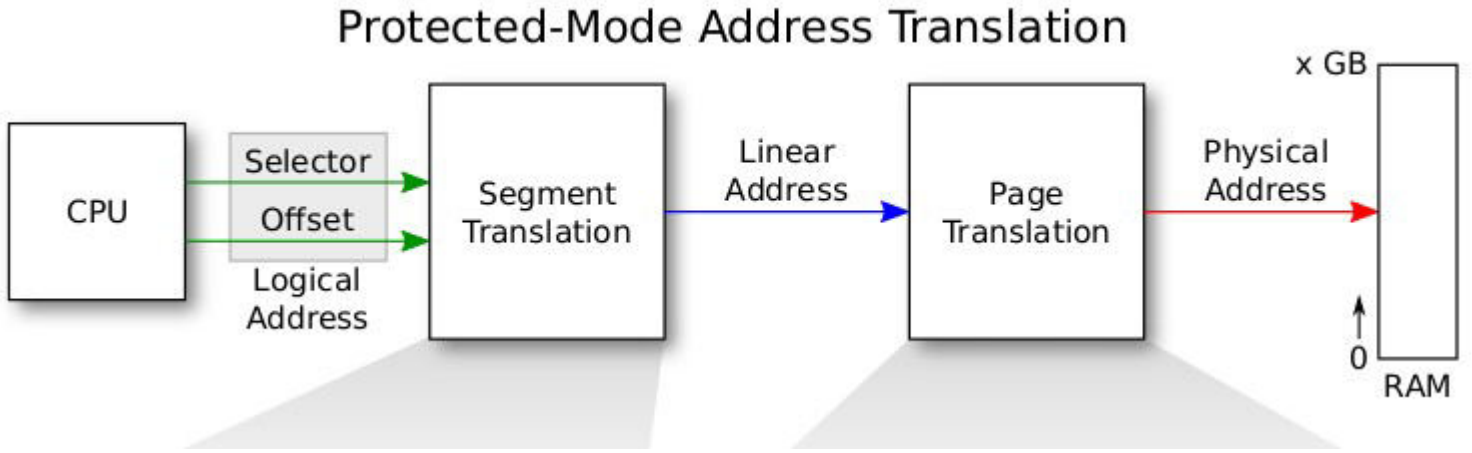
Some numbers and their ‘meaning’

- These numbers occur very frequently in discussion
- 0x 80000000 = 2 GB = KERNBASE
- 0x 100000 = 1 MB = EXTMEM
- 0x 80100000 = 2GB + 1MB = KERNLINK
- 0x E000000 = 224 MB = PHYSTOP
- 0x FE000000 = 3.96 GB = 4064 MB = DEVSPACE
  - 4096 – 4064 = 32 MB left on top

X86 Memory Management

X86 address : protected mode address translation



X86 paging

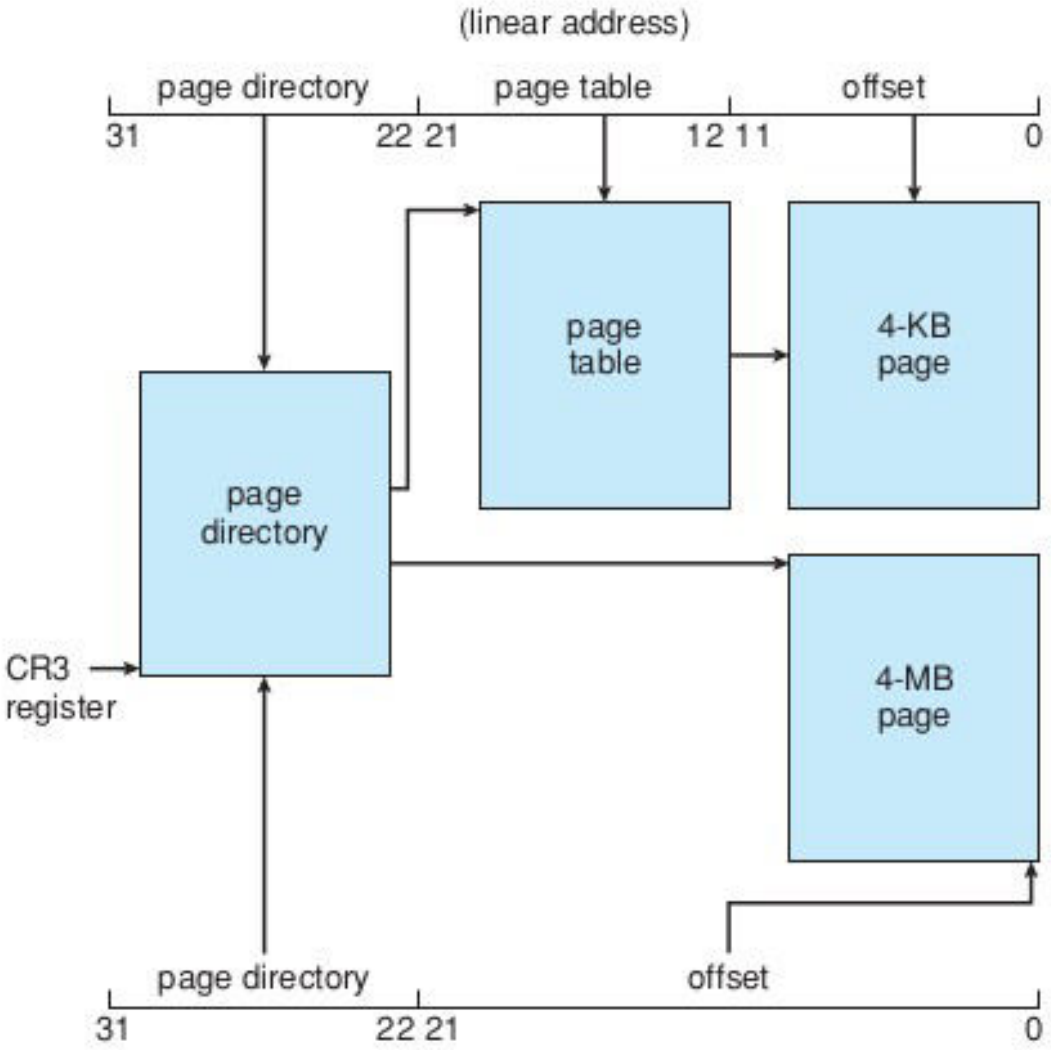
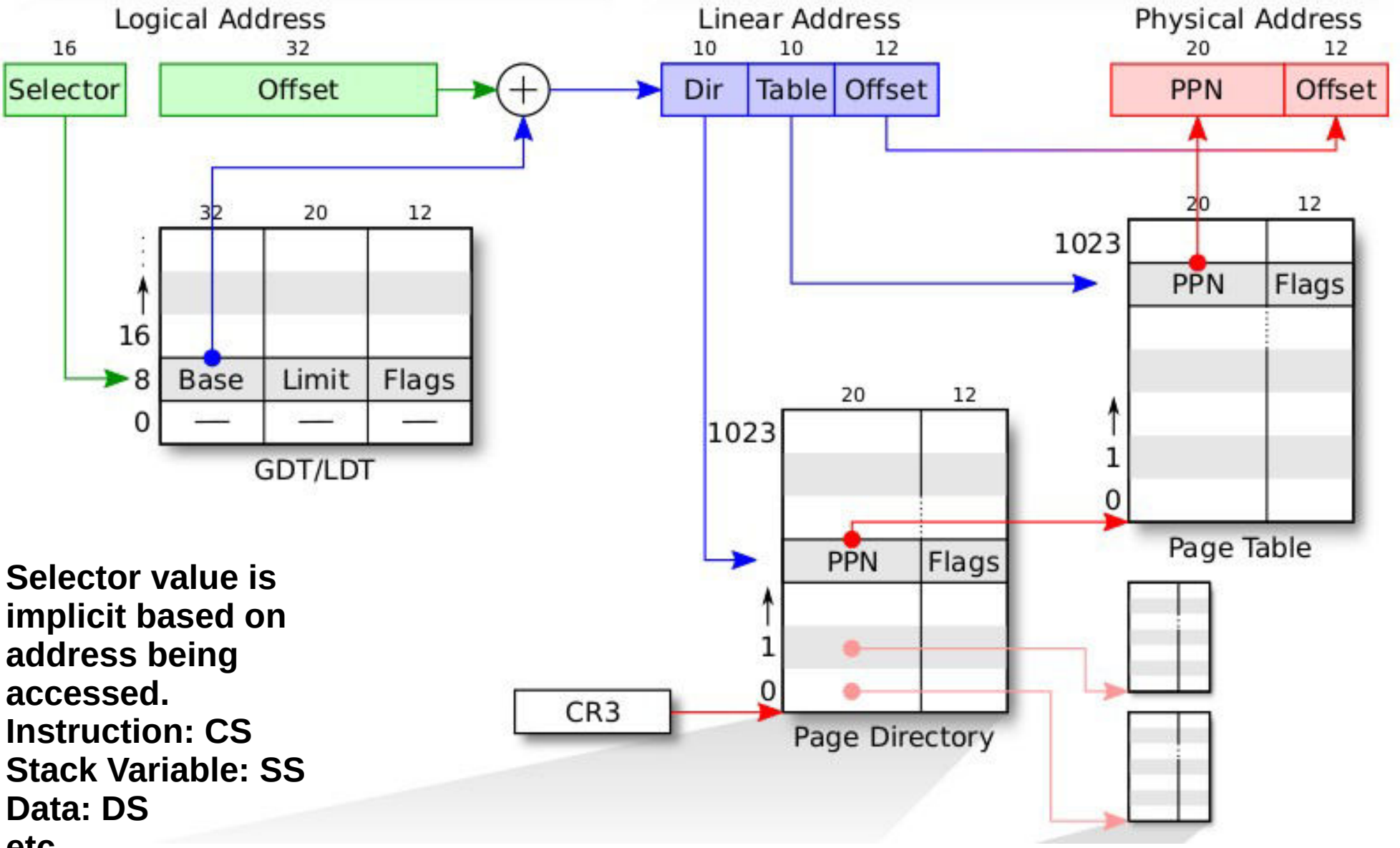


