# eXecute In Place support in NetBSD

Masao “uebs” Uebayashi
<uebayasi@tombi.co.jp>

BSDCan 2010

2010.5.13

# Who am I

- NetBSD developer
- Japanese
- Living in Yokohama
- Self-employed
  - Since Dec. 15 2008
  - Tombi Inc.

# Agenda

- Demonstration
- Introduction
- Program execution
- VM
  - Virtual memory management
  - Physical memory management
  - Fault handler, pager
  - :
- Design of XIP

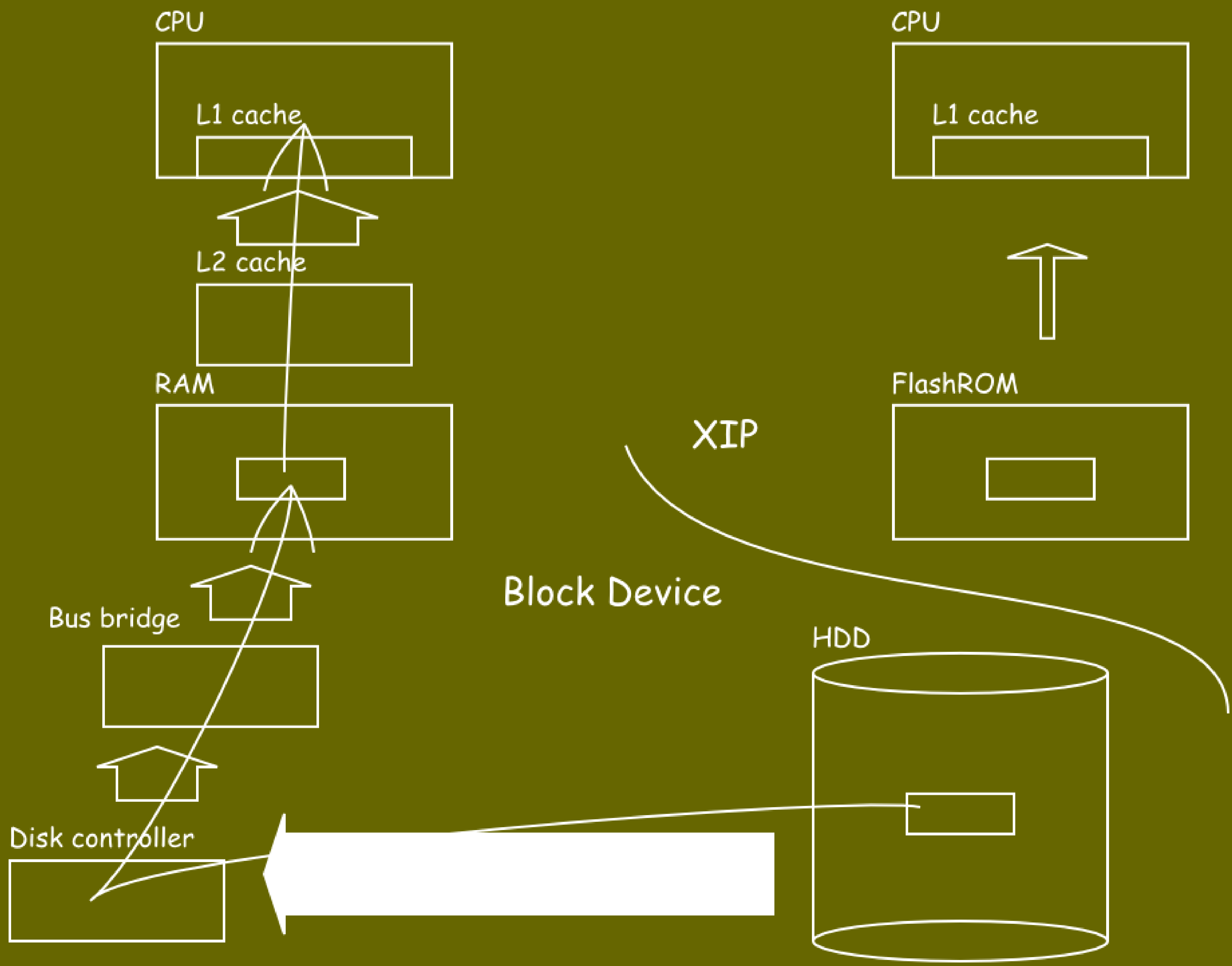
# Demonstration

XIP on NetBSD/arm (i.MX35)

# Introduction

What is XIP?

- Execute programs directly from devices
- No memory copy
- Only about userland programs
  - (Kernel XIP is another story)


CPU
L1 cache
L2 cache
RAM
Bus bridge
Disk controller
CPU
L1 cache
FlashROM
XIP
Block Device
HDD

# Introduction

- Who needs XIP?
  - Embedded devices
    - Memory saving for less power consumption
    - Boot time
  - Mainframes (Linux)
    - Memory saving for virtualized instances
  - :
  - “Nothing in between”

# Introduction

How to achieve XIP?

- Don't copy programs to memory when executing it
- “Execute” == `mmap()`
- :
- :
- :
- :
- :
- What does that *actually* mean?

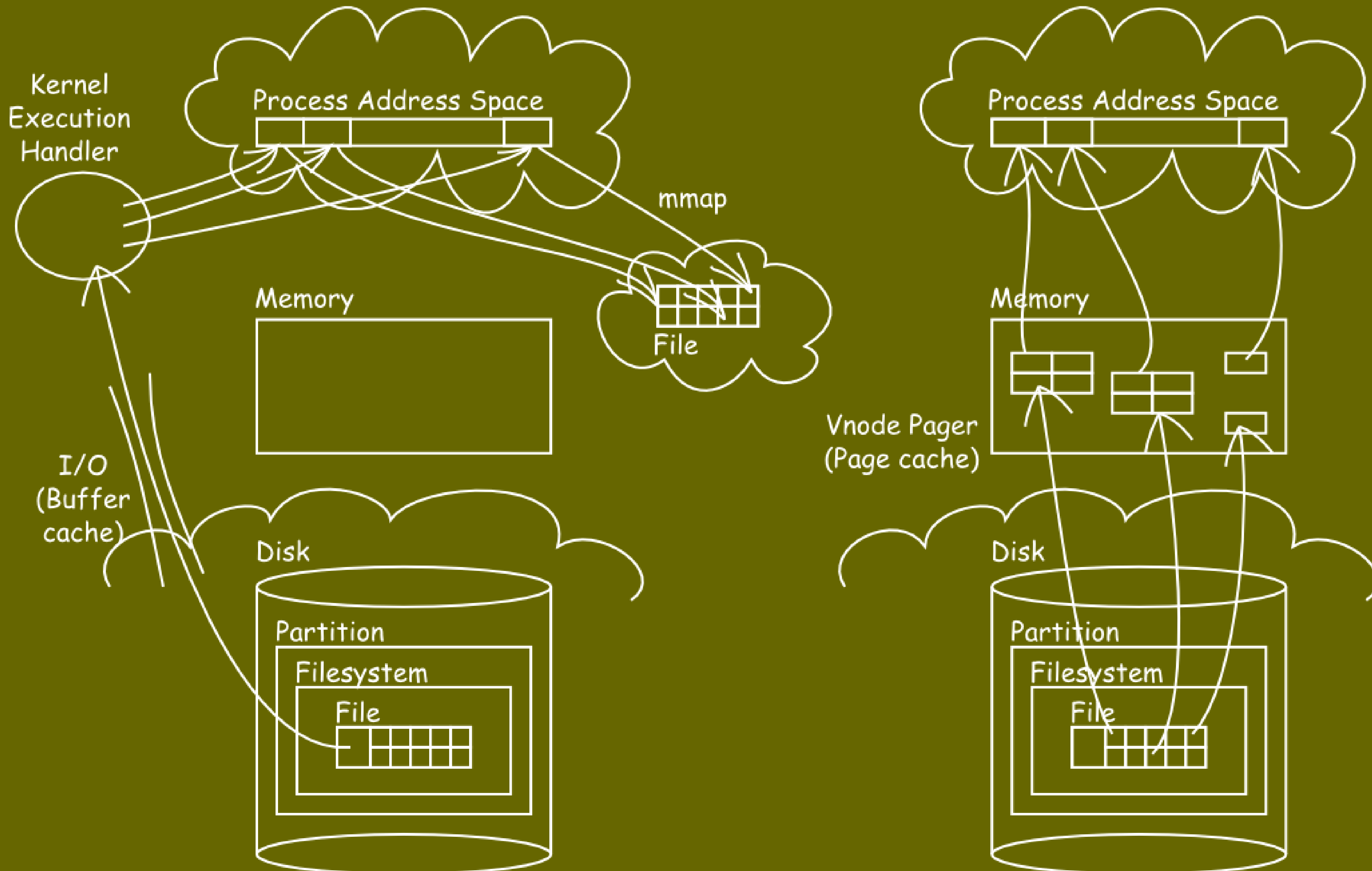
# Goals

- No hacks
  - Keep code cleanliness
  - Keep abstraction
    - Including device handling
  - :
  - :
- Performance
  - Latency
  - Memory efficiency

