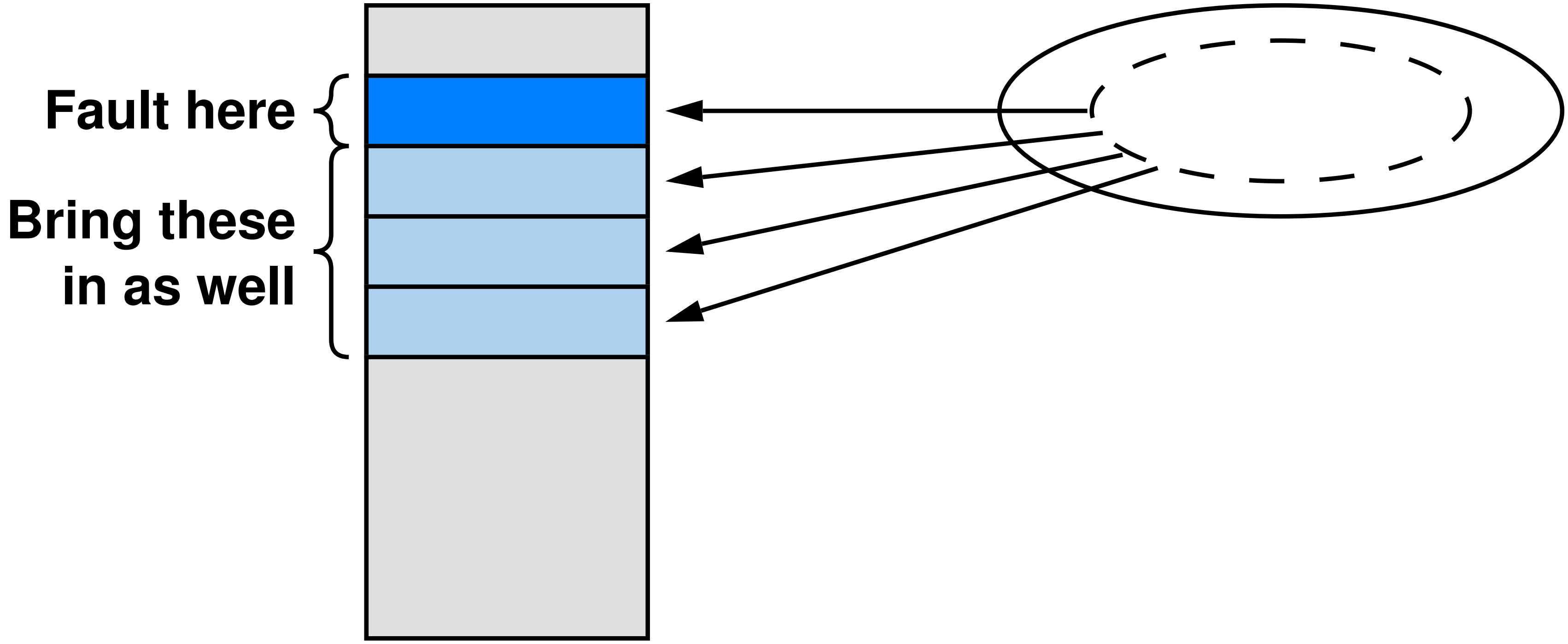
- Need a physical page
  - all physical pages are in use
  - pick any physical page
  - a physical page is now free
  - fetch page from disk and fix up page table

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



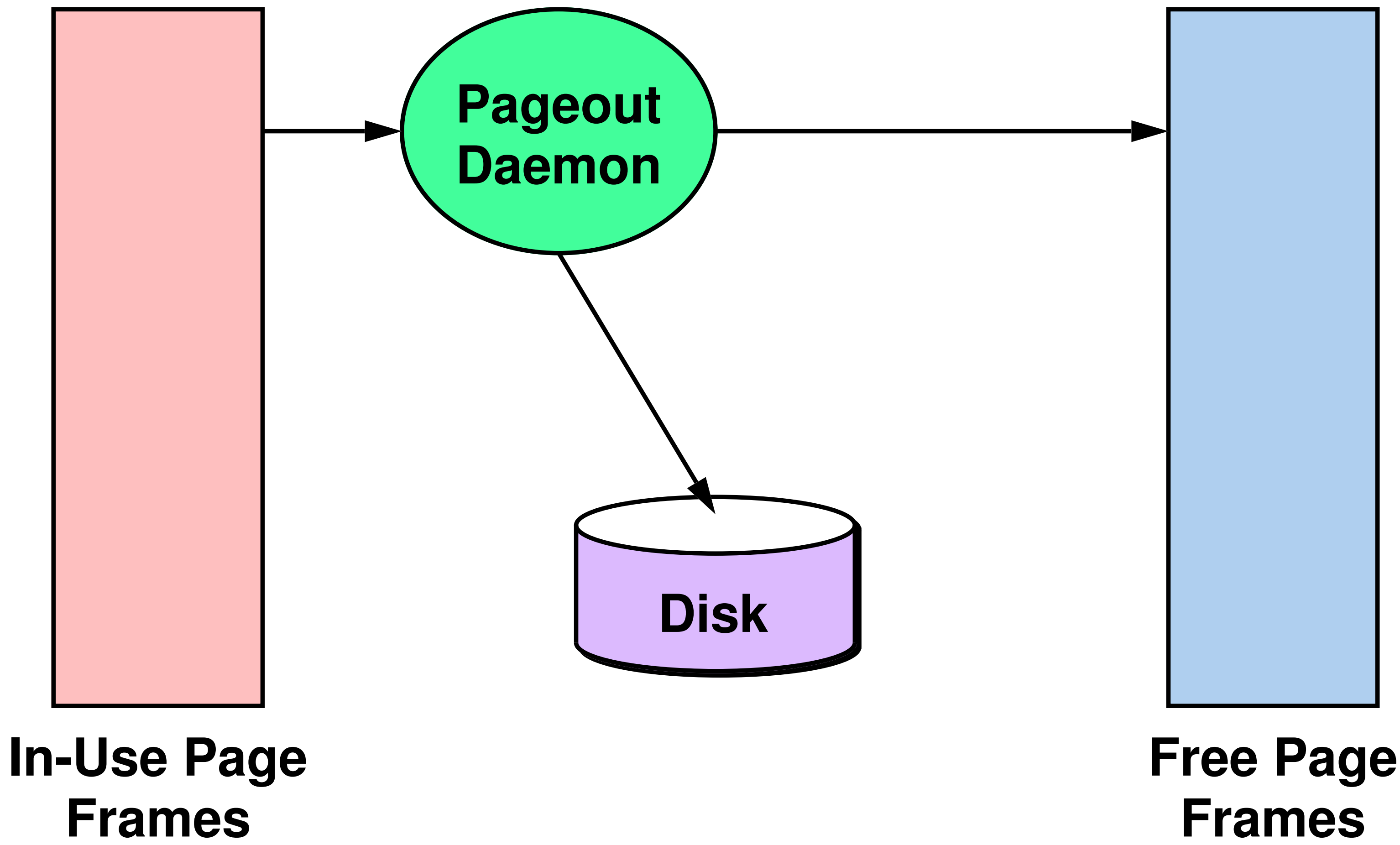
- This is *prefetching*, as we have seen before
  - accesses to pages is often sequential
  - gamble that this is worthwhile (since it takes up more memory)
- This improves step (4) on previous page
  - but it uses up physical memory faster
  - and what about steps (2) and (3)?

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"



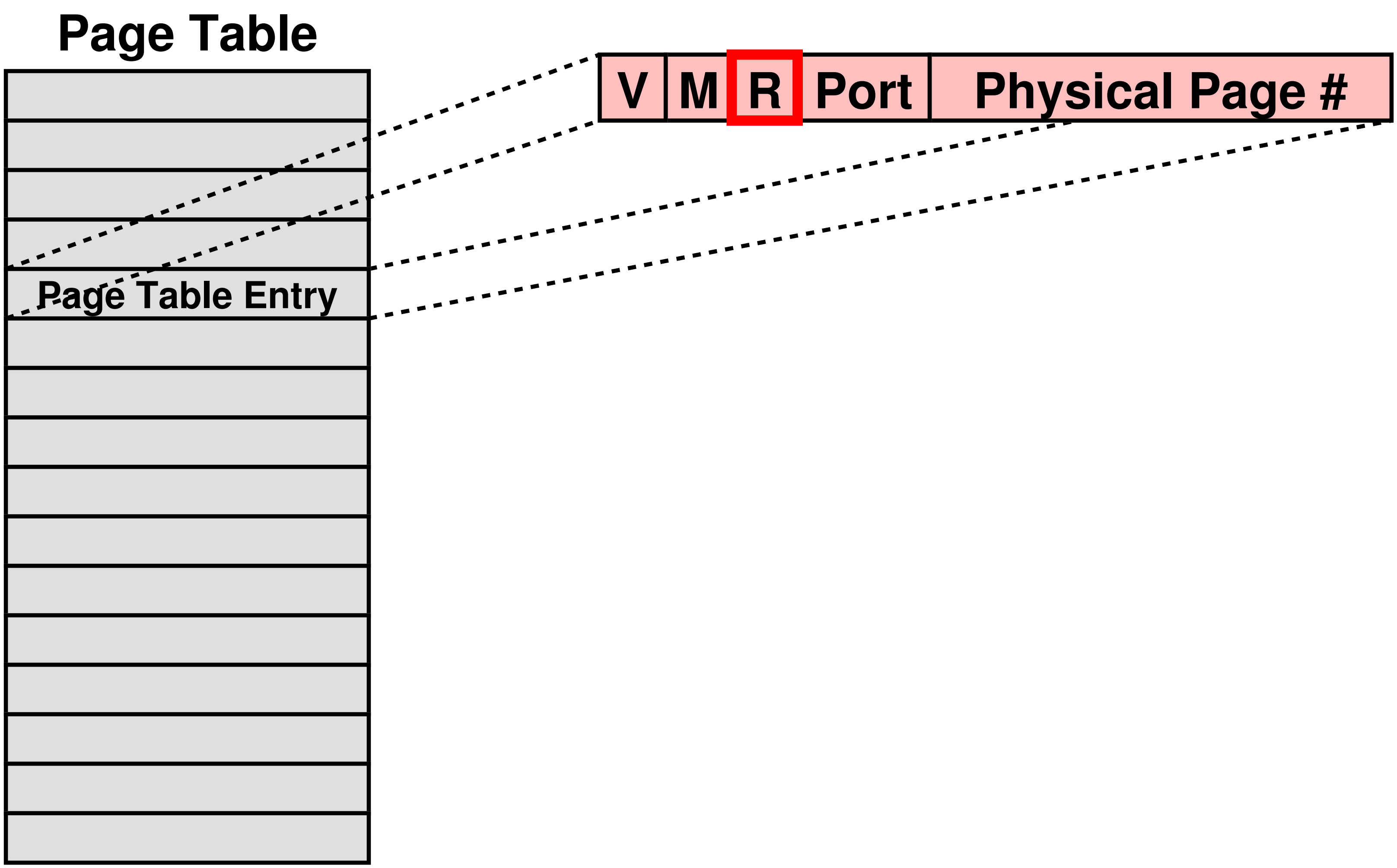
- ***Page frames*** **are used to keep track of physical pages**
- **Can use *multiple* pageout daemons**

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?

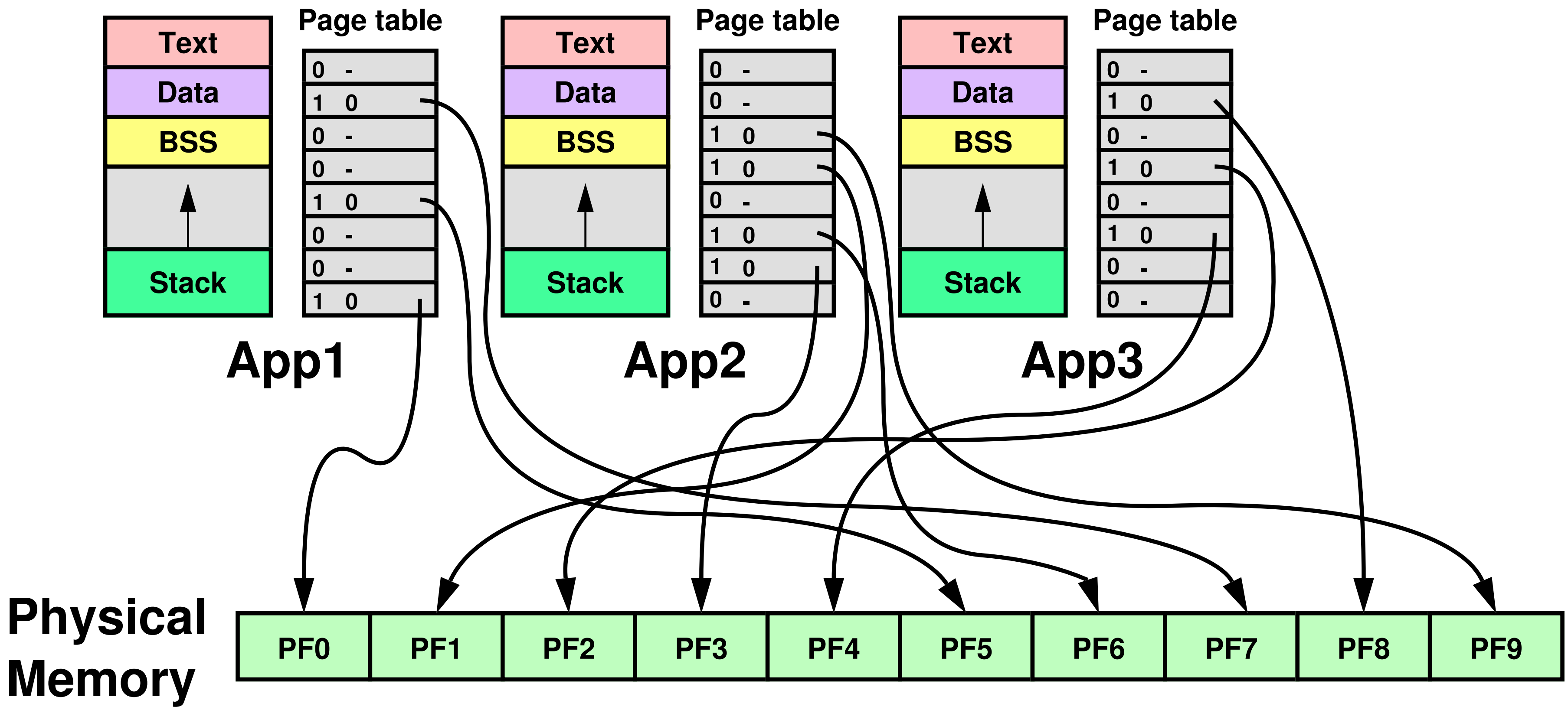
- Idealized policies:
  - FIFO (First-In-First-Out)
  - LRU (Least-Recently-Used)
  - LFU (Least-Frequently-Used)

Implementing LRU



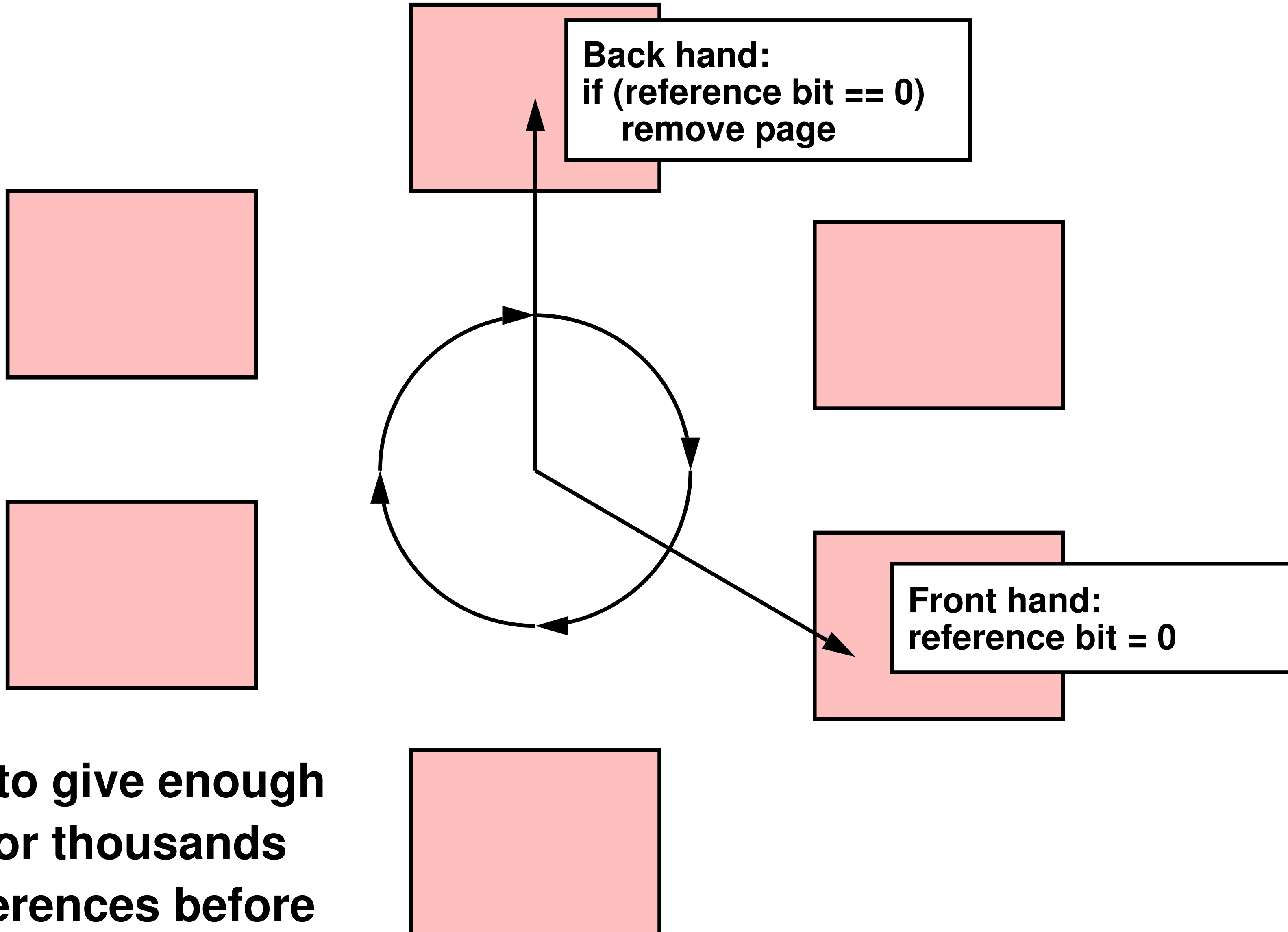
- To approximate LRU (a very coarse approximation), the *reference* bit in the page table entry is used

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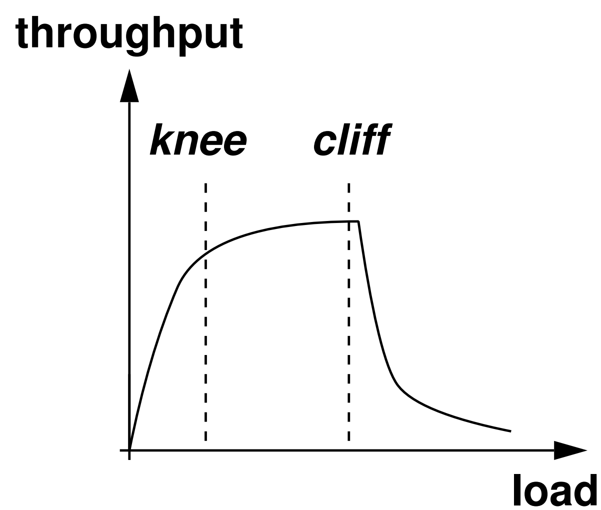
- ...
  - neither processes makes progress
- The problem
  - need 3 physical page frames, but only 2 are available



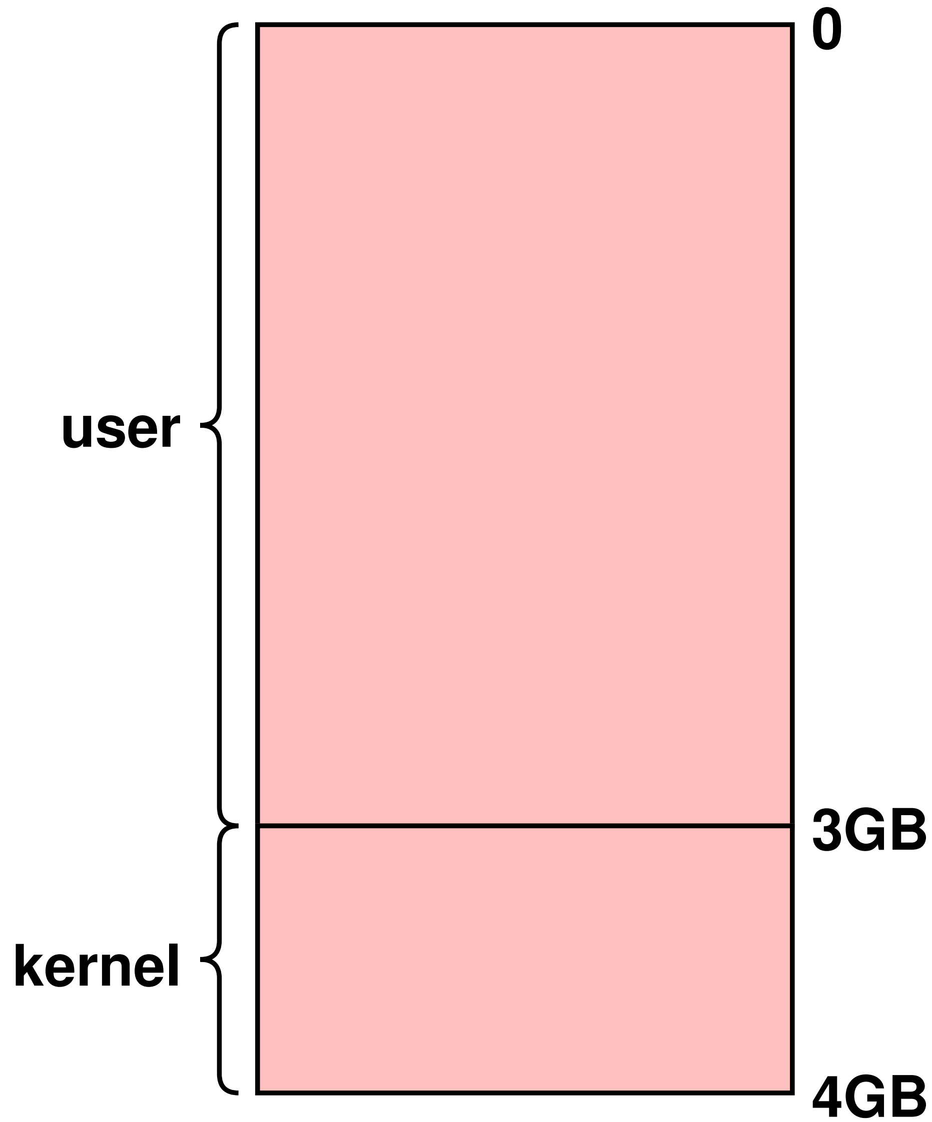
The Working-Set Principle

- 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*

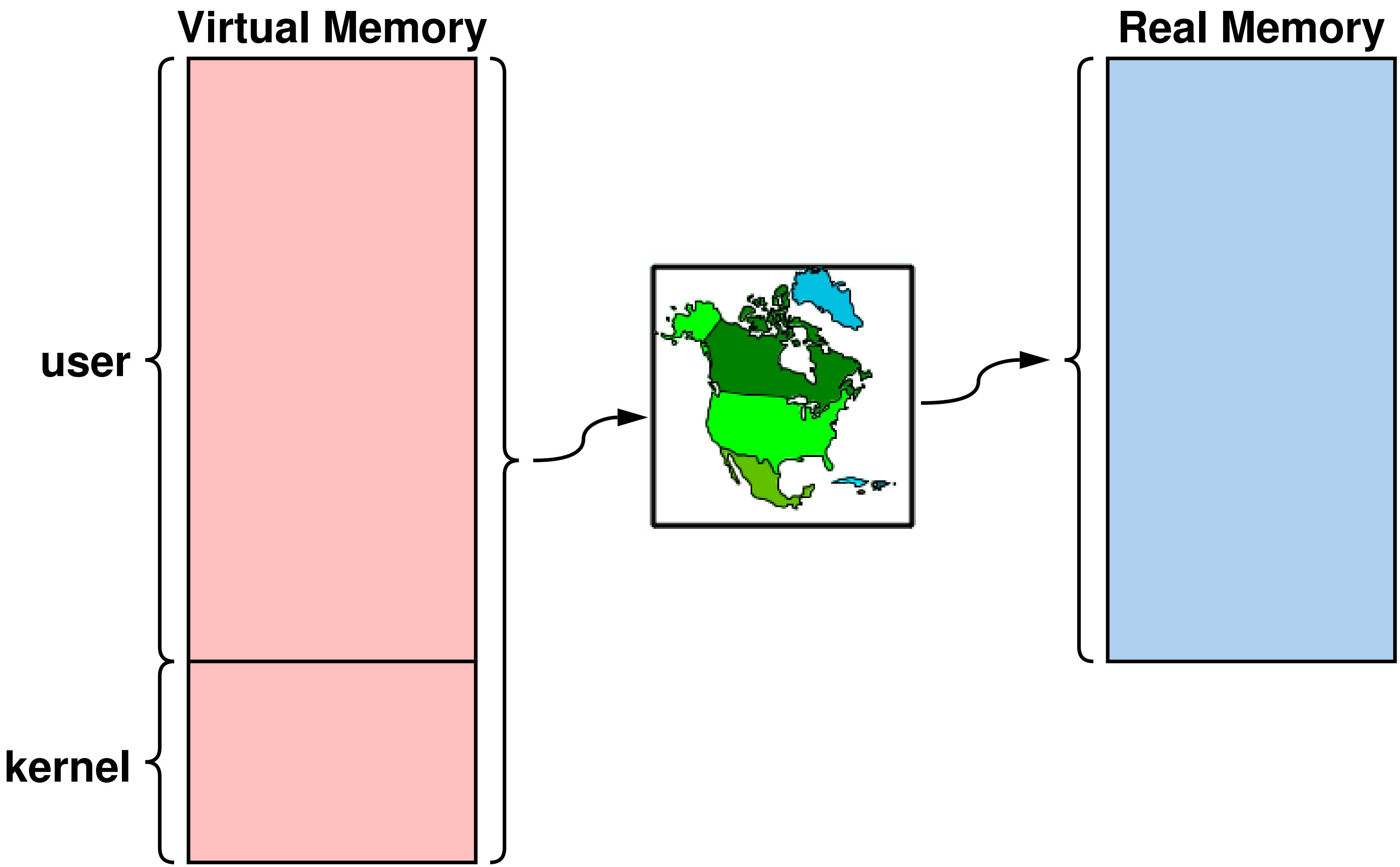
7.3 Operating System Issues

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

Linux Intel x86 VM Layout



Real Memory

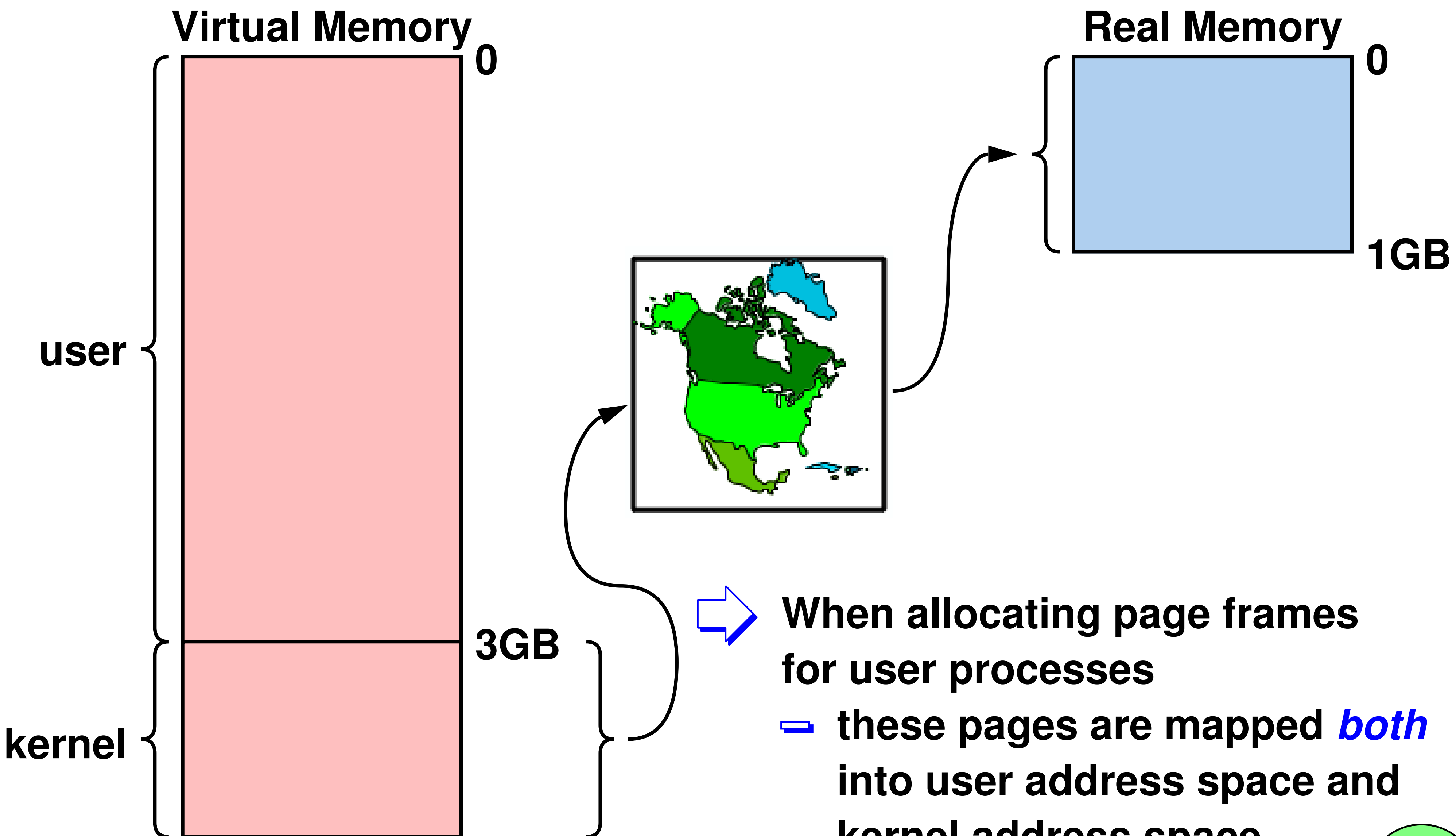


Memory Allocation

- User
  - virtual allocation
    - fork
    - pthread_create
    - exec
    - brk
    - mmap
  - real allocation
    - (not done)