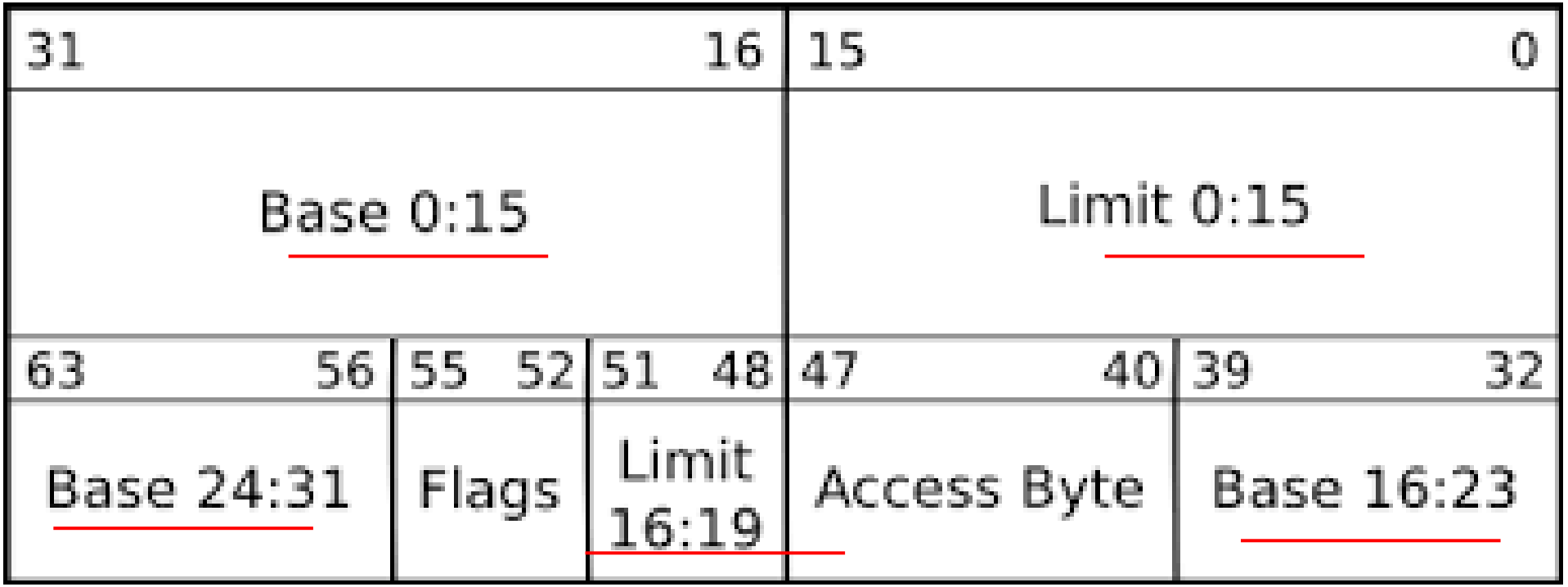
Figure 8.23 Paging in the IA-32 architecture.

Segmentation + Paging

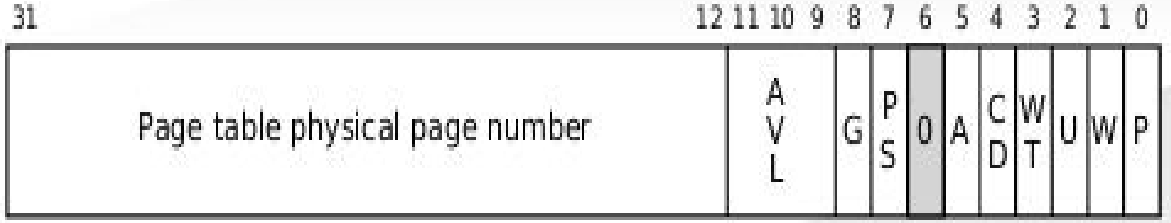


Selector value is implicit based on address being accessed.
Instruction: CS
Stack Variable: SS
Data: DS
etc.

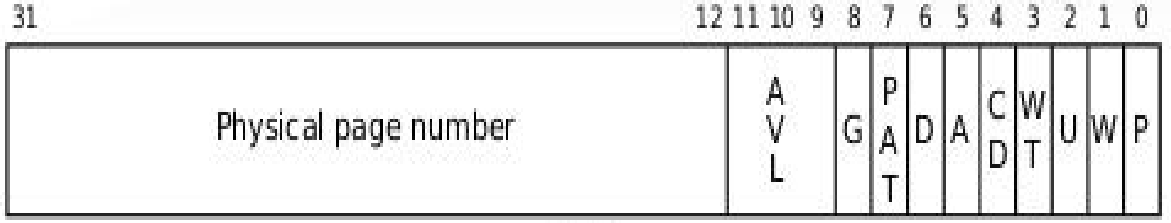
GDT Entry


31
16
15
0
Base 0:15
Limit 0:15
63
56
55
52
51
48
47
40
39
32
Base 24:31
Flags
Limit 16:19
Access Byte
Base 16:23

Page Directory Entry (PDE)
Page Table Entry (PTE)



PDE



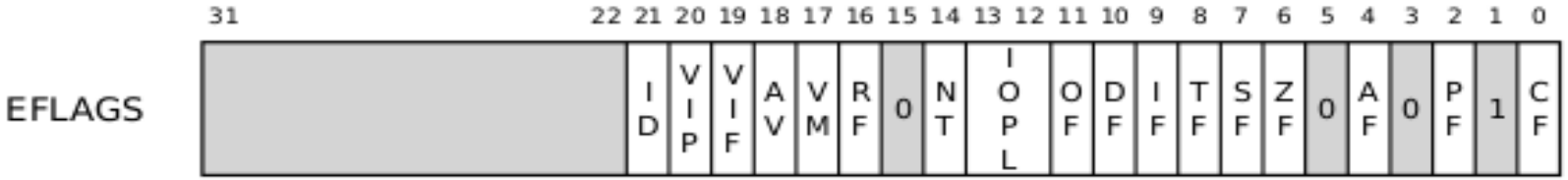
PTE

P	Present
W	Writable
U	User
WT	1=Write-through, 0=Write-back
CD	Cache disabled
A	Accessed
D	Dirty
PS	Page size (0=4KB, 1=4MB)
PAT	Page table attribute index
G	Global page
AVL	Available for system use

Segment selector

TI Table index (0=GDT, 1=LDT)
RPL Requester privilege level

EFLAGS register



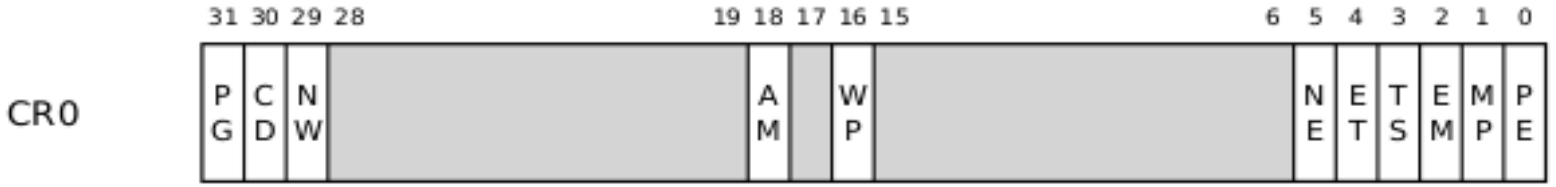
Status flags
- CF Carry flag
- PF Parity flag
- AF Auxiliary carry flag
- ZF Zero flag
- SF Sign flag
- OF Overflow flag

Control flags
- DF Direction flag

System flags
- TF Trap flag
- IF Interrupt enable flag
- IOPL I/O privilege level
- NT Nested task

- RF Resume flag
- VM Virtual-8086 mode
- AC Alignment check
- VIF Virtual intr. flag
- VIP Virtual intr. pending
- ID ID flag

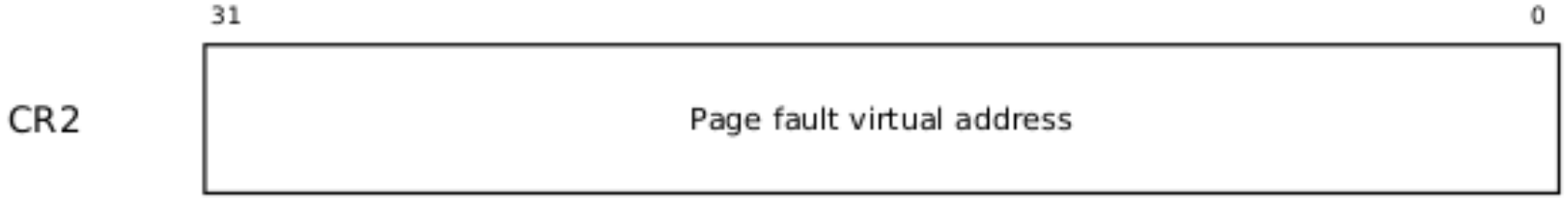
CR0



PE	Protection enabled	ET	Extension type	NW	Not write-through
MP	Monitor coprocessor	NE	Numeric error	CD	Cache disable
EM	Emulation	WP	Write protect	PG	Paging
TS	Task switched	AM	Alignment mask		

PG: Paging enabled or not **WP: Write protecion on/off**
PE: Protection Enabled --> protected mode.