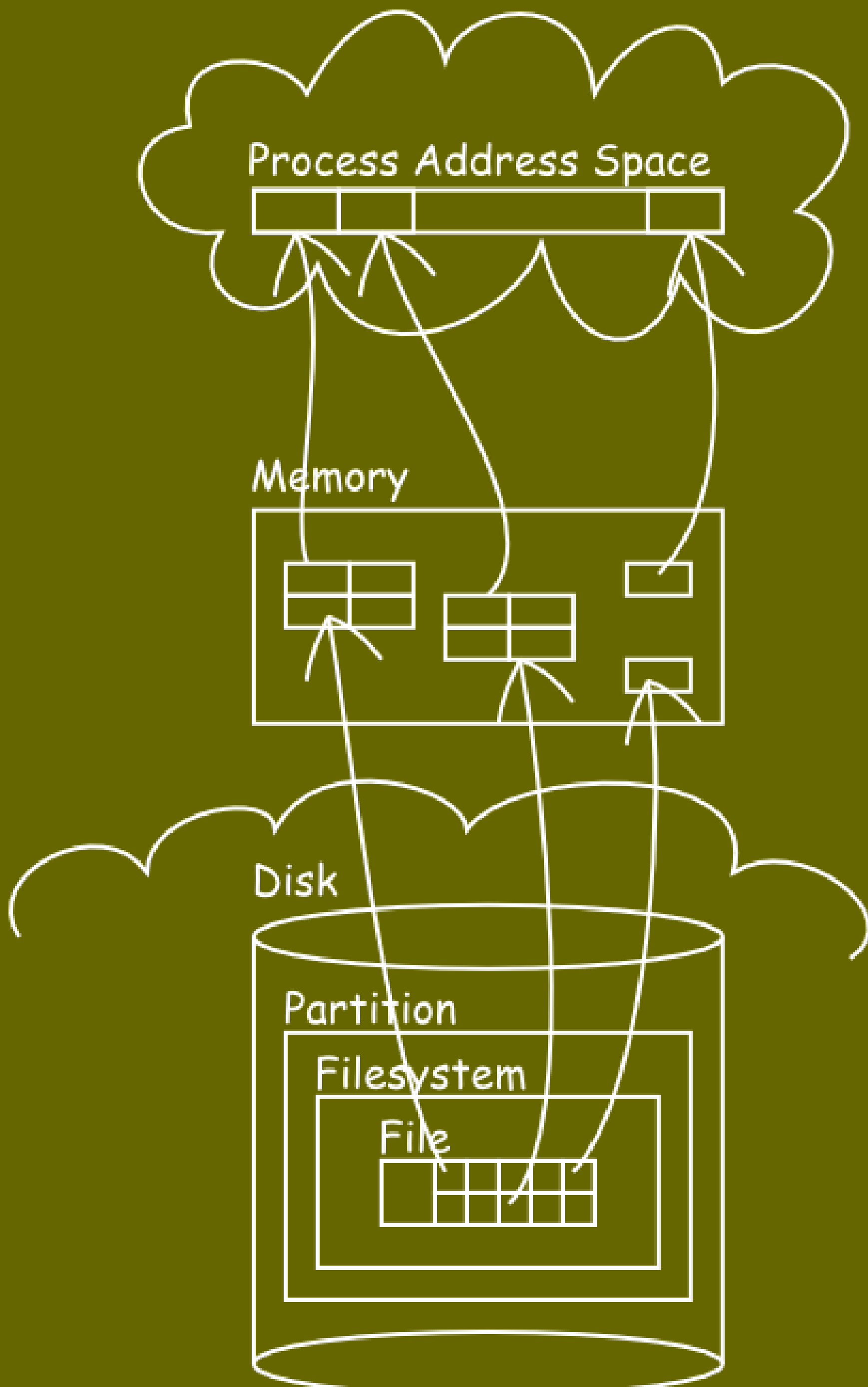
# Program execution

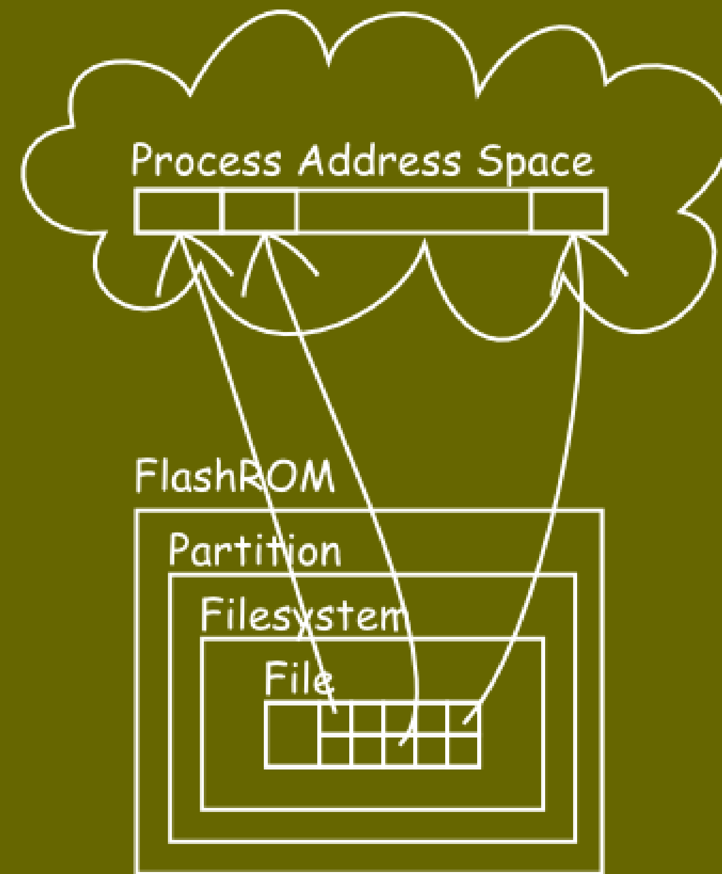
execve(2) → sys_execve()

- Prepare
  - Read program header using I/O
  - Map sections
  - Set program entry point
- Execute
  - Page fault is triggered
    - Load pages using VM
  - Execution is resumed



Kernel
Execution
Handler
Process Address Space
mmap
File
Memory
I/O
(Buffer
cache)
Disk
Partition
Filesystem
File
Process Address Space
Memory
Vnode Pager
(Page cache)
Disk
Partition
Filesystem
File


Process Address Space
Memory
Disk
Partition
Filesystem
File


Process Address Space
FlashROM
Partition
Filesystem
File

# Program execution

- I/O part needs no changes
  - If block device interface (d_strategy()) is provided
- VM part needs changes!!!

# Virtual memory management

http://en.wikipedia.org/wiki/Virtual_memory

- Virtual memory is a computer system technique which gives an application program the impression that it has contiguous working memory (an address space), while in fact it may be physically fragmented and may even overflow on to disk storage.
- Developed for multitasking kernels, virtual memory provides two primary functions:
  - Each process has its own address space, thereby not required to be relocated nor required to use relative addressing mode.
  - Each process sees one contiguous block of free memory upon launch. Fragmentation is hidden.

