Operating Systems

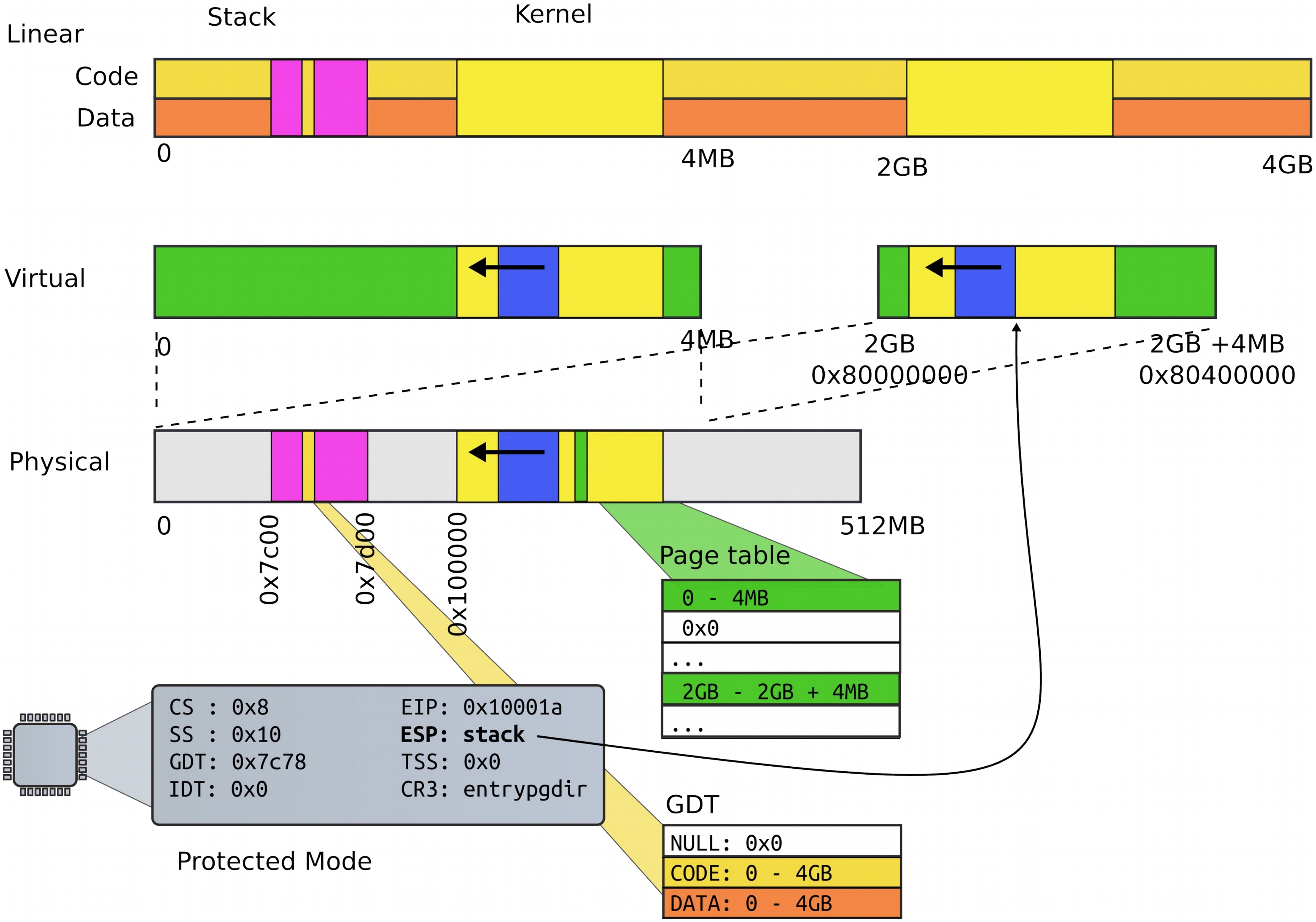
Lecture: Kernel Memory Allocator and Page Table

Anton Burtsev

Recap of the boot sequence

- Setup segments (data and code)
- Switched to protected mode
  - Loaded GDT (segmentation is on)
- Setup stack (to call C functions)
- Loaded kernel from disk
- Setup first page table
  - 2 entries [0 : 4MB] and [2GB : (2GB + 4MB)]
- Setup high-address stack
- Jumped to main()

State of the system after boot



CS : 0x8
SS : 0x10
GDT: 0x7c78
IDT: 0x0

EIP: 0x10001a
ESP: stack
TSS: 0x0
CR3: entrypgdir

Page table

0 - 4MB
0x0
...
2GB - 2GB + 4MB
...

GDT

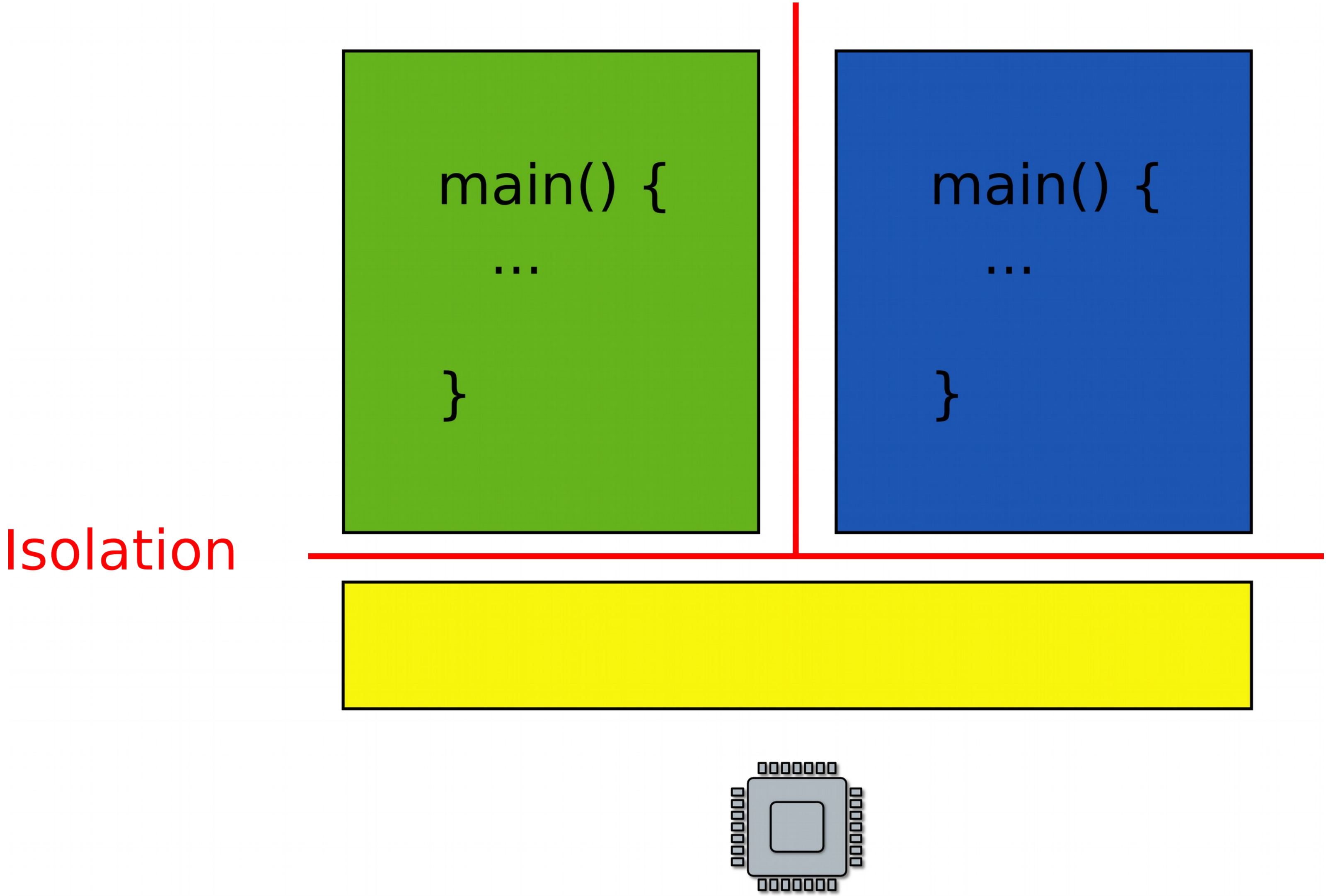
NULL: 0x0
CODE: 0 - 4GB
DATA: 0 - 4GB

Running in main()

```
// Bootstrap processor starts running C code here.
// Allocate a real stack and switch to it, first
// doing some setup required for memory allocator to work.
int
main(void)
{
    kinit1(end, P2V(4*1024*1024)); // phys page allocator
    kvmalloc(); // kernel page table
    mpinit(); // detect other processors
    lapicinit(); // interrupt controller
    seginit(); // segment descriptors
    cprintf("\ncpu%d: starting xv6\n\n", cpunum());
...
}
```

What's next?

We want to run multiple programs (processes)



```
main() {
    ...

}
```

```
main() {
    ...

}
```

Isolation

But what is a process?

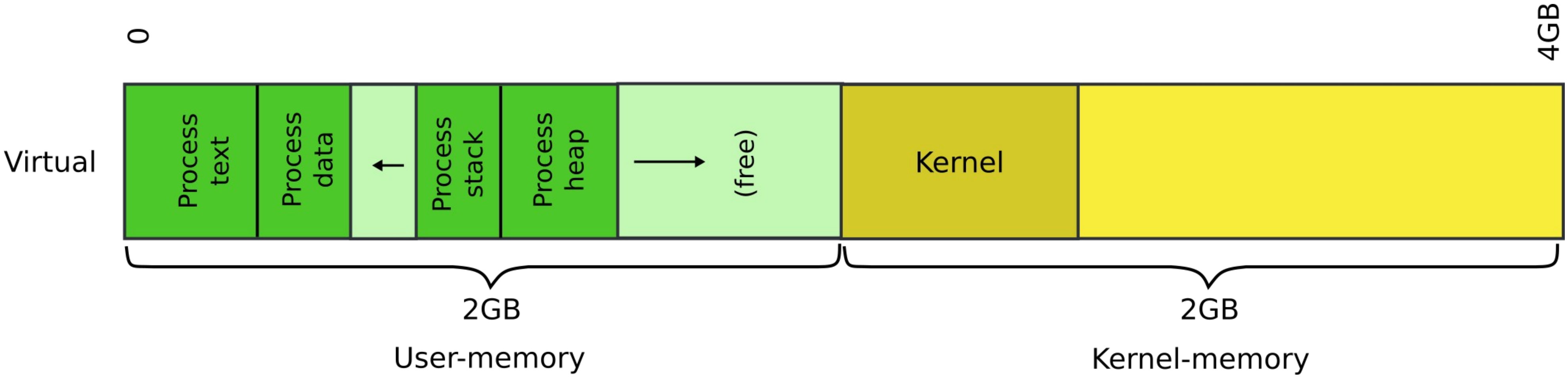
A couple of requirements

- Each process is a collection of resources
  - Memory
    - E.g., text, stack, heap
  - In-kernel state
    - E.g., open file descriptors, network sockets (connections)

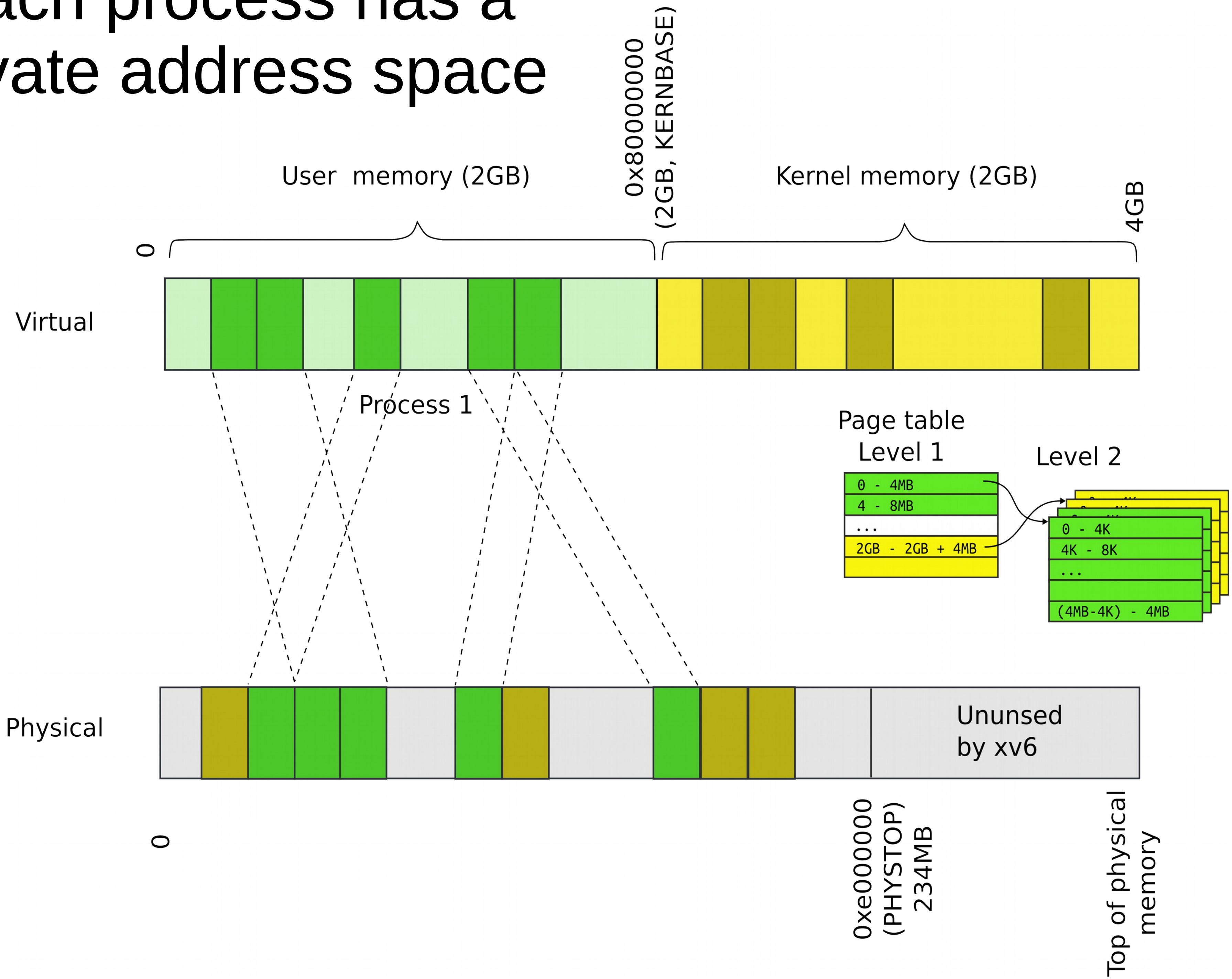
A couple of requirements

- Each process is a collection of resources
  - Memory
    - E.g., text, stack, heap
  - In-kernel state
    - E.g., open file descriptors, network sockets (connections)
- Processes are isolated from each other
  - Processes don't trust each other
    - Individual users, some privileged
  - Can't interfere with other processes
  - Can't change kernel (to affect other processes)

Each process will have a 2GB/2GB private address space

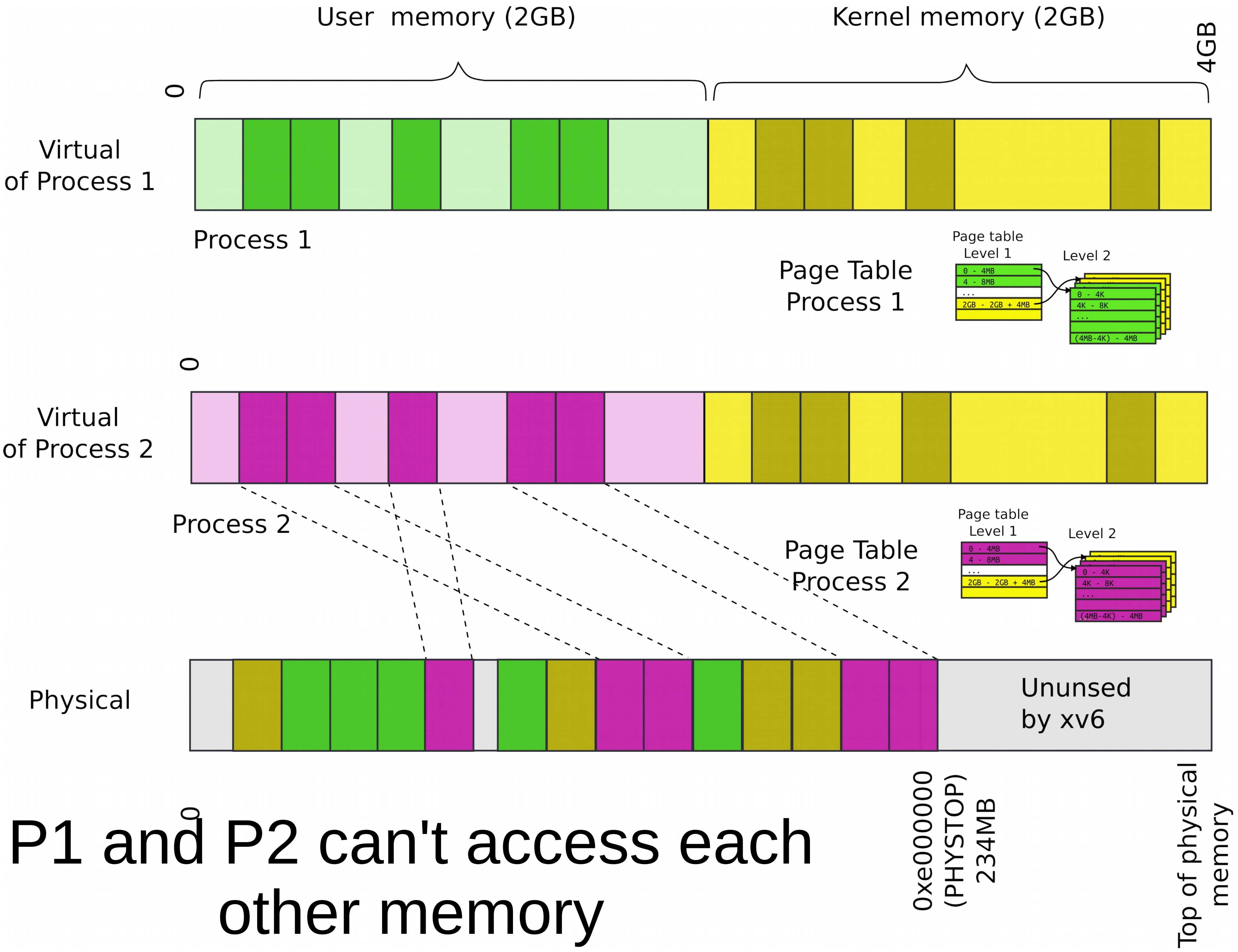


Each process has a private address space



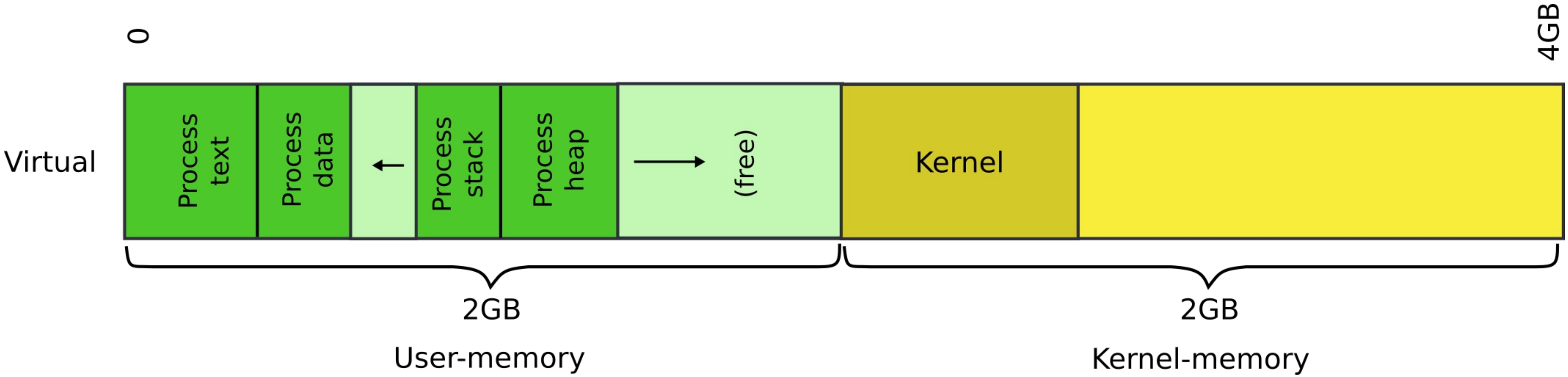
Each process maps the kernel

- It's not strictly required
  - But convenient for system calls
  - No need to change the page table when process enters the kernel with a system call
  - **Things are much faster!**

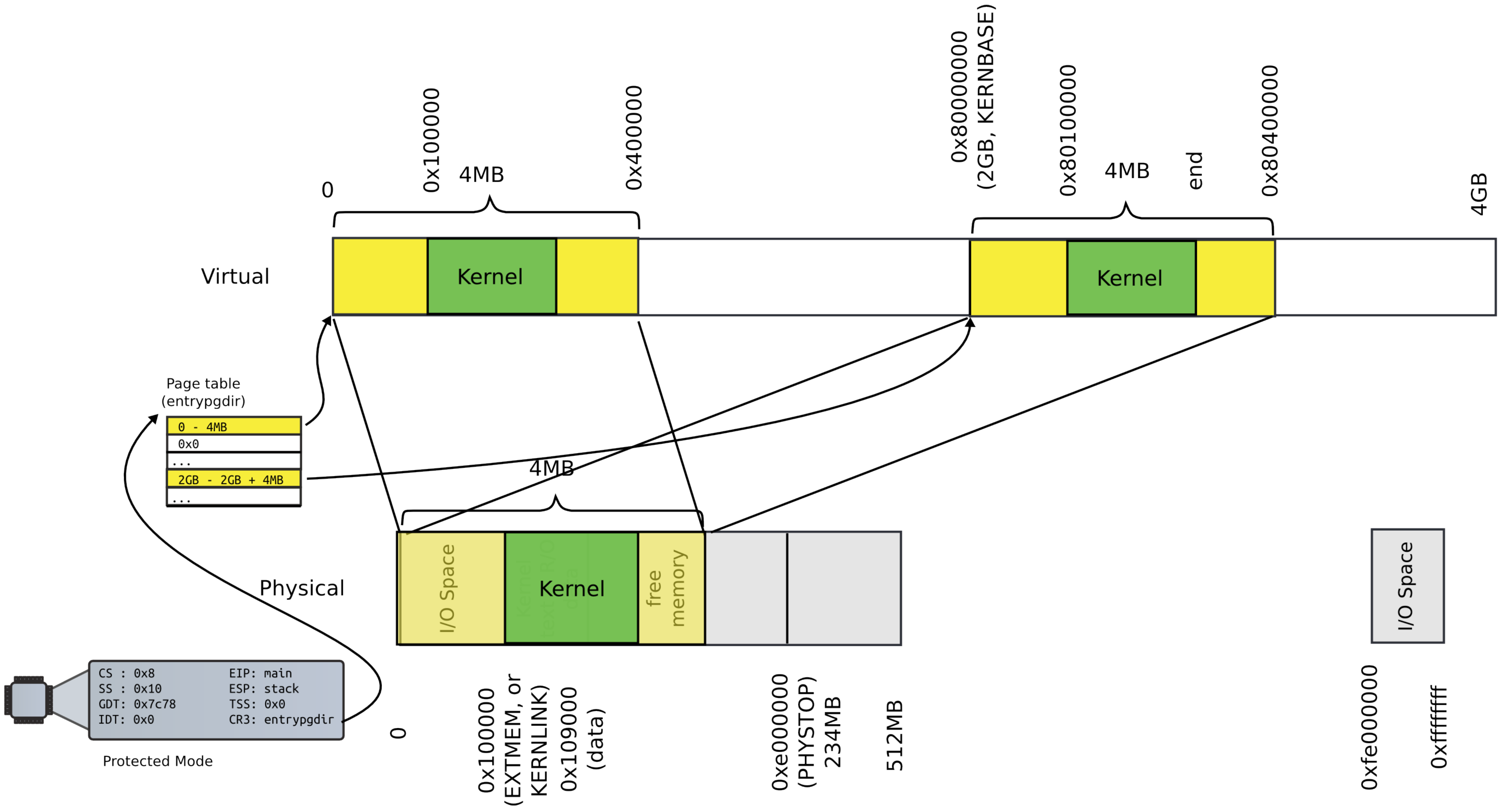


P1 and P2 can't access each other memory

Our goal: 2GB/2GB address space



Memory after boot



0 - 4MB
0x0
...
2GB - 2GB + 4MB
...

```
CS : 0x8          EIP: main
SS : 0x10         ESP: stack
GDT: 0x7c78       TSS: 0x0
IDT: 0x0          CR3: entrypgdir
```