CR2



CR3

PWT Page-level writes transparent

PCT Page-level cache disable

CR4

VME	Virtual-8086 mode extensions
PVI	Protected-mode virtual interrupts
TSD	Time stamp disable
DE	Debugging extensions
PSE	Page size extensions
PAE	Physical-address extension
MCE	Machine check enable
PGE	Page-global enable
PCE	Performance counter enable
OSFXSR	OS FXSAVE/FXRSTOR support
OSXMM-EXCPT	OS unmasked exception support

mmu.h : paging related macros

```
#define PTXSHIFT        12      // offset of PTX in a linear address
#define PDXSHIFT        22      // offset of PDX in a linear address
#define PDX(va)   (((uint)(va) >> PDXSHIFT) & 0x3FF)// page directory index
#define PTX(va)   (((uint)(va) >> PTXSHIFT) & 0x3FF)// page table index
// construct virtual address from indexes and offset
#define PGADDR(d, t, o) ((uint)((d) << PDXSHIFT | (t) << PTXSHIFT |
(o)))
// +--------10------+-------10-------+---------12----------+
// | Page Directory |   Page Table    | Offset within Page  |
// |      Index     |      Index      |                     |
// +----------------+-----------------+---------------------+
//  \--- PDX(va) --/ \--- PTX(va) --/
```

mmu.h : paging related macros

```
// Page directory and page table constants.
#define NPDENTRIES      1024    // # directory entries per page directory
#define NPTENTRIES      1024    // # PTEs per page table
#define PGSIZE          4096    // bytes mapped by a page
#define PGROUNDUP(sz)  (((sz)+PGSIZE-1) & ~(PGSIZE-1))
#define PGROUNDDOWN(a) (((a)) & ~(PGSIZE-1))
```

mmu.h : paging related macros

```
// Page table/directory entry flags.
#define PTE_P           0x001   // Present
#define PTE_W           0x002   // Writeable
#define PTE_U           0x004   // User
#define PTE_PS          0x080   // Page Size


// Address in page table or page directory entry
#define PTE_ADDR(pte)   ((uint)(pte) & ~0xFFF) // get
all but last 12 bits
#define PTE_FLAGS(pte)  ((uint)(pte) &  0xFFF) // get
last 12 bits
```

mmu.h : Segmentation related macros

```
// various segment selectors.

#define SEG_KCODE 1  // kernel code

#define SEG_KDATA 2  // kernel data+stack

#define SEG_UCODE 3  // user code

#define SEG_UDATA 4  // user data+stack

#define SEG_TSS   5  // this process's task state
```

mmu.h : Segmentation related macros

```
// various segment selectors.
#define SEG_KCODE 1  // kernel code
#define SEG_KDATA 2  // kernel data+stack
#define SEG_UCODE 3  // user code
#define SEG_UDATA 4  // user data+stack
#define SEG_TSS   5  // this process's task state
#define NSEGS     6
```

mmu.h : Segmentation related macros

```
struct segdesc { // 64 bit in size
  uint lim_15_0 : 16;  // Low bits of segment limit
  uint base_15_0 : 16; // Low bits of segment base address
  uint base_23_16 : 8; // Middle bits of segment base address
  uint type : 4;       // Segment type (see STS_ constants)
  uint s : 1;          // 0 = system, 1 = application
  uint dpl : 2;        // Descriptor Privilege Level
  uint p : 1;          // Present
  uint lim_19_16 : 4;  // High bits of segment limit
  uint avl : 1;        // Unused (available for software use)
  uint rsv1 : 1;       // Reserved
  uint db : 1;         // 0 = 16-bit segment, 1 = 32-bit segment
  uint g : 1;          // Granularity: limit scaled by 4K when set
  uint base_31_24 : 8; // High bits of segment base address
};
```

mmu.h : Segmentation related code

```
// Application segment type bits
#define STA_X       0x8     // Executable segment
#define STA_W       0x2     // Writeable (non-executable segments)
#define STA_R       0x2     // Readable (executable segments)

// System segment type bits
#define STS_T32A    0x9     // Available 32-bit TSS
#define STS_IG32    0xE     // 32-bit Interrupt Gate
#define STS_TG32    0xF     // 32-bit Trap Gate
```

Code from bootasm.S bootmain.c is over!
Kernel is loaded.
Now kernel is going to prepare itself

main() in main.c

- Initializes “free list” of page frames
  - In 2 steps. Why?
- Sets up page table for kernel
- Detects configuration of all processors
- Starts all processors
  - Just like the first processor
- Creates the first process!

- Initializes
  - LAPIC on each processor, IOAPIC
  - Disables PIC
  - “Console” hardware (the standard I/O)
  - Serial Port
  - Interrupt Descriptor Table
  - Buffer Cache
  - Files Table
  - Hard Disk (IDE)

main() in main.c

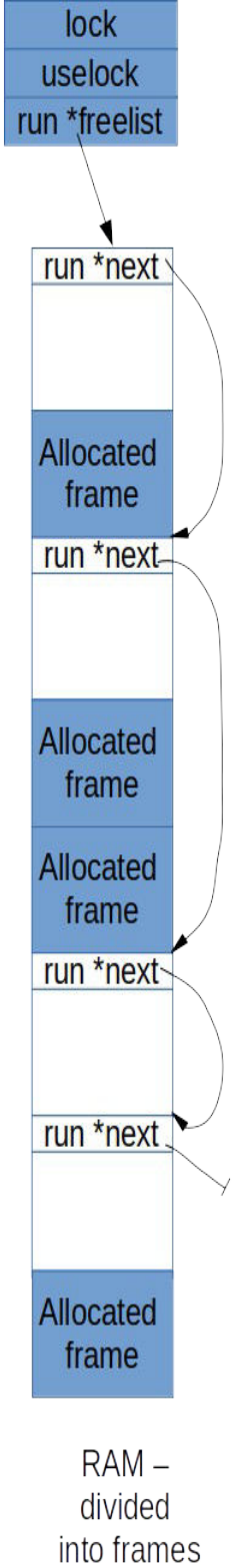
```
int

main(void) {

  kinit1(end,
P2V(4*1024*1024)); // phys
page allocator

  kvmalloc();      // kernel page
table
```

```
void

kinit1(void *vstart, void
*vend) {

  initlock(&kmem.lock,
"kmem");

  kmem.use_lock = 0;

  freerange(vstart, vend);

}
```

main() in main.c

```
void

freerange(void *vstart, void
*vend)

{

  char *p;

  p =
(char*)PGROUNDUP((uint)vst
art);

  for(; p + PGSIZE <=
(char*)vend; p += PGSIZE)

    kfree(p);

}
```

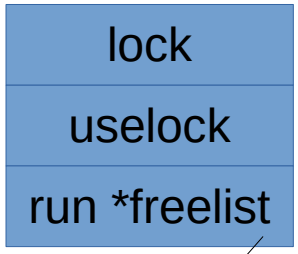
```
kfree(char *v) {
  struct run *r;
  if((uint)v % PGSIZE || v <
end || V2P(v) >= PHYSTOP)
    panic("kfree");
  // Fill with junk to catch
dangling refs.
  memset(v, 1, PGSIZE);
  if(kmem.use_lock)
    acquire(&kmem.lock);
  r = (struct run*)v;
  r->next = kmem.freelist;
  kmem.freelist = r;
  if(kmem.use_lock)
    release(&kmem.lock); }
```



Free List in XV6 Obtained after main() -> kinit1()

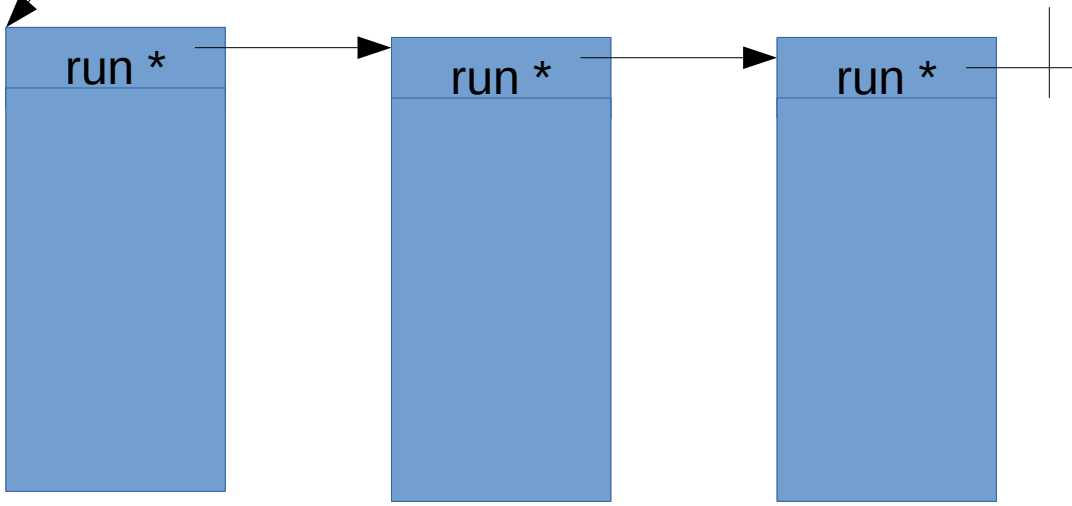
Pages obtained Between
end = 801154a8 = 2049 MB to P2V(4MB) = 2052 MB
Remember
Right now Logical = Physical address.

