Project #3: Stack Growth

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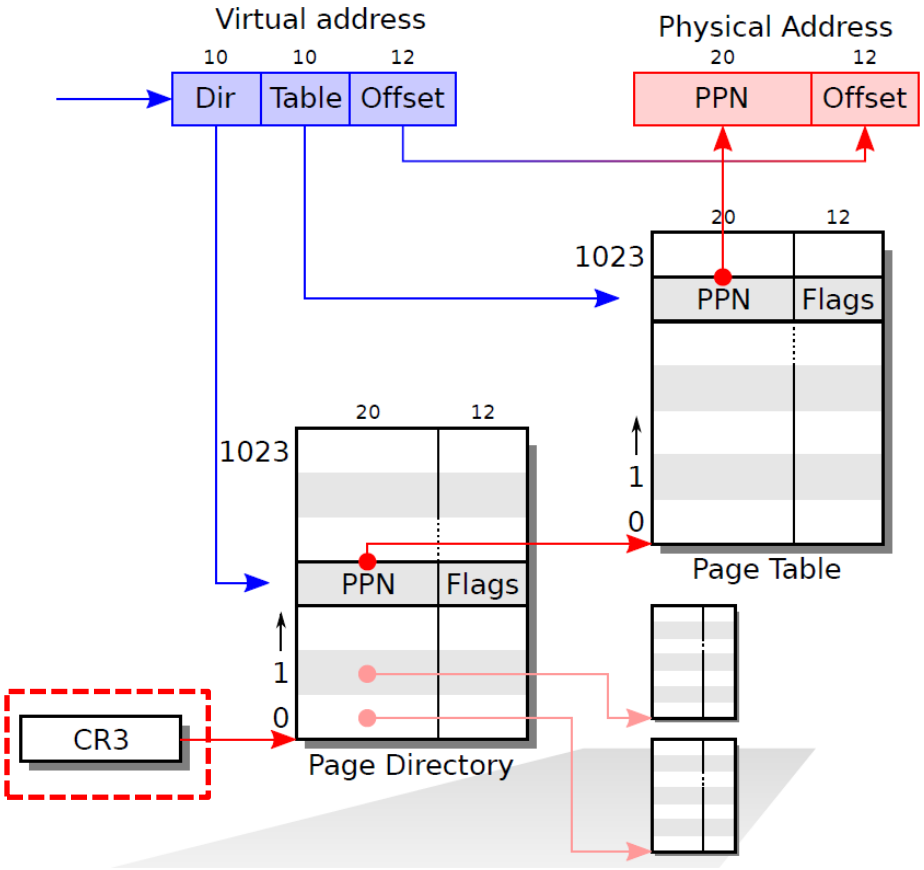
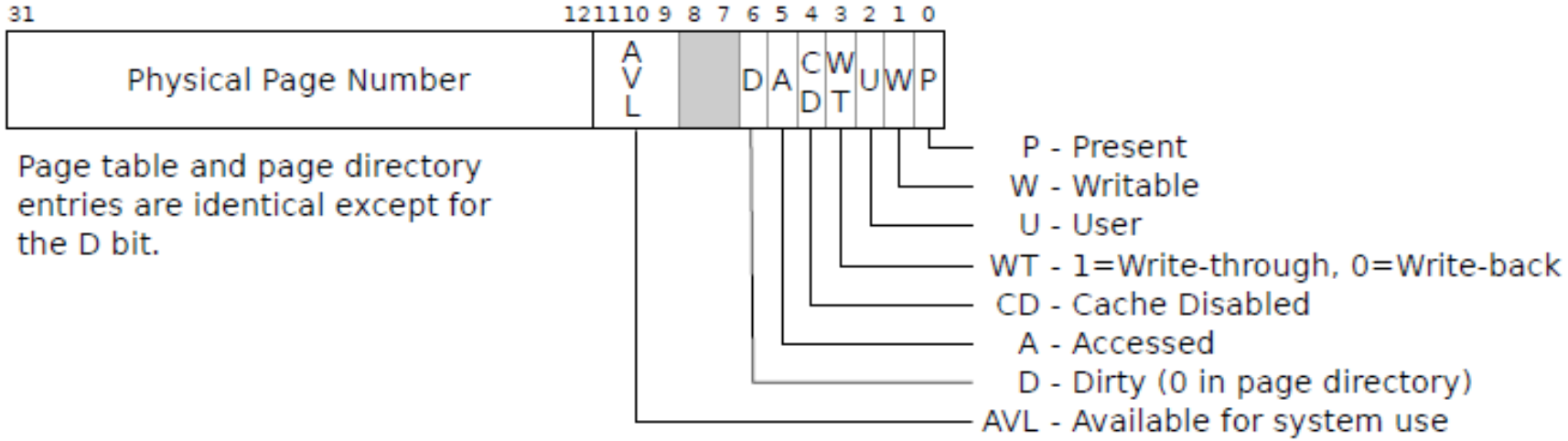
Page Table Hardware in x86



