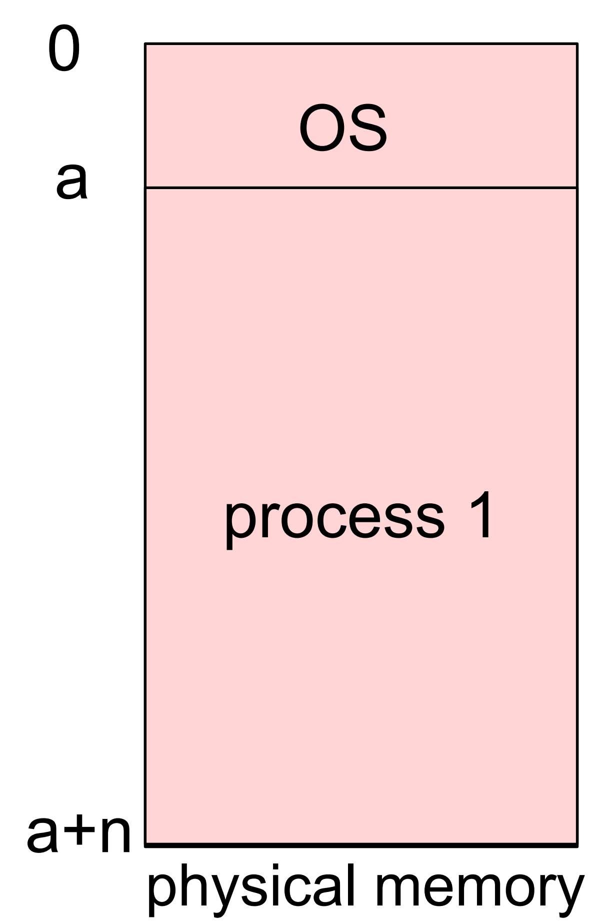
CS 134
Operating Systems

Feb 11, 2019

Virtual Memory

Memory

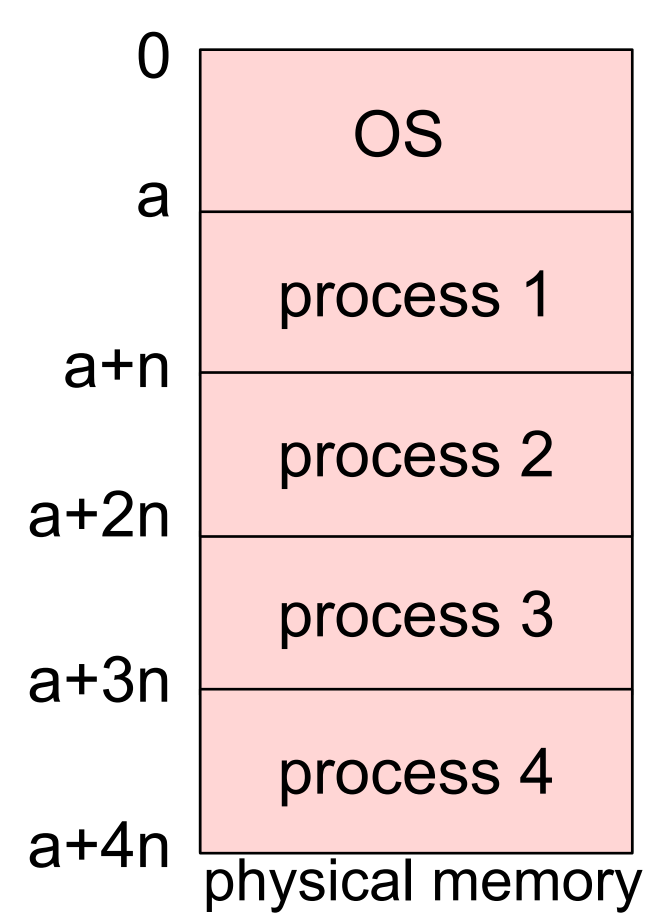
- For multiprogramming, must have multiple processes
- Each process must be in memory to execute
- Possibilities:
  - One process in memory: ***Swapping***: Swap it out to disk, swap in a new one



Memory

- For multiprogramming, must have multiple processes
- Each process must be in memory to execute
- Possibilities:
  - Multiple processes in memory: each in their own partition
    - Fixed-size equal partitions

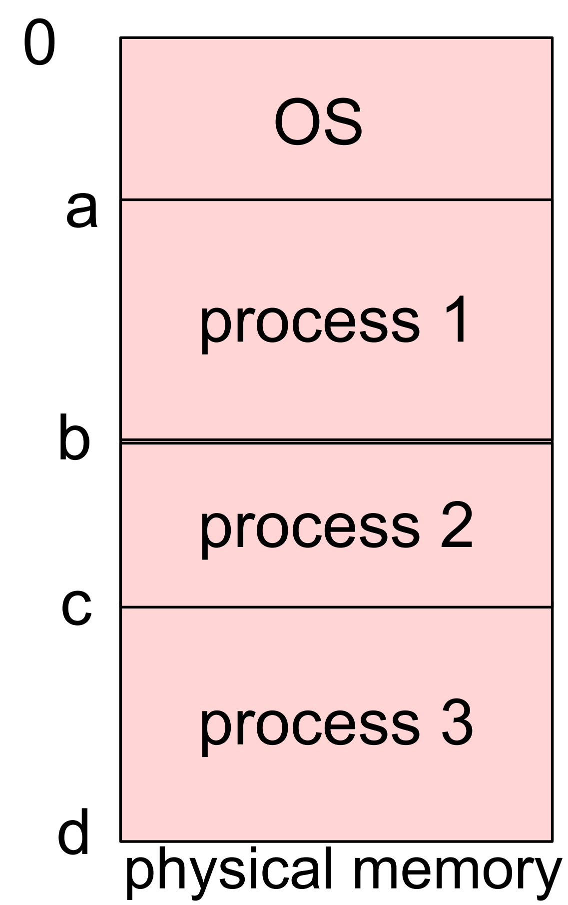
Internal fragmentation: fragmented memory *within* allocated memory blocks



Memory

- For multiprogramming, must have multiple processes
- Each process must be in memory to execute
- Possibilities:
  - Multiple processes in memory: each in their own partition
    - Fixed-size *non*-equal partitions

External fragmentation: fragmented memory *between* allocated memory blocks

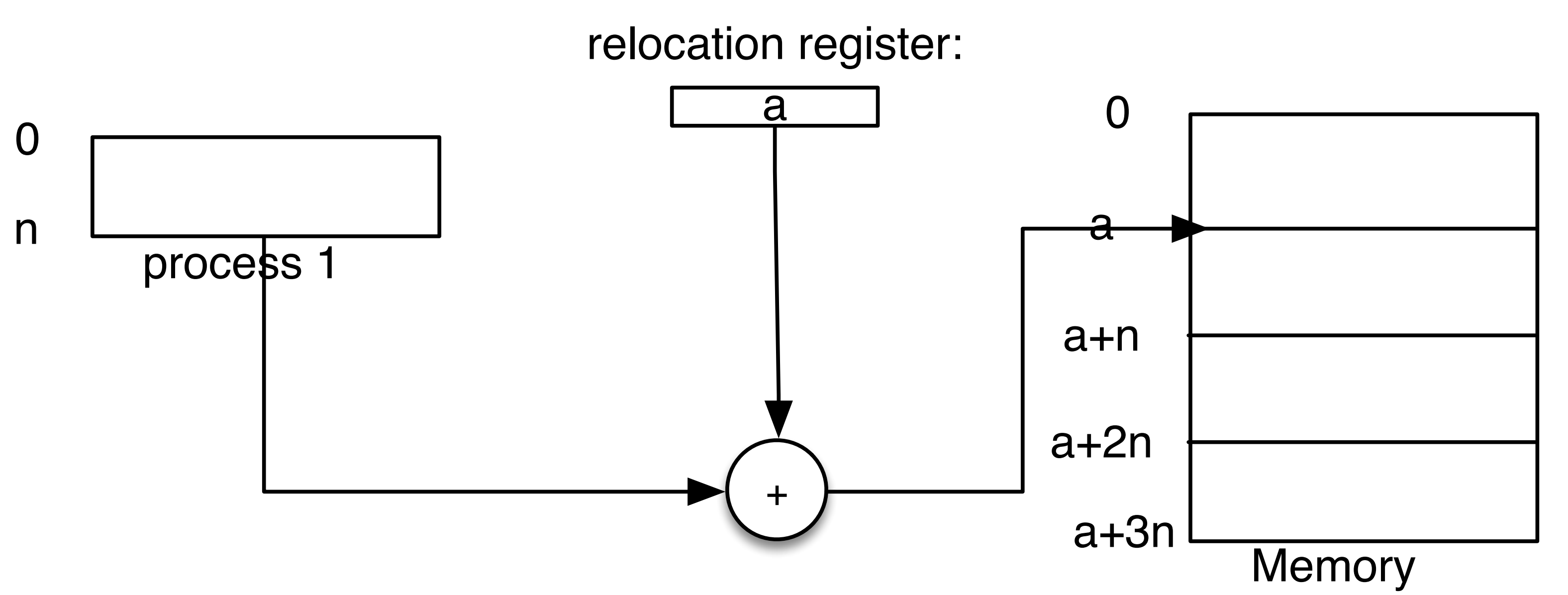


Address Binding

- When to map instructions and data references to actual memory locations
  - Link time
    - Absolute addressing. Works if well-known address at which user programs are loaded
  - Load time
    - Linker-loader relocates code as it loads into memory
    - Change all data references to take into account where loaded
    - Position-independent code
    - For PIE (position independent executables), subroutine calls are PC-relative. Static data references are indirected through a pointer to data location