Actually like this in memory



kmem

Seen independently



Back to main()

```
int

main(void) {

  kinit1(end, P2V(4*1024*1024)); // phys page allocator

  kvmalloc();      // kernel page table
```

```
// Allocate one page table for the machine for the kernel address

// space for scheduler processes.

void

kvmalloc(void)

{

  kpgdir = setupkvm();

  switchkvm();

}
```

Back to main()

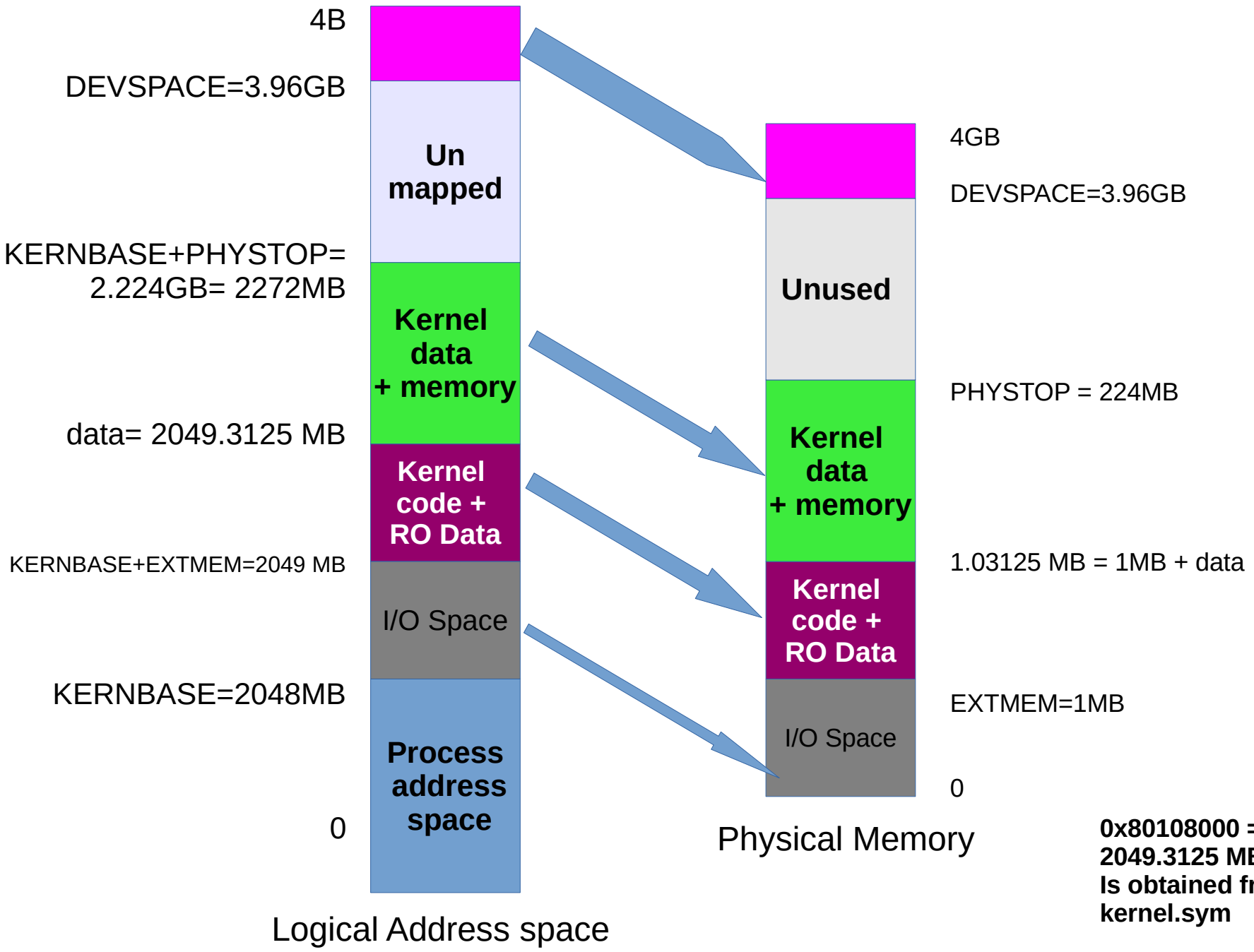
```
int
main(void) {
  kinit1(end, P2V(4*1024*1024)); // phys page allocator
  kvmalloc();      // kernel page table
```

```
// Allocate one page table for the machine for the kernel address
// space for scheduler processes.
void
kvmalloc(void)
{
  kpgdir = setupkvm(); // global var kpgdir
  switchkvm();
}
```

```
pde_t*
setupkvm(void)
{
  pde_t *pgdir;
  struct kmap *k;
  if((pgdir = (pde_t*)kalloc()) == 0)
    return 0;
  memset(pgdir, 0, PGSIZE);
  if (P2V(PHYSTOP) > (void*)DEVSPACE)
    panic("PHYSTOP too high");
 for(k = kmap; k < &kmap[NELEM(kmap)]; k++)
    if(mappages(pgdir, k->virt, k->phys_end - k->phys_start,
                (uint)k->phys_start, k->perm) < 0) {
      freevm(pgdir);
      return 0;
    }
  return pgdir;
}
```

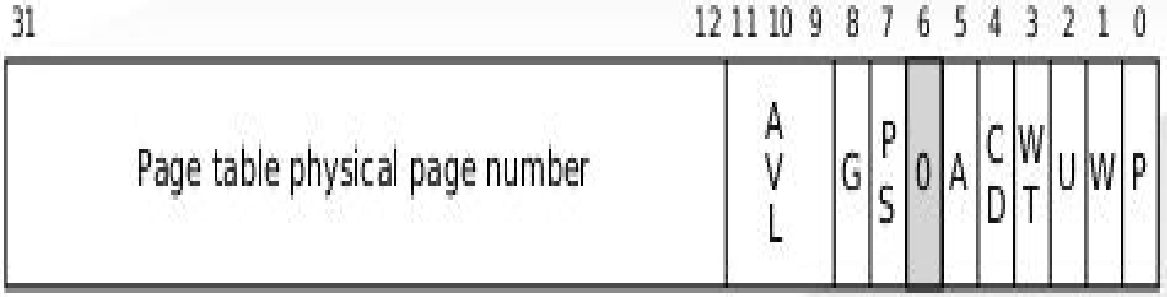
```
static struct kmap {
  void *virt;
  uint phys_start;
  uint phys_end;
  int perm;
} kmap[] = {
 { (void*)KERNBASE, 0,             EXTMEM,    PTE_W}, // I/O space
 { (void*)KERNLINK, V2P(KERNLINK), V2P(data), 0},     // kern text+rodata
 { (void*)data,     V2P(data),     PHYSTOP,   PTE_W}, // kern data+memory
 { (void*)DEVSPACE, DEVSPACE,      0,         PTE_W}, // more devices
};
```

kmap[] mappings done in kvmalloc(). This shows segmentwise, entries are done in page directory and page table for corresponding VA-> PA mappings