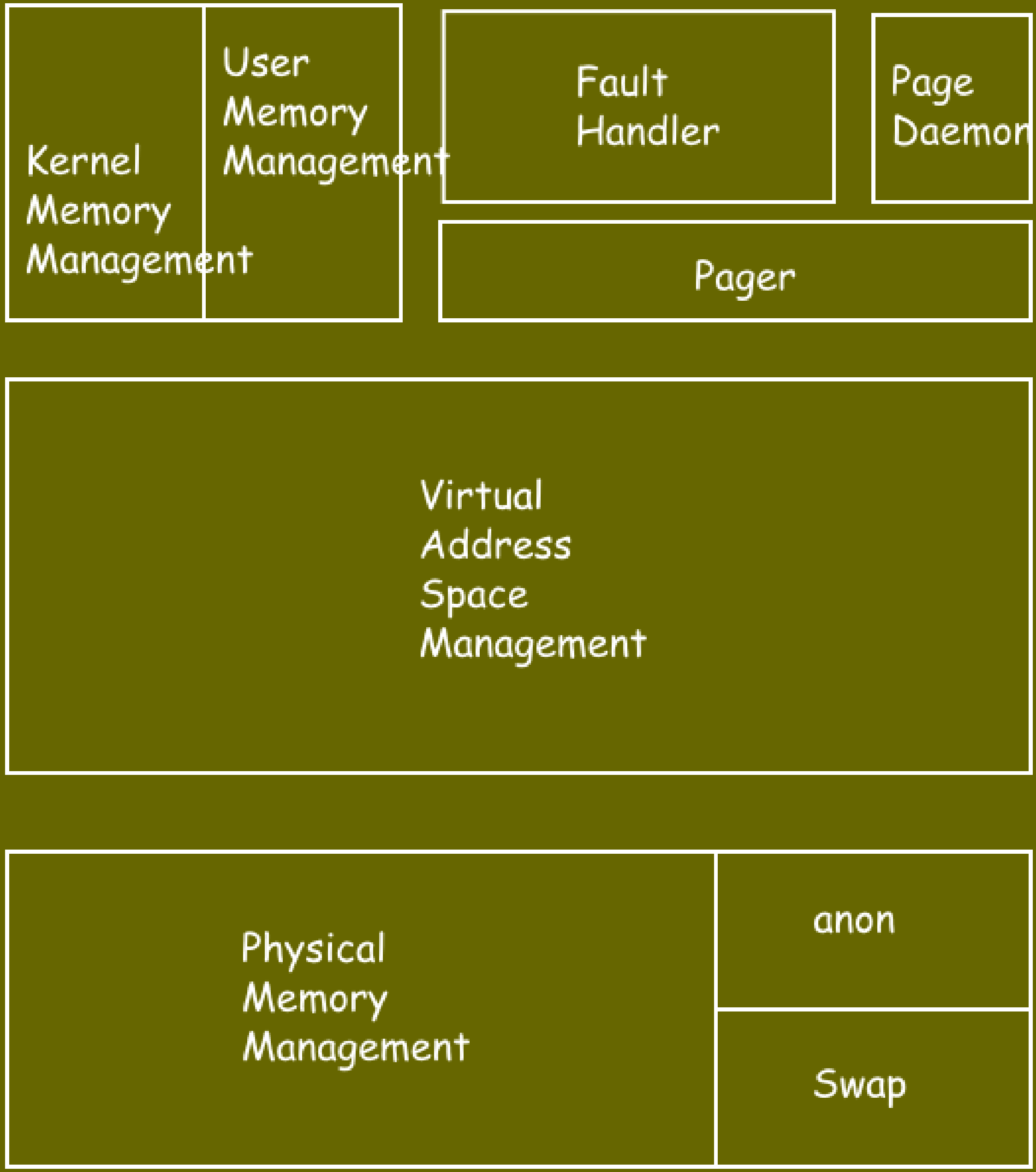
# Virtual memory management

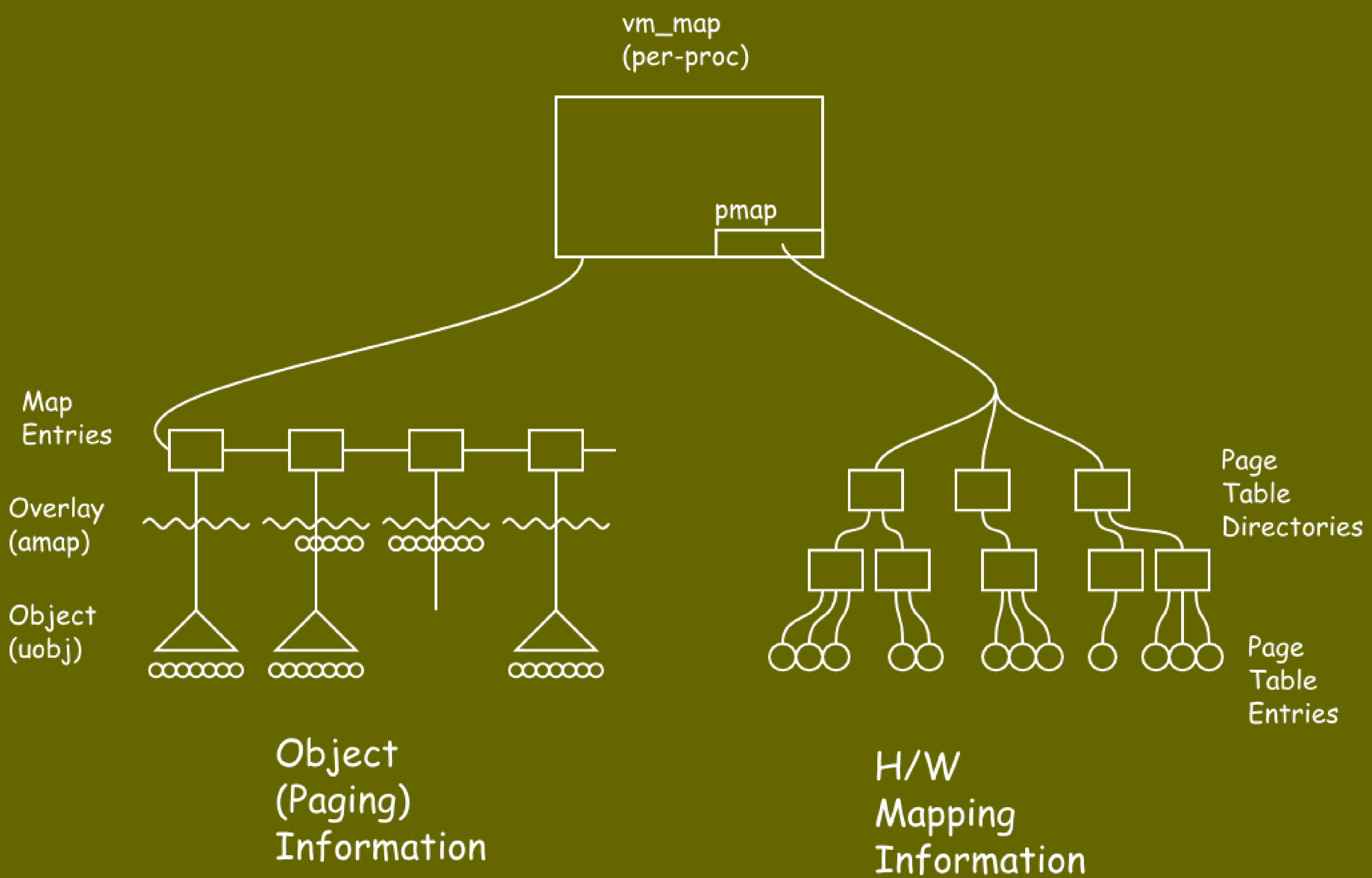
http://en.wikipedia.org/wiki/Virtual_memory

All implementations (excluding emulators) require hardware support. This is typically in the form of a memory management unit built into the CPU.

# Virtual memory management

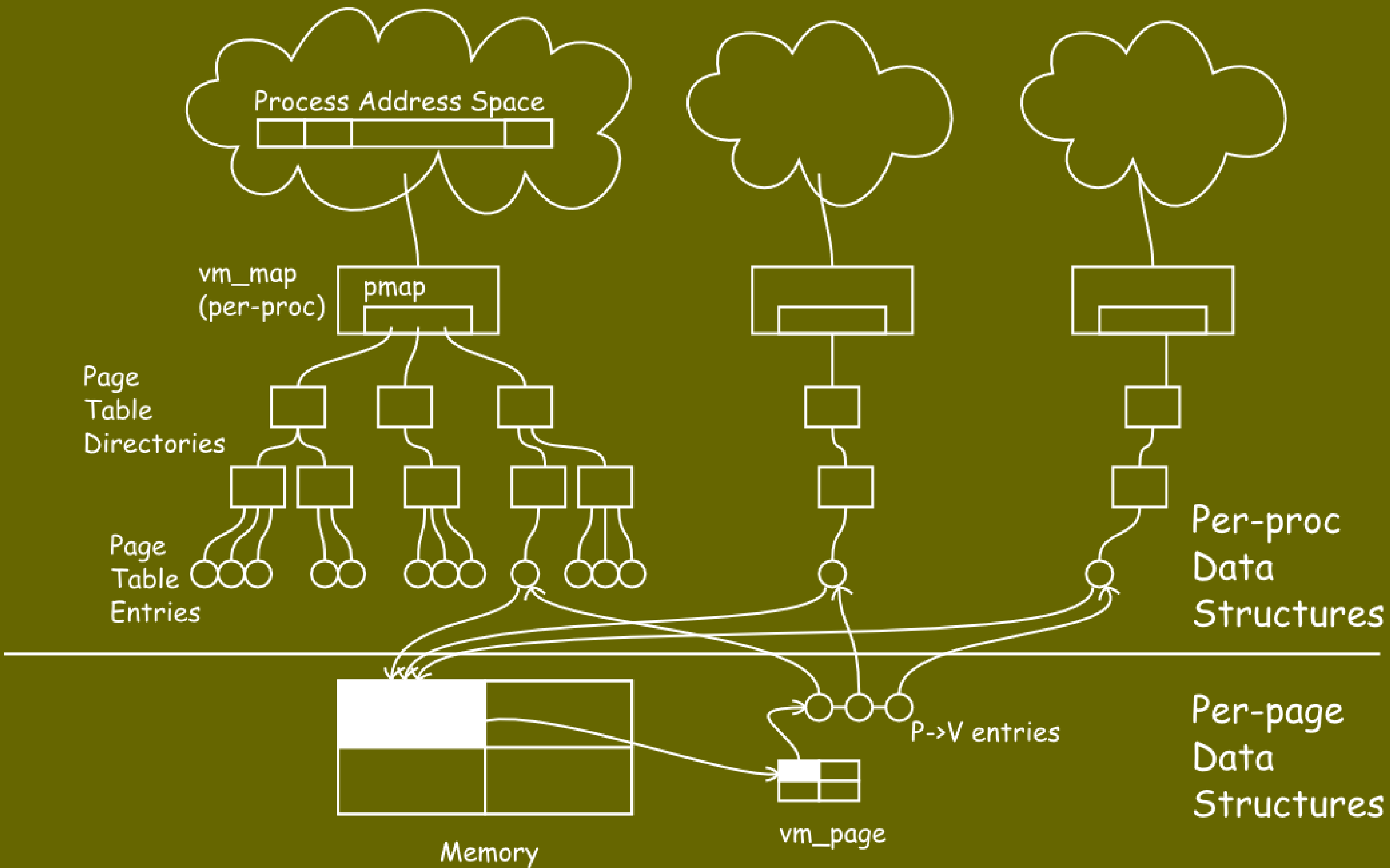
- Resource management
  - Virtual address space
  - Physical memory
- On-demand paging
  - Limited resource
  - Slow operation (I/O)
- Object abstraction
  - Linear mapping
  - Page cache