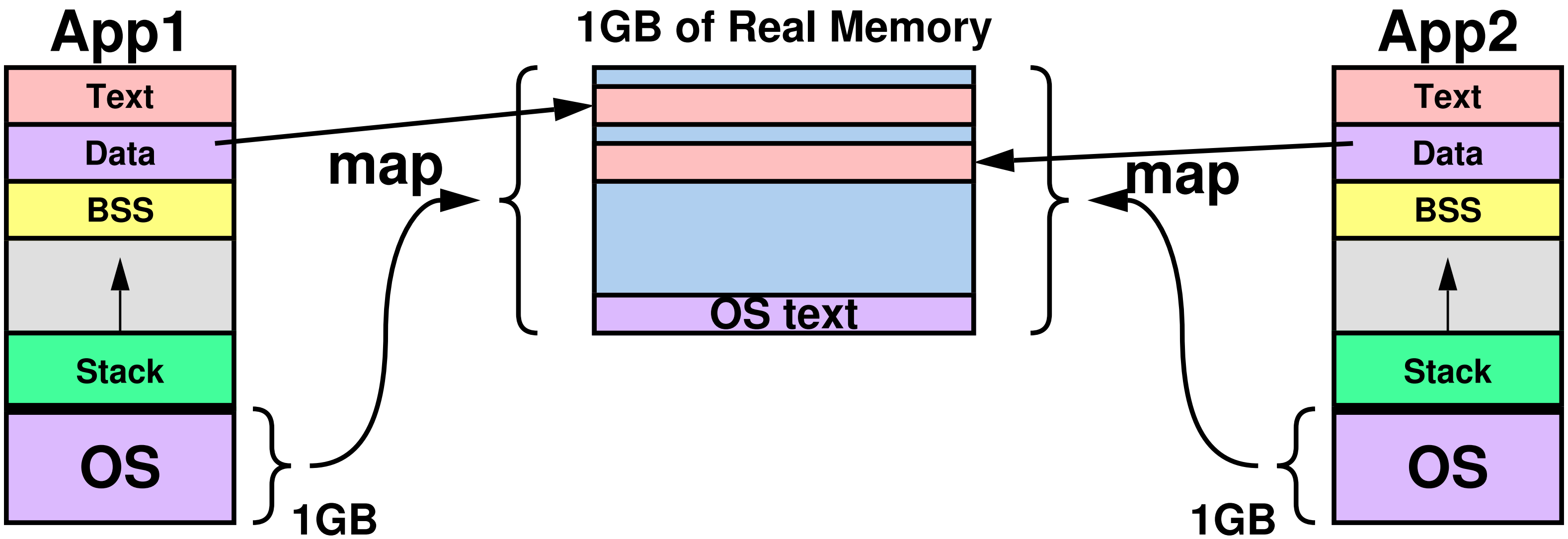
- OS kernel
  - virtual allocation
    - fork, etc.
    - kernel data structures
  - real allocation
    - page faults
    - kernel data structures
      - e.g., page tables

Example: 1GB Of Real Memory



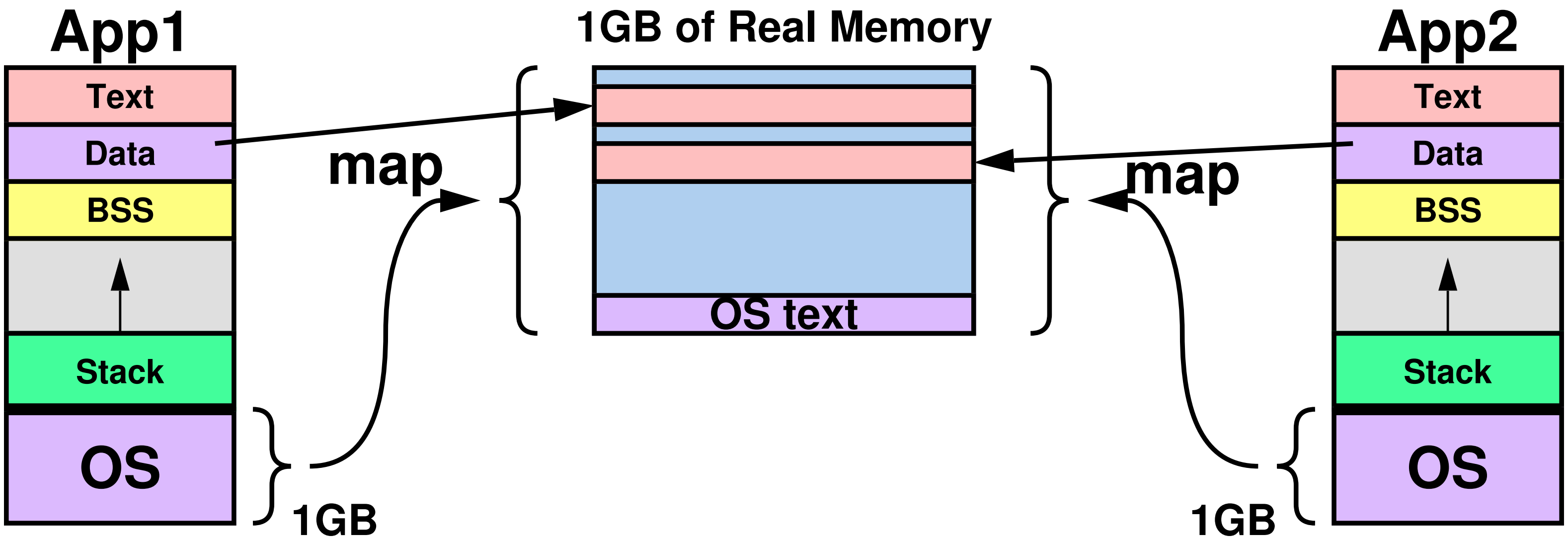
- When allocating page frames for user processes
  - these pages are mapped ***both*** into user address space and kernel address space

Example: 1GB Of Real Memory



- 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

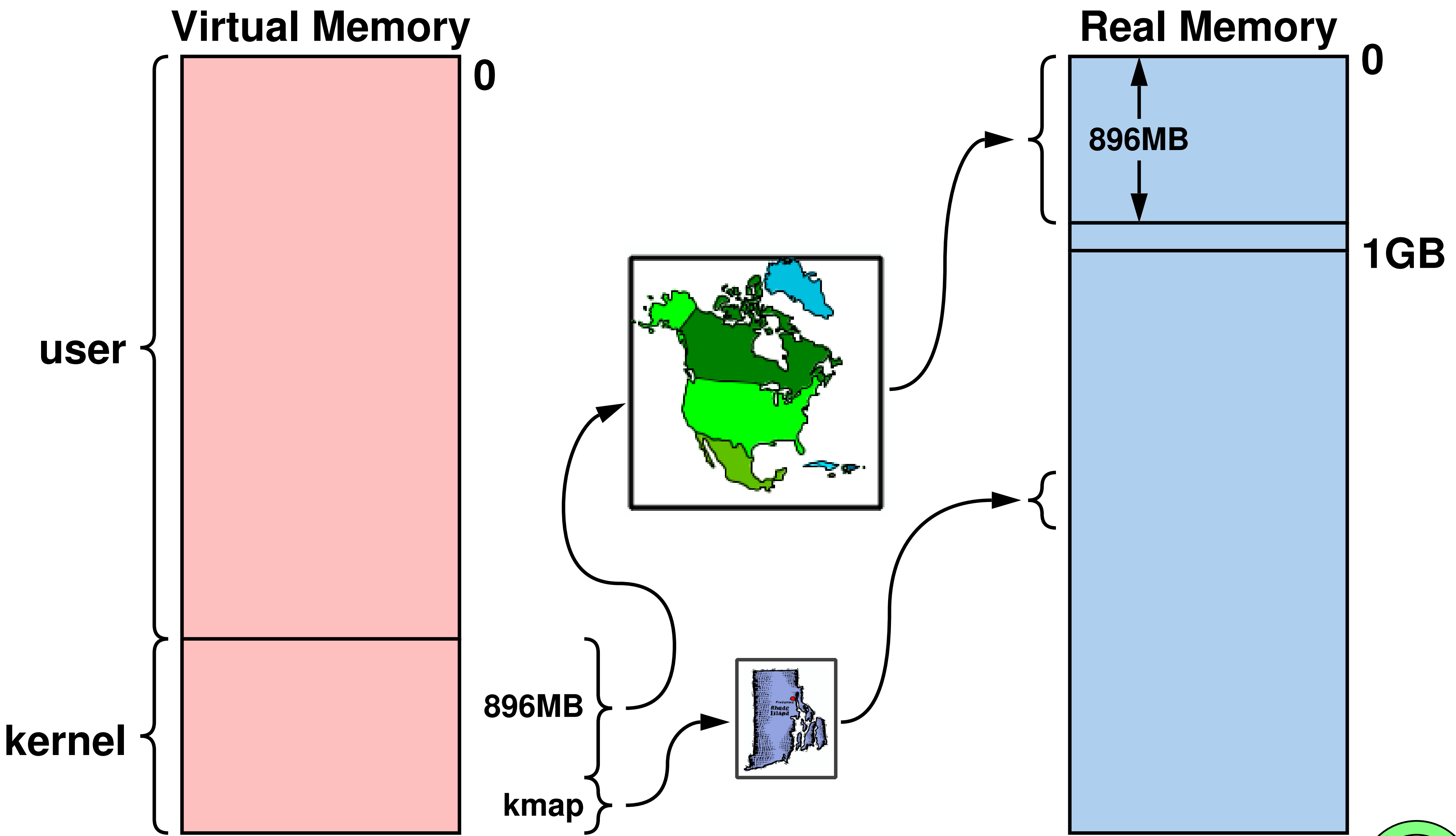
Example: 1GB Of Real Memory



- 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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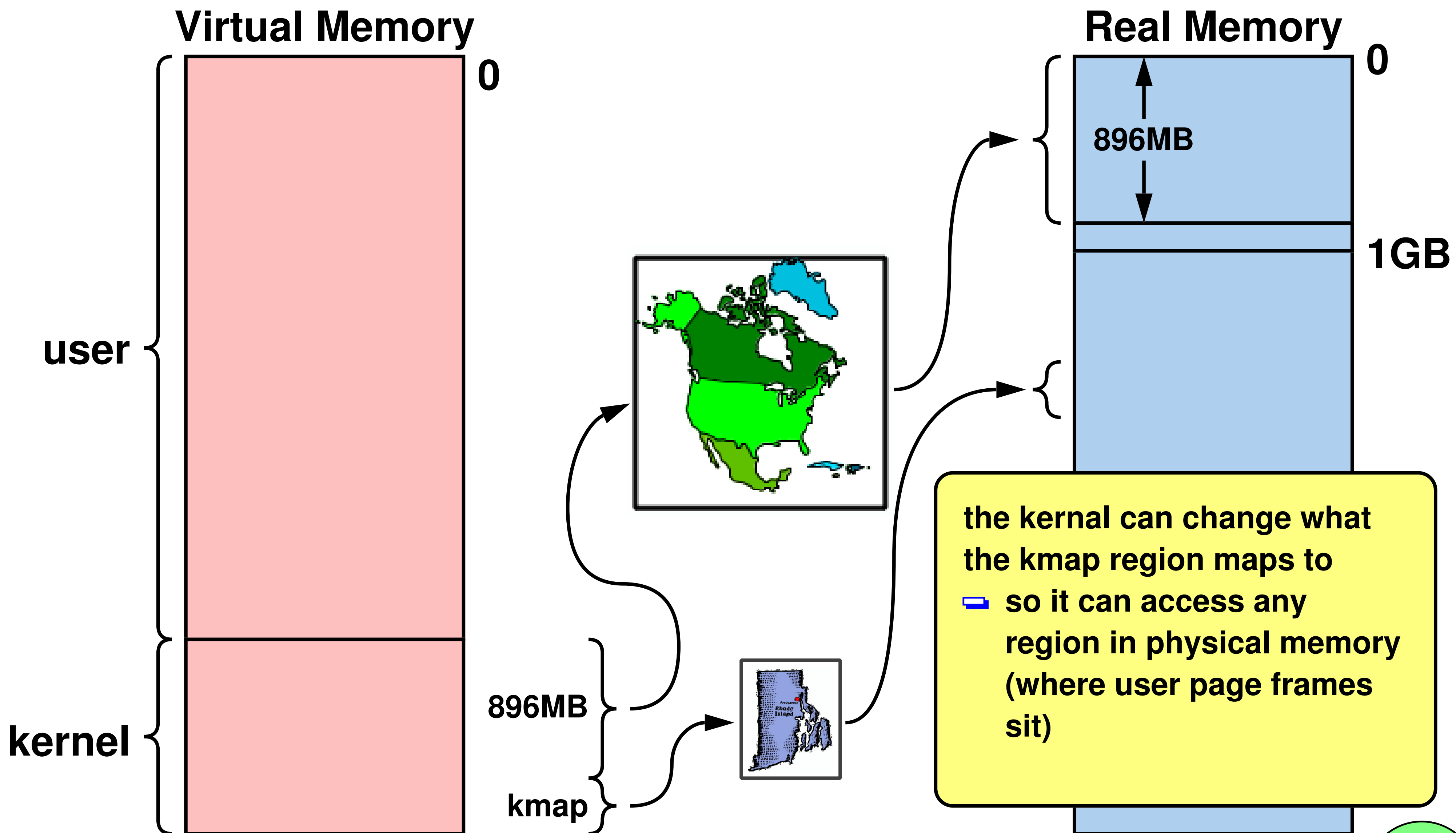


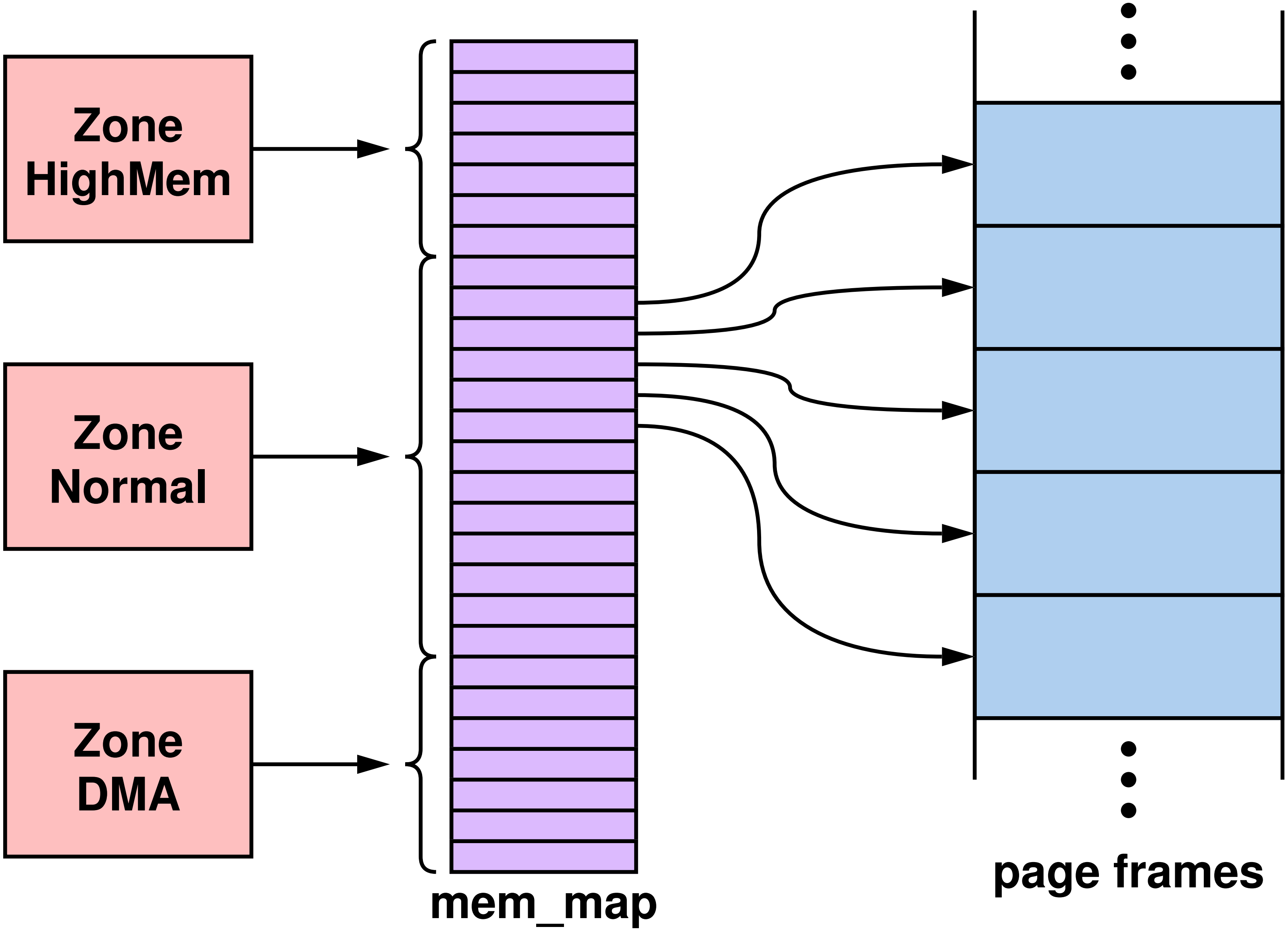
the kernal can change what the kmap region maps to

- so it can access any region in physical memory (where user page frames sit)