Outline

- Create the kernel address space
  - Create kernel memory allocator
  - Allocate memory for page tables
    - Page table directory and page table

Kernel memory allocator

- Kernel needs normal 2 level, 4KB page table
  - Right now we have
    - One (statically allocated) page table
    - That has only two entries
  - And it is a page table for 4MB pages
- 4KB page table is a better choice
  - Xv6 processes are small
  - Wasting 4MB on a program that fits into 1KB is absurd

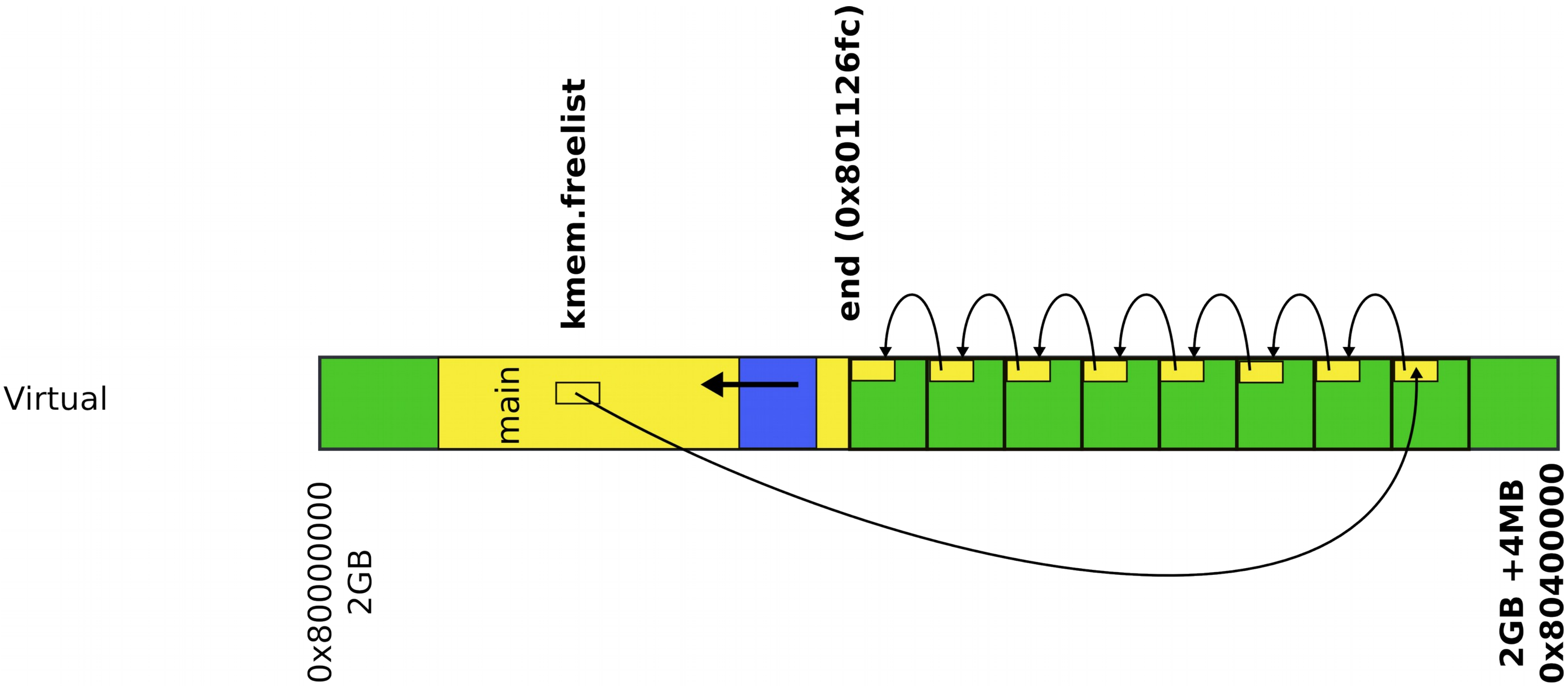
- But to create page tables we need memory
  - Where can it come from?

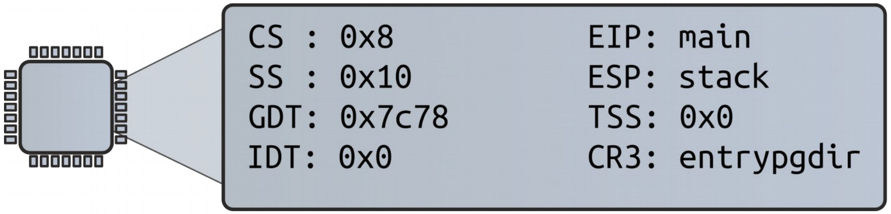
Simple memory allocator

- Goal:
  - `alloc()` and `free()`
  - To allocate page tables, stacks, data structures, etc.

What can it look like?

Page allocator

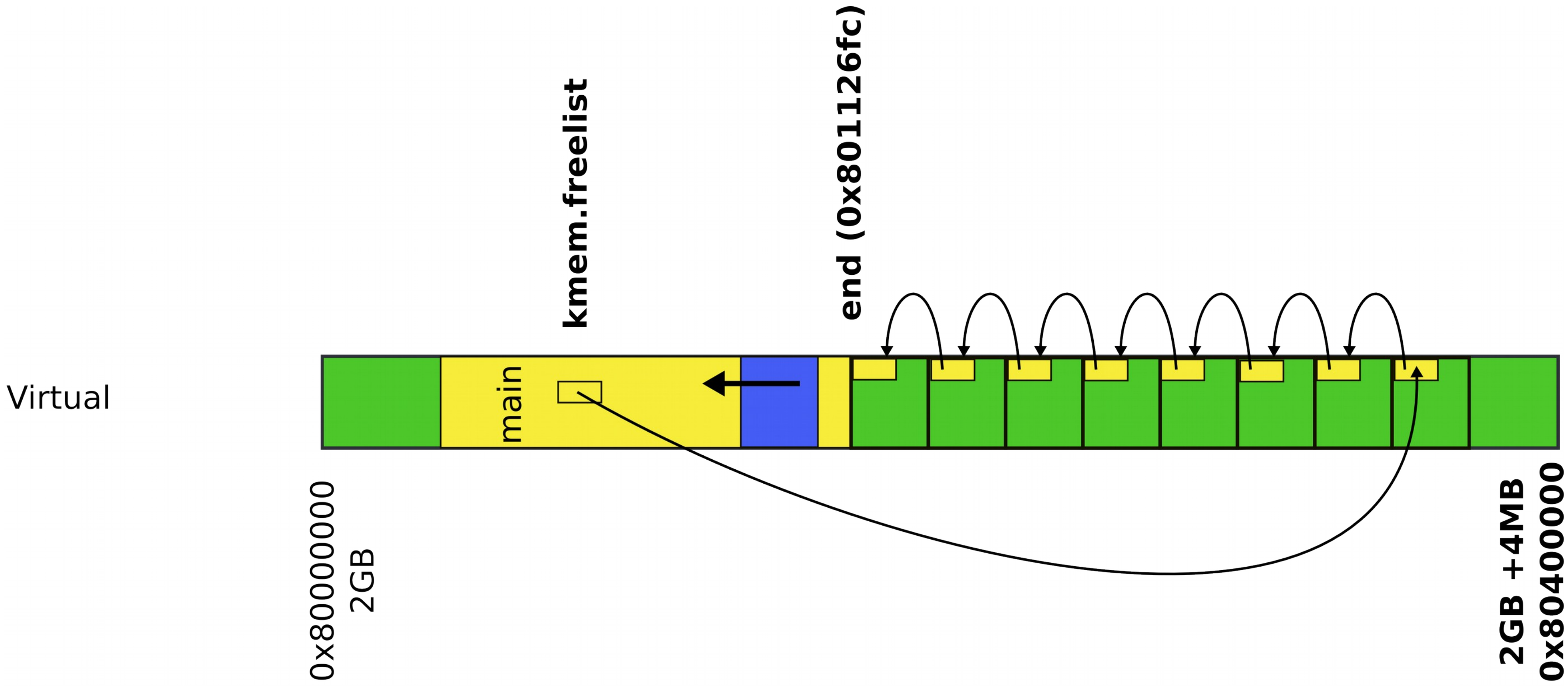


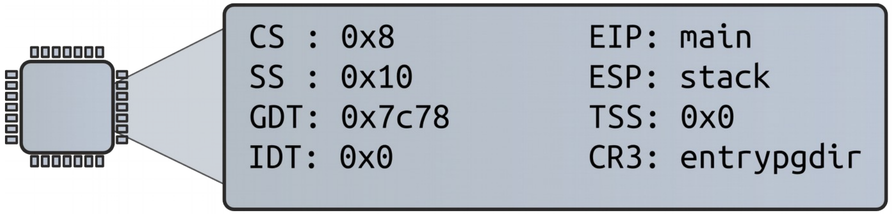


```
CS : 0x8             EIP: main
SS : 0x10            ESP: stack
GDT: 0x7c78          TSS: 0x0
IDT: 0x0             CR3: entrypgdir
```

Protected Mode

Page allocator



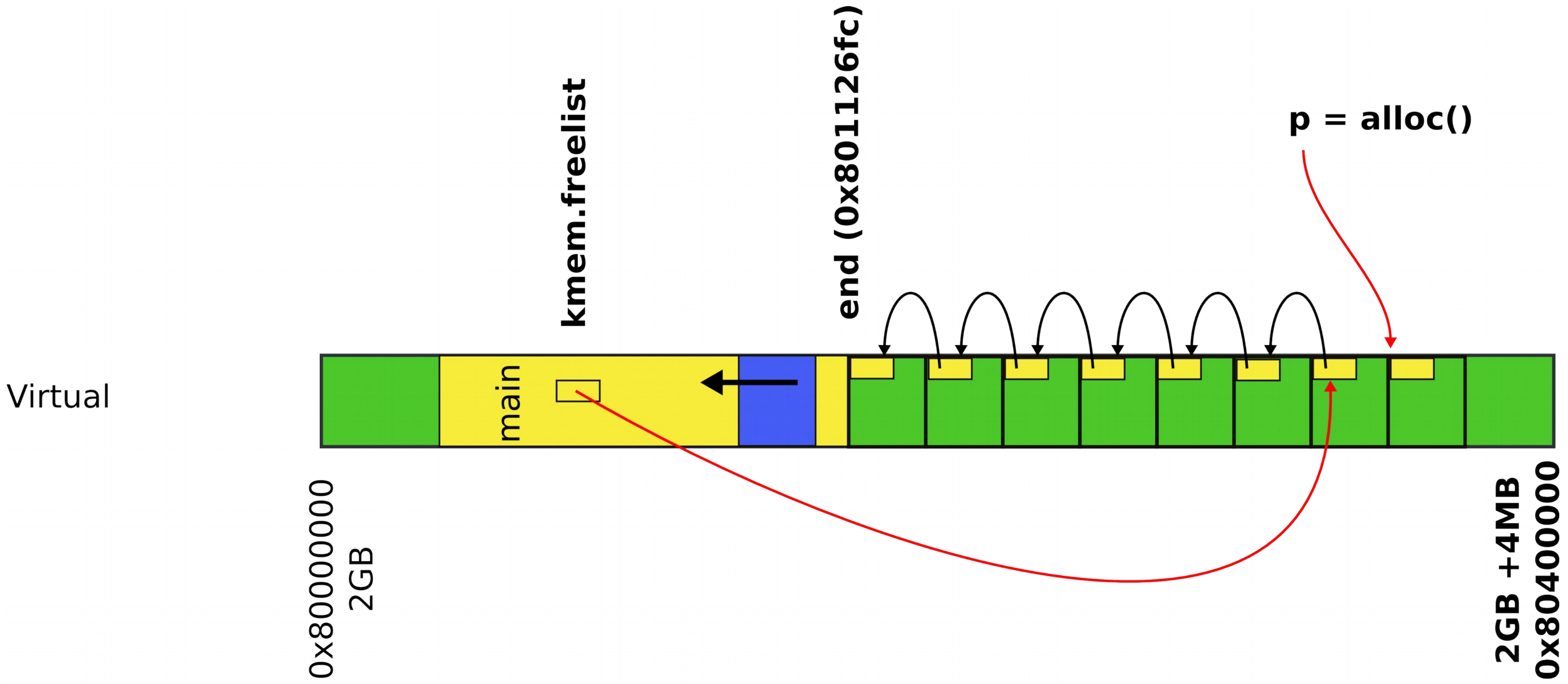


```
CS : 0x8          EIP: main
SS : 0x10         ESP: stack
GDT: 0x7c78       TSS: 0x0
IDT: 0x0          CR3: entrypgdir
```

Protected Mode

```
3014 struct run {
3015   struct run *next;
3016 };
```

Page allocator

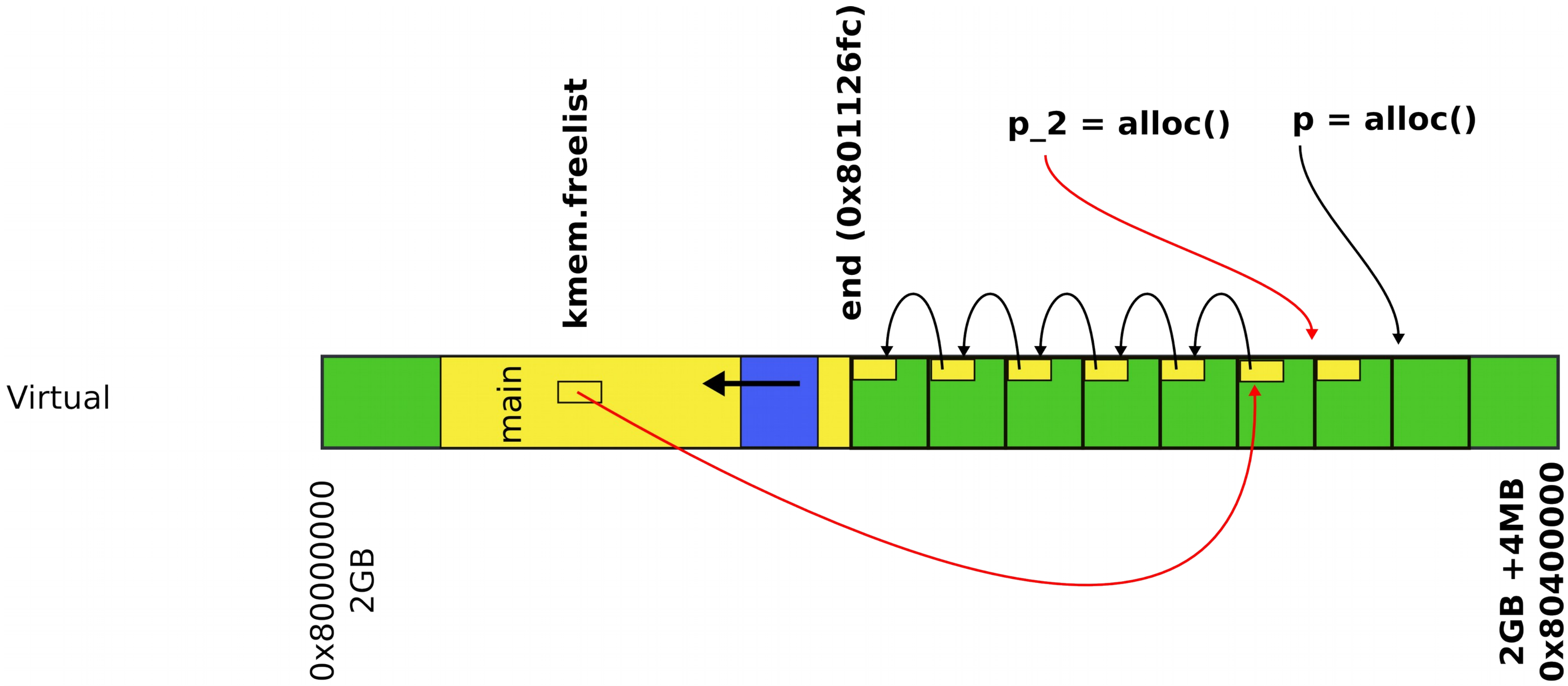


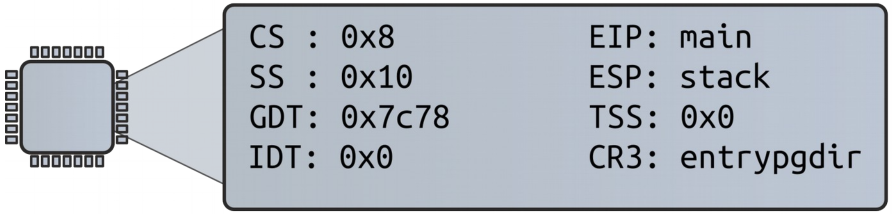
```
CS : 0x8          EIP: main
SS : 0x10         ESP: stack
GDT: 0x7c78       TSS: 0x0
IDT: 0x0          CR3: entrypgdir
```

Protected Mode

```
struct run {
  struct run *next;
};
```

Page allocator



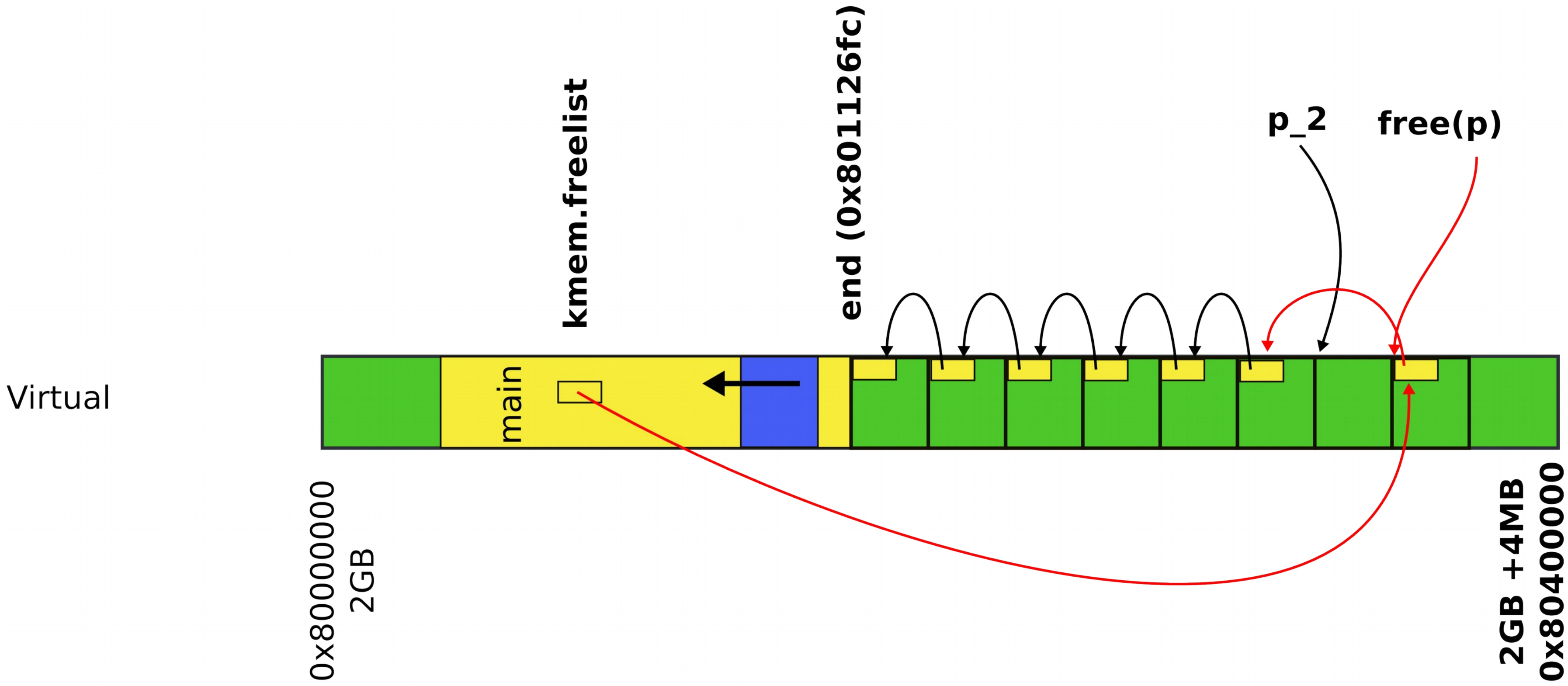


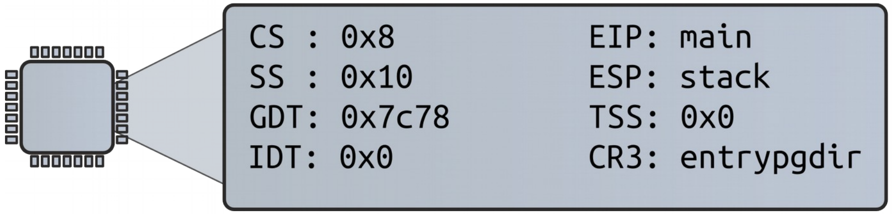
```
CS : 0x8           EIP: main
SS : 0x10          ESP: stack
GDT: 0x7c78        TSS: 0x0
IDT: 0x0           CR3: entrypgdir
```

