slides2

bootloader is located in bootmain.c , bootasm.S ⇒ bootblock

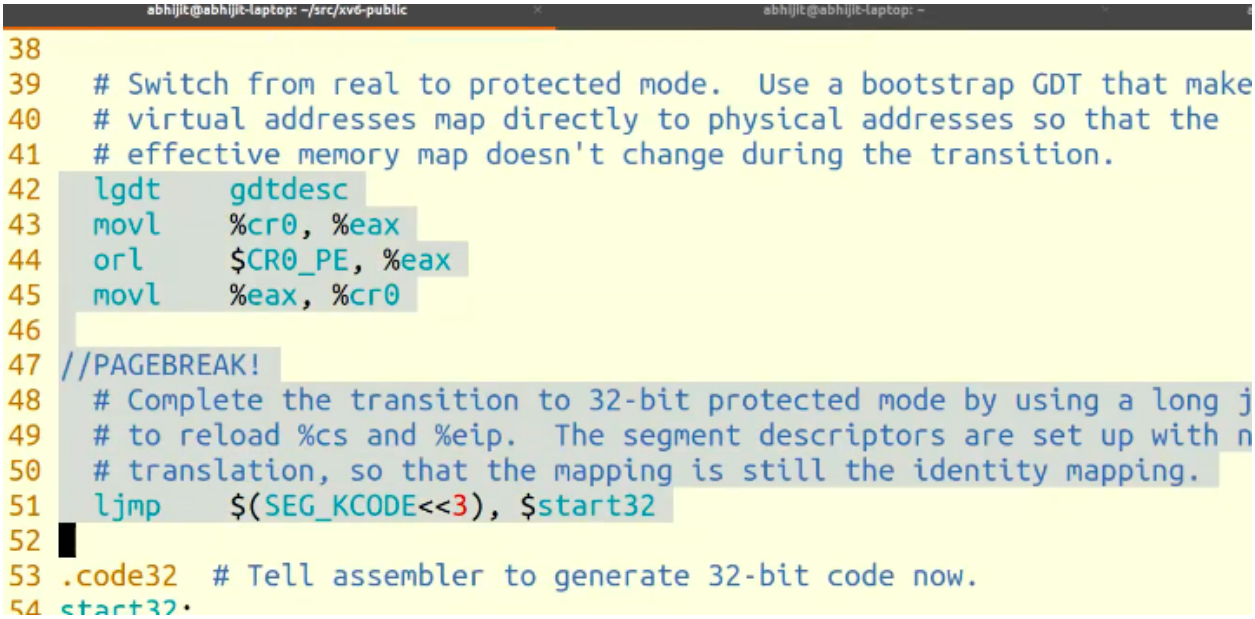
loaded in RAM at 0x7c00

start is location0x7c00

cli → disable interrupts

in the orignal scheme, we had 16 bit segments, and got 20 bit address, with 80286 processor, you will have 2mb i.e 21st bit for address.

they used an existing pin for address, which will be enabled/disabled . by default disabled.

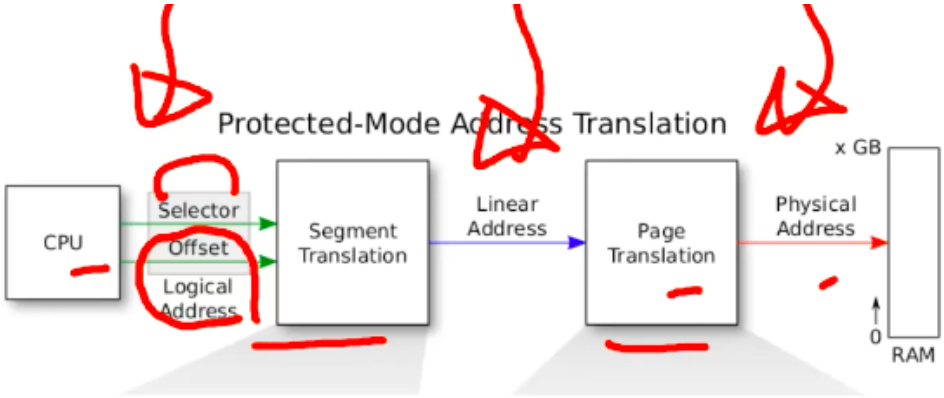


in protected mode, segmentation and paging both will be enabled.

segment registers are now used as index in segment descriptor table.

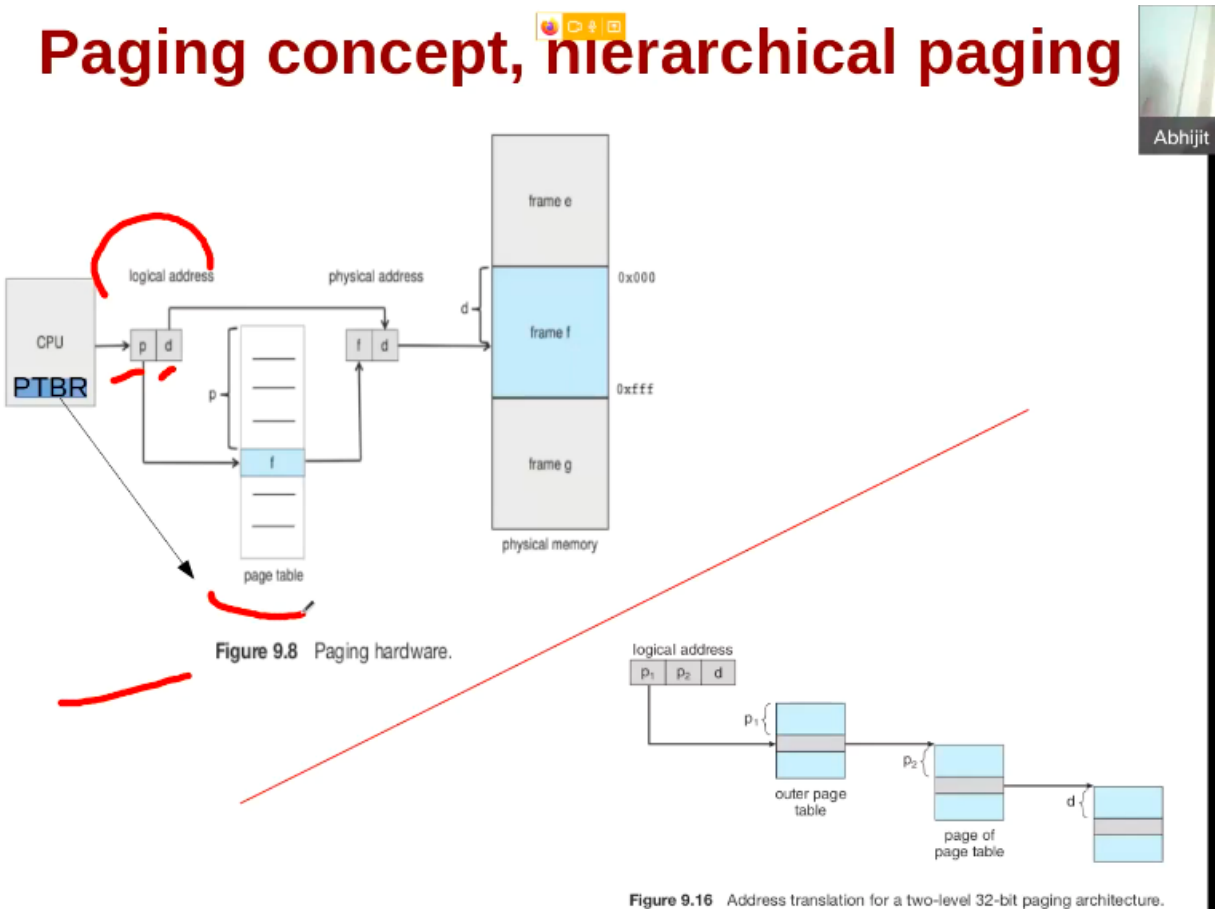
descriptor table consists of base limit pair.

the table is located in memory, a special register gdtr will give the address of segment descriptor table, who will store it in gdtr? OS will

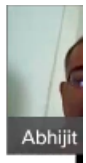


Both Segmentation and Paging are used in x86
X86 allows optionally one-level or two-level paging
Segmentation is a must to setup, paging is optional (needs to be enabled)
Hence different OS can use segmentation+paging in different ways

Heirarchical Paging



suppose we have 4gb of memory and 4kb page size then we have 2^32/ 2^12 ⇒ 2^20 entries in page table, which is way too much and hence we have hierarchical page table



X86 paging

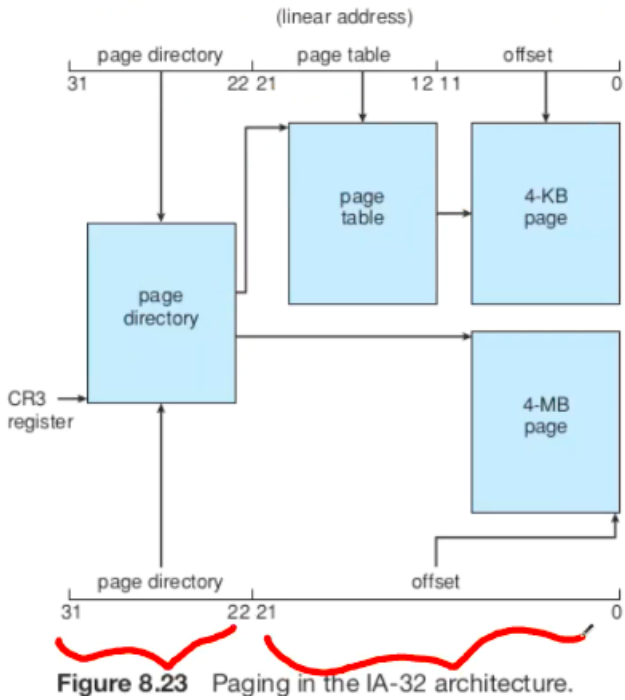


Figure 8.23 Paging in the IA-32 architecture.

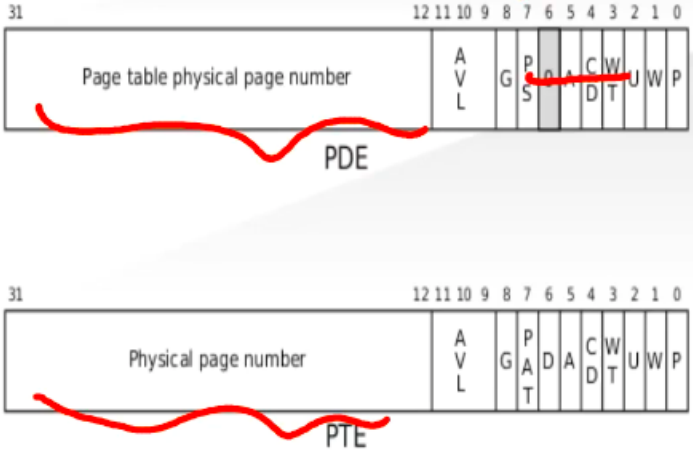
`pagesize= 2^offset bytes`

so for one level paging , page size is 2^22 is 4mb

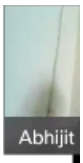
for 2 level paging, page size is 2^12 i.e 4kb size

CR3 gives the base of page directory table

Page Directory Entry (PDE)
Page Table Entry (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



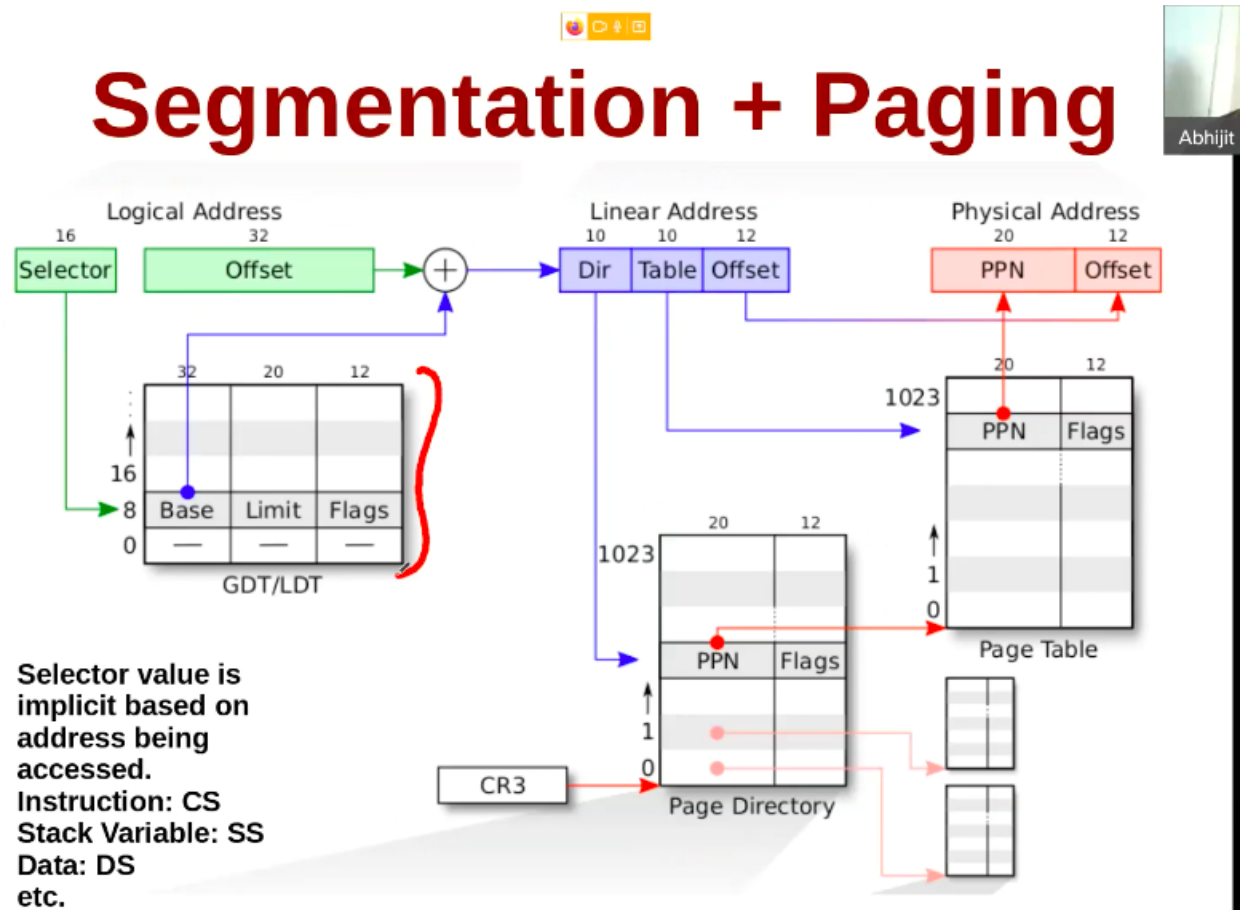
CR3

PWT Page-level writes transparent

PCT Page-level cache disable

CR4

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



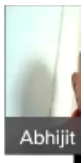

```
Role of kernel lies in creating gdt(segmentation) table, making gdtr point to gdt, setting up page directory, page table and making cr3 point to base of page directory, once kernel does this memory management is done.
```

xv6

xv6 configures the hardware by setting base=0, limit =4gb. so linear address is same as logical address, this is called identity mapping, hence segmentation is practically off.

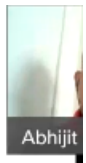
and limit is 4gb, which is maximum addressable space as 4gb=2^32, and address is 32 bit, so no address is out of bound.

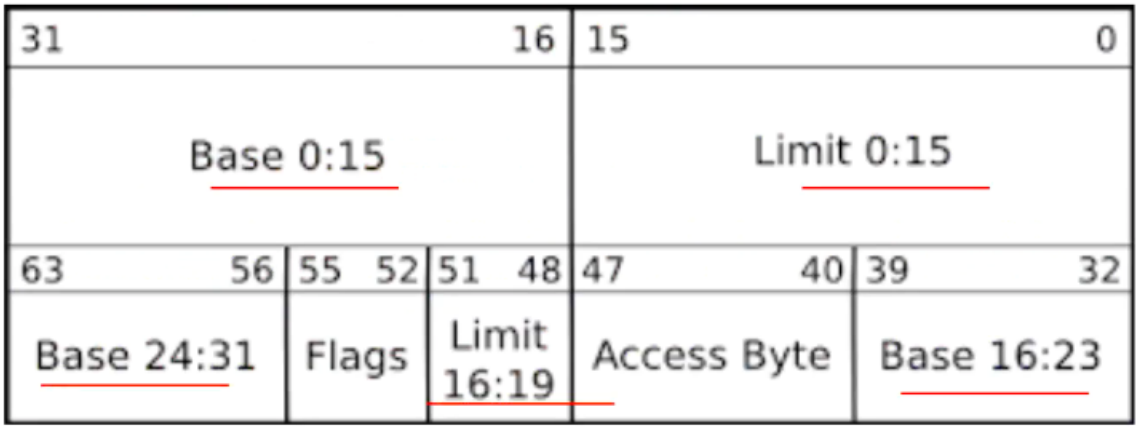
Segmentation + Paging setup of xv6



- xv6 configures the segmentation hardware by setting Base = 0, Limit = 4 GB
  - translate logical to linear addresses without change, so that they are always equal.
  - Segmentation is pratically off
- Once paging is enabled, the only interesting address mapping in the system will be linear to physical.
  - In xv6 paging is NOT enabled while loading kernel
  - After kernel is loaded 4 MB pages are used for a while
  - Later the kernel switches to 4 kB pages!

GDT Entry

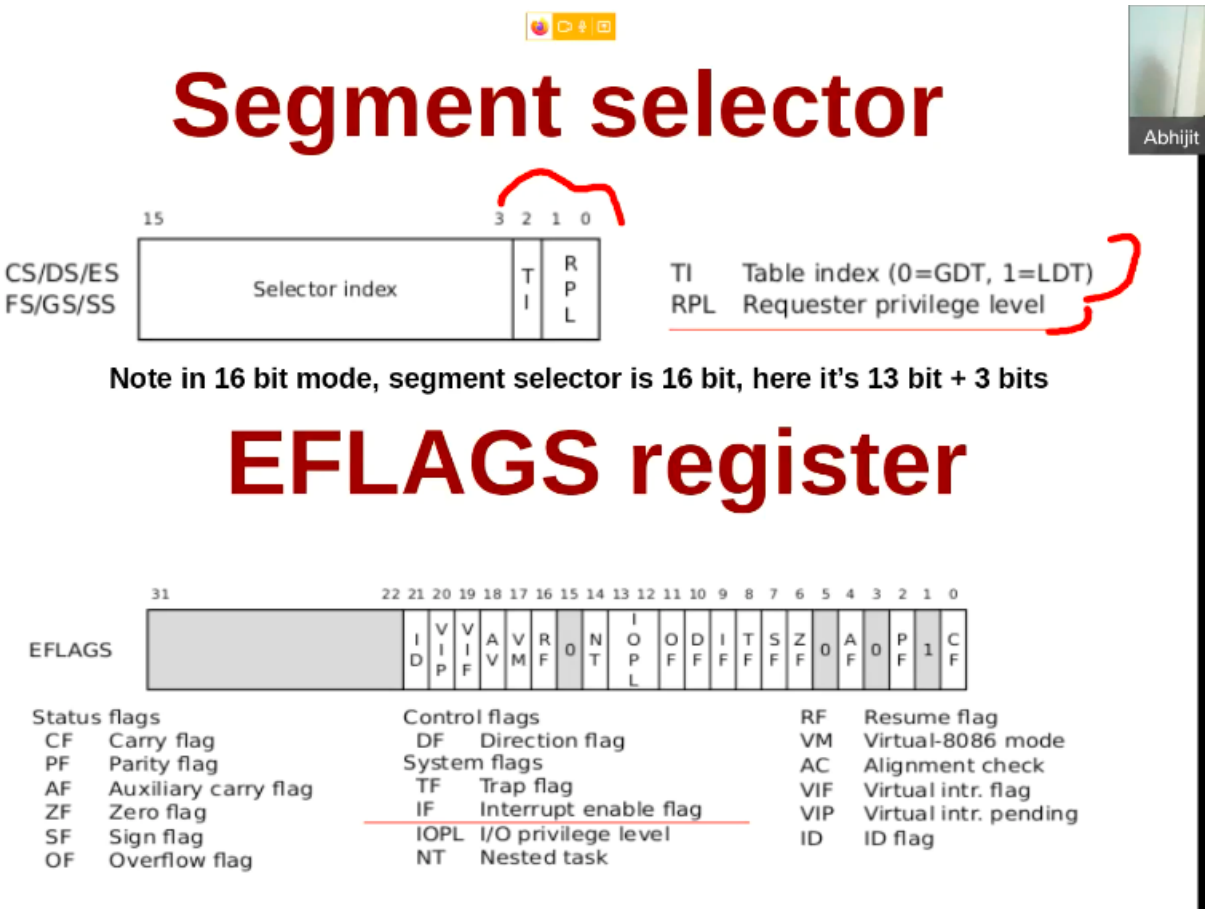




asm.h

```
#define SEG_ASM(type,base,lim)                                  \
        .word (((lim) >> 12) & 0xffff), ((base) & 0xffff);      \
        .byte (((base) >> 16) & 0xff), (0x90 | (type)),         \
                (0xC0 | (((lim) >> 28) & 0xf)), (((base) >> 24) & 0xff)
```

each entry is a 64bit entry. to make a entry in gdt table, for particular value of base limit pair, we have to do many bitwise operations for which a macro is defined in the asm.h file., that is SEG_ASM.



segment selector(CS,SS,DS,ES,FS,GS) now have a different meaning as shown in above image.

GDT stands for global descriptor table, LDT is local descriptor table.

3rd bit of segment selector 0→ GDT, 1→LDT

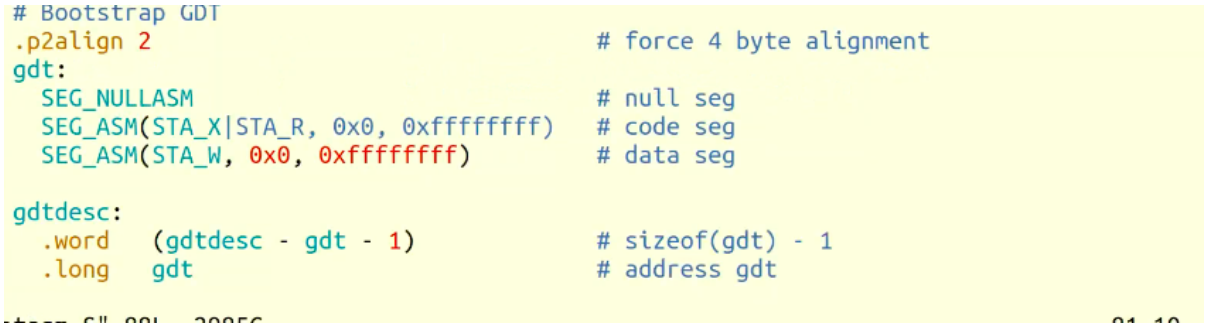
2 bits for RPL, which is used to transition from user mode to kernal mode and vice versa.