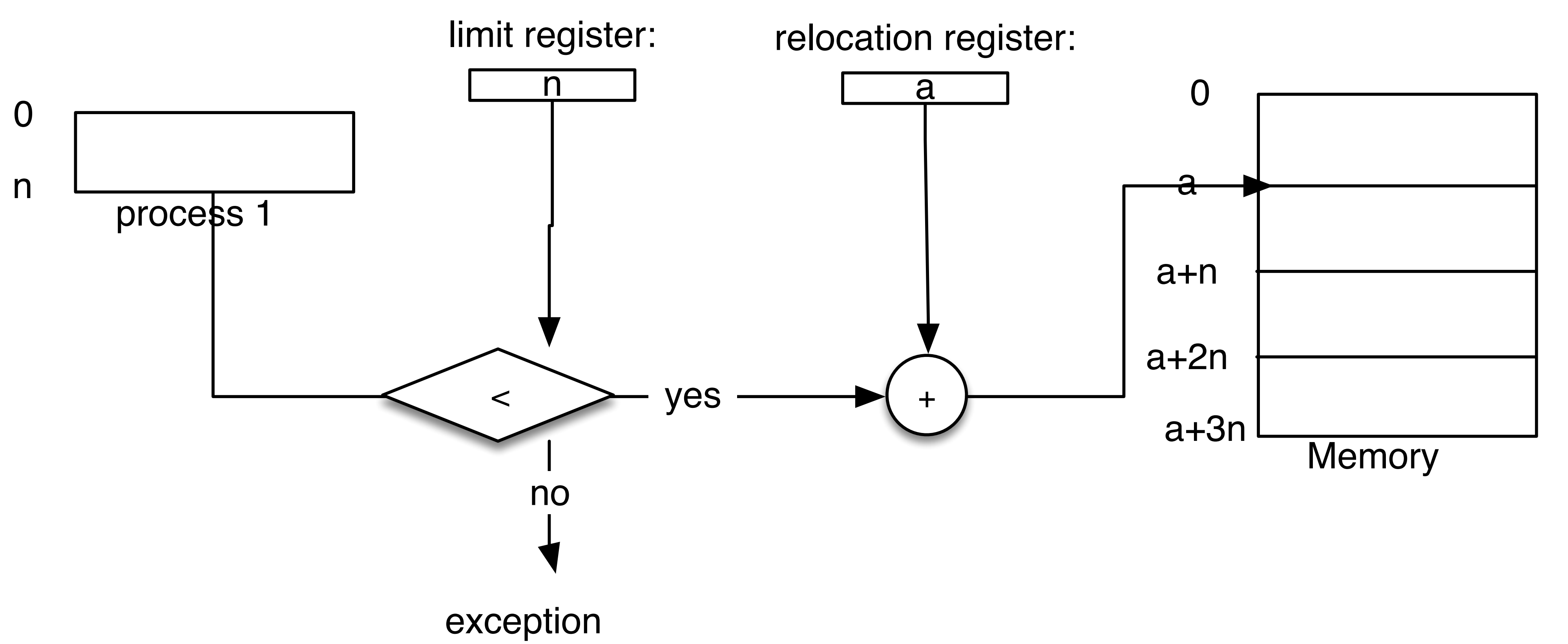
Address Binding

- When to map instructions and data references to actual memory locations
  - Execution time
    - Code uses *logical addresses* which are converted to *physical addresses*
    - Hardware: relocation register



Process Protection

- How to protect the memory of a process (or the OS) from other running processes?
  - Hardware solution: base (*aka* relocation) and limit registers

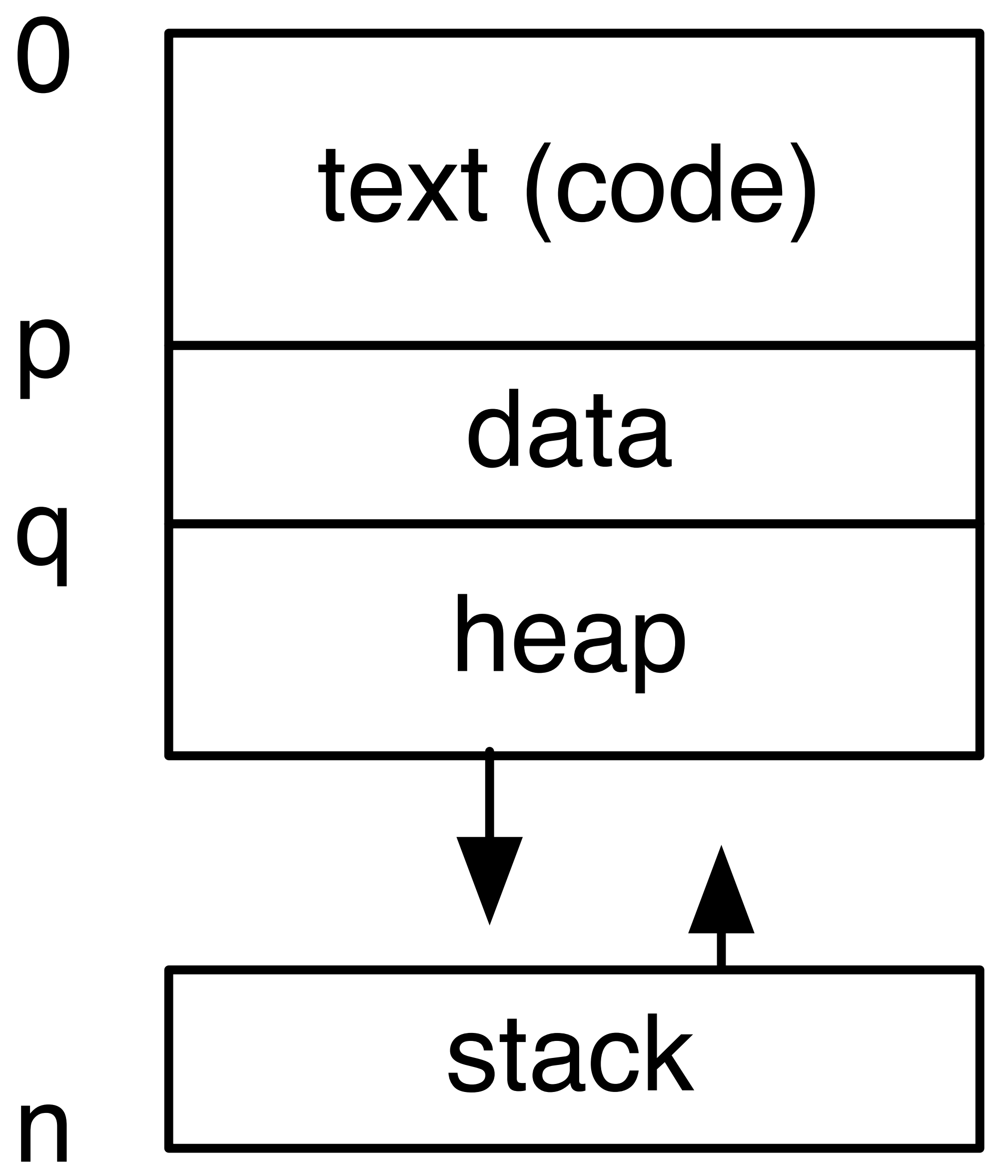


Disadvantage: can't easily share memory between processes

Process Protection

- How to protect the memory of a process (or the OS) from other running processes?
  - Software solution
    - Tagged data (e.g., Smalltalk/Lisp). No raw pointers
    - Virtual machine

Within a process address space

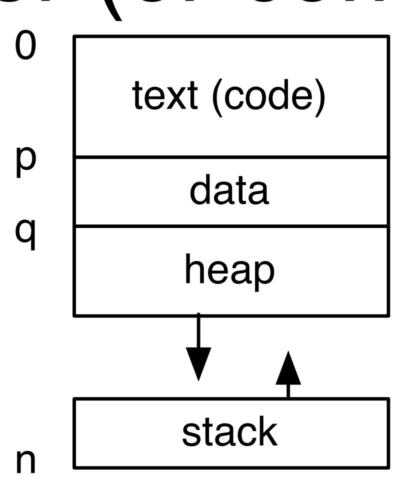


Fragmentation

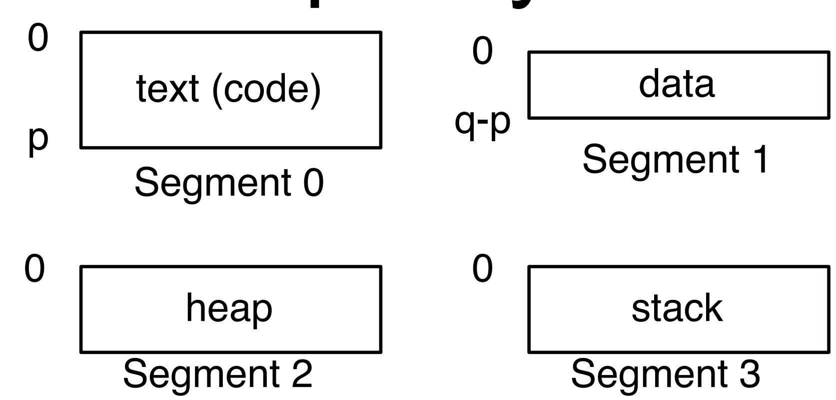
- External fragmentation
  - Space wasted *between* allocated memory blocks
  - Solutions
    - Compaction
      - Move blocks around dynamically to make free space contiguous. Only possible if relocation is dynamic at execution time
    - Non-contiguous
      - Don’t require all of the memory of a process to be contiguous: Segmentation/Paging
- Internal fragmentation
  - Space wasted *within* allocated memory blocks
  - Solutions:
    - Don’t use fixed-size blocks