Protected Mode

```
struct run {
  struct run *next;
};
```

Page allocator





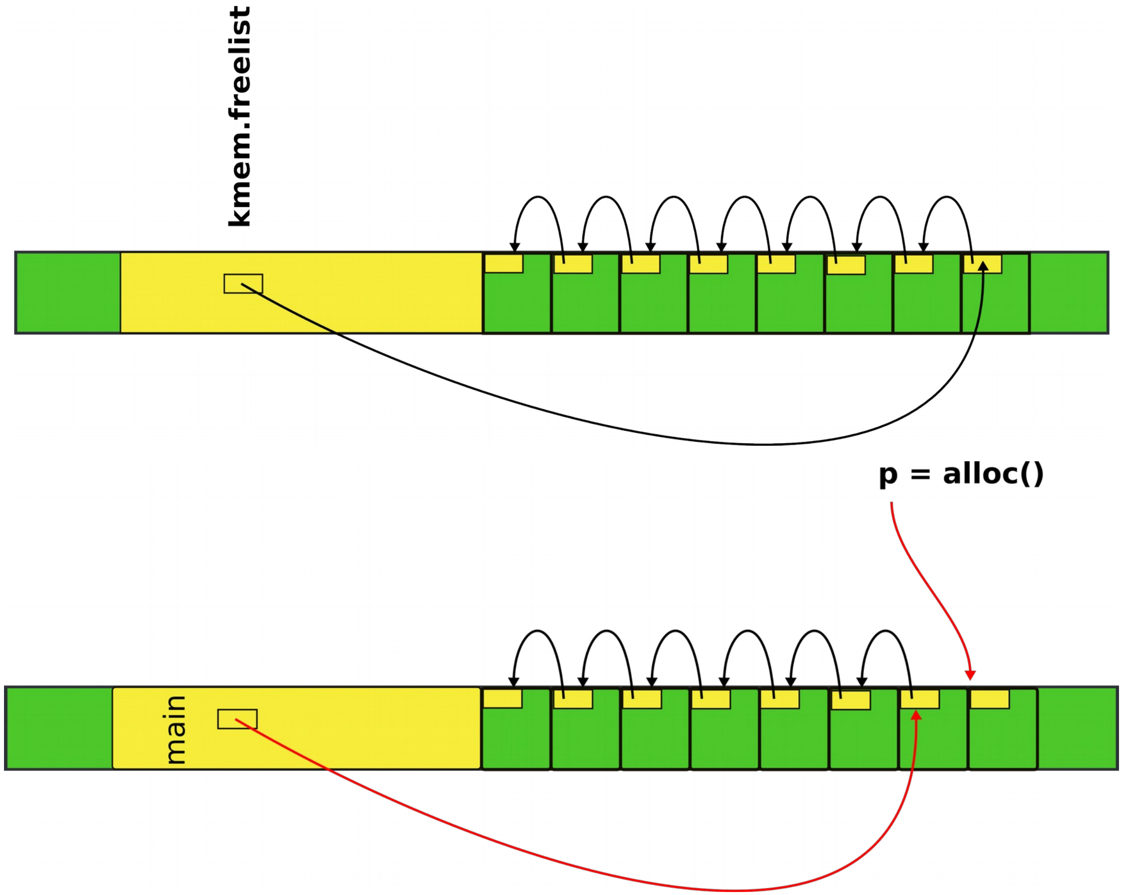
```
CS : 0x8          EIP: main
SS : 0x10         ESP: stack
GDT: 0x7c78       TSS: 0x0
IDT: 0x0          CR3: entrypgdir
```

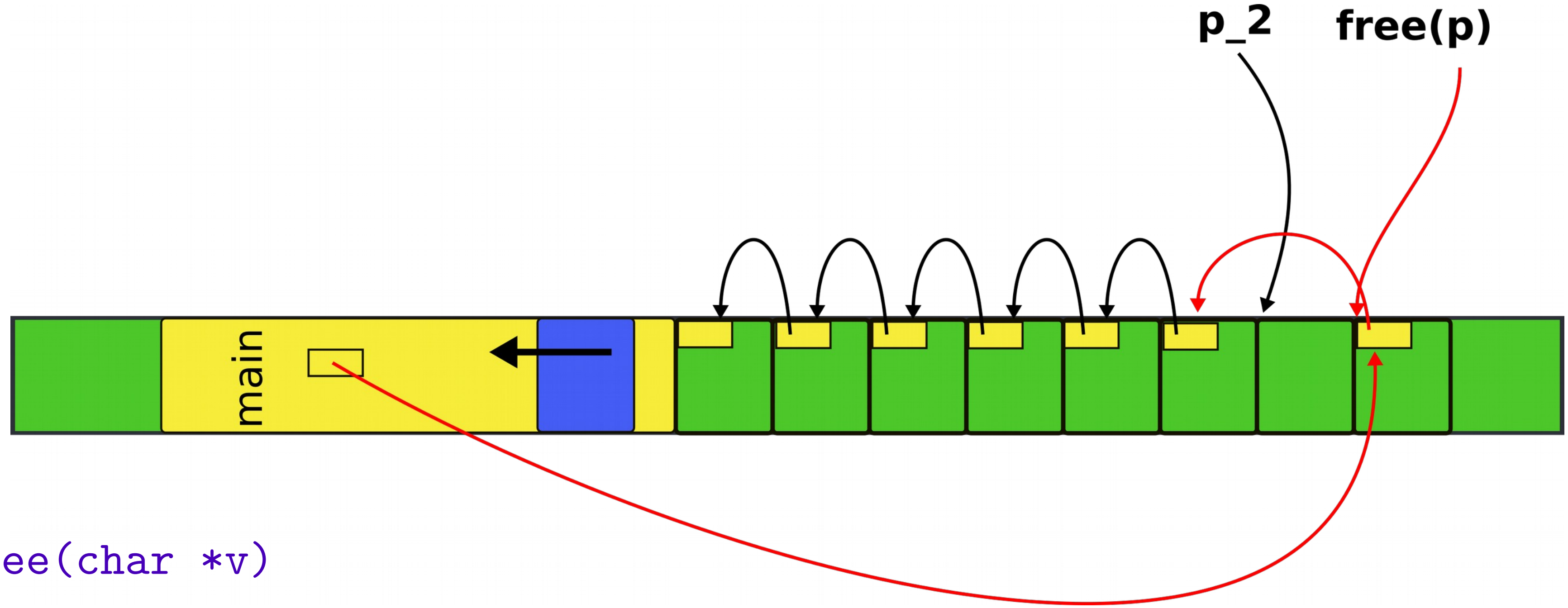
Protected Mode

```
struct run {
  struct run *next;
};
```

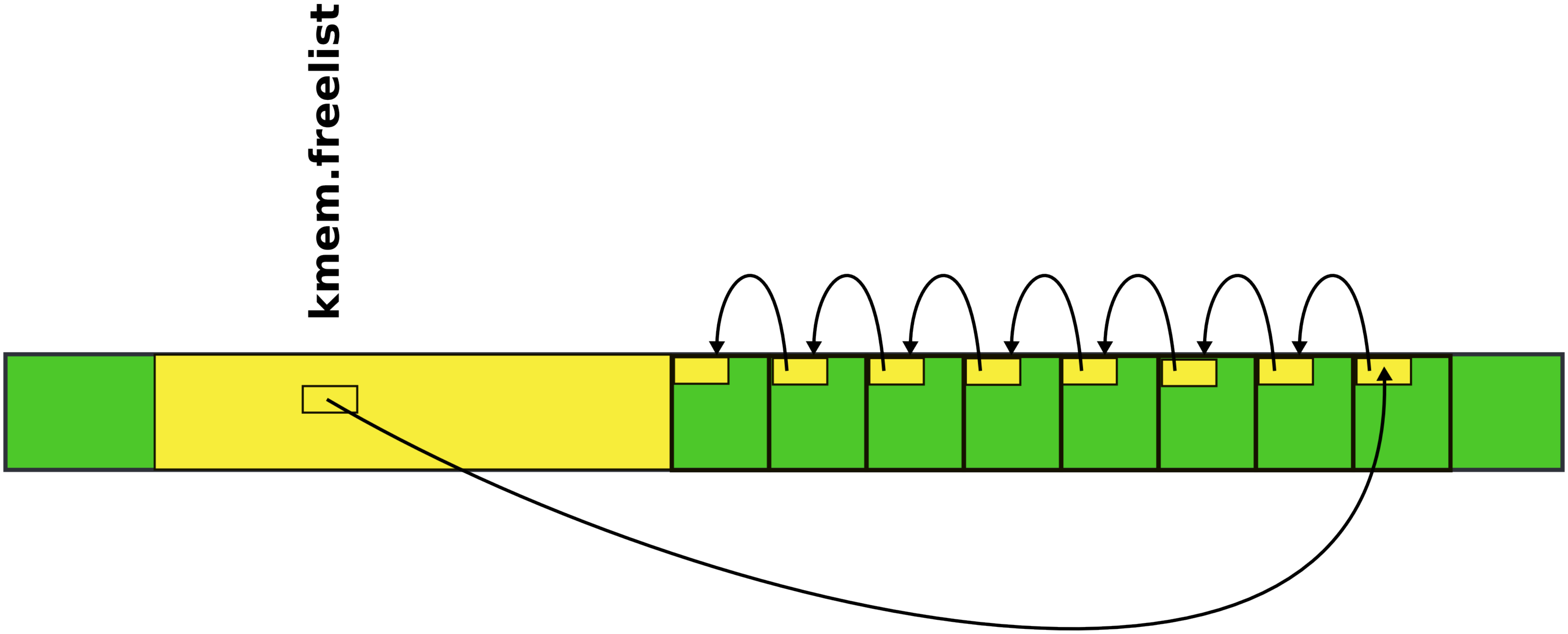
kalloc() - kernel allocator

```
3087 char*
3088 kalloc(void)
3089 {
3080   struct run *r;
...
3094   r = kmem.freelist;
3095   if(r)
3096     kmem.freelist = r->next;
…
3099   return (char*)r;
3099 }
```



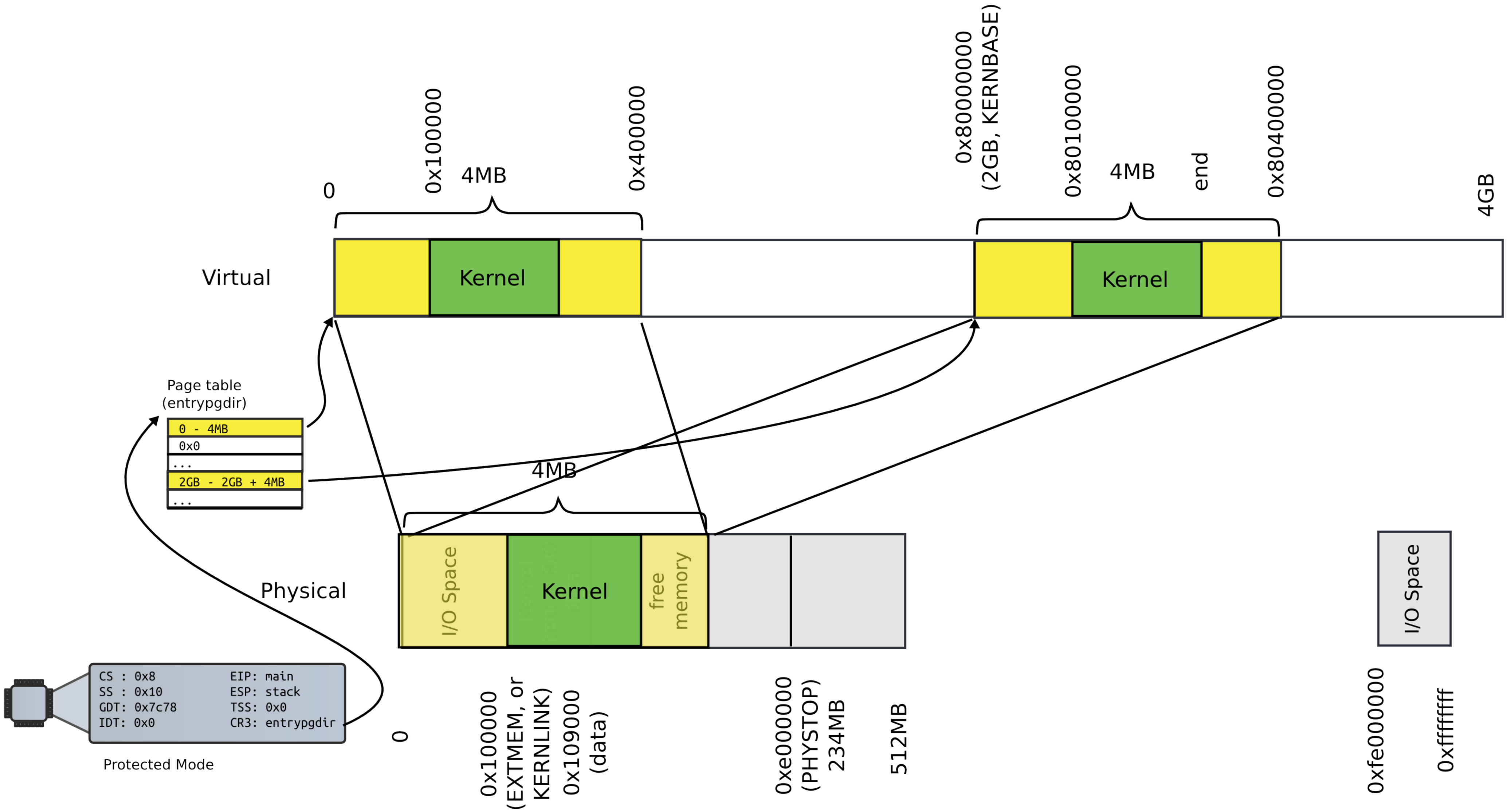


```
kfree(char *v)
{
  struct run *r;
...
  r = (struct run*)v;
  r->next = kmem.freelist;
  kmem.freelist = r;
...
}
```



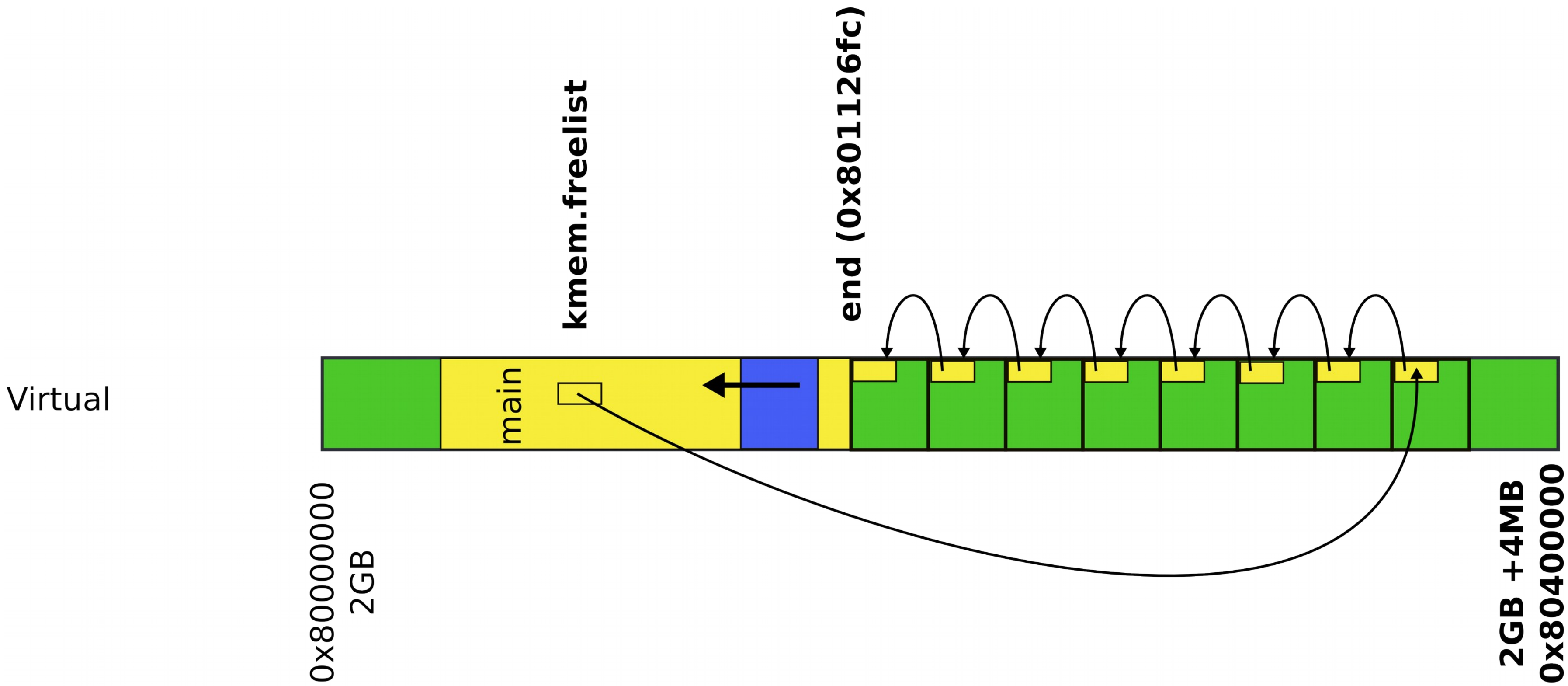
- Where can we get memory to keep the list itself?
  - Notice, the list is allocated within the pages
  - It has to write each page though to update the “next” pointer

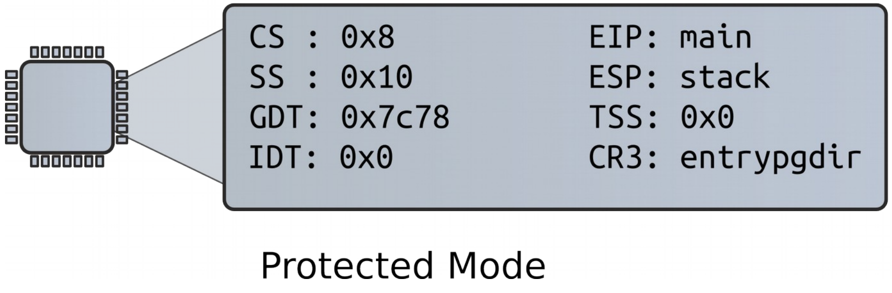
There is a bit of free memory in the 4MB page we've mapped



```
CS : 0x8          EIP: main
SS : 0x10         ESP: stack
GDT: 0x7c78       TSS: 0x0
IDT: 0x0          CR3: entrypgdir
```

Donate this free memory to the allocator





CS : 0x8
SS : 0x10
GDT: 0x7c78
IDT: 0x0
EIP: main
ESP: stack
TSS: 0x0
CR3: entrypgdir

- Take memory from the end of the kernel binary
- To the end of the 4MB page

kinit1(): donate free memory

```
int
main(void)
{
    kinit1(end, P2V(4*1024*1024)); // phys page allocator
    kvmalloc(); // kernel page table
    mpinit(); // detect other processors
    lapicinit(); // interrupt controller
    seginit(); // segment descriptors
    cprintf("\ncpu%d: starting xv6\n\n", cpunum());
    picinit(); // another interrupt controller
    ioapicinit(); // another interrupt controller
    consoleinit(); // console hardware
    uartinit(); // serial port
…
}
```

Freerange()

```
kinit1(void *vstart, void *vend)
{
...
  freerange(vstart, vend);
}
```

- Free range of memory from `vstart` to `vend` giving it to the allocator
- i.e., adding pages to the list

freerange()

```
freerange(void *vstart, void *vend)
{
  char *p;
  p = (char*)PGROUNDUP((uint)vstart);
  for(; p + PGSIZE <= (char*)vend; p += PGSIZE)
    kfree(p);
}
```

- `freerange()` internally simply frees the pages from `vstart` to `vend`
- `kfree()` adds them to the allocator list

Where do we start?

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

- What is this **end**?

```
extern char end[];
```

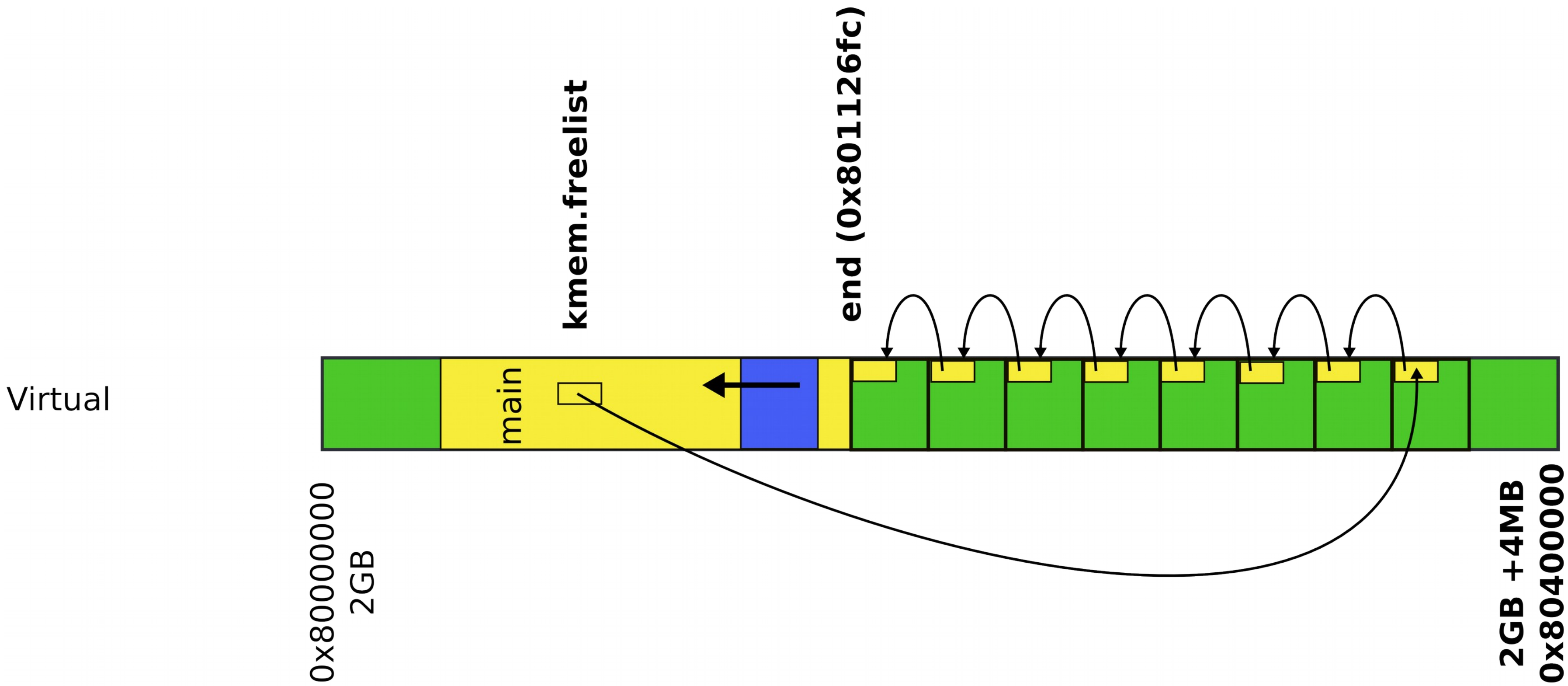
Where do we start?