`in xv6 we only use GDT, HENCE 3RD BIT is always 0`

the entry actually is now going to be 13 bits in Segment Selector.

Lets move to code

`line 42: lgdt gdtdesc`



```
# Bootstrap GDT
.p2align 2                                  # force 4 byte alignment
gdt:
  SEG_NULLASM                               # null seg
  SEG_ASM(STA_X|STA_R, 0x0, 0xffffffff)     # code seg
  SEG_ASM(STA_W, 0x0, 0xffffffff)           # data seg

gdtdesc:
  .word   (gdtdesc - gdt - 1)               # sizeof(gdt) - 1
  .long   gdt                               # address gdt
```

fig 1: for code

gdt table is hardcoded and has 3 enteries here

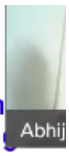
2nd entry: STA_X→ executable permission, STA_R→ read permission, for base 0 ,limit 4gb

3rd entry: STA_W→ write permission for base 0 ,limit 4gb

gdtdesc is 6 byte data (word→2 byte, 4byte→long) 2 bytes for storing size of gdt, 4 bytes for storing 32 bit address of gdt table.

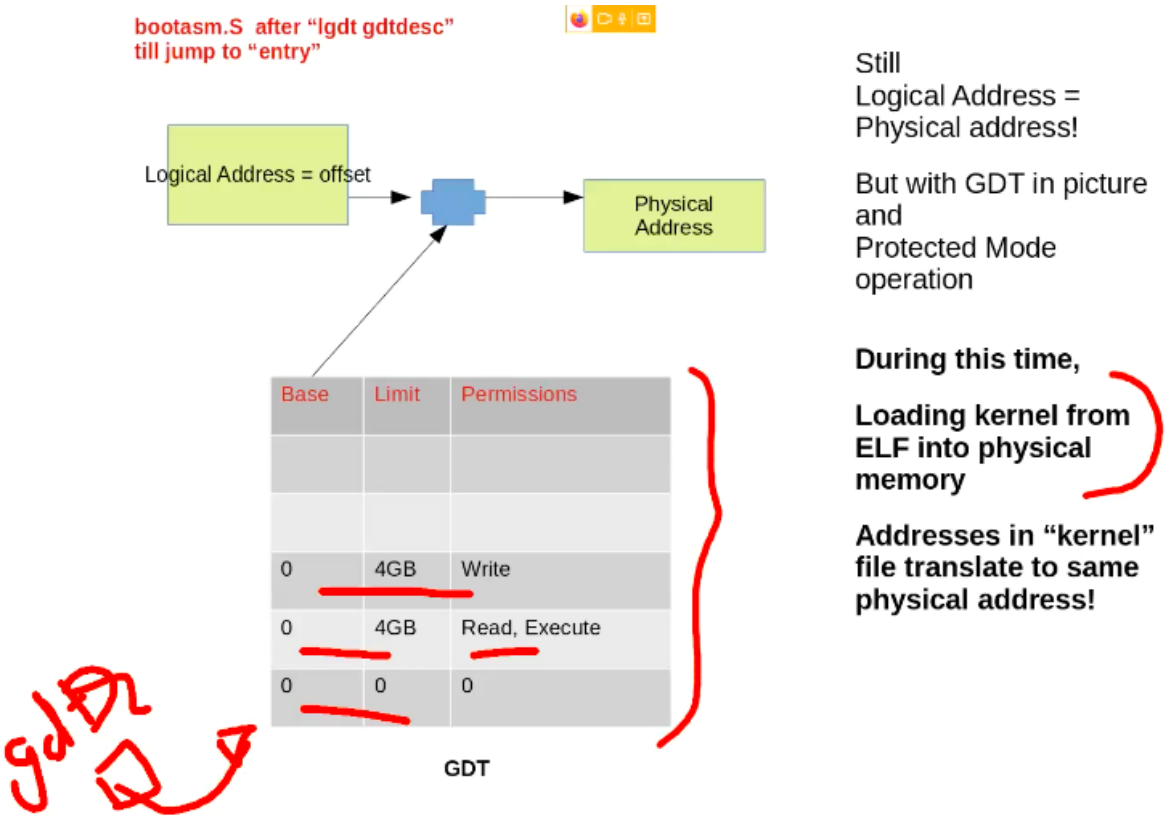
```
lgdt    gdtdesc
...
# Bootstrap GDT
.p2align 2   # force 4 byte alignment
gdt:
  SEG_NULLASM     # null seg
  SEG_ASM(STA_X|STA_R, 0x0, 0xffffffff)   # code seg
  SEG_ASM(STA_W, 0x0, 0xffffffff)

   # data seg

gdtdesc:
  .word   (gdtdesc - gdt - 1)
# sizeof(gdt) - 1
  .long   gdt
```

lgdt

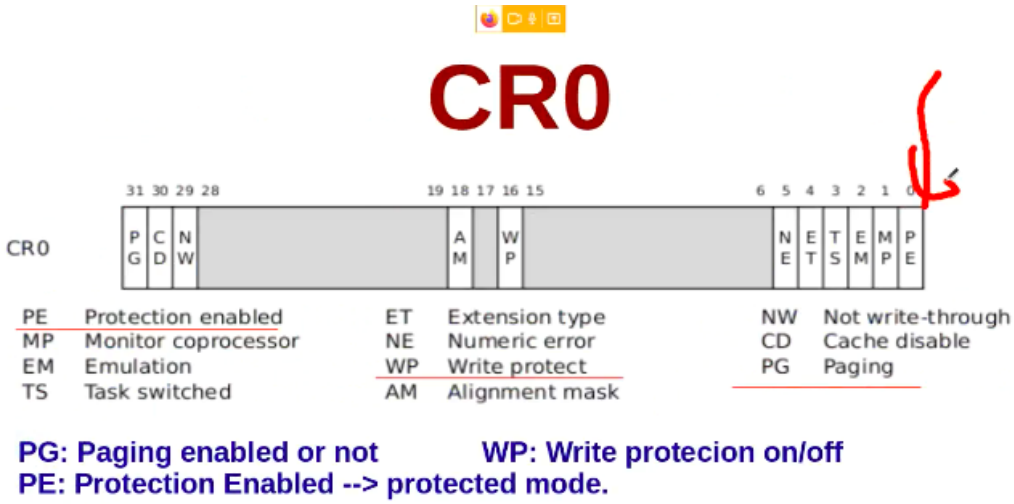


- load the processor's (GDT) register with value gdtdesc which points to the table
- table gdt : The table has a null entry, one entry for executable code, and one entry to data.
- all segments have a base address of zero and the maximum possible limit
- The code segment descriptor has a flag set that indicates that the code should run in 32-bit mode
- With this setup, when the boot loader enters protected mode, logical addresses map one-to-one to physical addresses.
- At gdtdesc we have this data
  - 2, <4 byte addr of gdt>
  - Total 6 bytes
  - GDTR is : <address 4 byte>, <table limit 2 byte>
  - So lgdt gdtdesc loads these two values in GDTR

table limit 2 byte is the size of gdt table



gdtr register points to base of this gdt table. `Note protected mode is still not enabled.`

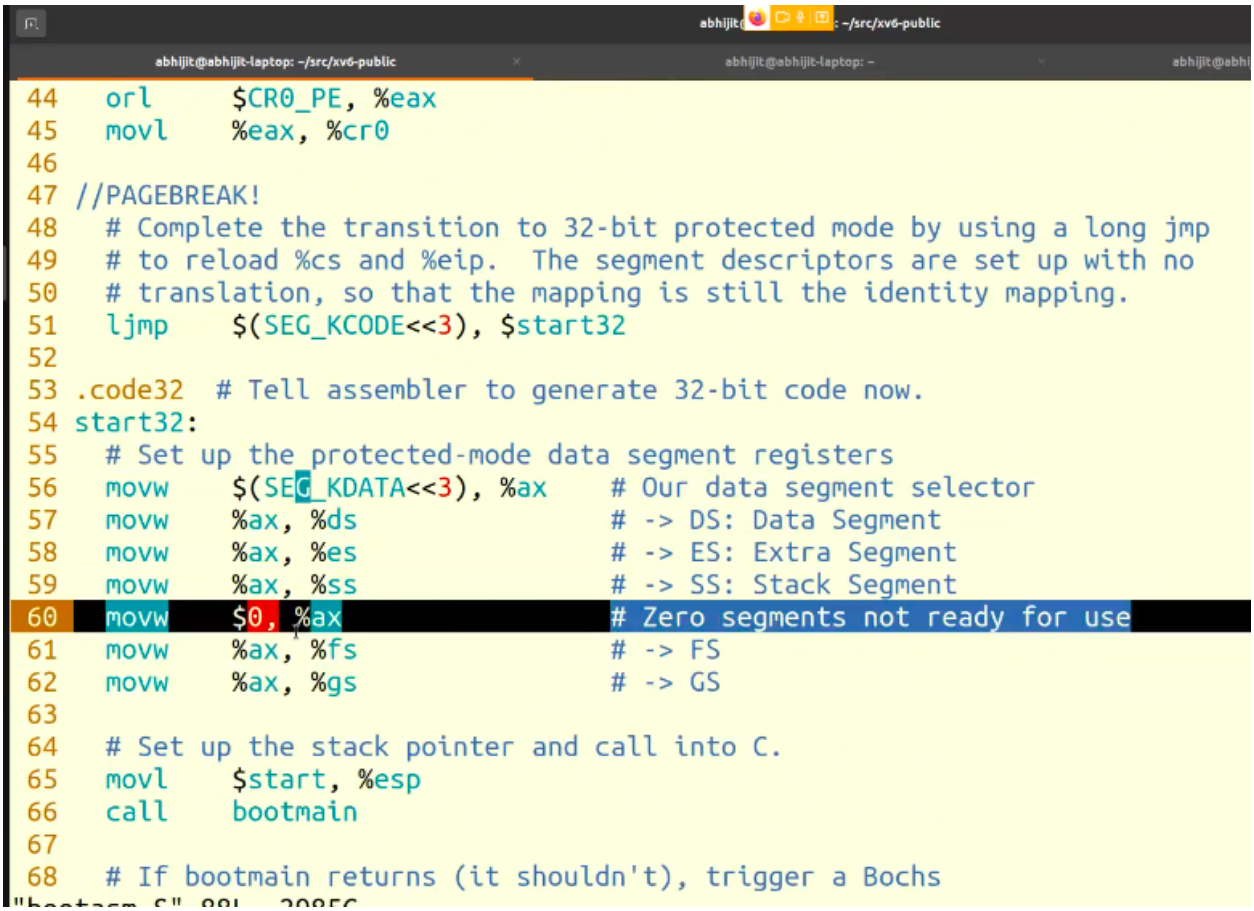


last bit of CR0 register is protected mode enable.

In fig 1: for code we can see 3 lines of code enabling that and then a ljmp instruction.

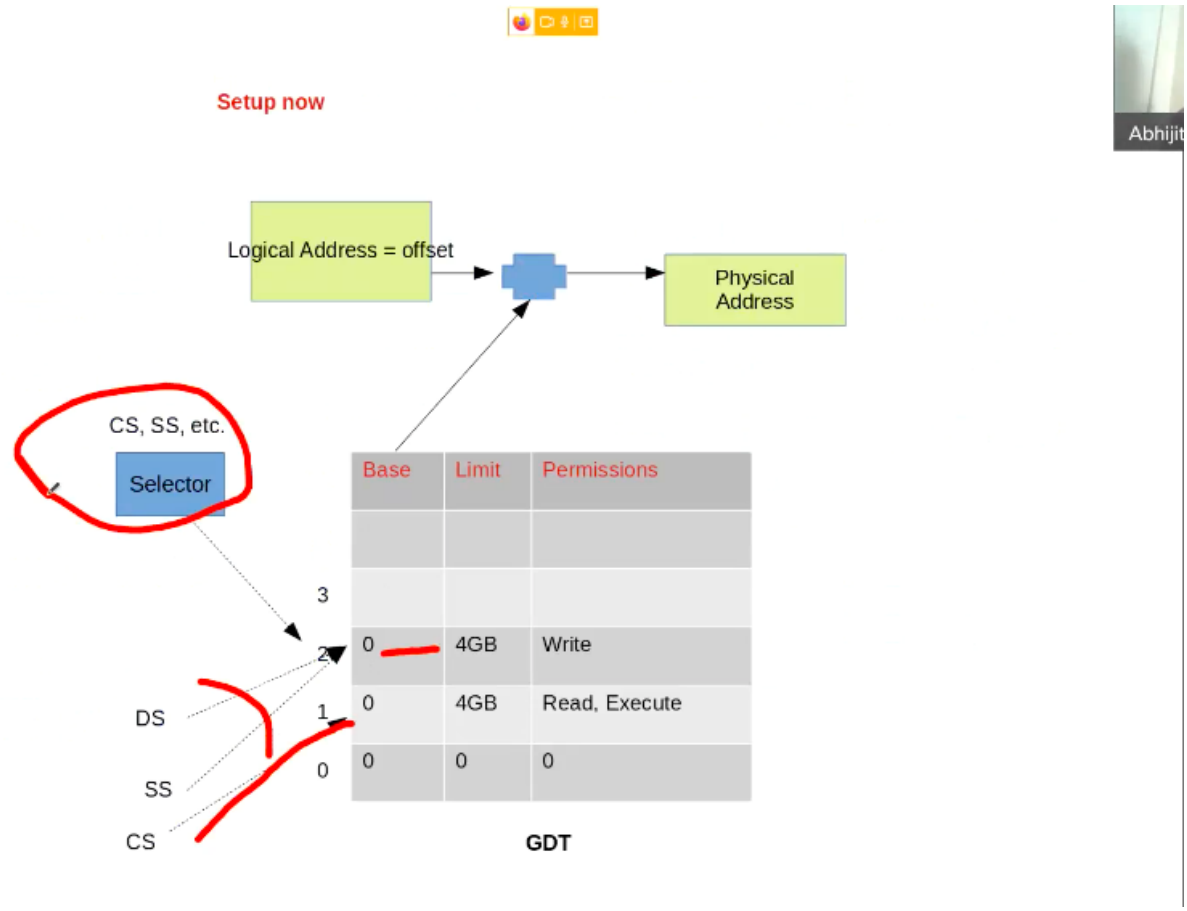
SEG_KCODE=1, which is left shifted by 3 and put into code segment, and jumps to start32.

why left shift by 3? because last 3 bits of segment selector which are not part of value, they are 2 bit of RPL and 1 bit for table index(TI)



now at line 56, SEG_KDATA is 2 which is left shifted by 3 and put into ax

so DS,ES,SS gets loaded by 2, whereas FS AND GS is loaded with 0. and we are in protected mode.



at line 65 we copy $start i.e. 0x7c00 into stack pointer, $esp=0x7c00, now stack pointer will grow from 0x7c00 upto 0. boot loader code was loaded at 0x7c00 to upwards, and below that is stack.

then we call bootmain, since it is call instr, it will push the returnvalue into stack at 0x7c00 and now jumps to c code of bootmain. the setup of stack was necessary to execute C program,else we cannot execute C code.

which will load the kernel from disk into RAM and then do paging setup and RUN the Kernel. As of now MMu setup of x86 is done, protected mode, gdt table setup.

why are there different permissions?

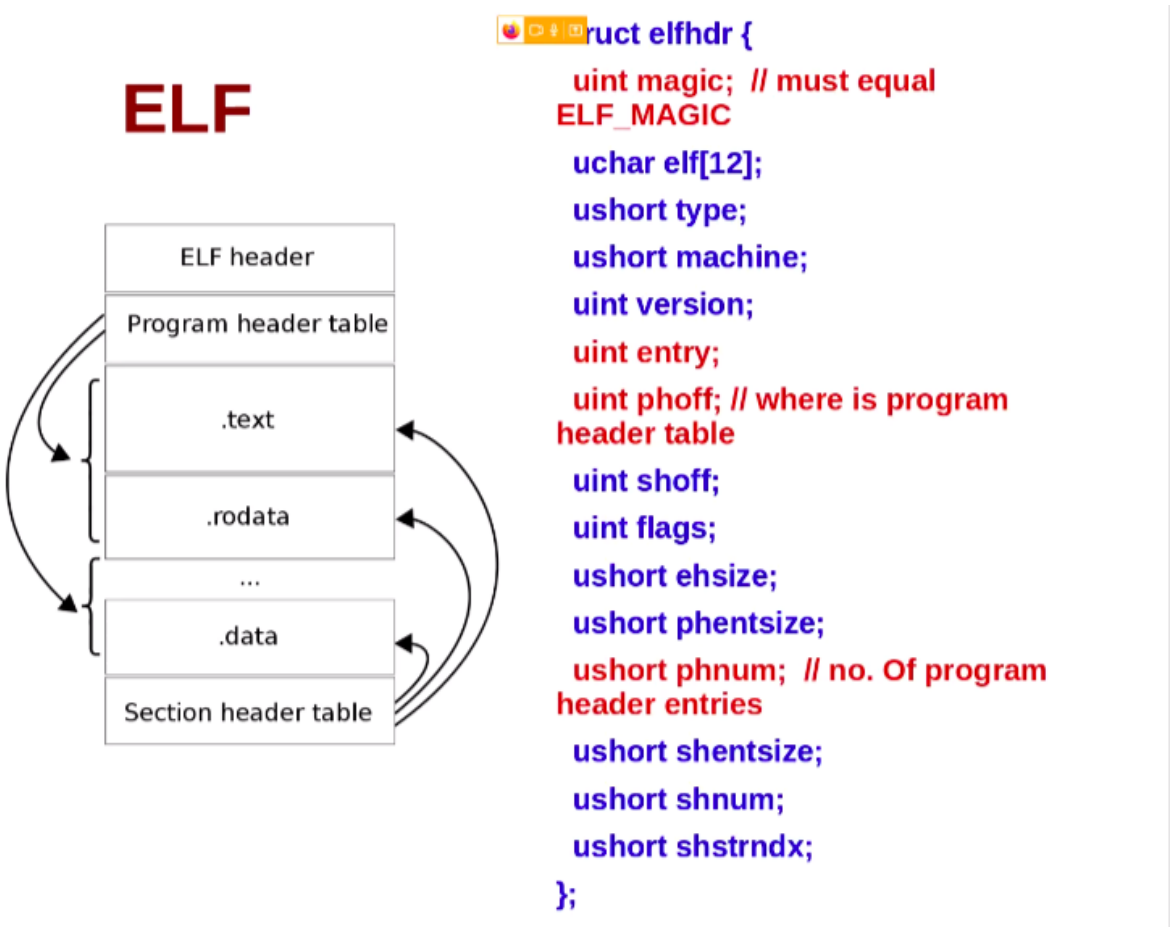
we don’t want the code segment to be read and execute, we dont want code to be written over.

job of bootmain is to load kernel from disk to memory

bootmain(): already in memory, as part of 'bootblock'

- bootmain.c , expects to find a copy of the kernel executable on the disk starting at the second sector (sector = 1).
  - Why?
- The kernel is an ELF format binary
- Bootmain loads the first 4096 bytes of the ELF binary. It places the in-memory copy at address 0x10000
- readseg() is a function that runs OUT instructions in particular IO ports, to issue commands to read from Disk

```
void
bootmain(void)
{
  struct elfhdr *elf;
  struct proghdr *ph, *eph;
  void (*entry)(void);
  uchar* pa;

  elf = (struct elfhdr*)0x10000;  // scratch space

  // Read 1st page off disk
  readseg((uchar*)elf, 4096, 0);
```



ELF magic is number that identifies that this is a elf file,it is 0x464C457FU #defined in elf.h