Segmentation

- Provides multiple address spaces for a given process
  - Handy for separate data/stack/code
  - Good for sharing code/data between processes
  - Easy granularity to specify protection
    - no execute on stack!
  - Address is (segment num, offset within segment)
  - Need segment base/limit registers (1/segment)
  - Programmer (or compiler) must specify different segments



process with single segment



process with 4 segments

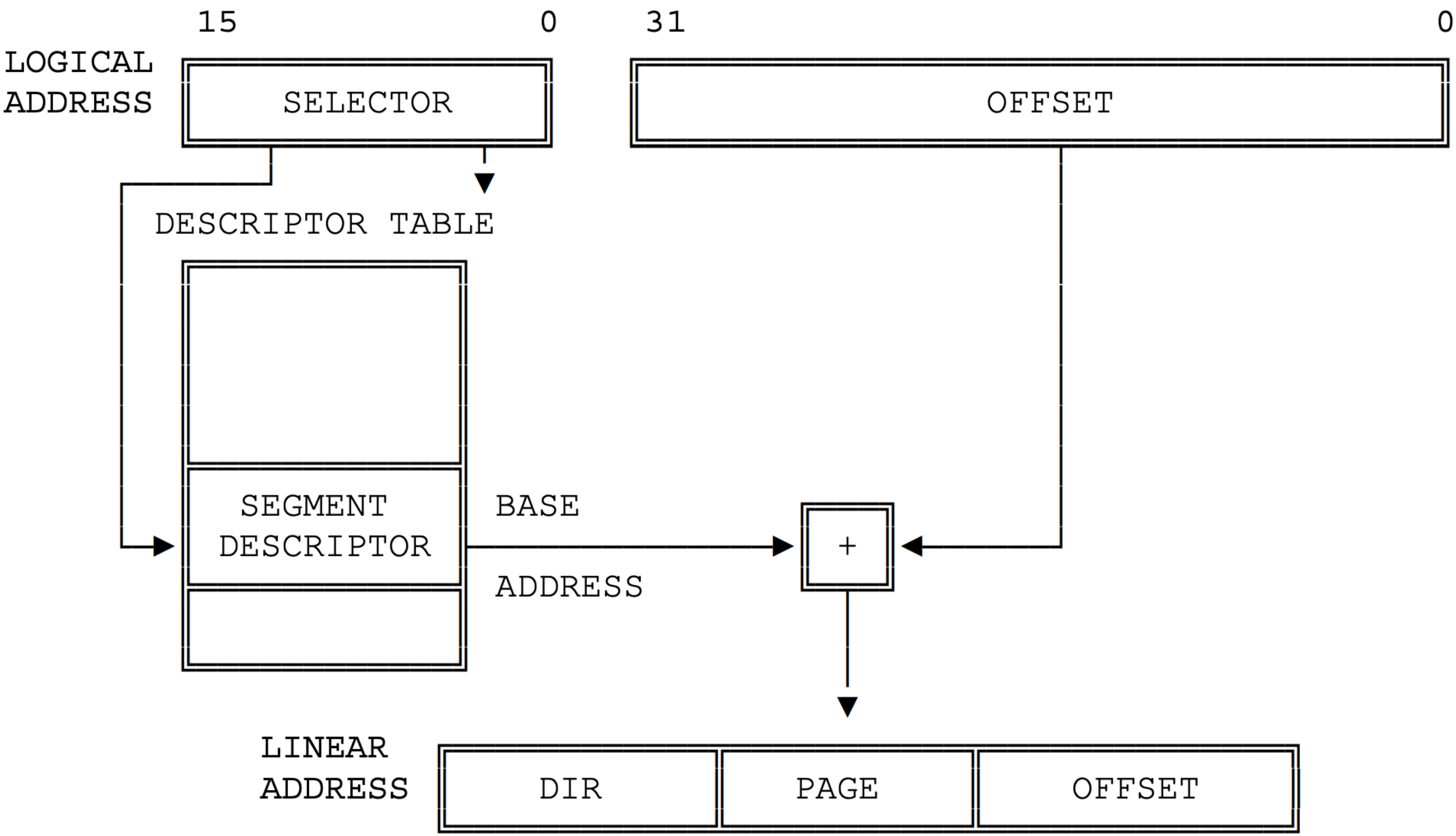
Segmentation

- Pros
  - Easy to share segments between processes
  - Segment-specific protection
  - No internal fragmentation
- Cons
  - Must still worry about external fragmentation: each segment must still have contiguous physical memory
  - Programmer/Compiler/Linker must be aware of different segments

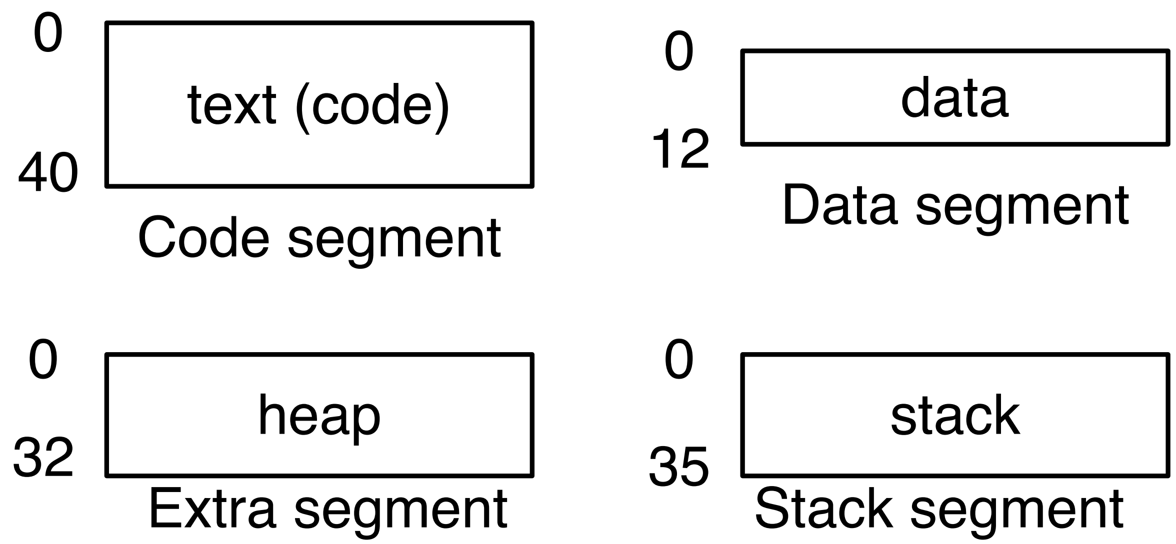
Segmentation on x86 (protected mode)

- There are four segments:
  - CS: code segment DS: data segment
  - SS: stack segment ES: extra segment
- Segment register contains:
  - Local/Global descriptor table bit
  - RPL: requested privilege level (2-bit)
  - an offset into a descriptor table
- Descriptor table entry contains:
  - 32-bit segment base
  - 20-bit segment limit (effectively 32-bit)
  - DPL: descriptor privilege level (2-bit)
  - Present bit

Segmentation on x86 (protected mode)



Segmentation on x86, simplified example



Registers:

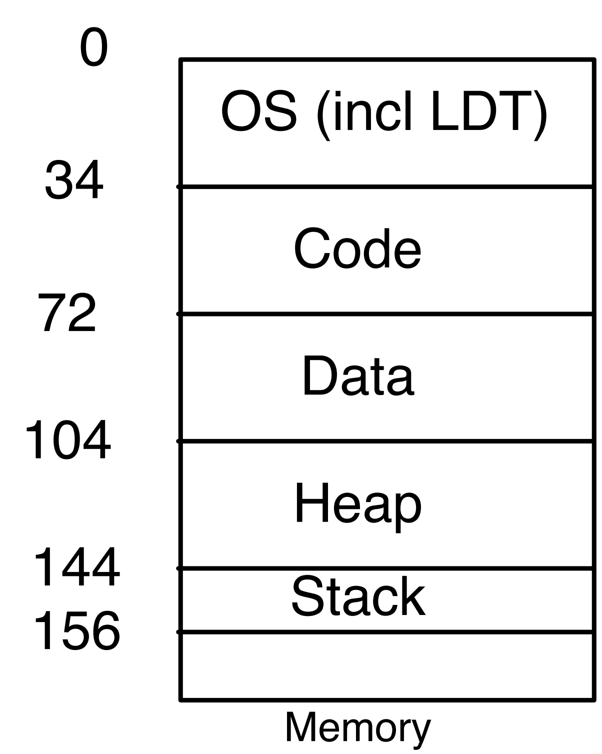
```
%CS: Local, CPL=3, offset=1
%DS: Local, CPL=3, offset=2
%SS: Local, CPL=3, offset=3
%ES: Local, CPL=3, offset=4
%SP: 12
%LDTR: 14
```

Local Descriptor table:

```
0: unused
1: Bounds=104, Limit=40,DPL=3,P
2: Bounds=144, Limit=12,DPL=3,P
3: Bounds= 72, Limit=32,DPL=3,P
4: Bounds= 34, Limit=38,DPL=3,P
```