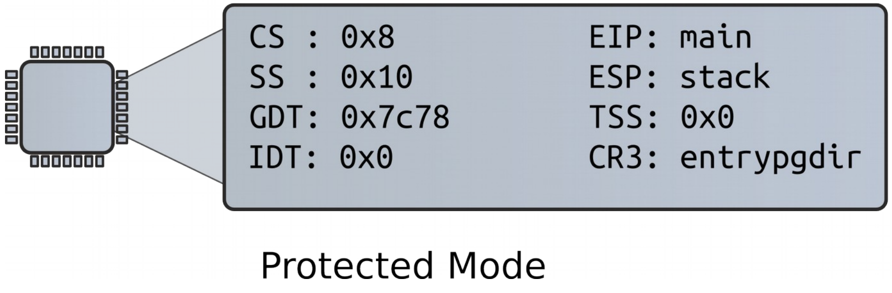
```
int
main(void)
{
    kinit1(end, P2V(4*1024*1024)); // phys page allocator
    kvmalloc(); // kernel page table
    mpinit(); // detect other processors
```

- What is this **end**?

```
extern char end[]; // first address after
                         kernel loaded from ELF file
```

Donate this free memory to the allocator





```
CS : 0x8          EIP: main
SS : 0x10         ESP: stack
GDT: 0x7c78       TSS: 0x0
IDT: 0x0          CR3: entrypgdir
```

Recap

- Kernel has a memory allocator
  - It allocates memory in chunks of 4KB
  - Good enough to maintain kernel data structures

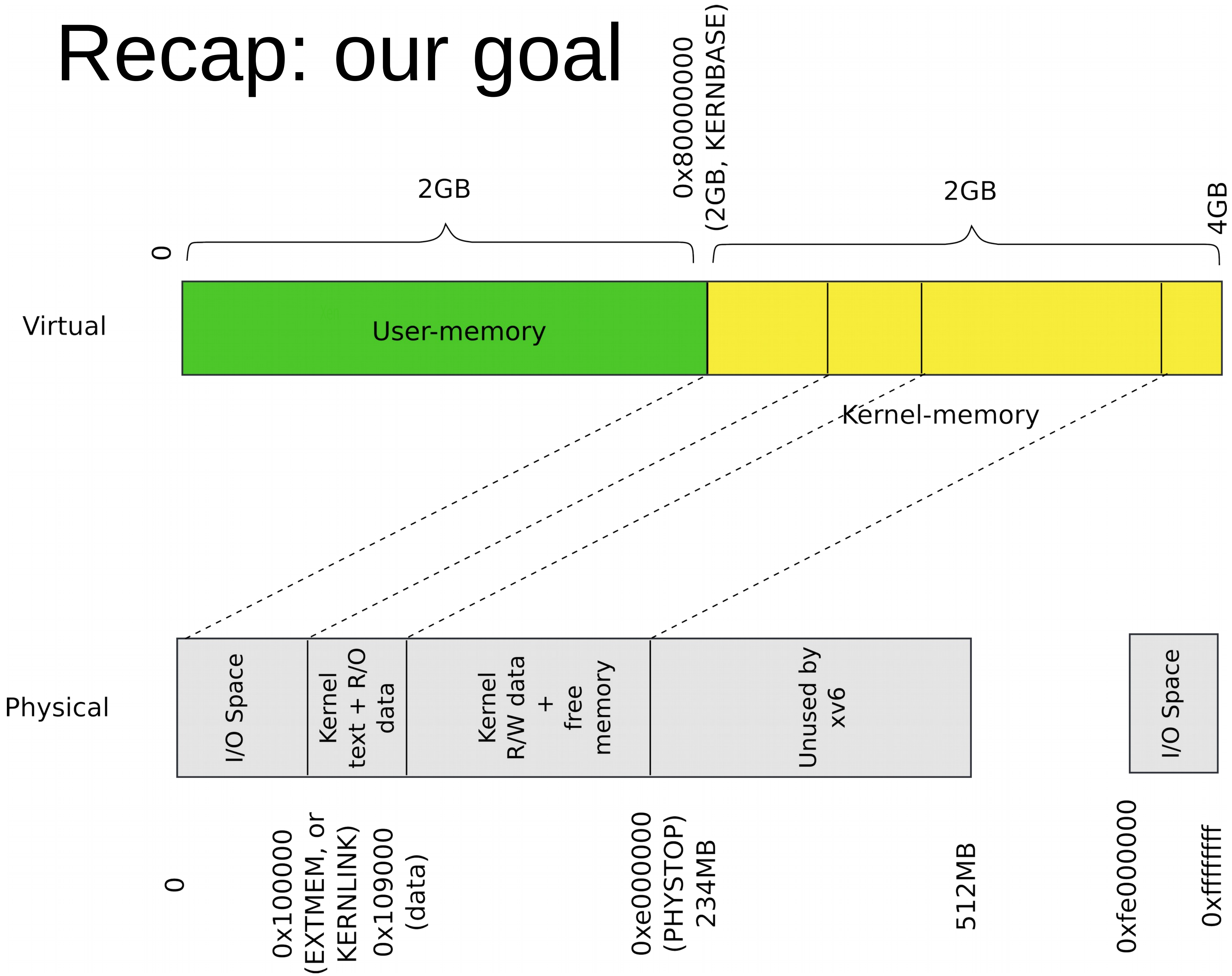
Kernel page table
(4KB page tables)

Back to main(): Kernel address space

```
int
main(void)
{
    kinit1(end, P2V(4*1024*1024)); // phys page allocator
    kvmalloc(); // kernel page table
    mpinit(); // detect other processors
    lapicinit(); // interrupt controller
    seginit(); // segment descriptors
    cprintf("\ncpu%d: starting xv6\n\n", cpunum());
    picinit(); // another interrupt controller
    ioapicinit(); // another interrupt controller
    consoleinit(); // console hardware
    uartinit(); // serial port
…
}
```

- What do you think has to happen?
  - i.e., how to construct a kernel address space?

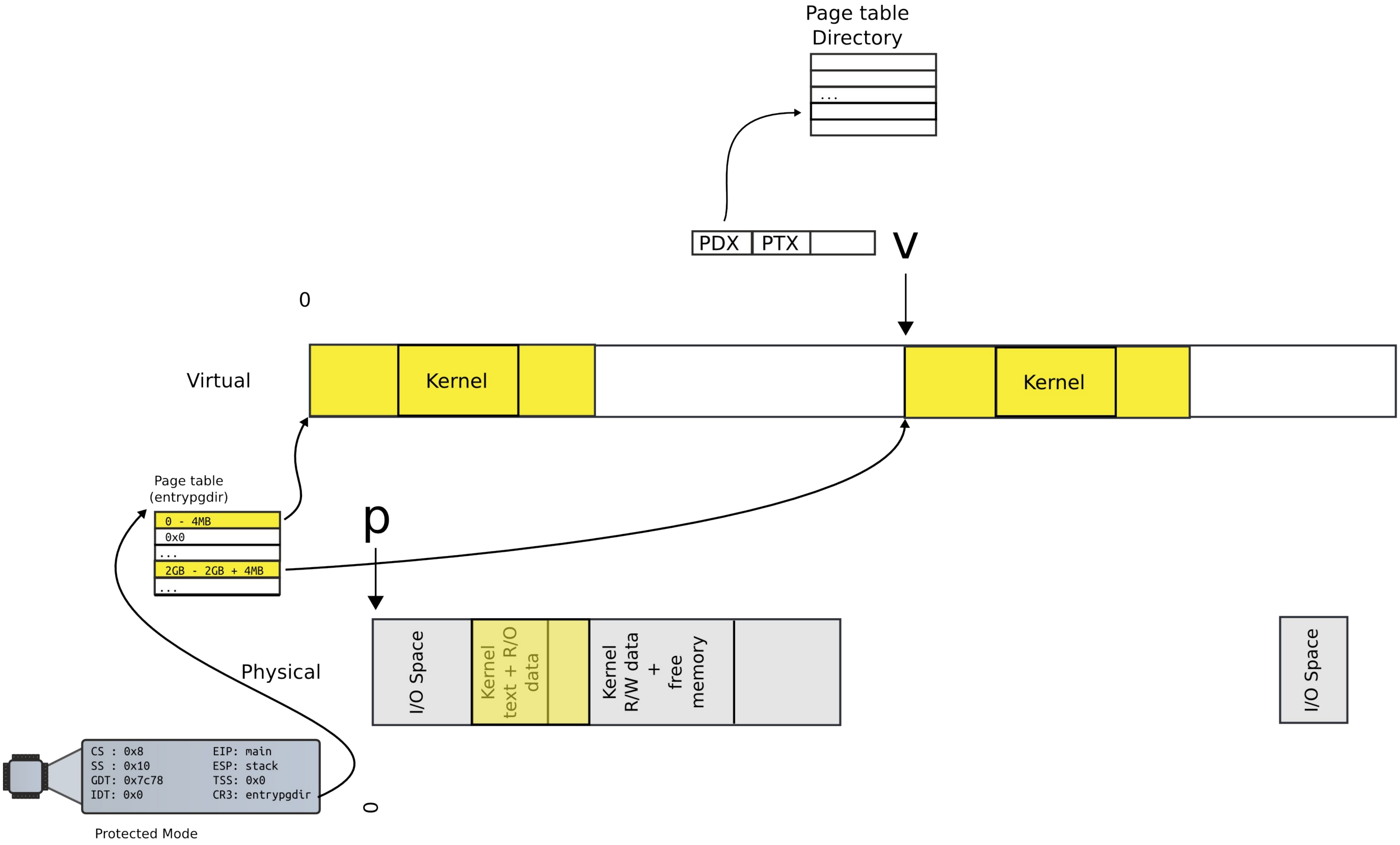
Recap: our goal



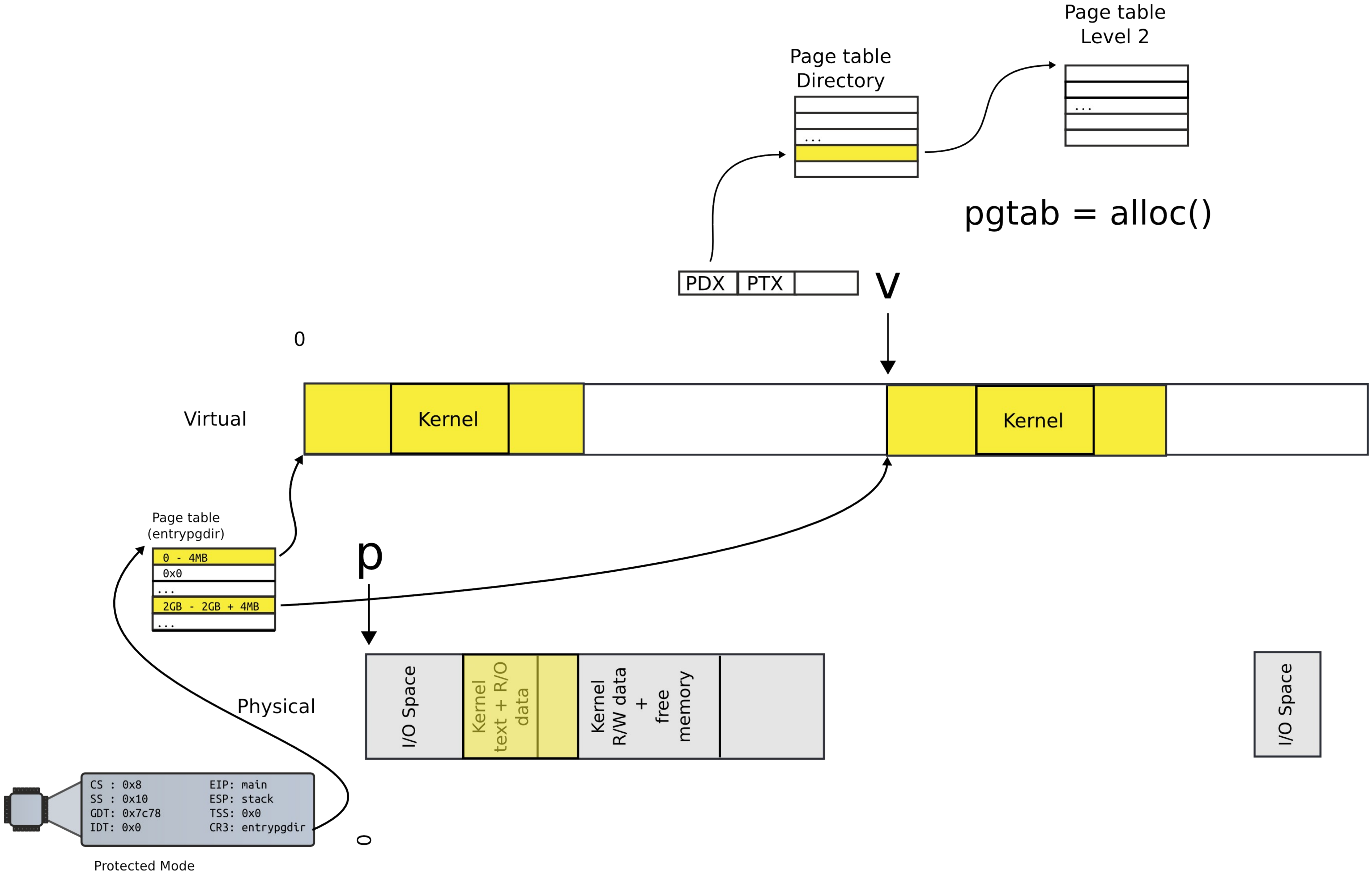
Outline

- Map a region of virtual memory into page tables
  - Start from 2GBs
  - Iterate memory page by page
  - Allocate page table directory and page tables as we go
  - Fill in page table entries with proper physical addresses
- We've created the kernel memory allocator
  - Can allocate space for page table directory and page tables

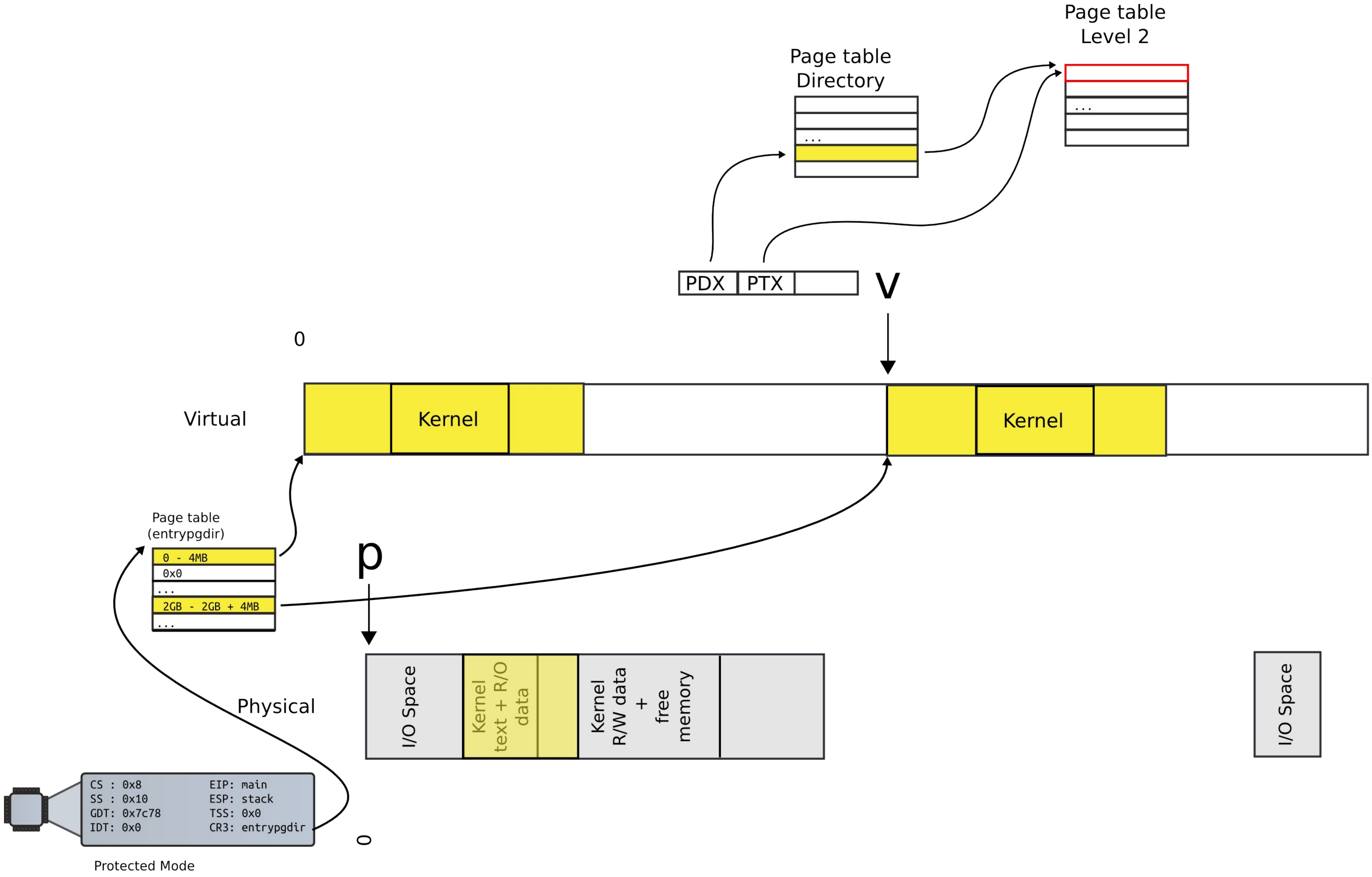
Allocate page table directory entry



Allocate next level page table



Locate PTE entry



Page table
Level 2

...

Page table
Directory

...

PDX PTX

V

0

Virtual

Kernel

Kernel

Page table
(entrypgdir)

0 - 4MB
0x0
...
2GB - 2GB + 4MB
...

p

I/O Space

Kernel
text + R/O
data

Kernel
R/W data
+
free
memory

I/O Space

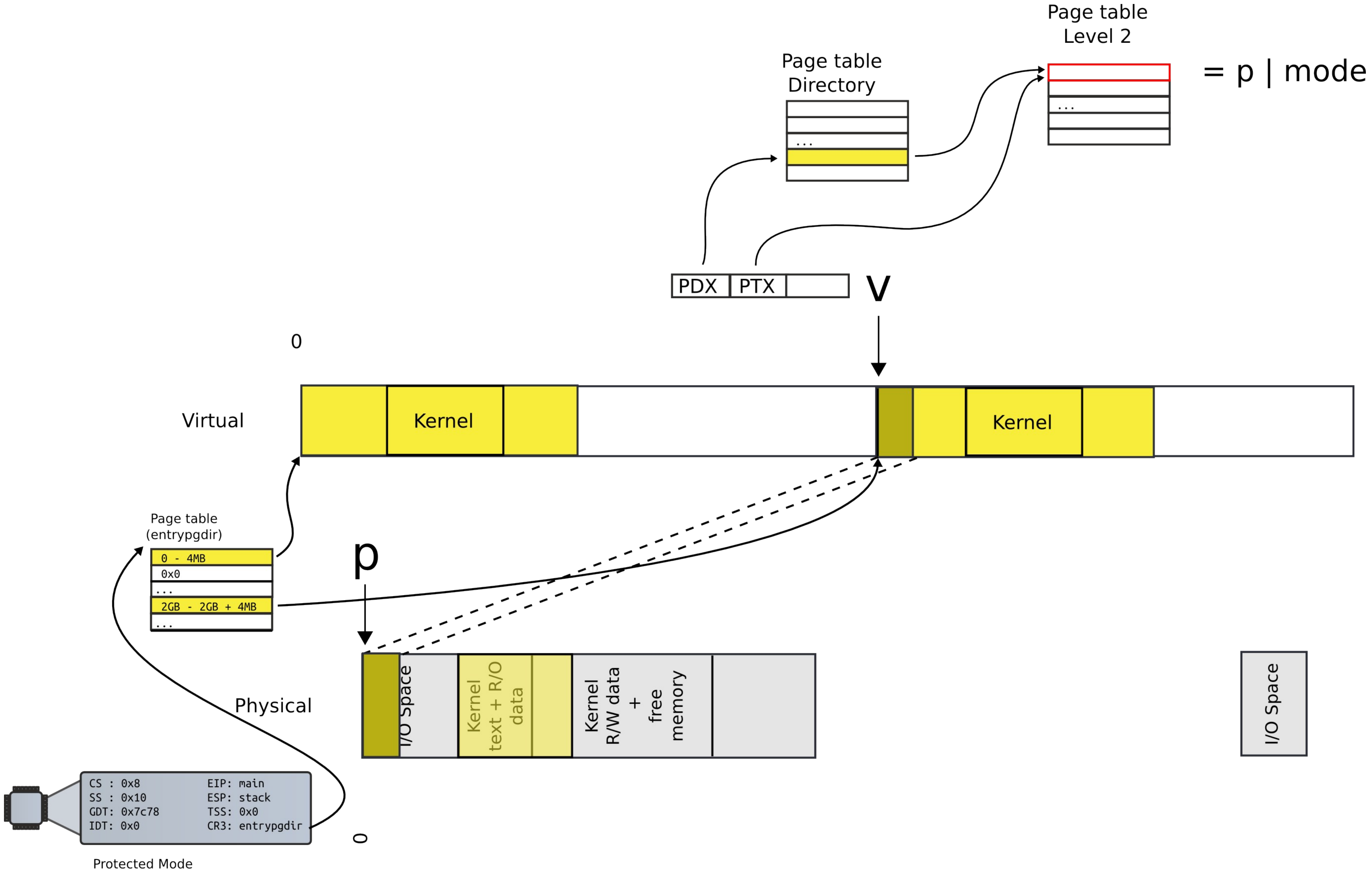
Physical

```
CS : 0x8          EIP: main
SS : 0x10         ESP: stack
GDT: 0x7c78       TSS: 0x0
IDT: 0x0          CR3: entrypgdir
```

0

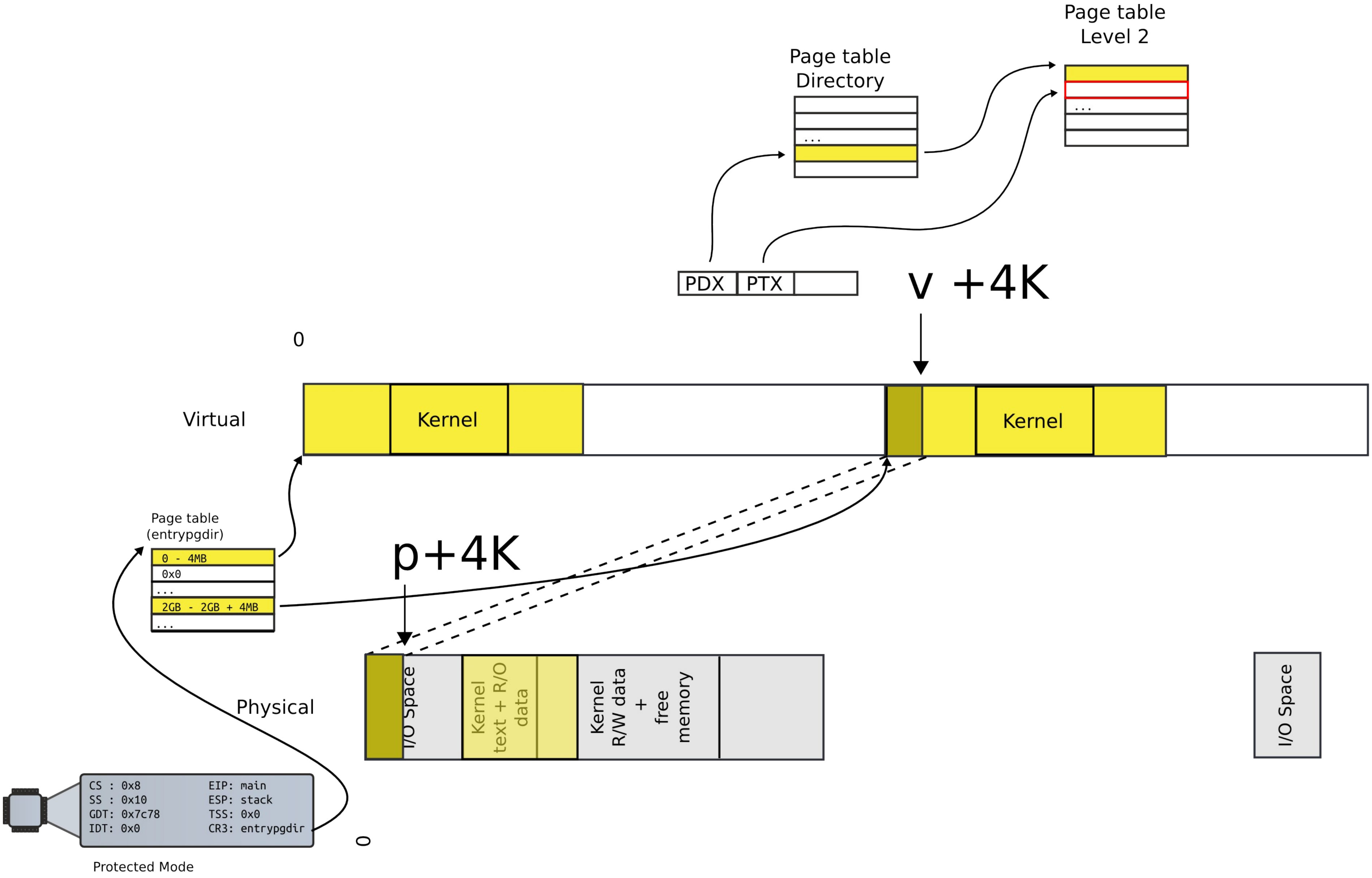
Protected Mode

Update mapping with physical addr



```
CS : 0x8          EIP: main
SS : 0x10         ESP: stack
GDT: 0x7c78       TSS: 0x0
IDT: 0x0          CR3: entrypgdir
```