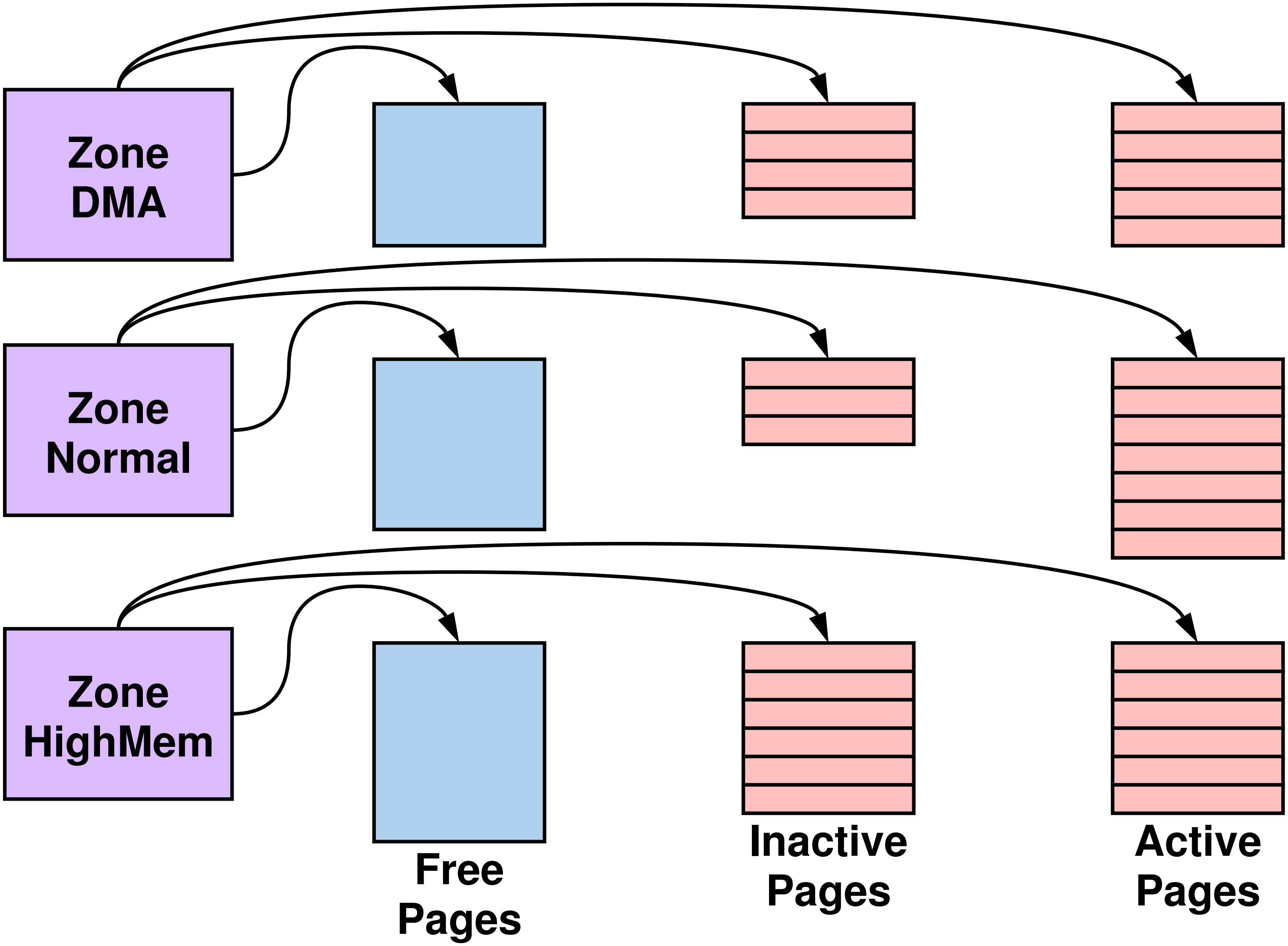
Mem_map and Zones

- **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



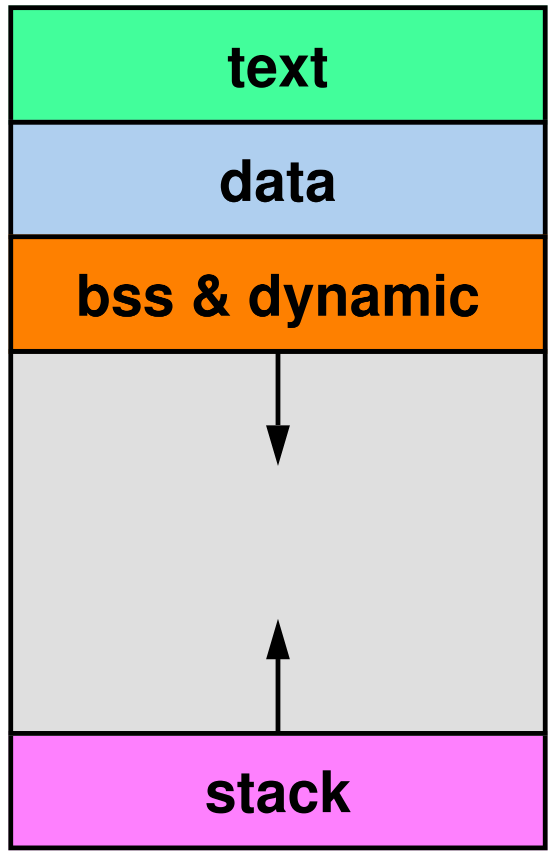
Page Lists


Zone
DMA
Zone
Normal
Zone
HighMem
Free
Pages
Inactive
Pages
Active
Pages

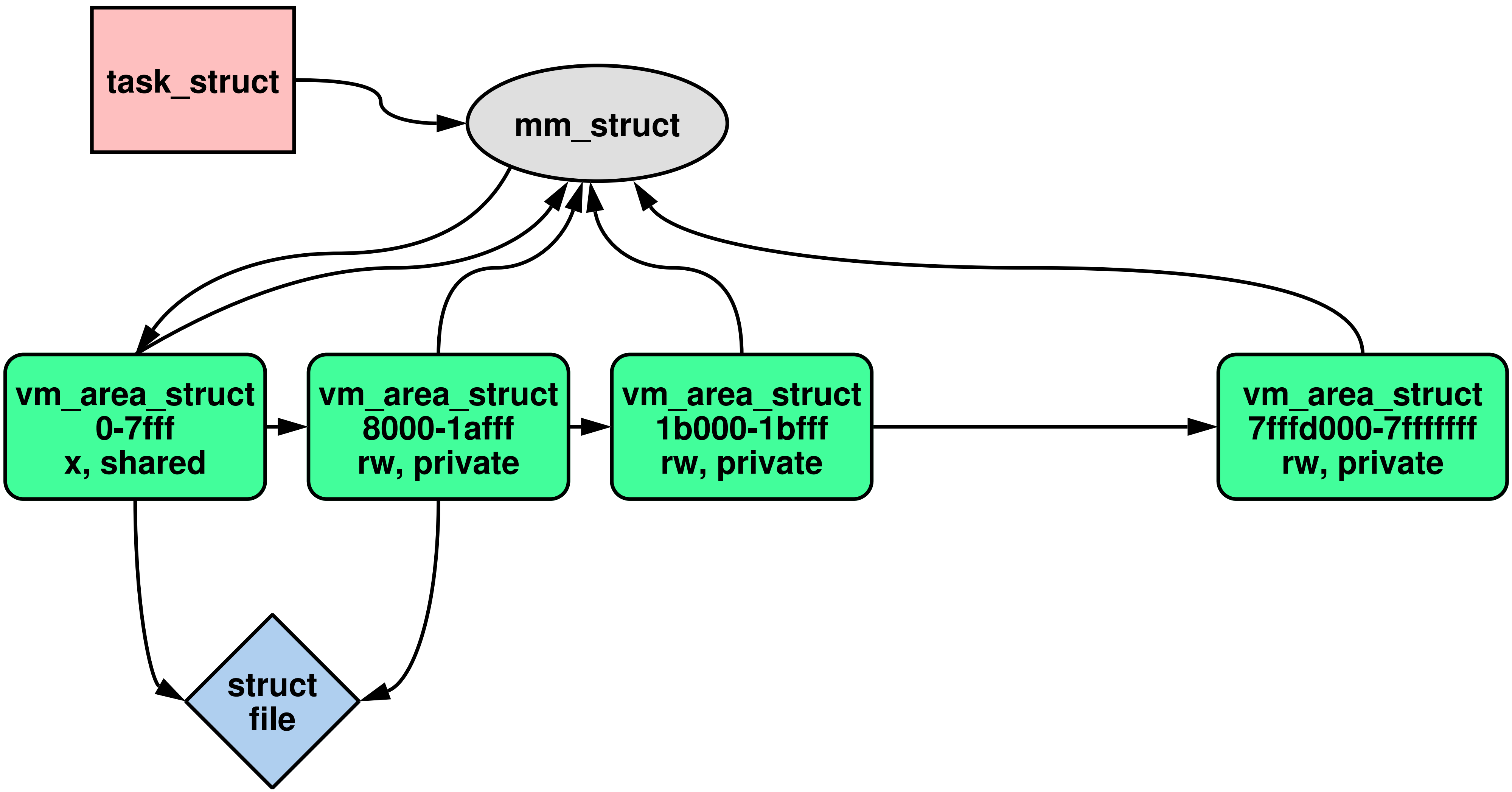
Page Lists

- 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

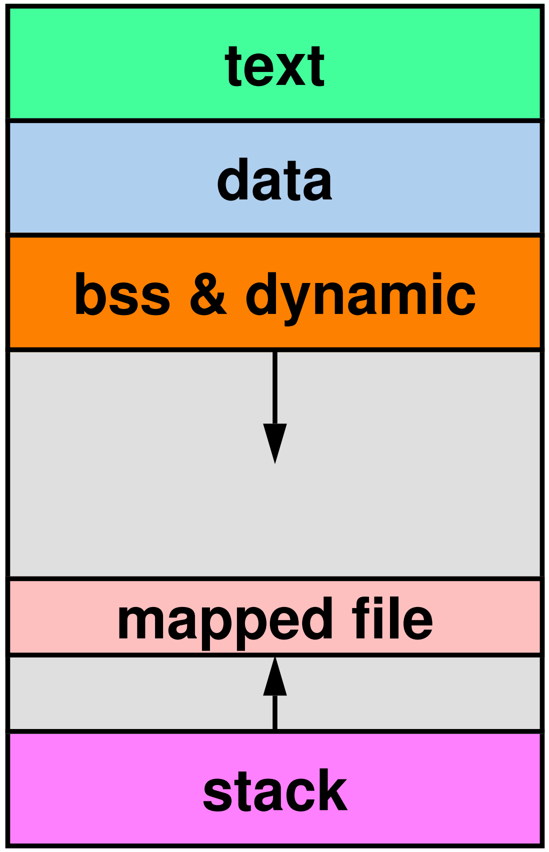


Address-Space Representation (Somewhat Simplified)

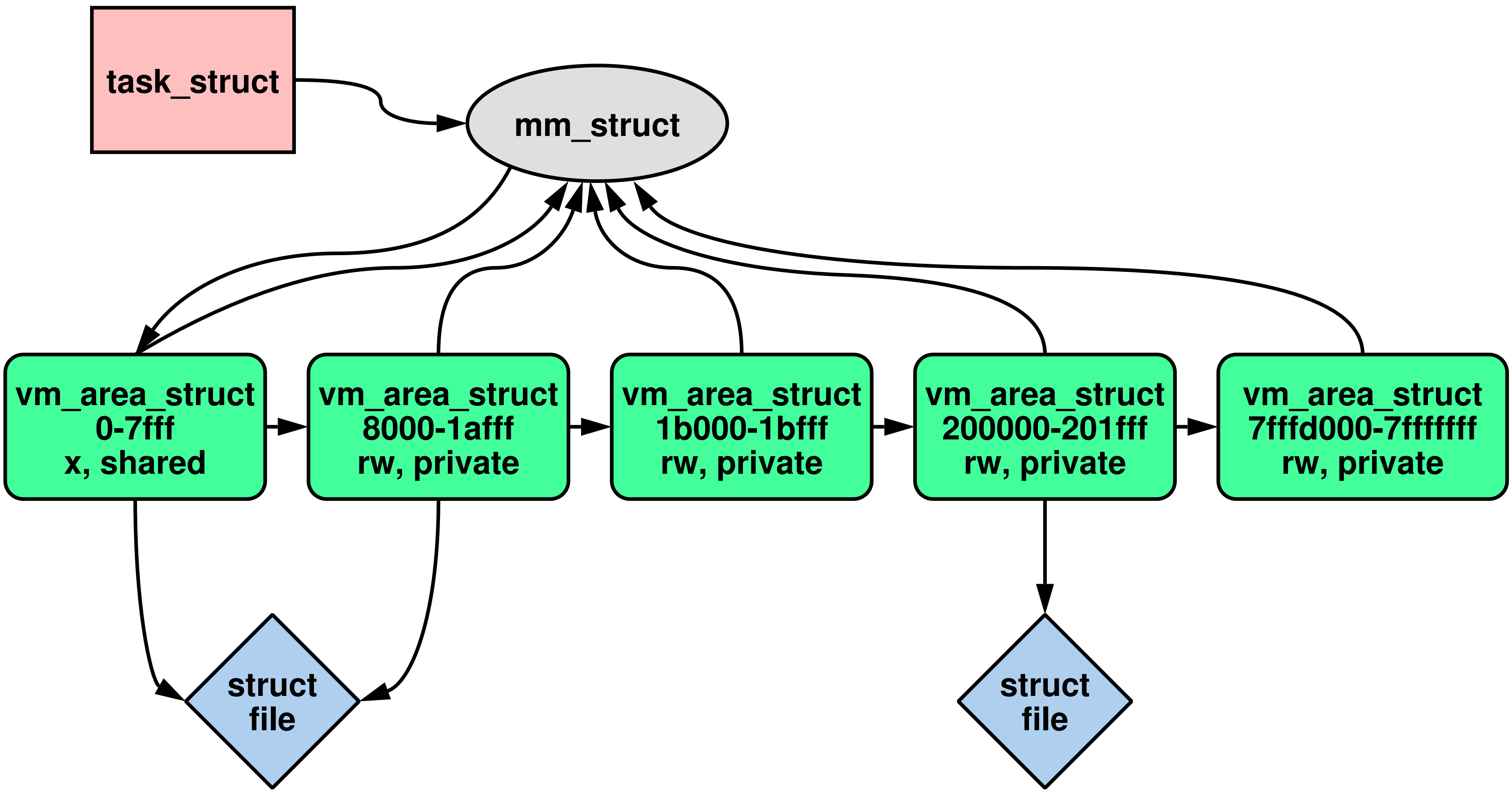


- `vm_area_struct` is what we used to call `as_region`

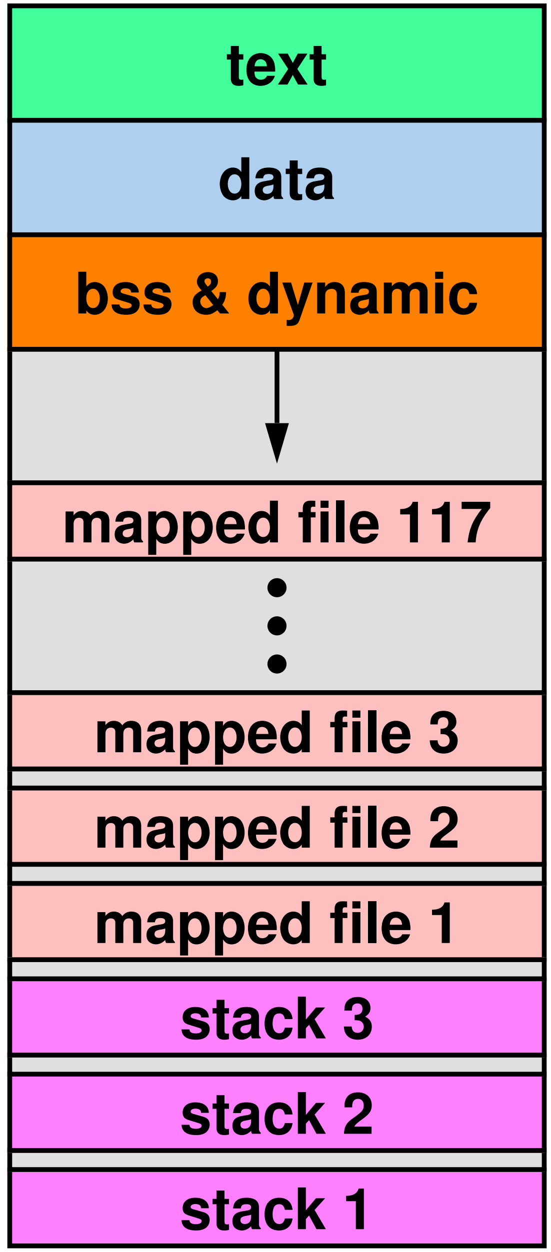
Adding a Mapped File



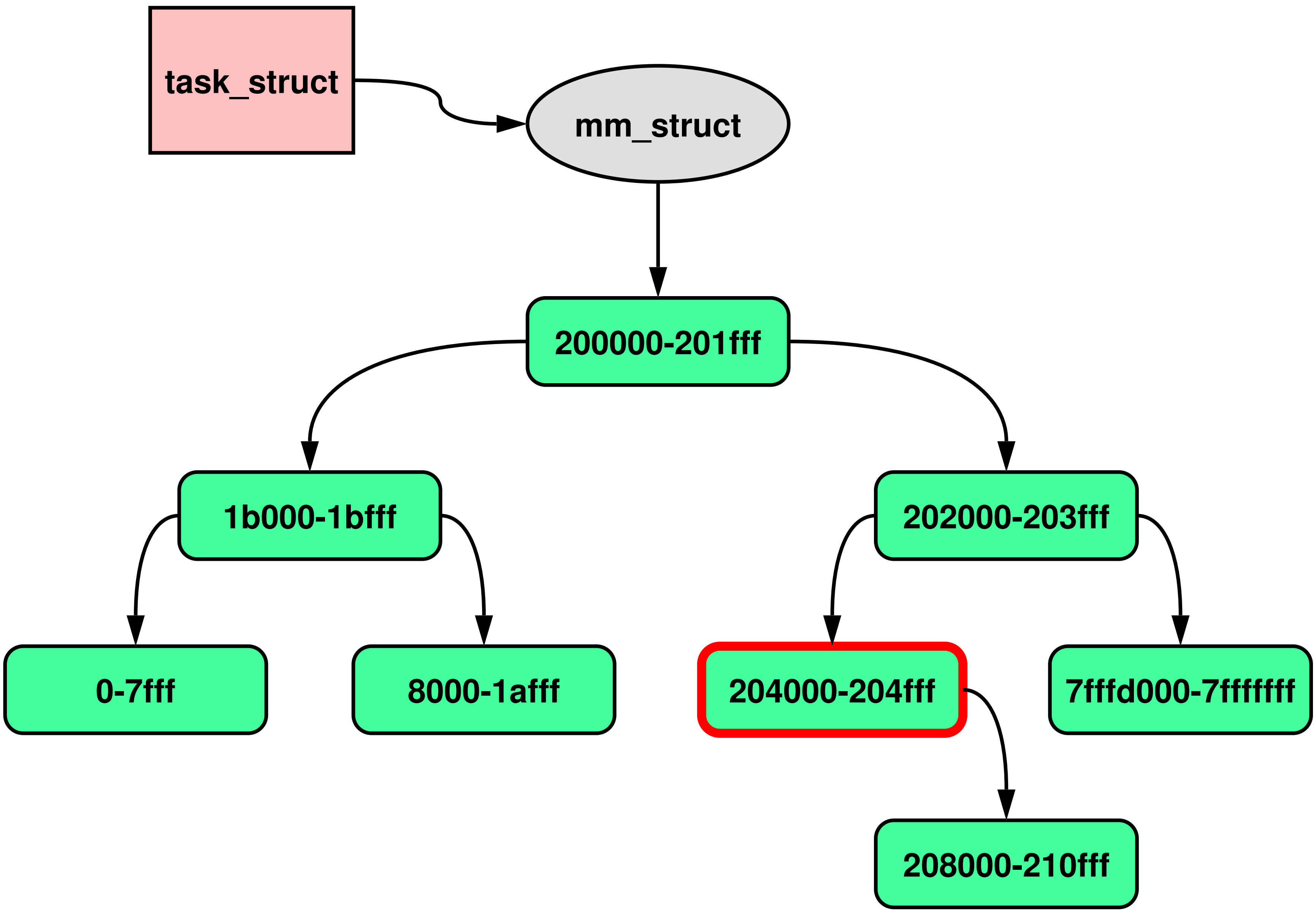
Address-Space Representation: More Areas



Adding More Stuff



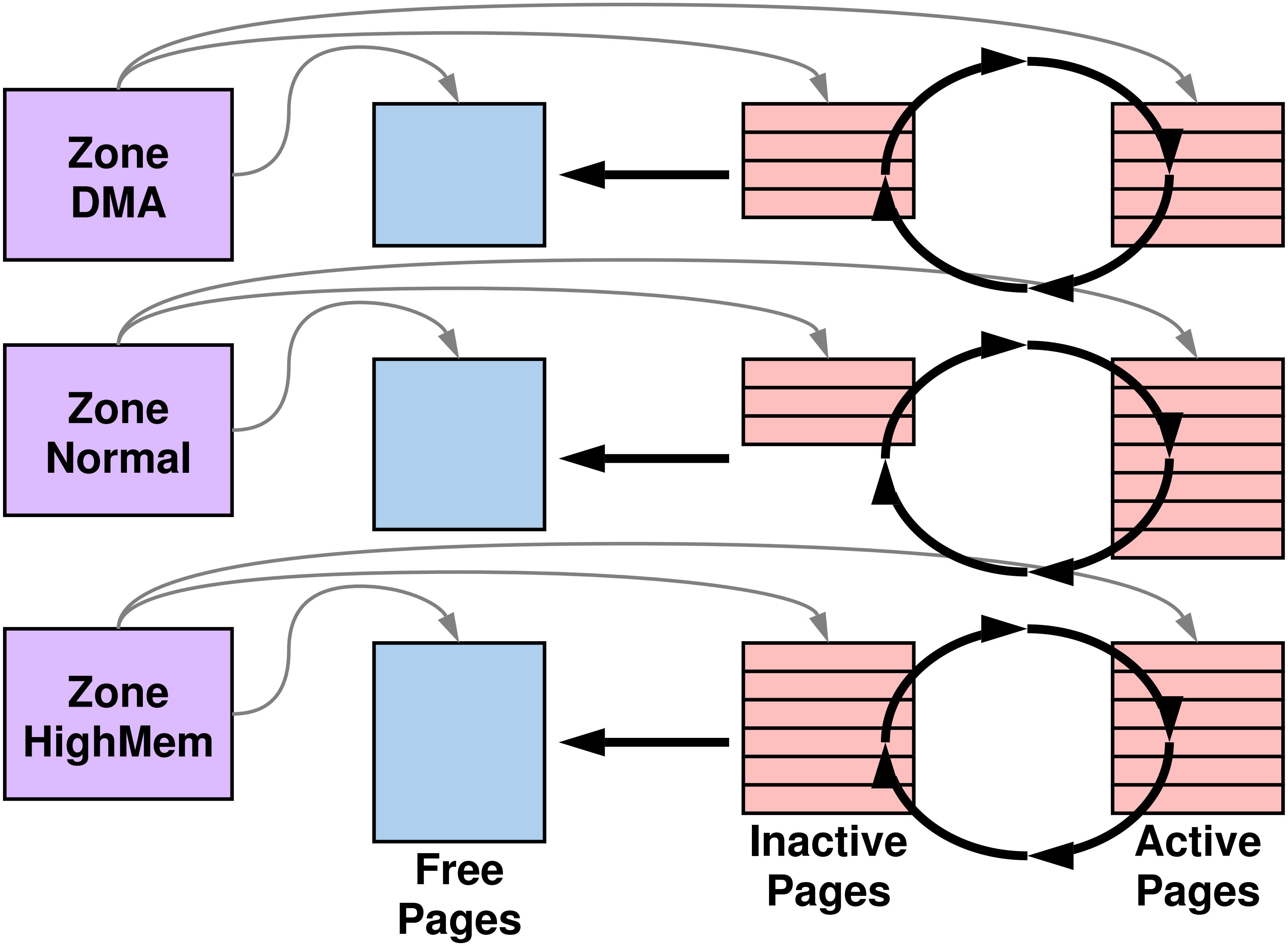
Address-Space Representation: Reality



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)
  - hardware page tables
- Globalling, *free and inactive page list* are maintained

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- Example usage 1: What happens when a *page fault* occurs?

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  - hardware page tables

- Globalling, *free and inactive page list* are maintained

- Example usage 1: What happens when a *page fault* occurs?
  1) page fault came from the hardware because V=0 for a page
  2) traps into the kernel, the kernel:
     2a) gets a free page frame
     2b) looks at the memory map and copy the page from disk into this free page frame
     2c) adjust hardware page table to point to this page frame

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)
  - hardware page tables
- Globalling, *free and inactive page list* are maintained
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- Example usage 2: What happens when *pageout daemon* wants to free up a *modified/dirty* page?
  1) find from which process/address space the page frame belongs to
  2) look at the memory map and find the corresponding backing store, write back the page content to disk
  3) *unmap* this page from the corresponding *page table*
  4) free the page frame

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  - *Memory Map* (i.e., that's how the address space is represented)
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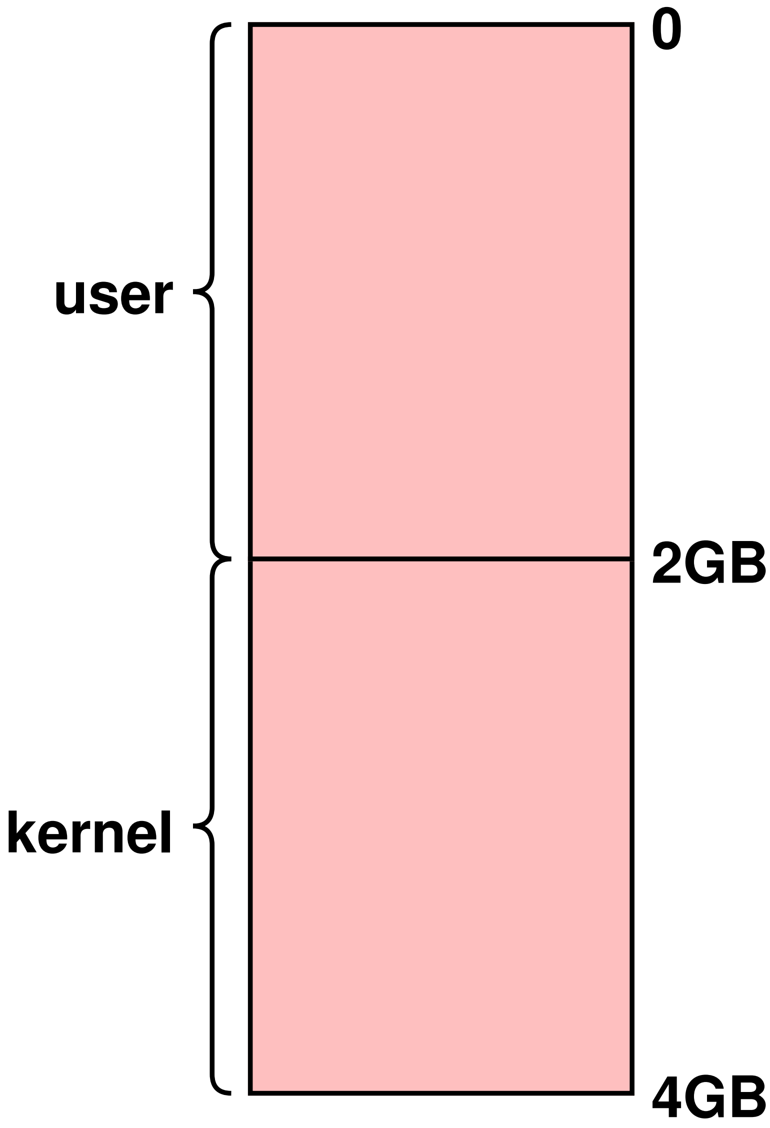
Windows x86 Layout

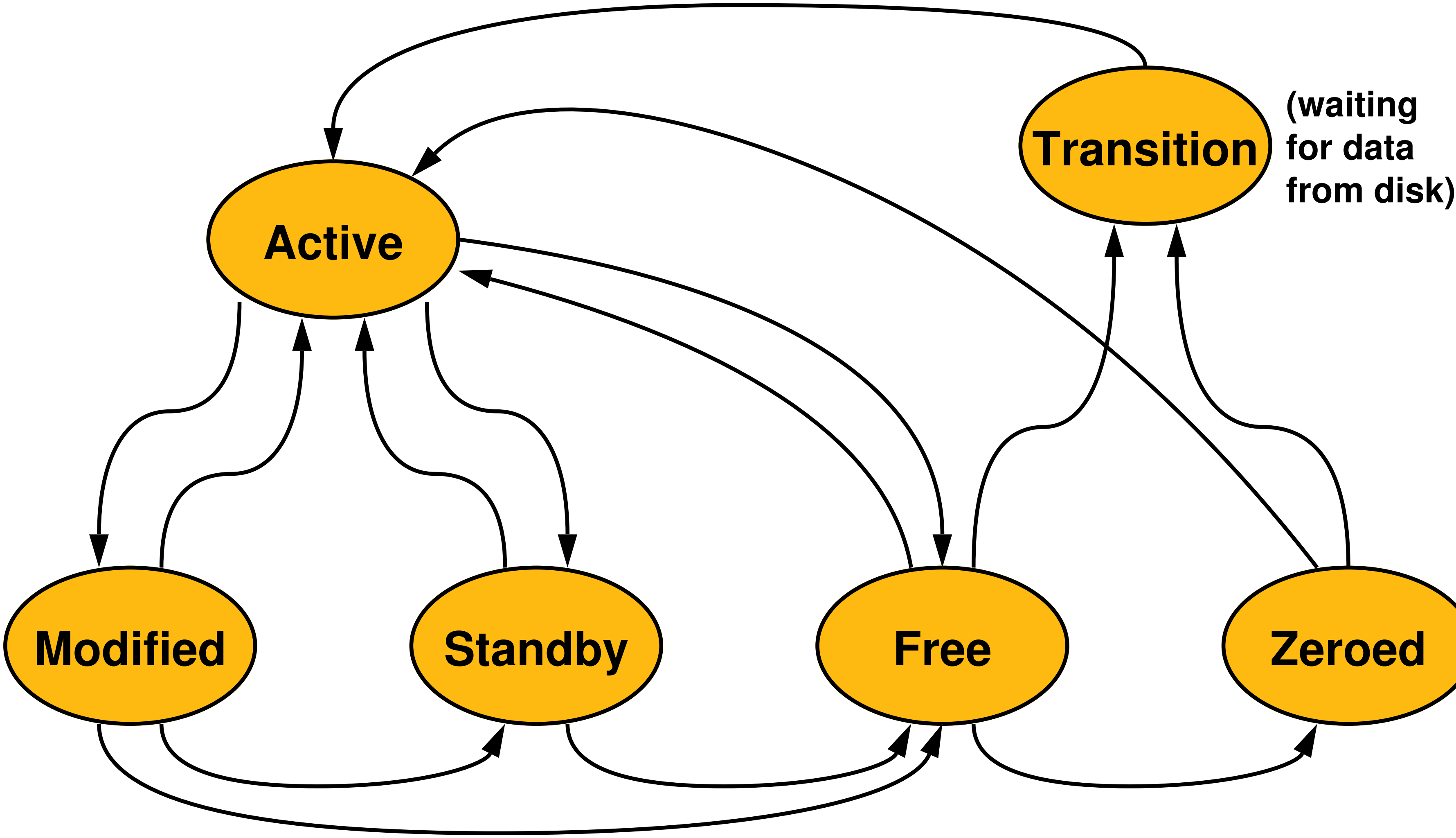
- Two choices



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 accidentally modify the address space