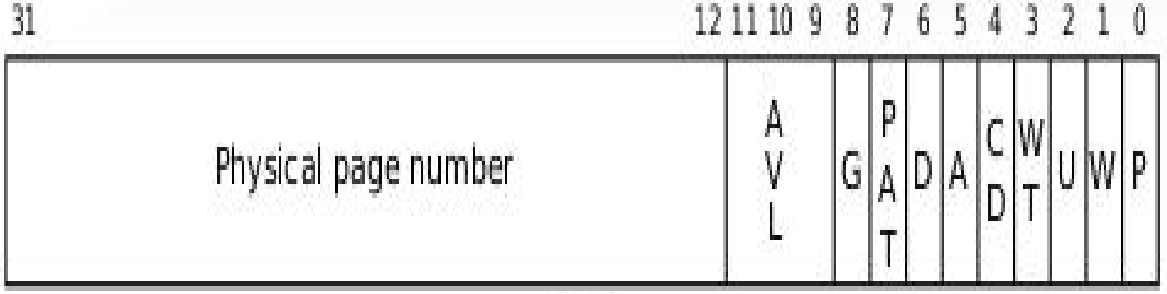


0x80108000 =data = 2049.3125 MB Is obtained from kernel.sym

Remidner: PDE and PTE entries

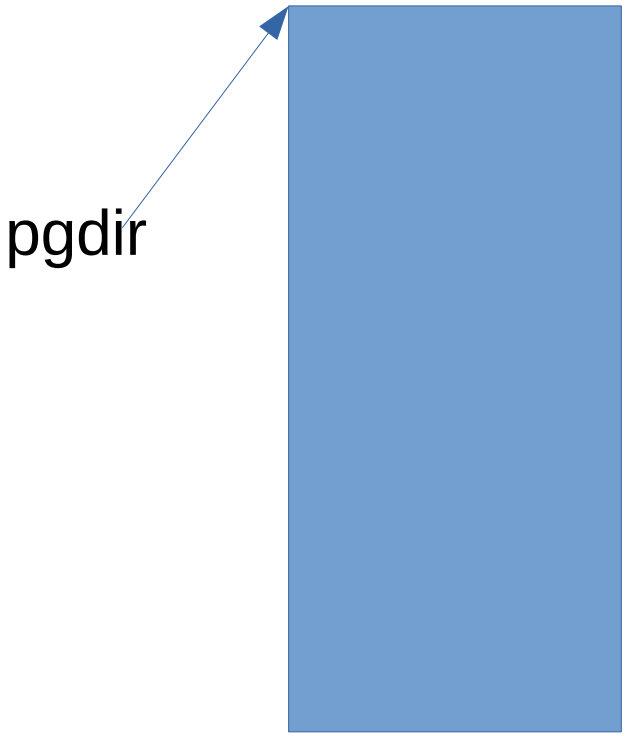


PDE

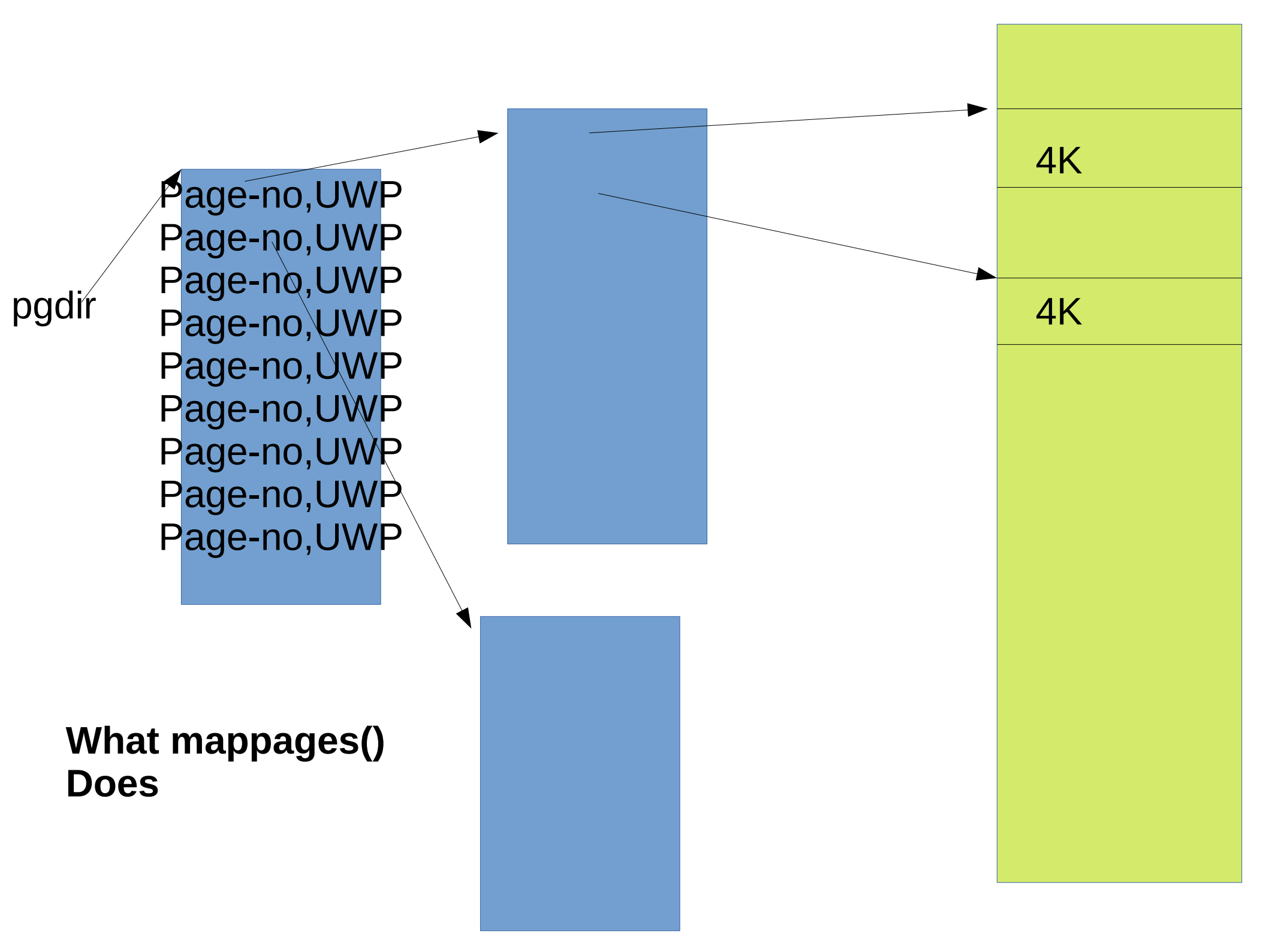


PTE

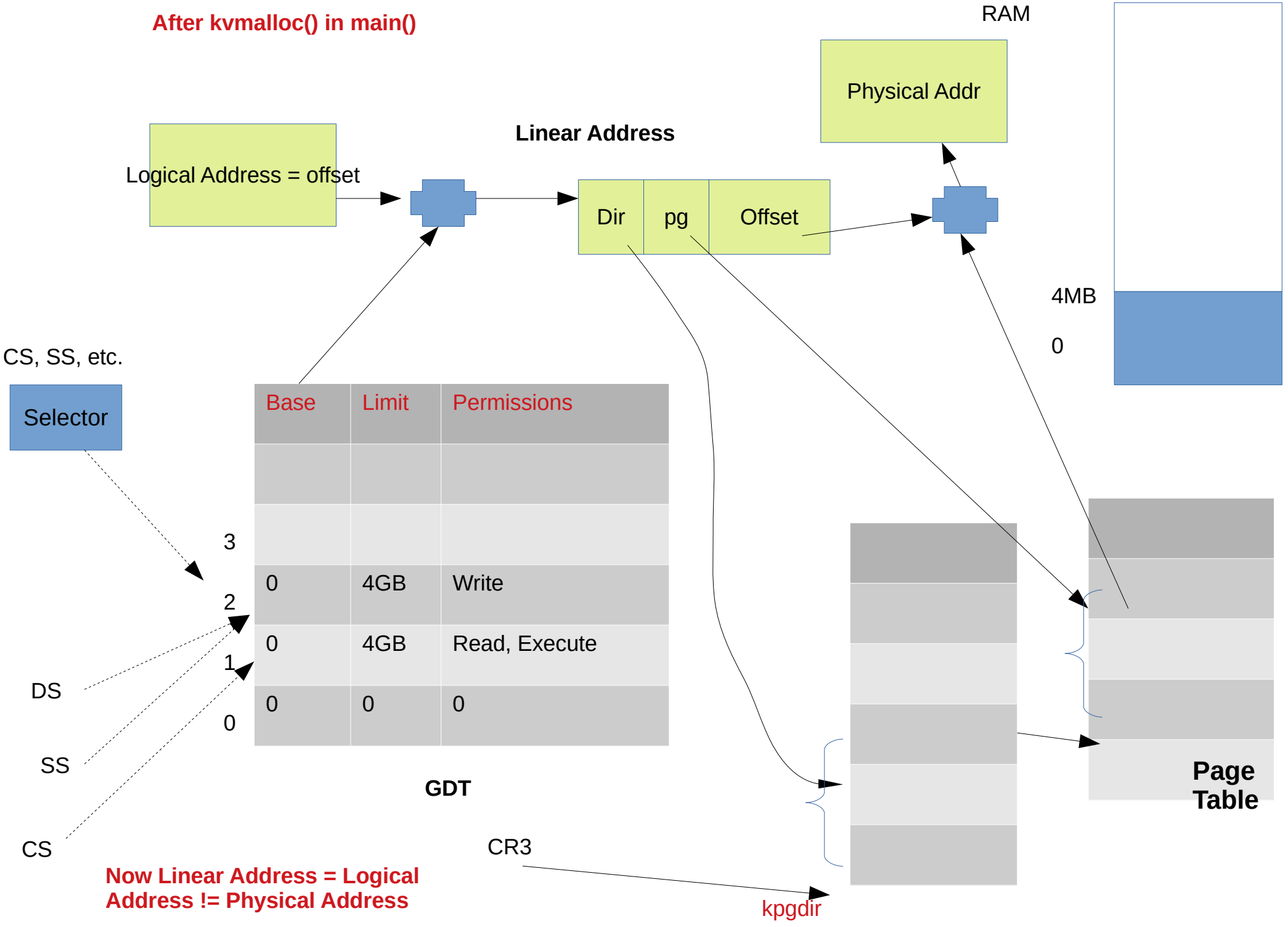
P	Present
W	Writable
U	User
WT	1=Write-through, 0=Write-back
CD	Cache disabled
A	Accessed
D	Dirty
PS	Page size (0=4KB, 1=4MB)
PAT	Page table attribute index
G	Global page
AVL	Available for system use



Before mappages()