Move to next page



This is exactly what kernel is doing

Allocate page tables

```
int
main(void)
{
    kinit1(end, P2V(4*1024*1024)); // phys page allocator
    kvmalloc(); // kernel page table
    mpinit(); // detect other processors
    lapicinit(); // interrupt controller
    seginit(); // segment descriptors
    cprintf("\ncpu%d: starting xv6\n\n", cpunum());
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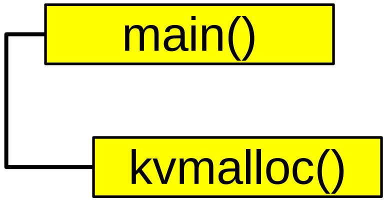
…
}
```

kvmalloc()

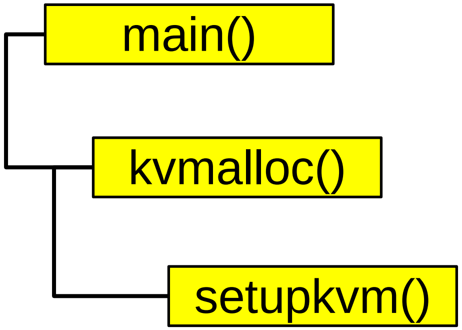


main()

kvmalloc()

```
kvmalloc(void)
{
  kpgdir = setupkvm();
  switchkvm();
}
```

Allocate page table directory



main()

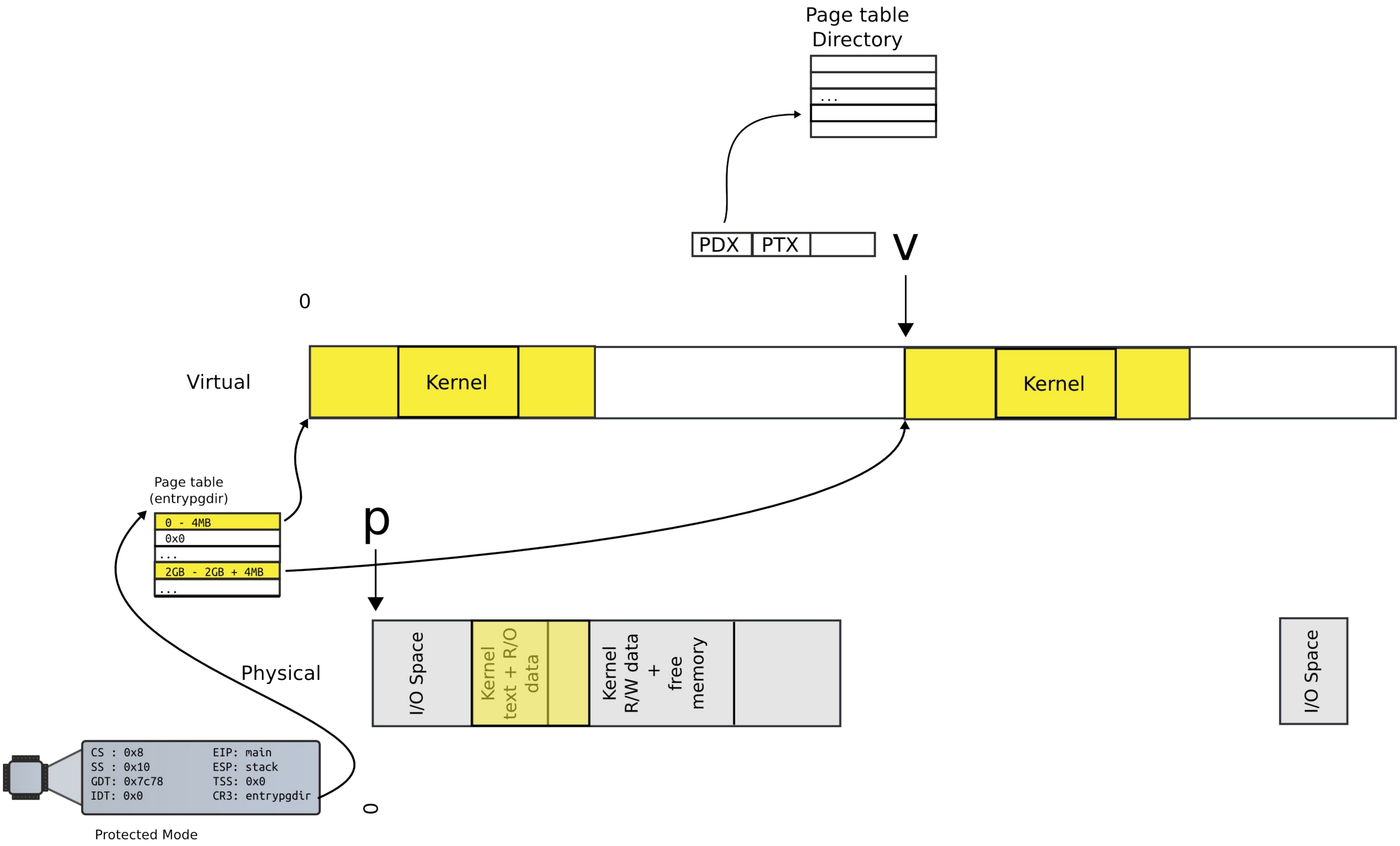
kvmalloc()

setupkvm()

```
pde_t*
setupkvm(void)
{
  pde_t *pgdir;
  struct kmap *k;

  if((pgdir = (pde_t*)kalloc()) == 0)
    return 0;
  memset(pgdir, 0, PGSIZE);
...
  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)
       return 0;
  return pgdir;
}
```

Allocate page table directory



Iterate in a loop: map physical pages

```
pde_t*
setupkvm(void)
{
  pde_t *pgdir;
  struct kmap *k;

  if((pgdir = (pde_t*)kalloc()) == 0)
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  memset(pgdir, 0, PGSIZE);
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  for(k = kmap; k < &kmap[NELEM(kmap)]; k++)
    if(mappages(pgdir, k->virt, k->phys_end - k->phys_start,
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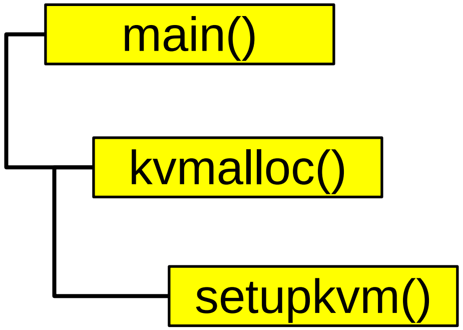

main()

kvmalloc()

setupkvm()

Iterate in a loop: map physical pages

```
pde_t*
setupkvm(void)
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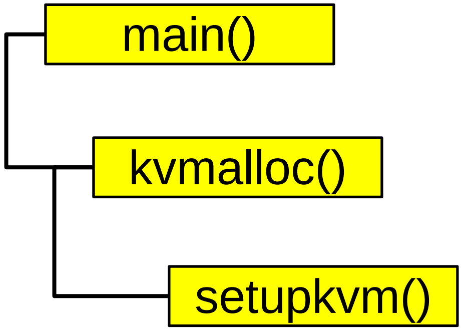
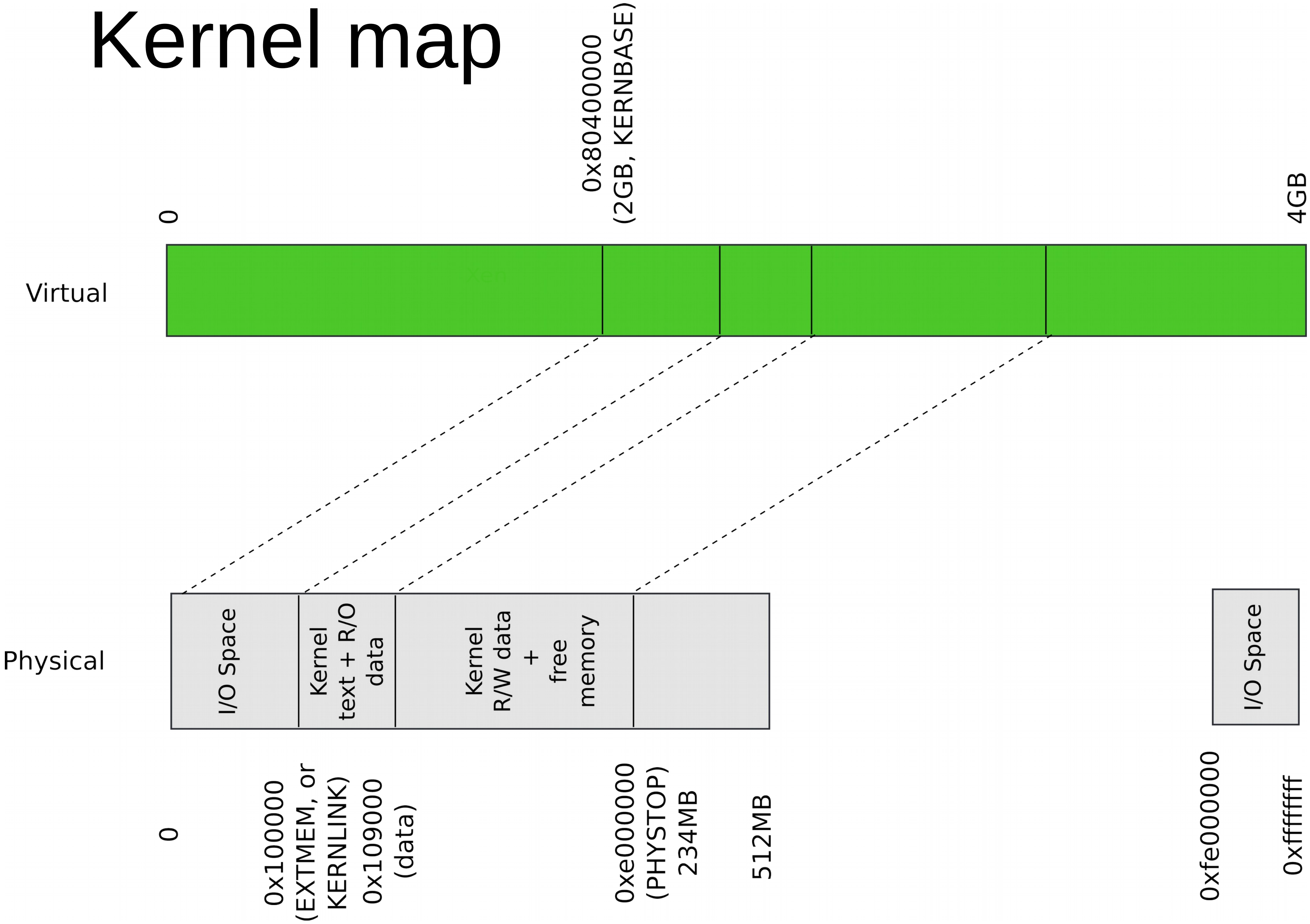
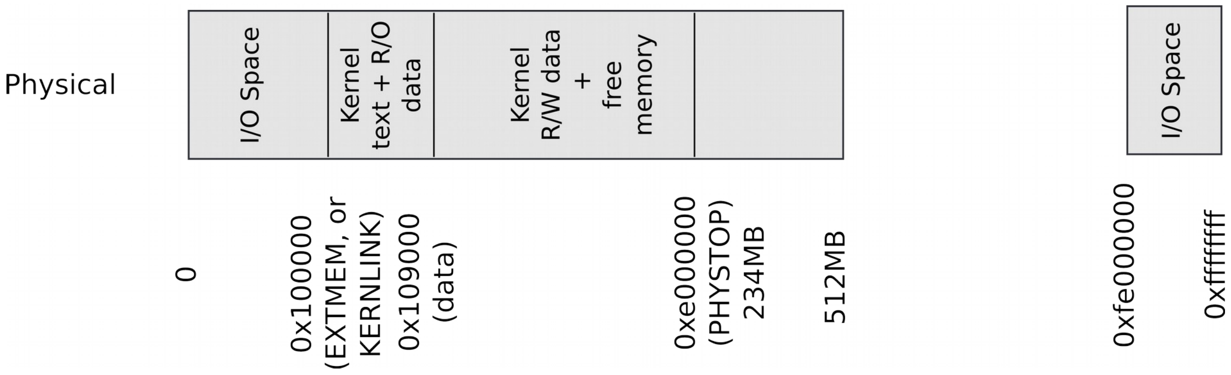
    if(mappages(pgdir, k->virt, k->phys_end - k->phys_start,
               (uint)k->phys_start, k->perm) < 0)
       return 0;
  return pgdir;
}
```



Kernel map


0x80400000
(2GB, KERNBASE)
0
4GB
Virtual
Physical
I/O Space
Kernel
text + R/O
data
Kernel
R/W data
+
free
memory
I/O Space
0
0x100000
(EXTMEM, or
KERNLINK)
0x109000
(data)
0xe000000
(PHYSTOP)
234MB
512MB
0xfe000000
0xffffffff

Kmap – kernel map

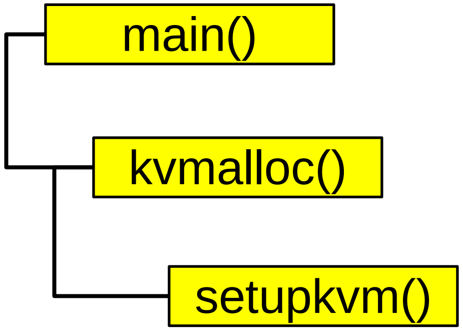


```
static struct kmap {
    void *virt;
    uint phys_start;
    uint phys_end;
    int perm;
} kmap[] = {
    { (void*)KERNBASE, 0, EXTMEM, PTE_W}, // I/O space
    { (void*)KERNLINK, V2P(KERNLINK), V2P(data), 0},//text+rodata
    { (void*)data, V2P(data), PHYSTOP, PTE_W}, // kern data+memory
    {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

Iterate in a loop: map physical pages

```
pde_t*
setupkvm(void)
{
  pde_t *pgdir;
  struct kmap *k;

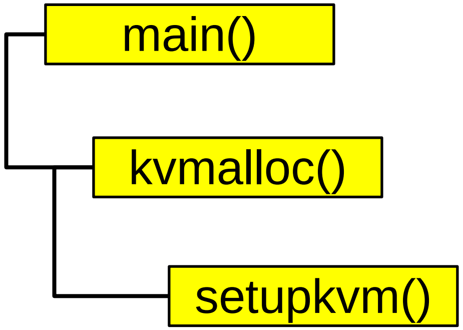
  if((pgdir = (pde_t*)kalloc()) == 0)
    return 0;
  memset(pgdir, 0, PGSIZE);
...
  for(k = kmap; k < &kmap[NELEM(kmap)]; k++)
    if(mappages(pgdir, k->virt, k->phys_end - k->phys_start,
               (uint)k->phys_start, k->perm) < 0)
       return 0;
  return pgdir;
}
```



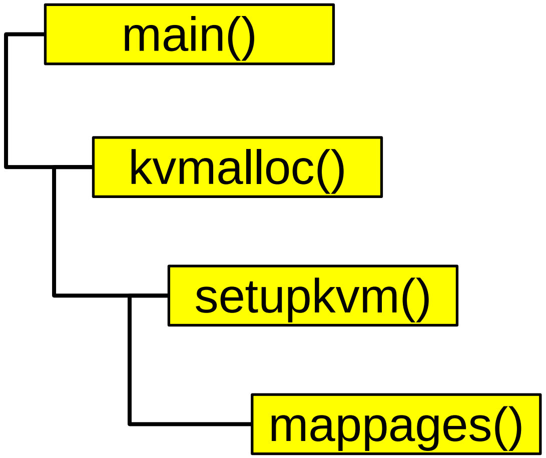
Map a region of memory

```
pde_t*
setupkvm(void)
{
  pde_t *pgdir;
  struct kmap *k;

  if((pgdir = (pde_t*)kalloc()) == 0)
    return 0;
  memset(pgdir, 0, PGSIZE);
...
  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)
       return 0;
  return pgdir;
}
```

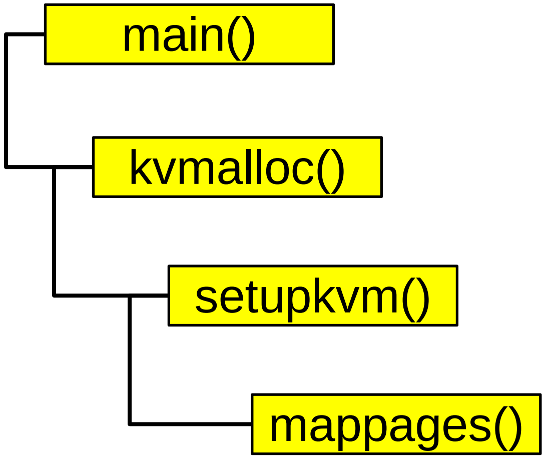


```c
mappages(pde_t *pgdir, void *va, uint size, uint pa, int perm)
{
  char *a, *last;
  pte_t *pte;

  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;
}
```



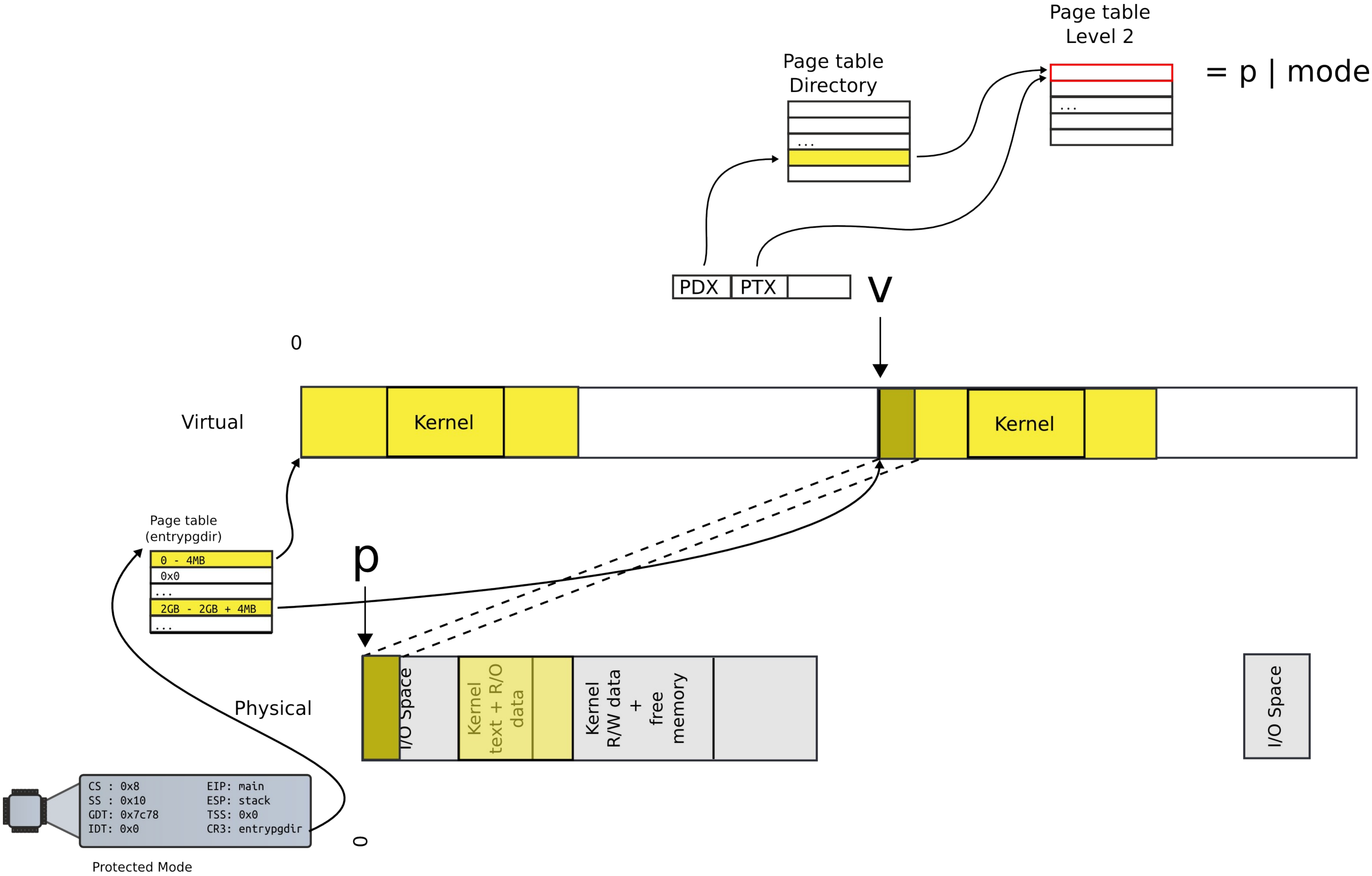
- Get the start (`a`) and end (`last`) pages fo the virtual address range we are mapping
- Then work in a loop mapping every page one by one

```
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;
}
```

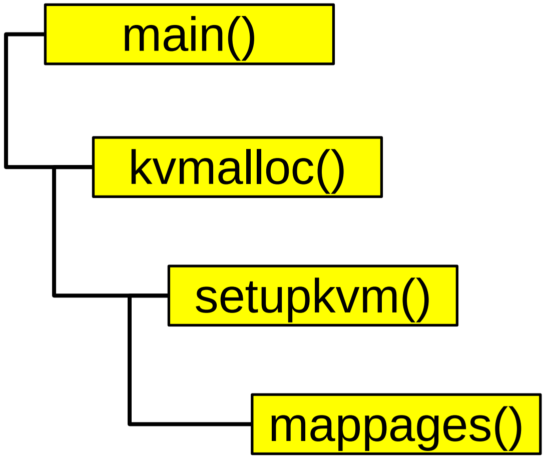


- First lookup the page table directory entry (`pte`) corresponding to the virtual address (`a`) we're mapping

Locate the page table entry



```
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;
}
```



main()