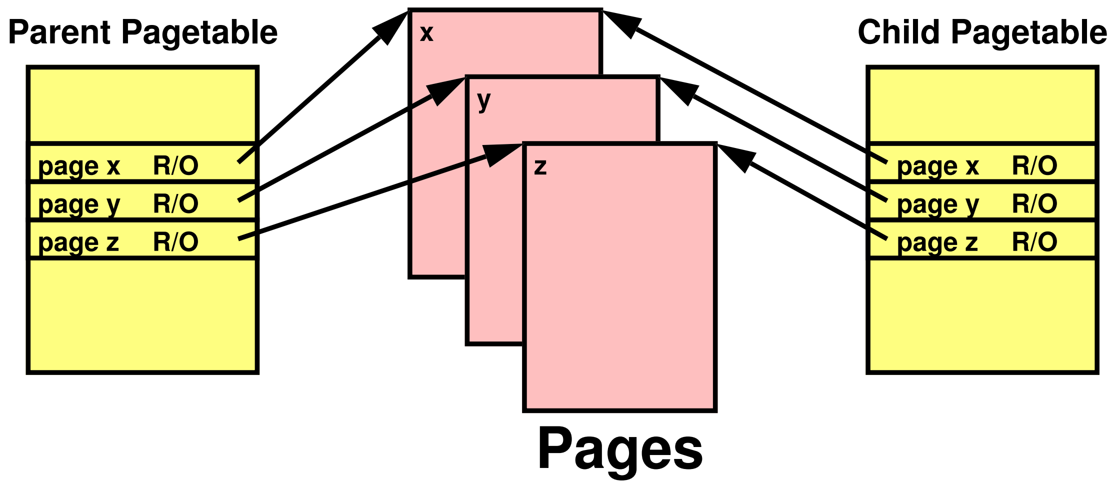
A Better `fork()`

- 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()`

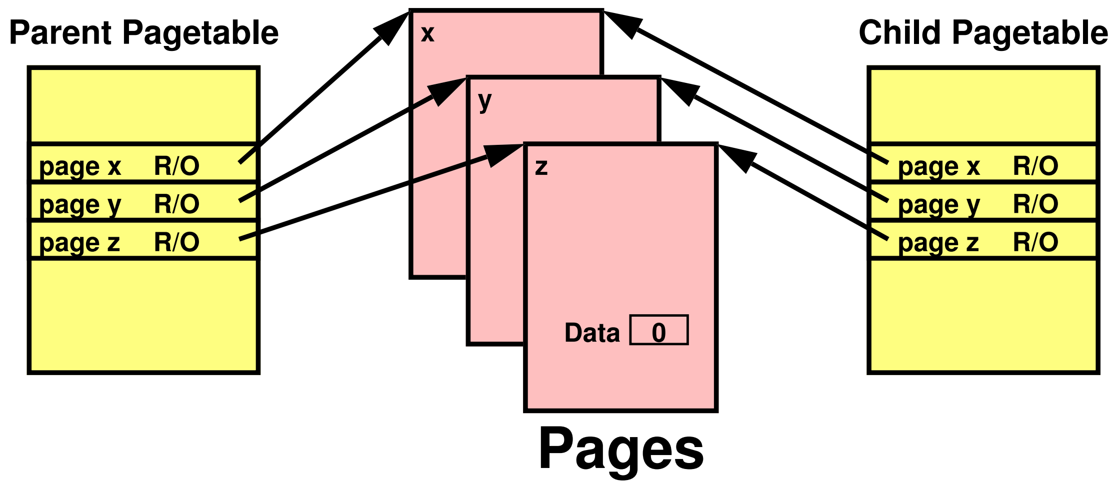
- Given that demand paging is the way to go, we need to use *copy-on-write*
  - a process gets a *private* copy of the page after a thread in the process performs a *write* for the *first time*
    - if a virtual memory segment is *R/W* and *privately mapped*, then we need to perform copy-on-write
  - *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
  - *copy on write:* when one of the processes tries to modify the data, a copy of the page is created and used
    - this is another reason for a *page fault*

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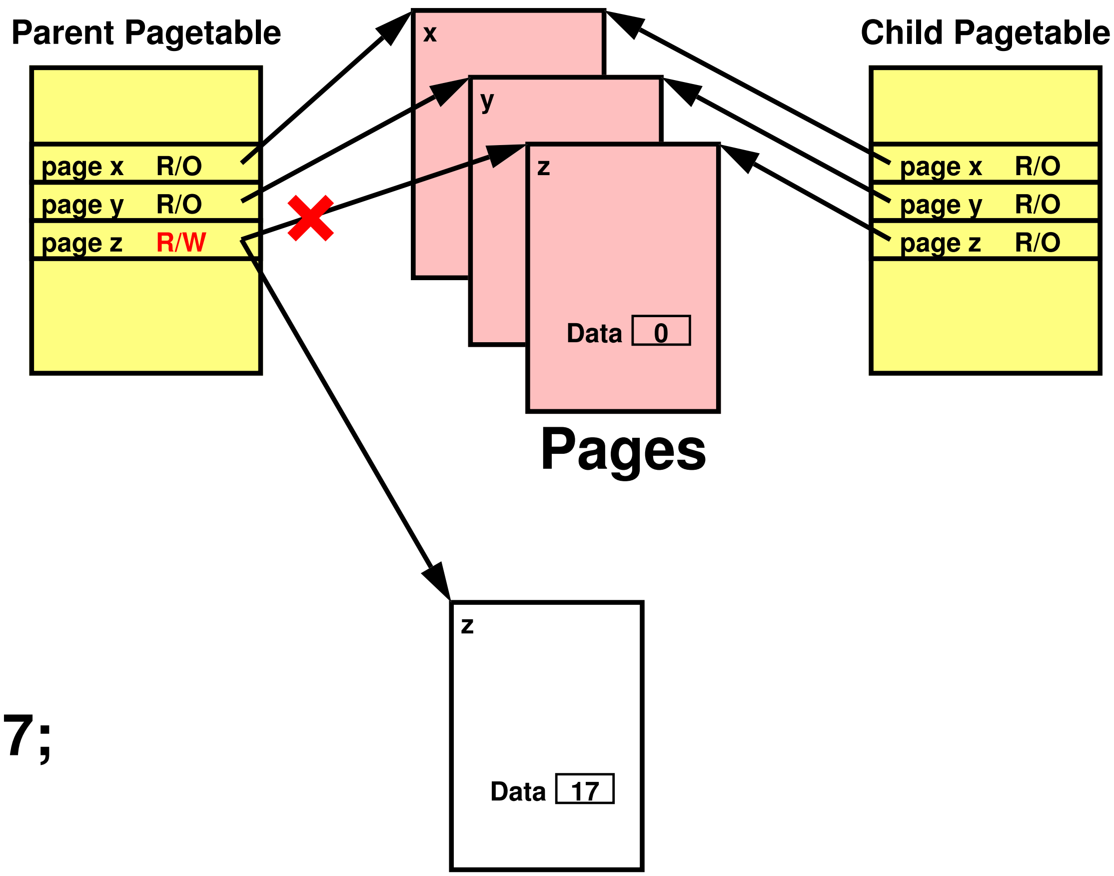

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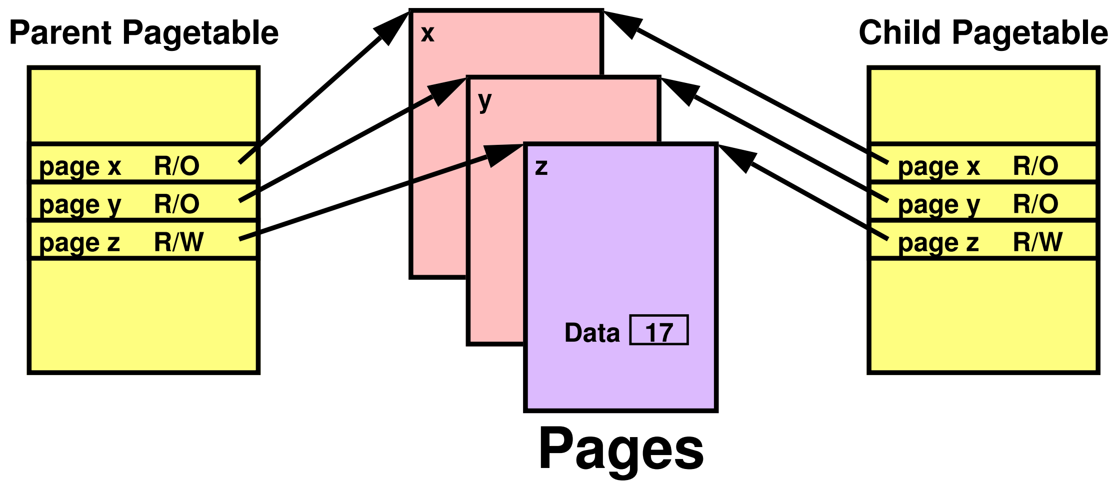
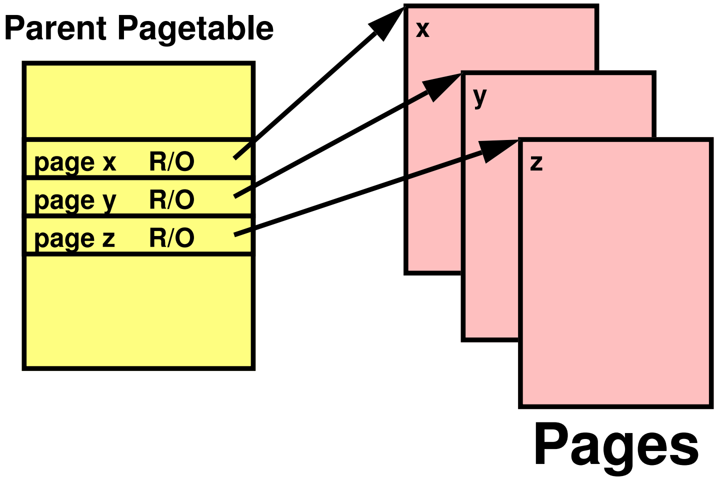
Share-Mapped Files



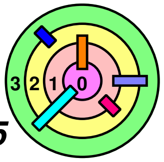
Data = 17;

- 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

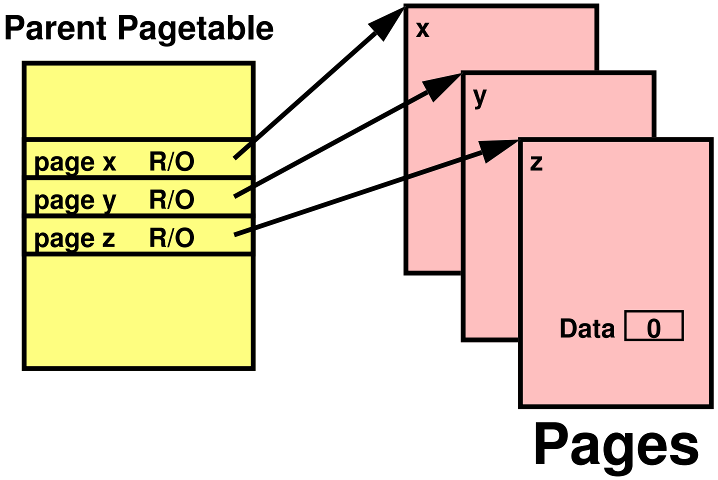
Private Mapping - Copy on Write Occurs before `fork()`



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



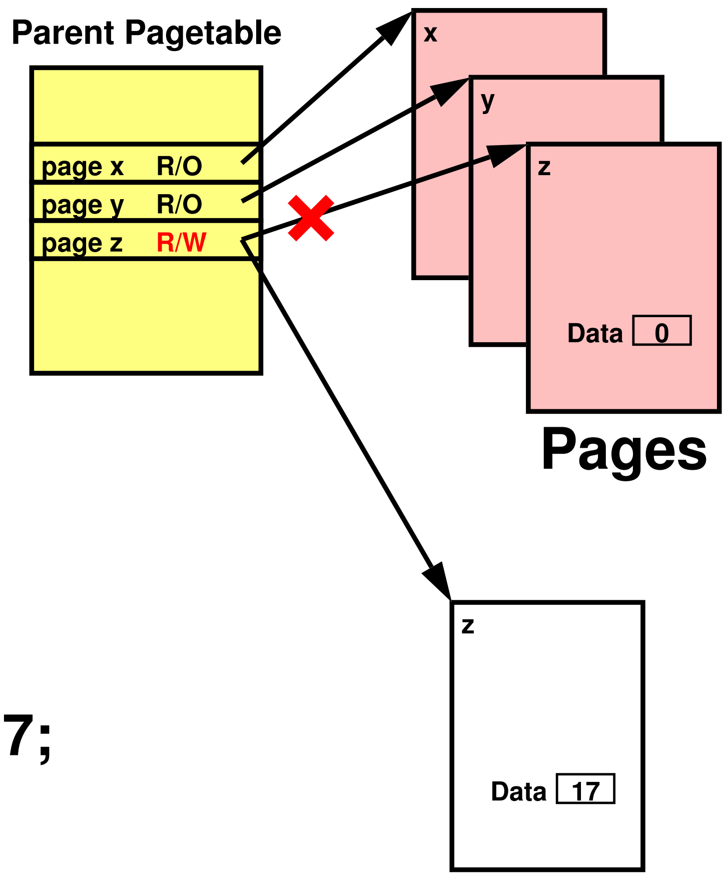
Private Mapping - Copy on Write Occurs before `fork()`



Data = 17;

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

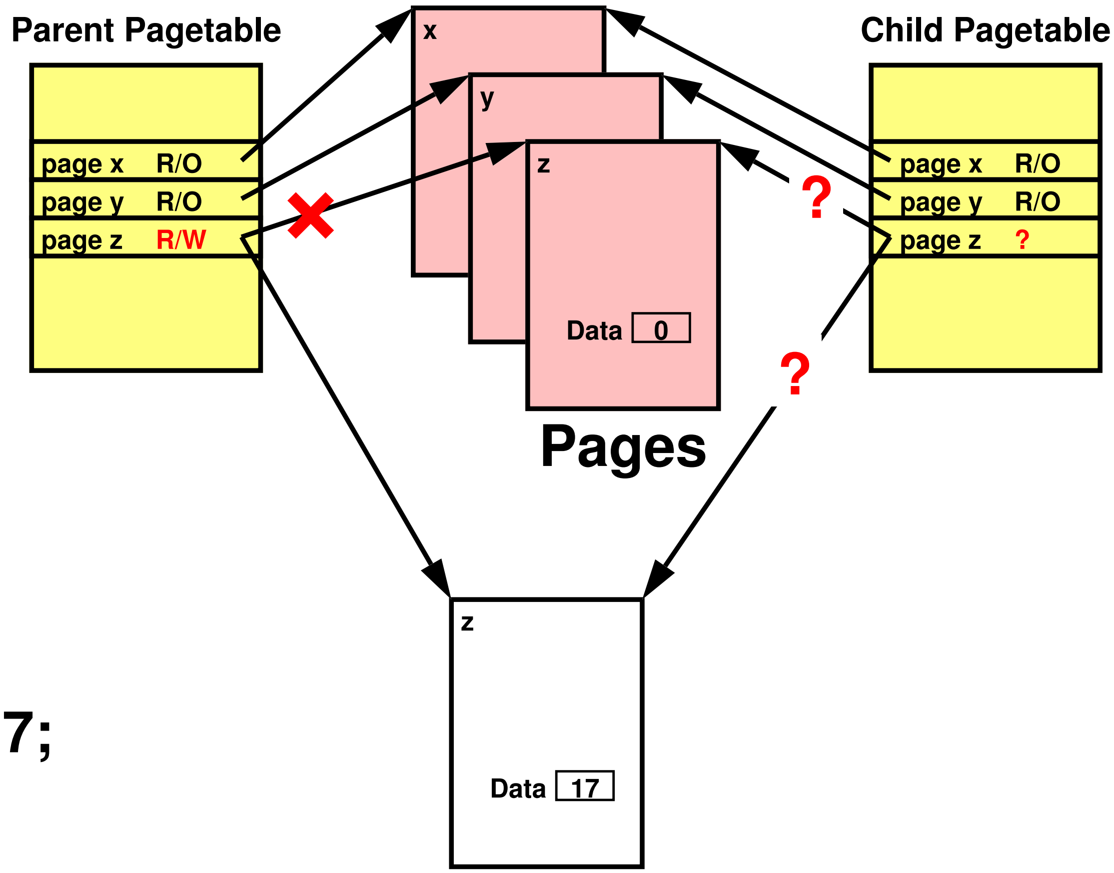
Private Mapping - Copy on Write Occurs before `fork()`



Data = 17;

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

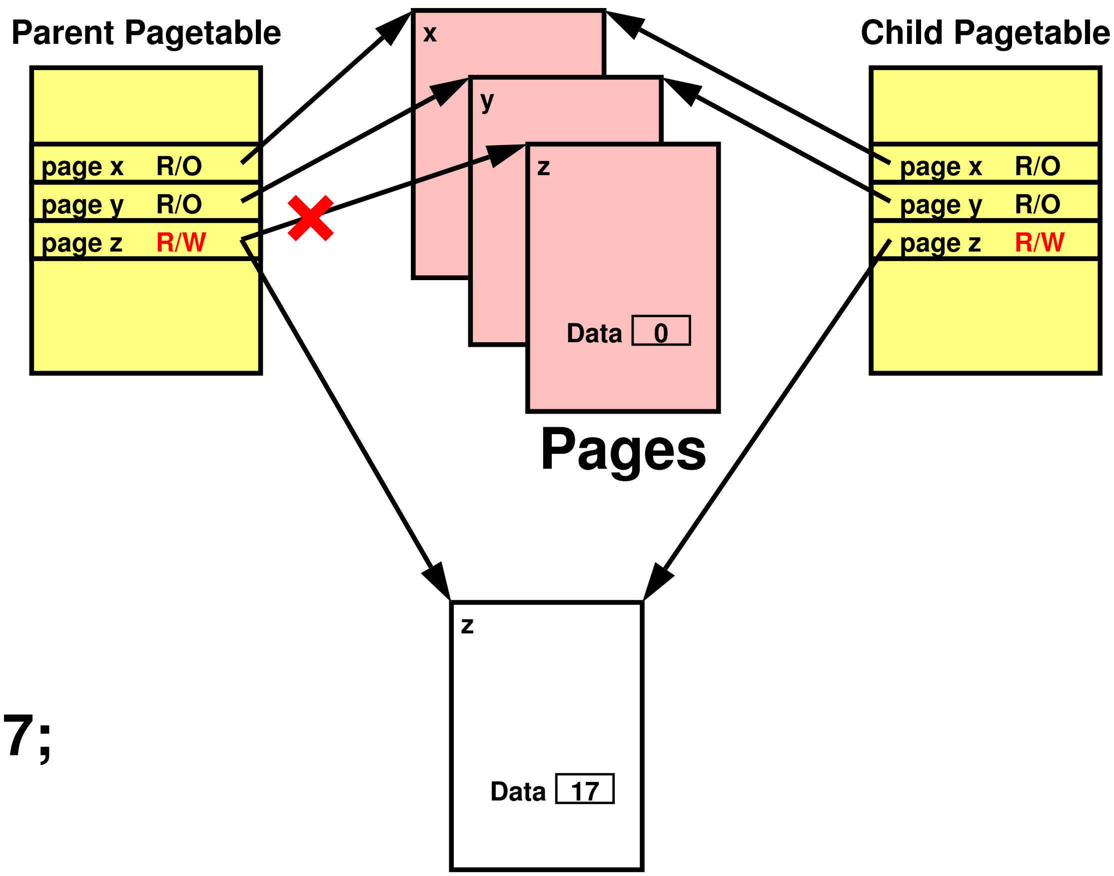
A Private-Mapped File Changes



Data = 17;

- 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

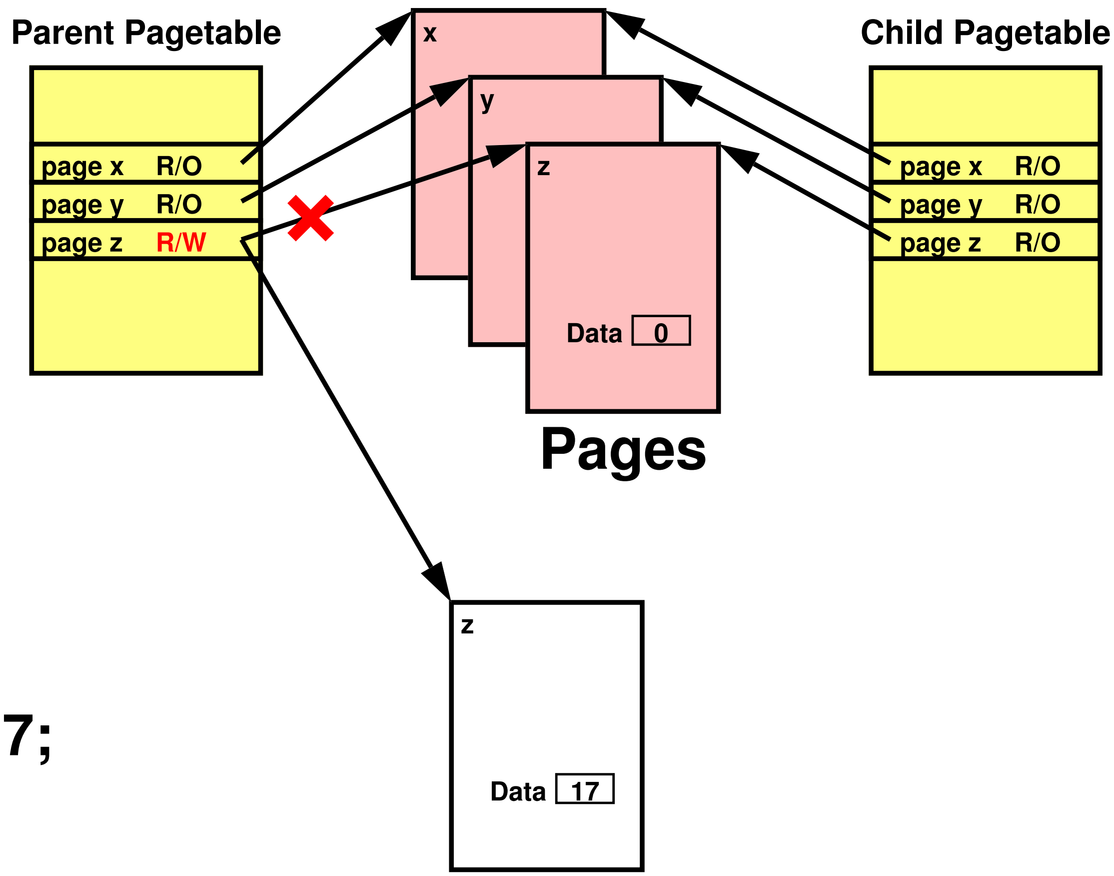
A Private-Mapped File Changes



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**

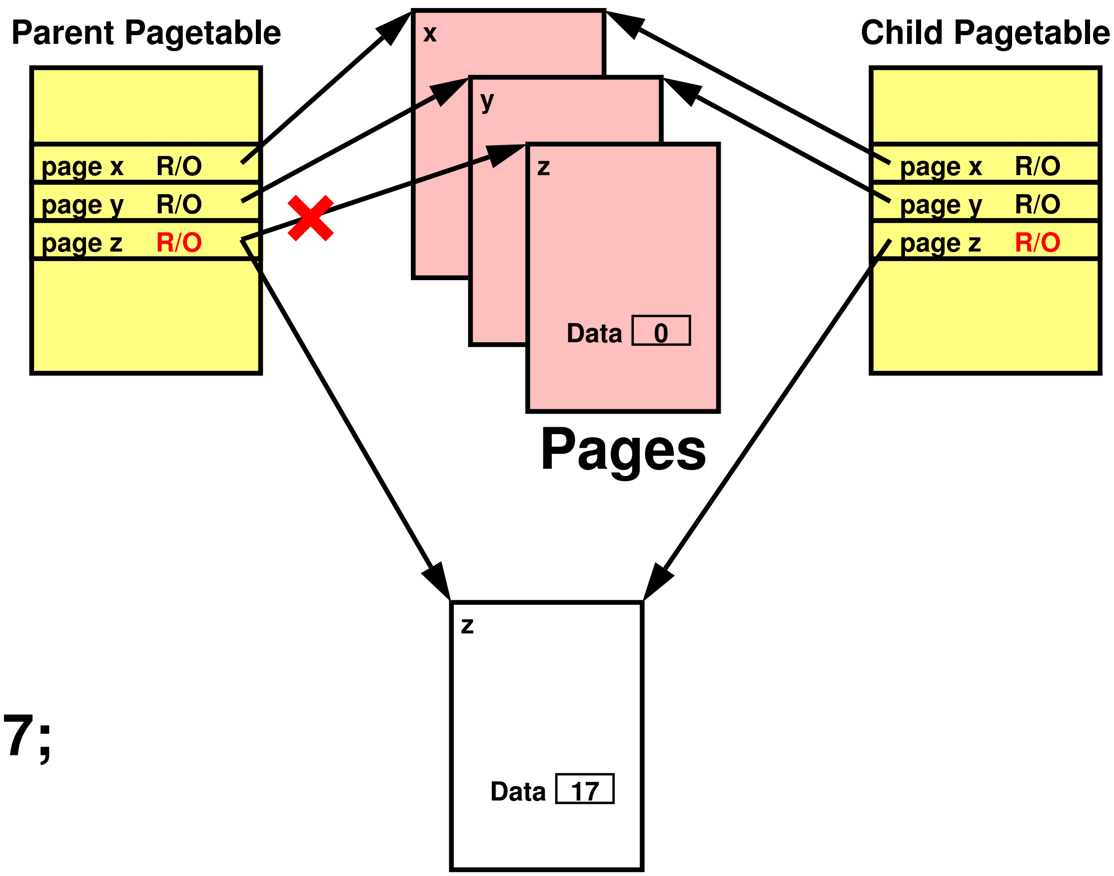
A Private-Mapped File Changes



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

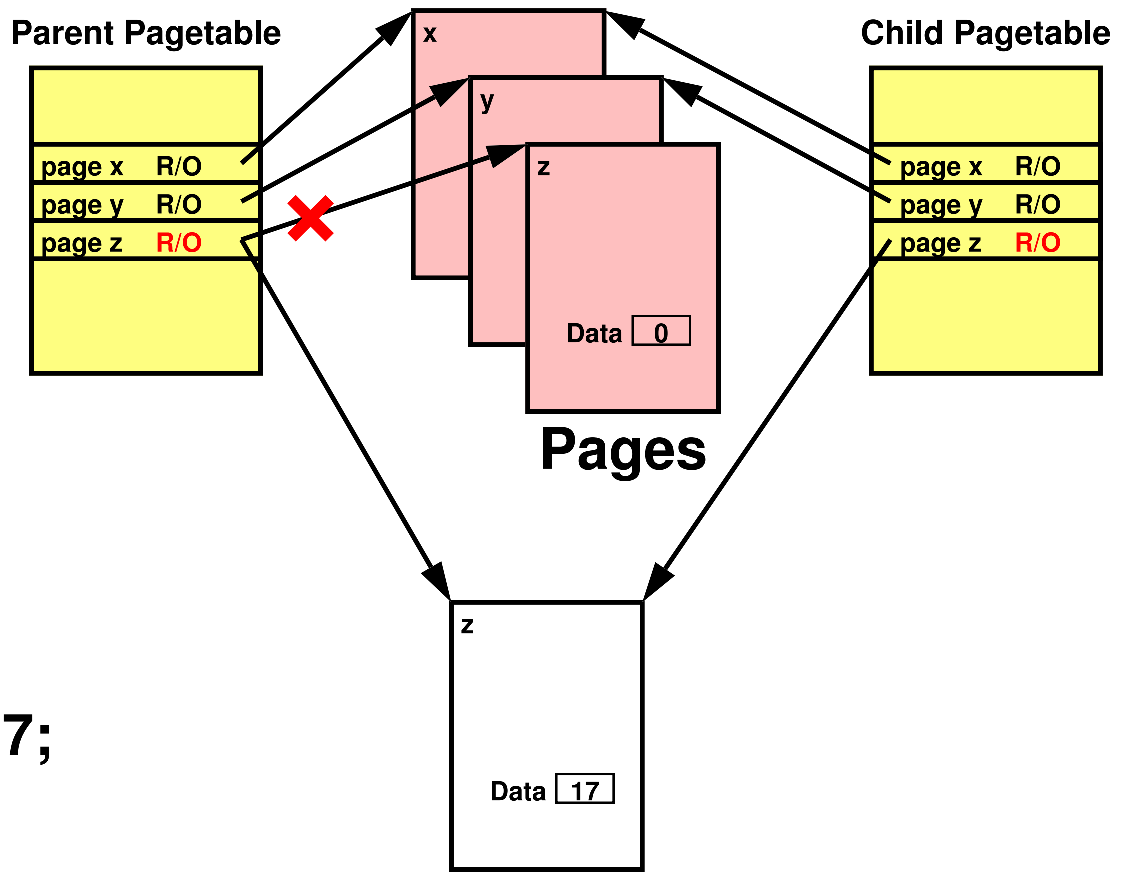
A Private-Mapped File Changes



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

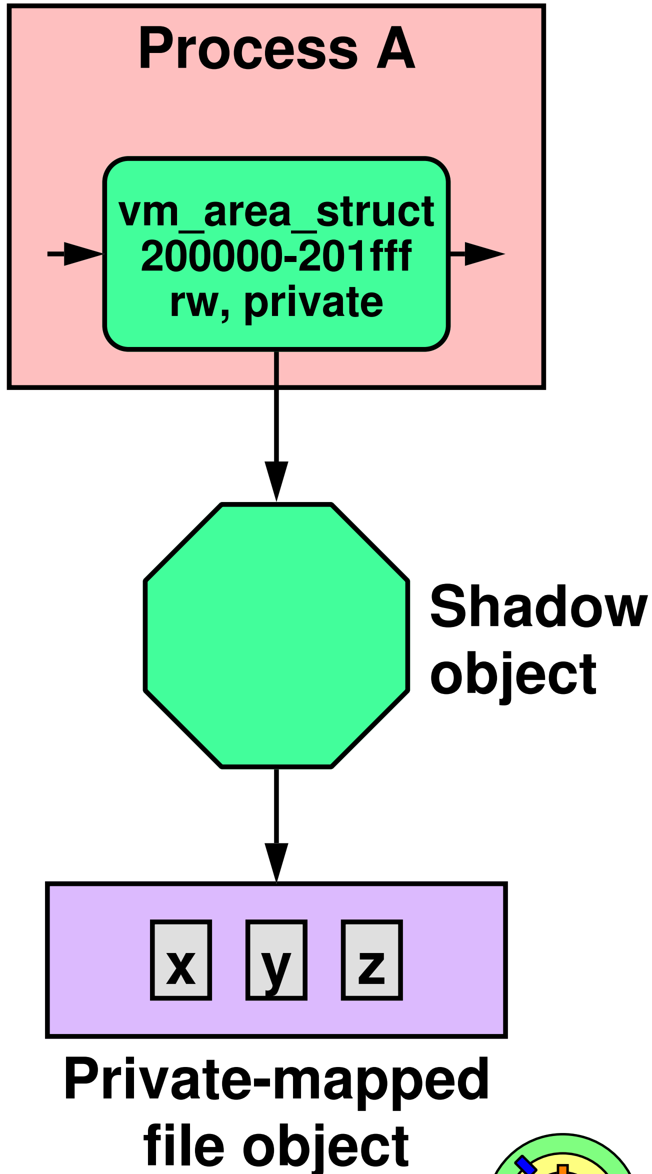


Data = 17;