- **32bit address space**
  - 2^{20} (1,048,576) page table entries (PTEs)
  - 20-bit physical page number (PPN)
- **Two-level page table**
  - Page directory has 1024 references to page table pages
  - Next 10 bits of the virtual address to select a PTE from the page table

Page Table Hardware in x86 (Cont'd)



- `PTE_P` indicates whether the PTE is present
- `PTE_W` controls whether instructions are allowed to issue writes to the page
- `PTE_U` controls whether user programs are allowed to use the page

Virtual Address Space in xv6

- Layout of the virtual address space and the physical memory.

main.c

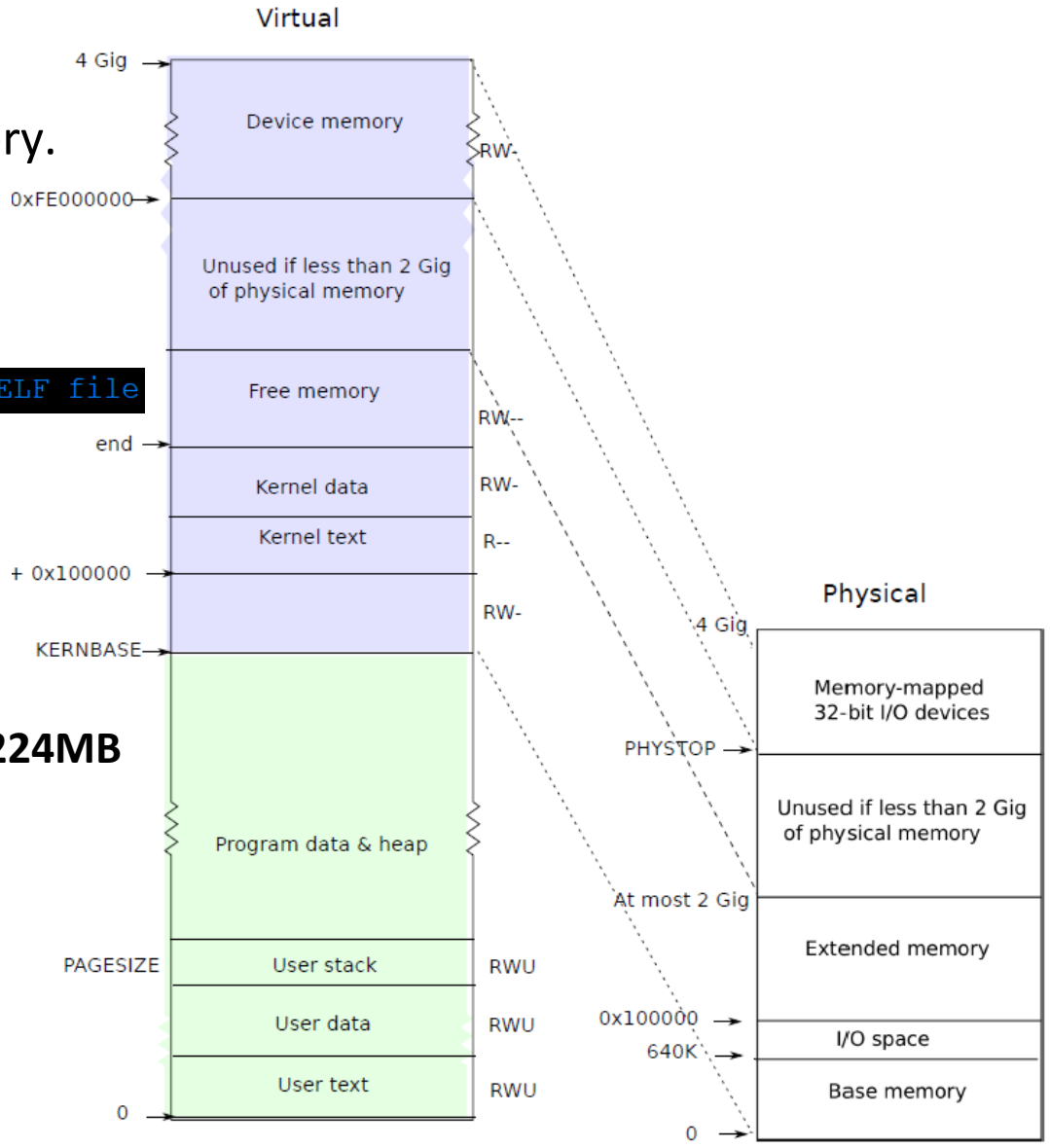
```
extern char end[];
// first address after kernel loaded from ELF file
```