Kernel Memory Management
User Memory Management
Fault Handler
Page Daemon
Pager
Virtual Address Space Management
Physical Memory Management
anon
Swap


vm_map
(per-proc)
pmap
Map
Entries
Overlay
(amap)
Object
(uobj)
Page
Table
Directories
Page
Table
Entries
Object
(Paging)
Information
H/W
Mapping
Information

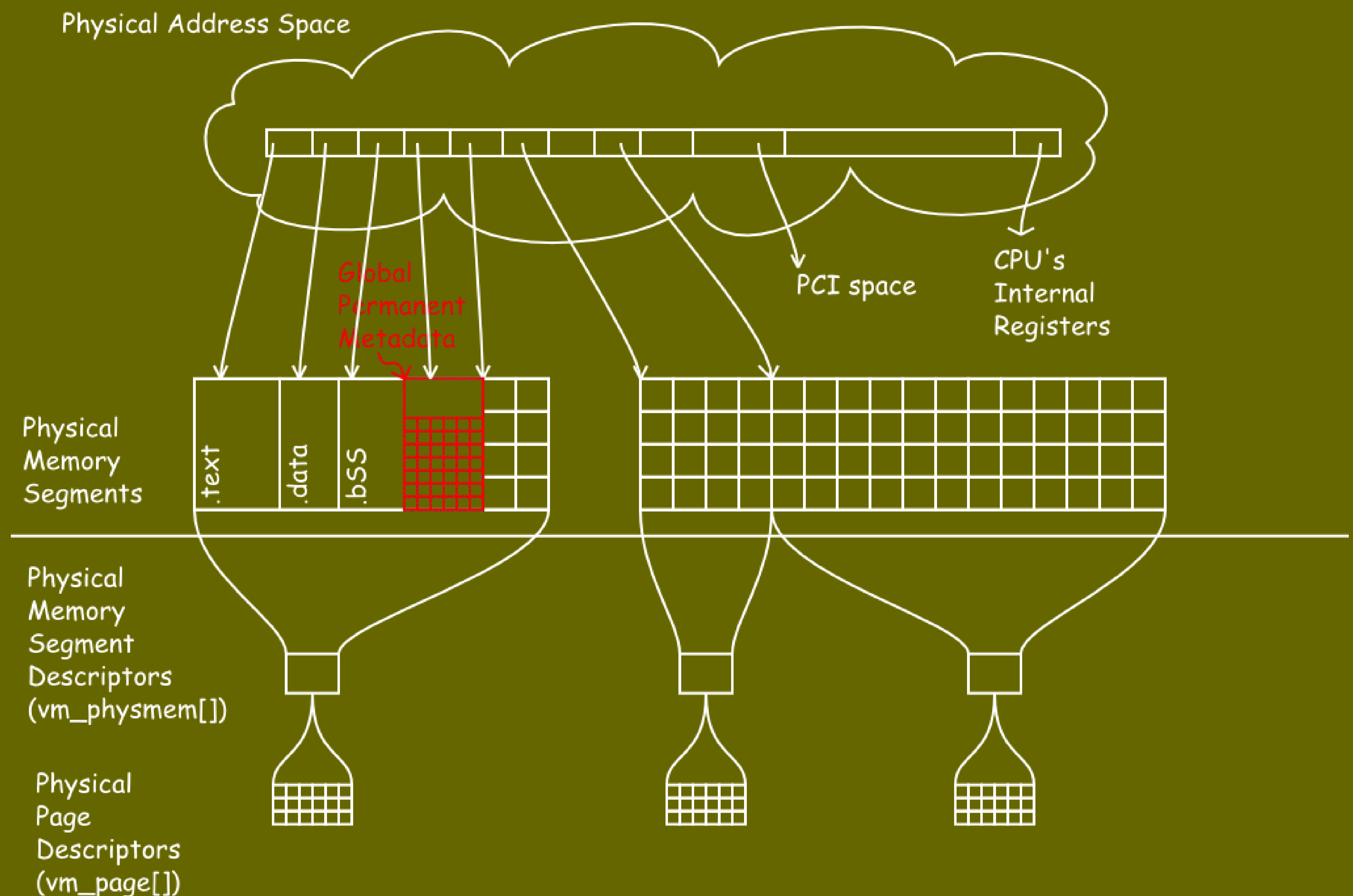
# Virtual memory management

- Behavior == object oriented + event driven
- Preparation
  - API
    - Kernel API
    - User API (== syscall)
- Resolution
  - Fault handler
  - VM objects -> pager


Process Address Space
vm_map
(per-proc)
pmap
Page
Table
Directories
Page
Table
Entries
Per-proc
Data
Structures
Per-page
Data
Structures
P->V entries
Memory
vm_page

# Physical memory management

- Structure
  - vm_physseg
    - Continuous physical memory segment
    - Registered at bootstrap
    - (hotplug is not yet)
  - vm_page
    - Per-page metadata
    - Page's **state**
    - MI vs. MD (vm_page_md)
    - CPU cache vs. page cache


Physical Address Space
Global
Permanent
Metadata
PCI space
CPU's
Internal
Registers
Physical
Memory
Segments
.text
.data
.bSS
Physical
Memory
Segment
Descriptors
(vm_physmem[])
Physical
Page
Descriptors
(vm_page[])