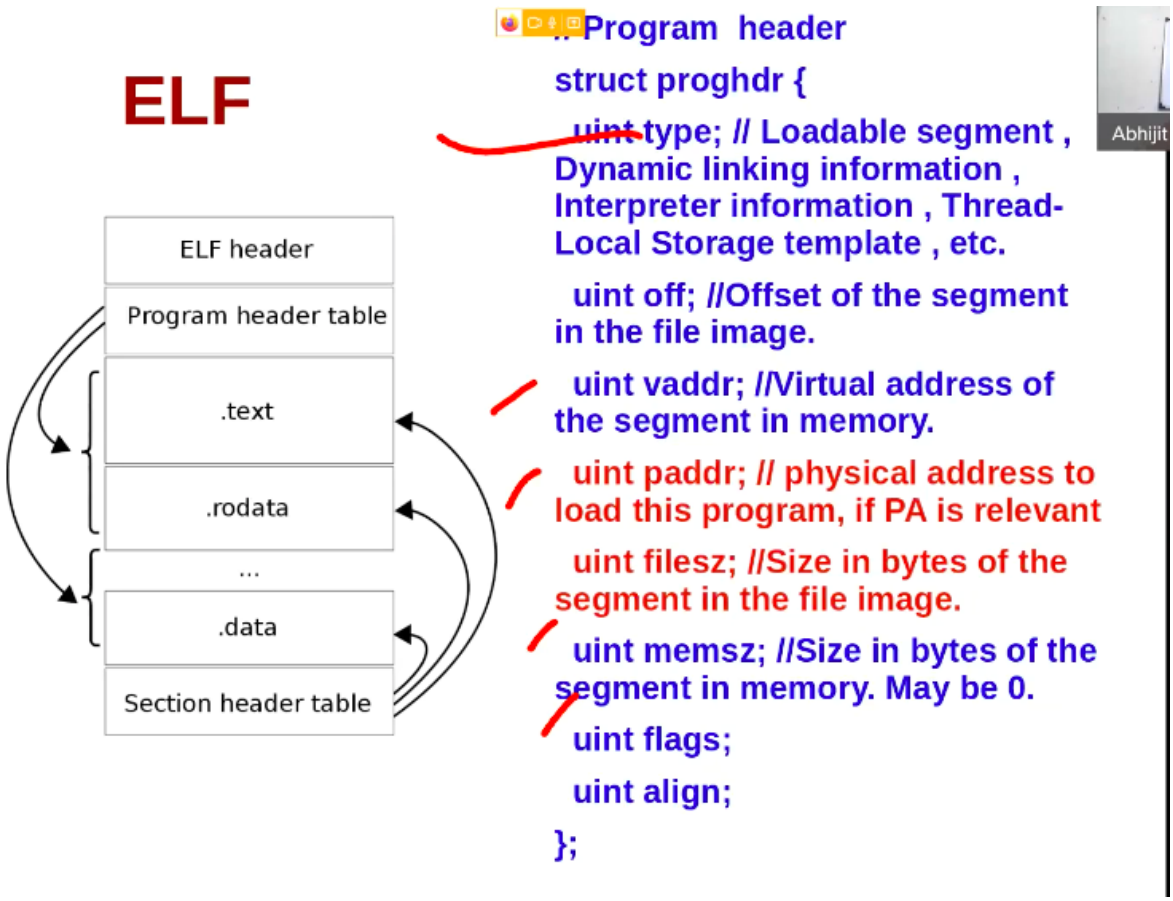
size of elf header is 52 bytes

https://stackoverflow.com/questions/64795450/xv6-bootmain-loading-kernel-elf-header

entry is the index to first instruction in elf file that should be executed first

phoff, where in the file is program header located

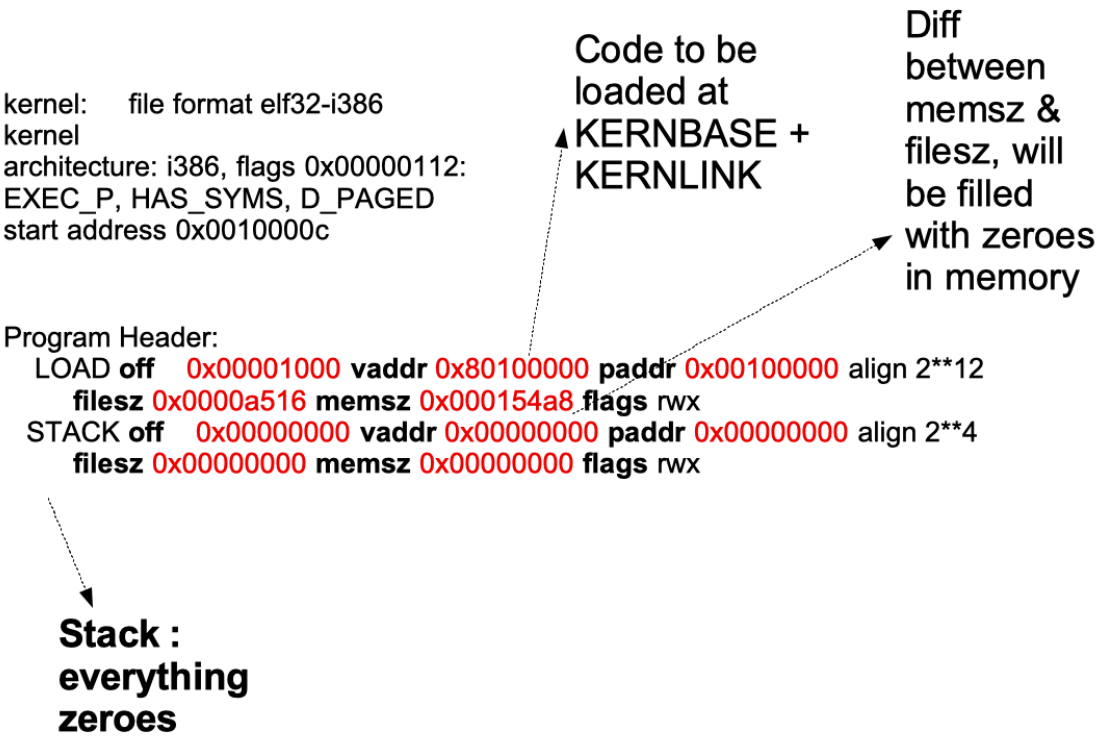
the first readseg() effectively only reads the header + program headers in scratch space at 0x10000(4 zeroes)

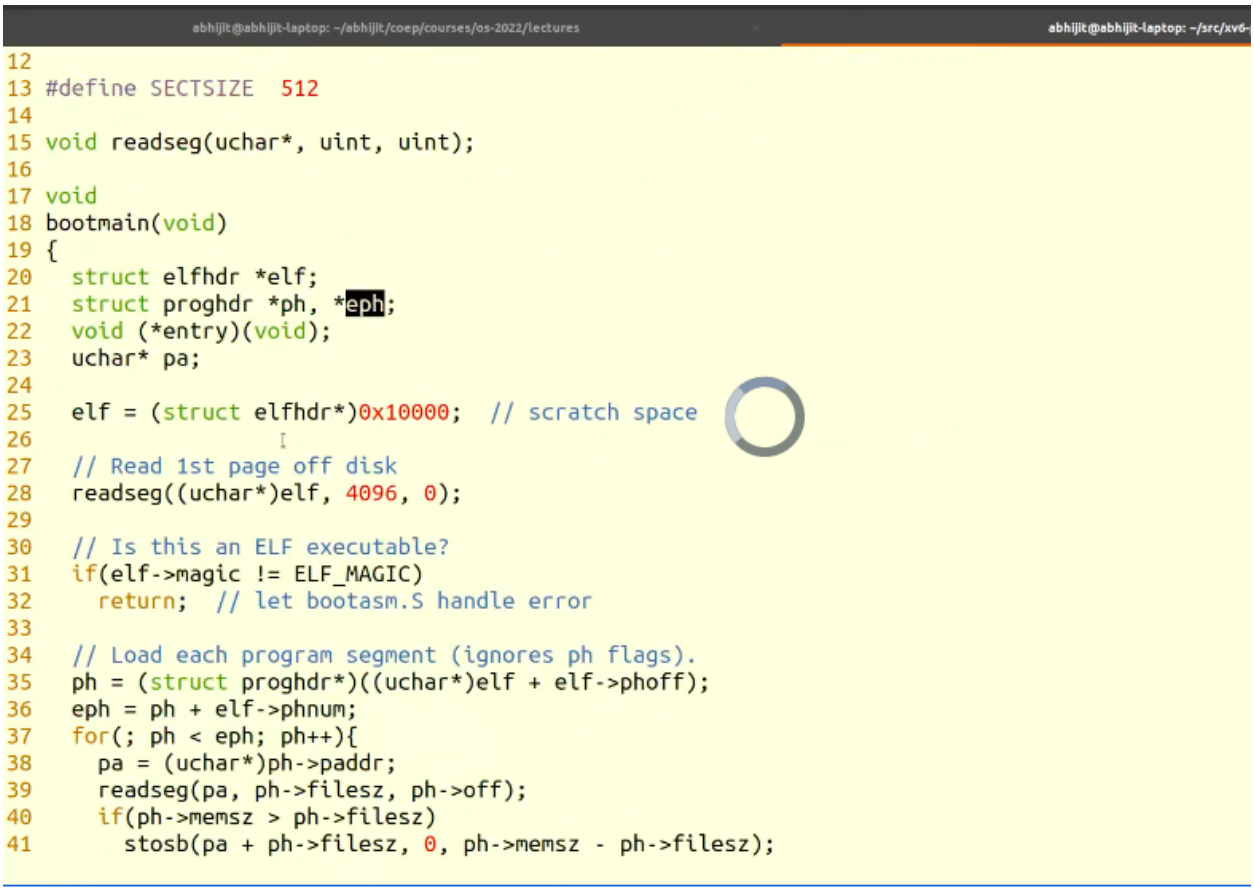


0x80100000 → virtual addr of KERNEL, physical address is 0x00100000

there are 3 program headers of elf file of kernel

Run ‘objdump -x -a kernel | head -15’ & see this





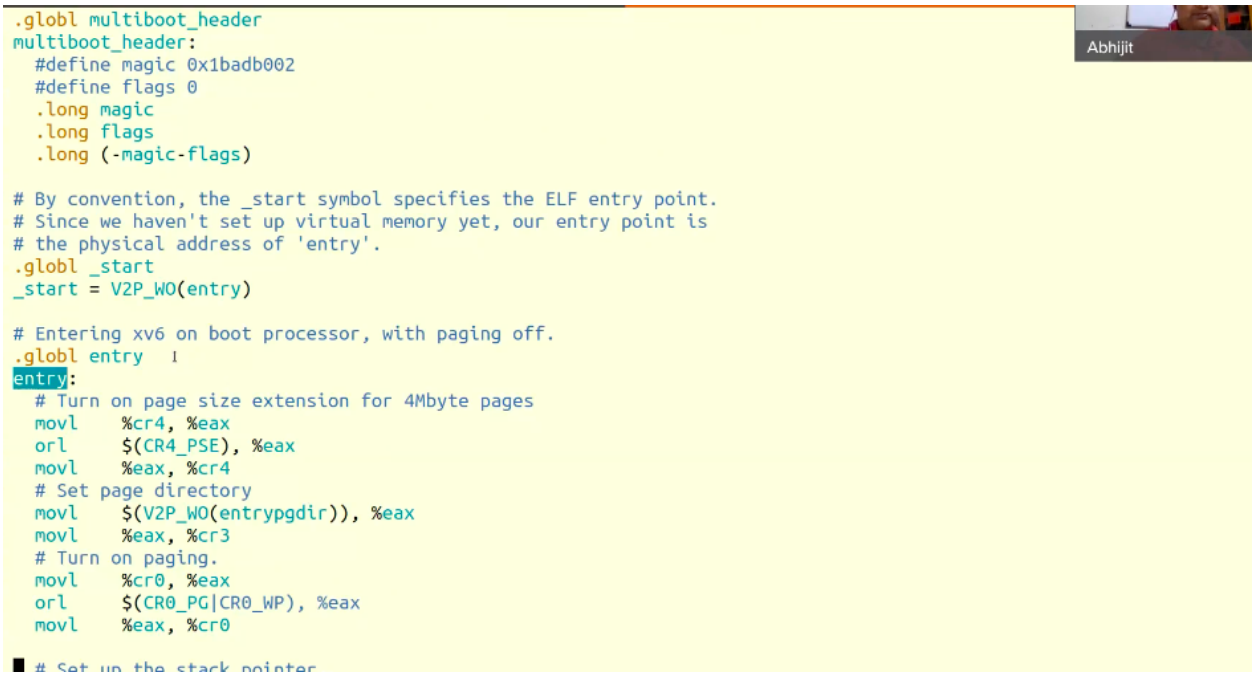
readseg reads the segment according to sector size(512 bytes) and calls readsect, which runs some instr to read content from disk.

the for loop is responsible for loading kernel into memory, pa is the address in the physical memory where kernel is to be loaded and readseg loads that segment into that address.

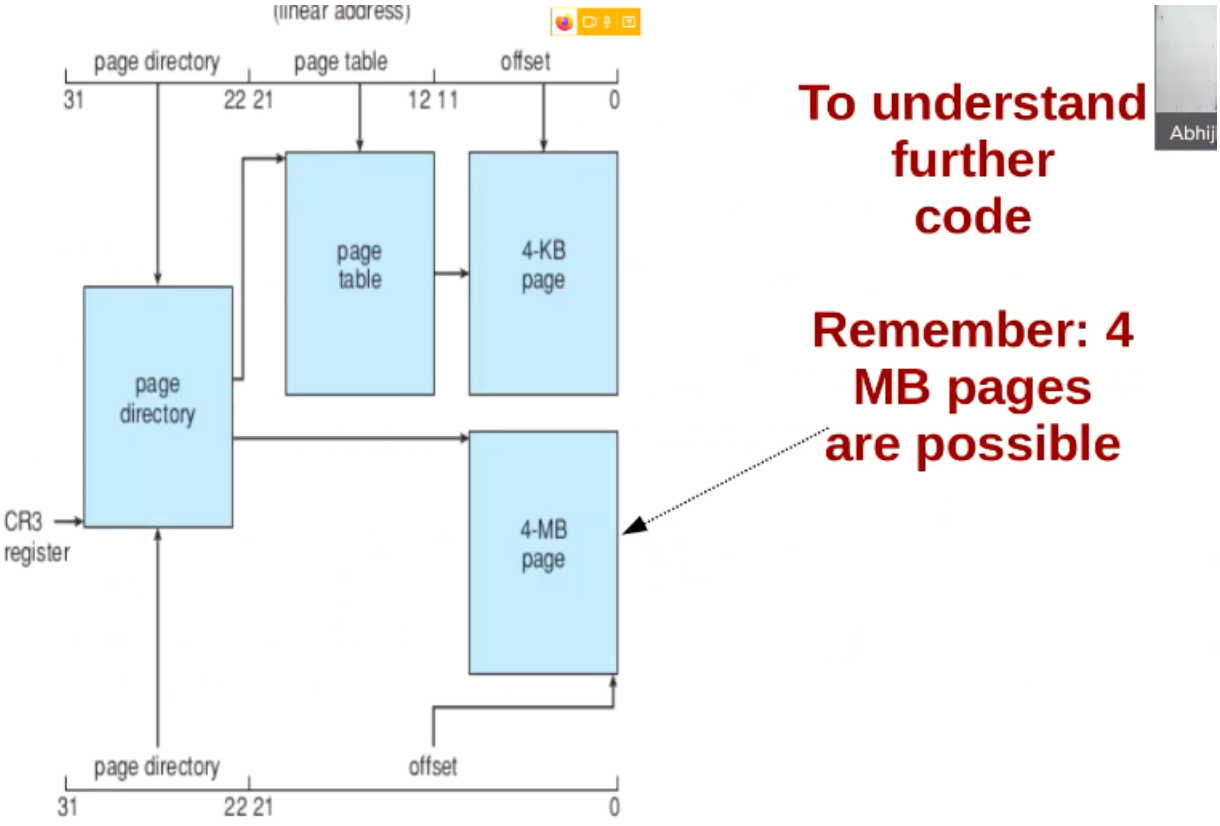
stosb will fill the gap of memsz-filesz with zeroes.

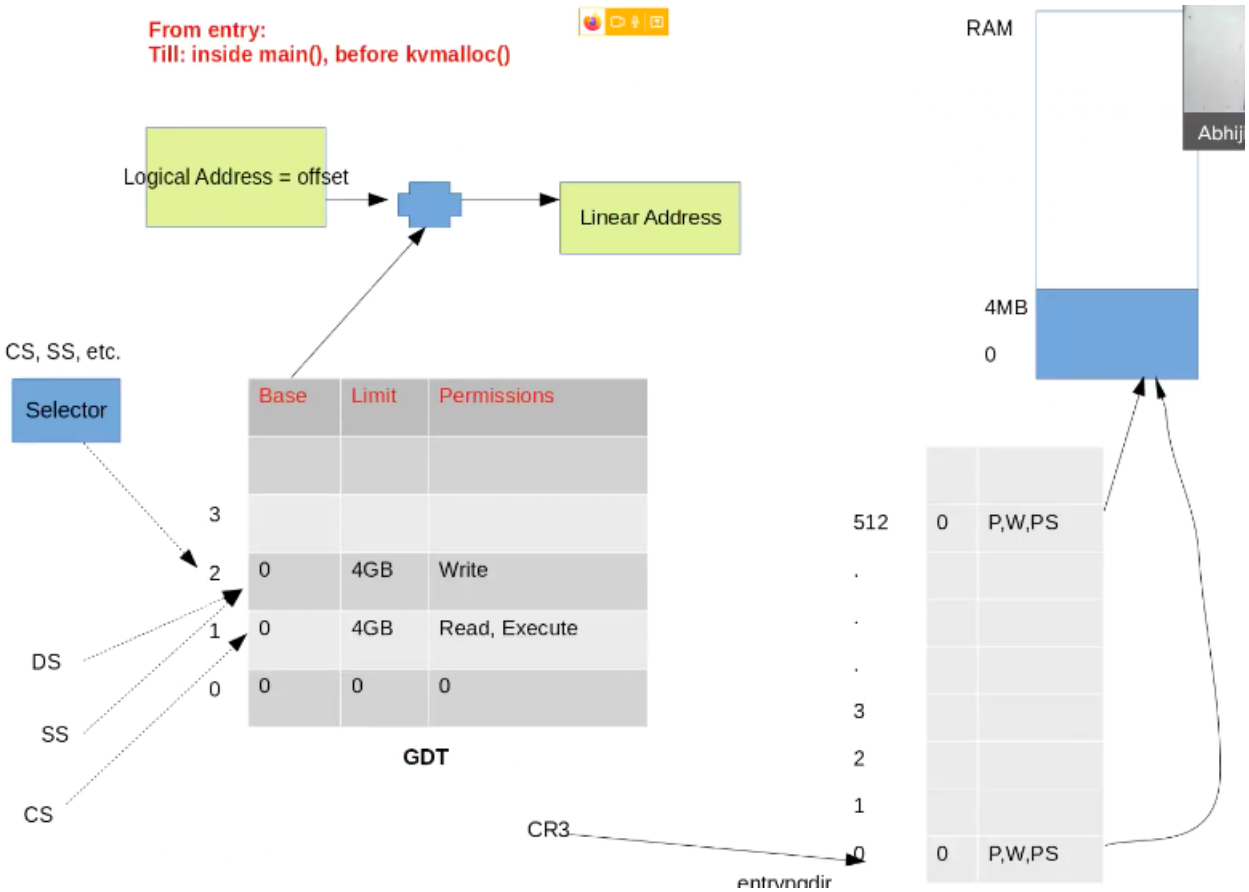
Jump to Entry

```
  // Call the entry point from the
ELF header.
  // Does not return!
  /* Abhijit:
   * elf->entry was set by Linker
using kernel.ld
   * This is address 0x80100000
specified in kernel.ld
   * See kernel.asm for kernel
assembly code).
   */
```



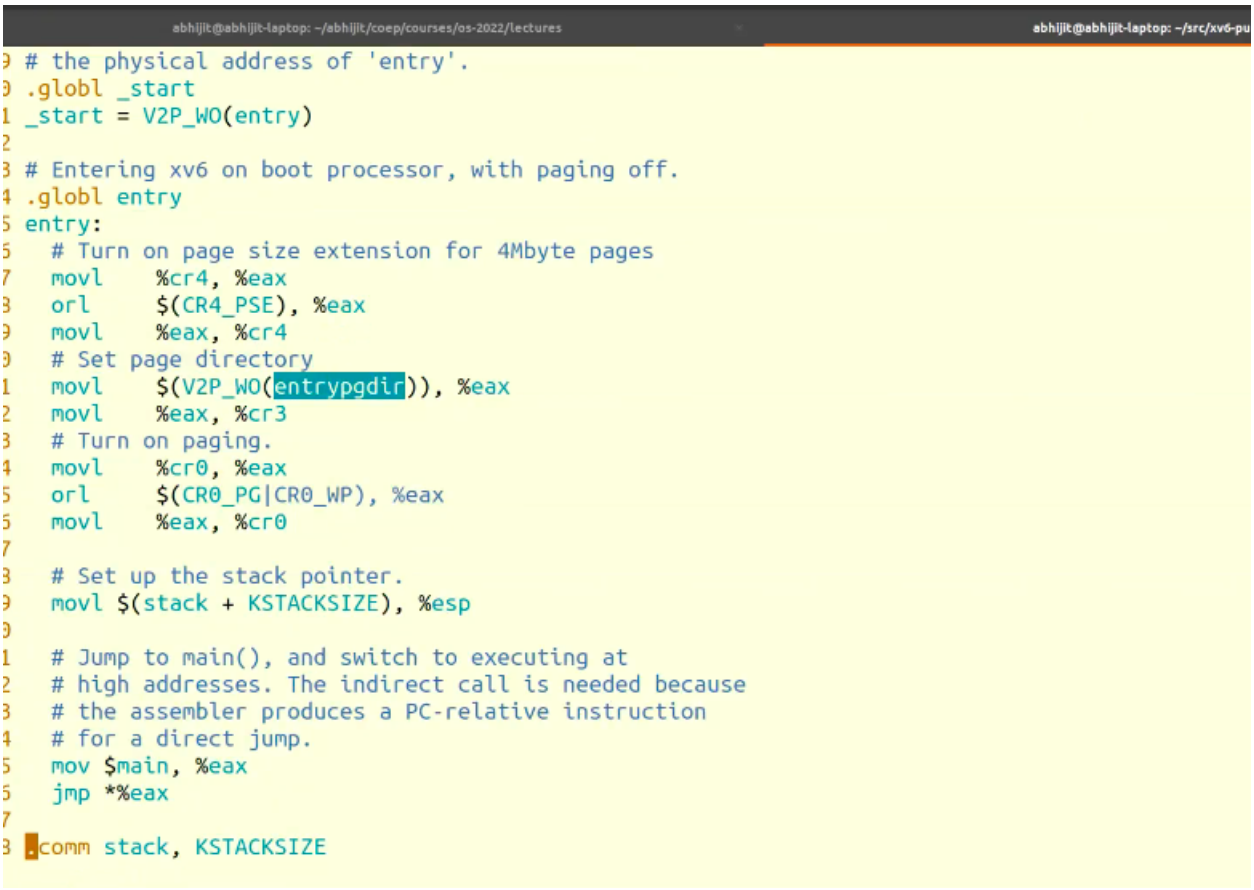
this is the code of entry called in bootmain.c