memlayout.h

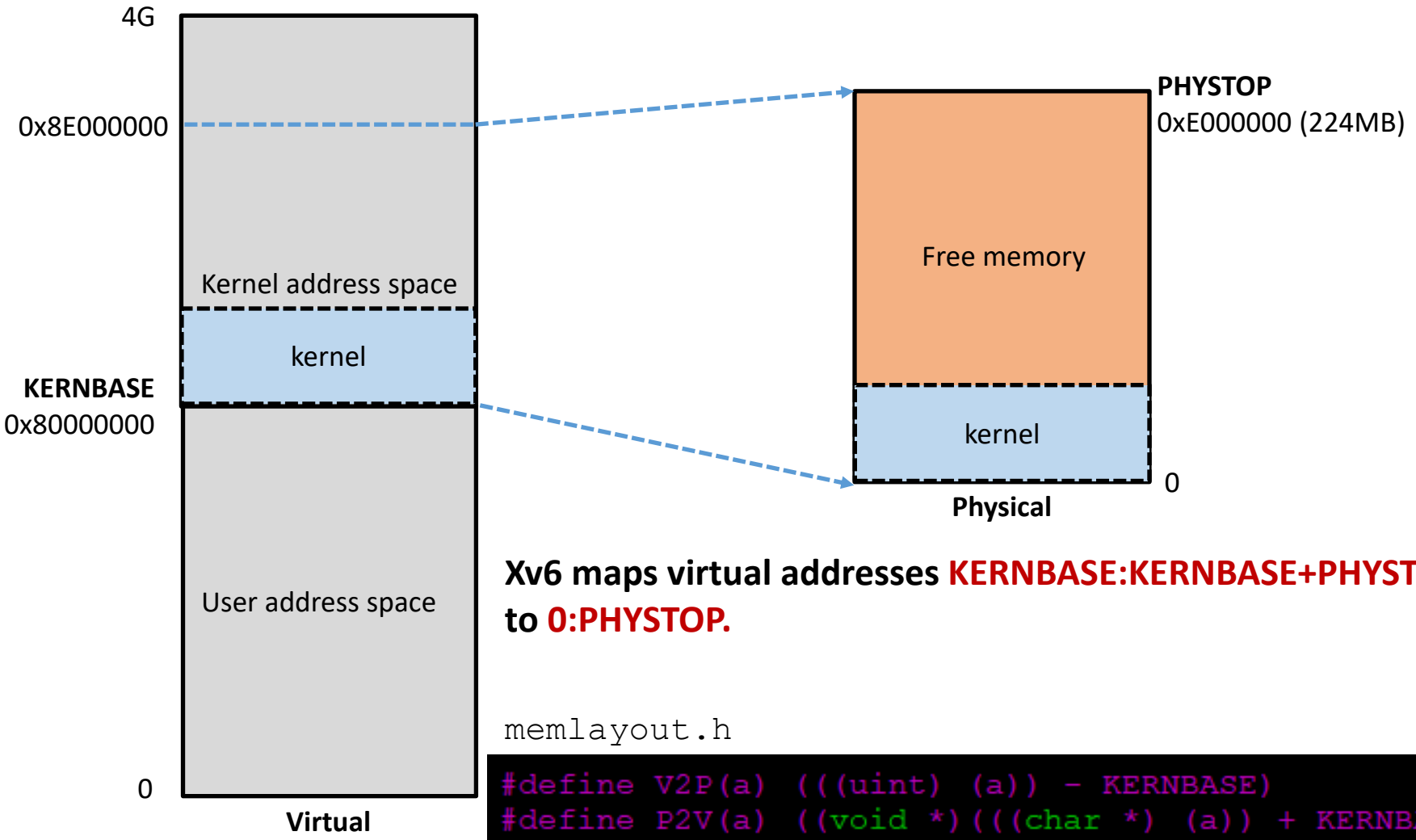
```
#define KERNBASE 0x80000000
#define PHYSTOP 0xE000000
```

2GB

224MB



Virtual Address Space in xv6



Xv6 maps virtual addresses KERNBASE:KERNBASE+PHYSTOP to 0:PHYSTOP.

memlayout.h

```
#define V2P(a) (((uint) (a)) - KERNBASE)
#define P2V(a) ((void *)(((char *) (a)) + KERNBASE))
```

proc.h

types.h

```
typedef uint pde_t;
```

```
// Per-process state
struct proc {
  uint sz;                     // Size of process memory (bytes)
  pde_t* pgdir;                // Page table
  char *kstack;                // Bottom of kernel stack for this process
  enum procstate state;        // Process state
  int pid;                     // Process ID
  struct proc *parent;         // Parent process
  struct trapframe *tf;        // Trap frame for current syscall
  struct context *context;     // swtch() here to run process
  void *chan;                  // If non-zero, sleeping on chan
  int killed;                  // If non-zero, have been killed
  struct file *ofile[NOFILE];  // Open files
  struct inode *cwd;           // Current directory
  char name[16];               // Process name (debugging)
  int nice;
};
```