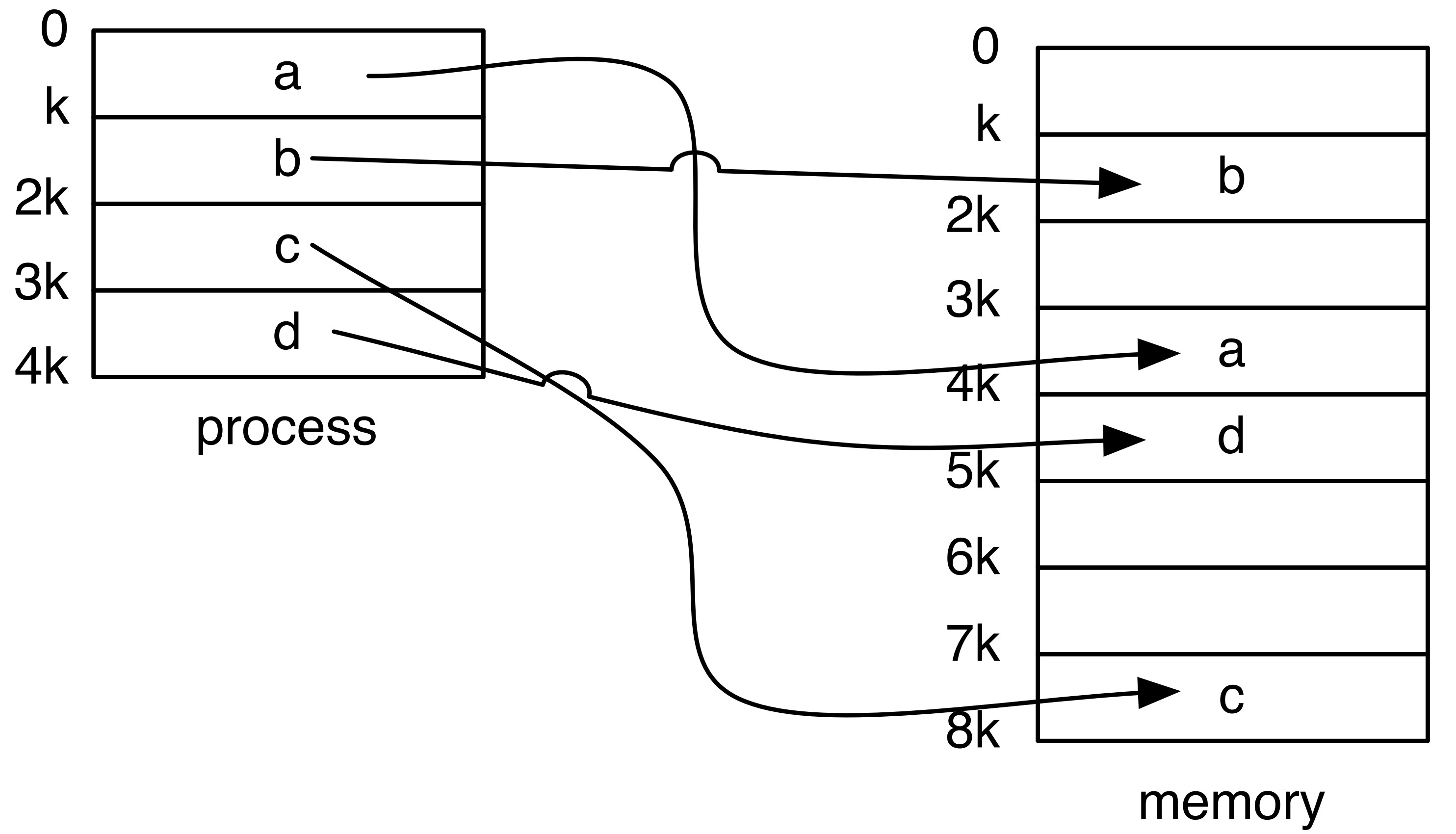
Example code:

```
0x04: movl %(ebx), %eax
0x06: push %eax
0x08: add $0x2, %esp
```



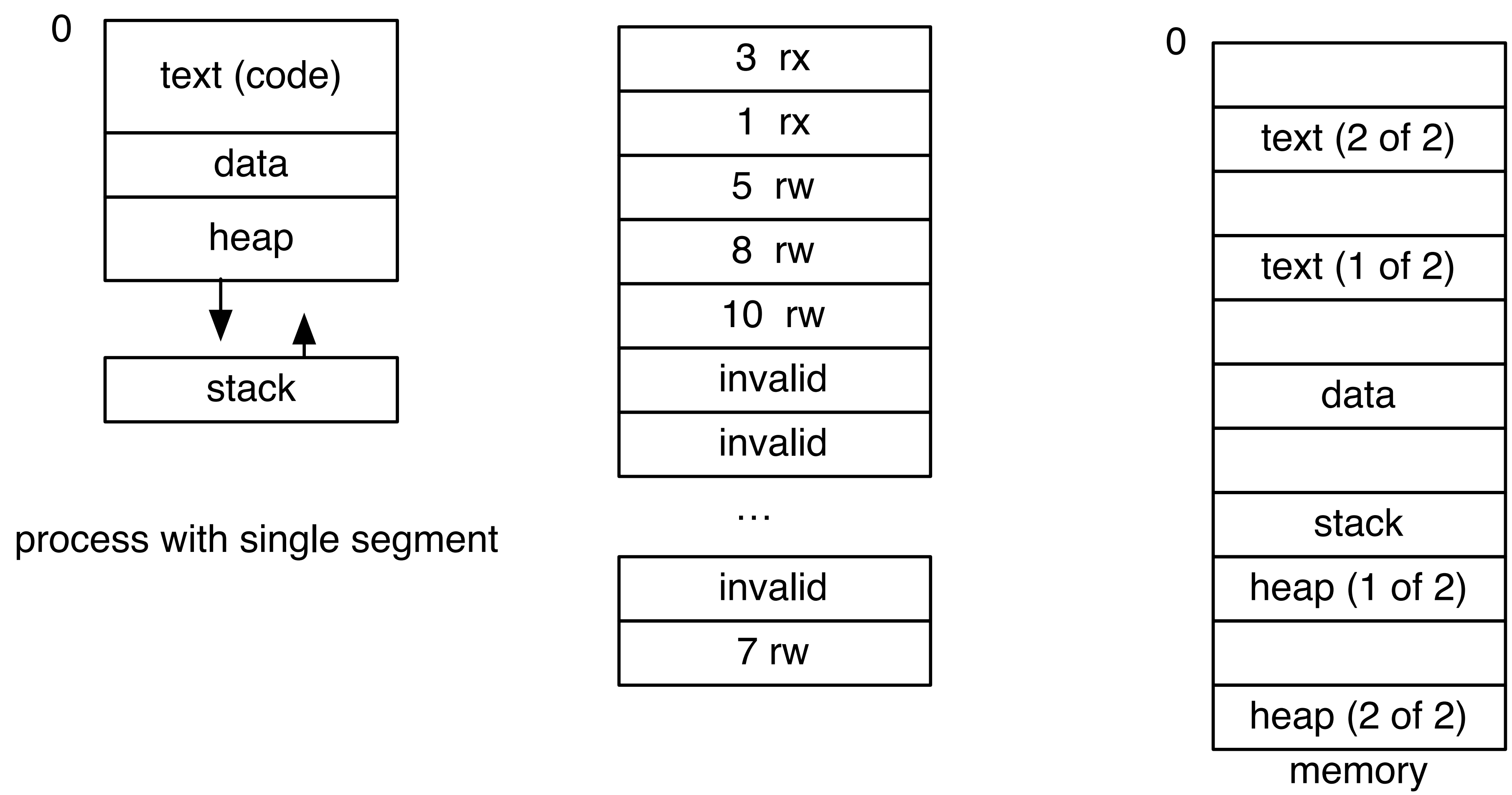
Paging

- Map contiguous virtual address space to non-contiguous physical address space
  - Idea:
    - break virtual address space into fixed-size *pages* (aka virtual pages)
    - break physical address space into fixed size *frames* (aka physical pages)



Implementing Paging

- **Page table**
  - index into the table is a *page number*
  - Each entry is a *page table entry*
    - frame number
    - Present bit (valid/not valid)
    - Permissions
    - Modified
    - …



Implementing Paging

- Done in hardware (MMU)
  - Page-table register points to page table (physical address)
    - Must be saved/restored on context-switch
    - Page table per process

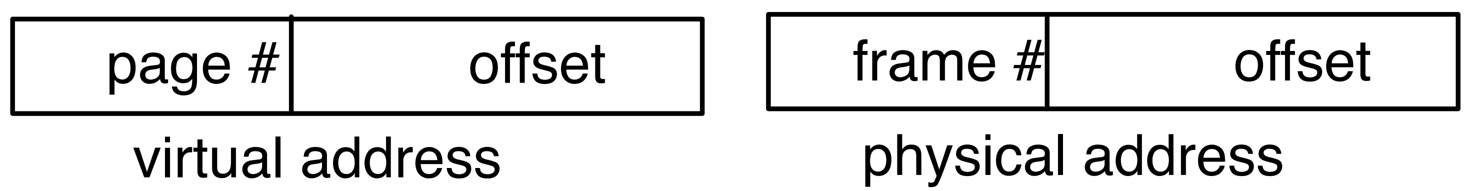
```
convertToPhysicalAddress(logicalAddress) {
  pageNumber = upper bits of logicalAddress
  if pageNumber out of range, generate exception (aka fault)
  if !pageTable[pageNumber].present generate page fault
  offset = lower bits of logicalAddress
  upper bits of physicalAddress=pageTable[pageNumber].frameNumber
  lower bits of physicalAddress = offset
```