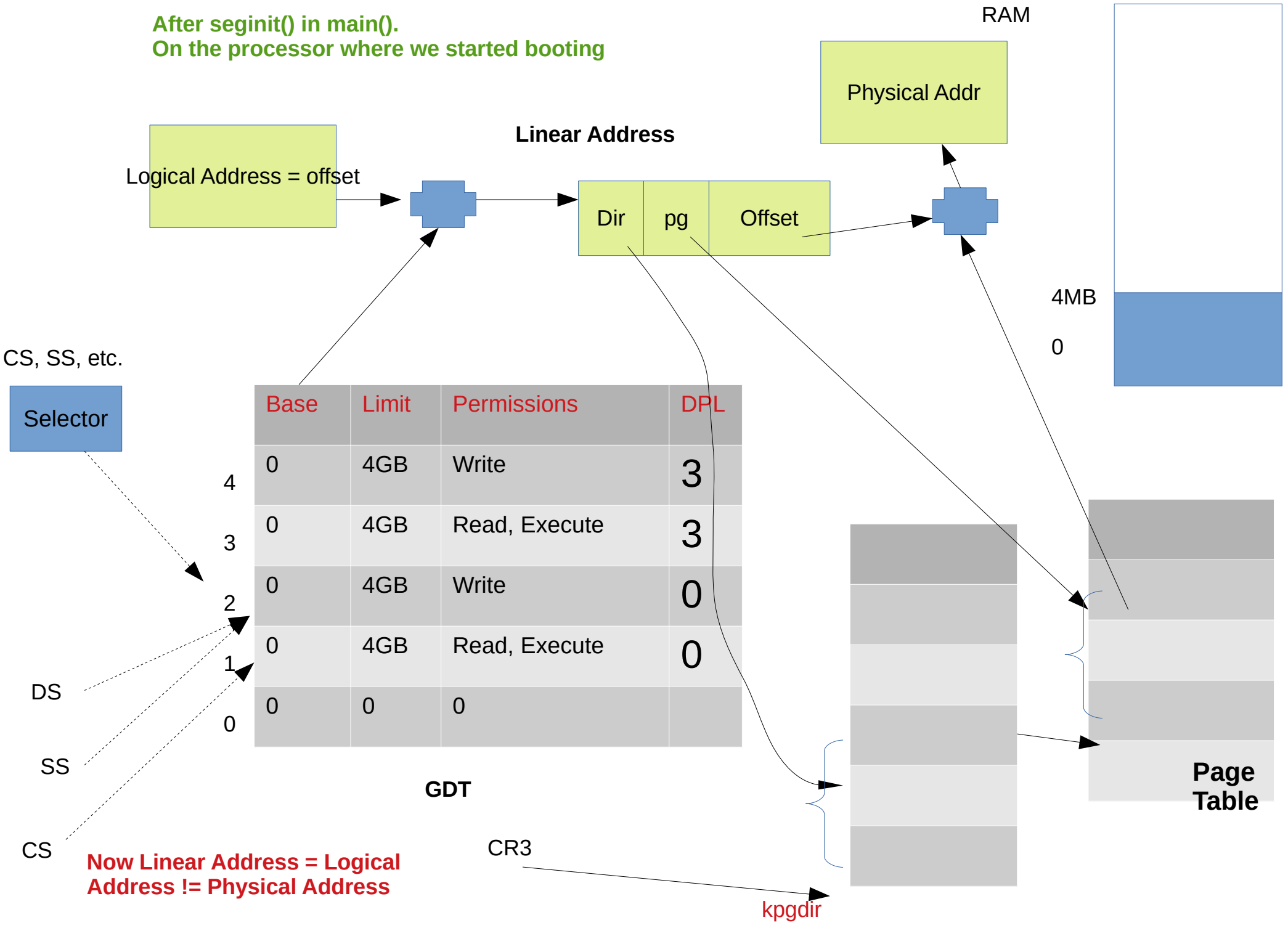


What mappages()
Does


After kvmalloc() in main()
RAM
Physical Addr
Linear Address
Logical Address = offset
Dir
pg
Offset
4MB
0
CS, SS, etc.
Selector
Base
Limit
Permissions
3
0
4GB
Write
2
0
4GB
Read, Execute
1
0
0
0
DS
SS
CS
GDT
Page Table
CR3
kpgdir
Now Linear Address = Logical Address != Physical Address

main()->seginit()

- Re-initialize GDT
- Once and forever now
- Just set 4 entries
  - All spanning 4 GB
  - Differing only in permissions and privilege level

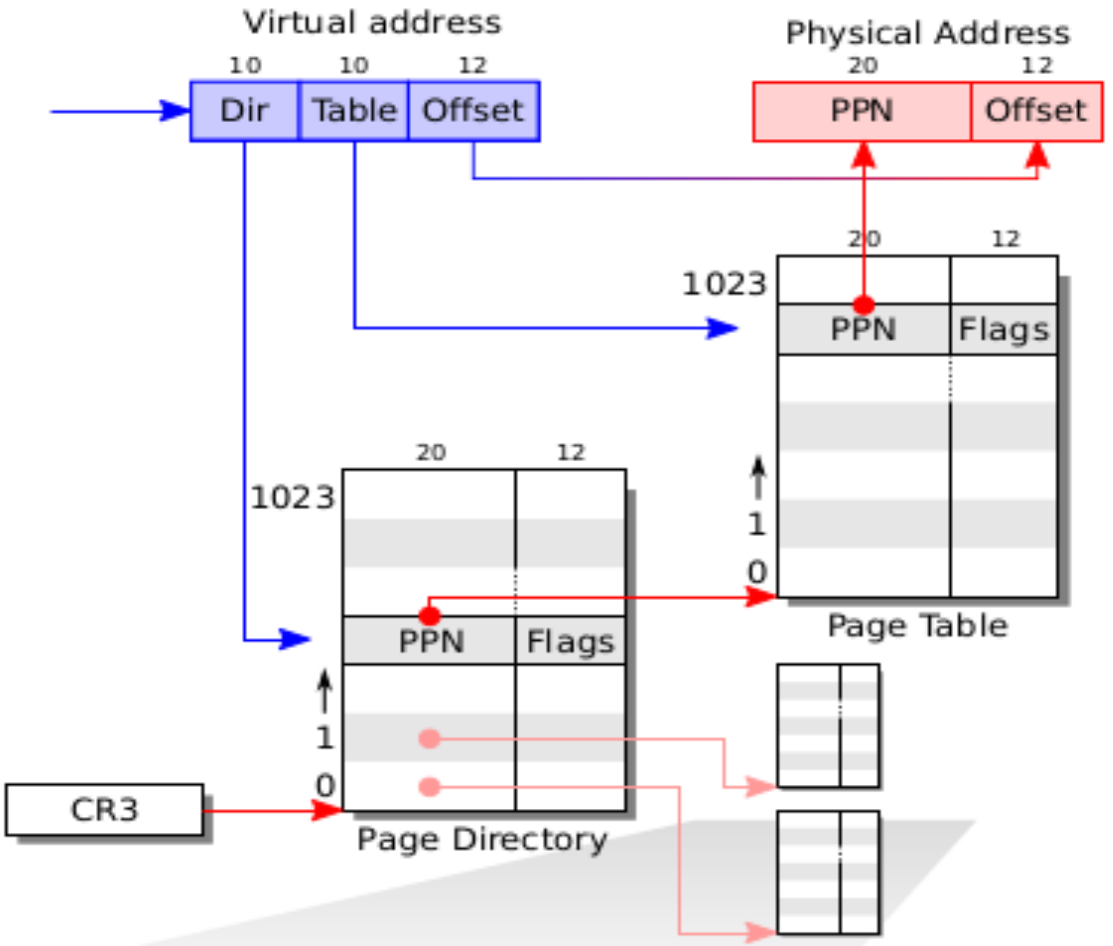

After seginit() in main().
On the processor where we started booting
RAM
Physical Addr
Linear Address
Logical Address = offset
Dir
pg
Offset
4MB
0
CS, SS, etc.
Selector
Base
Limit
Permissions
DPL
4
0
4GB
Write
3
3
0
4GB
Read, Execute
3
2
0
4GB
Write
0
1
0
4GB
Read, Execute
0
0
0
0
0
DS
SS
CS
GDT
Page Table
CR3
kpgdir
Now Linear Address = Logical Address != Physical Address

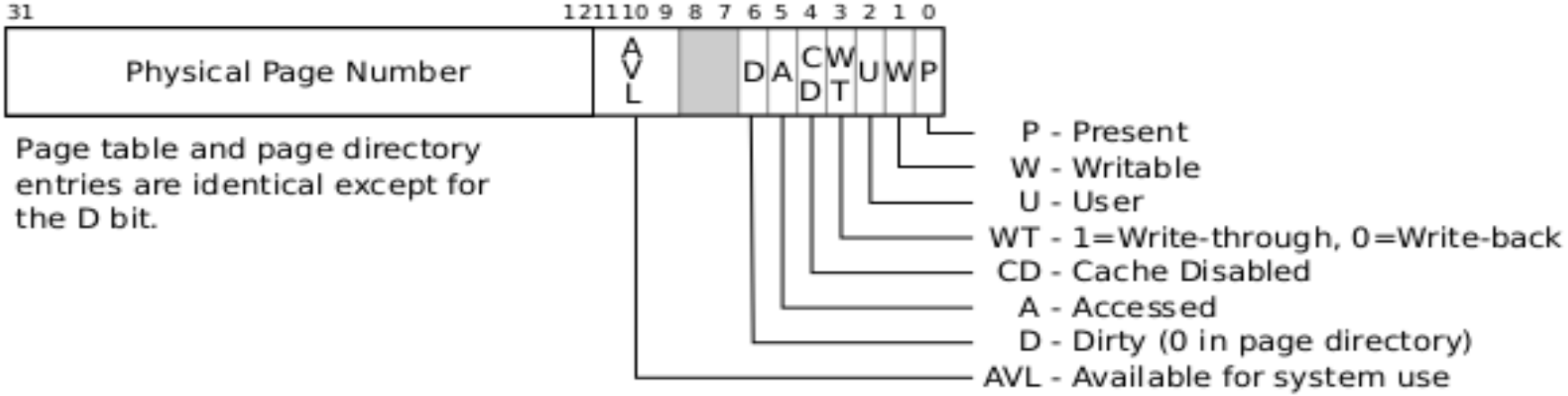
After seginit()

- While running kernel code, necessary to switch CS, DS, SS to index 1,2,2 in GDT
- While running user code, necessary to switch CS, DS, SS to index 3,4,4 in GDT
- This happens automatically as part of “trap” handling (covered separately)