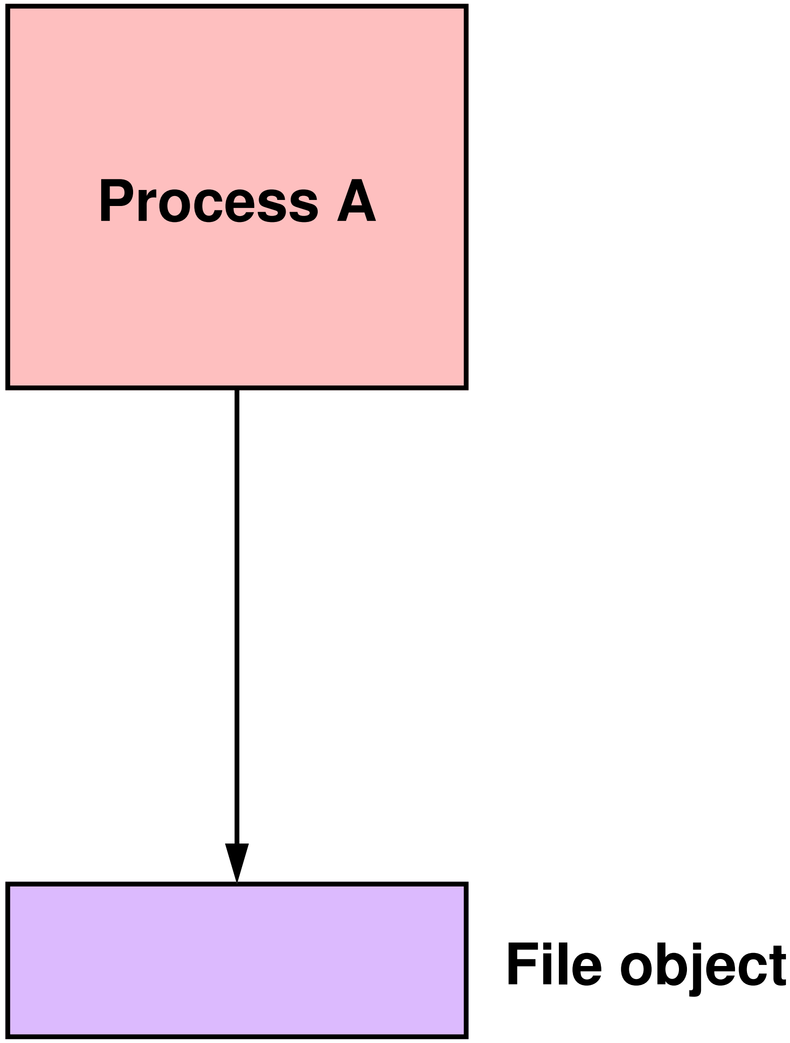
- Complication: what if the page is modified before `fork()`?
  - but what if now the parent or the child calls `fork()`?
    - afterwards, another process calls `fork()` again, etc.?
    - cannot use PTEs to keep track

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*

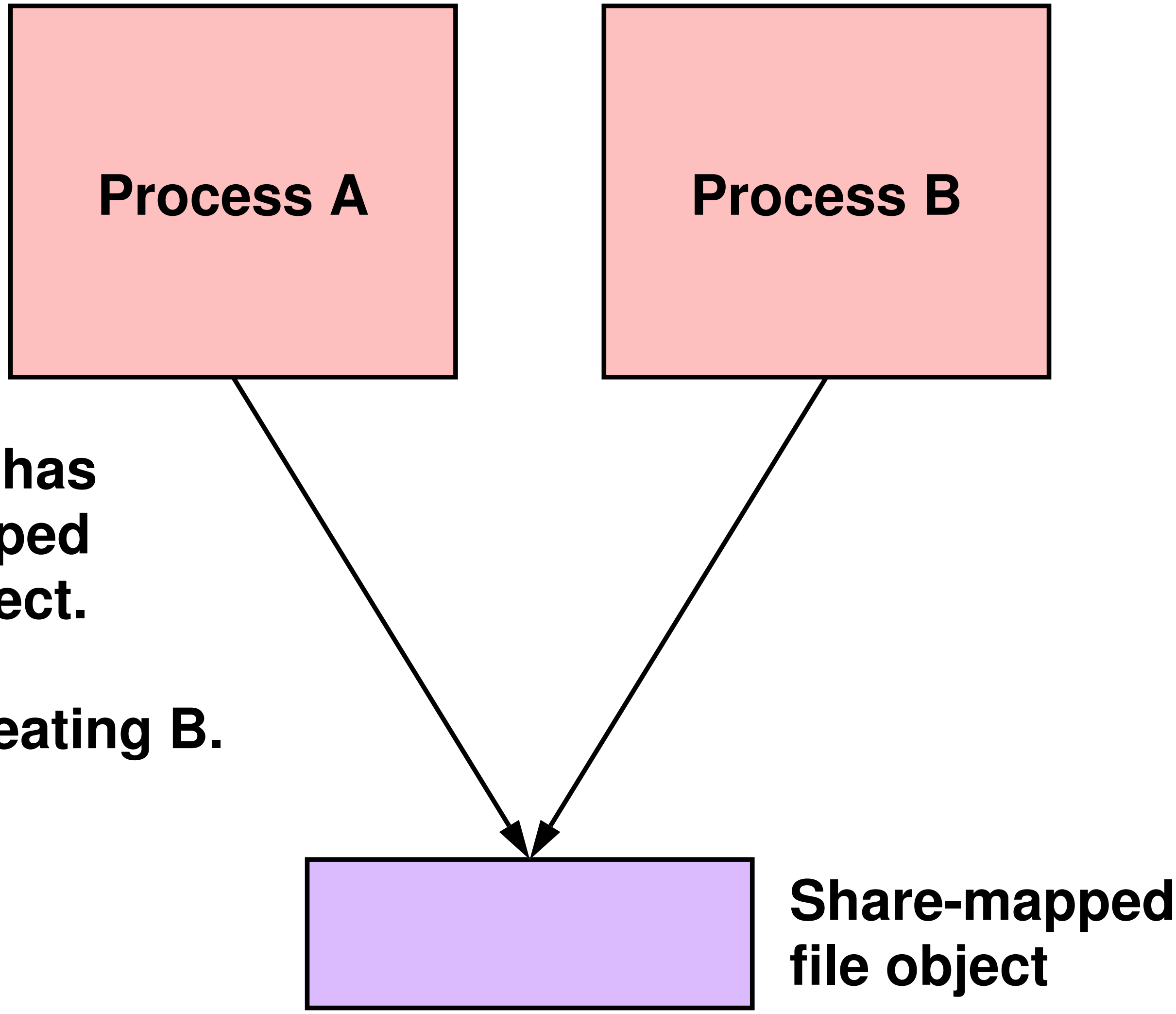


Share Mapping (1)



Process A has share mapped the file object.

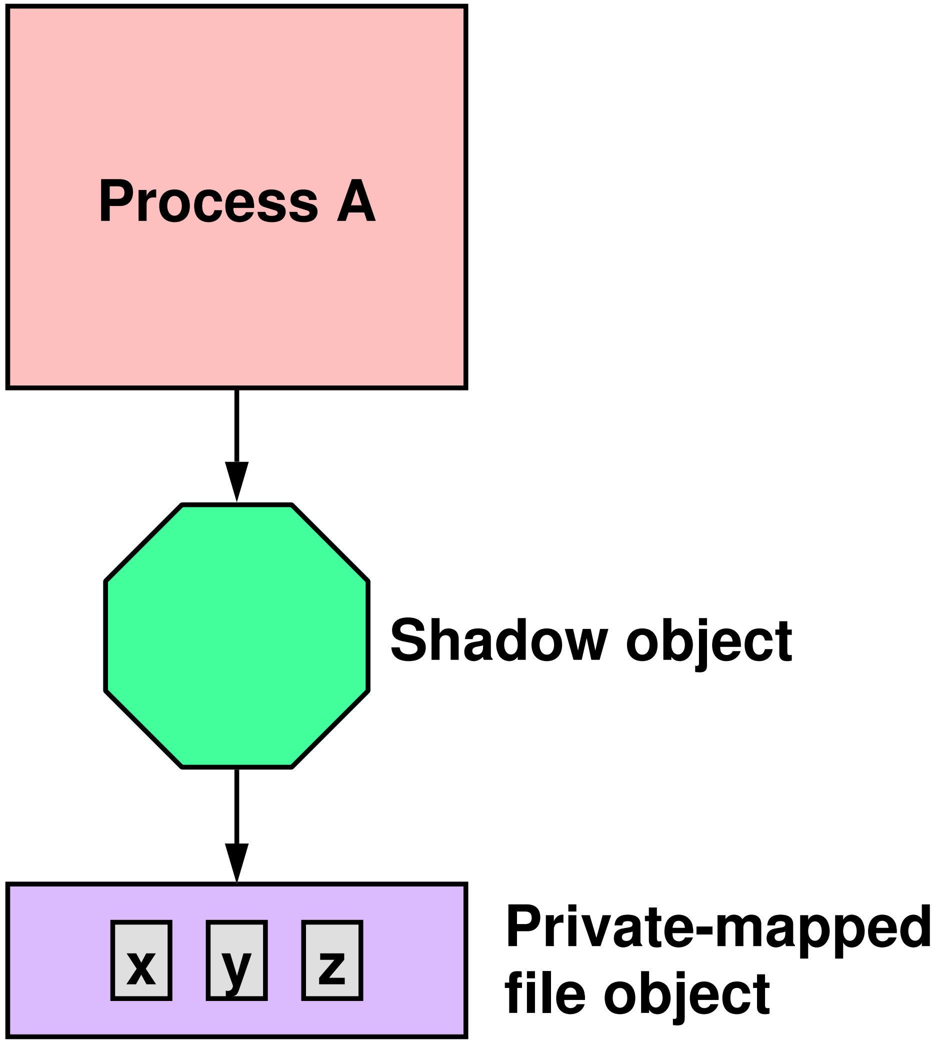
Share Mapping (2)



Process A has
share mapped
the file object.

A forks, creating B.

Private Mapping (1)



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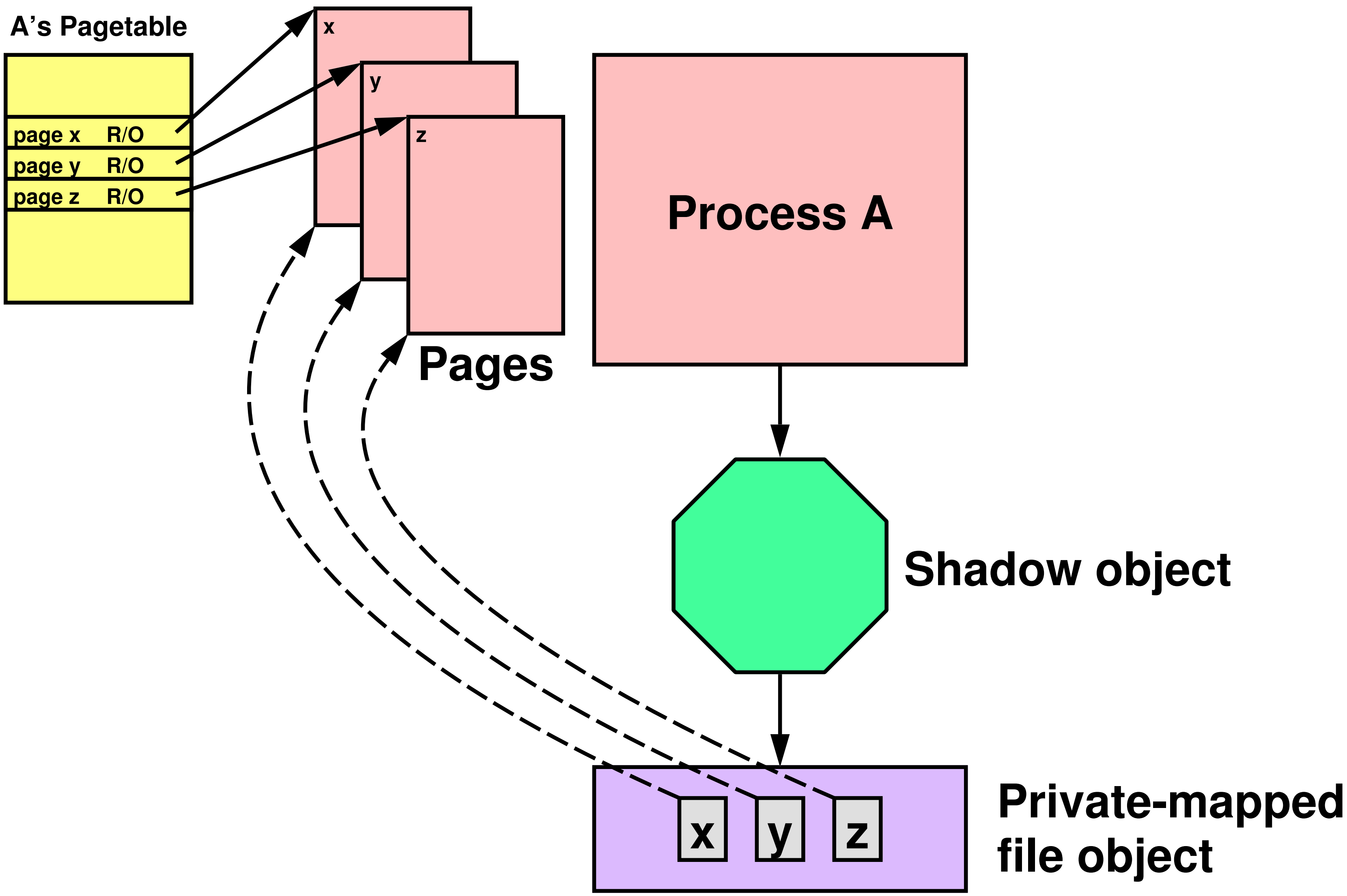

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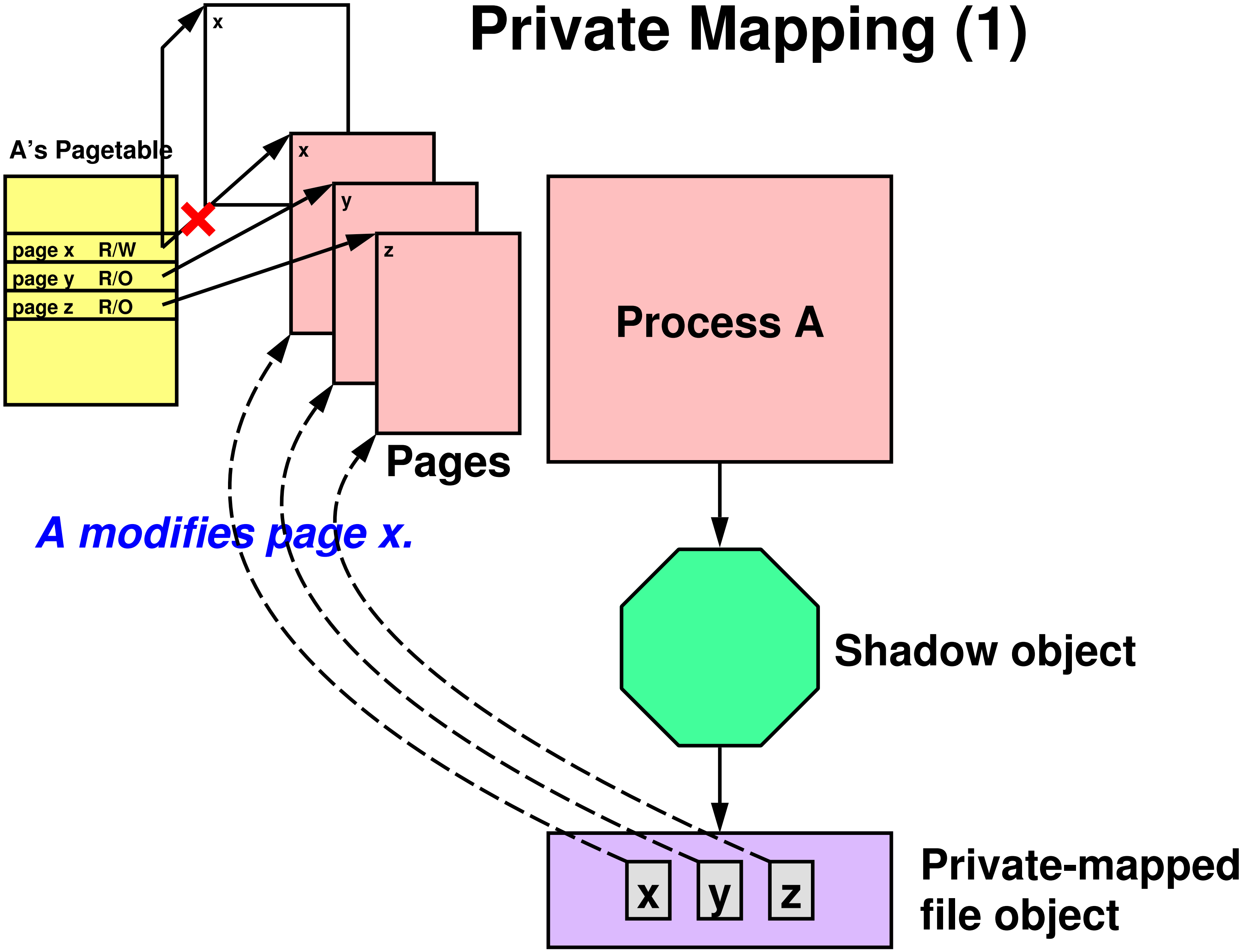
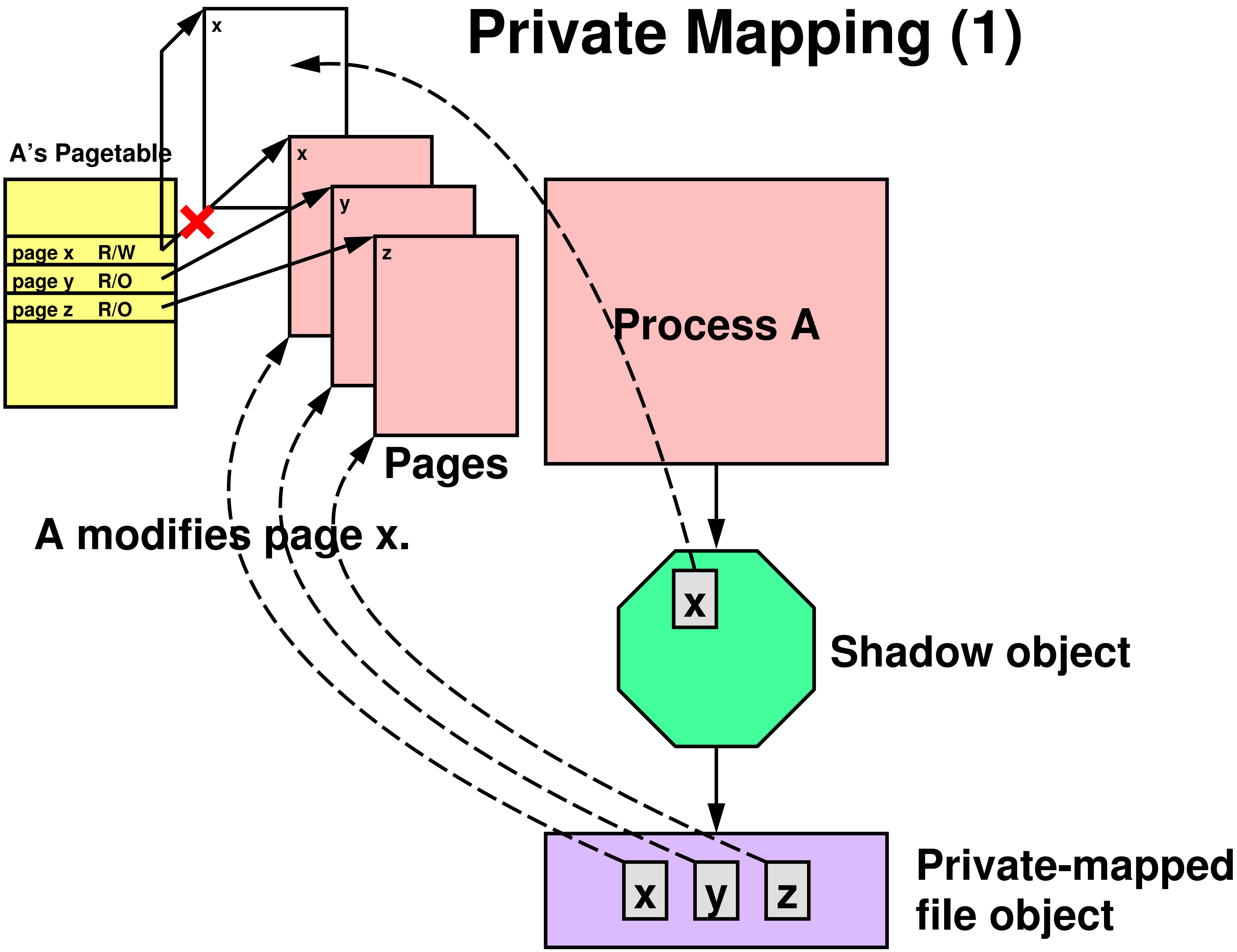


A modifies page x.