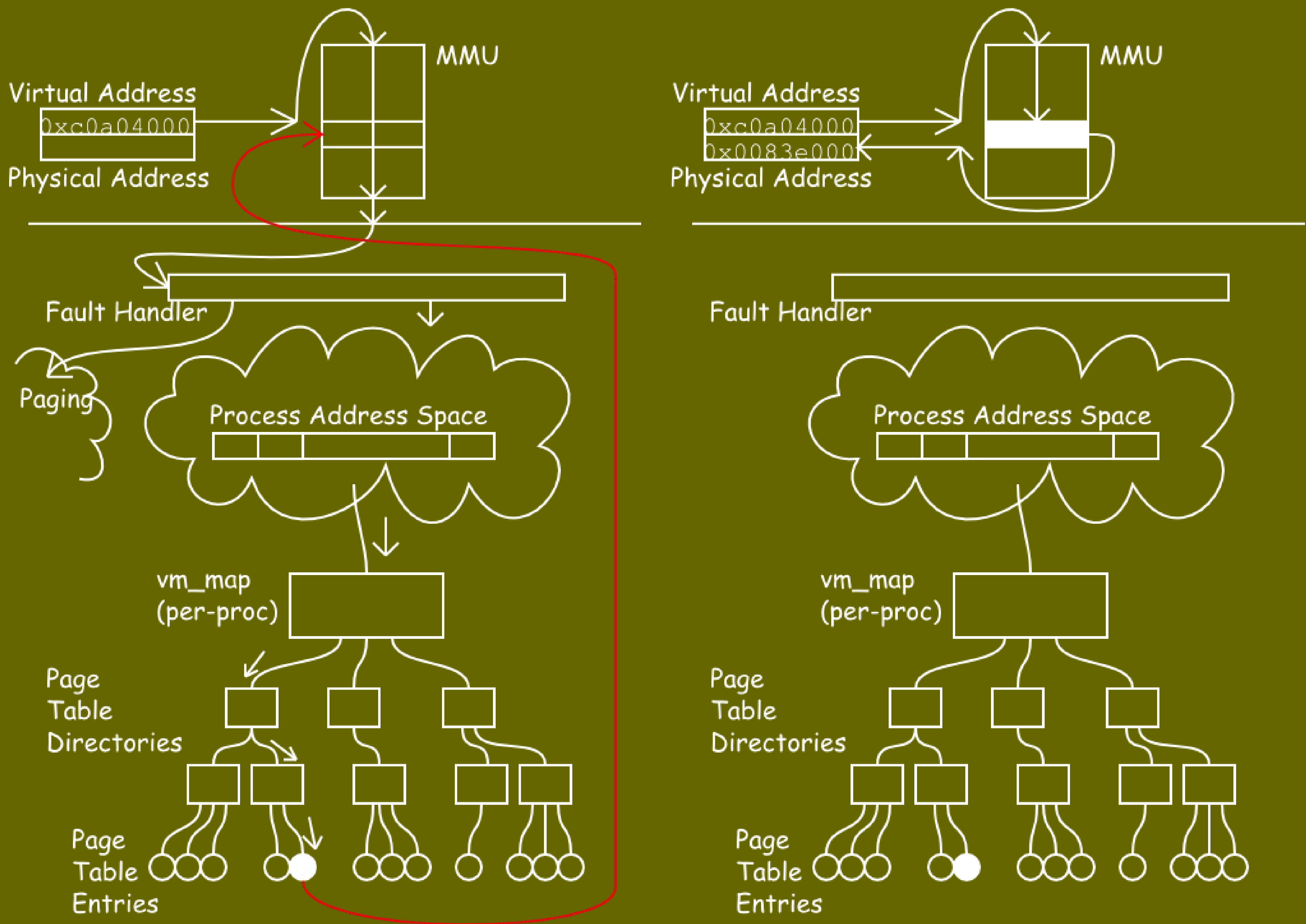
# Fault handler

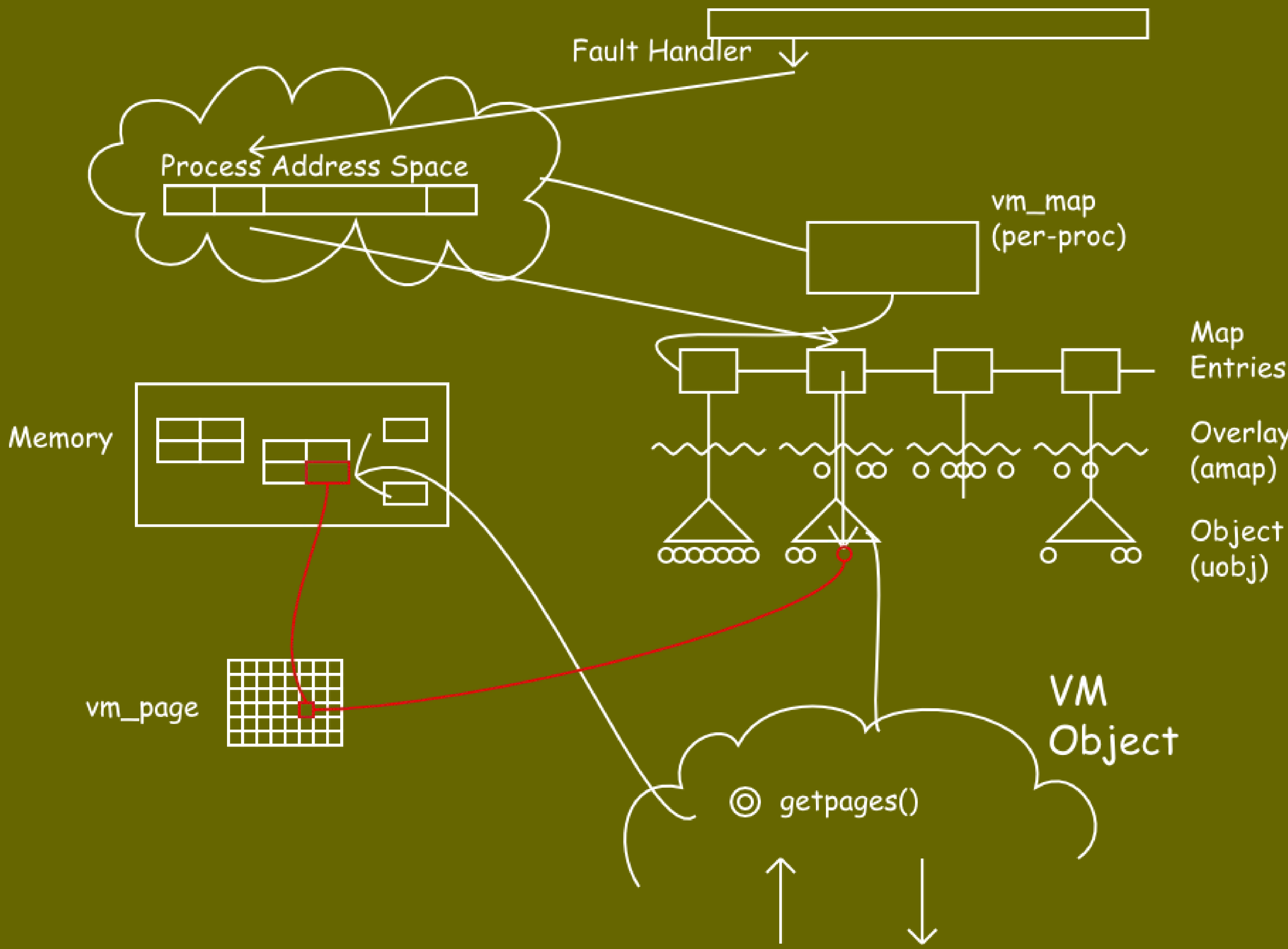
- On-demand operations
  - Paging (page cache <-> backing store)
    - `getpages()` returning `*vm_page[]`
  - H/W mapping (TLB <-> page table)
    - `pmap_enter()` with `vm_page->phys_addr`
- Optimizations
  - Pre-fault
  - Copy-on-write
- Relying on H/W assistance (MMU)

# Fault handler

Behavior

- Suspend the faulting context
- Resolve things
  - Paging (== I/O == slow)
  - *** do dirty things here ***
  - H/W mapping
- Resume the faulted context


MMU
Virtual Address
0xc0a04000
Physical Address
Fault Handler
Paging
Process Address Space
vm_map
(per-proc)
Page
Table
Directories
Page
Table
Entries
MMU
Virtual Address
0xc0a04000
0x0083e000
Physical Address
Fault Handler
Process Address Space
vm_map
(per-proc)
Page
Table
Directories
Page
Table
Entries


Fault Handler
Process Address Space
vm_map
(per-proc)
Map
Entries
Memory
Overlay
(amap)
Object
(uobj)
vm_page
VM
Object
getpages()