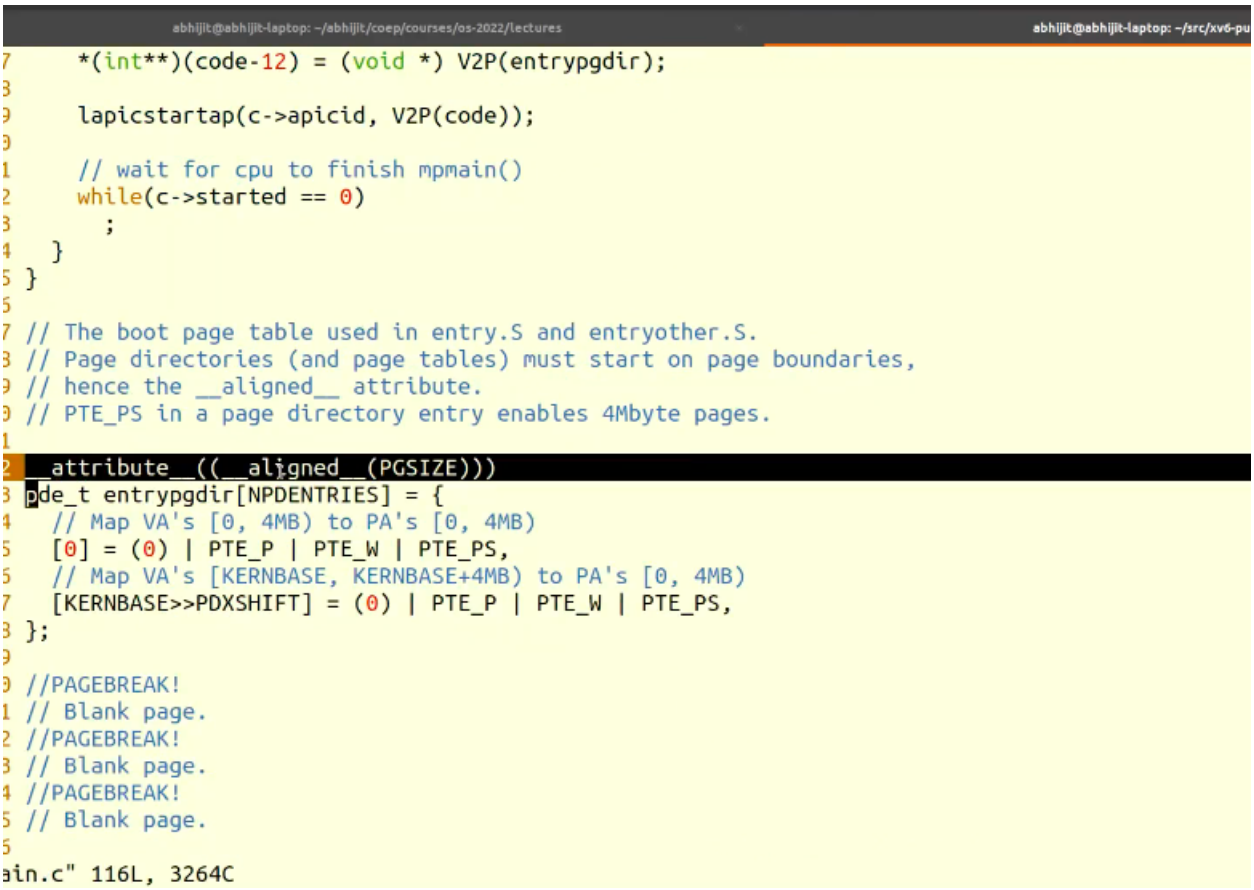




how big the kernel code actually is?

we are going to set up 4mb pages, both 0 and 512 entry in the page directory points to lowest value in the physical memory, and CR3 register points to page directory base table as discussed before. remember we have loaded kernel into 0x100000 address which is the part of this lowest 4mb page that 0 and 512 entry points to.


abhijit@abhijit-laptop: ~/abhijit/coep/courses/os-2022/lectures
abhijit@abhijit-laptop: ~/src/xv6-pu
the physical address of 'entry'.
.globl _start
_start = V2P_WO(entry)
# Entering xv6 on boot processor, with paging off.
.globl entry
entry:
# Turn on page size extension for 4Mbyte pages
movl %cr4, %eax
orl $(CR4_PSE), %eax
movl %eax, %cr4
# Set page directory
movl $(V2P_WO(entrypgdir)), %eax
movl %eax, %cr3
# Turn on paging.
movl %cr0, %eax
orl $(CR0_PG|CR0_WP), %eax
movl %eax, %cr0
# Set up the stack pointer.
movl $(stack + KSTACKSIZE), %esp
# Jump to main(), and switch to executing at
# high addresses. The indirect call is needed because
# the assembler produces a PC-relative instruction
# for a direct jump.
mov $main, %eax
jmp *%eax
.comm stack, KSTACKSIZE



entrypgdir is an array of pde_t (which is uint→4 bytes) which has NPDENTRIES(#defined 1024)

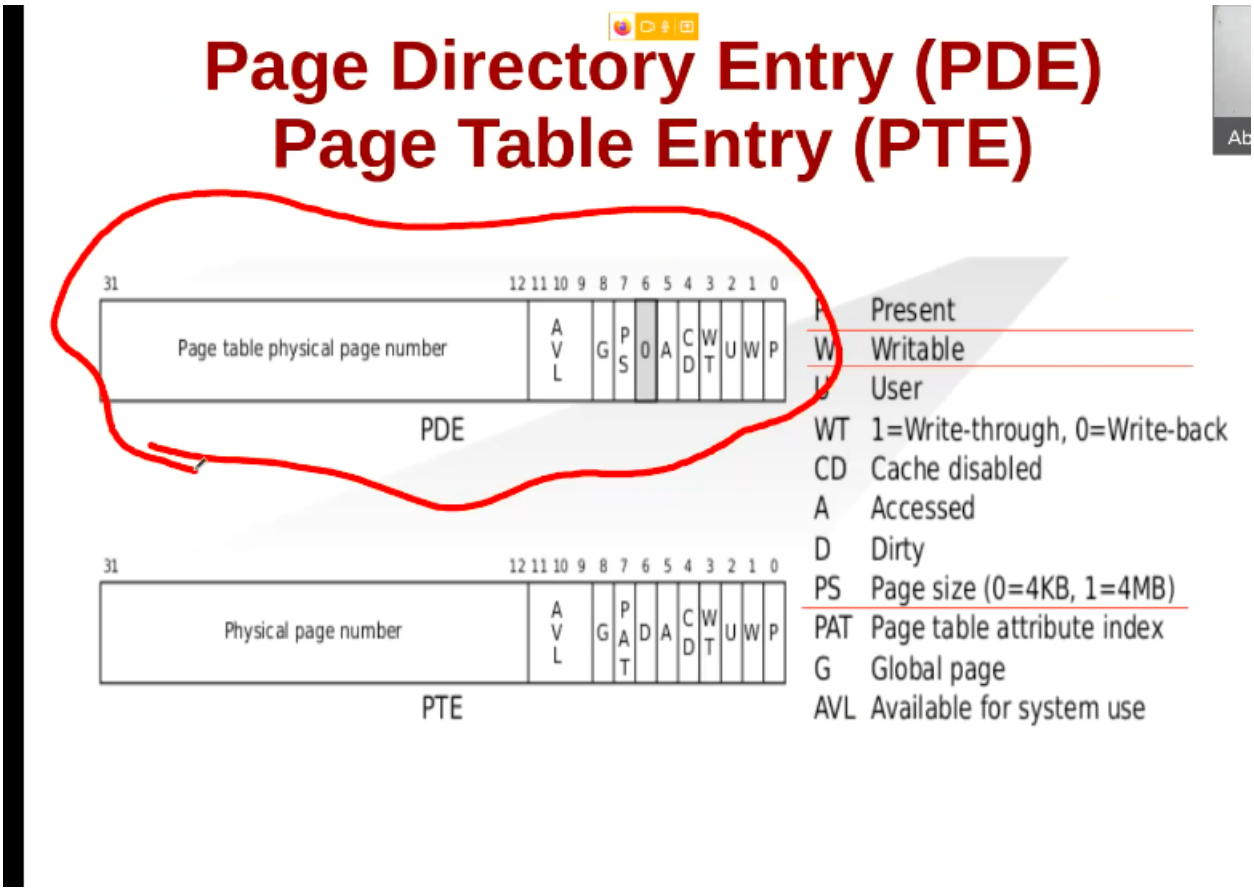
1024*4=4096B→ 4mb, out of which 2 entries are initialized,

[0] is the 0the entry of the page table

[1] is KERNBASE(virtual address of kernel) right shifted by PDXSHIFT i.e (#defined 22), why? because for 4mb pages 22 bit is the offset and to get the page directory number we right shift by 22 (which results in 512) hence making the 512th entry in the page table also point to the lowest 4mb page in memory

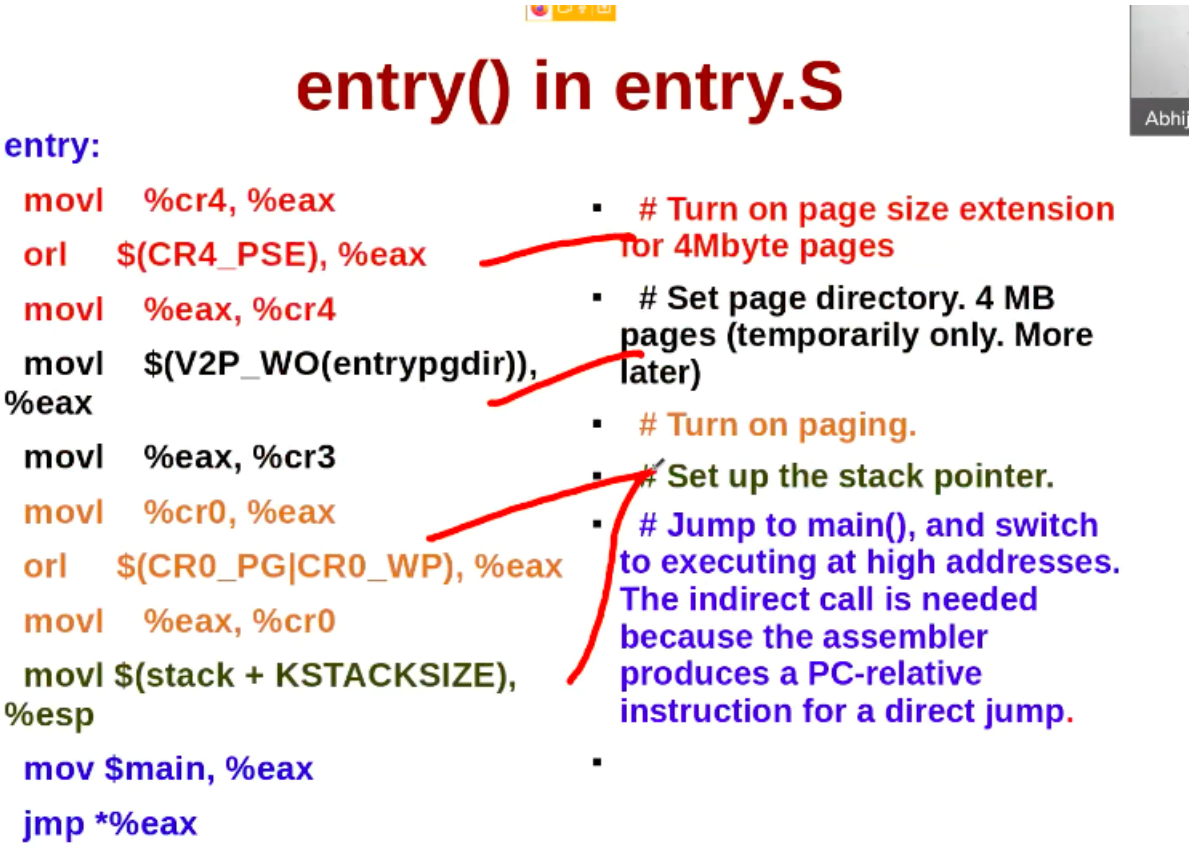
This is entry page directory during entry(), beginning of kernel
Mapping 0:0x400000 (i.e. 0: 4MB) to physical addresses 0:0x400000. is required as long as entry is executing at low addresses, but will eventually be removed.
This mapping restricts the kernel instructions and data to 4 Mbytes.

the value that we are setting is 0 | PTE_P | PTE_W | PTE_PS



so we are setting Present(entry valid or invalid), Writable and the PS(page size) bit to 1 i.e making page size to 4mb

NOTE:the stack setup at 0x7c00 is not available, hence we allocate a new stack of 4kb



CR4_PSE

V2P_WO converts virtual address of kernel to physical address of entrypgdir to eax which is moved to cr3(substract KERNBASE)

Here we use physical address using V2P_WO because paging is not turned on yet

```
#define EXTMEM  0x100000            // Start of extended memory
#define PHYSTOP 0xE000000           // Top physical memory
#define DEVSPACE 0xFE000000         // Other devices are at high addresses

// Key addresses for address space layout (see kmap in vm.c for layout)
#define KERNBASE 0x80000000         // First kernel virtual address
#define KERNLINK (KERNBASE+EXTMEM)  // Address where kernel is linked

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

#define V2P_WO(x) ((x) - KERNBASE)    // same as V2P, but without casts
#define P2V_WO(x) ((x) + KERNBASE)    // same as P2V, but without casts
```

CR0_PG means paging(32 bit) to be enabled, CR0_WP→ write protect enabled

line 59 moves some value to esp

KSTACKSIZE is 4096 #defined

stack variable is at line 68, .comm stack,KSTACKSIZE which means allocate a data of size KSTACKSIZE which is 4kb

so stack pointer is initialized here once again(of size=4kb), to value stack + KSTACKSIZE

jmp $main is not done directly, code generated by assembler will be according to particular value of program counter.the indirect call is needed because assembler produces a PC-relative instruction for a direct jump.

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

$main function is in 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
}

// Other CPUs jump here from entryother.S.
static void
mpenter(void)
{
  switchkvm();
  seginit();
  lapicinit();
```

kernel reinitializes in seginit(),and other init functions

7c00-7dff(512bytes)bootsector ends,+480kb(empty) till 1mb, usme 10000 pe elf header

processes

Process related data structures in kernel code

- Kernel needs to maintain following types of data structures for managing processes
  - List of all processes
  - Memory management details for each, files opened by each etc.
  - Scheduling information about the process
  - Status of the process
  - List of processes “waiting” for different events to occur,
  - Etc.

Process control block is most impo DS for the process

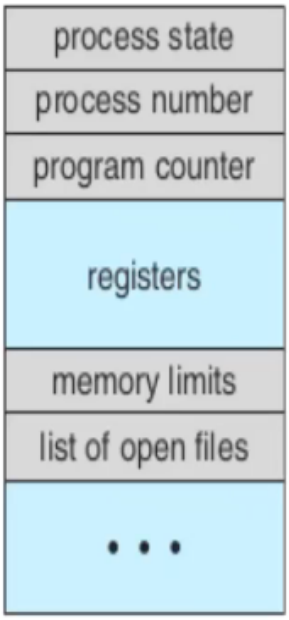


Figure 3.3 Process control block (PCB).

Process Control Block

- A record representing a process in operating system's data structures
- OS maintains a "list"of PCBs, one for each process
- Called "`struct task_struct`" in Linux kernel code and "`struct proc`" in xv6 code

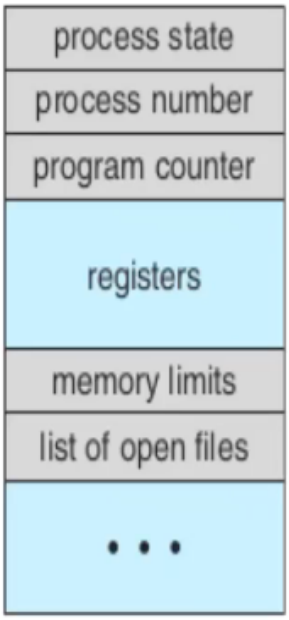


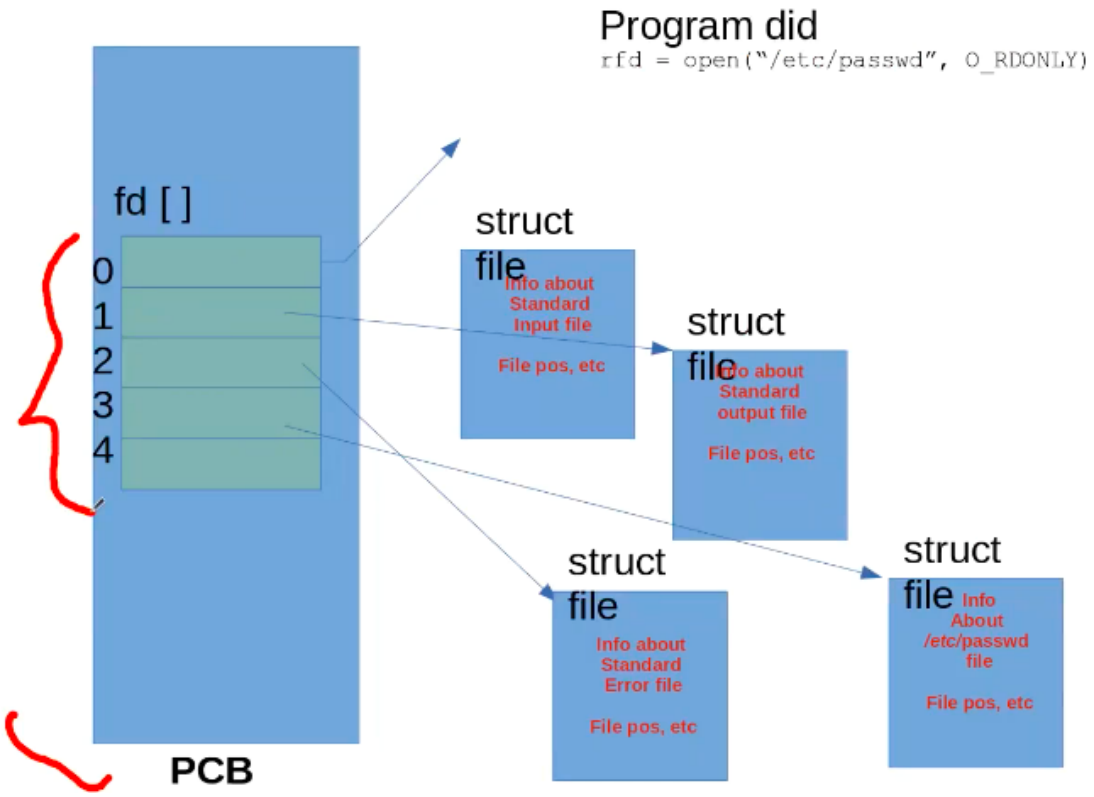
Figure 3.3 Process control block (PCB).

Fields in PCB

- Process ID (PID)
- Process State
- Program counter
- Registers
- Memory limits of the process
- Accounting information
- I/O status
- Scheduling information
- array of file descriptors (list of open files)
- ...etc

In a multitasking system, process gets switched, hence we need to store registers related to process in PCB.

List of open files



file descriptor is just the index of array of pointers in the PCB.

first 3 inputs are stdin,stdout,stderr.

PCB is stored in the kernel memory i.e /proc

PCB in xv6

```
/ XV6 Code : Per-process state
enum procstate { UNUSED, EMBRYO, SLEEPING,
RUNNABLE, RUNNING, ZOMBIE };

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)
;

struct {
  struct spinlock lock;
  struct proc proc[NPROC];
 ptable;
```

```
struct file {
  enum { FD_NONE,
FD_PIPE, FD_INODE } type;
  int ref; // reference count
  char readable;
  char writable;
  struct pipe *pipe;
  struct inode *ip;
  uint off;
};
```

ofile is the list of open files of struct file. procstate is zombie/orphan/running/sleeping

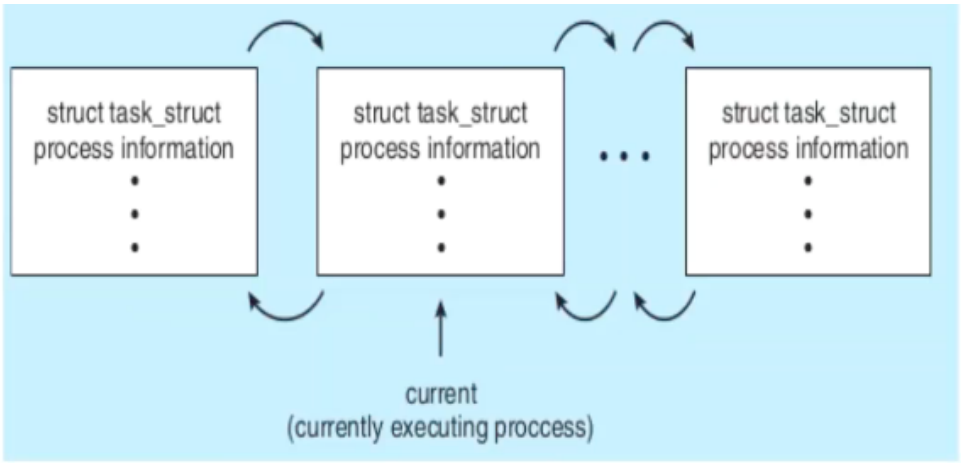
in struct file, off is the offset of file

ptable is a global variable which is the main DS for process, ptable.proc[i] will give PCB for any process. this is only data structure for process in xv6.

Process Queues/Lists inside OS

- Different types of queues/lists can be maintained by OS for the processes
  - A queue of processes which need to be scheduled
  - A queue of processes which have requested input/output to a device and hence need to be put on hold/wait
  - List of processes currently running on multiple CPUs
  - Etc.

in xv6, since there is only 1 array of ptable, then it contains all types of process, whereas some OS might have different queues as described in above image.

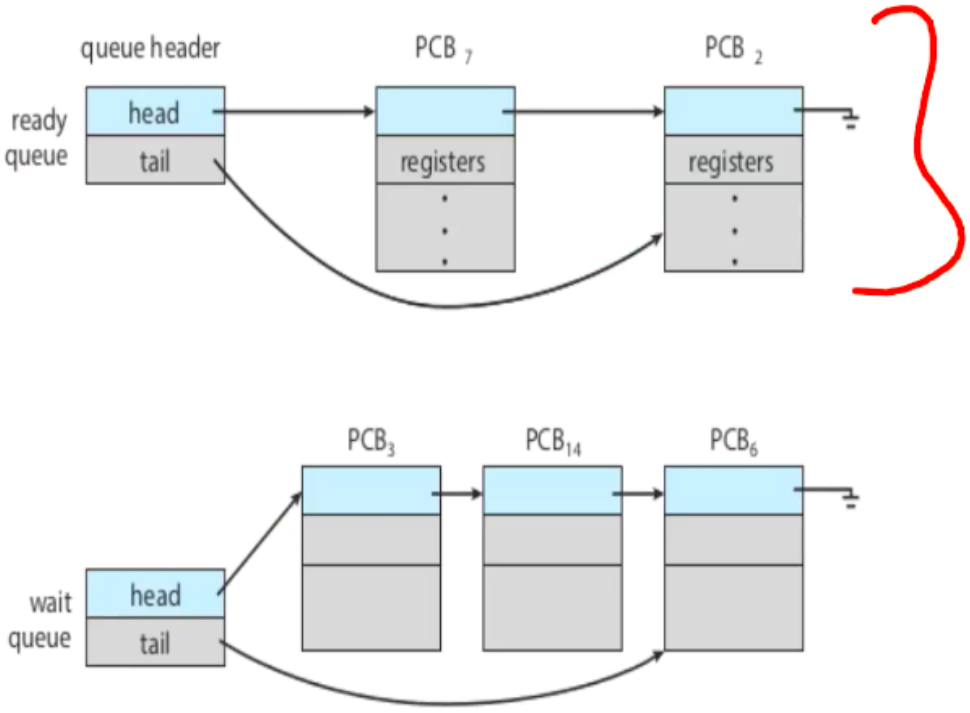