Paging

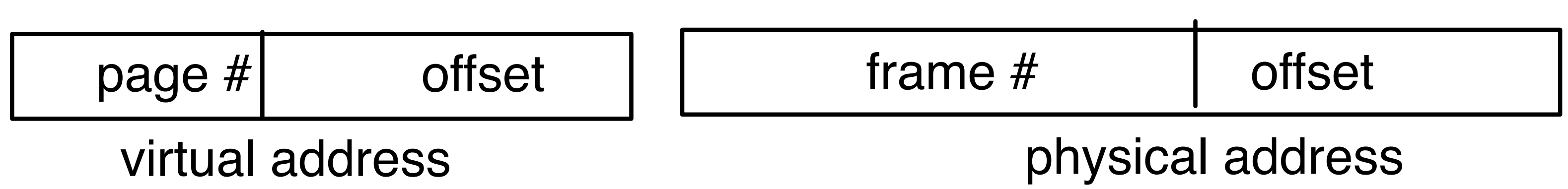
- Pros
  - No external fragmentation
    - Unallocated memory can be allocated to any process
  - Transparent to programmer/compiler/linker
  - Can put individual frames out to disk (VM)
- Cons
  - Translating from virtual to physical address requires an additional memory access
  - Unused pages in a process still require page table entries
  - Internal fragmentation
    - On average, 1/2 frame size per "segment"

Relationship between virtual/physical addresses

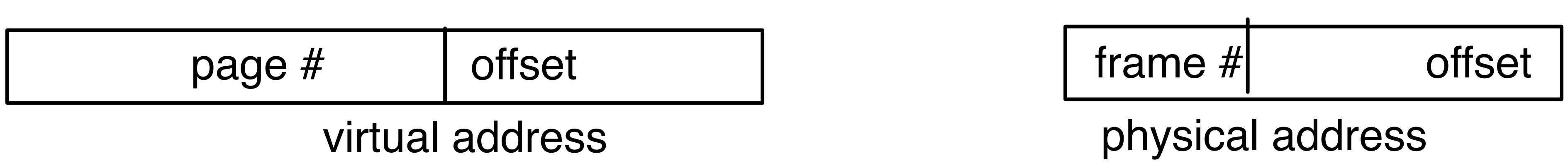
- Virtual address the same size as the physical address



- Virtual address smaller than physical address



- Virtual address bigger than physical address

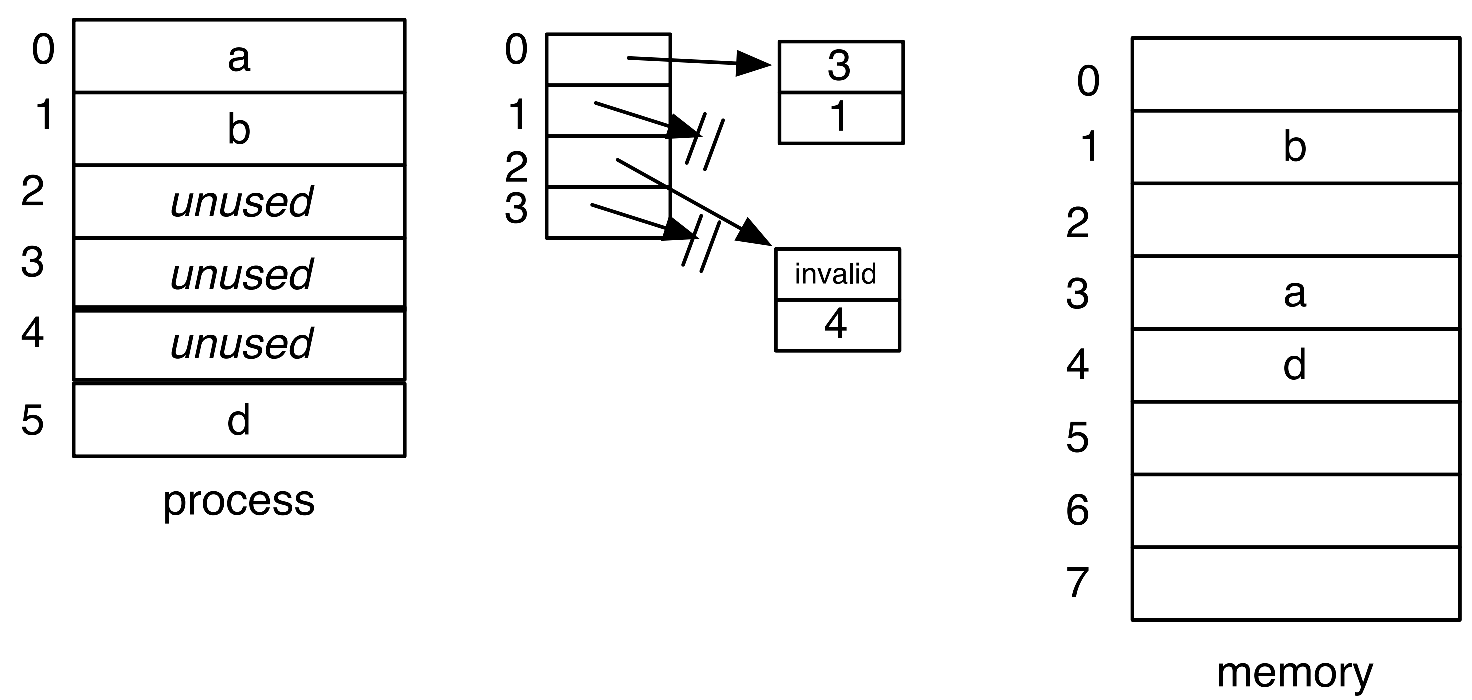


Dealing with holes in virtual address space

- With large address space (and small pages), page tables can be very large
  - 32-bit virtual addresses, 4K page: 2^{20} page table entries/process

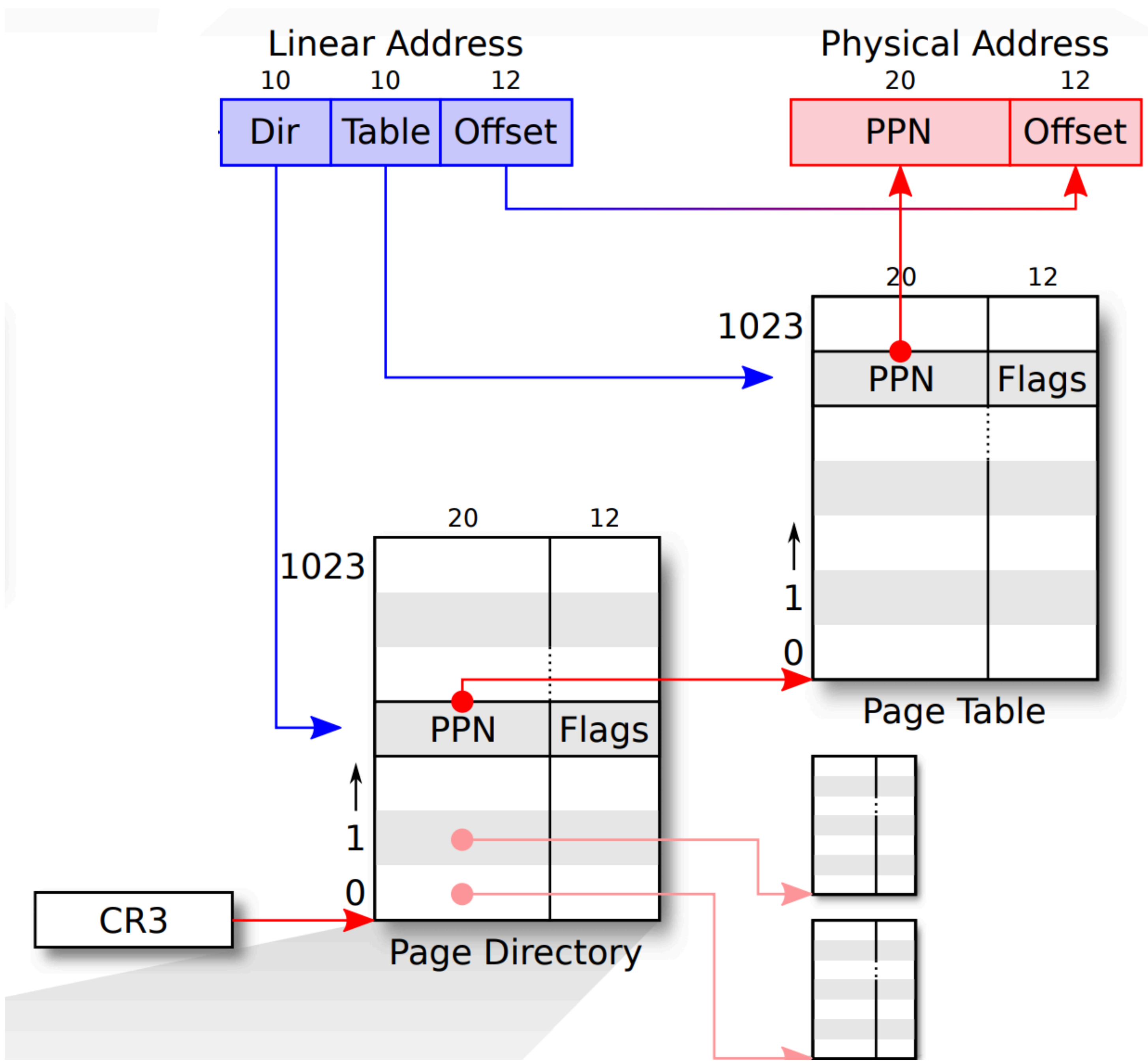
Dealing with holes in virtual address space