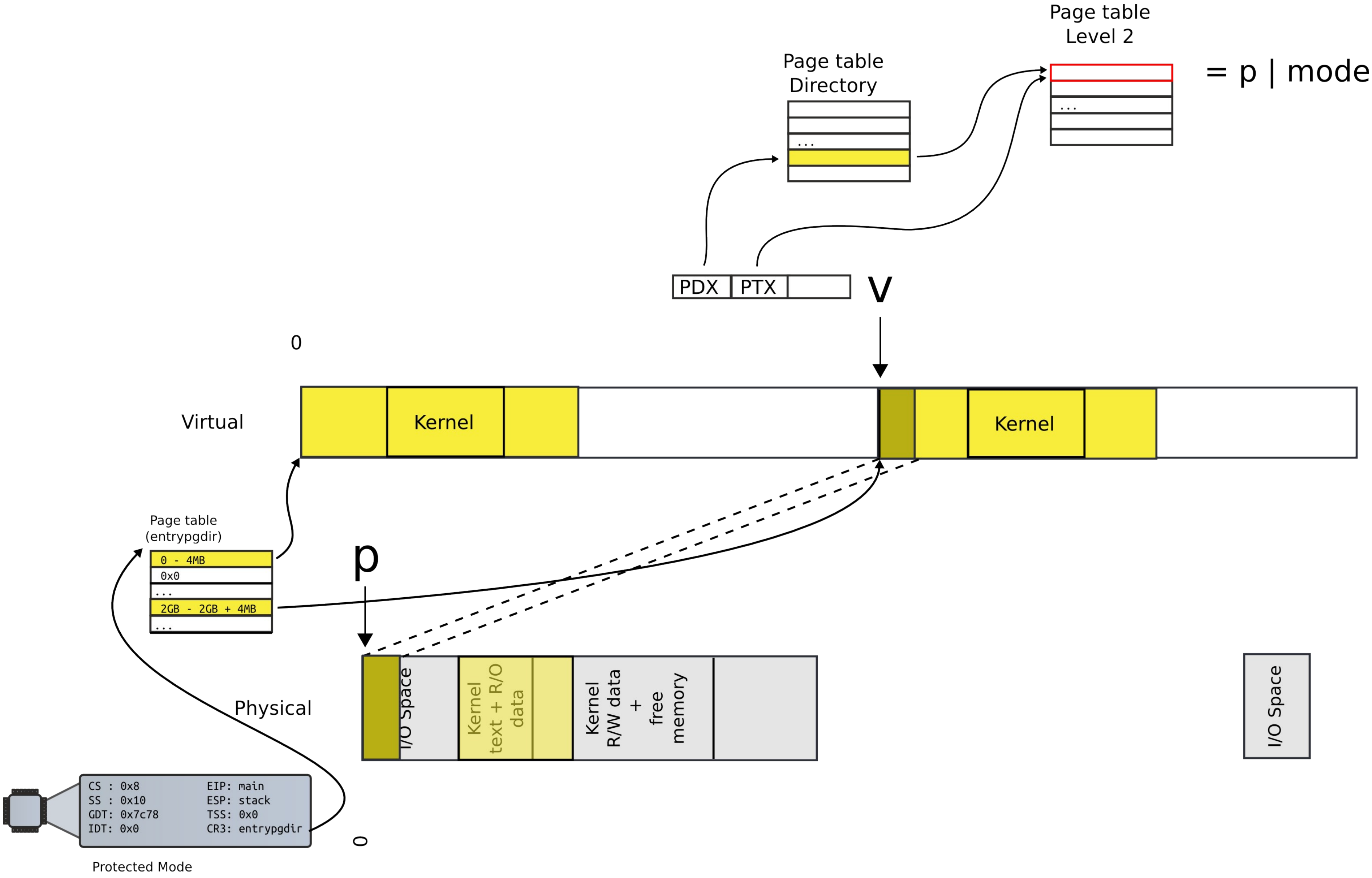
kvmalloc()

setupkvm()

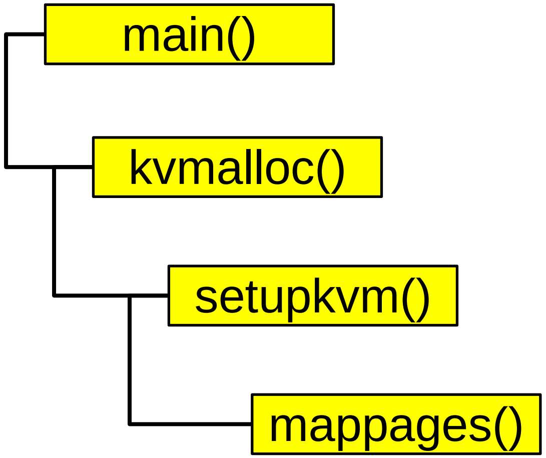
mappages()

- Update the page directory entry (`*pte`) with the physical address (`pa`)

Update mapping with physical addr



```
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;
}
```

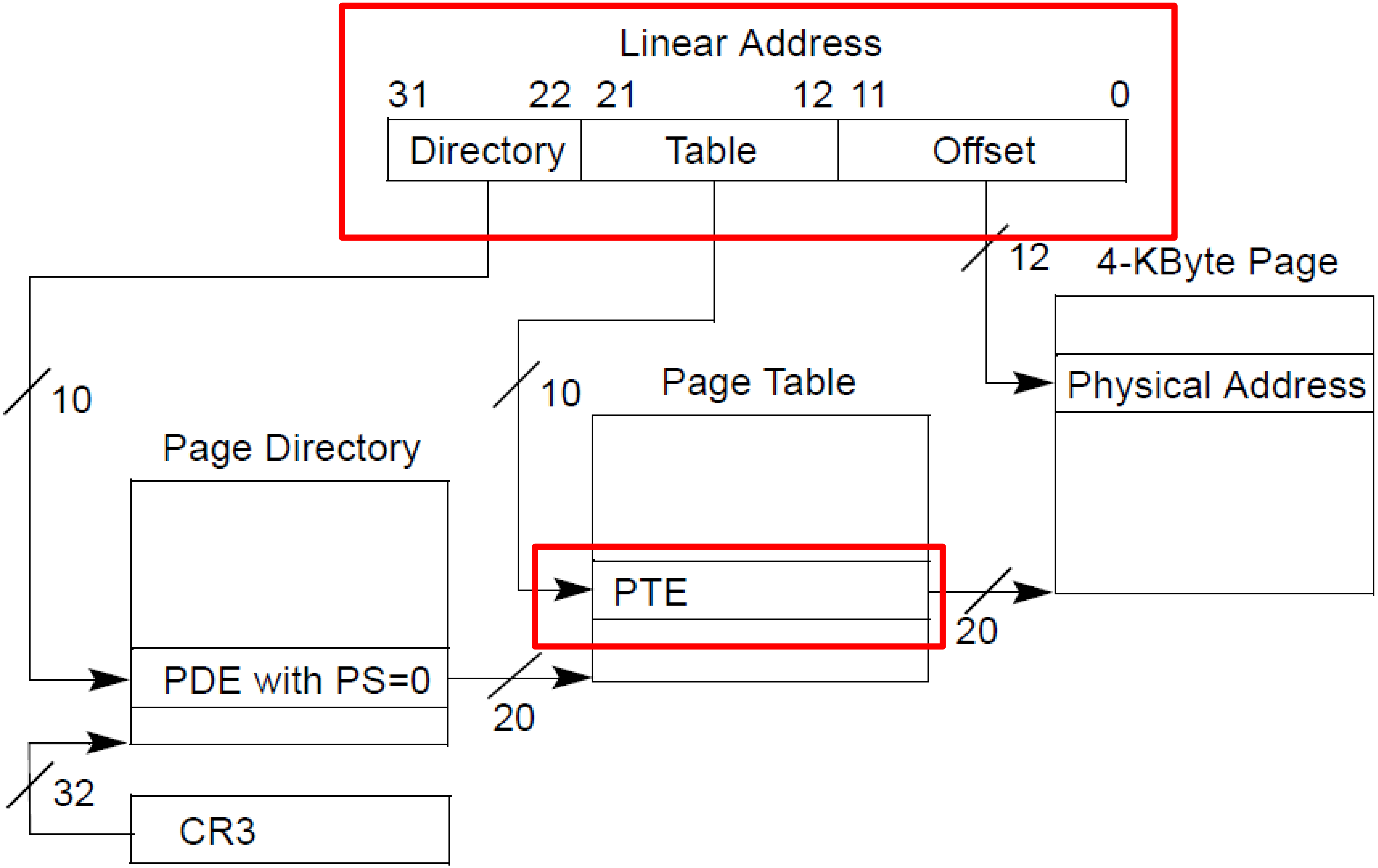


- But we need a function that locates the `pte` for us...

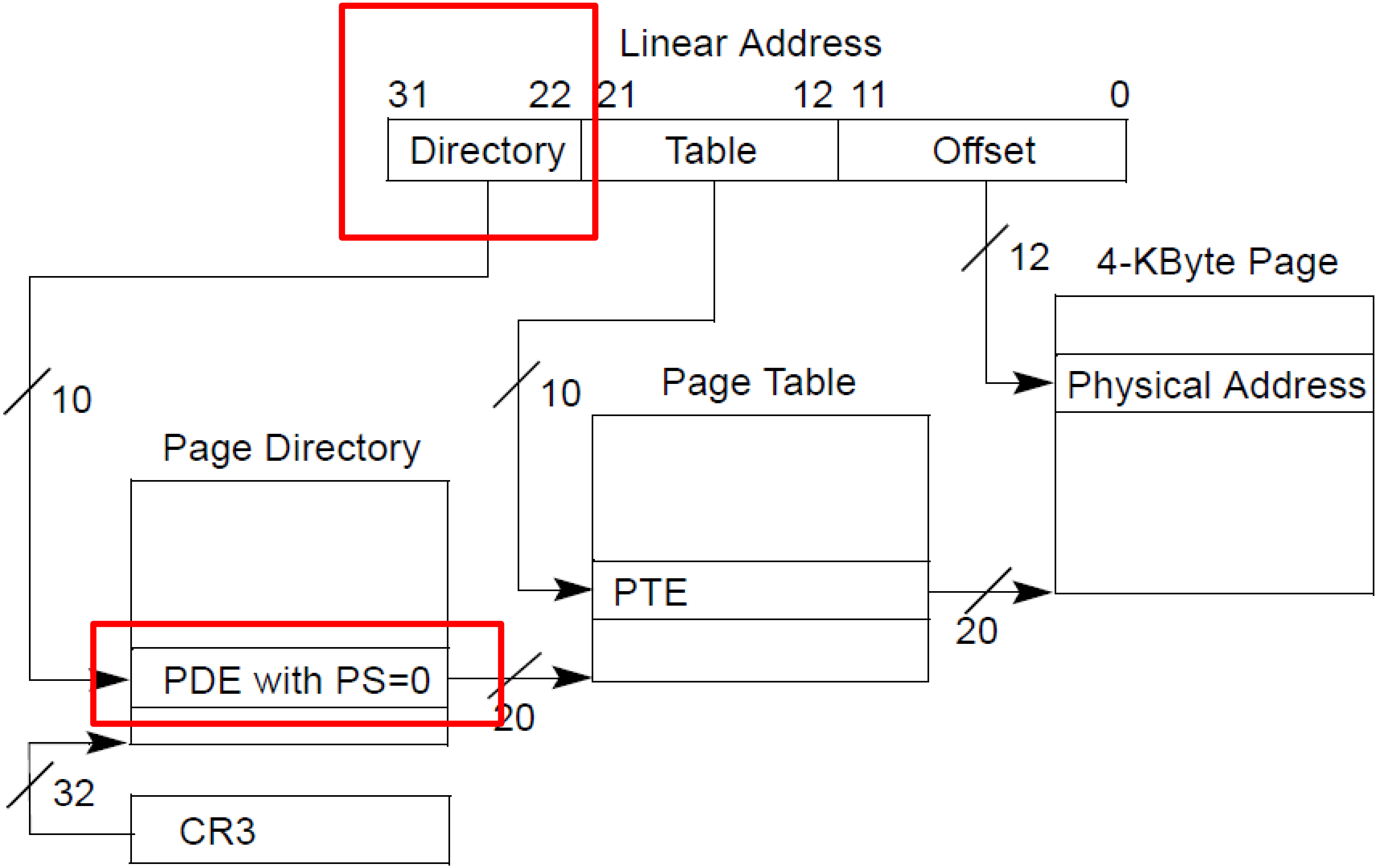
What should it look like?

- A function takes a virtual address
- Returns a page table directory entry that maps it

Recap of the page table

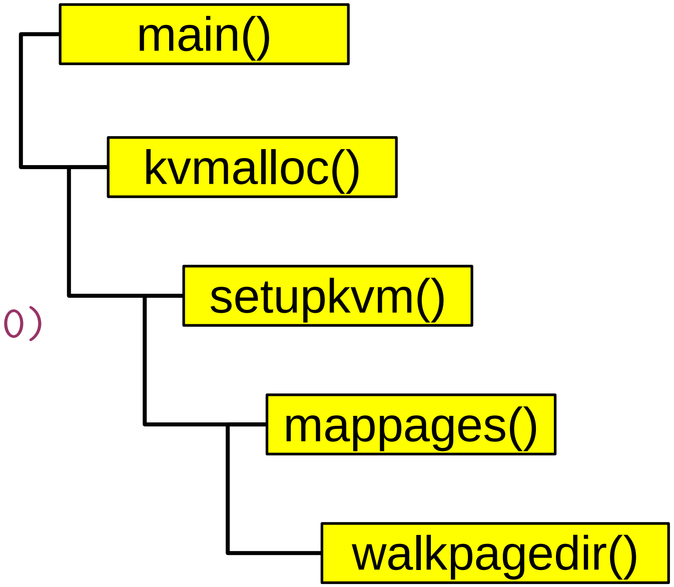


Locate the PDE frist



```
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);
...
        *pde = V2P(pgtab) | PTE_P | PTE_W | PTE_U;
    }
    return &pgtab[PTX(va)];
}
```

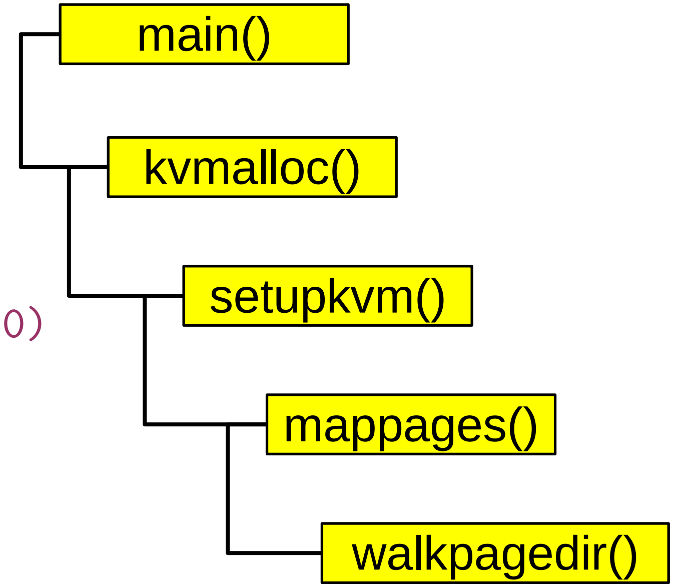
Locate the page table directory entry for this virtual address



- Locate the page directory entry (`*pde`)

```
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);
...
        *pde = V2P(pgtab) | PTE_P | PTE_W | PTE_U;
    }
    return &pgtab[PTX(va)];
}
```

Locate the page table directory entry for this virtual address



- Locate the page directory entry (`*pde`)

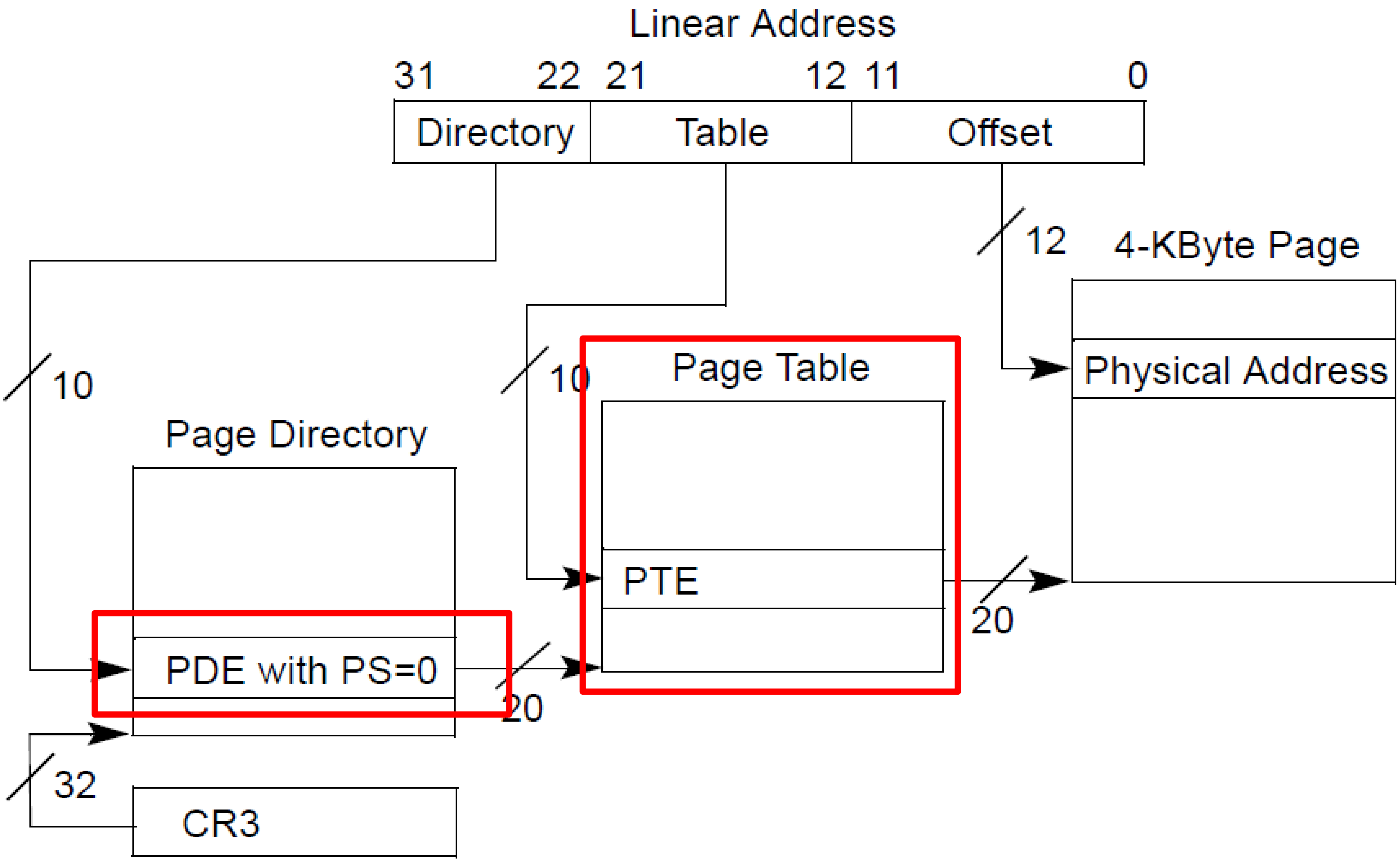
PDX()

```
// +--------10------+-------10-------+---------12----------+
// | Page Directory |   Page Table   | Offset within Page  |
// |      Index     |     Index      |                     |
// +----------------+----------------+---------------------+
// \--- PDX(va) --/ \--- PTX(va) --/

// page directory index
#define PDX(va) (((uint)(va) >> PDXSHIFT) & 0x3FF)

// page table index
#define PTX(va) (((uint)(va) >> PTXSHIFT) & 0x3FF)
…
#define PTXSHIFT 12 // offset of PTX in a linear address
#define PDXSHIFT 22 // offset of PDX in a linear address
```

PDX()

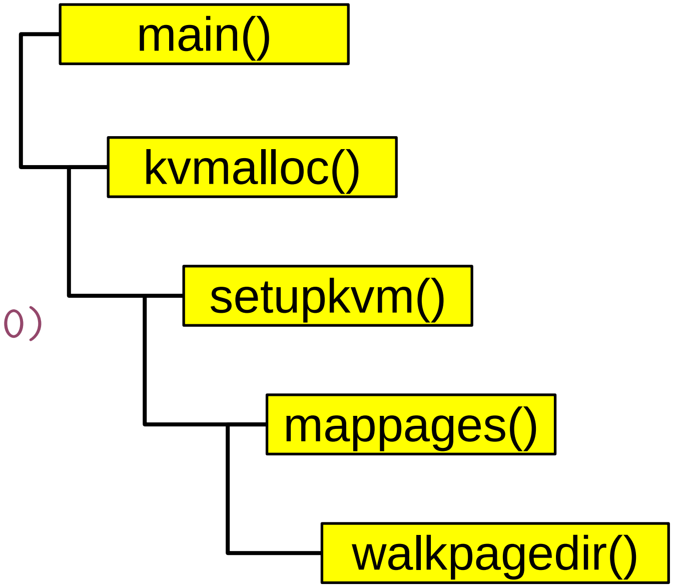
```
// +--------10------+-------10-------+---------12----------+
// | Page Directory |    Page Table   | Offset within Page  |
// |    Index       |     Index      |                     |
// +----------------+----------------+---------------------+
// \--- PDX(va) --/  \--- PTX(va) --/

// page directory index
#define PDX(va) (((uint)(va) >> PDXSHIFT) & 0x3FF)

// page table index
#define PTX(va) (((uint)(va) >> PTXSHIFT) & 0x3FF)
…
#define PTXSHIFT 12 // offset of PTX in a linear address
#define PDXSHIFT 22 // offset of PDX in a linear address
```

Check if level 2 page table is allocated



```
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);
...
        *pde = V2P(pgtab) | PTE_P | PTE_W | PTE_U;
    }
    return &pgtab[PTX(va)];
}
```

Check if the level 2 page is allocated already


main()