```
// Linux data structure
struct task_struct {
    long state;/*state of the process */
    struct sched_entity se; /* scheduling information */
    struct task_struct *parent; /*this process's parent */
    struct list_head children; /*this process's children */
    struct files_struct *files; /* list of open files */
    struct mm_struct *mm;/*address space */
```

```
struct list_head {
    struct list_head
*next, *prev;
};
```

struct list_head has next and prev pointers.

suppose many pcbs having list_head children, which are linked, i.e. linking of internal members of pcb


queue header
PCB 7
PCB 2
ready queue
head
tail
registers
registers
PCB3
PCB14
PCB6
wait queue
head
tail

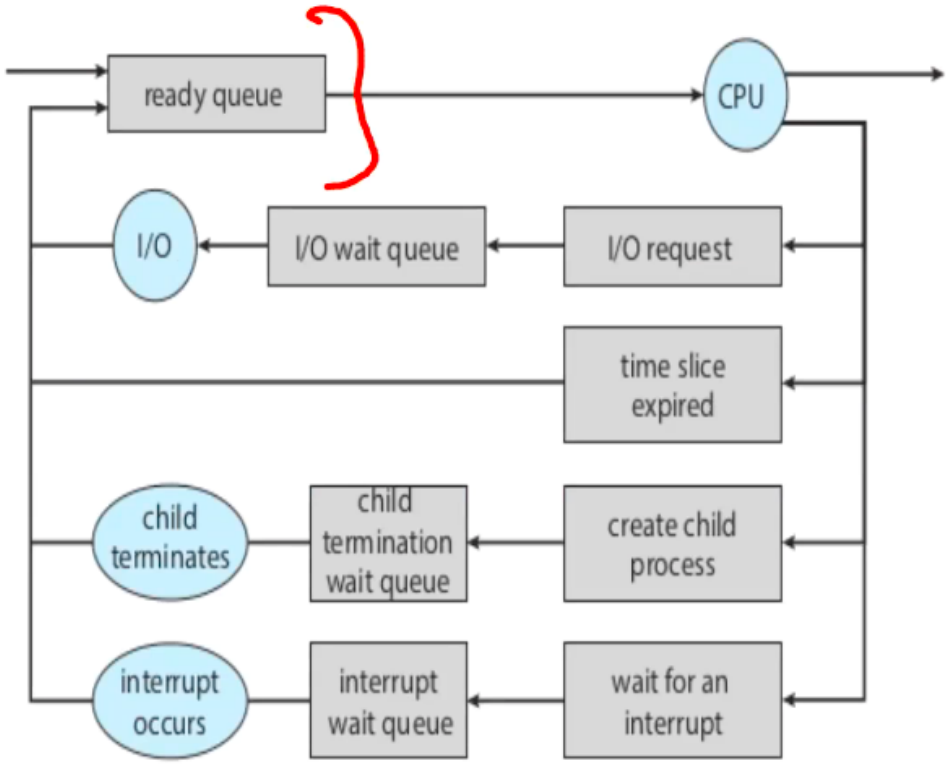


Figure 3.5 Queueing-diagram representation of process scheduling.

scheduler selects 1 process from ready queue and moved to cpu, if time slice expired, it is scheduled in ready queue at back, or if it does i/o it is put i/o wait queue, after I/O is done, it is pushed back in ready queue.

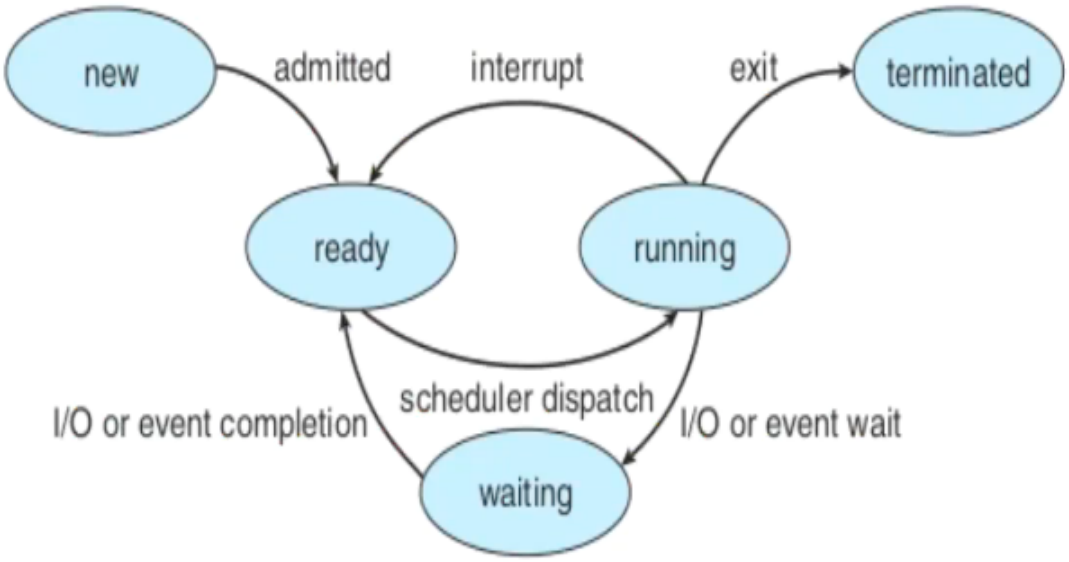


Figure 3.2 Diagram of process state.

- **Conceptual diagram**

a process is in new state, when fork happened. once pcb is completely constructed, it is move to ready queue, and state marked as ready. while running it is in running state, then from running state it has various paths. process can exit only by exit() syscall. for a process to exit, it has to be running first.If timer interrupt occurs it again moves to ready state. if I/o event occurs, it is moved to wait queue (waiting state) when keyboard interrupt is handled it is again moved to ready state.

whatever is not shown in diagram is not possible, i.e. a waiting process can never terminate.

how does user interrupt terminate process(ctrl+c)?

ctrl+c provides a signal called as SIGINT, and then signal handler code gets executed,this diagram has nothing to do with user interrupt.the process is not terminated by exit() then, it is terminated by kernel's code. This diagram is for process's state transition for process's code.similarly for segfault kernal's code handles.

“Giving up” CPU by a process or blocking

```
int main() {
i = j + k;
scanf("%d", &k);
}
int scanf(char *x, ...) {
...
read(0, ..., ...);
}
int read(int fd, char *buf, int len) {
...
__asm__ { "int 0x80..."}
...
}
```

OS Syscall

```
sys_read(int fd, char *buf, int len) {
 file f  = current->fdarray[fd];
 int offset = f->position;
 ...
 disk_read(... , offset, ...);
}
disk_read(...., offset, .... ) {
__asm__("outb PORT ..");
return;
}
```

after disk_read returns, interrupt listener is set for disk read ,move the process from ready queue to wait queue and call the scheduler code, this is called blocking.

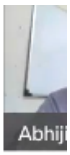
context switch

execution context of a process includes;-

Context Switch

- Context
  - Execution context of a process
  - CPU registers, process state, memory management information, all configurations of the CPU that are specific to execution of a process/kernel
- Context Switch
  - Change the context from one process/OS to OS/another process
  - Need to save the old context and load new context
  - Where to save? --> PCB of the process

Context Switch



- Is an overhead
- No useful work happening while doing a context switch
- Time can vary from hardware to hardware
- Special instructions may be available to save a set of registers in one go

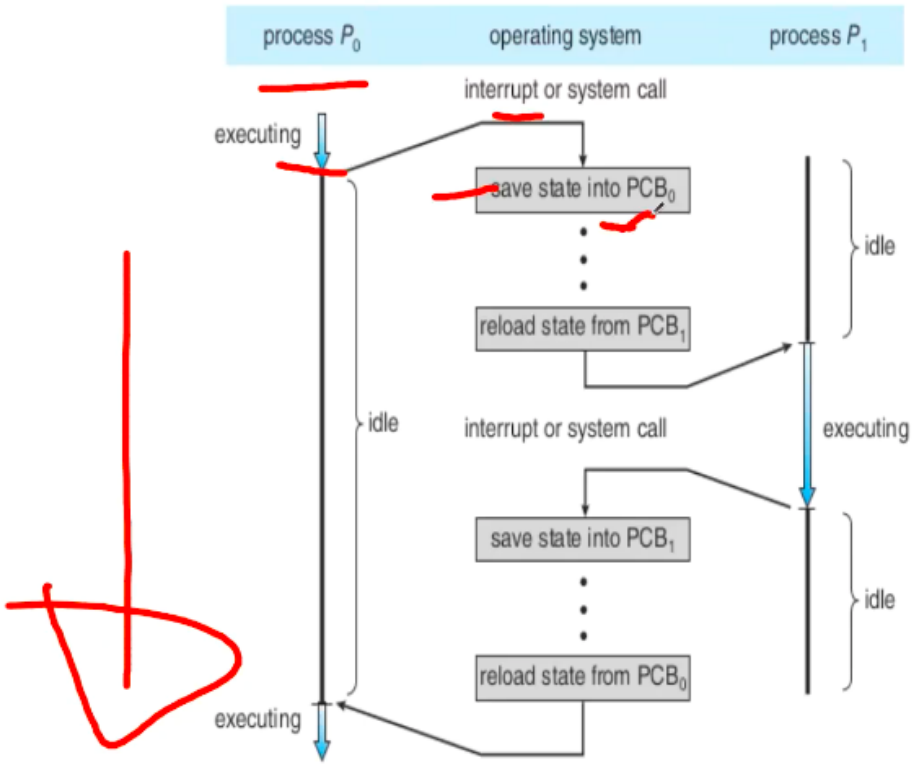
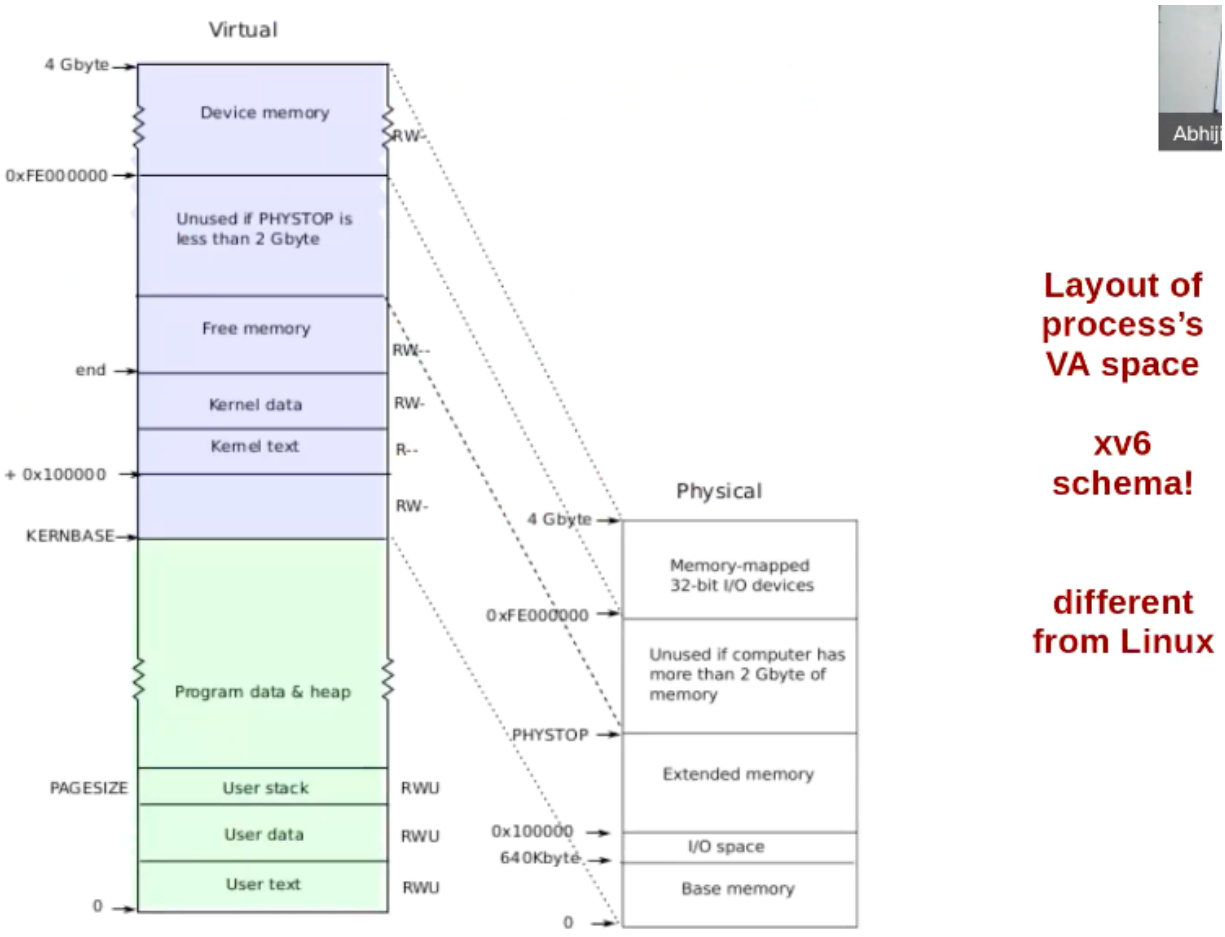


Figure 3.6 Diagram showing context switch from process to process.

Pecularity of context switch

- When a process is running, the function calls work in LIFO fashion
  - Made possible due to calling convention
- When an interrupt occurs
  - It can occur anytime
  - Context switch can happen in the middle of execution of any function
- After context switch
  - One process takes place of another
  - This “switch” is obviously not going to happen using calling convention, as no “call” is happening
  - Code for context switch must be in assembly!

xv6 code



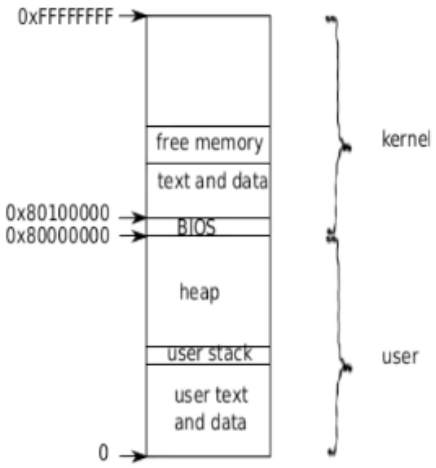
xv6 memory mapping diagram

KERNBASE IS 0X80000000 i.e 2gb, kernel code starts from 0x80100000 is 2gb+1mb

PHYSTOP IS 224mb

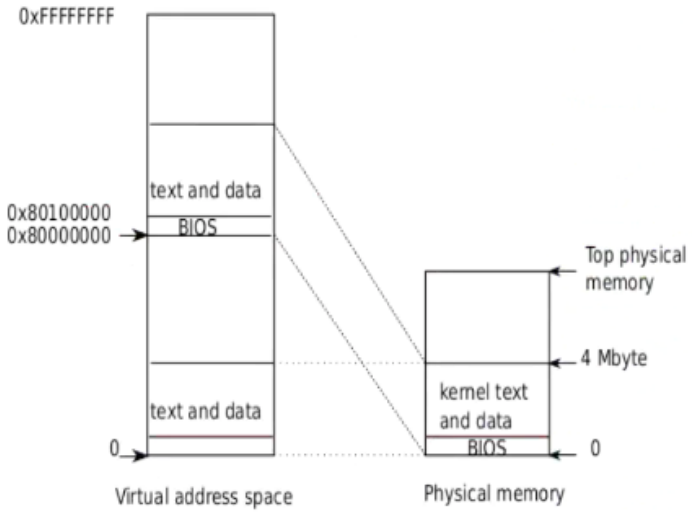
when a process is created and page table is setup the page table needs to have mapping of all these shown in above diagram.

Logical layout of memory for a process



- Address 0: code
- Then globals
- Then stack
- Then heap
- Each processe's address space maps kernel's text, data also --> so that system calls run with these mappings
- Kernel code can directly access user memory now

Kernel mappings in user address space actual location of kernel

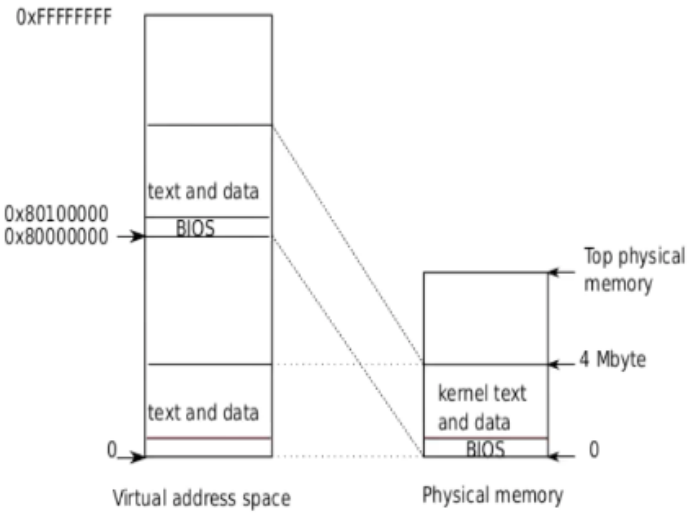


- Kernel is loaded at 0x100000 physical address
- PA 0 to 0x100000 is BIOS and devices
- Process's page table will map

  VA 0x80000000 to PA 0x00000 and

  VA 0x8010000 to 0x100000

Kernel mappings in user address space actual location of kernel



- Kernel is not loaded at the PA 0x80000000 because some systems may not have that much memory
- 0x80000000 is called KERNBASE in xv6

in xv6 every process has 2 stacks, a user stack, a kernel stack. first for running application code, second for running kernel code(syscalls, exceptions) on behalf of application

Imp Concepts

- A process has two stacks
  - user stack: used when user code is running
  - kernel stack: used when kernel is running on behalf of a process
- Note: there is a third stack also!
  - The kernel stack used by the scheduler itself
  - Not a per process stack

Struct proc