main.c

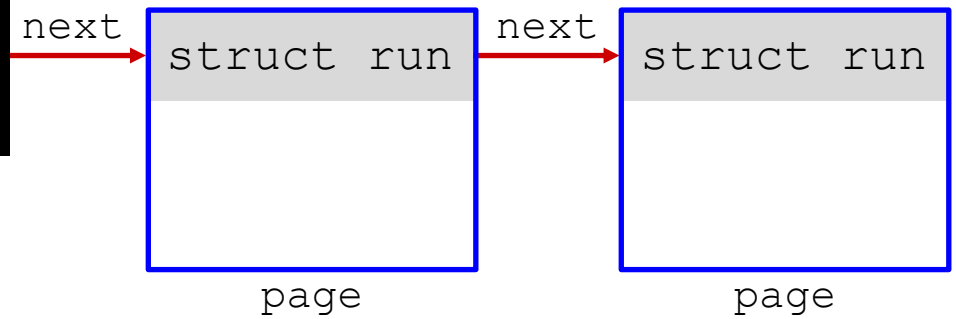
```
int
main(void)
{
  kinit1(end, P2V(4*1024*1024)); // phys page allocator
  kvmalloc();      // kernel page table
  mpinit();        // detect other processors
  lapicinit();     // interrupt controller
  seginit();       // segment descriptors
  picinit();       // disable pic
  ioapicinit();    // another interrupt controller
  consoleinit();   // console hardware
  uartinit();      // serial port
  pinit();         // process table
  tvinit();        // trap vectors
  binit();         // buffer cache
  fileinit();      // file table
  ideinit();       // disk
  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
}
```

Initialization free physical page's list

- **kinit1(), kinit2()**
  - kmem.freelist

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

struct {
  struct spinlock lock;
  int use_lock;
  struct run *freelist;
} kmem;
```



Creating a page table

```
// Set up kernel part of a page table.
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;
}
```

page directory 생성 (1페이지 크기)

주어진 범위만큼의 virtual page number를 physical frame number로 매핑하는 page table entry 생성

Creating a page table

```
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;
}
```

원하는 virtual page의 PTE를 반환

찾은 PTE에 physical address 및 flag를 설정

범위에 있는 다음 페이지로 이동

Creating a page table

```
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)];
}
```

User address space in xv6 (exec)

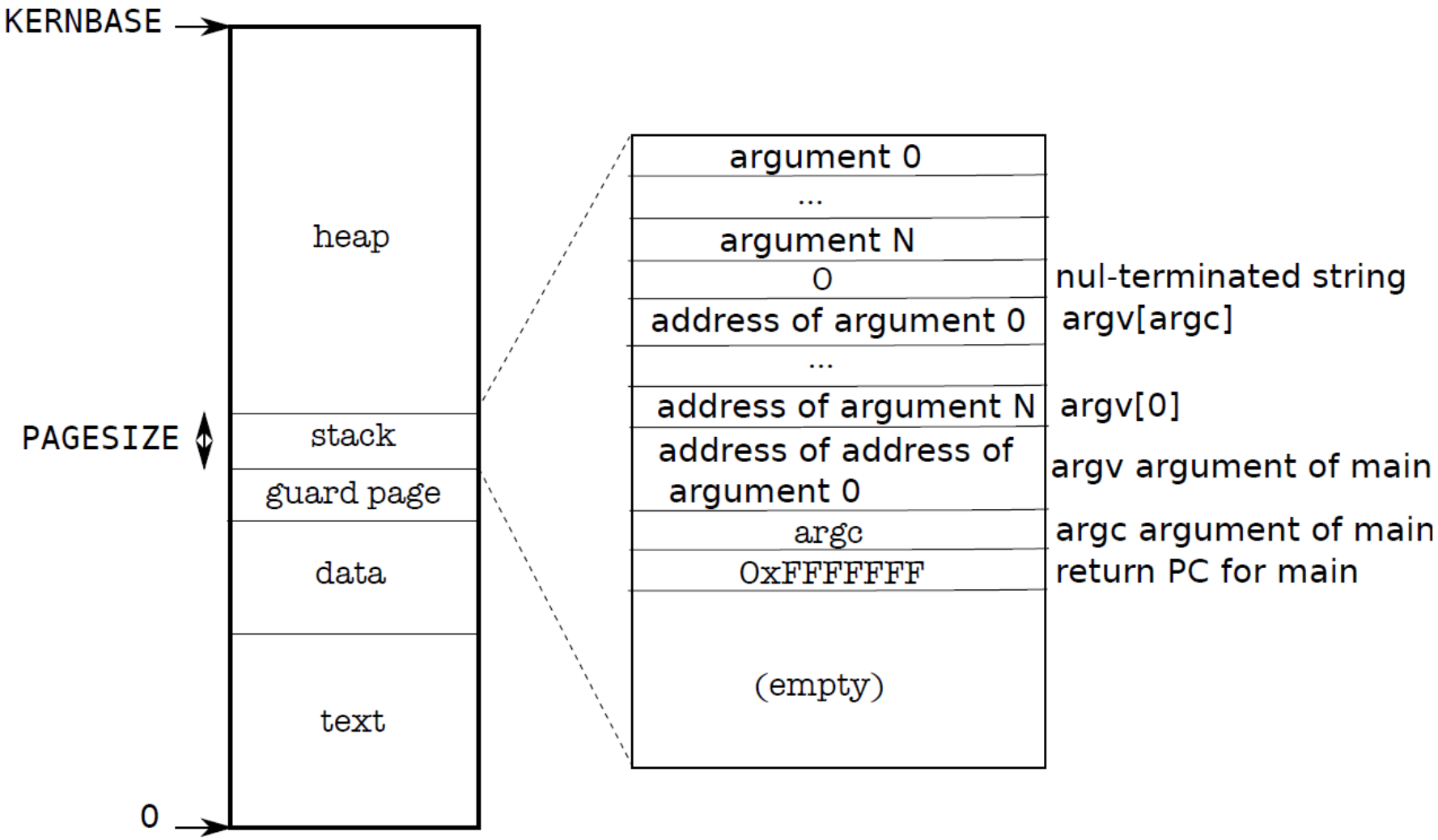


Figure 2-3. Memory layout of a user process with its initial stack.

User address space in xv6

- `int exec(char *path, char **argv)`