# Pager

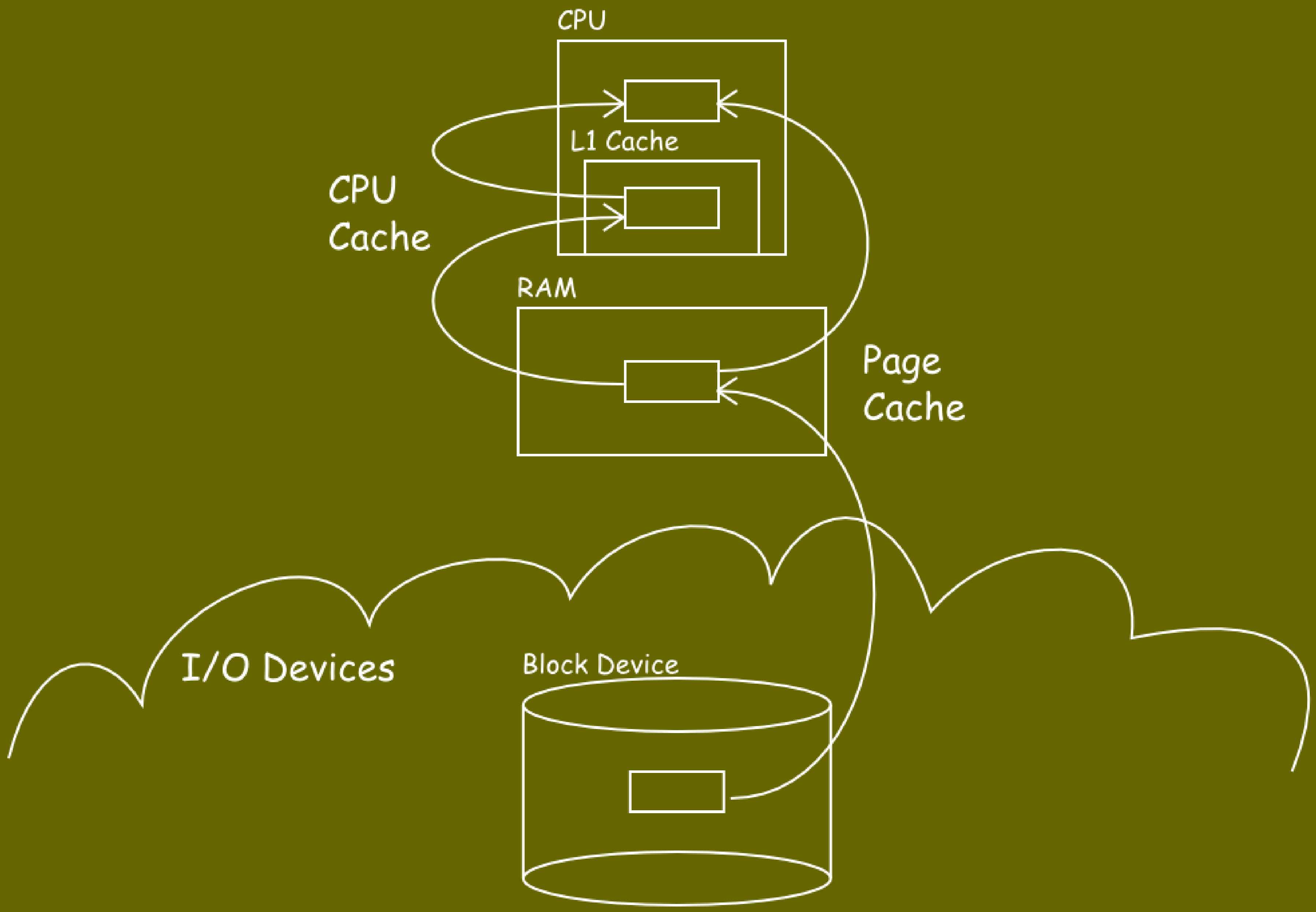
- Object-oriented abstraction
  - Linear space
  - PAGE_SIZE wise
  - Any backing store
    - Vnode
    - Swap (aobj)
- VM object's operation
  - “get pages”
  - “put pages”

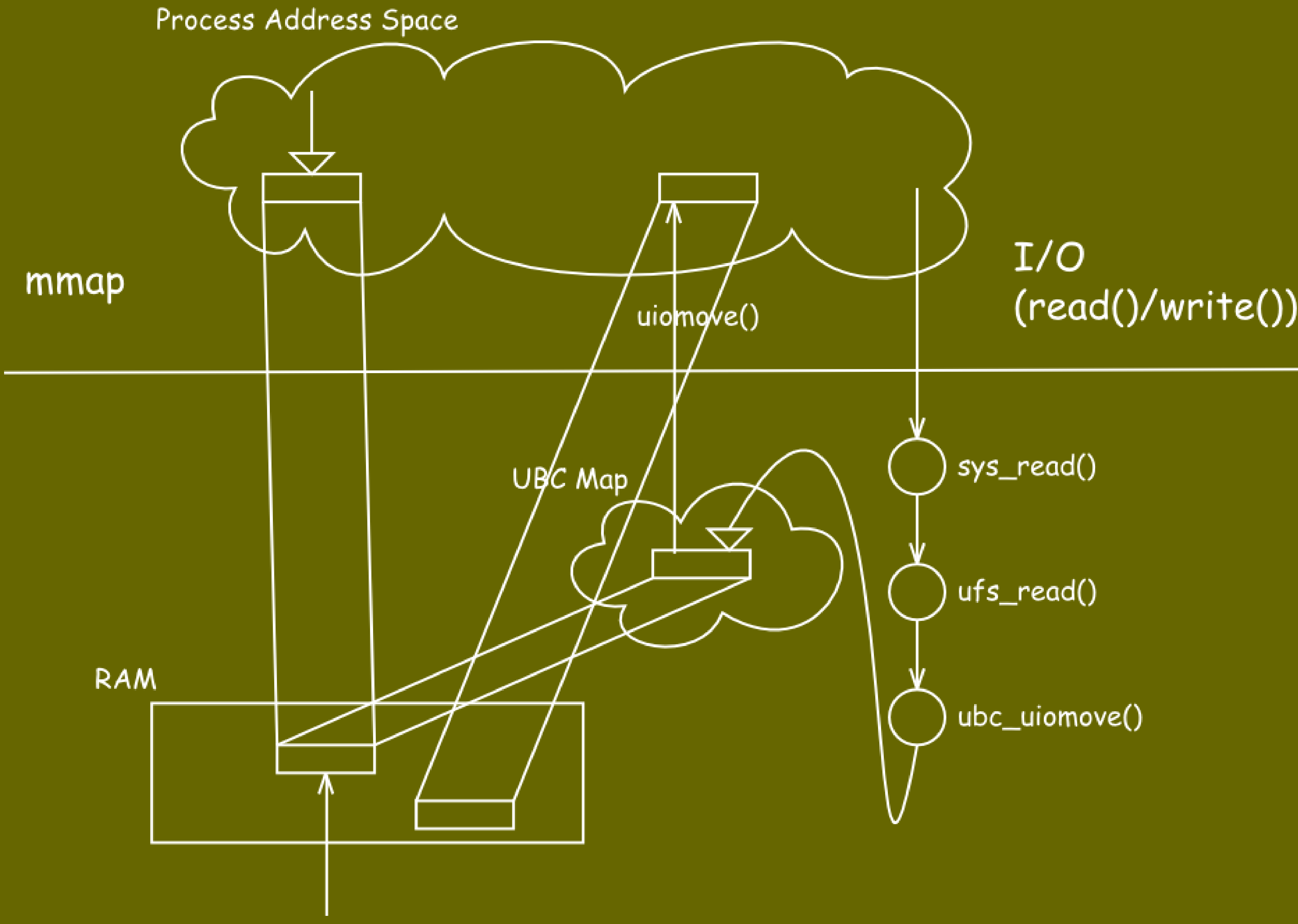
# Pager

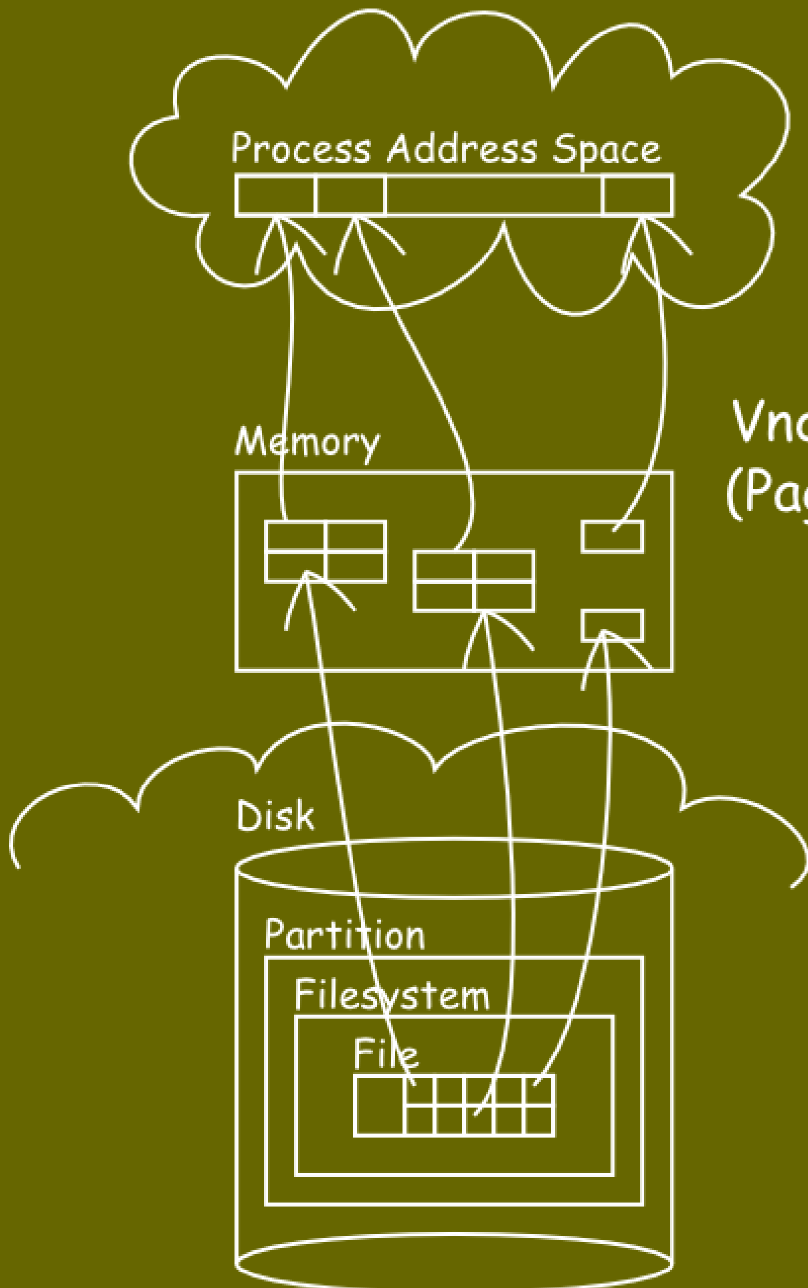
- Device pager
  - Character device
  - mmap(2)'ing /dev/XXX
  - “Unmanaged”
  - Its own “special” handler
    - “Steal” the handling onto its region
    - No generic support
    - No copy-on-write, etc.
    - Its own `pmap_enter(9)` callsite (ugly)