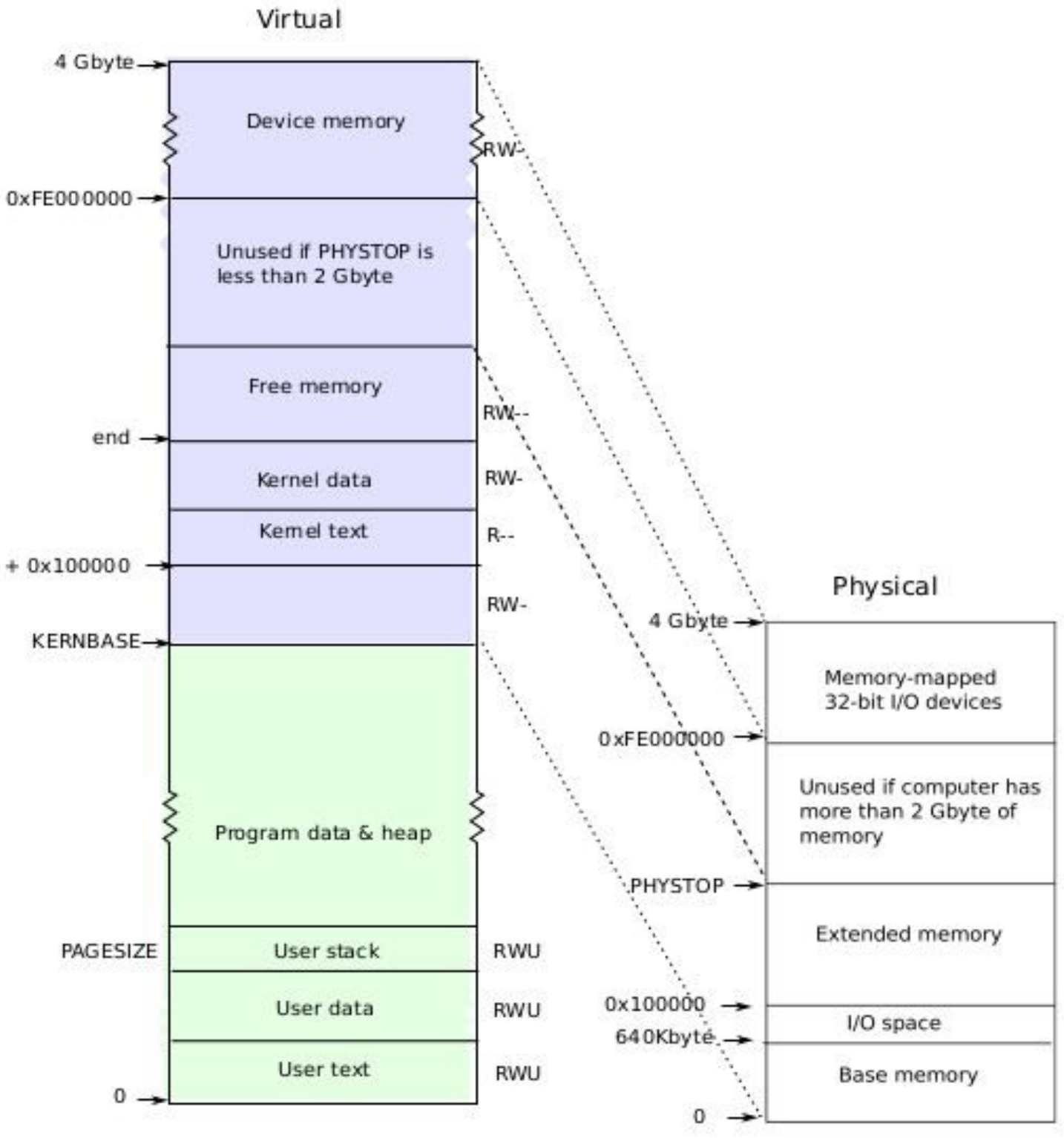
Memory Management

X86 page table hardware

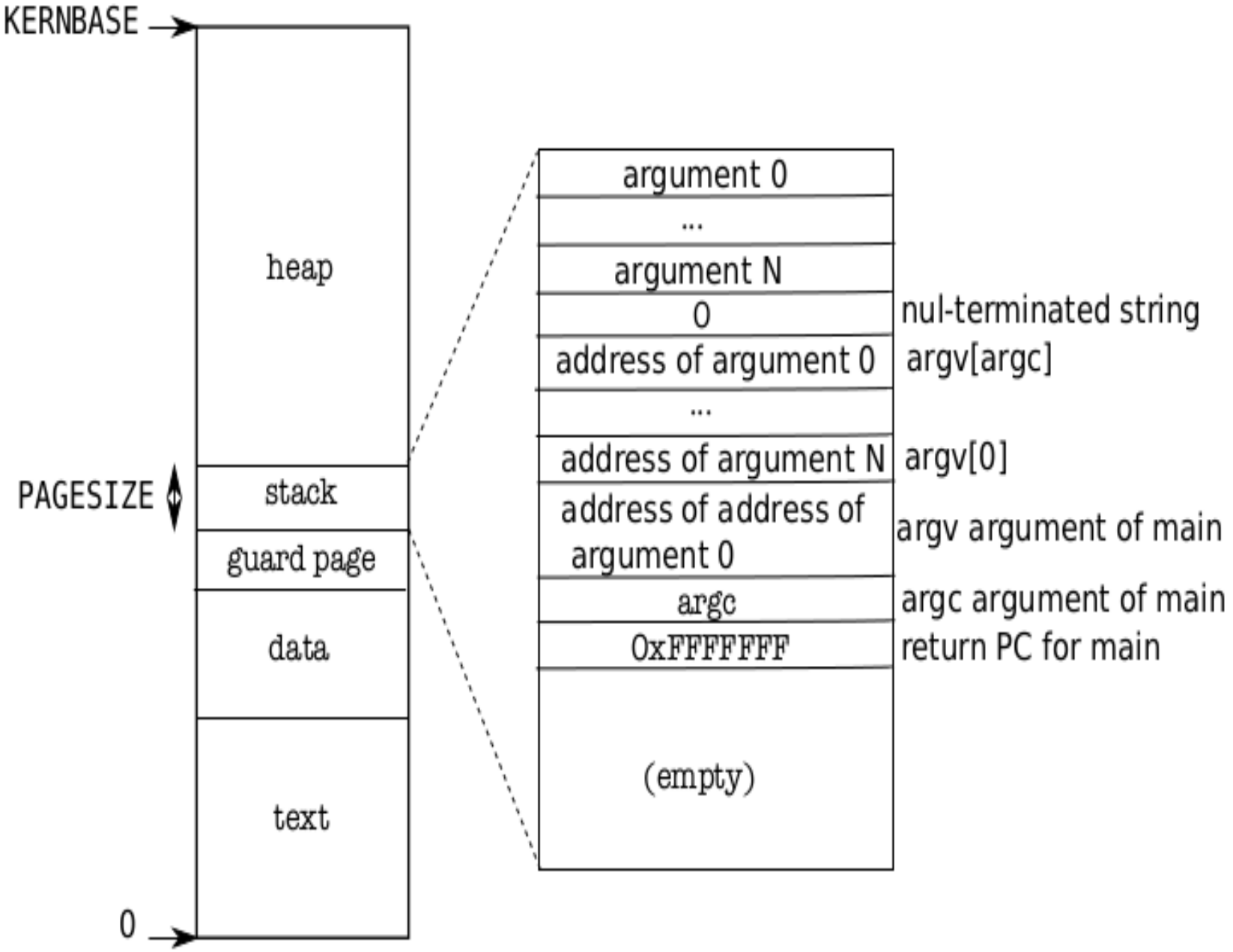




Page table and page directory entries are identical except for the D bit.



Layout of process's VA space

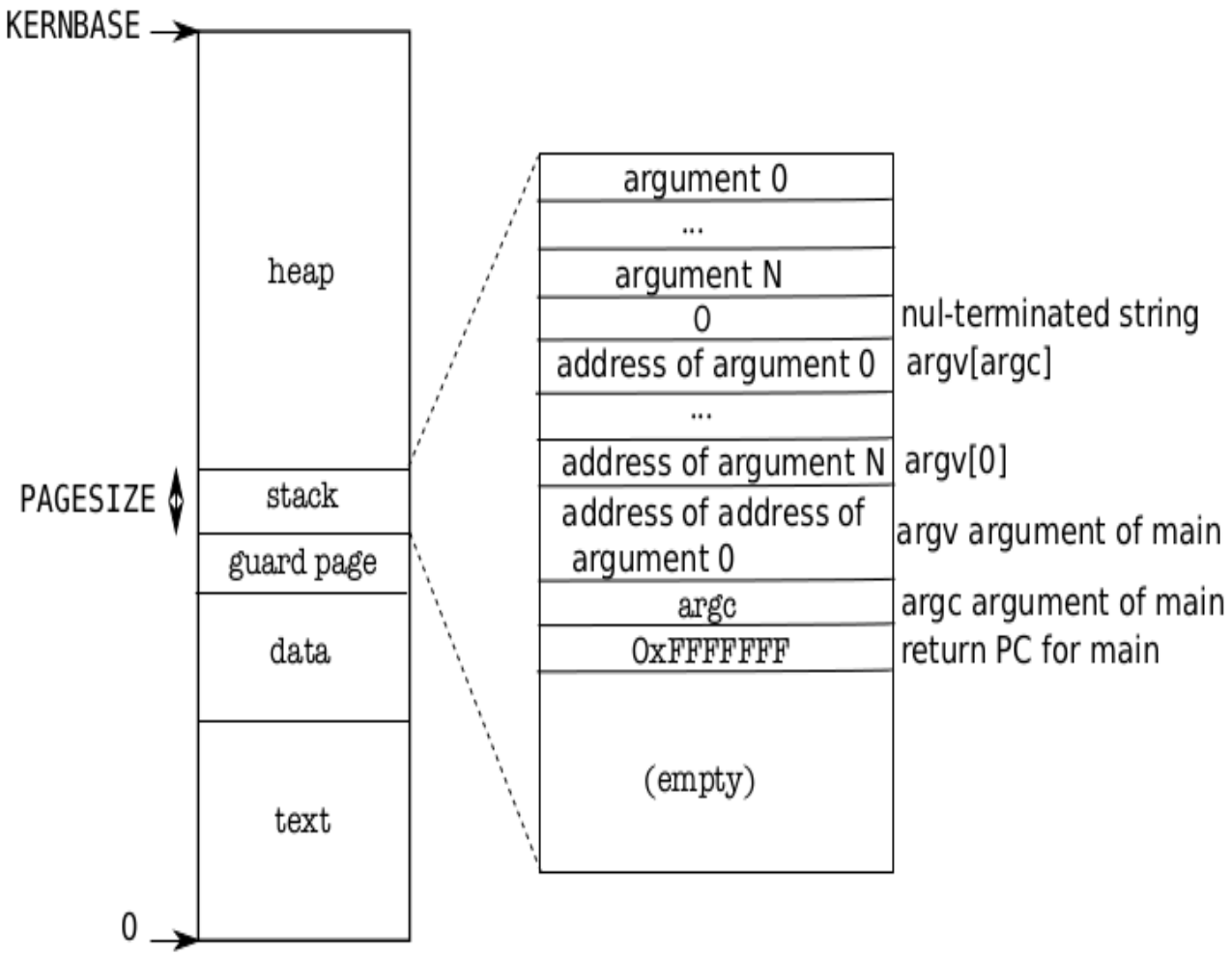


Memory Layout of a user process

After exec()