```
// Load program into memory.
sz = 0;
for(i=0, off=elf.phoff; i<elf.phnum; i++, off+=sizeof(ph)){
  if(readi(ip, (char*)&ph, off, sizeof(ph)) != sizeof(ph))
    goto bad;
  if(ph.type != ELF_PROG_LOAD)
    continue;
  if(ph.memsz < ph.filesz)
    goto bad;
  if(ph.vaddr + ph.memsz < ph.vaddr)
    goto bad;
  if((sz = allocuvm(pgdir, sz, ph.vaddr + ph.memsz)) == 0)
    goto bad;
  if(ph.vaddr % PGSIZE != 0)
    goto bad;
  if(loaduvm(pgdir, (char*)ph.vaddr, ip, ph.off, ph.filesz) < 0)
    goto bad;
}
iunlockput(ip);
end_op();
ip = 0;
```

프로그램을 읽어오는데 필요한 물리 메모리를 할당하고 PTE를 생성한다.

파일로부터 프로그램 이미지를 메모리로 읽어온다.

User address space in xv6

- `int exec(char *path, char **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)
  goto bad;
clearpteu(pgdir, (char*)(sz - 2*PGSIZE));
sp = sz;
```

  - 프로그램 이미지 위에 stack을 위한 페이지 할당
  - 두 개의 페이지를 할당하지만 guard page는 사용하지 않음
    - `clearpteu()`는 guard page를 inaccessible하게 만들기 위한 함수

```
curproc->pgdir = pgdir;
curproc->sz = sz;
curproc->tf->eip = elf.entry;  // main
curproc->tf->esp = sp;
```

새로 생성된 프로세스 이미지 크기를 `proc` 구조체에 저장

User address space in xv6

- **allocuvm()**
  - Allocate page tables and physical memory to grow process

```
int
allocuvm(pde_t *pgdir, uint oldsz, uint newsz)
{
  char *mem;
  uint a;

  if(newsz >= KERNBASE)
    return 0;
  if(newsz < oldsz)
    return oldsz;

  a = PGROUNDUP(oldsz);
  for(; a < newsz; a += PGSIZE){
    mem = kalloc();
    if(mem == 0){
      cprintf("allocuvm out of memory\n");
      deallocuvm(pgdir, newsz, oldsz);
      return 0;
    }
    memset(mem, 0, PGSIZE);
    if(mappages(pgdir, (char*)a, PGSIZE, V2P(mem), PTE_W|PTE_U) < 0){
      cprintf("allocuvm out of memory (2)\n");
      deallocuvm(pgdir, newsz, oldsz);
      kfree(mem);
      return 0;
    }
  }
  return newsz;
}
```