# Pager

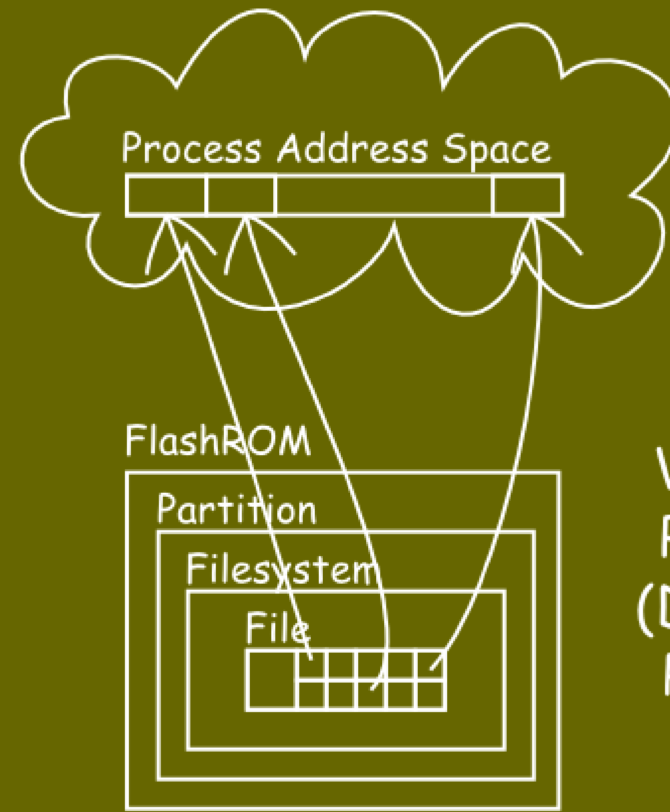
- Vnode pager
  - Glue file/filesystem into VM
    - Represent file as VM object
    - Address space vs. filesystem / block address
    - Paging vs. filesystem state
    - “genfs” functions
    - :
  - :
  - Filesystem is complex but useful component


CPU
L1 Cache
CPU
Cache
RAM
Page
Cache
I/O Devices
Block Device


Process Address Space
mmap
I/O
(read()/write())
uiomove()
UBC Map
sys_read()
ufs_read()
ubc_uiomove()
RAM




Vnode Pager (Page Cache)




XIP Vnode Pager (Device Page)

# Pager

Vnode pager for XIP

Return physical address back to the fault handler

But can't use `vm_page` because the physical address is specific to the “activation”

-> Return the physical address by encoding it in “`struct vm_page *`”

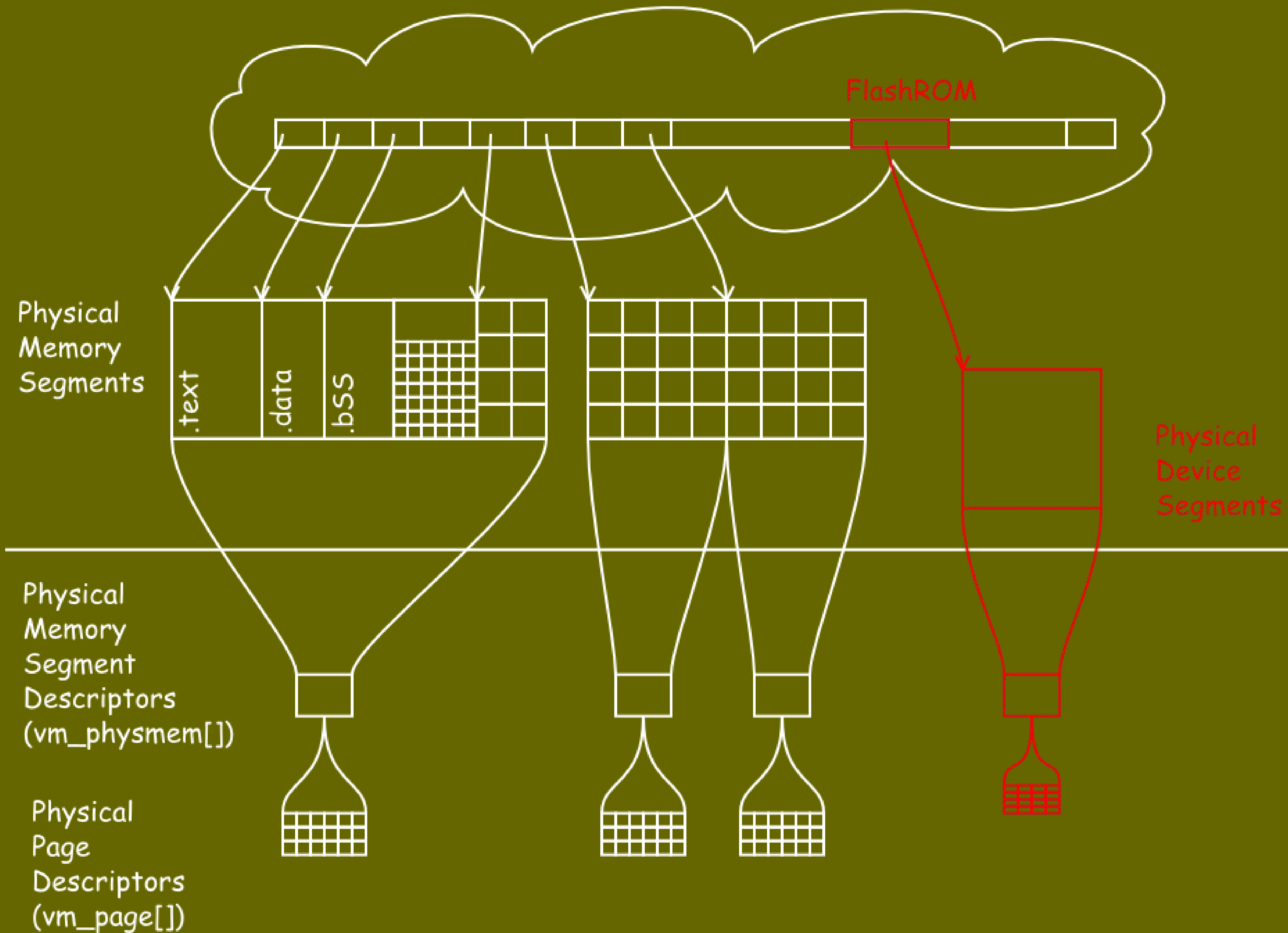
```
(struct vm_page *)((intptr_t)phys_addr | MAGIC)
```

-> ”This is part of a device's segment, the offset to it is XXX”

# “Device segment” and “device page”

- Exist on devices
  - Memory-addressable device region
  - Attached during device configuration
- “Managed”
  - Which virtual address is mapped to which physical address?
  - Track P->V mapping
- Paging?
  - Depend on usage?  XXX to be considered