```
// 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. allocated, ready to run, running, wait-
ing for I/O, or exiting.
  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. Process's context
  void *chan;                  // If non-zero, sleeping on chan. More when we discuss
sleep, wakeup
  int killed;                  // If non-zero, have been killed
  struct file *ofile[NOFILE];  // Open files, used by open(), read(),...
  struct inode *cwd;           // Current directory, changed with "chdir()"
  char name[16];               // Process name (for debugging)
};
```

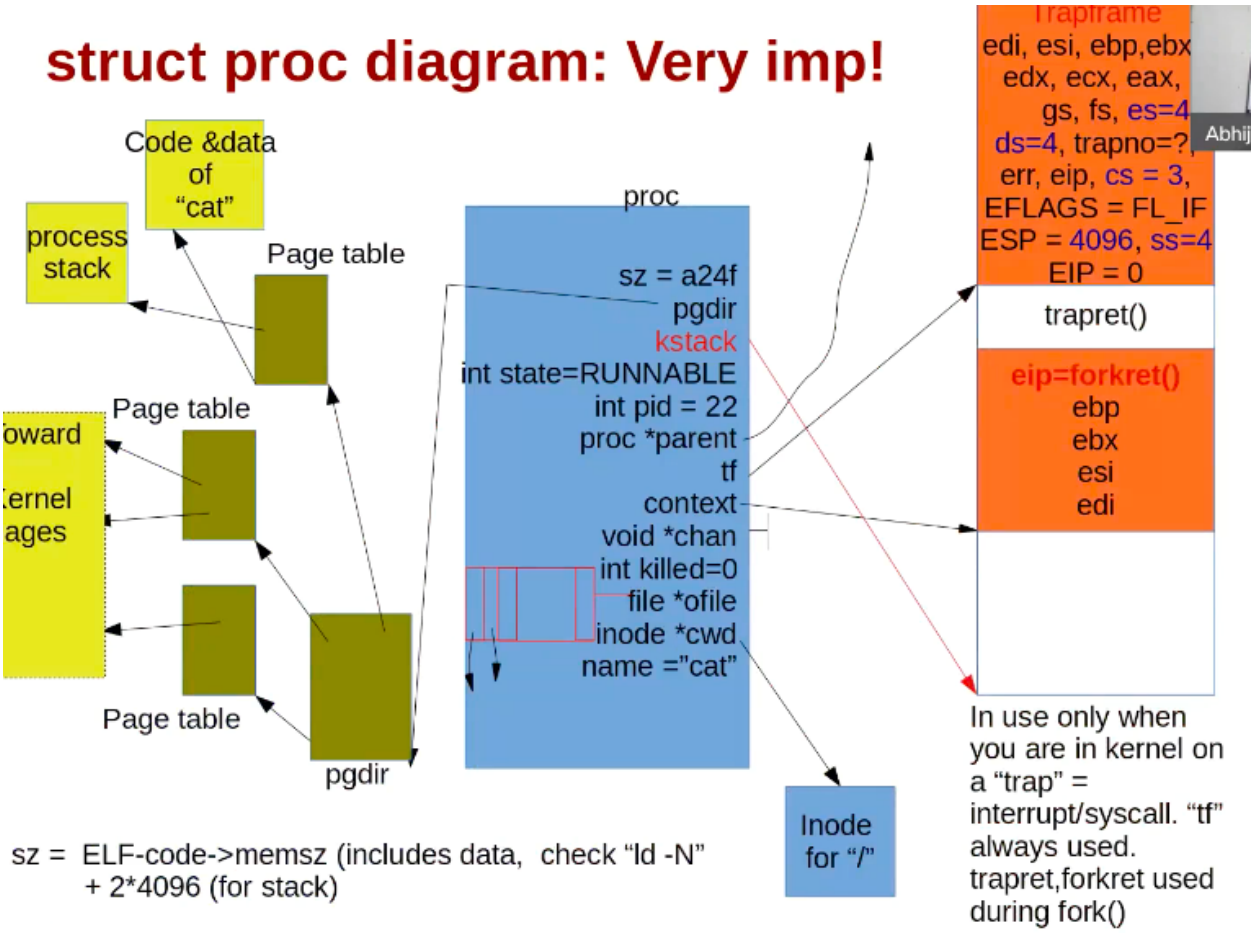
sz is the maximum virtual address, available in the elf file, sz has to be less than 2gb since process in xv6 has to be less than 2gb(KERNBASE=2gb see diagram).

pgdir is a pointer to base of page table, xv6 uses 2 level paging.this pointer will be loaded in cr3

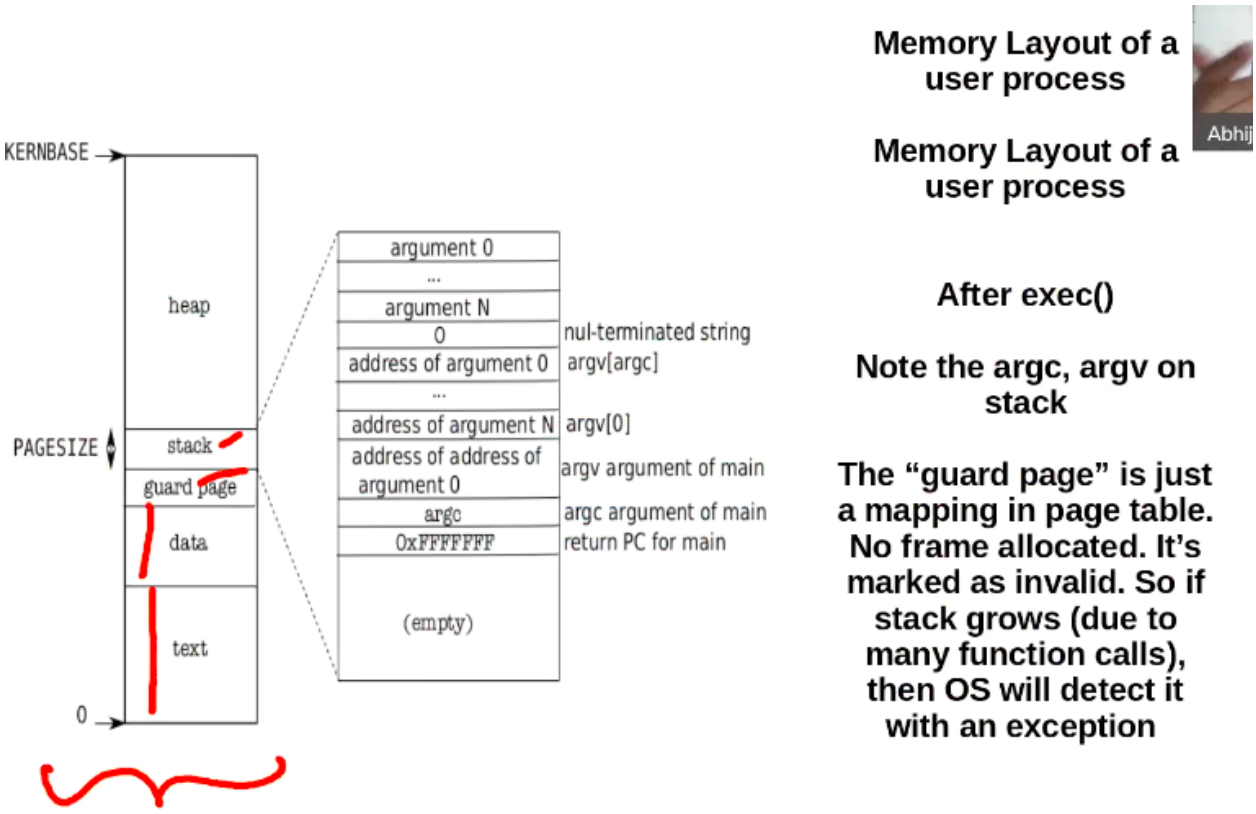
kstack is pointer to the kernel stack(4k in size)

ofile is the array of file pointers pointing to a entry in file descriptor table

struct proc diagram: Very imp!



sz = ELF-code->memsz (includes data, check "ld -N" + 2*4096 (for stack)



all the pages that get allocated are from the free memory region as shown in xv6 memory mapping diagram.this free memory is arround 200mb.

when a process is executing syscall, it is using kernal stack.

Handling traps

Handling traps

- Transition from user mode to kernel mode
  - On a system call
  - On a hardware interrupt
  - User program doing illegal work (exception)
- Actions needed, particularly w.r.t. to hardware interrupts
  - Change to kernel mode & switch to kernel stack
  - Kernel to work with devices, if needed
  - Kernel to understand interface of device

there are 2 types of kernel stacks, one process wala other general kernel stack

Handling traps

- **Actions needed on a trap**
  - **Save the processor's registers (context) for future use**
  - **Set up the system to run kernel code (kernel context) on kernel stack**
  - **Start kernel in appropriate place (sys call, intr handler, etc)**
  - **Kernel to get all info related to event (which block I/O done?, which sys call called, which process did exception and what type, get arguments to system call, etc)**

if a process was executing and using registers, on context switch some registers needs to be saved. then kernel's registers are loaded(kernel's context) kernel should get the info about the interrupt by the hardware

Privilege level

- The x86 has 4 protection levels, numbered 0 (most privilege) to 3 (least privilege).
- In practice, most operating systems use only 2 levels: 0 and 3, which are then called kernel mode and user mode, respectively.
- The current privilege level with which the x86 executes instructions is stored in %cs register, in the field CPL.

Privilege level

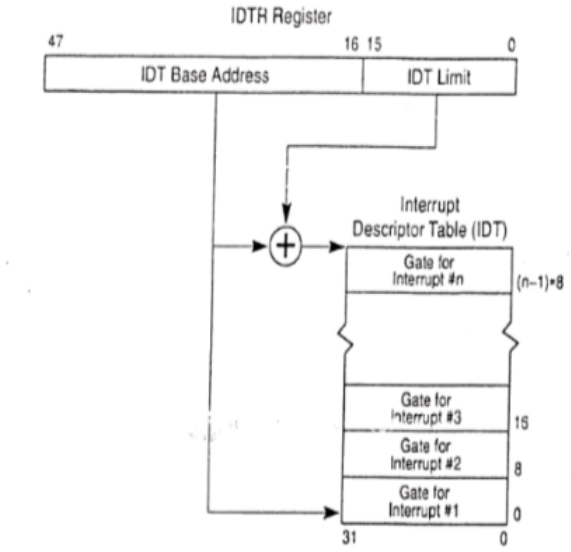
- Changes automatically on
  - “int” instruction
  - hardware interrupt
  - exeception
- Changes back on
  - iret
- “int” 10 --> makes 10th hardware interrupt. S/w interrupt can be used to create hardware interrupt’
- Xv6 uses “int 64” for actual system calls

in linux 0x80 is used for syscall

Interrupt Descriptor Table (IDT)

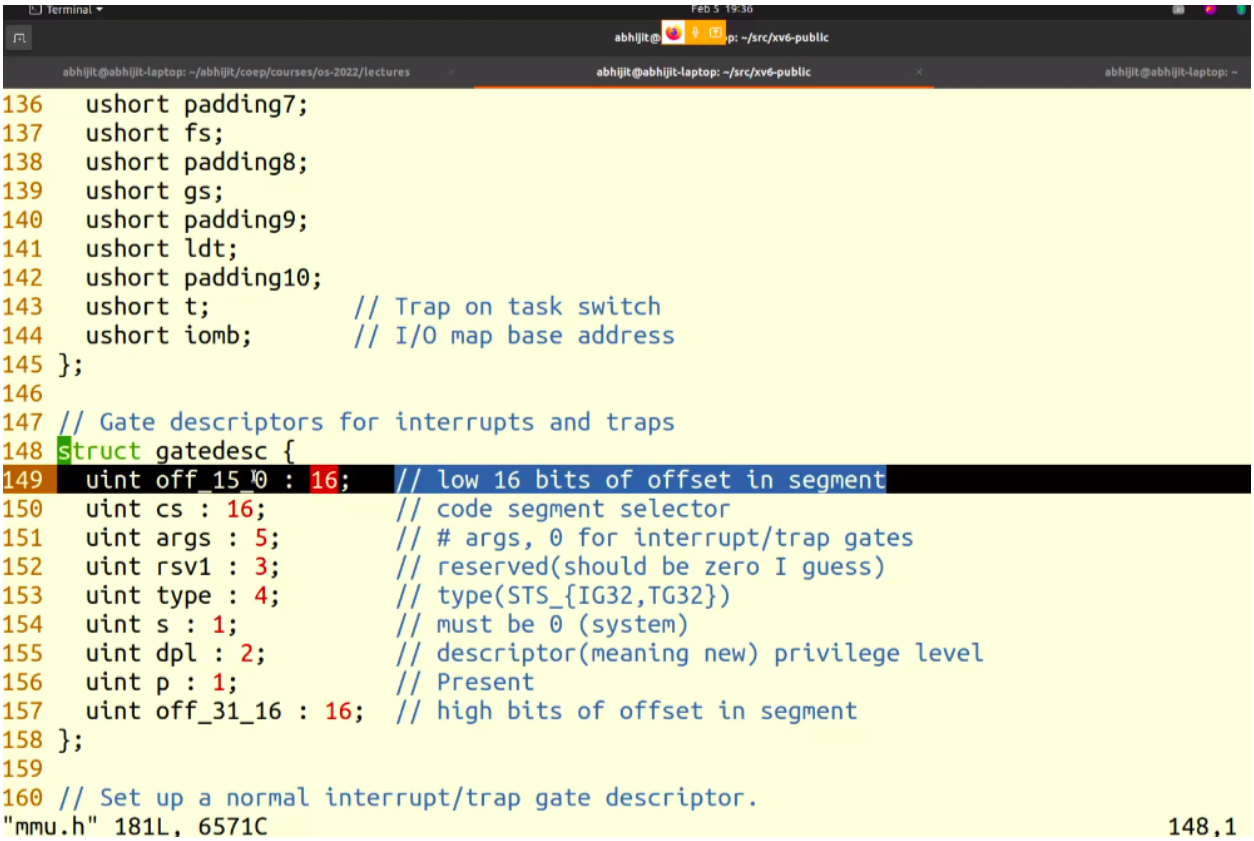
- IDT defines intertupt handlers
- Has 256 entries
  - each giving the %cs and %eip to be used when handling the corresponding interrupt.
- Interrupts 0-31 are defined for software exceptions, like divide errors or attempts to access invalid memory addresses.
- Xv6 maps the 32 hardware interrupts to the range 32-63
- and uses interrupt 64 as the system call interrupt

IDTR and IDT



entries in the idt table are called gates.

lets see xv6 code



this C structure is an entry in the IDT table

: 16 means field of 16 bits, and so on

Setting IDT entries

```
void
tvinit(void)
{
  int i;
  for(i = 0; i < 256; i++)
    SETGATE(idt[i], 0, SEG_KCODE<<3, vectors[i], 0);
    SETGATE(idt[T_SYSCALL], 1, SEG_KCODE<<3,
              vectors[T_SYSCALL], DPL_USER);
  /* value 1 in second argument --> don't disable
interrupts
         * DPL_USER means that processes can raise
this interrupt. */
    initlock(&tickslock, "time");
}
```