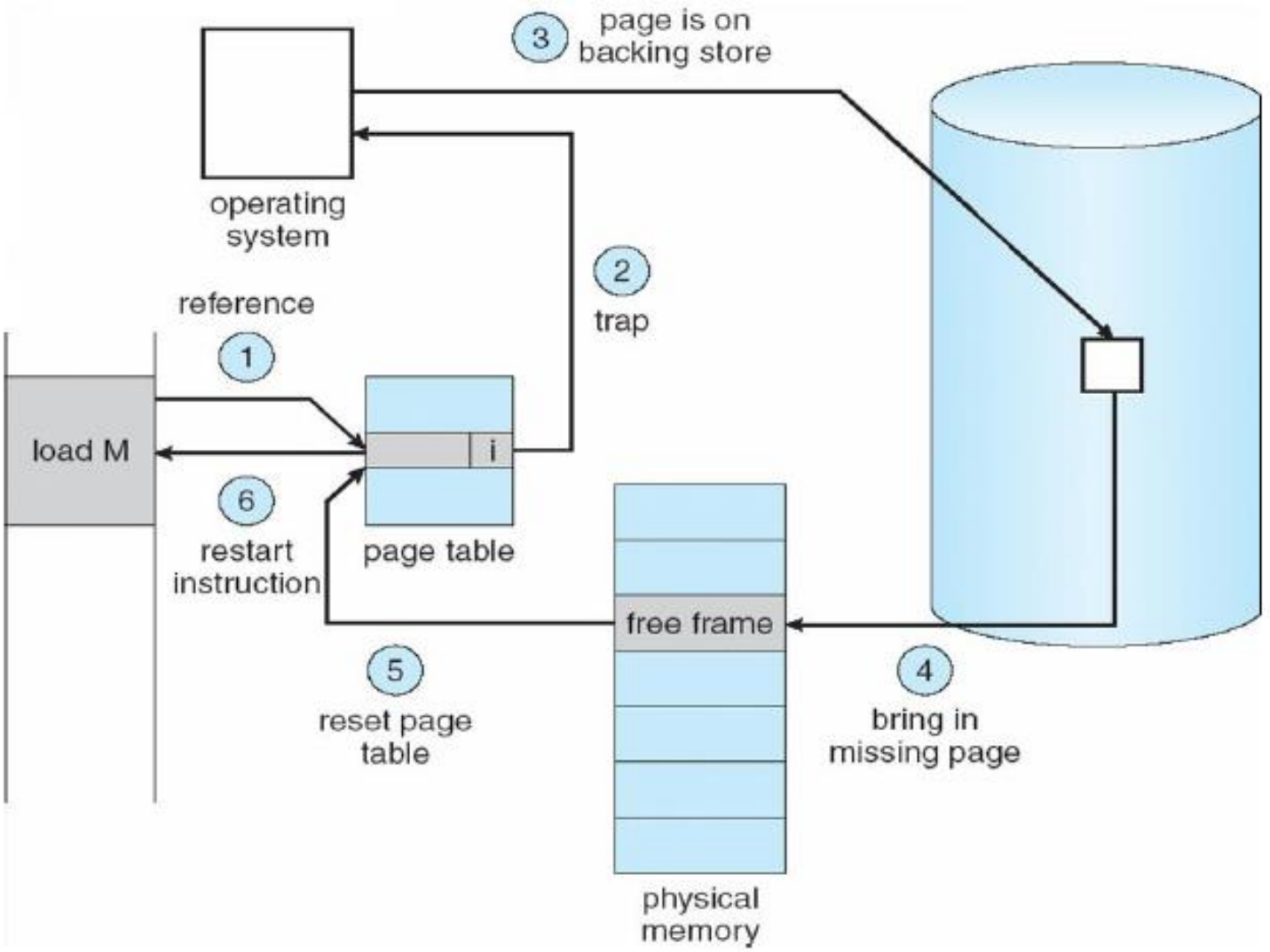
User address space in xv6

- **`sbrk` system call**
  - Shrink or grow process's memory (Heap)
  - `growproc()`

```
// Grow current process's memory by n bytes.
// Return 0 on success, -1 on failure.
int
growproc(int n)
{
  uint sz;
  struct proc *curproc = myproc();

  sz = curproc->sz;
  if(n > 0){
    if((sz = allocuvm(curproc->pgdir, sz, sz + n)) == 0)
      return -1;
  } else if(n < 0){
    if((sz = deallocuvm(curproc->pgdir, sz, sz + n)) == 0)
      return -1;
  }
  curproc->sz = sz;
  switchuvm(curproc);
  return 0;
}
```

Handling Page Faults



Page Fault Exception in Intel x86

- **Conditions**
  - There is no translation for the linear address
  - There is a translation for the linear address, but its access rights do not permit the access

- **CR2 stores the linear address that caused a page fault**
- **CR3 stores the physical address of Page directory**

- **Processor triggers interrupt 14 (page fault)**

Page fault handler in xv6

- If page fault occurs, "`trapno`" of trapframe automatically filled with `T_PGFLT` and call trap function in `trap.c`

```
// x86 trap and interrupt constants.

// Processor-defined:
#define T_DIVIDE         0      // divide error
#define T_DEBUG          1      // debug exception
#define T_NMI            2      // non-maskable interrupt
#define T_BRKPT          3      // breakpoint
#define T_OFLOW          4      // overflow
#define T_BOUND          5      // bounds check
#define T_ILLOP          6      // illegal opcode
#define T_DEVICE         7      // device not available
#define T_DBLFLT         8      // double fault
// #define T_COPROC      9      // reserved (not used since 486)
#define T_TSS           10      // invalid task switch segment
#define T_SEGNP         11      // segment not present
#define T_STACK         12      // stack exception
#define T_GPFLT         13      // general protection fault
#define T_PGFLT         14      // page fault
// #define T_RES        15      // reserved
#define T_FPERR         16      // floating point error
#define T_ALIGN         17      // aligment check
```