- ## Multilevel page table
  - Virtual address broken down into multiple page numbers: PT1 and PT2
  - PT1 is used as index into top-level PT to find second-level PT
  - PT2 is used as index into second-level PT to find PTE
  - If parts of address space are unused, top-level PT can show second-level PT not present

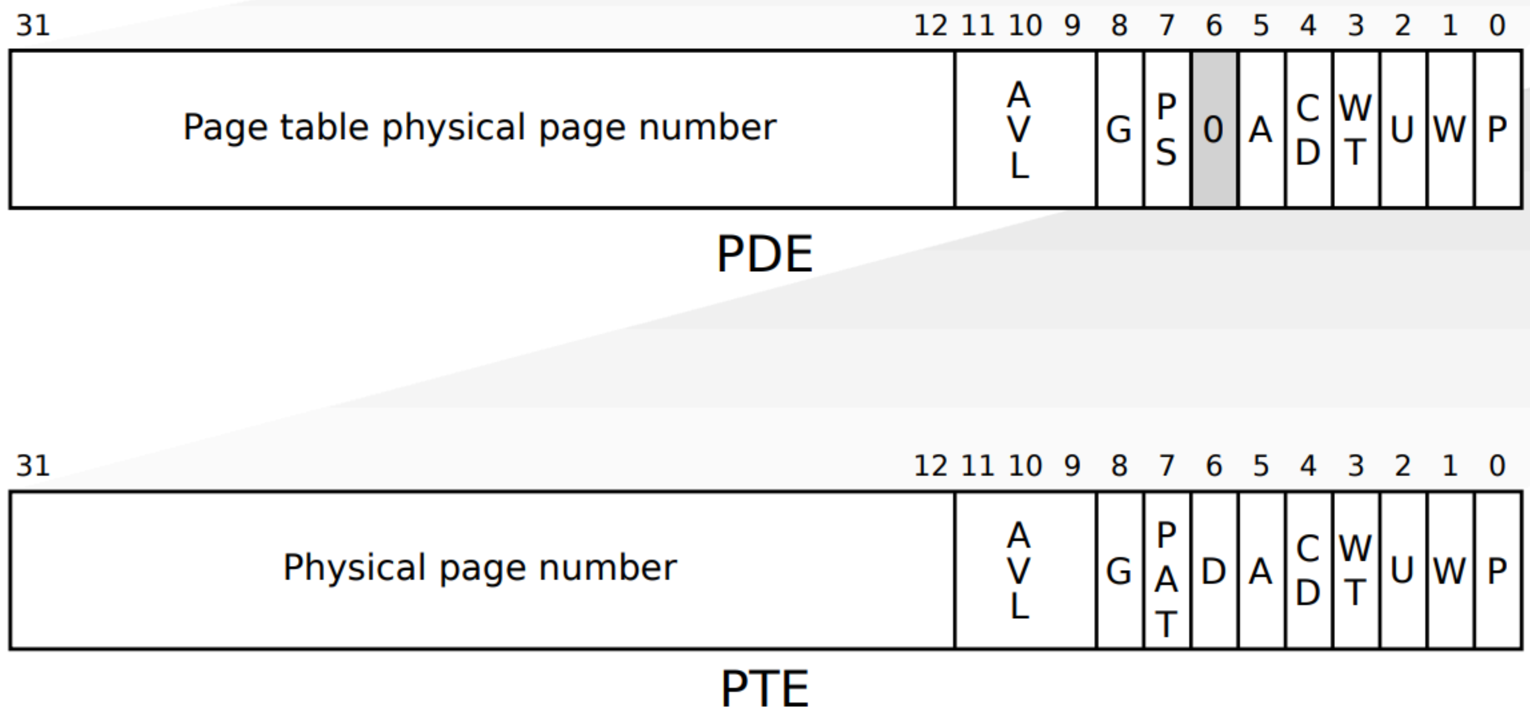


Paging on x86

- %CR3 contains pointer to first-level page table (*Page directory*).