Private Mapping (1)



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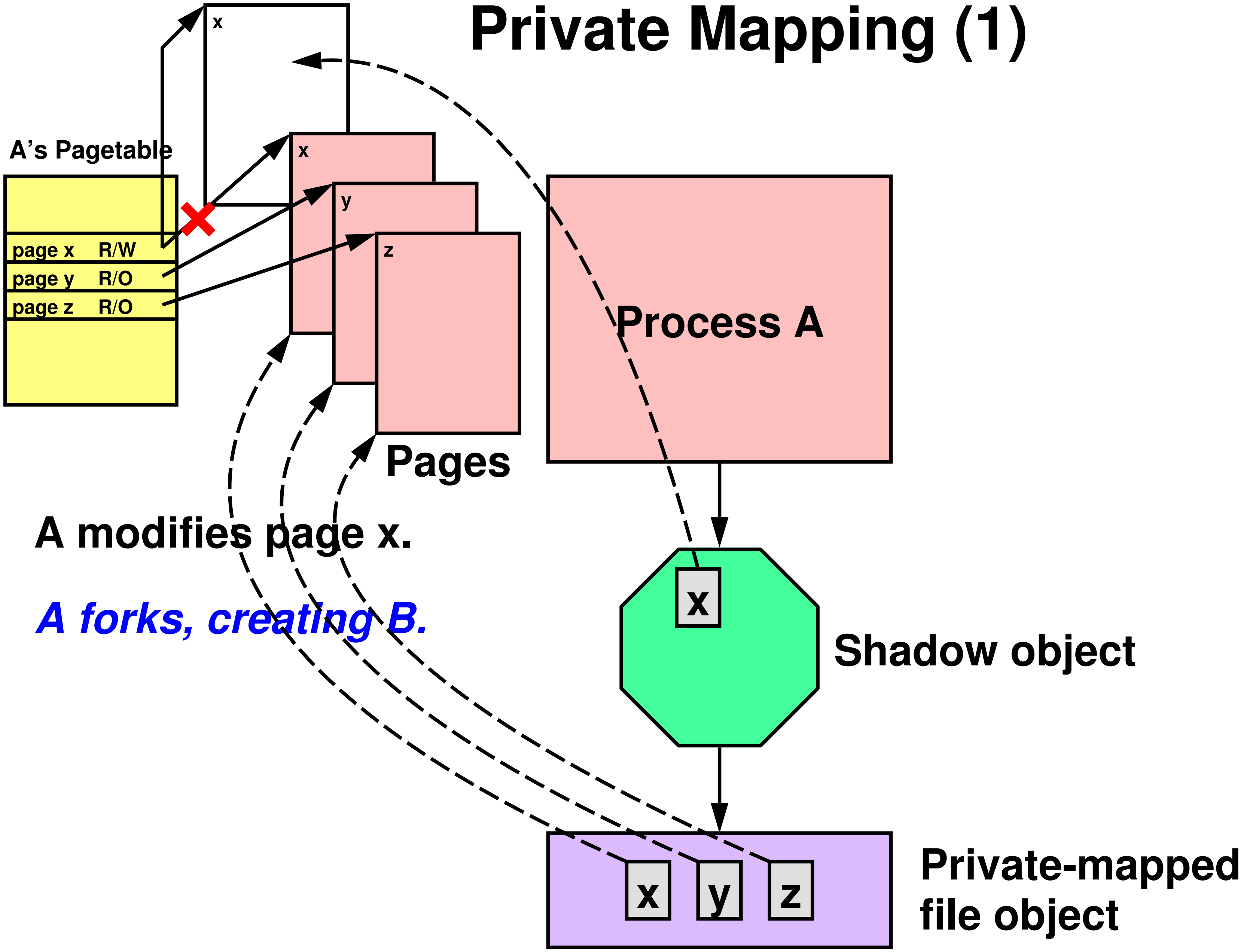
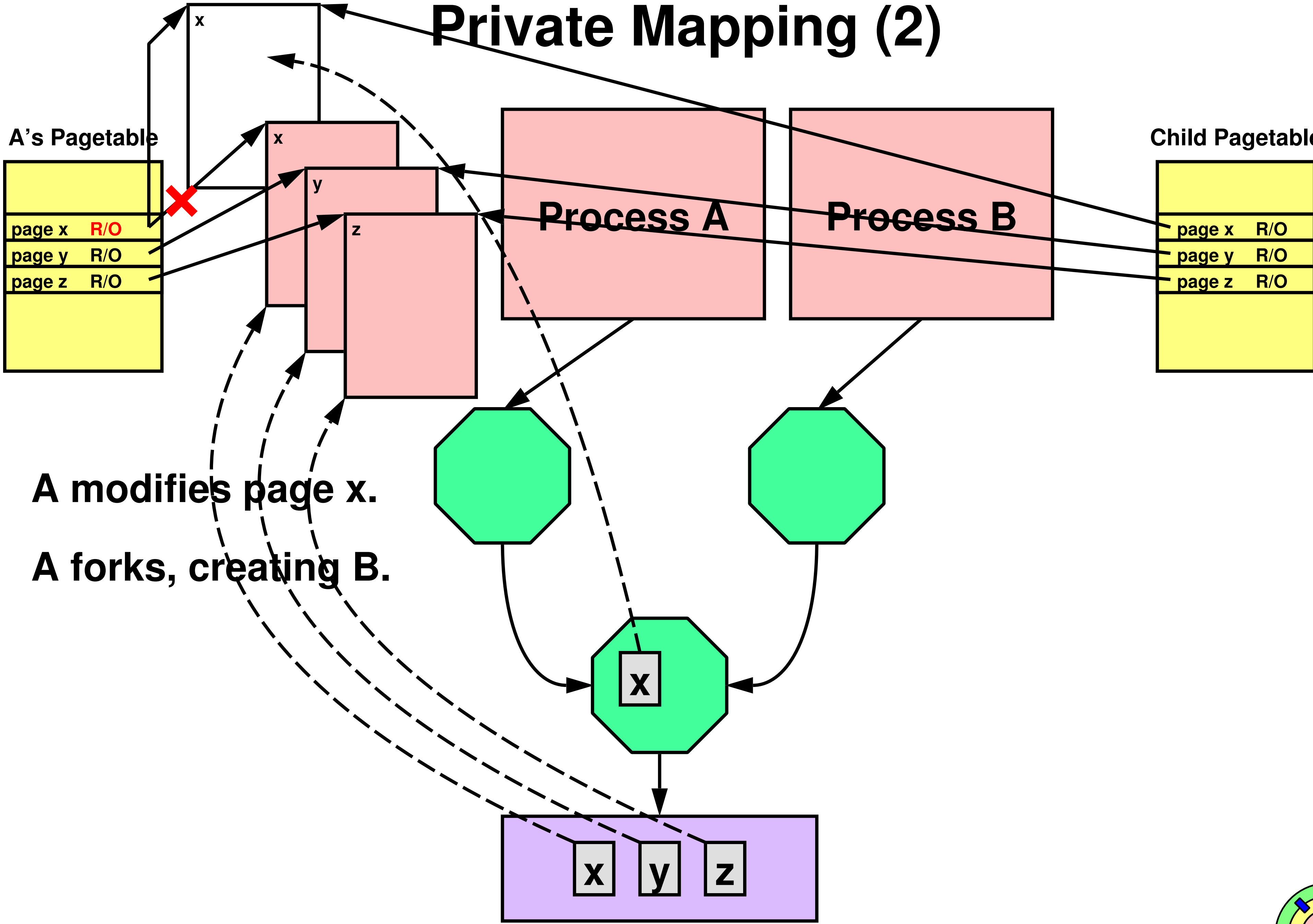


A modifies page x.

A forks, creating B.

Private Mapping (2)



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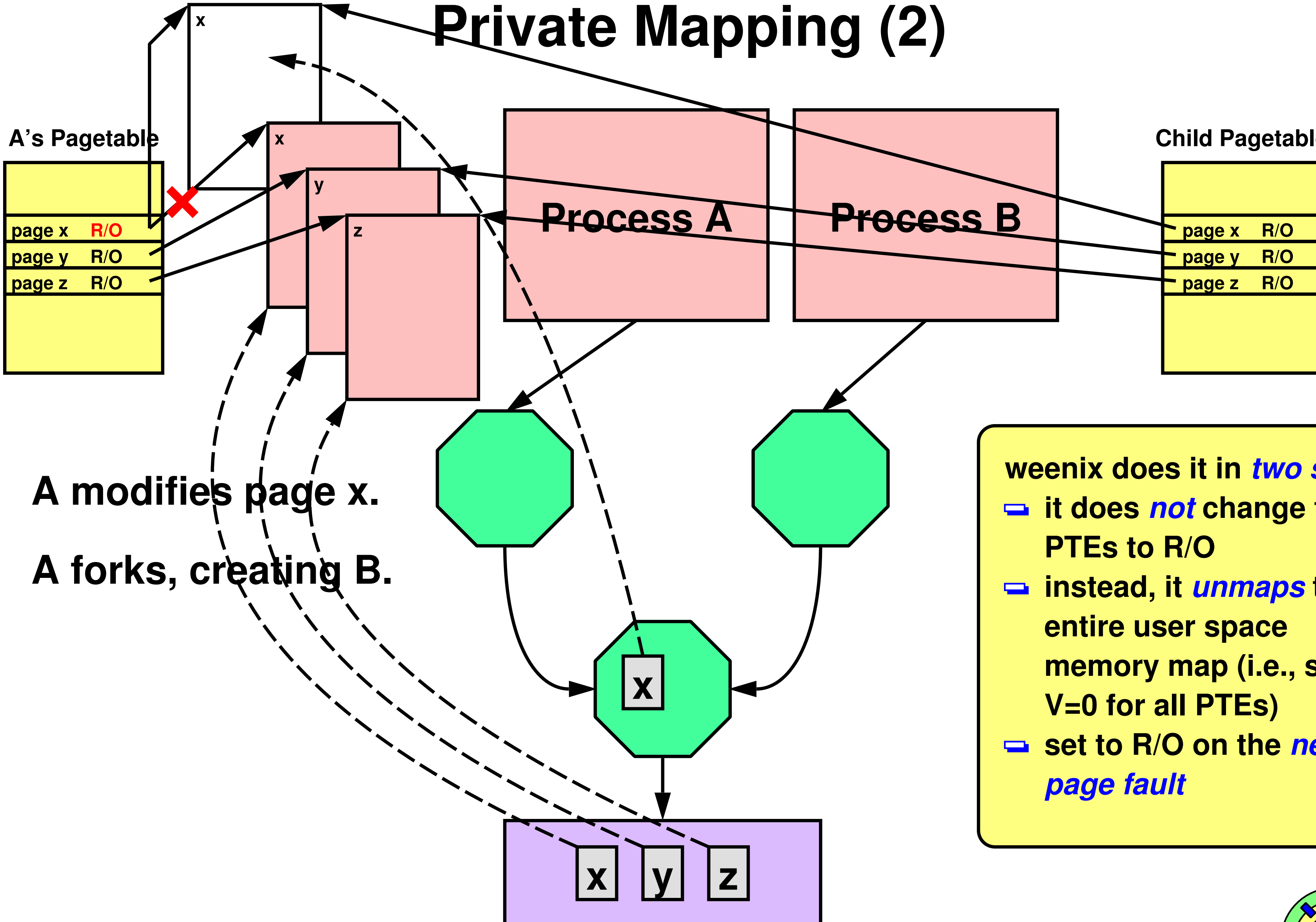


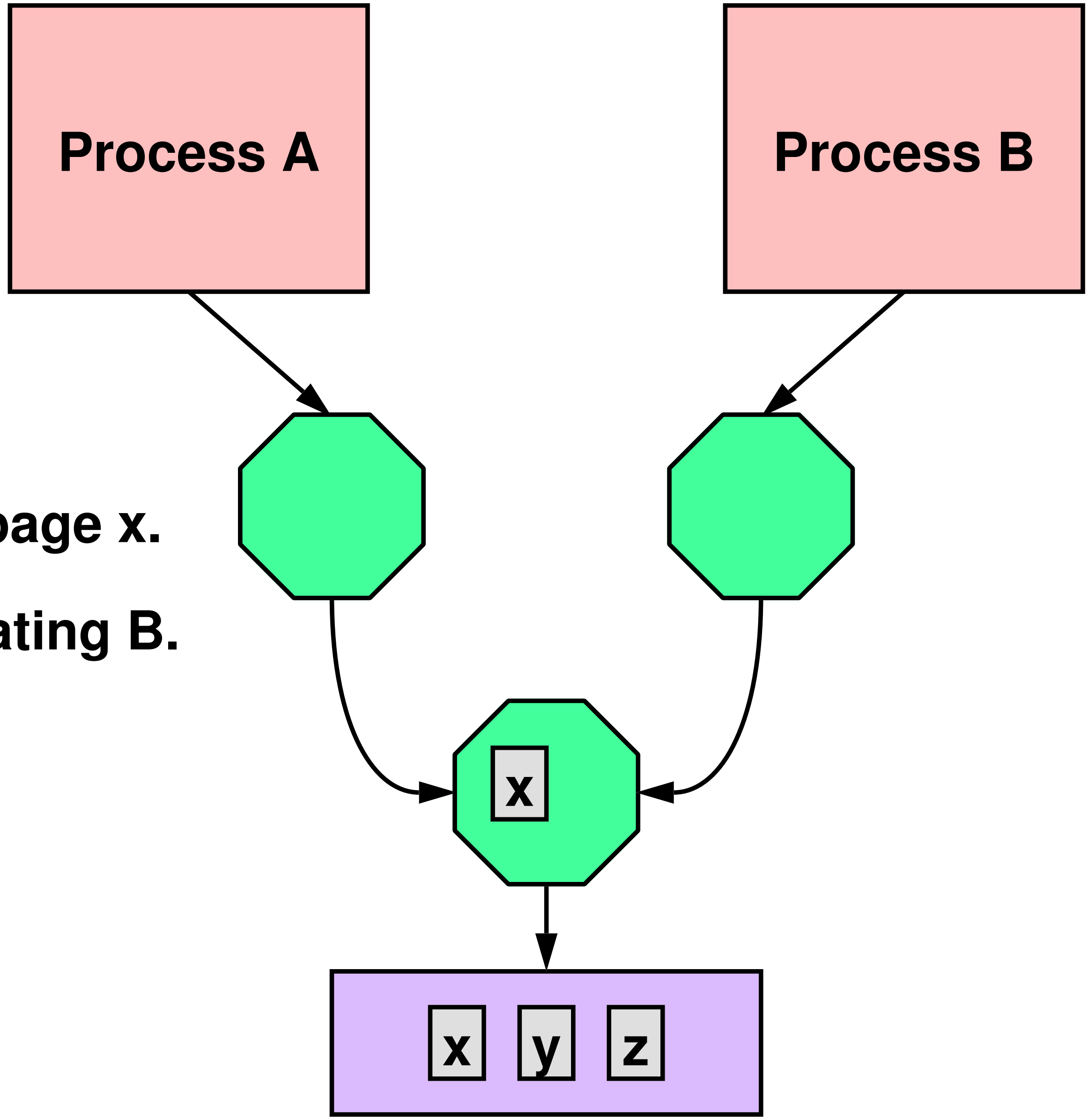
A modifies page x.

A forks, creating B.

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)



A modifies page x.

A forks, creating B.

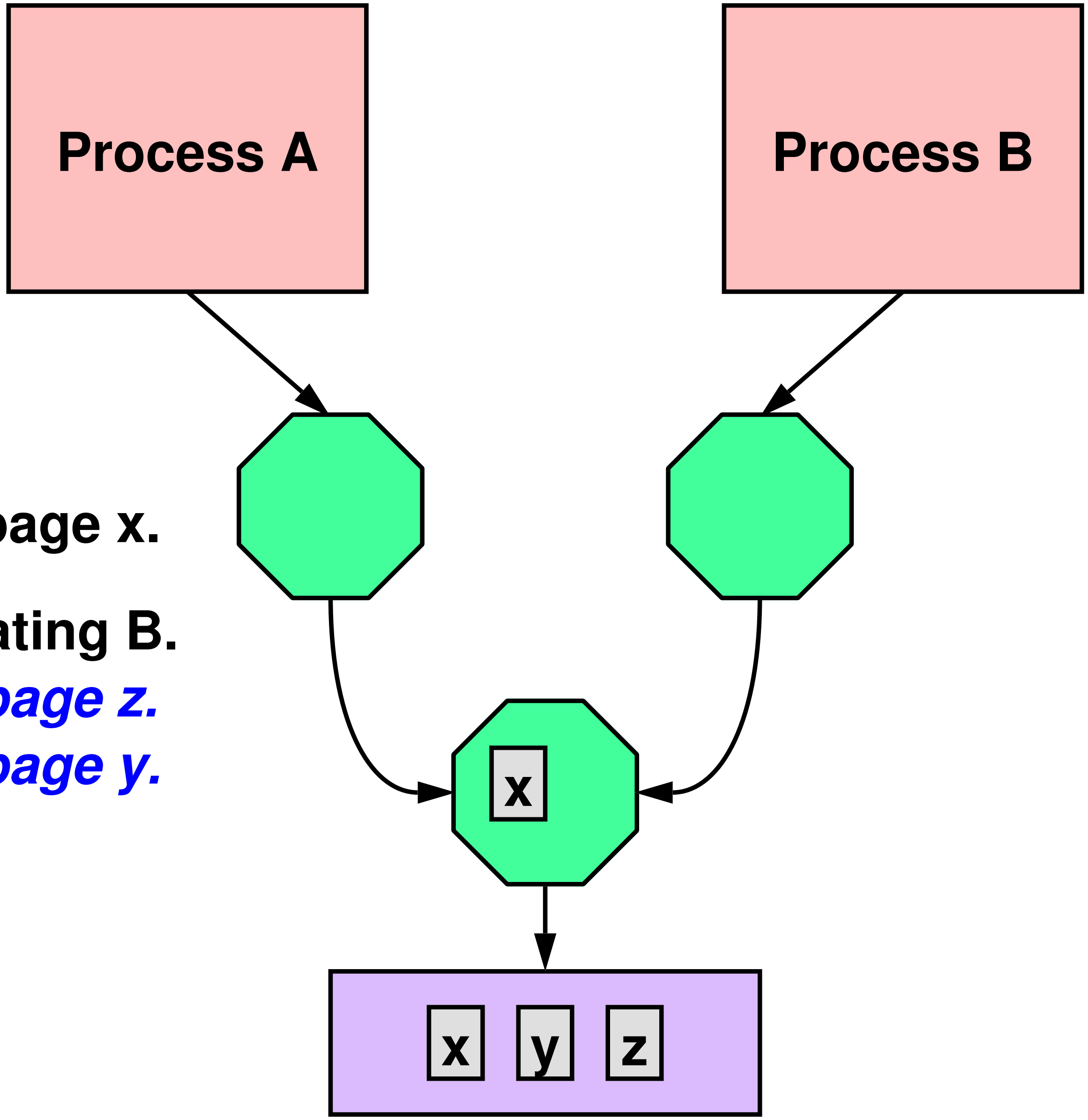
Private Mapping (2)

A modifies page x.

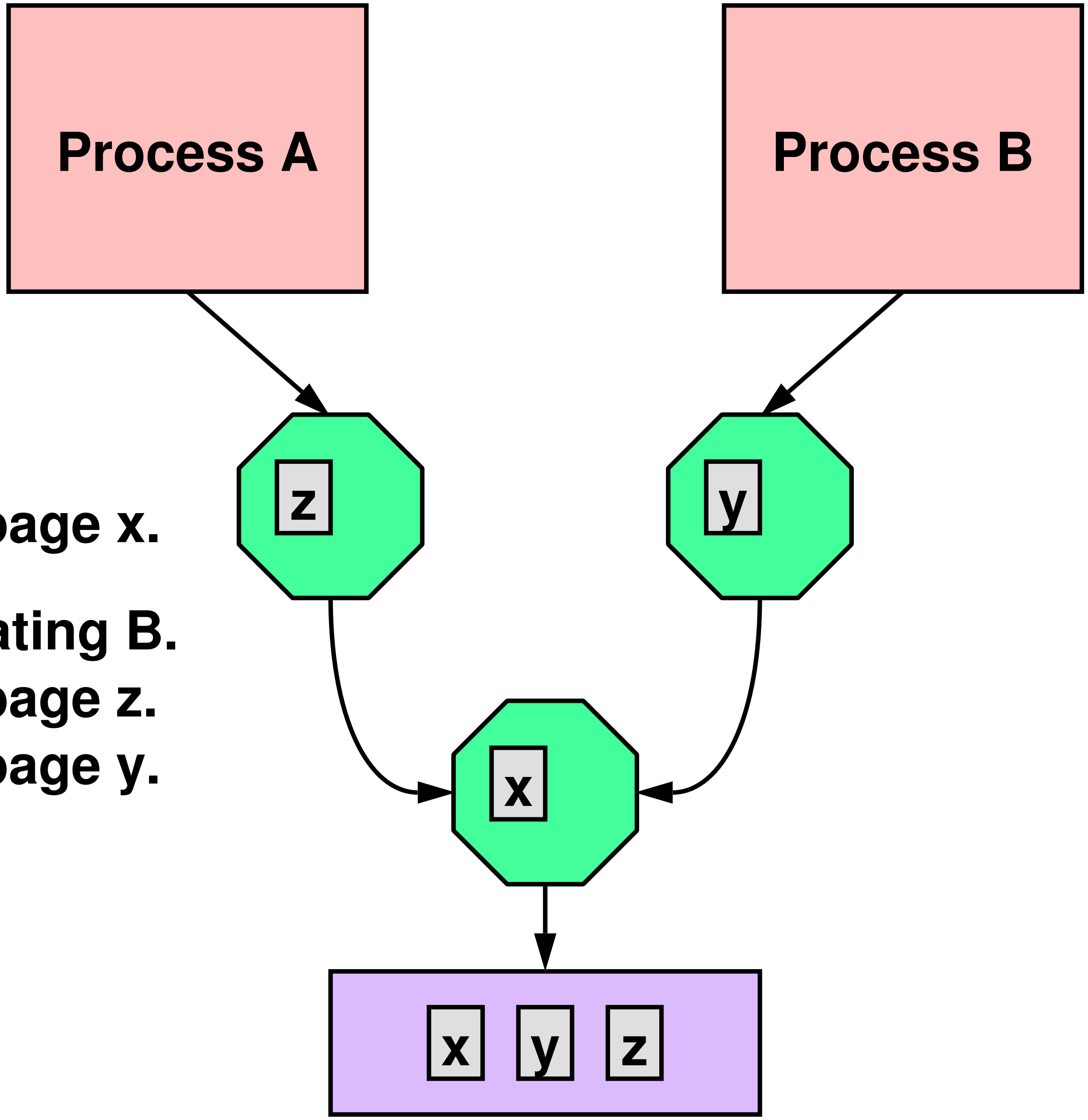
A forks, creating B.

A modifies page z.

B modifies page y.



Private Mapping (2)



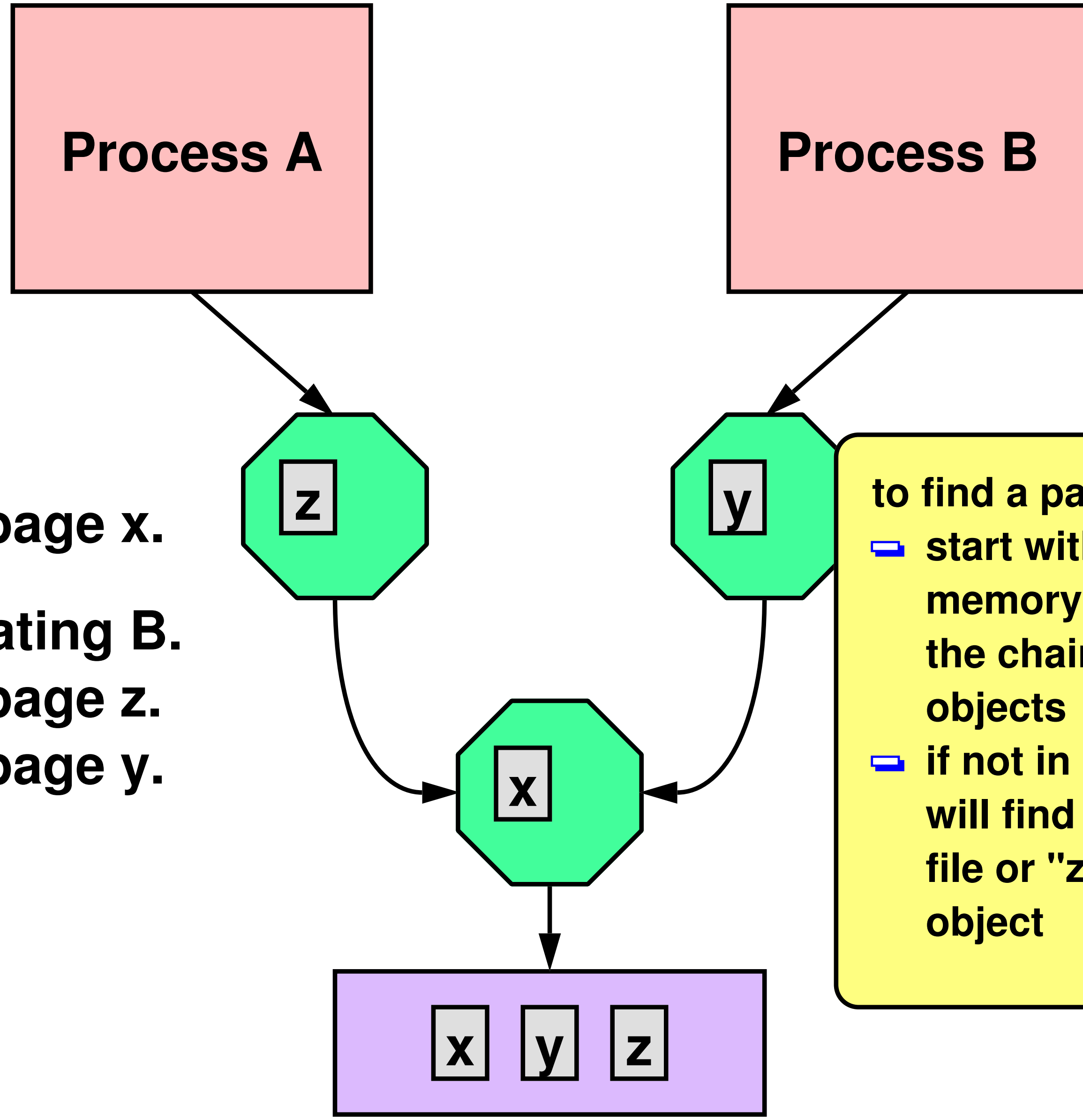
A modifies page x.

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

Private Mapping (2)

A modifies page x.

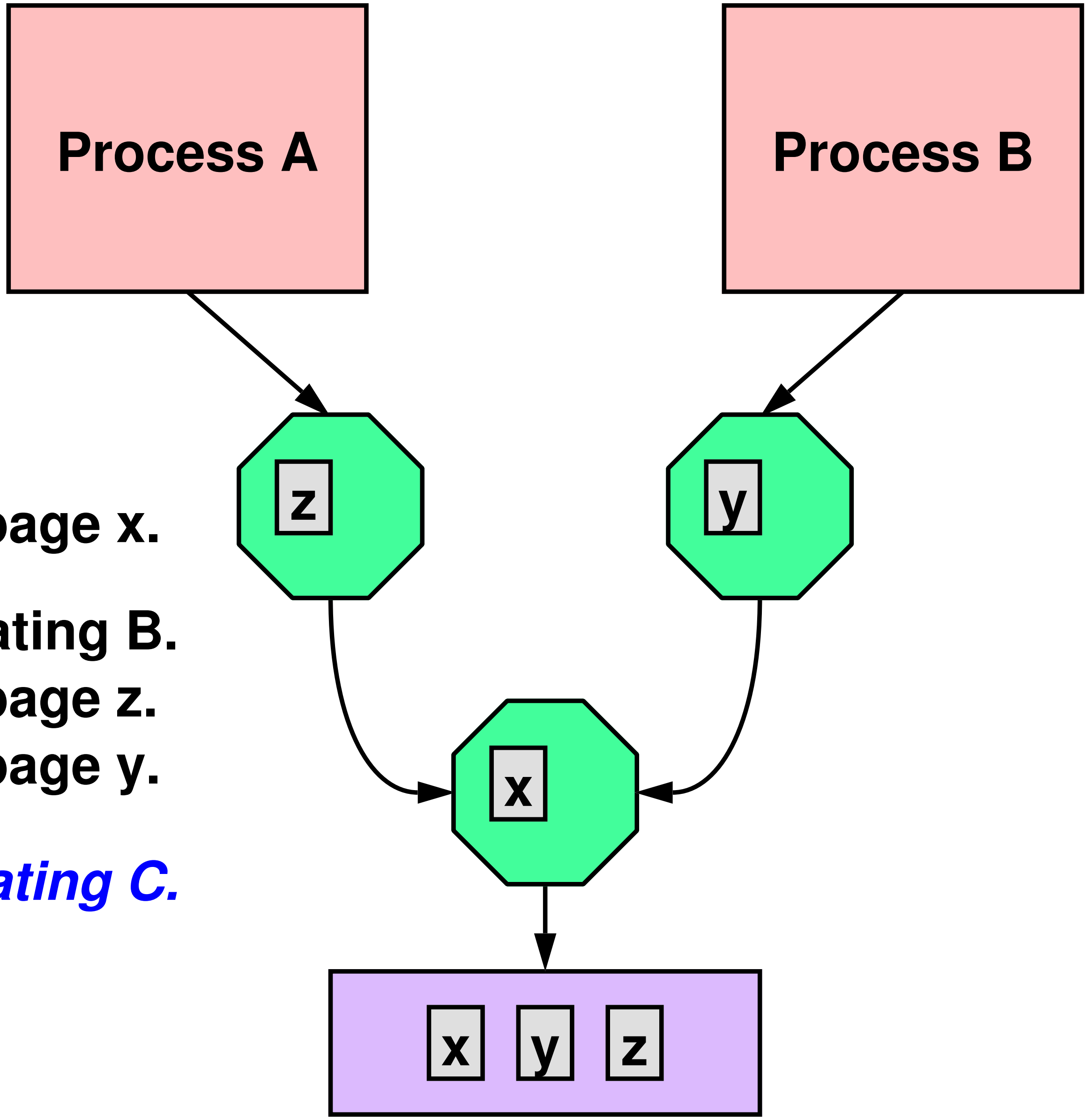
A forks, creating B.
A modifies page z.
B modifies page y.