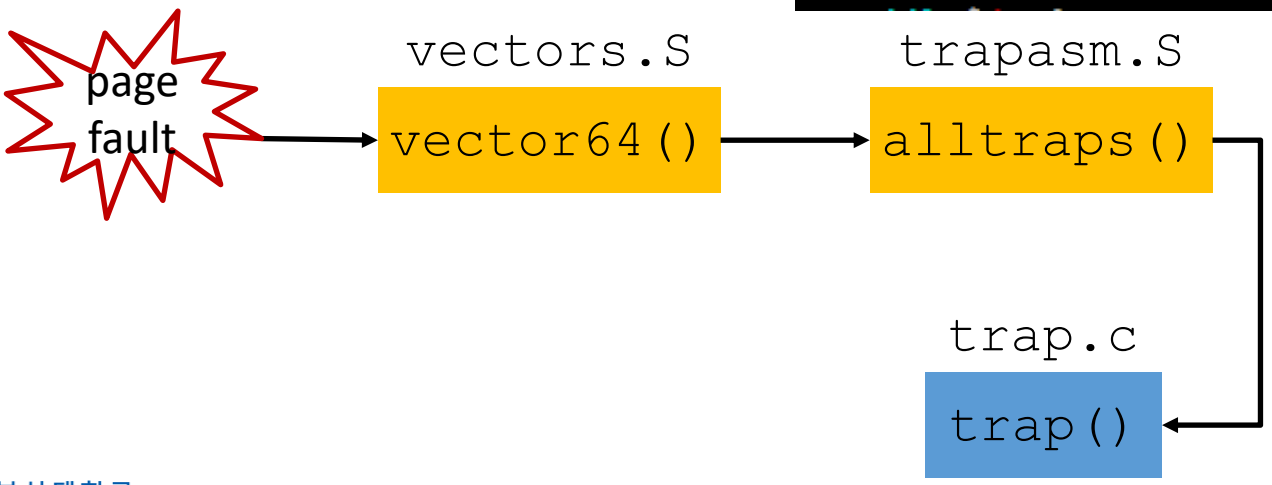
Page fault handler in xv6

```
.globl vector14
vector14:
  pushl $14
  jmp alltraps
```

```
.globl alltraps
alltraps:
  # Build trap frame.
  pushl %ds
  pushl %es
  pushl %fs
  pushl %gs
  pushal

  # Set up data segments.
  movw $(SEG_KDATA<<3), %ax
  movw %ax, %ds
  movw %ax, %es

  # Call trap(tf), where tf=%esp
  pushl %esp
  call trap
```



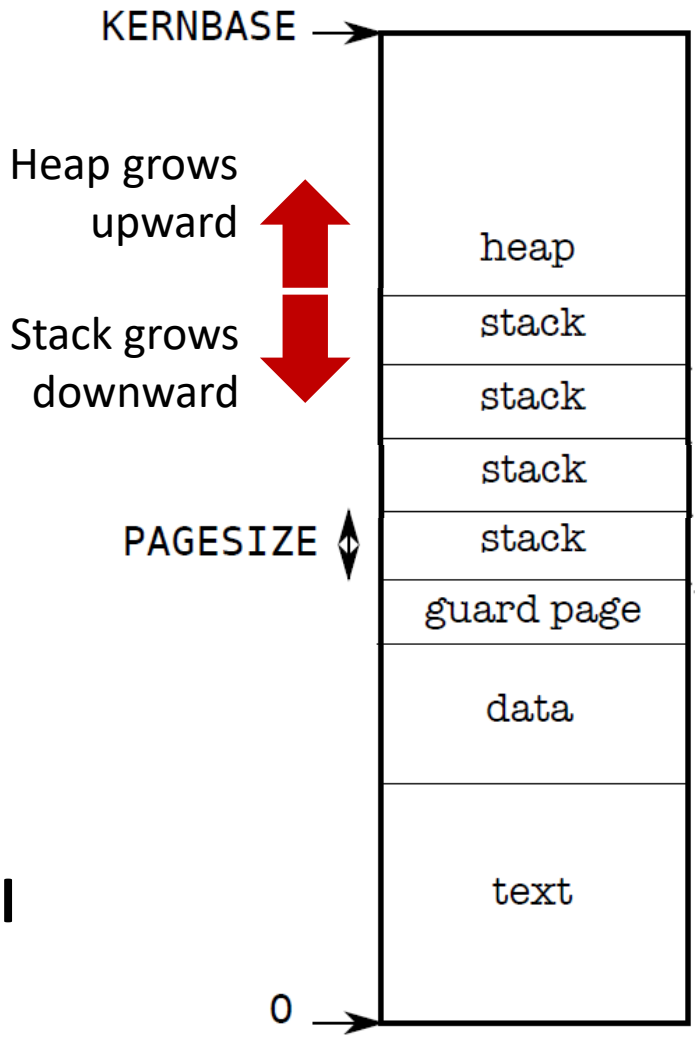
Page fault handler in xv6

- **trap.c**
  - trap()
  - You have to make your “own” page fault handler!
  - Currently, implemented as below...
    - rcr2() -> **page fault address**

```
//PAGEBREAK: 13
default:
  if(myproc() == 0 || (tf->cs&3) == 0){
    // In kernel, it must be our mistake.
    cprintf("unexpected trap %d from cpu %d eip %x (cr2=0x%x)\n",
            tf->trapno, cpuid(), tf->eip, rcr2());
    panic("trap");
  }
  // In user space, assume process misbehaved.
  cprintf("pid %d %s: trap %d err %d on cpu %d "
          "eip 0x%x addr 0x%x--kill proc\n",
          myproc()->pid, myproc()->name, tf->trapno,
          tf->err, cpuid(), tf->eip, rcr2());
  myproc()->killed = 1;
}
```