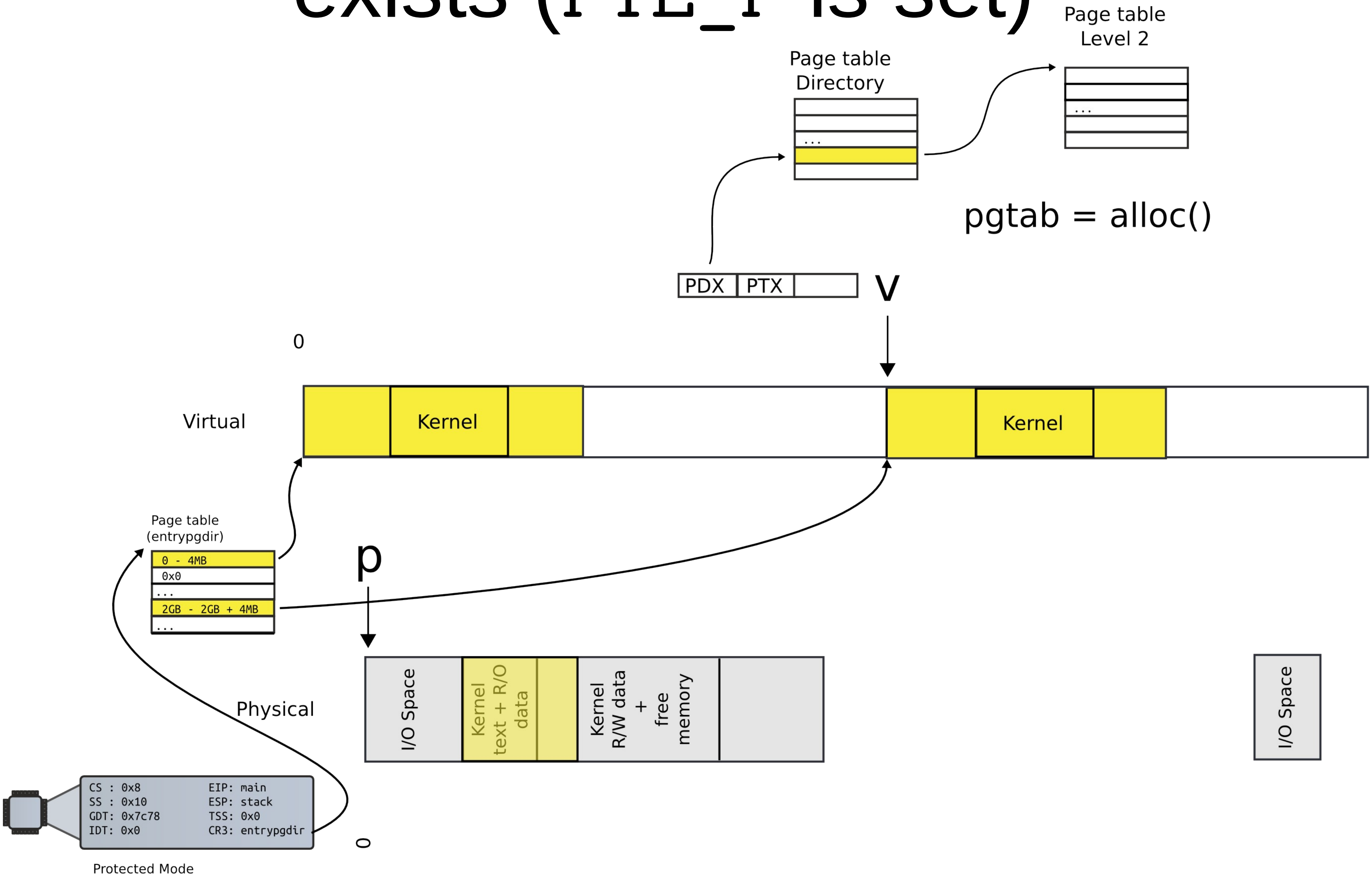
kvmalloc()

setupkvm()

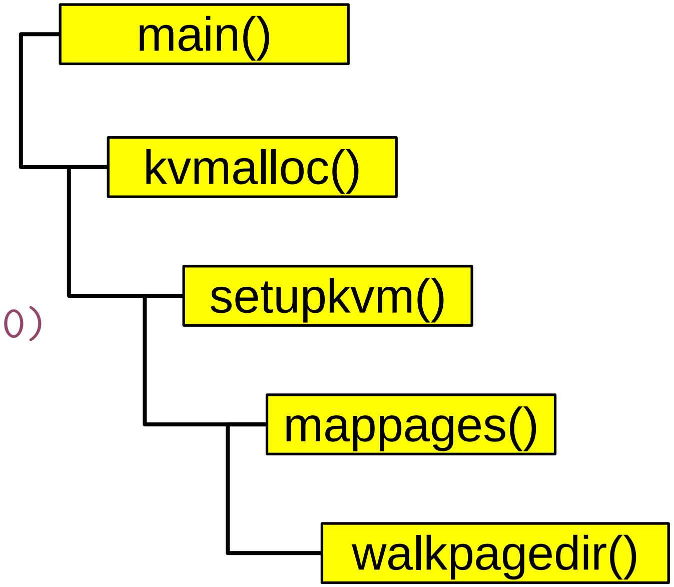
mappages()

walkpagedir()

See if the next page table level exists (`PTE_P` is set)

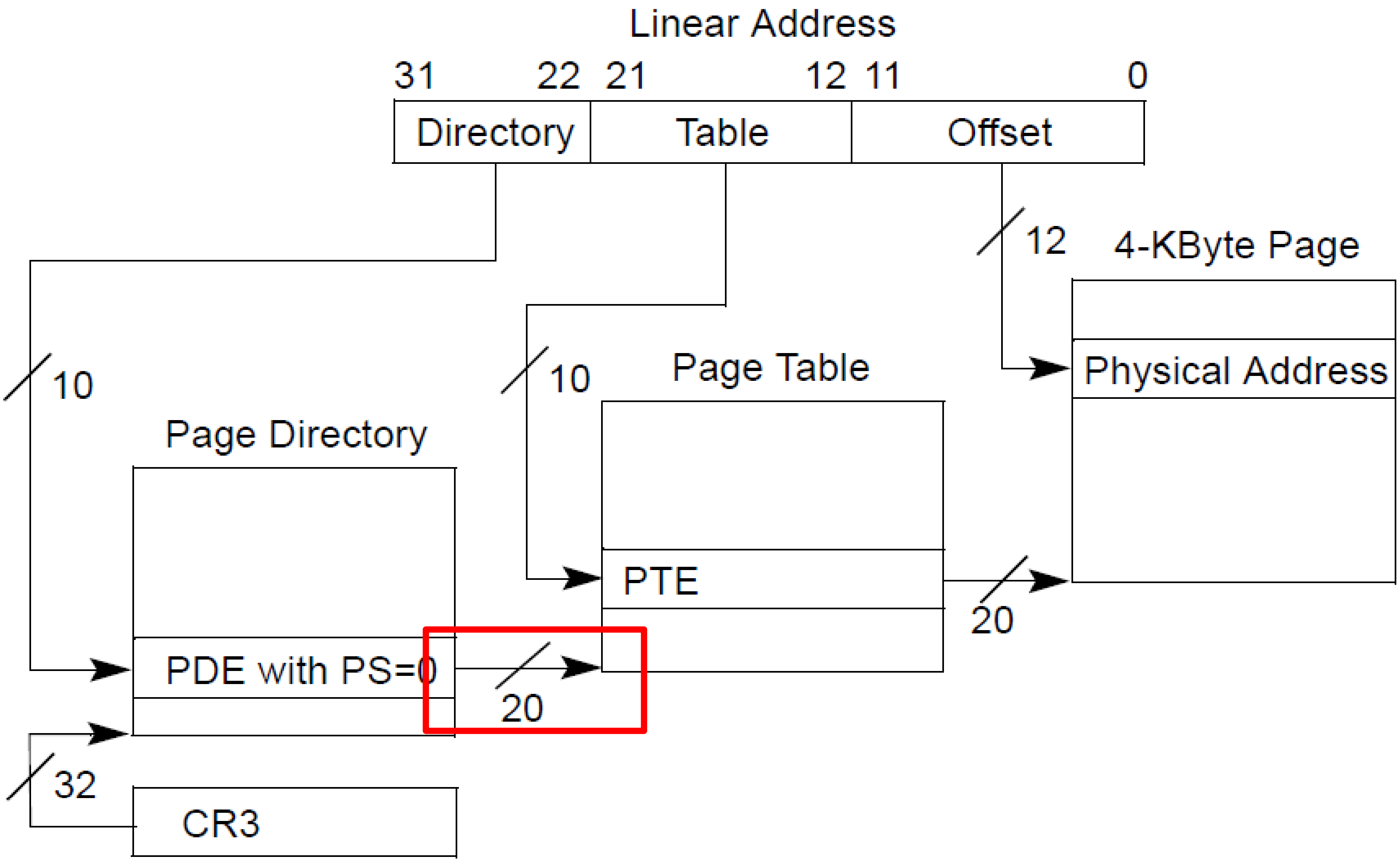


```
walkpgdir(pde_t *pgdir, const void *va, int alloc)
{
    pde_t *pde;
    pte_t *pgtab;

    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);
...
        *pde = V2P(pgtab) | PTE_P | PTE_W | PTE_U;
    }
    return &pgtab[PTX(va)];
}
```



- If yes, locate the page (`pgtab`) containing the level 2 page table

PDE contains 20 bits which represent physical page number



Getting level 2 page

```
                pgtab = (pte_t*)P2V(PTE_ADDR(*pde));
```

- We need two things
  - Convert from 20 bits of physical page number to physical address of the page
  - `PTE_ADDR(*pde)`
  - Convert from physical address of that page to virtual address
  - `P2V(...)`
    - We can’t access physical addresses directly
    - We can only access virtual addresses
      - Registers, mov instructions, etc. contain virtual addresses
      - Physical address has to be mapped by the current page table

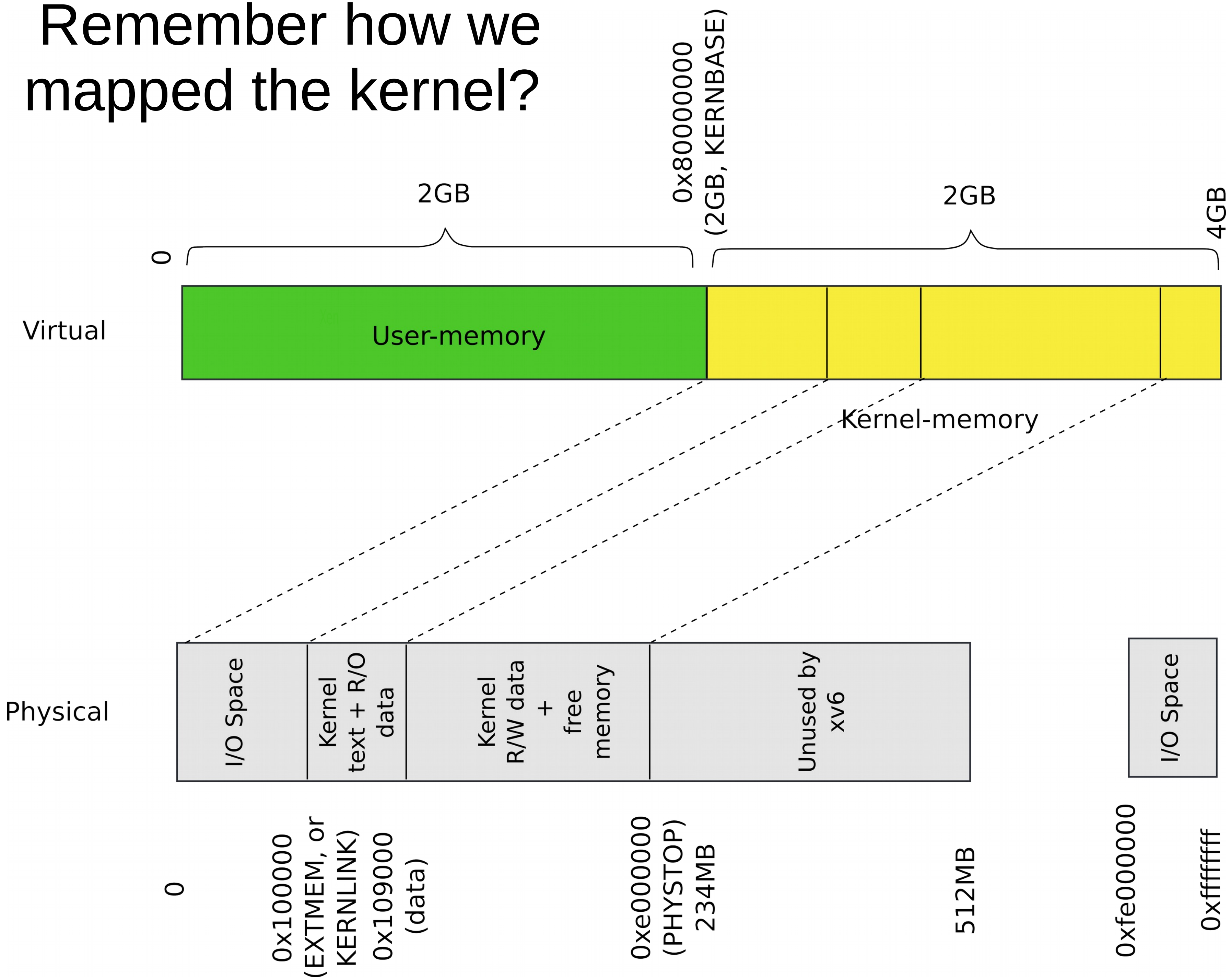
Step 1

- Convert from 20 bits of physical page number to physical address of the page
  - `PTE_ADDR(*pde)`
  - This is trivial

Step 2

- Convert from physical address of that page to virtual address
  - `P2V(...)`
  - This seems a bit tricky

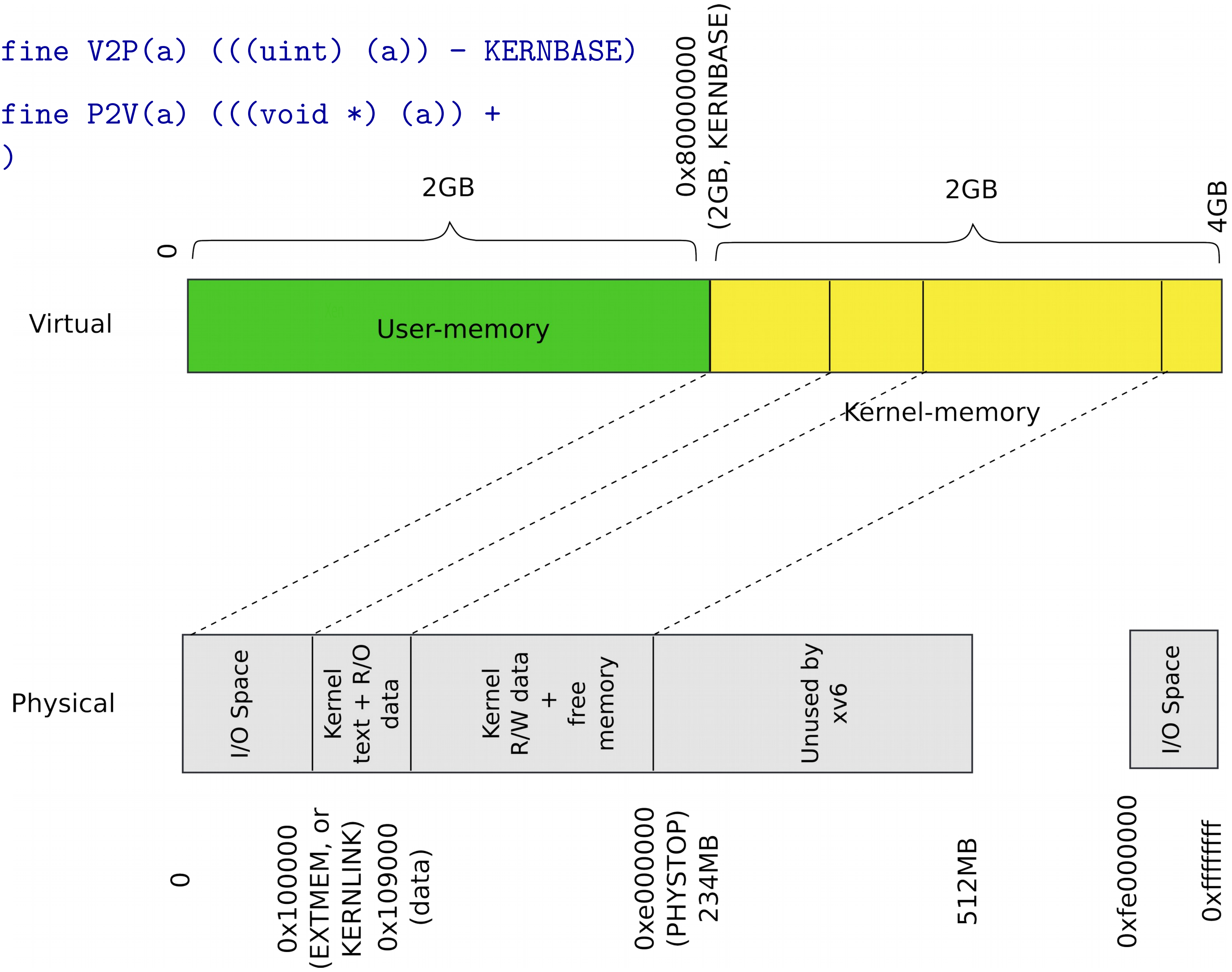
Remember how we mapped the kernel?



```
#define KERNBASE 0x80000000 // First kernel virtual address
```

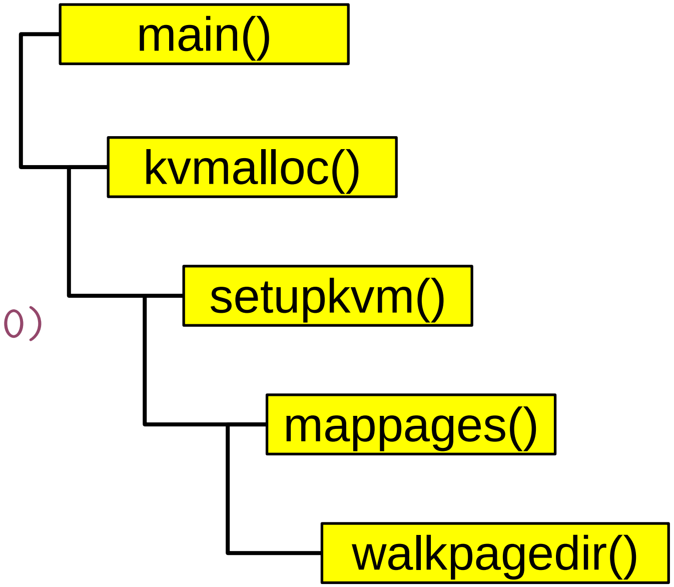
```
#define V2P(a) (((uint) (a)) - KERNBASE)
```

```
#define P2V(a) (((void *) (a)) + KERNBASE)
```



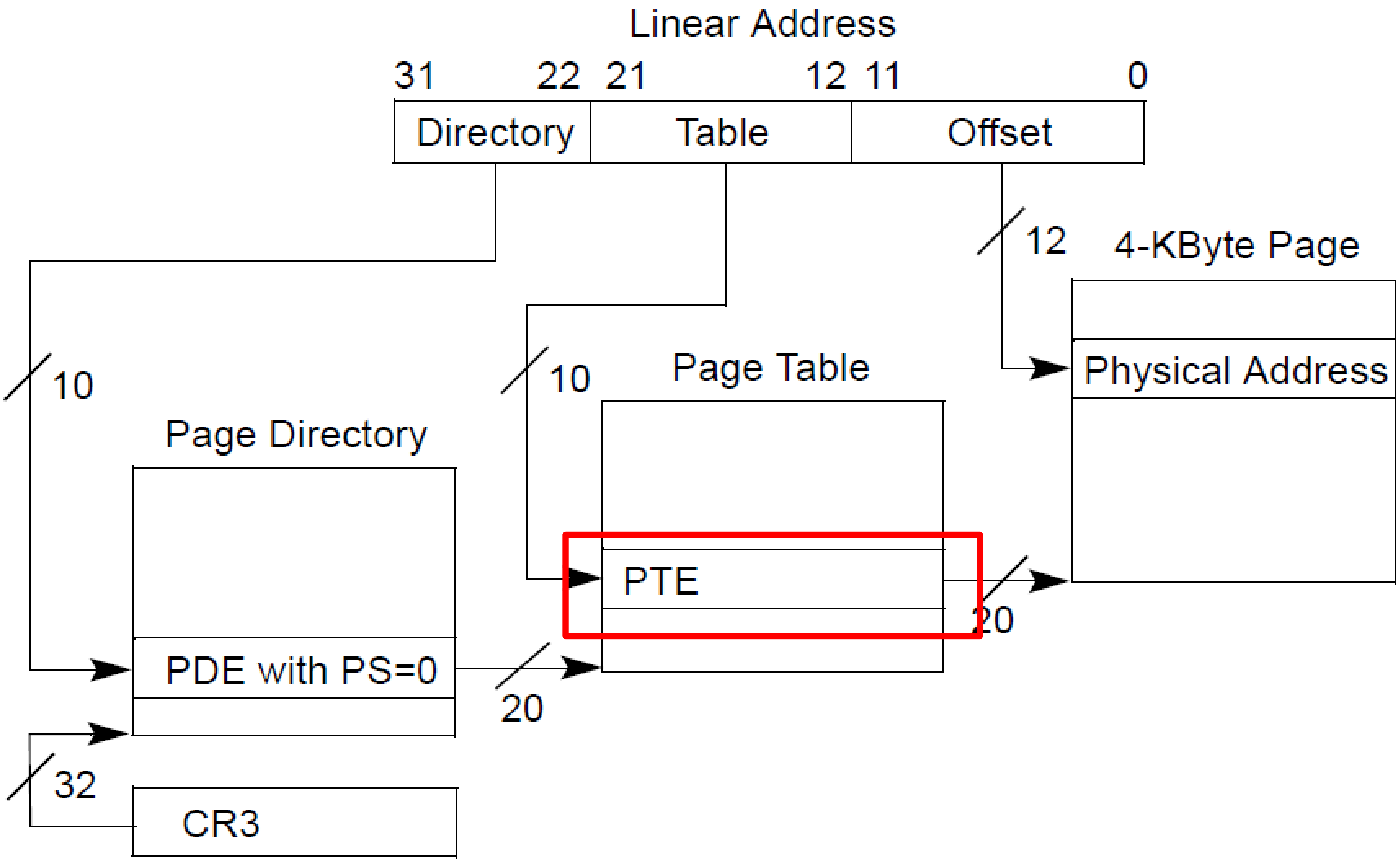
Walk page table

```
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);
...
        *pde = V2P(pgtab) | PTE_P | PTE_W | PTE_U;
    }
    return &pgtab[PTX(va)];
}
```



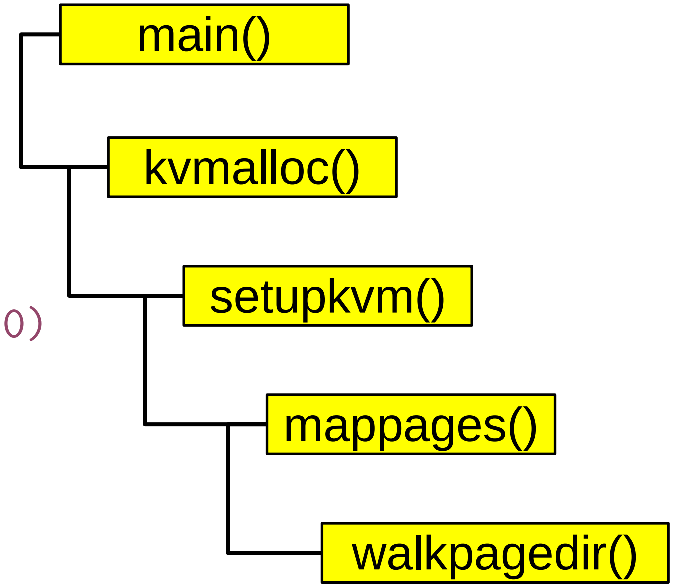
- Page table Level 2 exists
- Return the PTE entry

Return a pointer to PTE



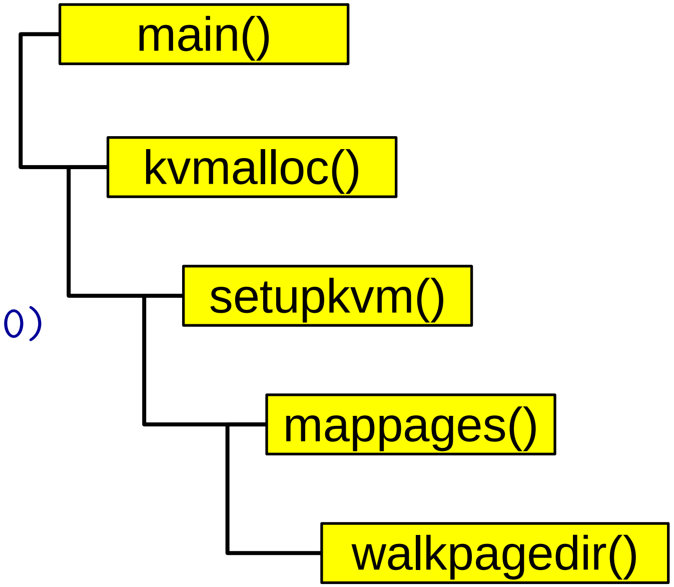
Walk page table

```
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);
...
        *pde = V2P(pgtab) | PTE_P | PTE_W | PTE_U;
    }
    return &pgtab[PTX(va)];
}
```