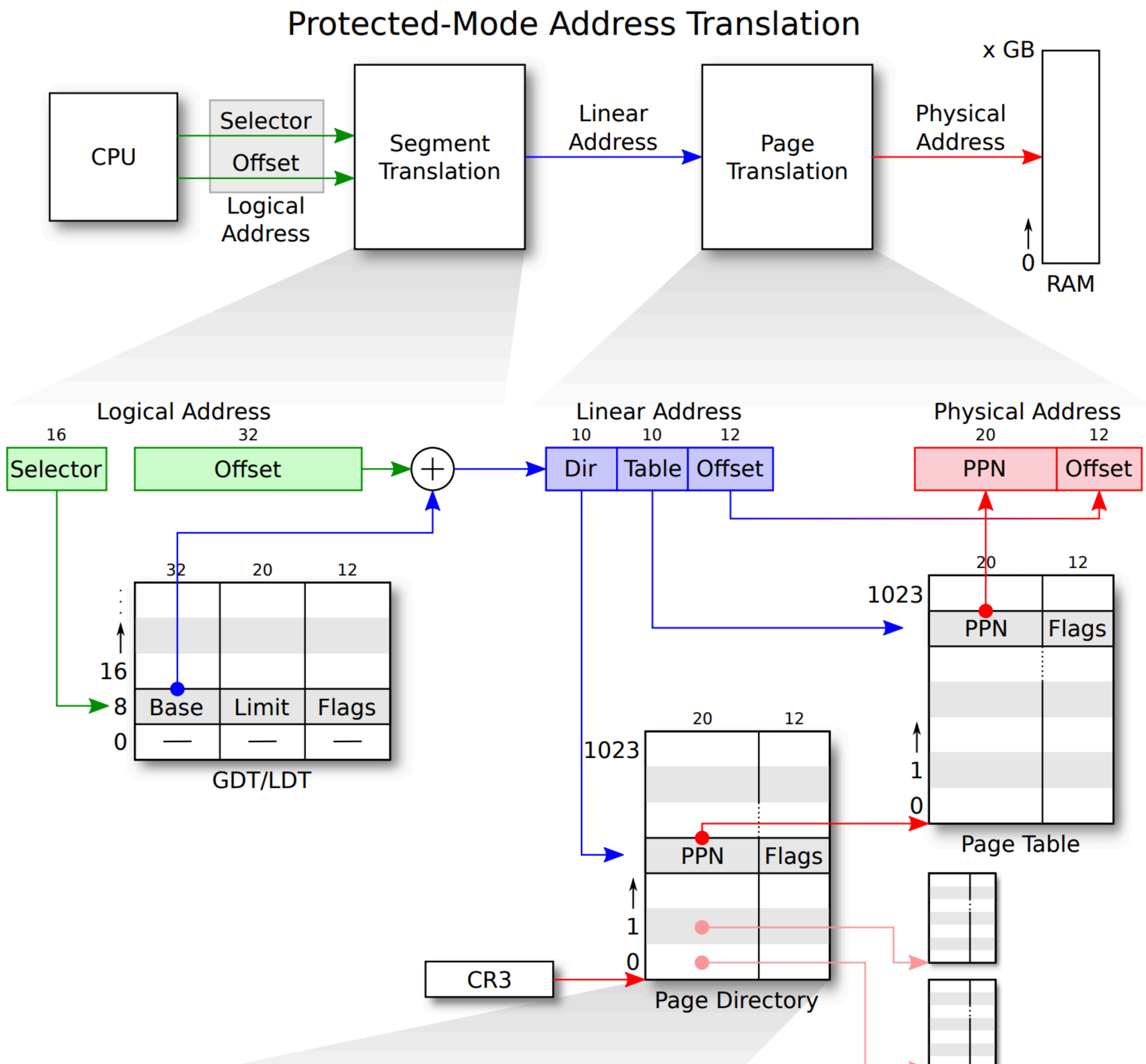


Page table entries on x86



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

Segmentation/Paging interaction on x86



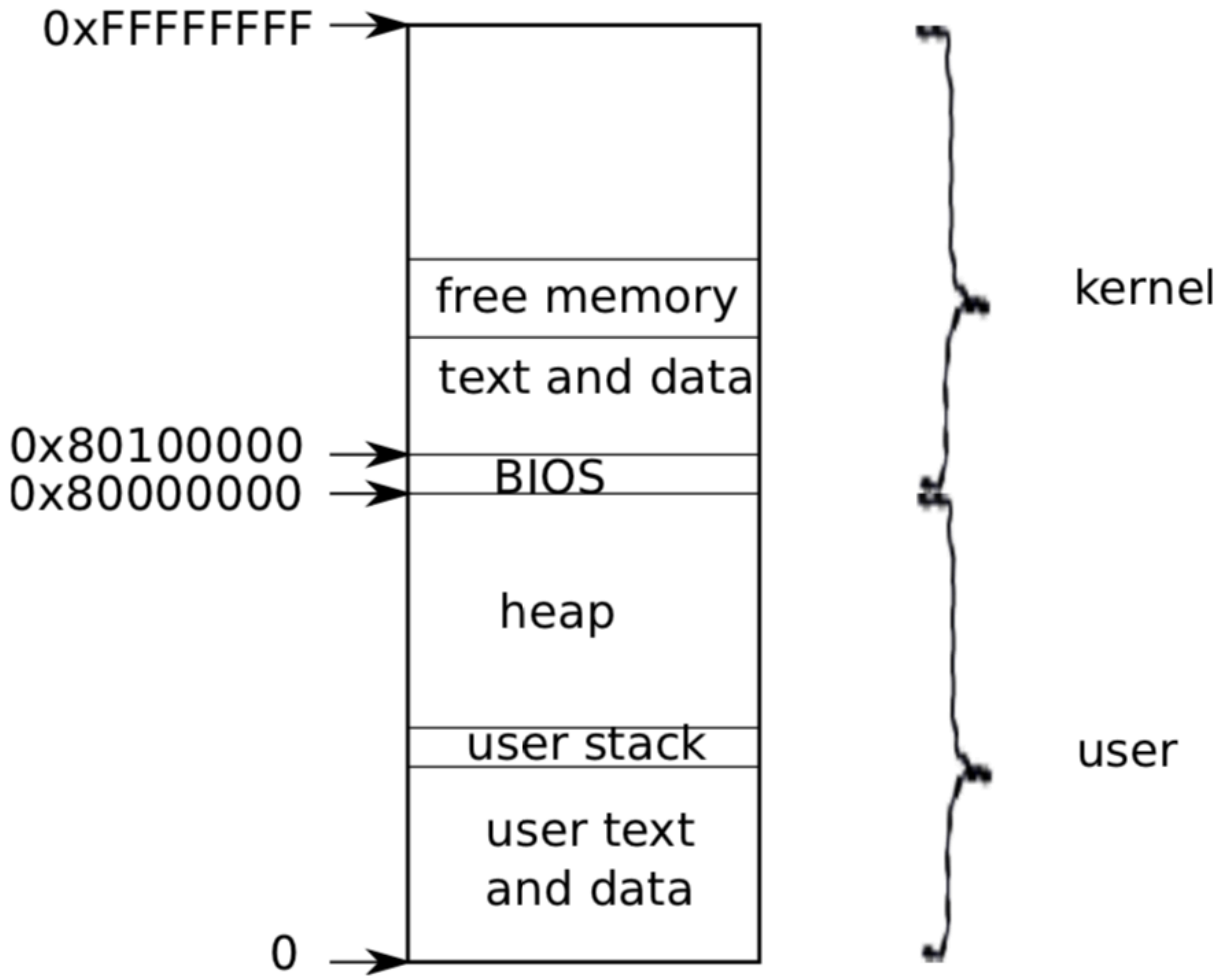
Exceptions

- What if the PDE or PTE doesn't have Present bit set?
  Or, what if trying to write and W bit not set?
  Or, what if trying access and U mode not set?
  - Page fault exception
  - Kernel can:
    - Kill process
    - Install/modify PTE and then resume the process
      - For example, after loading the page of memory from disk

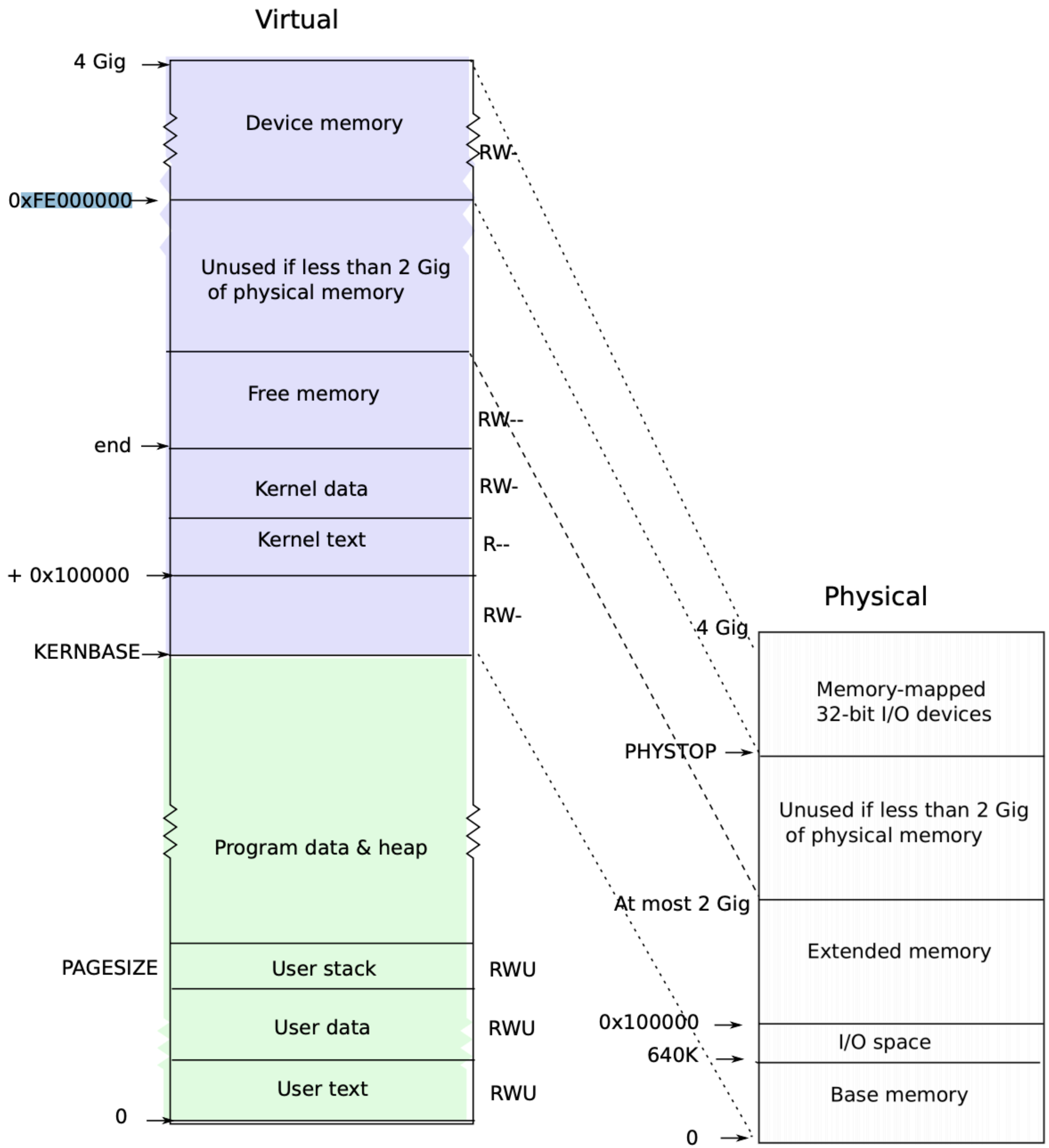
Why use virtual memory in kernel?

- Why does the kernel need a page table?
  - Hardware often makes it difficult to turn off paging
  - Would need to turn it off/on when entering/exiting a system call
  - Without page table, we'd have external memory fragmentation

xv6 address space



xv6 address space



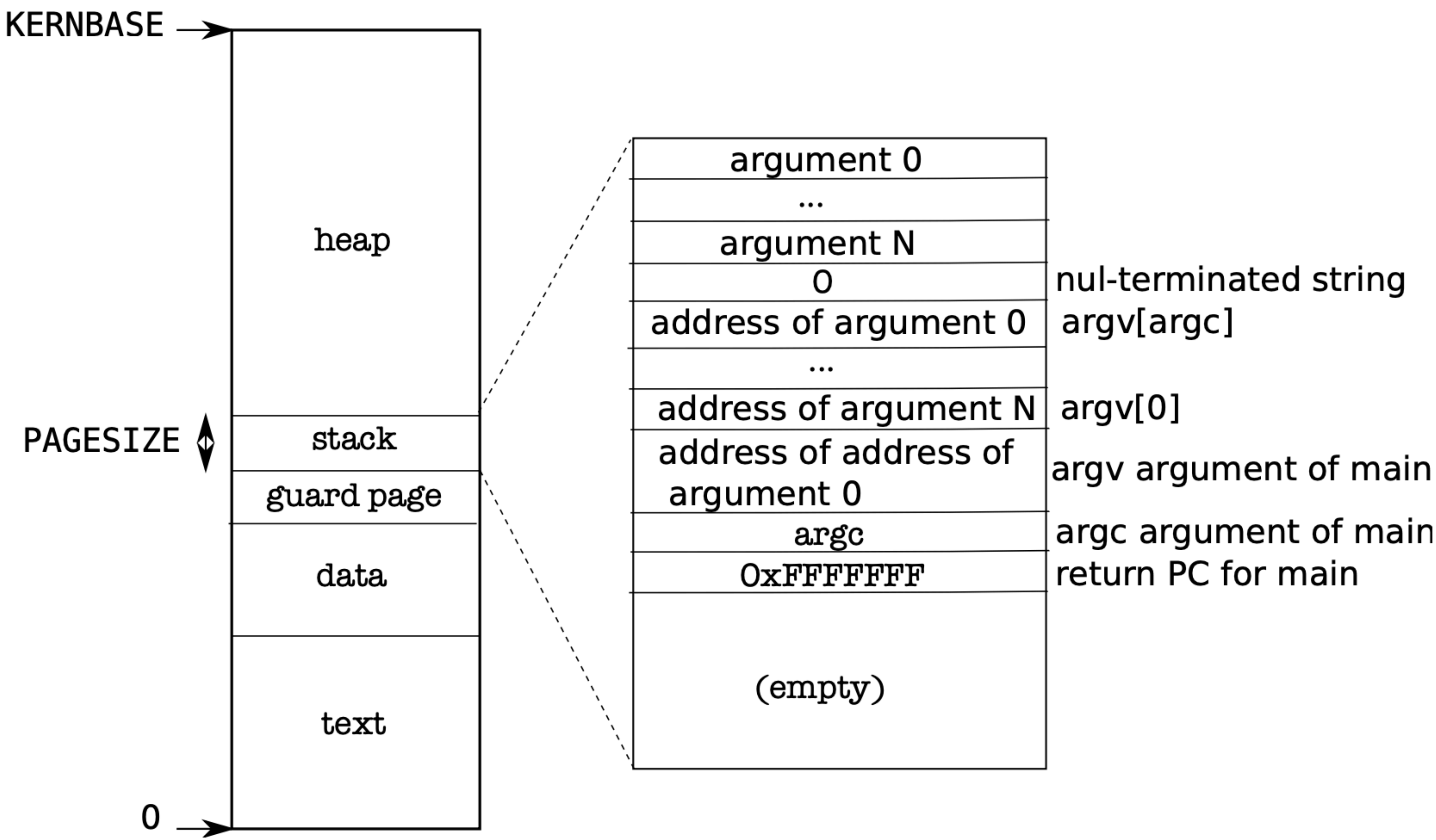
Processes on xv6

- Each has its own:
  - address space
  - page table (although second half of page dir and associated page tables could be shared)
- Kernel switches page tables (%CR3) when switching processes