# Physical Address Space

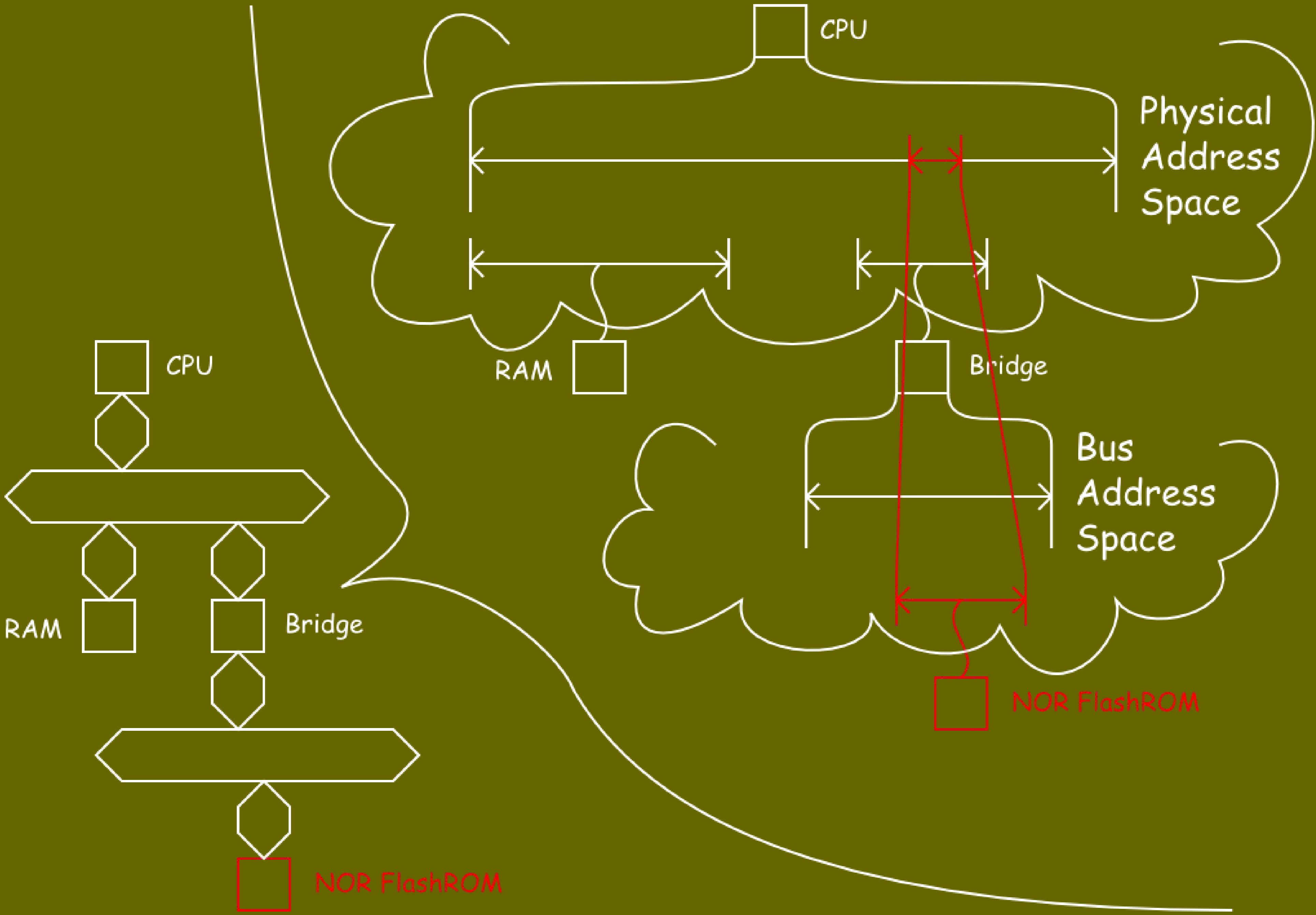


# Design

- Introduce “device segment” and “device page”
- Switch XIP by mount point
  - Mark mount point as XIP
  - vnode pager checks if vnode is on XIP mount
  - If yes, return “device pages” back to generic fault handler
- Teach (generic) fault handler and vnode pager about “device page” handling

# Design

- Device driver interface for "device page"
  - `bus_space_physload(9)`
  - `bus_space_physload_device(9)`
  - Device drivers *must* register their "possibly managed" bus address space
    - VM allocates "context" internally to keep track of the "managed" device pages

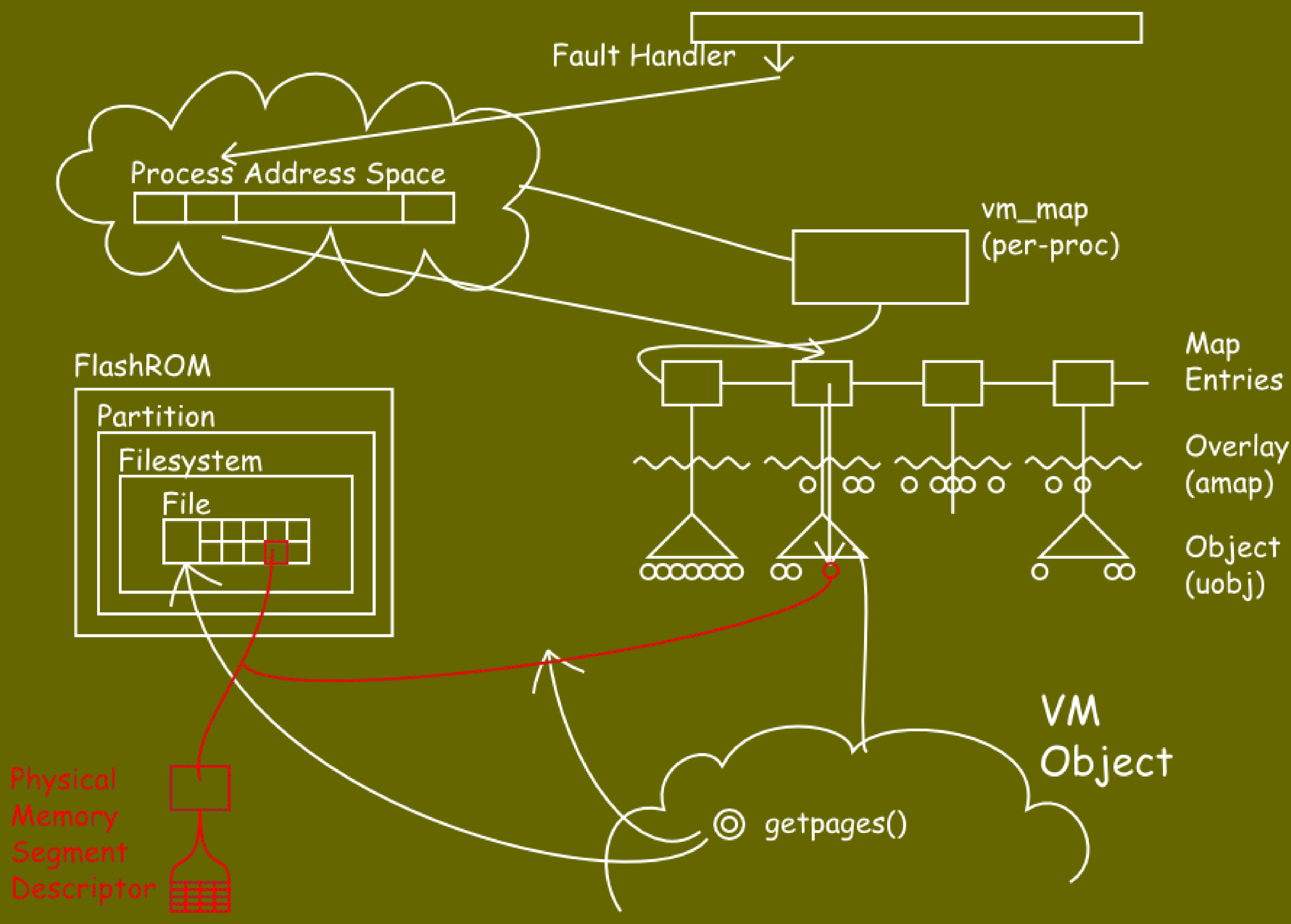


CPU
Physical
Address
Space
RAM
Bridge
Bus
Address
Space
NOR FlashROM
CPU
RAM
Bridge
NOR FlashROM

# Design

Mount and device driver
-> Interfaced using “device segment”

- Device driver registers its segment and gets “device segment” as a cookie (to VM)
- When mounting the device, the “device segment” is associated with the mount point
- Vnode pager refers to the “device segment” cookie


Fault Handler
Process Address Space
vm_map
(per-proc)
Map
Entries
Overlay
(amap)
Object
(uobj)
FlashROM
Partition
Filesystem
File
VM
Object
getpages()
Physical
Memory
Segment
Descriptor

# Implementation

uebayasi-xip branch on anoncvs.NetBSD.org

# TODO

- More tests, measurements, and tuning
- Write more FlashROM device drivers (glues)
- Explicit mount option or not
- Optimized filesystem (Linux's AXFS)
- xmd(4) - XIP memory disk
- Memory hotplug, NUMA, ...
- Convert framebuffers to use `bus_space_physload(9)`

# Summary

- Basic XIP support for NetBSD is implemented
  - Available in netbsd-6 (hopefully)
- A new concept "device page" is introduced and driver API is provided
  - bus_space_physload_device(9)
- Clean design
  - No special MD code
  - No special device drivers
  - No hacks