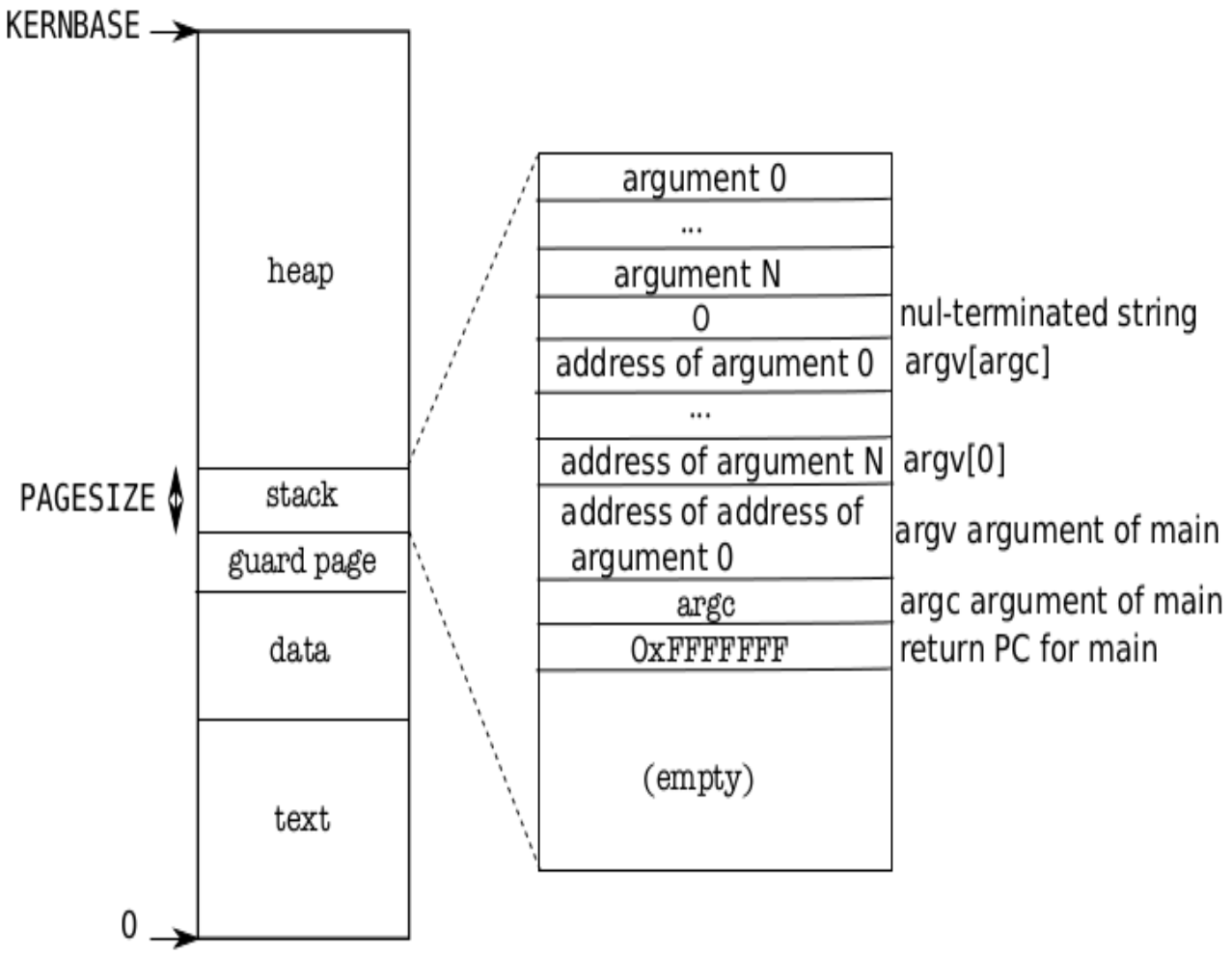
Note the argc, argv on stack

Memory Layout of a user process



The “guard page” is just a mapping in page table. No frame allocated. It’s marked as invalid. So if stack grows (due to many function calls), then OS will detect it with an exception

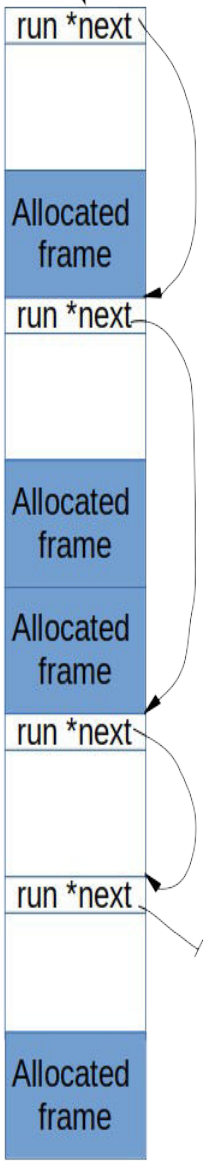
Memory Layout of a user process



On sbrk()
The system call to grow process's address space.
Calls growproc()

growproc()
Allocate a frame, Add an entry in page table at the top (above proc->sz)
//This entry can't go beyond KERNBASE
Calls switchuvm()

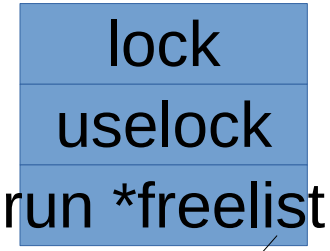
Switchuvm()
Ultimately loads CR3, invalidating cache



RAM – divided into frames

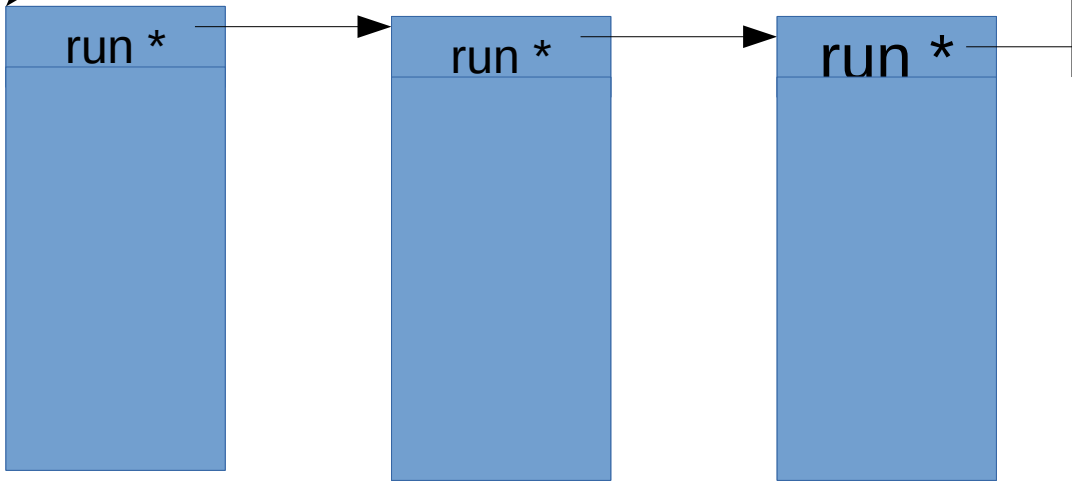
Free List in XV6

Actually like this in memory



kmem

Seen independently



exec()

- **sys_exec()**

  exec(path, argv)

- **exec(parth, argv)**

```
ip = namei(path))
readi(ip, (char*)&elf, 0, sizeof(elf)) != sizeof(elf)
for(i=0, off=elf.phoff; i<elf.phnum; i++, off+=sizeof(ph)){
    if(readi(ip, (char*)&ph, off, sizeof(ph)) != sizeof(ph))
    if((sz = allocuvm(pgdir, sz, ph.vaddr + ph.memsz)) == 0)
    if(loaduvm(pgdir, (char*)ph.vaddr, ip, ph.off, ph.filesz) < 0)
}
```

exec()

- **exec(parth, argv)**

```
// Allocate two pages at the next page boundary.
 // Make the first inaccessible.  Use the second as the user stack.
 sz = PGROUNDUP(sz);
 if((sz = allocuvm(pgdir, sz, sz + 2*PGSIZE)) == 0)
// Push argument strings, prepare rest of stack in ustack.
  for(argc = 0; argv[argc]; argc++) {
    sp = (sp - (strlen(argv[argc]) + 1)) & ~3;
    if(copyout(pgdir, sp, argv[argc], strlen(argv[argc]) + 1) < 0)
```