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)

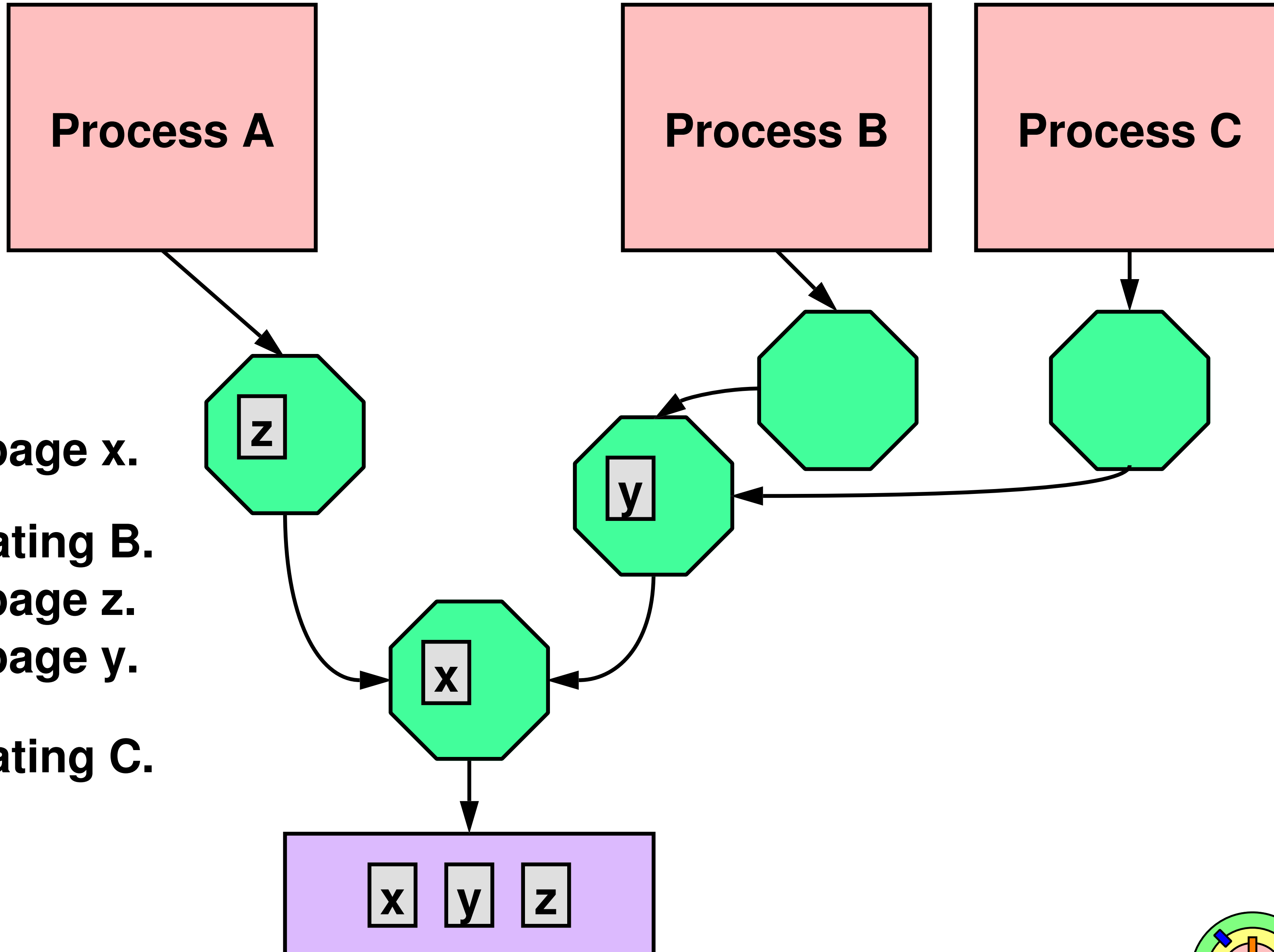


A modifies page x.

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

B forks, creating C.

Private Mapping (3)

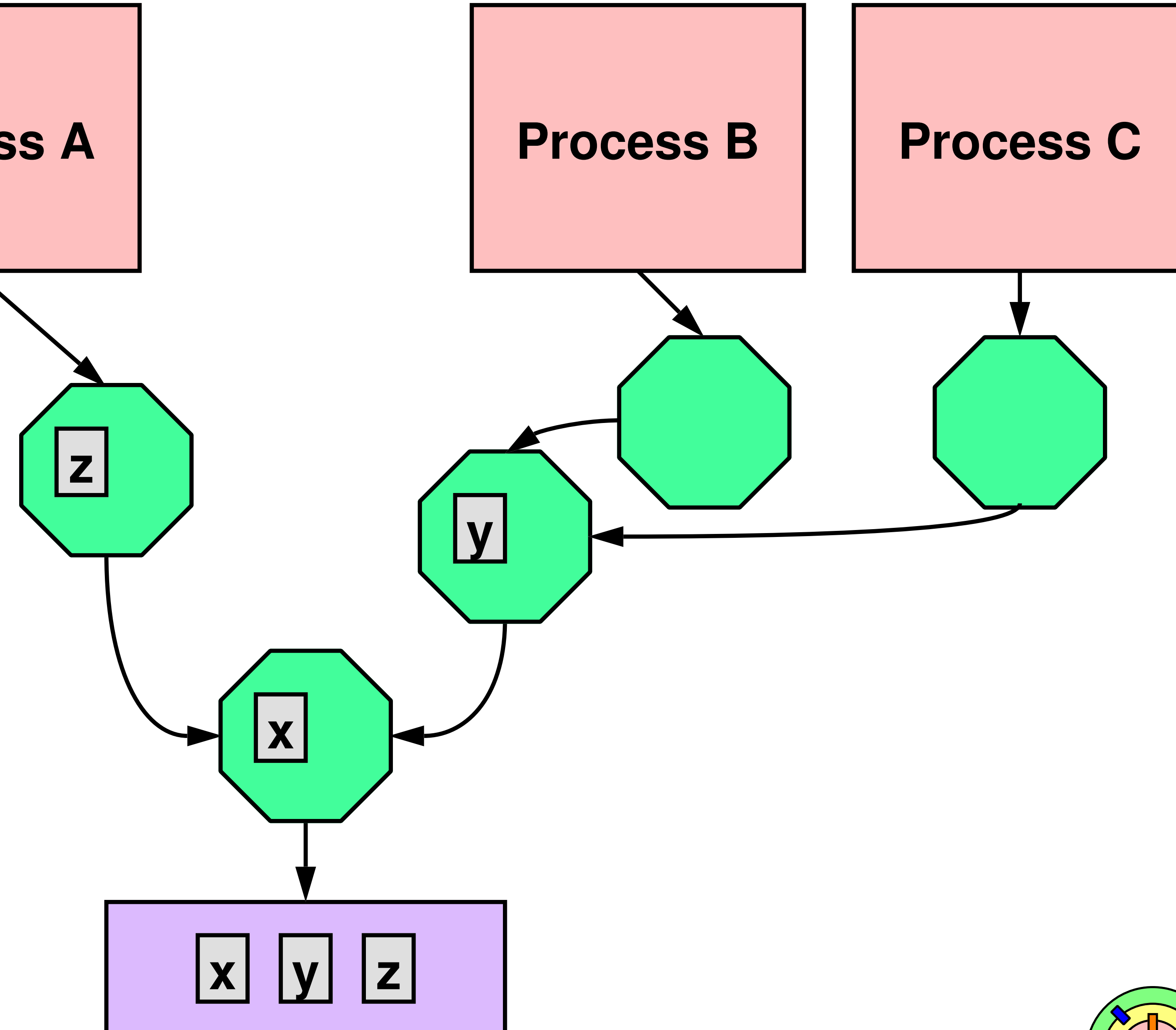


A modifies page x.

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

B forks, creating C.

Private Mapping (3)



A modifies page x.

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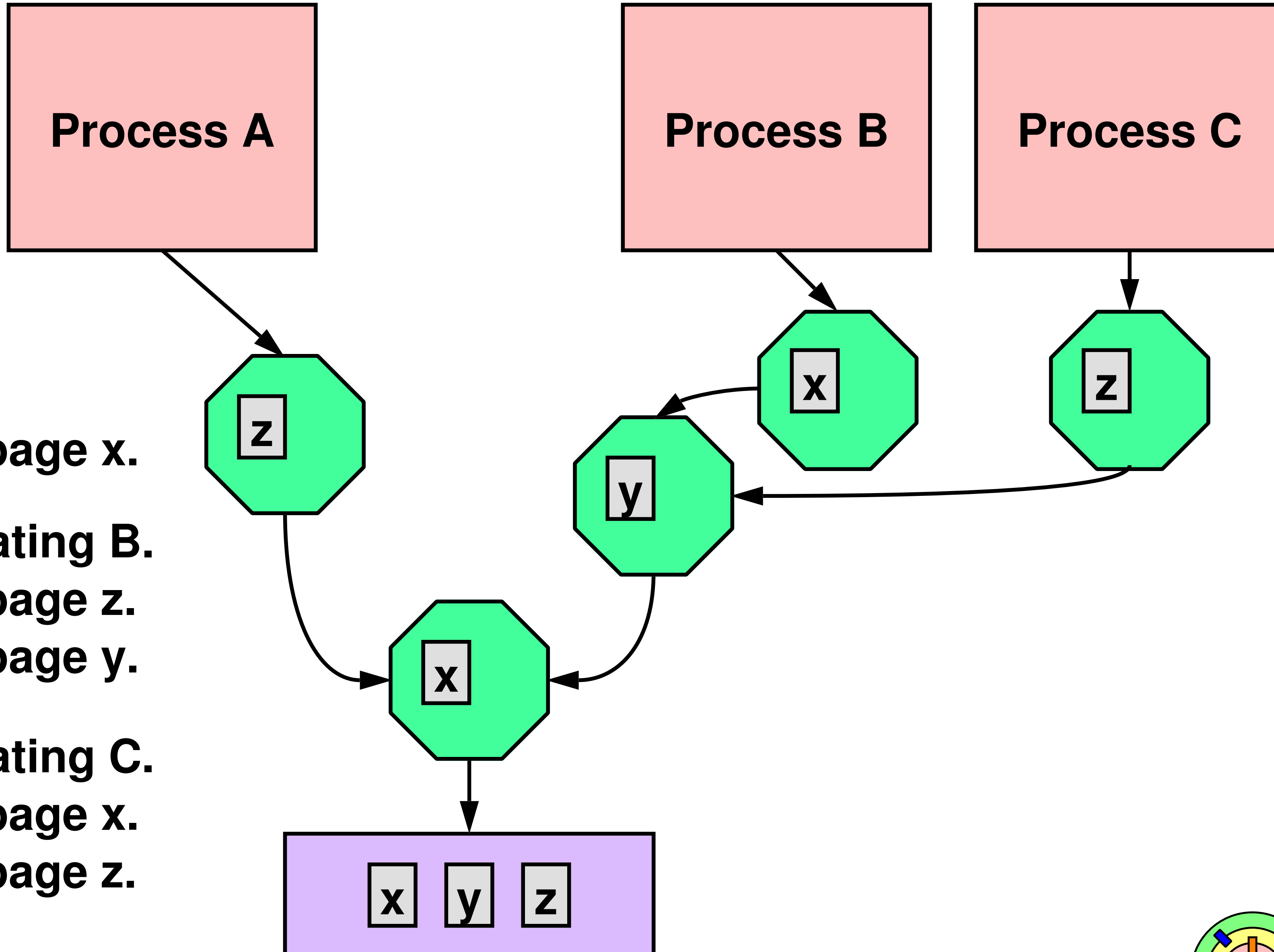
B forks, creating C.
B modifies page x.
C modifies page z.

Private Mapping (3)

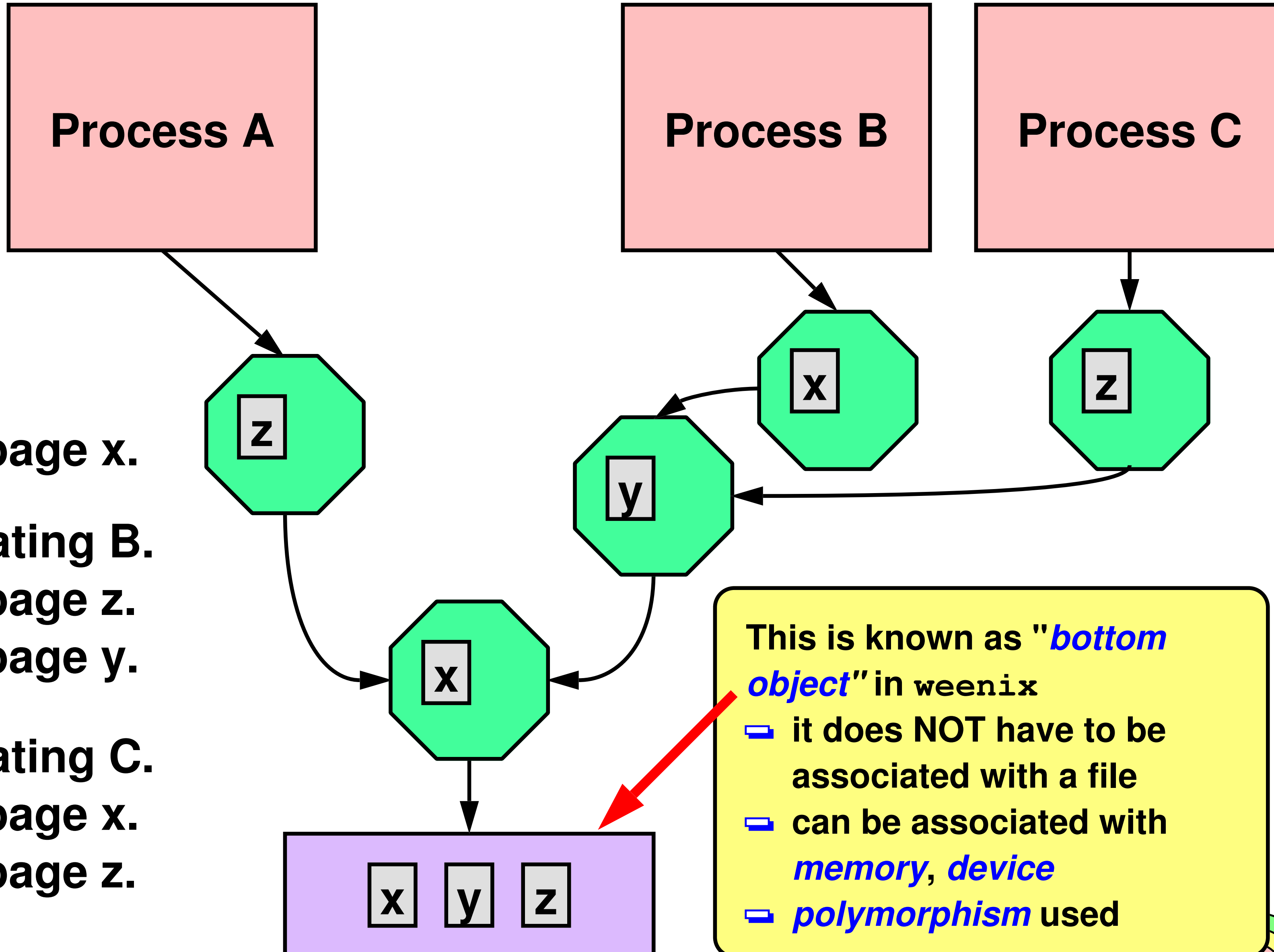


A modifies page x.

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)



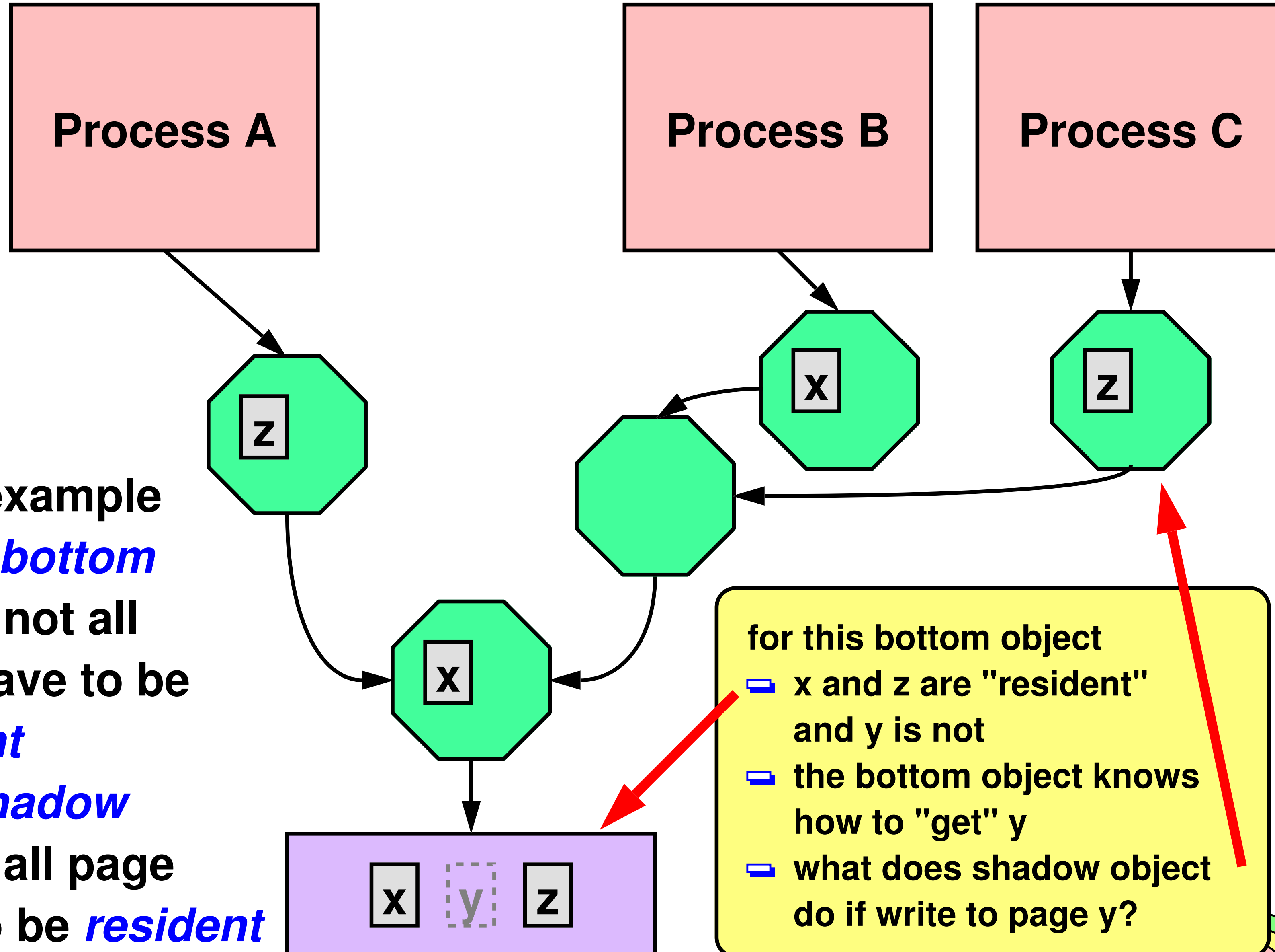
A modifies page x.

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

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

This is known as "*bottom object*" in `weenix`
- it does NOT have to be associated with a file
- can be associated with *memory*, *device*
- *polymorphism* used

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***

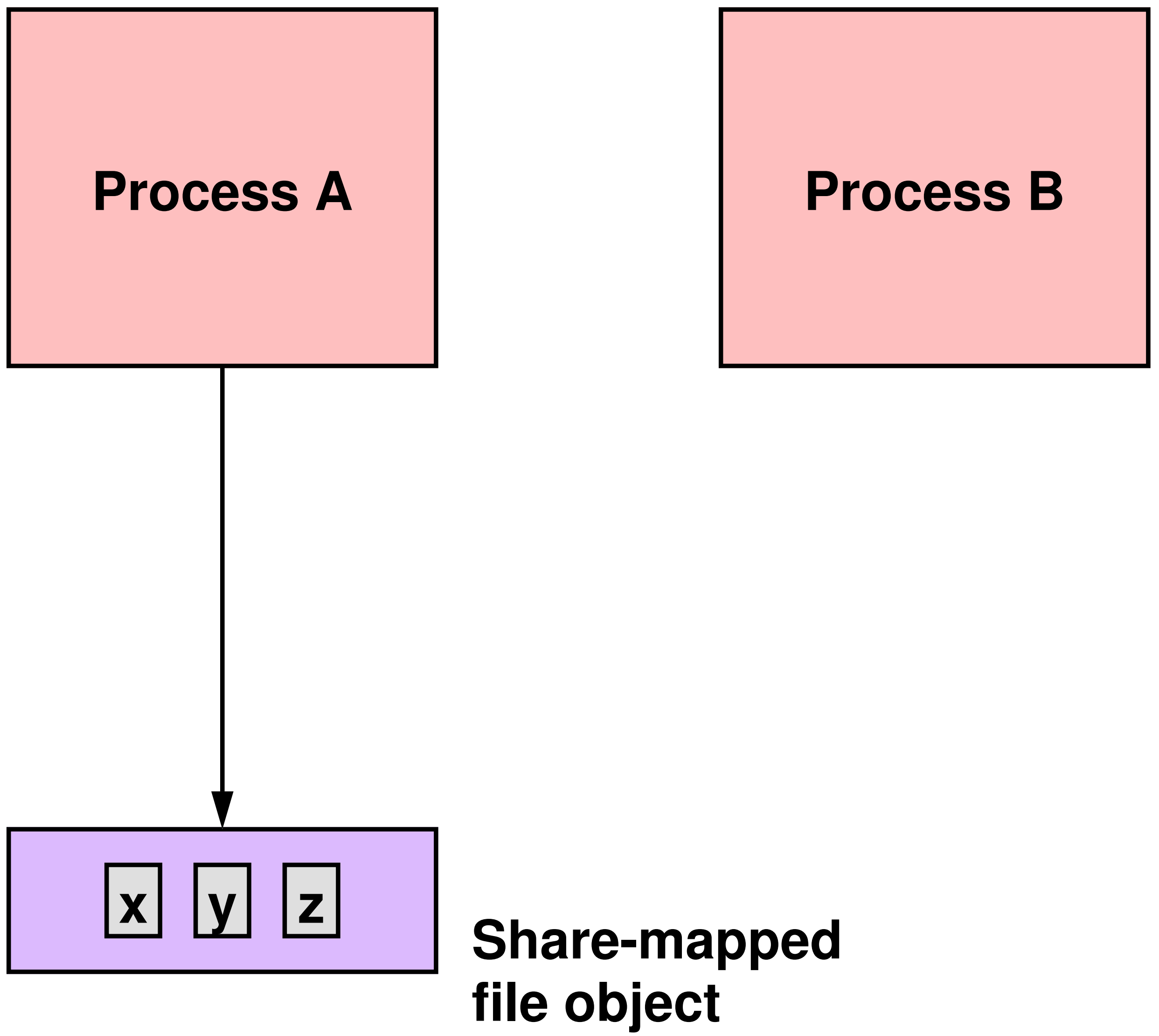
for this bottom object

- x and z are "resident" and y is not
- the bottom object knows how to "get" y
- what does shadow object do if write to page y?