Address space reasoning

- User virtual addresses start at 0
  - And go to 2GB, all contiguous. No external fragmentation. Pages can be mapped to any physical frame
- Kernel and user spaces are mapped:
  - No need to change page tables on a system call
- Kernel mapped at same place for all processes
  - Easier switching between processes
- Easy for kernel to R/W user memory
  - Just use user virtual addresses
- Easy for kernel to R/W physical memory
  - virtual addr = phys addr + 0x80000000

xv6: Memory layout of user process



xv6: Starting the first process

```
void
userinit(void)
{
  struct proc *p;
  extern char _binary_initcode_start[],
              _binary_initcode_size[];

  p = allocproc();

  initproc = p;
  if((p->pgdir = setupkvm()) == 0)
    panic("userinit: out of memory?");
  inituvm(p->pgdir, _binary_initcode_start,
    (int)_binary_initcode_size);
  p->sz = PGSIZE;
  memset(p->tf, 0, sizeof(*p->tf));
  p->tf->cs = (SEG_UCODE << 3) | DPL_USER;
  p->tf->ds = (SEG_UDATA << 3) | DPL_USER;
  p->tf->es = p->tf->ds;
  p->tf->ss = p->tf->ds;
  p->tf->eflags = FL_IF;
  p->tf->esp = PGSIZE;
  p->tf->eip = 0;  // beginning of initcode.S
  …
}
```

proc.c

xv6: Starting the first process

```
void
user
{
  st
  ex

  p

  in
  if

  in

  p-
  me
  p-
  p-
  p-
  p-
  p-
  p-
  p-
  …
}
```

```
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
};

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;
}
```

vm.c

xv6: Starting the first process

```
void
userinit(void)
{
  struct proc *p;
  extern char _binary_initcode_start[],
              _binary_initcode_size[];

  p = allocproc();

  initproc = p;
  if((p->pgdir = setupkvm()) == 0)
    panic("userinit: out of memory?");
  inituvm(p->pgdir, _binary_initcode_start,
    (int)_binary_initcode_size);
  p->sz = PGSIZE;
  memset(p->tf, 0, sizeof(*p->tf));
  p->tf->cs = (SEG_UCODE << 3) | DPL_USER;
  p->tf->ds = (SEG_UDATA << 3) | DPL_USER;
  p->tf->es = p->tf->ds;
  p->tf->ss = p->tf->ds;
  p->tf->eflags = FL_IF;
  p->tf->esp = PGSIZE;
  p->tf->eip = 0;  // beginning of initcode.S
  …
}
```

proc.c

xv6: Starting the first process

```
void
userinit(void)
{
  struct proc *p;
  extern char _binar
              _binar

  p = allocproc();

  initproc = p;
  if((p->pgdir = setu
    panic("userinit:
  inituvm(p->pgdir, _
    (int)_binary_ini
  p->sz = PGSIZE;
  memset(p->tf, 0, sizeof(*p->tf));
  p->tf->cs = (SEG_UCODE << 3) | DPL_USER;
  p->tf->ds = (SEG_UDATA << 3) | DPL_USER;
  p->tf->es = p->tf->ds;
  p->tf->ss = p->tf->ds;
  p->tf->eflags = FL_IF;
  p->tf->esp = PGSIZE;
  p->tf->eip = 0;  // beginning of initcode.S
  …
}
```

proc.c

```
void
inituvm(pde_t *pgdir, char *init, uint sz)
{
  char *mem;

  if(sz >= PGSIZE)
    panic("inituvm: more than a page");
  mem = kalloc();
  memset(mem, 0, PGSIZE);
  mappages(pgdir, 0, PGSIZE, V2P(mem), PTE_W|PTE_U);
  memmove(mem, init, sz);
}
```

vm.c

xv6: Starting the first process

```
void
switchuvm(struct proc *p)
{
  if(p == 0)
    panic("switchuvm: no process");
  if(p->kstack == 0)
    panic("switchuvm: no kstack");
  if(p->pgdir == 0)
    panic("switchuvm: no pgdir");

  pushcli();
  mycpu()->gdt[SEG_TSS] = SEG16(STS_T32A, &mycpu()->ts,
                                sizeof(mycpu()->ts)-1, 0);
  mycpu()->gdt[SEG_TSS].s = 0;
  mycpu()->ts.ss0 = SEG_KDATA << 3;
  mycpu()->ts.esp0 = (uint)p->kstack + KSTACKSIZE;
  // setting IOPL=0 in eflags *and* iomb beyond the tss segment limit
  // forbids I/O instructions (e.g., inb and outb) from user space
  mycpu()->ts.iomb = (ushort) 0xFFFF;
  ltr(SEG_TSS << 3);
  lcr3(V2P(p->pgdir));  // switch to process's address space
  popcli();
}
```

proc.c

xv6: Starting the first process

```
void
switchuvm(struct proc
{
  if(p == 0)
    panic("switchuvm:
  if(p->kstack == 0)
    panic("switchuvm:
  if(p->pgdir == 0)
    panic("switchuvm:

  pushcli();
  mycpu()->gdt[SEG_TS

  mycpu()->gdt[SEG_TSS].s = 0;
  mycpu()->ts.ss0 = S
  mycpu()->ts.esp0 =
  // setting IOPL=0 i
  // forbids I/O inst
  mycpu()->ts.iomb =
  ltr(SEG_TSS << 3);
  lcr3(V2P(p->pgdir))
  popcli();
}
```

before lcr3

```
(qemu) info pg
VPN range     Entry          Flags        Physical page
[80000-803ff]  PDE[200]      ----A--UWP
  …
  [80115-803ff]  PTE[115-3ff] --------WP 00115-003ff
[80400-8dfff]  PDE[201-237] ----A--UWP
  [80400-8dfff]  PTE[000-3ff] ---DA---WP 00400-0dfff
[fe000-febff]  PDE[3f8-3fa] -------UWP
  [fe000-febff]  PTE[000-3ff] --------WP fe000-febff
[fec00-fefff]  PDE[3fb]      ----A--UWP
  …
[ff000-fffff]  PDE[3fc-3ff] -------UWP
  [ff000-fffff]  PTE[000-3ff] --------WP ff000-fffff
```

```
(qemu) info pg
VPN range     Entry          Flags        Physical page
[00000-003ff]  PDE[000]      -------UWP
  [00000-00000]  PTE[000]      -------UWP 0dfbd
[80000-803ff]  PDE[200]      -------UWP
  [80000-800ff]  PTE[000-0ff] --------WP 00000-000ff
  [80100-80106]  PTE[100-106] ---------P 00100-00106
  [80107-803ff]  PTE[107-3ff] --------WP 00107-003ff
[80400-8dfff]  PDE[201-237] -------UWP
  [80400-8dfff]  PTE[000-3ff] --------WP 00400-0dfff
[fe000-fffff]  PDE[3f8-3ff] -------UWP
  [fe000-fffff]  PTE[000-3ff] --------WP fe000-fffff
```

after lcr3

xv6: Starting the first process

```
// Create PTEs for virtual addresses starting at va that refer to
// physical addresses starting at pa. va and size might not
// be page-aligned.
static int
mappages(pde_t *pgdir, void *va, uint size, uint pa, int perm)
{
  char *a, *last;
  pte_t *pte;

  a = (char*)PGROUNDDOWN((uint)va);
  last = (char*)PGROUNDDOWN(((uint)va) + size - 1);
  for(;;){
    if((pte = walkpgdir(pgdir, a, 1)) == 0)
      return -1;
    if(*pte & PTE_P)
      panic("remap");
    *pte = pa | perm | PTE_P;
    if(a == last)
      break;
    a += PGSIZE;
    pa += PGSIZE;
  }
  return 0;
}
```

vm.c

xv6: Starting the first process

```
// Return the address of the PTE in page table pgdir
// that corresponds to virtual address va.  If alloc!=0,
// create any required page table pages.
static pte_t *
walkpgdir(pde_t *pgdir, const void *va, int alloc)
{
  pde_t *pde;
  pte_t *pgtab;

  pde = &pgdir[PDX(va)];
  if(*pde & PTE_P){
    pgtab = (pte_t*)P2V(PTE_ADDR(*pde));
  } else {
    if(!alloc || (pgtab = (pte_t*)kalloc()) == 0)
      return 0;
    // Make sure all those PTE_P bits are zero.
    memset(pgtab, 0, PGSIZE);
    // The permissions here are overly generous, but they can
    // be further restricted by the permissions in the page table
    // entries, if necessary.
    *pde = V2P(pgtab) | PTE_P | PTE_W | PTE_U;
  }
  return &pgtab[PTX(va)];
}
```

vm.c