Project #3. Stack growth

- **Initial size of stack**
  - Prepare 1 page initially
  - Can be grow up to 4 pages
- **Growth of stack**
  - Implementation of page fault handler
  - New page should be allocated to this process if current stack is full
- **When stack pointer reaches guard page, occurs stack overflow and kill process**



Page Fault Handler Implementation

- trap.c

```
void
trap(struct trapframe *tf)
{
  if(tf->trapno == T_SYSCALL){
    if(myproc()->killed)
      exit();
    myproc()->tf = tf;
    syscall();
    if(myproc()->killed)
      exit();
    return;
  }

  switch(tf->trapno){
  case T_PGFLT:
    pagefault();
    break;
  case T_IRQ0 + IRQ_TIMER:
    if(cpuid() == 0){
      acquire(&tickslock);
      ticks++;
      wakeup(&ticks);
      release(&tickslock);
    }
    lapiceoi();
    break;
```

Page Fault Handler Implementation

- **int exec(char *path, char **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)
  goto bad;
clearpteu(pgdir, (char*)(sz - 2*PGSIZE));
sp = sz;
```

  - 가상주소공간에 4개의 stack page 공간 확보
    - 실제로는 하나의 physical page만 할당
    - 나머지 virtual page는 page entry는 생성하되 physical page는 할당하지 않음.
  - allocuvm()을 변형해 stack 공간 할당을 위한 함수 구현 (ex: allocuvm_stack)

Page Fault Handler Implementation

- **vm.c**
  - `void pagefault(void)` 구현
    - `rcr2()`를 호출해 page fault가 발생한 virtual address 결정
    - virtual address가 valid한 값인지 확인
      - 현재 stack의 top의 다음 page에 속한 주소인지 확인
      - 4 stack pages의 범위를 벗어나는지 확인
    - Print out **"[Pagefault] Invalid access!"** when approaching abnormal address
    - Print out **"[Pagefault] Allocate new page!"** if page-fault handler is executed normally
    - 새로운 페이지를 할당하고 page table에 매핑한다.
    - `lcr3(V2P(pde_t))` – reloading cr3

Page Fault Handler Implementation

- **vm.c**
  - void pagefault(void)구현

```
//PAGEFAULT
void pagefault(void)
{
        ...
        addr = rcr2();
        ...
        if( addr is valid ) {
                1 physical page alloc
                ...
                lcr3(V2P(myproc()->pgdir));
                cprintf("[Pgaefault]Aoocate new page!\n");
        }
        else {
                cprintf("[Pagefault]Invalid access!\n");
                myproc()->killed = 1;
        }
 }
```

Page Fault Handler Implementation

- **vm.c : copyuvm()**
  - Fork() 함수에서 호출
  - parent의 page table을 child process로 복사하는 함수
  - Stack에 4개의 page가 할당 되었지만 physical page는 할당되지 않았기 때문에 panic 발생
  - physical page가 할당되지 않은 상태에서도 'panic'이 발생하지 않도록 수정

```
pde_t*
copyuvm(pde_t *pgdir, uint sz)
{
  pde_t *d;
  pte_t *pte;
  uint pa, i, flags;
  char *mem;

  if((d = setupkvm()) == 0)
    return 0;
  for(i = 0; i < sz; i += PGSIZE){
    if((pte = walkpgdir(pgdir, (void *) i, 0)) == 0)
      panic("copyuvm: pte should exist");
    if(!(*pte & PTE_P))
      panic("copyuvm: page not present");
    pa = PTE_ADDR(*pte);
    flags = PTE_FLAGS(*pte);
    if((mem = kalloc()) == 0)
      goto bad;
```

Project #3. Template Code

- **Download xv6-pnu-3.tar.gz from PLATO**
- **Modifications**
  - `freemem()` system call
    - Return the number of free pages in `kmem.freelist`

Submission

- **Compress your xv6 folder as `StudentID-3.tar.gz`**
  - `$tar -czvf StudentID-3.tar.gz ./xv6-pnu-3`
  - Please command `$make clean` before compressing
- **Submit your `tar.gz` file through PLATO**
- **Due date: 5/13 (Thr.), 23:59**
- **Late submission penalty**
  - -25% penalty of total mark per day
- **PLEASE DO NOT COPY !!**
  - YOU WILL GET F IF YOU COPIED

Tips

- Reading xv6 commentary will help you a lot
  - https://pdos.csail.mit.edu/6.828/2018/xv6/book-rev11.pdf
    - The line numbers in this book refer to the source booklet below
    - Reading Chap. 2 “Page tables” of xv6-commentary will help your project
  - https://pdos.csail.mit.edu/6.828/2018/xv6/xv6-rev11.pdf