```
11 // Interrupt descriptor table (shared by all CPUs).
12 struct gatedesc idt[256];
13 extern uint vectors[];  // in vectors.S: array of 256 entry pointers
14 struct spinlock tickslock;
15 uint ticks;
16
17 void
18 tvinit(void)
19 {
20   int i;
21
22   for(i = 0; i < 256; i++)
23     SETGATE(idt[i], 0, SEG_KCODE<<3, vectors[i], 0);
24   SETGATE(idt[T_SYSCALL], 1, SEG_KCODE<<3, vectors[T_SYSCALL], DPL_USER);
25
26   initlock(&tickslock, "time");
27 }
28
29 void
30 idtinit(void)
31 {
32   lidt(idt, sizeof(idt));
33 }
34
35 //PAGEBREAK: 41
-- VISUAL --                                                    13,1
```

line 12 has idt table, which is part of data part of kernel, it gets loaded when kernel was loaded in memory in bootmain

tvinit loads IDT table into memory

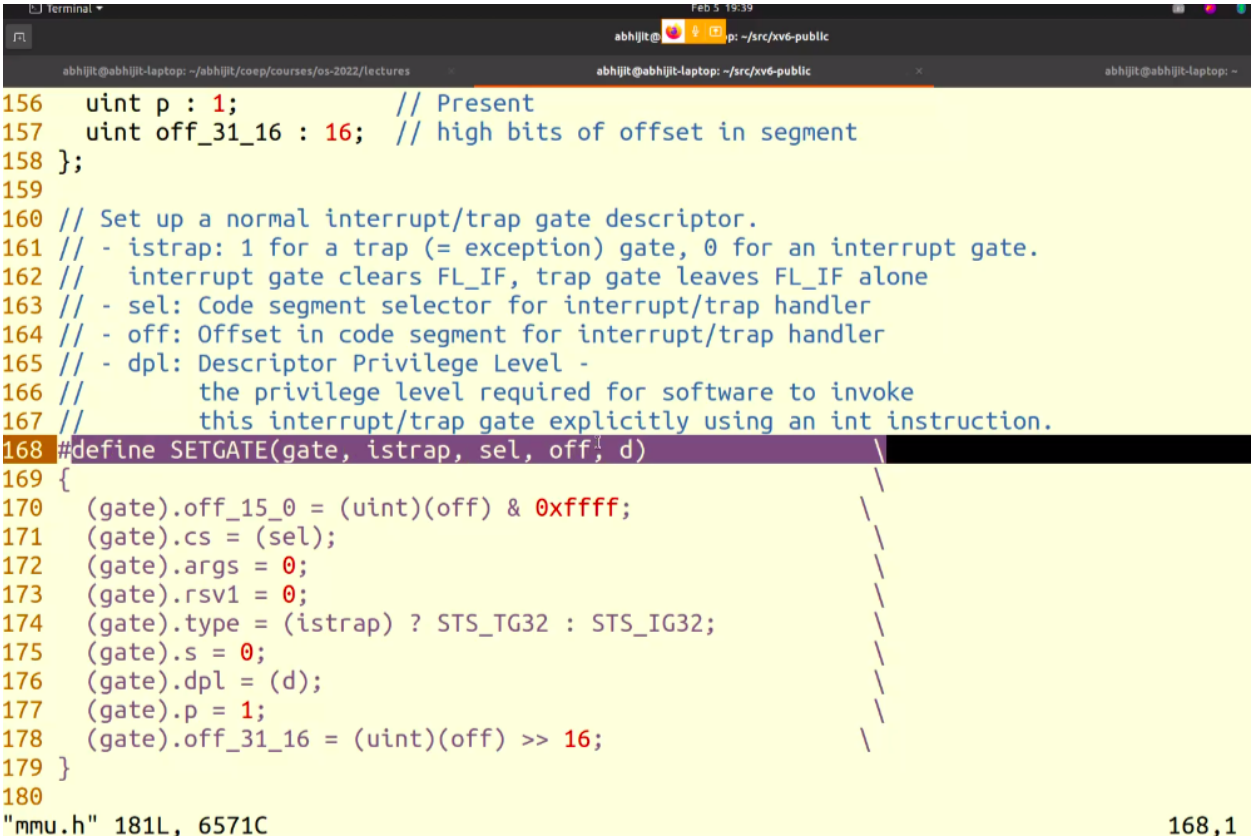
vectors[i] is the address of function that is to be executed, which is externed at line 13, defined in vectors.S

T_SYSCALL is #defined 64

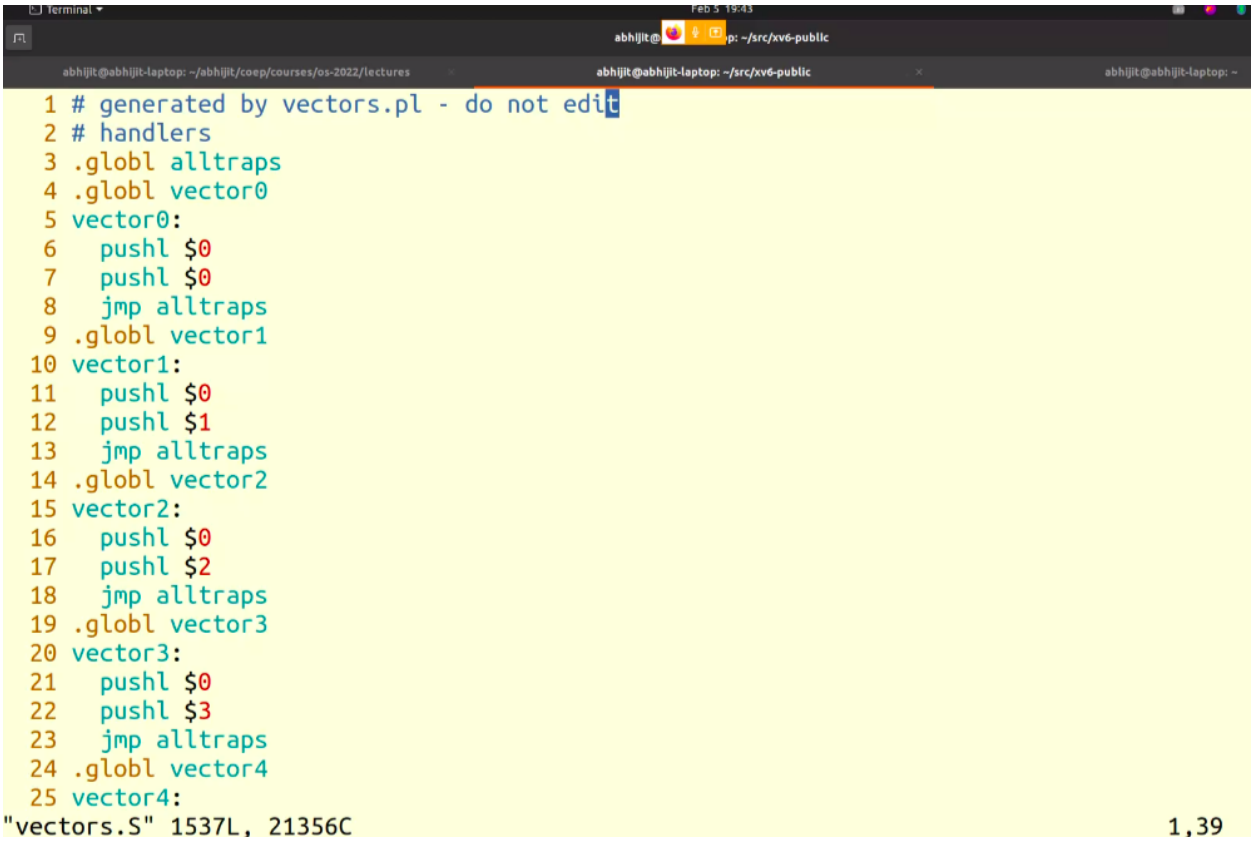
DPL_USR is 0x3

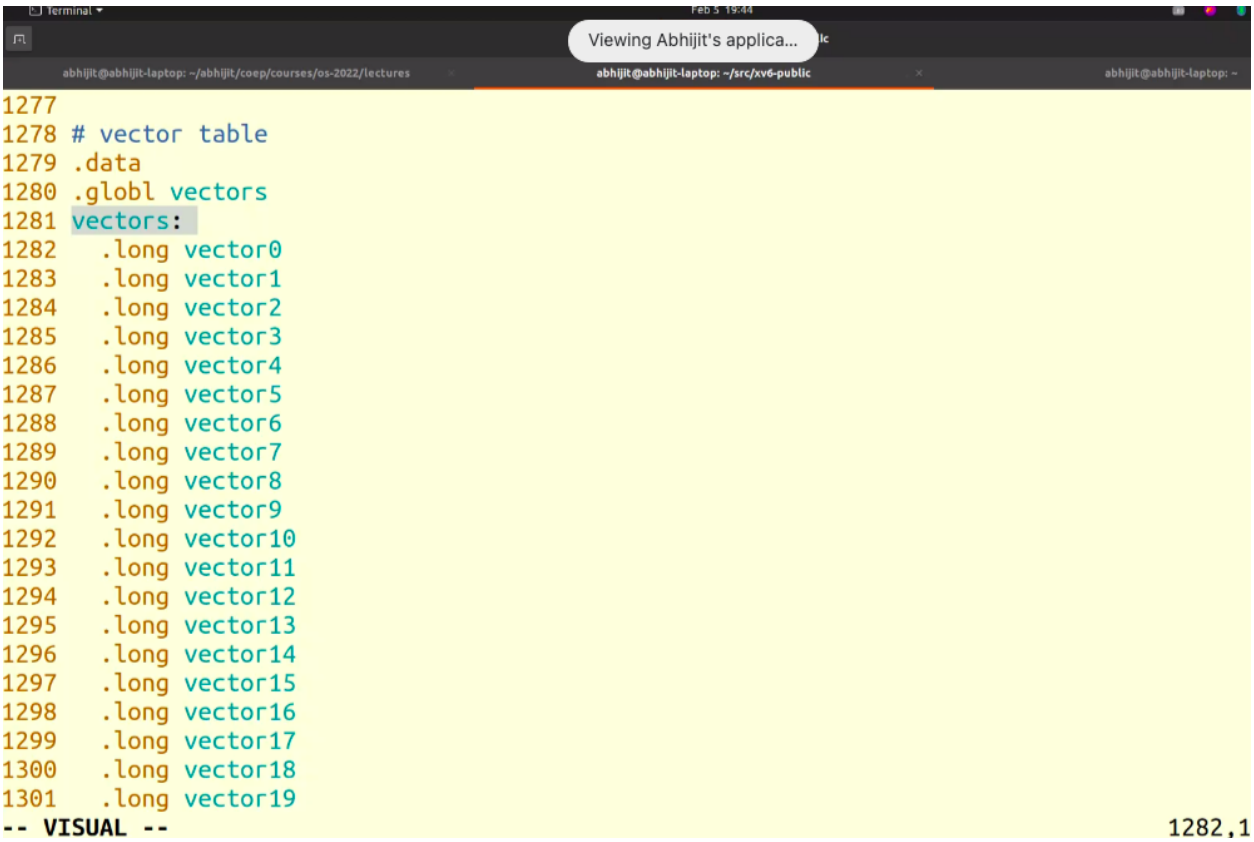
for syscall we are overwriting istrap=1, and d=3 in SETGATE, i.e at line 24

SETGATE



Vectors.S

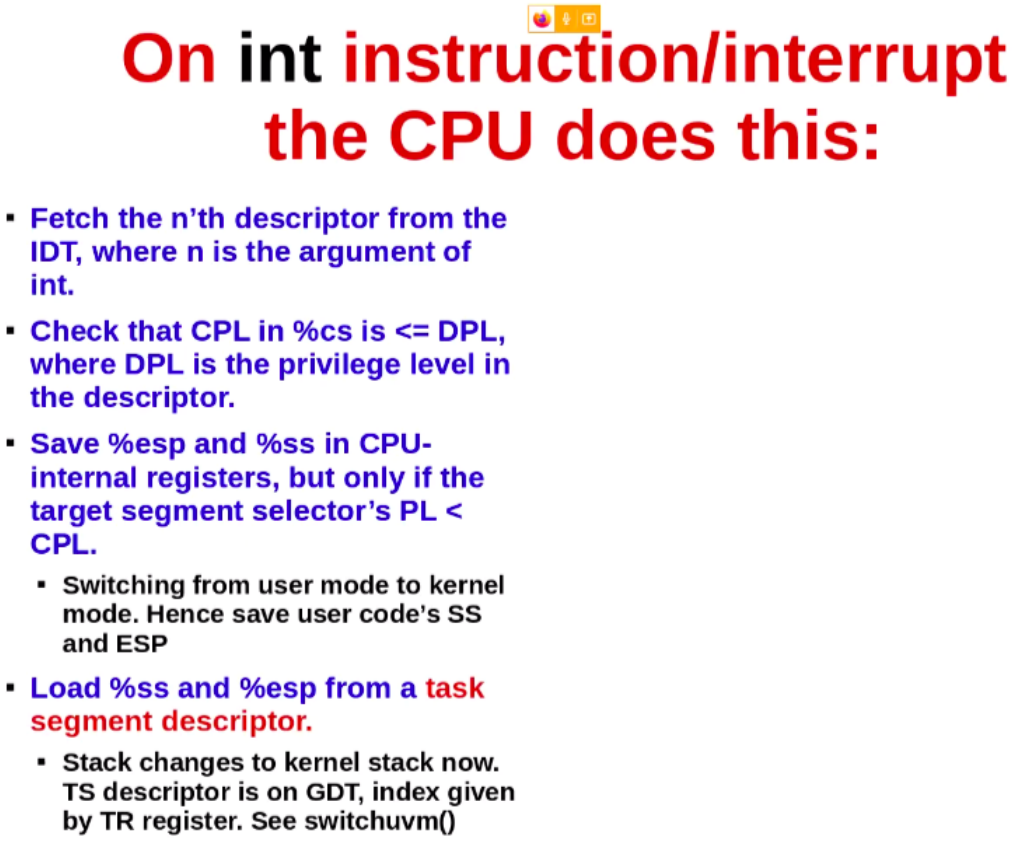

Terminal
abhijit@abhijit-laptop: ~/abhijit/coep/courses/os-2022/lectures
abhijit@abhijit-laptop: ~/src/xv6-public
abhijit@abhijit-laptop: ~
1 # generated by vectors.pl - do not edit
2 # handlers
3 .globl alltraps
4 .globl vector0
5 vector0:
6 pushl $0
7 pushl $0
8 jmp alltraps
9 .globl vector1
10 vector1:
11 pushl $0
12 pushl $1
13 jmp alltraps
14 .globl vector2
15 vector2:
16 pushl $0
17 pushl $2
18 jmp alltraps
19 .globl vector3
20 vector3:
21 pushl $0
22 pushl $3
23 jmp alltraps
24 .globl vector4
25 vector4:
"vectors.S" 1537L, 21356C
1,39


Terminal
Viewing Abhijit's applica...
abhijit@abhijit-laptop: ~/abhijit/coep/courses/os-2022/lectures
abhijit@abhijit-laptop: ~/src/xv6-public
abhijit@abhijit-laptop: ~
1277
1278 # vector table
1279 .data
1280 .globl vectors
1281 vectors:
1282 .long vector0
1283 .long vector1
1284 .long vector2
1285 .long vector3
1286 .long vector4
1287 .long vector5
1288 .long vector6
1289 .long vector7
1290 .long vector8
1291 .long vector9
1292 .long vector10
1293 .long vector11
1294 .long vector12
1295 .long vector13
1296 .long vector14
1297 .long vector15
1298 .long vector16
1299 .long vector17
1300 .long vector18
1301 .long vector19
-- VISUAL --
1282,1

this is vectors array

a interrupt first pushes 0, then number of interrupt and then jmp to alltraps

tvinit() is called into main.c, a file which we have already seen.



---

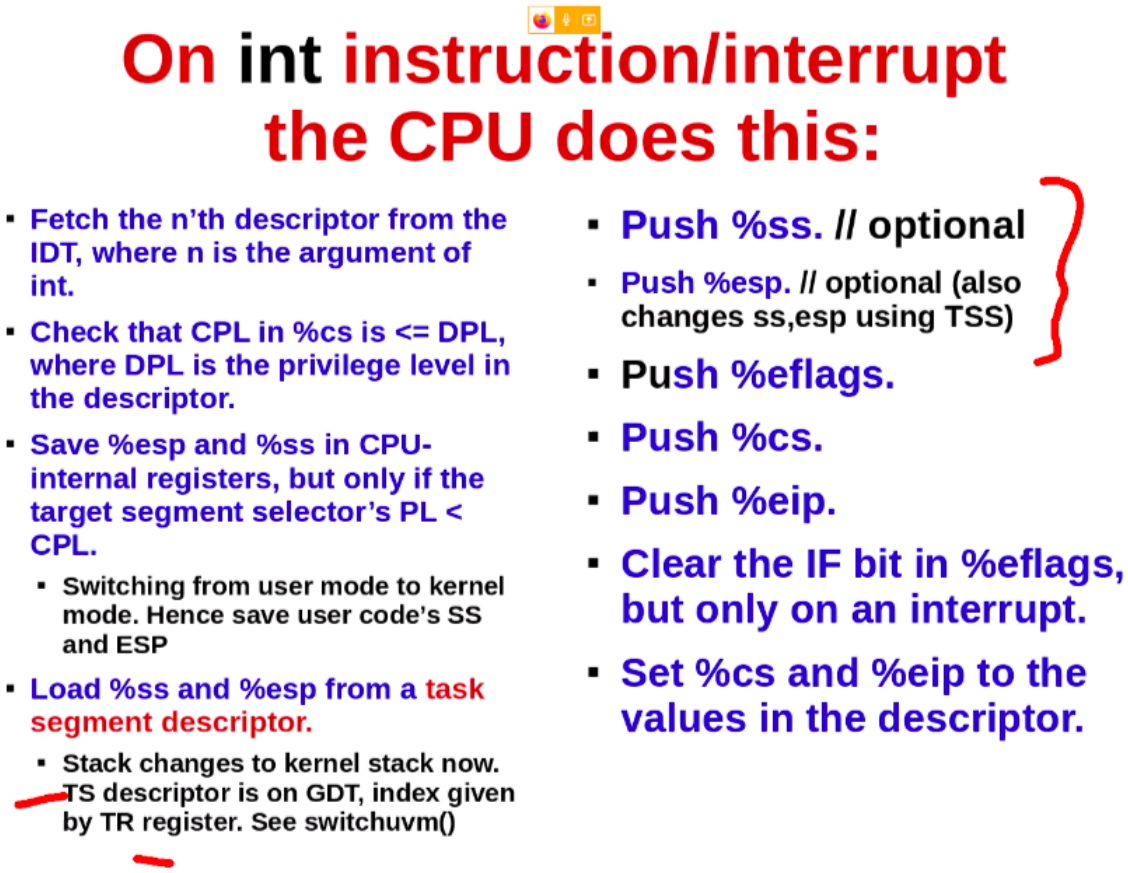
if a syscall is to be made, int 64, 64th IDT entry is loaded in hardware

2nd point means all levels are 0, except syscall which is 3, if application code was running, CPL=3, and DPL=3 so no problem, it is checking that you should go to lower level, why is this so, because process manufacturer always had 4 levels, OS used only 2 levels

if you are in syscall your cpl=3, and for other interrupts dpl=0,hence you cannot be interrupted in syscall?

ss and esp are saved in internal registers,only if you are going to lower level, i.e. transition from user to kernel mode, so you have to use kernel stack, processor gets the

kernel stacker using the task segment descriptor.



---

optional push of ss and esp is done on kernel stack,then eflags,cs,eip is pushed mandatory on kernel stack, then we push 0 and 64

clear the IF bit, only on hardware interrupt(interrupt), that is interrupts are disabled now.

After “int” ‘s job is done

- IDT was already set
  - Remember vectors.S
- So jump to 64th entry in vector’s

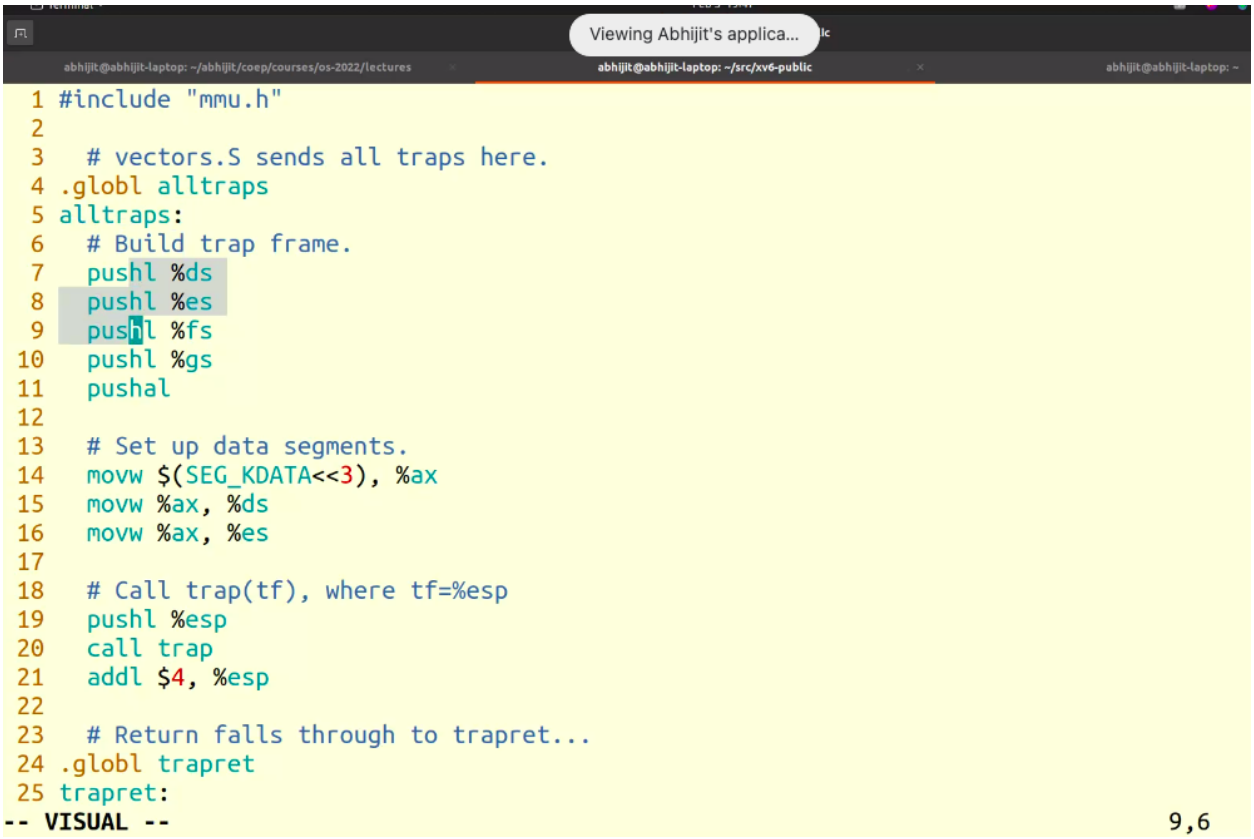
```
vector64:
  pushl $0
  pushl $64
  jmp alltraps
```

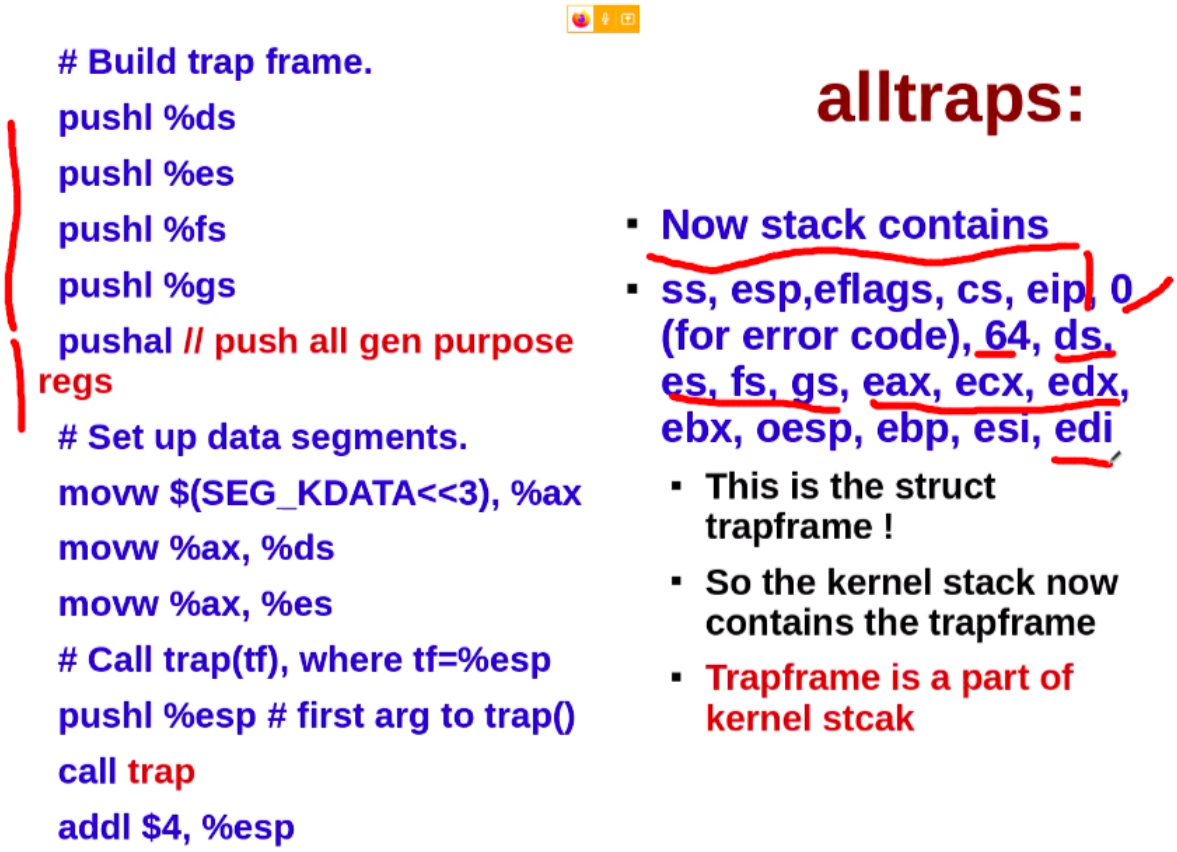
  - So now stack has ss, esp,eflags, cs, eip, 0 (for error code), 64
  - Next run alltraps from trapasm.S

---

0 and 64 are pushed by our code, ss,esp,eflags cs,eip is loaded in stack by hardware.

0 will be replaced by errno, there is a single function that handles all traps, so we need to push trap number on stack as well


Viewing Abhijit's applica...
abhijit@abhijit-laptop: ~/abhijit/coep/courses/os-2022/lectures
abhijit@abhijit-laptop: ~/src/xv6-public
abhijit@abhijit-laptop: ~
1 #include "mmu.h"
2
3 # vectors.S sends all traps here.
4 .globl alltraps
5 alltraps:
6 # Build trap frame.
7 pushl %ds
8 pushl %es
9 pushl %fs
10 pushl %gs
11 pushal
12
13 # Set up data segments.
14 movw $(SEG_KDATA<<3), %ax
15 movw %ax, %ds
16 movw %ax, %es
17
18 # Call trap(tf), where tf=%esp
19 pushl %esp
20 call trap
21 addl $4, %esp
22
23 # Return falls through to trapret...
24 .globl trapret
25 trapret:
-- VISUAL --
9,6



---

trap is called on line 20 on alltraps

struct trapframe is all these values defined in reverse order

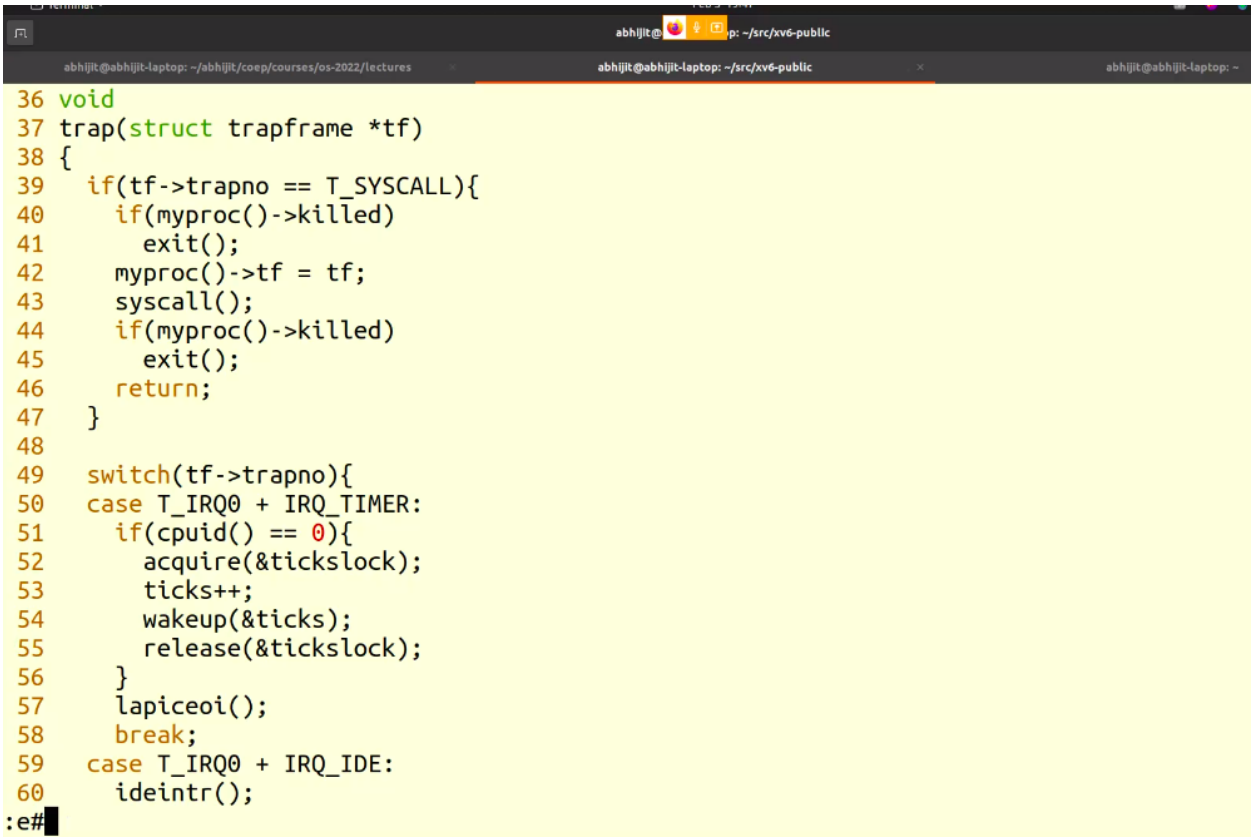
```
149 // hardware and by trapasm.S, and passed to trap().
150 struct trapframe {
151   // registers as pushed by pusha
152   uint edi;
153   uint esi;
154   uint ebp;
155   uint oesp;      // useless & ignored
156   uint ebx;
157   uint edx;
158   uint ecx;
159   uint eax;
160
161   // rest of trap frame
162   ushort gs;
163   ushort padding1;
164   ushort fs;
165   ushort padding2;
166   ushort es;
167   ushort padding3;
168   ushort ds;
169   ushort padding4;
170   uint trapno;
171
172   // below here defined by x86 hardware
173   uint err;
-- VISUAL --                                                    158,1
```

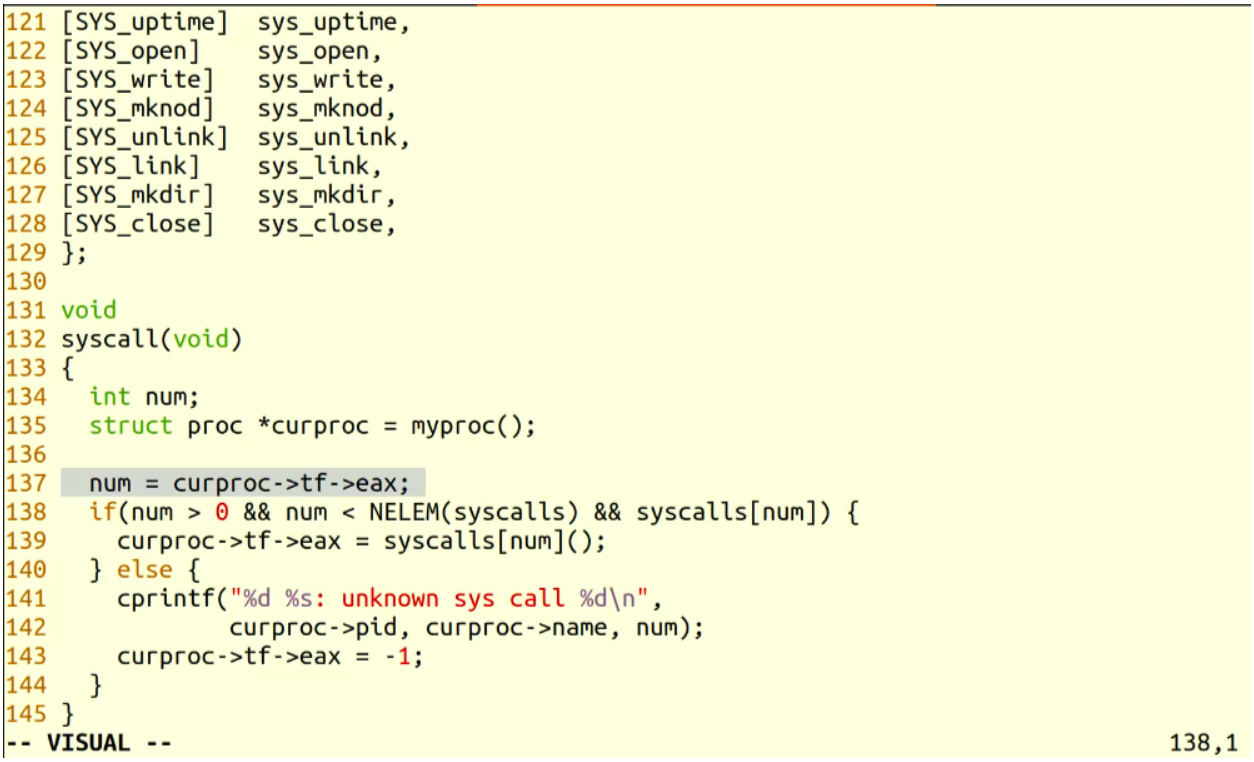
before call trap, esp was pushed on stack, which now becomes the argument to trap function