- Page table Level 2 exists
- Return the PTE entry

```
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);
...
        *pde = V2P(pgtab) | PTE_P | PTE_W | PTE_U;
    }
    return &pgtab[PTX(va)];
}
```



main()

kvmalloc()

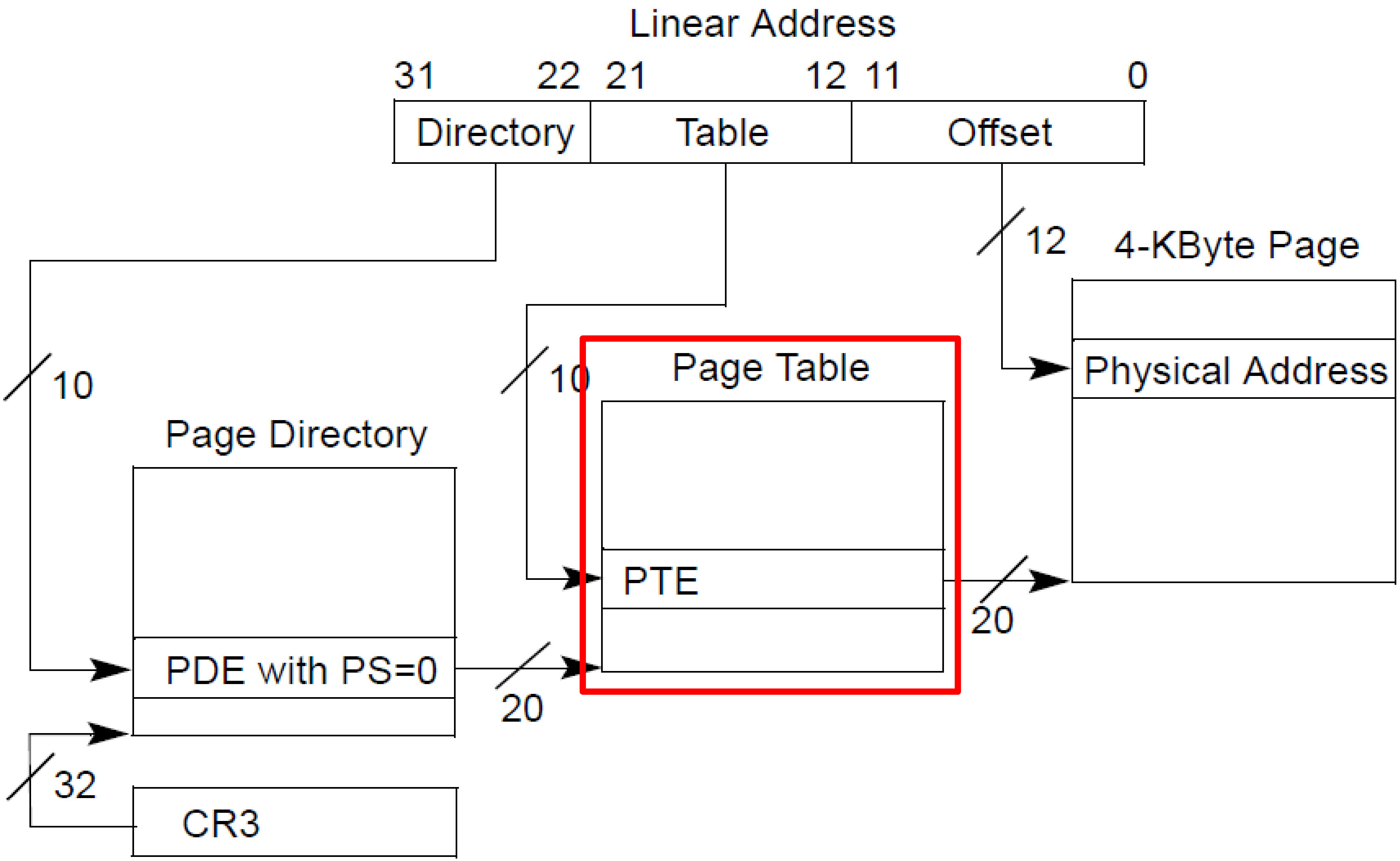
setupkvm()

mappages()

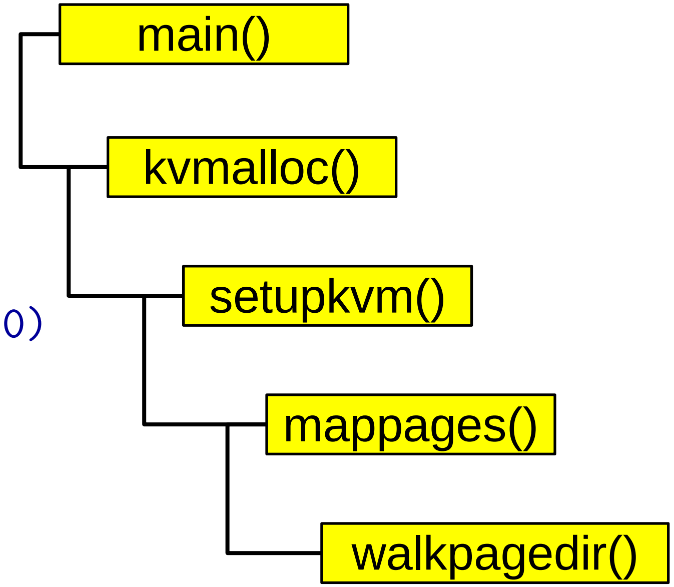
walkpagedir()

- Page table Level 2 does not exist
  - Allocate one

Level 2 page table is not allocated

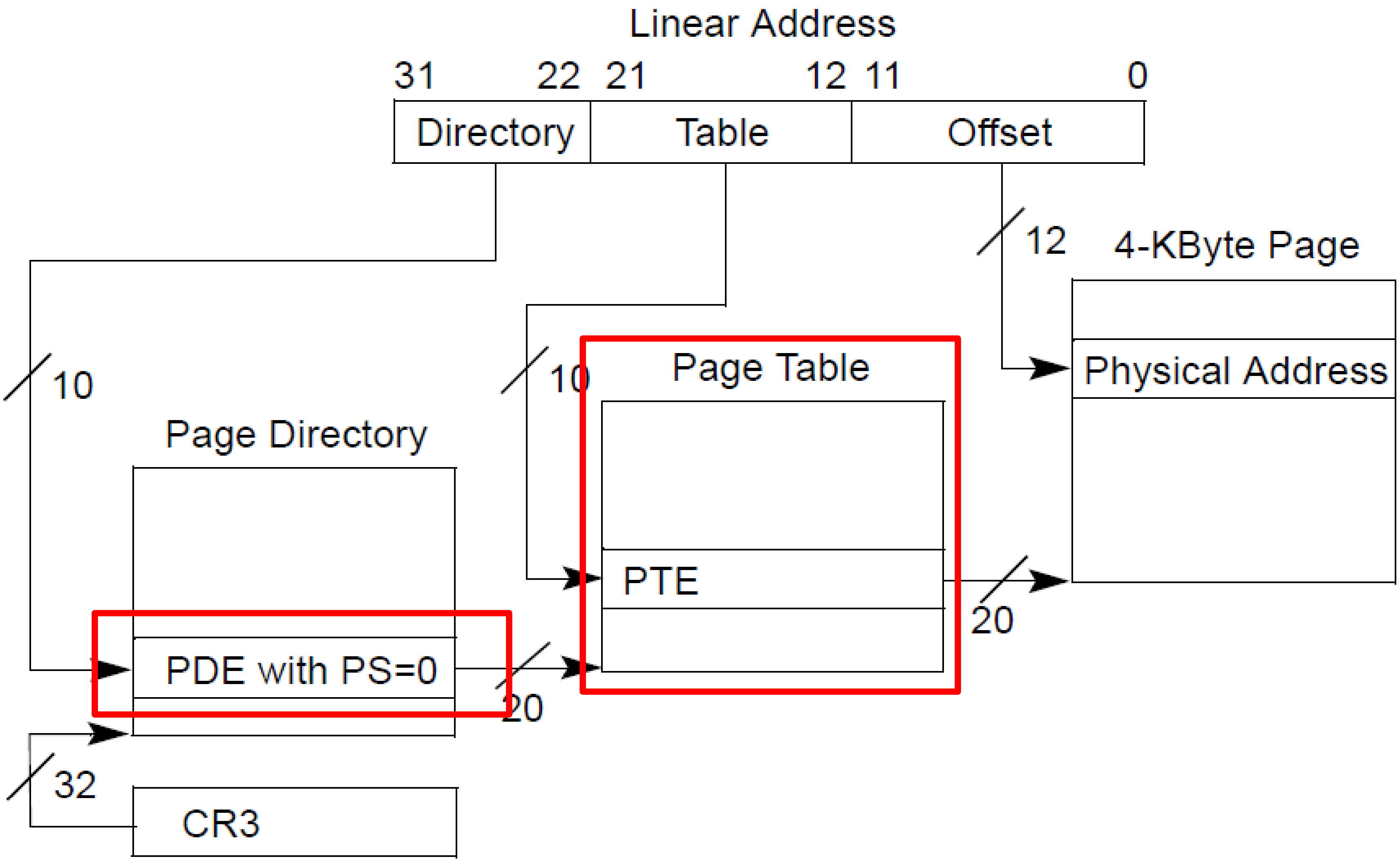


```
walkpgdir(pde_t *pgdir, const void *va, int alloc)
{
    pde_t *pde;
    pte_t *pgtab;

    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);
...
        *pde = V2P(pgtab) | PTE_P | PTE_W | PTE_U;
    }
    return &pgtab[PTX(va)];
}
```



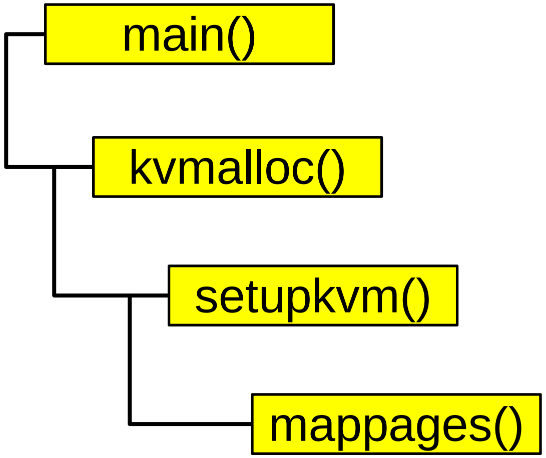
- Allocate the new page
- Initialize it with zeros
- Update the page directory entry (`*pde`)

Now the level 2 page table is allocated



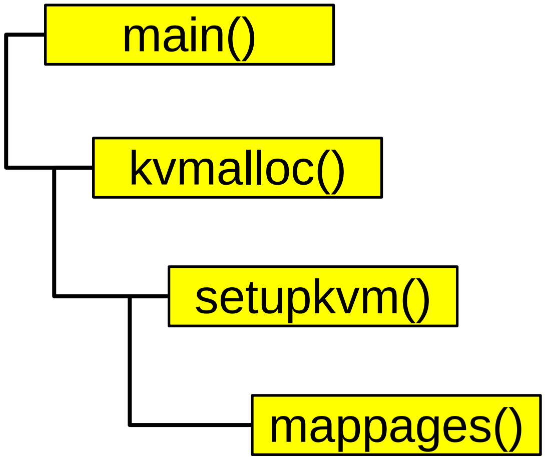
Back to `mappages()` function that maps a region of virtual memory into continuous region of physical memory

```
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;
}
```



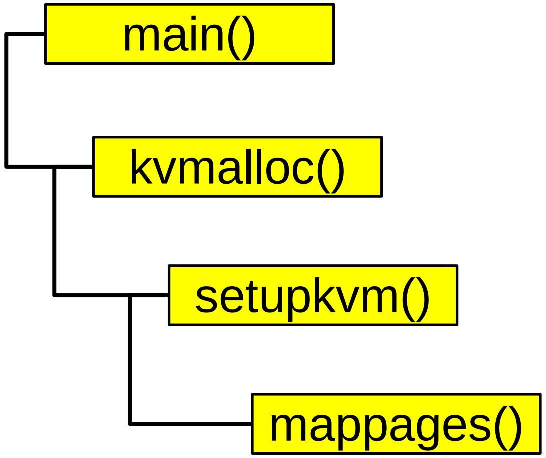
Remember we just discussed `walkpgdir()`

```c
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;
}
```



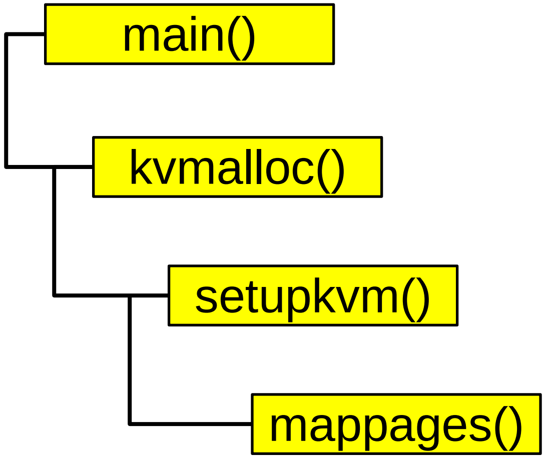
Page present (PTE_P) – panic

```
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;
}
```



- Update page table entry
  - Where does *pte point?
  - pa – physical address of the page

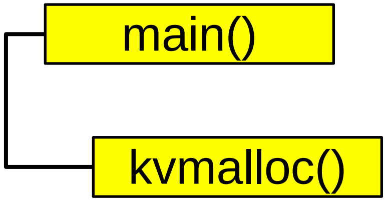
```
mappages(pde_t *pgdir, void *va, uint size, uint pa, int perm)
{
  char *a, *last;
  pte_t *pte;

  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;
}
```



- Move to the next page

kvmalloc()

```
kvmalloc(void)
{
    kpgdir = setupkvm();
    switchkvm();
}
```

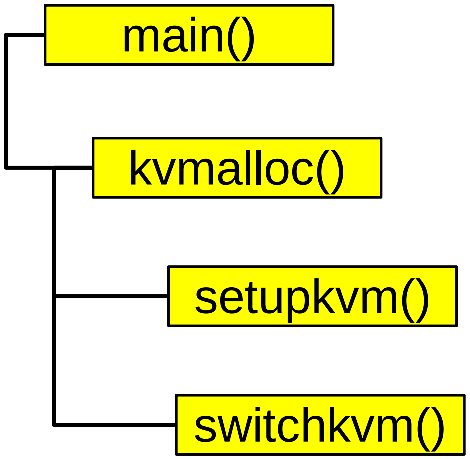


main()

kvmalloc()

Switch to the new page table

```
void
switchkvm(void)
{
  lcr3(v2p(kpgdir));
}
```



main()

kvmalloc()

setupkvm()

switchkvm()

Recap

- Kernel has a memory allocator
- Kernel has a its own address space
  - It uses 4KB page tables
- It is ready to create processes

main()

```
main(void)
{
  kinit1(end, P2V(4*1024*1024)); // phys page allocator
  kvmalloc(); // kernel page table
  mpinit(); // detect other processors
  lapicinit();     // interrupt controller
  seginit();       // segment descriptors
  cprintf("\ncpu%d: starting xv6\n\n", cpunum());
  picinit();       // another interrupt controller
  ioapicinit();    // another interrupt controller
  consoleinit();   // console hardware
  uartinit();      // serial port
  pinit();         // process table
  tvinit();        // trap vectors
  binit();         // buffer cache
  fileinit();      // file table
  ideinit();       // disk
  if(!ismp)
    timerinit();   // uniprocessor timer
  startothers();   // start other processors
  kinit2(P2V(4*1024*1024), P2V(PHYSTOP)); // must come after startothers()
  userinit();      // first user process
  mpmain();        // finish this processor's setup
}
```

```
main(void)
{
  kinit1(end, P2V(4*1024*1024)); // phys page allocator
  kvmalloc(); // kernel page table
  mpinit(); // detect other processors
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  if(!ismp)
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  kinit2(P2V(4*1024*1024), P2V(PHYSTOP)); // must come after startothers()
  userinit();      // first user process
  mpmain();        // finish this processor's setup
}
```
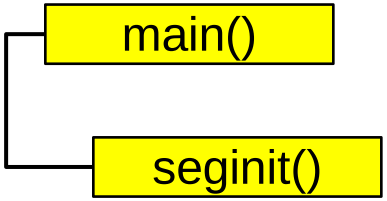

main()

Initialize GDT

```
// Set up CPU’s kernel segment descriptors.
// Run once on entry on each CPU.
void
seginit(void)
{
  struct cpu *c;

  // Map "logical" addresses to virtual addresses using identity map.
  // Cannot share a CODE descriptor for both kernel and user
  // because it would have to have DPL_USR, but the CPU forbids
  // an interrupt from CPL=0 to DPL=3.
  c = &cpus[cpuid()];
  c->gdt[SEG_KCODE] = SEG(STA_X|STA_R, 0, 0xffffffff, 0);
  c->gdt[SEG_KDATA] = SEG(STA_W, 0, 0xffffffff, 0);
  c->gdt[SEG_UCODE] = SEG(STA_X|STA_R, 0, 0xffffffff, DPL_USER);
  c->gdt[SEG_UDATA] = SEG(STA_W, 0, 0xffffffff, DPL_USER);
  lgdt(c->gdt, sizeof(c->gdt));
}
```



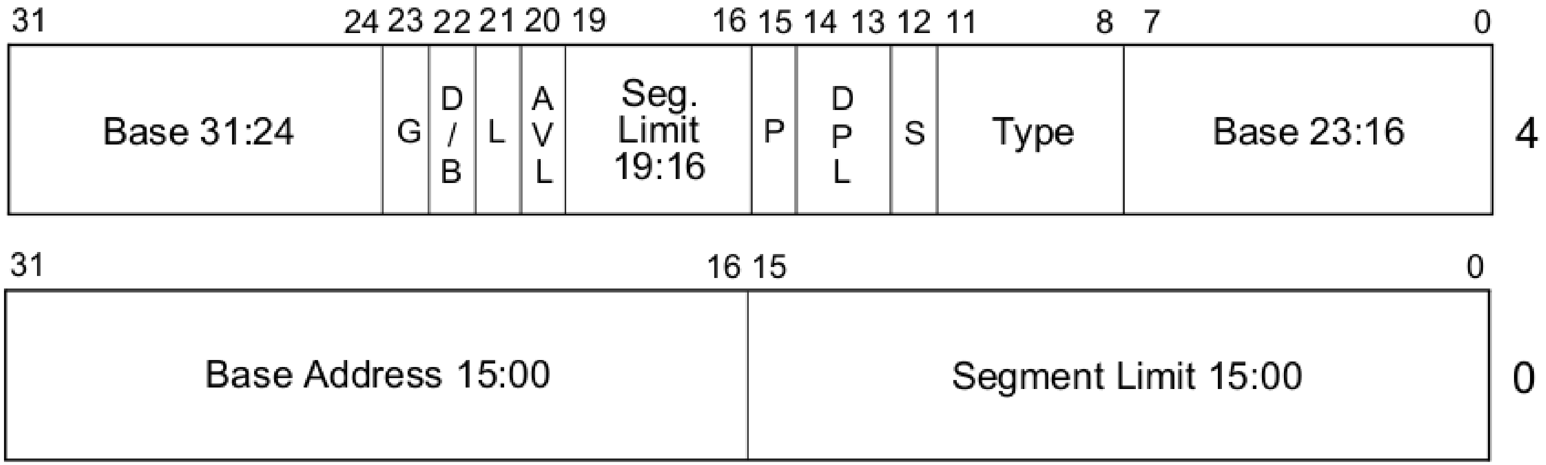
main()

seginit()

Struct CPU

```
// Per-CPU state
struct cpu {
  uchar apicid;                // Local APIC ID
  struct context *scheduler;   // swtch() here to enter scheduler
  struct taskstate ts;         // Used by x86 to find stack for interrupt
  struct segdesc gdt[NSEGS];   // x86 global descriptor table
  volatile uint started;       // Has the CPU started?
  int ncli;                    // Depth of pushcli nesting.
  int intena;                  // Were interrupts enabled before pushcli?
  struct proc *proc;           // The process running on this cpu or null
};

extern struct cpu cpus[NCPU];
```

Segment descriptor



31 24	23	22	21	20	19 16	15	14 13	12	11 8	7 0	
Base 31:24	G	D / B	L	A V L	Seg. Limit 19:16	P	D P L	S	Type	Base 23:16	4

31 16	15 0	
Base Address 15:00	Segment Limit 15:00	0

L — 64-bit code segment (IA-32e mode only)
AVL — Available for use by system software
BASE — Segment base address
D/B — Default operation size (0 = 16-bit segment; 1 = 32-bit segment)
DPL — Descriptor privilege level
G — Granularity
LIMIT — Segment Limit
P — Segment present
S — Descriptor type (0 = system; 1 = code or data)
TYPE — Segment type

Segment Descriptor

```
// Segment Descriptor
struct segdesc {
  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
};
```

```
main(void)
{
  kinit1(end, P2V(4*1024*1024)); // phys page allocator
  kvmalloc(); // kernel page table
  mpinit(); // detect other processors
  lapicinit();     // interrupt controller
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  cprintf("\ncpu%d: starting xv6\n\n", cpunum());
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  uartinit();      // serial port
  pinit();         // process table
  tvinit();        // trap vectors
  binit();         // buffer cache
  fileinit();      // file table
  ideinit();       // disk
  if(!ismp)
    timerinit();   // uniprocessor timer
  startothers();   // start other processors
  kinit2(P2V(4*1024*1024), P2V(PHYSTOP)); // must come after startothers()
  userinit();      // first user process
  mpmain();        // finish this processor's setup
}
```

main()

Print on the screen

```
// Print to the console. only understands %d, %x, %p, %s.
void
cprintf(char *fmt, …)
{
...
  if (fmt == 0)
    panic("null fmt");

  argp = (uint*)(void*)(&fmt + 1);
  for(i = 0; (c = fmt[i] & 0xff) != 0; i++){
    if(c != '%'){
      consputc(c);
      continue;
    }
    c = fmt[++i] & 0xff;
    if(c == 0)
      break;
    switch(c){
...
    case 's':
      if((s = (char*)*argp++) == 0)
        s = "(null)";
      for(; *s; s++)
        consputc(*s);
      break;
...
  }
```

Print one character

```
void
consputc(int c)
{
...
  if(c == BACKSPACE){
    uartputc(’\b’); uartputc(’ ’); uartputc(’\b’);
  } else
    uartputc(c);
  cgaputc(c);
}
...
void
uartputc(int c)
{
  int i;

  if(!uart)
    return;
  for(i = 0; i < 128 && !(inb(COM1+5) & 0x20); i++)
    microdelay(10);
  outb(COM1+0, c);
}
```

```
main(void)
{
  kinit1(end, P2V(4*1024*1024)); // phys page allocator
  kvmalloc(); // kernel page table
  mpinit(); // detect other processors
  lapicinit();     // interrupt controller
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  cprintf("\ncpu%d: starting xv6\n\n", cpunum());
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  userinit();      // first user process
  mpmain();        // finish this processor's setup
}
```

main()

Thank you!
(Next time: interrupts!)