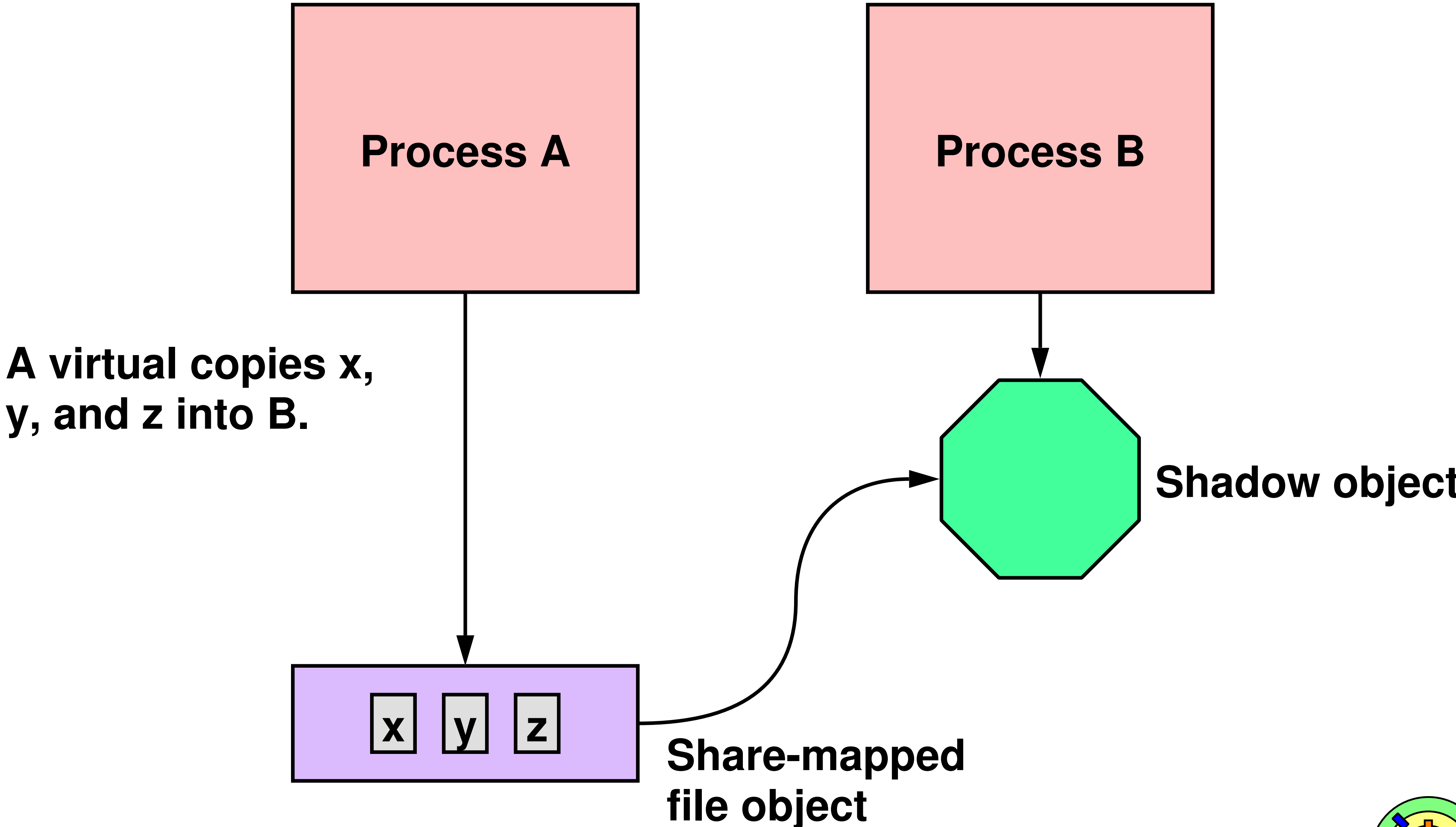
Virtual Copy

- 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

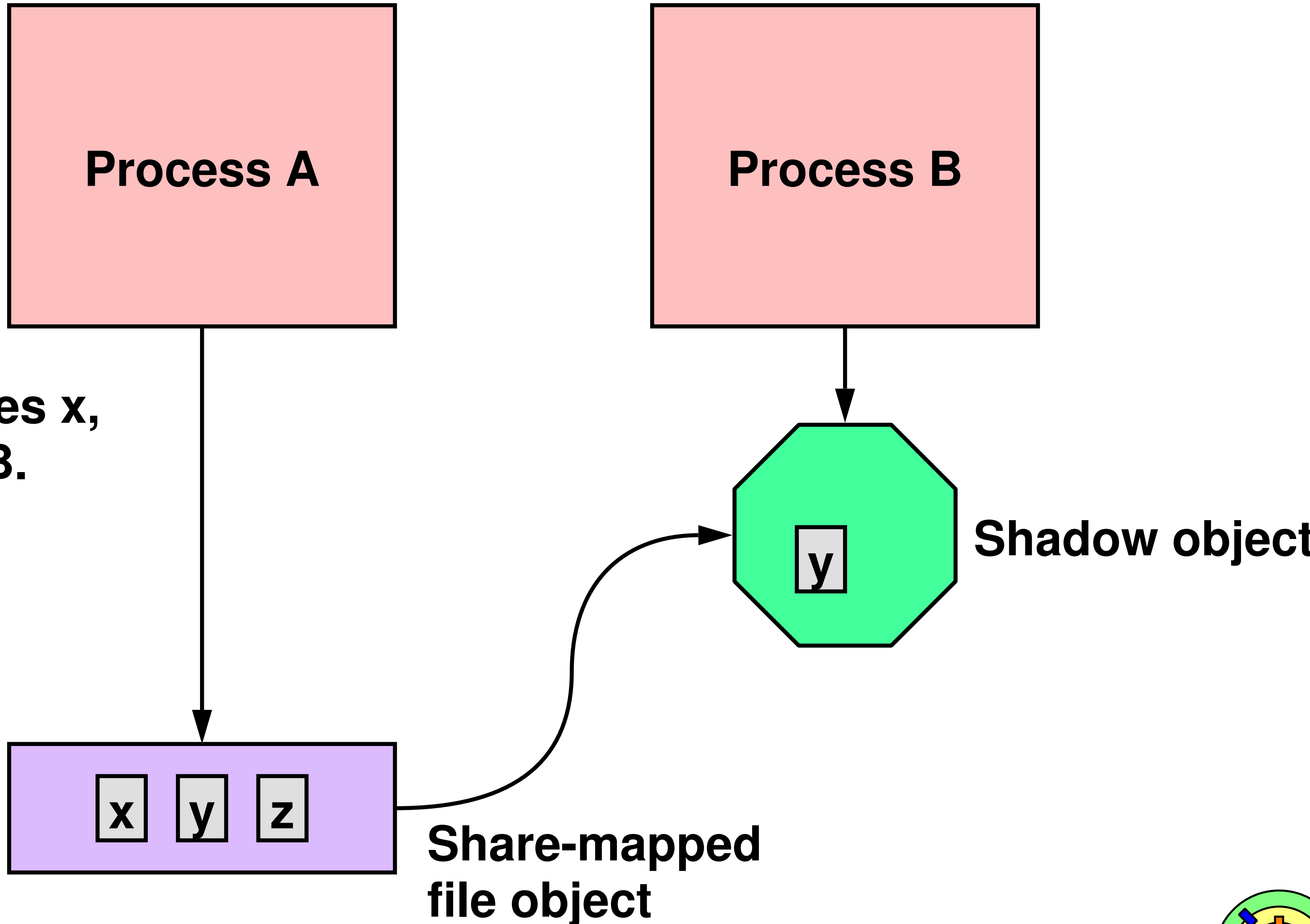


Share and Private Mapping



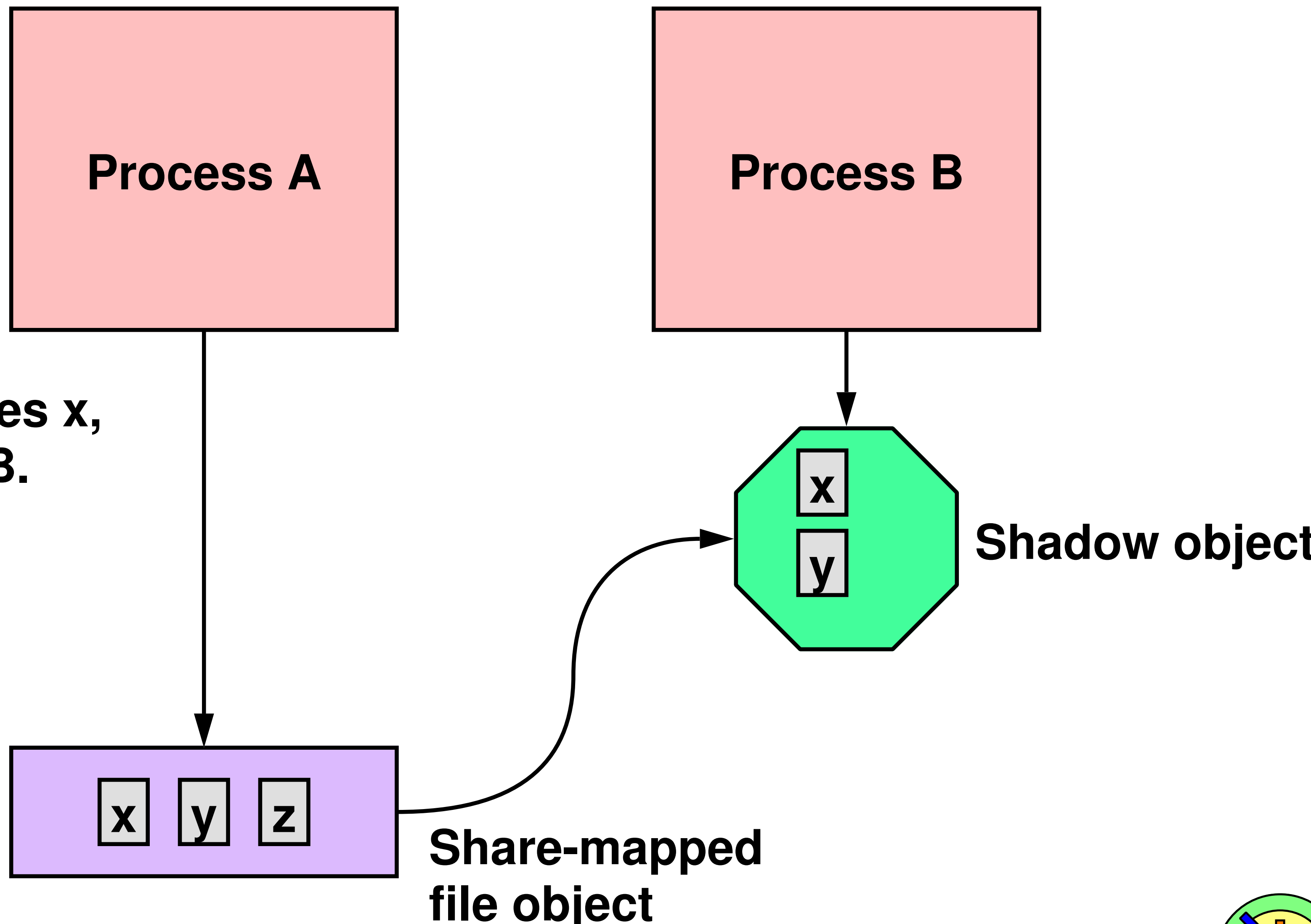
Share and Private Mapping

A virtual copies x, y, and z into B.
B modifies y.

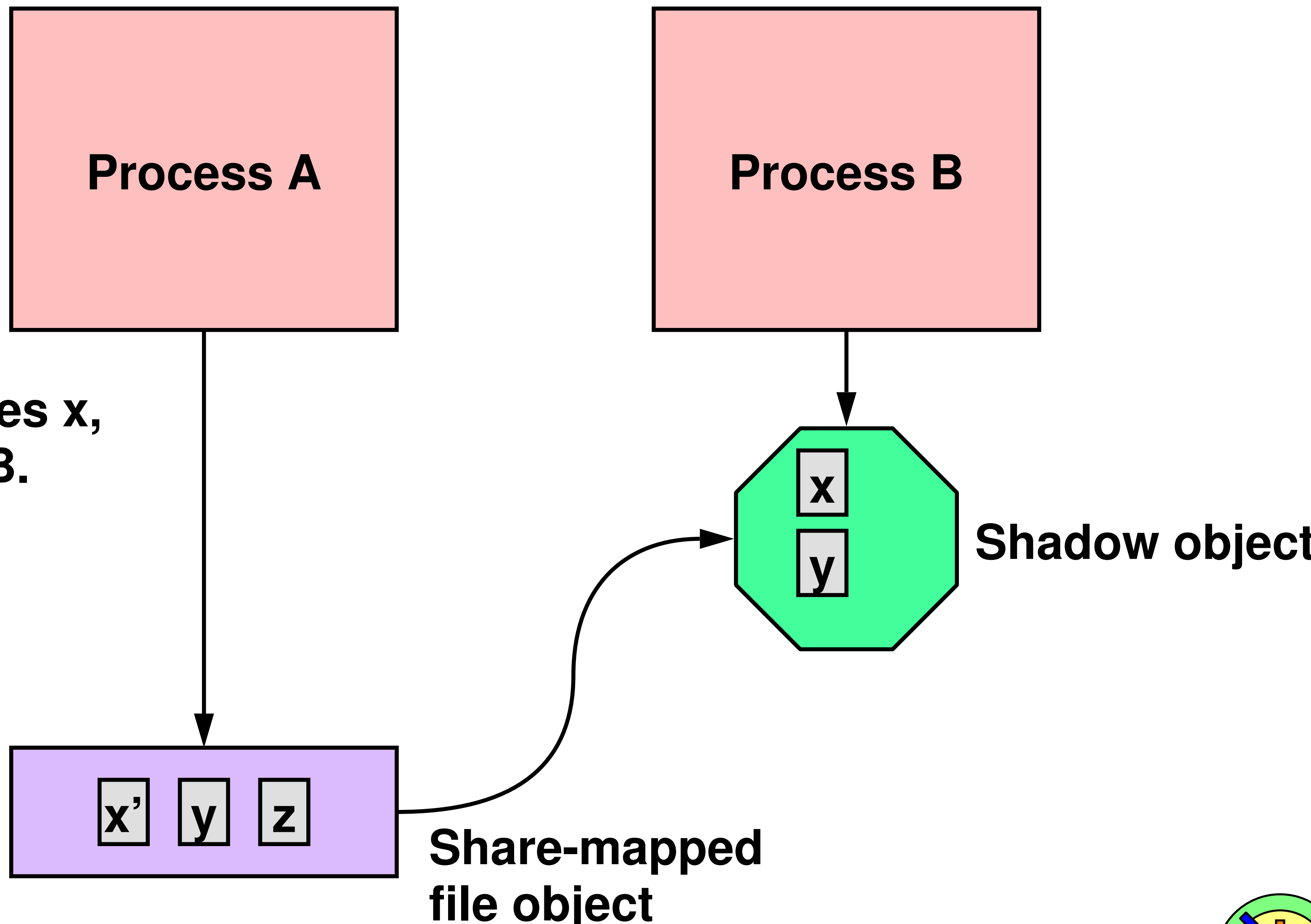


Share and Private Mapping

A virtual copies x,
y, and z into B.
B modifies y.
A modifies x.



Share and Private Mapping



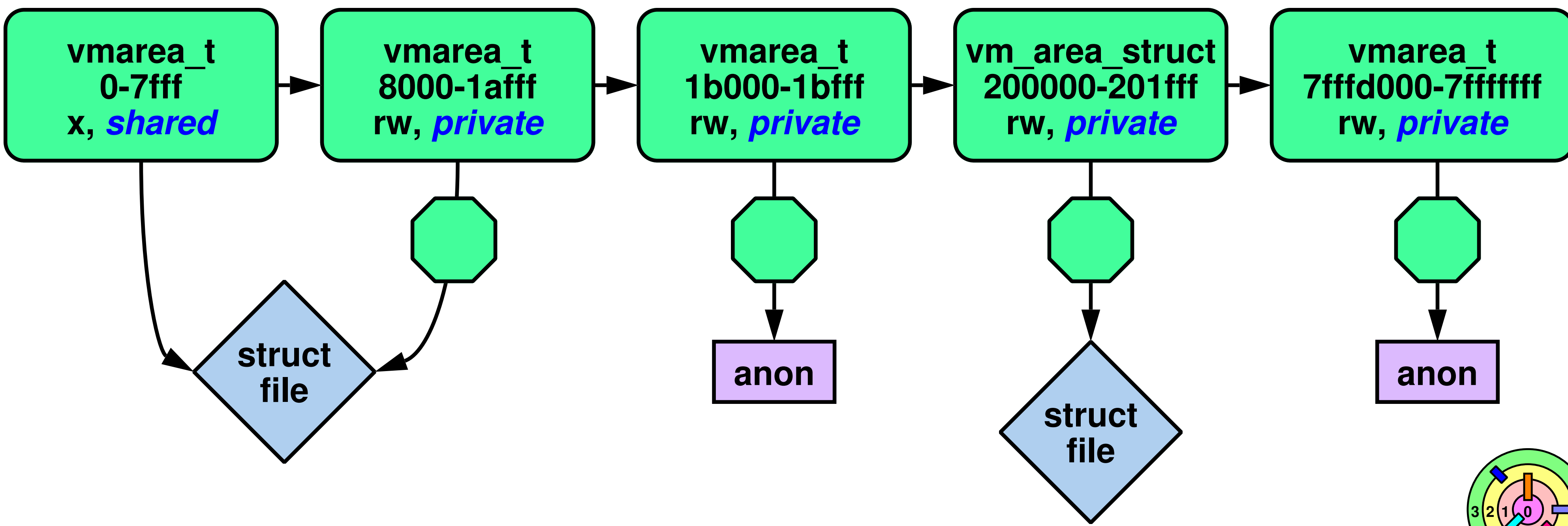
A virtual copies x, y, and z into B.
B modifies y.
A modifies x.

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

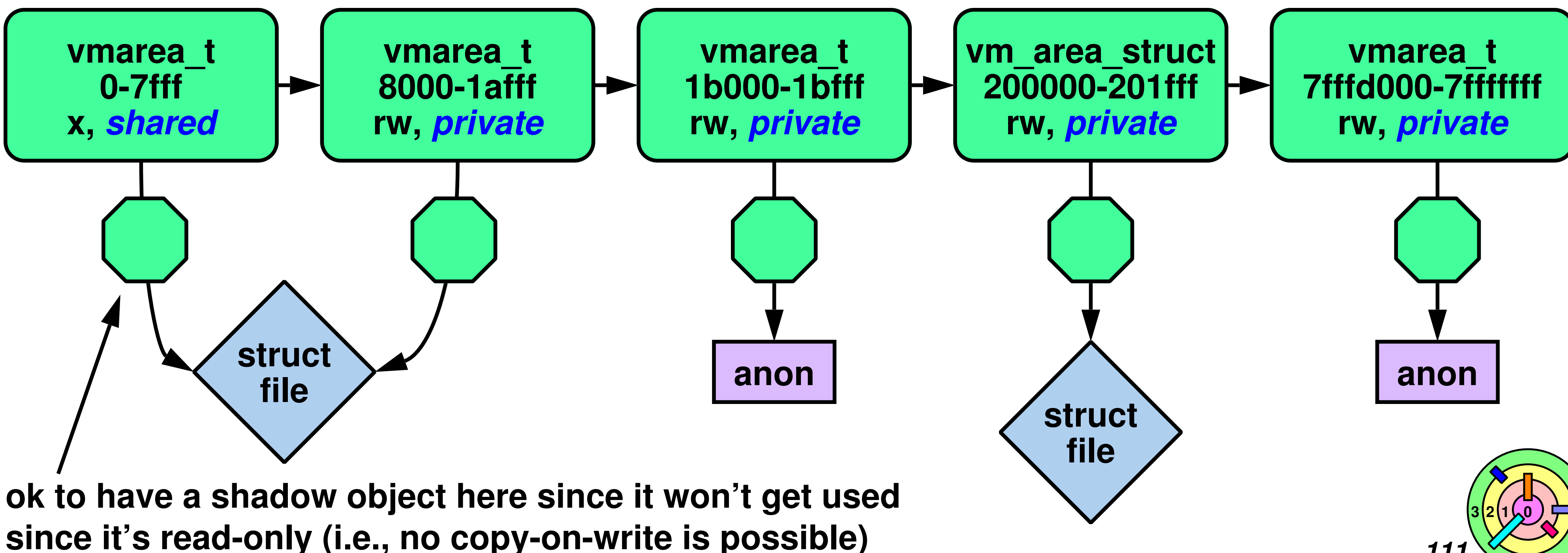
Memory Management Objects in `weenix`

- 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



Memory Management Objects in `weenix`

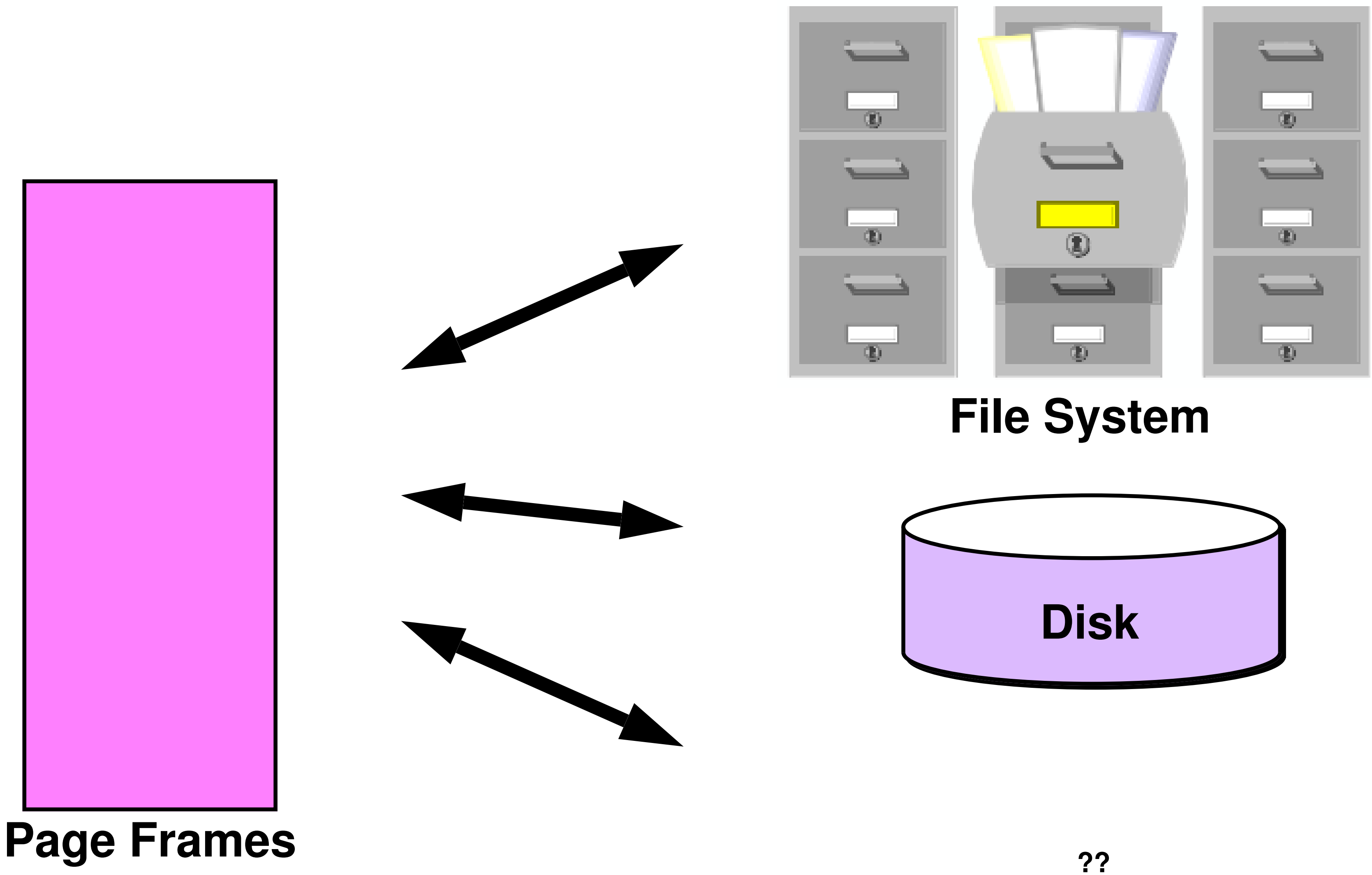
- In `weenix`, an *mmobj* is used to manage *page frames*
  - types of *mmobj* in kernel assignments are:
    - there's one that lives *inside a vnode* (`vn->vn_mmobj`)
    - a *shadow object* is an mmobj
    - an *anonymous object* (meaning not associated with a file and not a shadow object) is an mmobj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



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 accidentally
    - 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

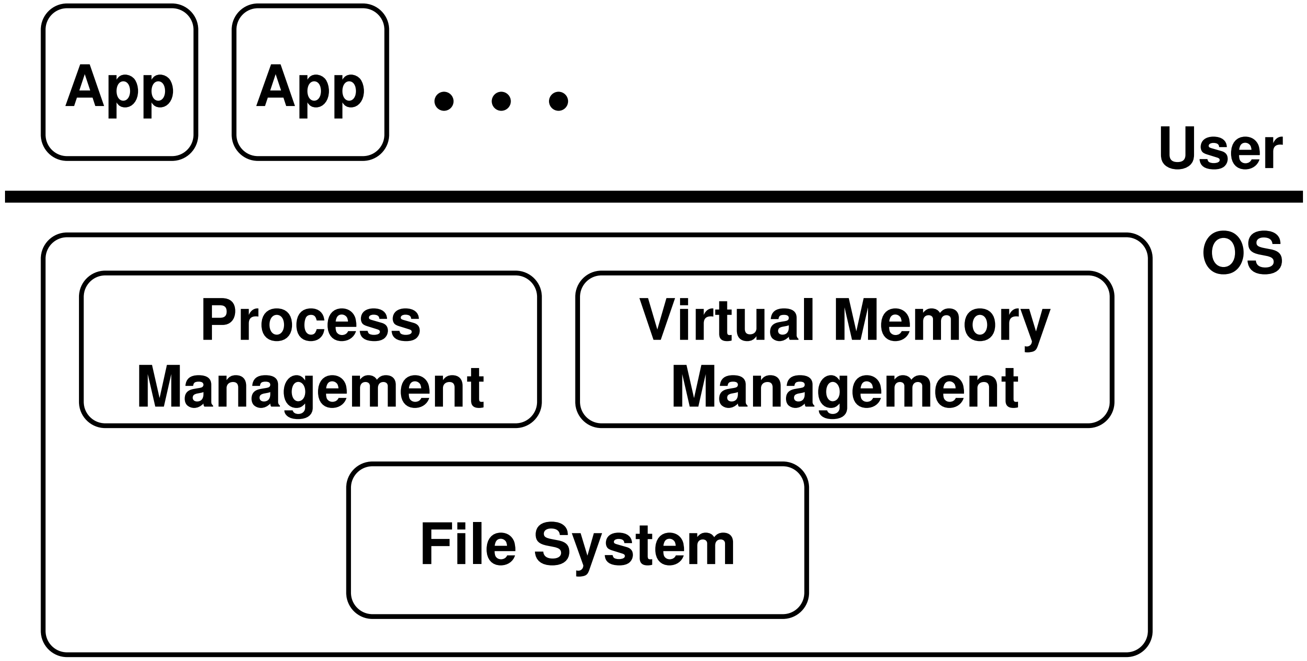
Space Allocation in Linux

- 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

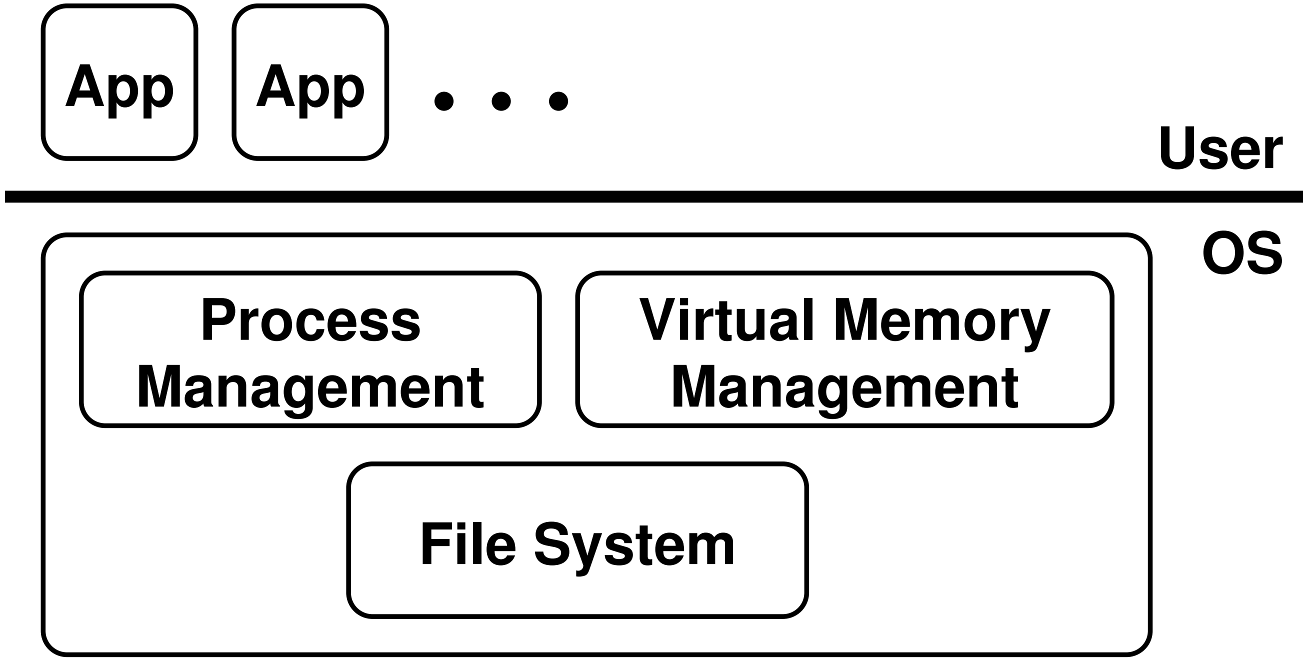
- Space reservation
  - allocation of virtual memory
- Space commitment
  - reservation of physical resources
    - paging space + physical memory
- `MapViewOfFile` (sort of like `mmap`)
  - no over-commitment
- Thread creation
  - creator specifies both reservation and commitment for stack pages

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()`)