```
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){
  .....
```

trap()

- Argument is trapframe
- In alltraps
  - Before “call trap”, there was “push %esp” and stack had the trapframe
  - Remember calling convention --> when a function is called, the stack contains the arguments in reverse order (here only 1 arg)


abhijit@abhijit-laptop: ~/src/xv6-public
abhijit@abhijit-laptop: ~/abhijit/coep/courses/os-2022/lectures
abhijit@abhijit-laptop: ~/src/xv6-public
abhijit@abhijit-laptop: ~
36 void
37 trap(struct trapframe *tf)
38 {
39 if(tf->trapno == T_SYSCALL){
40 if(myproc()->killed)
41 exit();
42 myproc()->tf = tf;
43 syscall();
44 if(myproc()->killed)
45 exit();
46 return;
47 }
48
49 switch(tf->trapno){
50 case T_IRQ0 + IRQ_TIMER:
51 if(cpuid() == 0){
52 acquire(&tickslock);
53 ticks++;
54 wakeup(&ticks);
55 release(&tickslock);
56 }
57 lapiceoi();
58 break;
59 case T_IRQ0 + IRQ_IDE:
60 ideintr();
:e#


121 [SYS_uptime] sys_uptime,
122 [SYS_open] sys_open,
123 [SYS_write] sys_write,
124 [SYS_mknod] sys_mknod,
125 [SYS_unlink] sys_unlink,
126 [SYS_link] sys_link,
127 [SYS_mkdir] sys_mkdir,
128 [SYS_close] sys_close,
129 };
130
131 void
132 syscall(void)
133 {
134 int num;
135 struct proc *curproc = myproc();
136
137 num = curproc->tf->eax;
138 if(num > 0 && num < NELEM(syscalls) && syscalls[num]) {
139 curproc->tf->eax = syscalls[num]();
140 } else {
141 cprintf("%d %s: unknown sys call %d\n",
142 curproc->pid, curproc->name, num);
143 curproc->tf->eax = -1;
144 }
145 }
-- VISUAL -- 138,1

trap()

- Has a switch
  - switch(tf->trapno)
  - Q: who set this trapno?
- Depending on the type of trap
  - Call interrupt handler

- Timer
  - wakeup(&ticks)
- IDE: disk interrupt
  - Ideintr()
- KBD
  - Kbdintr()
- COM1
  - Uatrintr()
- If Timer
  - Call yield() -- calls sched()
- If process was killed (how is that done?
  - Call exit()!

---

trapno, was pushed in vectors.S for each vector

what happens when trap returns?

trap returns in alltraps

```
  # Call trap(tf), where tf=%esp
  pushl %esp
  call trap
  addl $4, %esp

  # Return falls through to trapret...
.globl trapret
trapret:
VISUAL --                                                    22,0-1
```

when trap() returns

```
#Back in alltraps
 call trap
 addl $4, %esp

 # Return falls through to trapret...
.globl trapret
trapret:
 popal
 popl %gs
 popl %fs
 popl %es
 popl %ds
 addl $0x8, %esp  # trapno and errcode
 iret
```

- Stack had (trapframe)
  - ss, esp,eflags, cs, eip, 0 (for error code), 64, ds, es, fs, gs, eax, ecx, edx, ebx, oesp, ebp, esi, edi, esp
- add $4 %esp
  - esp
- popal
  - eax, ecx, edx, ebx, oesp, ebp, esi, edi
- Then gs, fs, es, ds
- add $0x8, %esp
  - 0 (for error code), 64
- iret
  - ss, esp,eflags, cs, eip,

---

after trap returns, we add 4 to esp, to pop the pushed esp, (removing stack pointer's value from stack,because it was just use as argument to trap(), now it is not needed)

then we call popal, which will pop all the general purpose registers from the stack

then add 8, will remove error code, and interrupt number

iret is opposite of int instruction so pop that 5 values, and uses ss and esp value,so the stack switches back to application stack,also cs and eip will be overwritten, so process will now resume

NOTE:struct trapframe{} in c file was definition of struct, while in assembly code we created a instance of that struct, we cannot create a instance of this struct in C code, because int instr will make lookup into idt and jump to some location which pushes some value on stack, then we push some other values to build the trapframe.

trapframe is all the essential info needed to handle a trap.

NOTE:the stack used here is per process kernel stack allocated in entry.S

compiler works with only general purpose registers in calling conventions(pushed by pushal)

how a syscall actually works?

in Usys.S, there is a macro which creates an entry for a syscall,and we create a entry for each syscall here.

lets consider fork, for example then

.globl fork;

fork:

    movl $SYS_fork,eax;

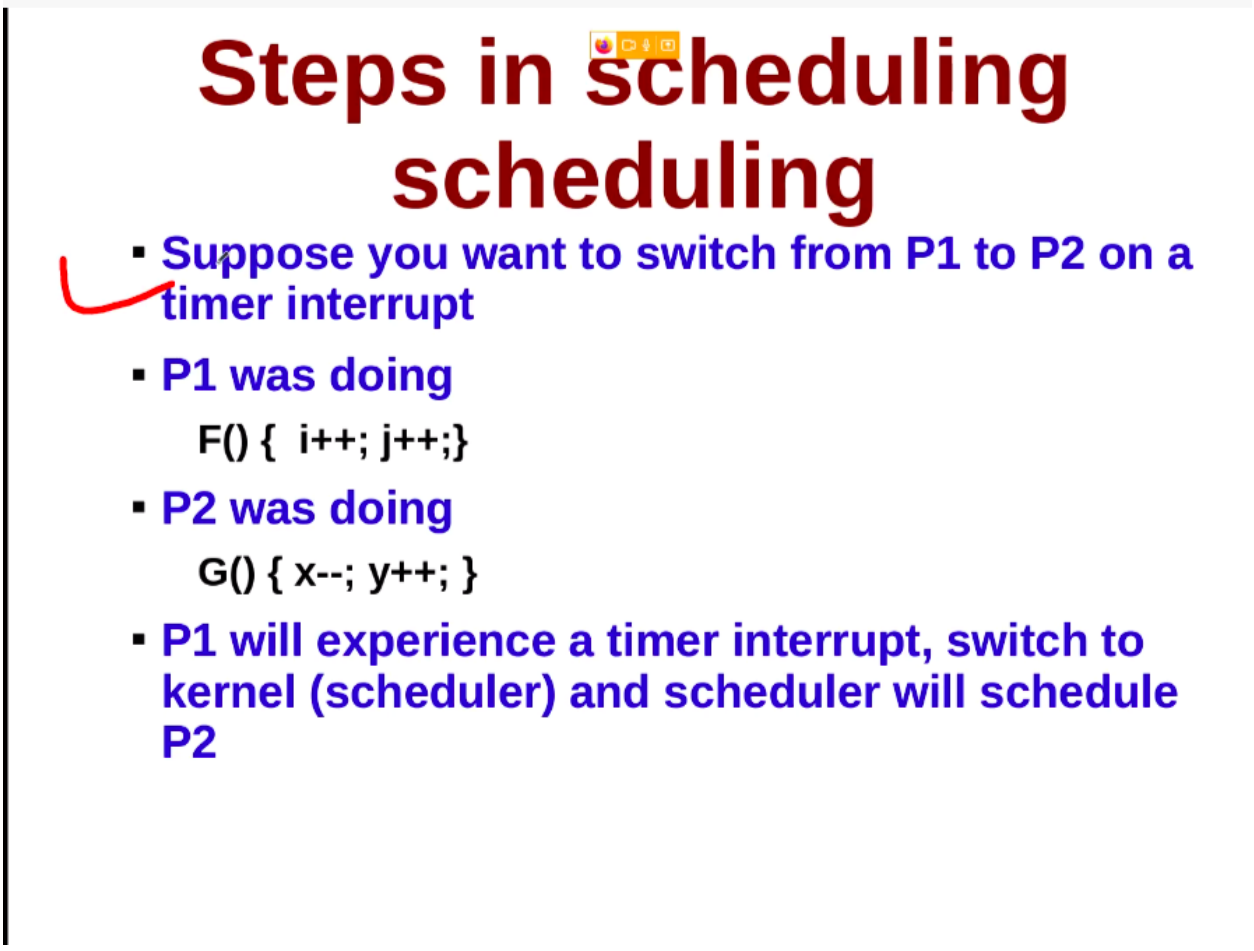
    int 64;

    ret

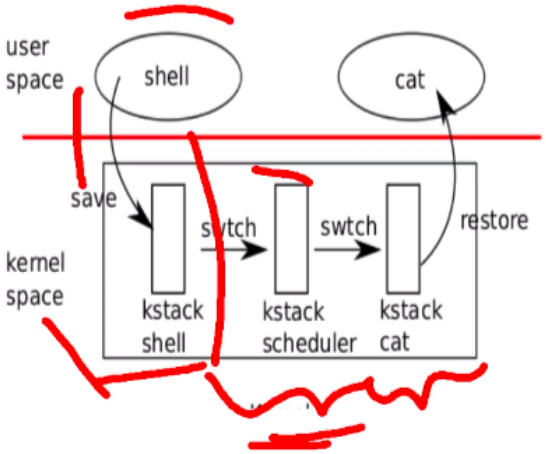
such a code is generated for each syscall, here SYS_fork is a macro defined in file, which is basically a number that we push in eax,then we call int 64, which jumps into vectors.S, then push 0 push 64 then jmp to alltraps, push some values then call trap, which checks for syscall then call syscall and then inside the syscall() seen in syscall.c file, we access this eax value through the trapframe, as an index to a array of function pointers to the actual syscall functions which are written in sysfiles.c and sysproc.c

to sum up, tvinit() in main creates an idt table of type gatedesc of 256 enteries, which are set using SETGATE macro, that maps each idt with a vector array containing the function to be called on a particular interrupt, this vector array is defined in vectors.S, which will push 0, push trapNumber, then jmp to alltraps, inside alltraps, we push other necessary values to generate the trapframe, which is used as a argument to the trap function, which has a switch for trapnumber, if it is a syscall then syscall function is called which checks the value in eax register(defined in usys.s) of trapframe, that value is mapped to array of function pointers that point to a function that needs to be executed for the syscall

Scheduler



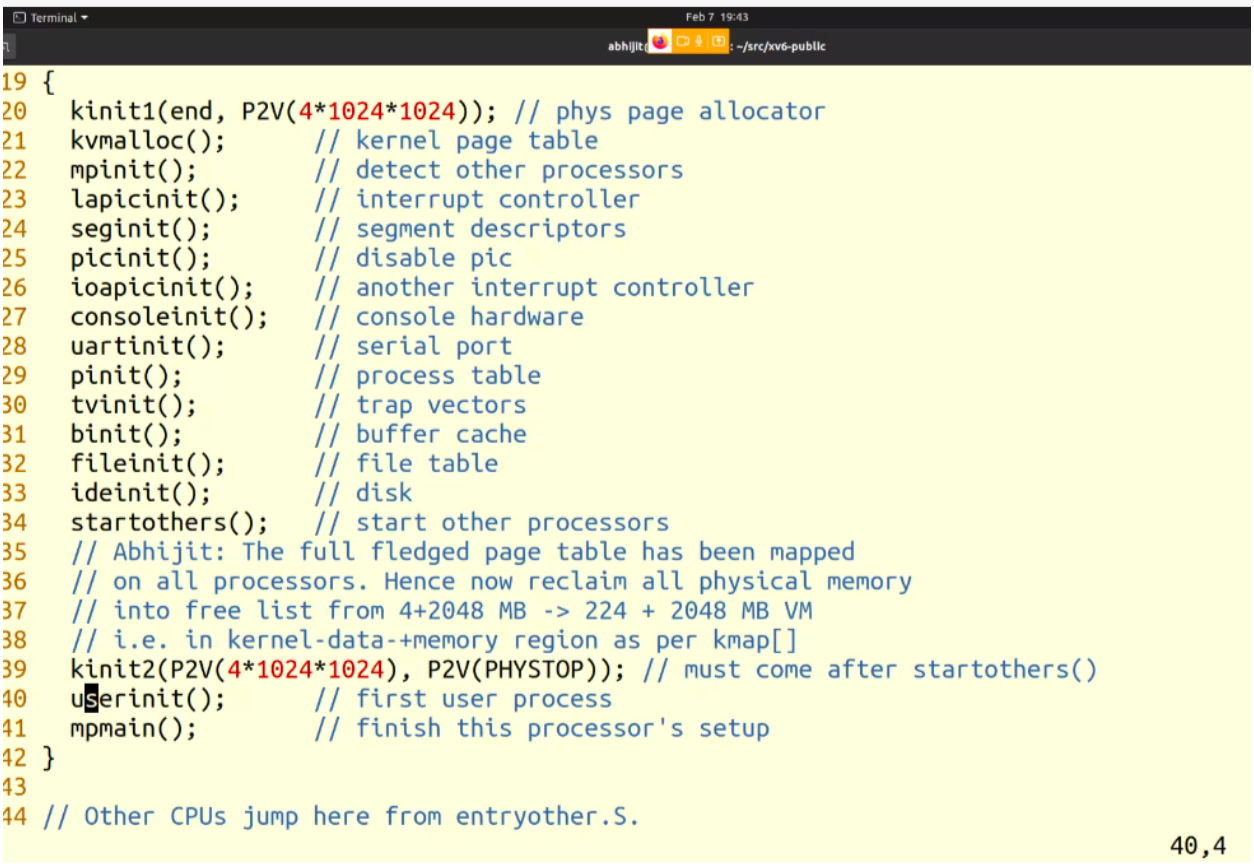
4 stacks need to change!



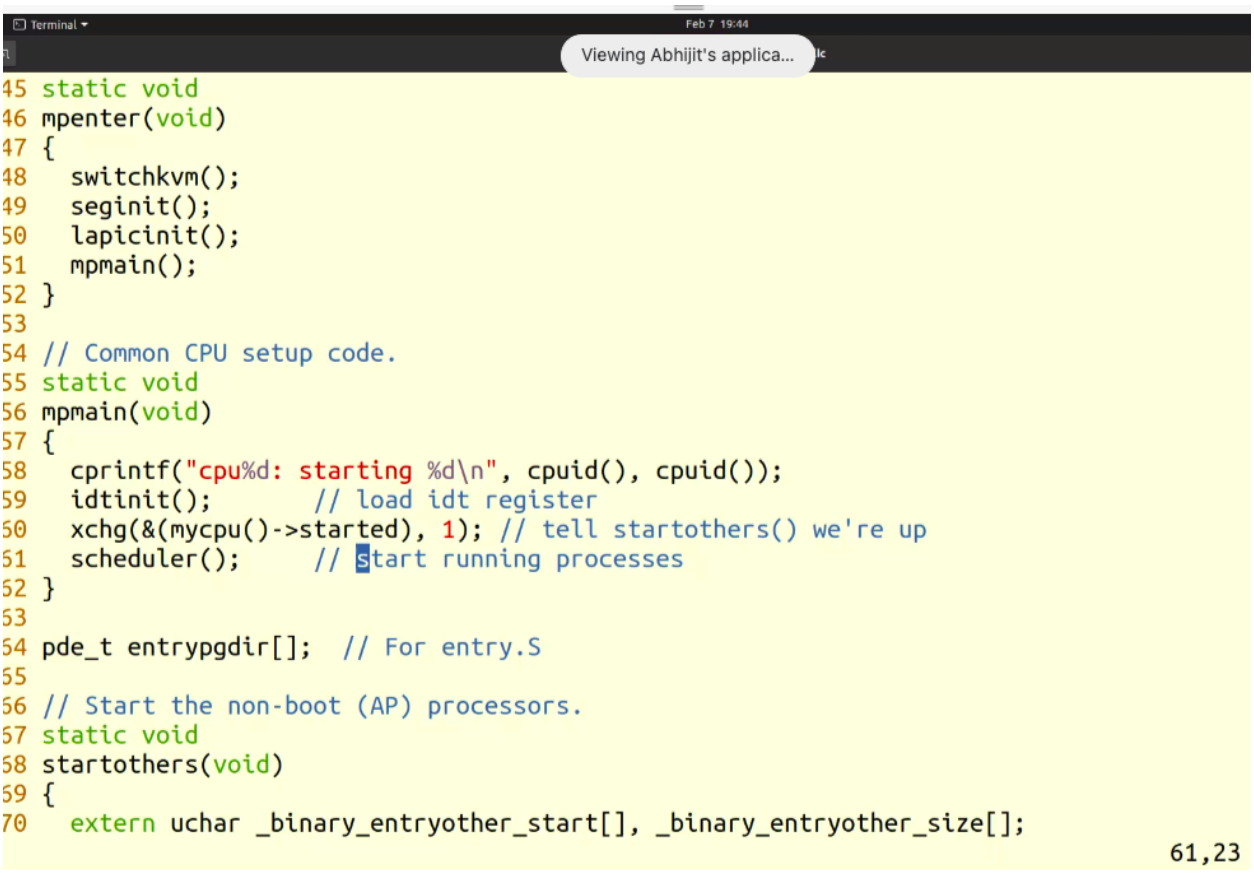
- User stack of process -> kernel stack of process
  - Switch to kernel stack
  - The normal sequence on any interrupt !
- Kernel stack of process -> kernel stack of scheduler
  - Why?
- Kernel stack of scheduler -> kernel stack of new process . Why?
- Kernel stack of new process -> user stack of new process

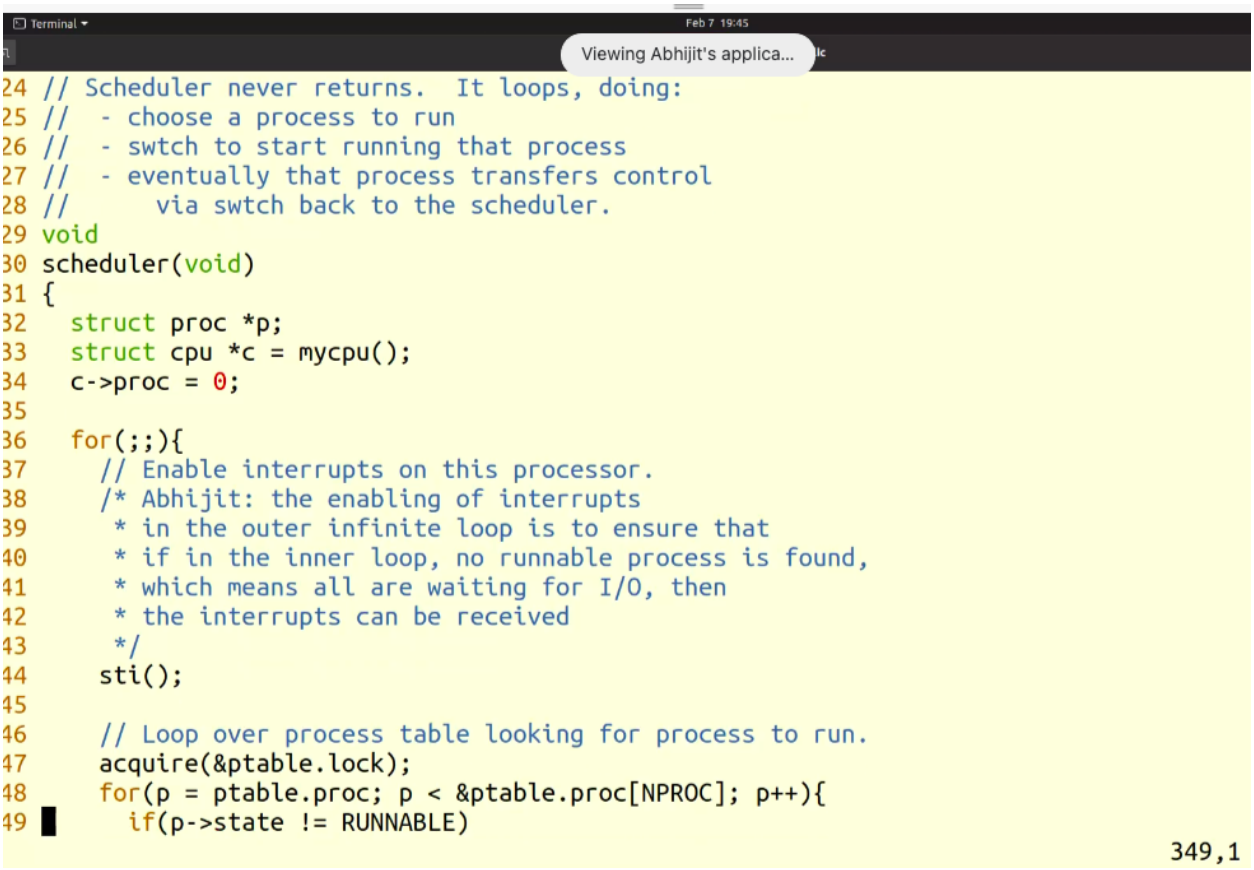
when shell is running and their is timer interrupt, context of shell is need to be saved, it is saved in kernel stack of shell, scheduler is to be run after that, the context of shell is currently stored on top of kstack, scheduler needs lot of functions, so needs a stack of its own, so a different stack is used for scheduler, before scheduler starts it process, kernel stack is changed to scheduler stack, then now when scheduler wants to pass control to cat, then again stack needs to be changed to context of kernel stack of cat process. So first it was user stack of shell, then when timer interrupt occured,context is stored on kernel stack of shell.,then kstack of scheduler then kstack of cat

inside main.c code of xv6



function called mpinit was called which actually detected multiple processors and initialize them. the mpmain will start all the processor’s execution, it will make all the processor run, in symmetric multiprocessing system. mpmain calls scheduler.


Terminal
Feb 7 19:44
Viewing Abhijit's applica...
45 static void
46 mpenter(void)
47 {
48   switchkvm();
49   seginit();
50   lapicinit();
51   mpmain();
52 }
53
54 // Common CPU setup code.
55 static void
56 mpmain(void)
57 {
58   cprintf("cpu%d: starting %d\n", cpuid(), cpuid());
59   idtinit();   // load idt register
60   xchg(&(mycpu()->started), 1); // tell startothers() we're up
61   scheduler();   // start running processes
62 }
63
64 pde_t entrypgdir[]; // For entry.S
65
66 // Start the non-boot (AP) processors.
67 static void
68 startothers(void)
69 {
70   extern uchar _binary_entryother_start[], _binary_entryother_size[];
61,23

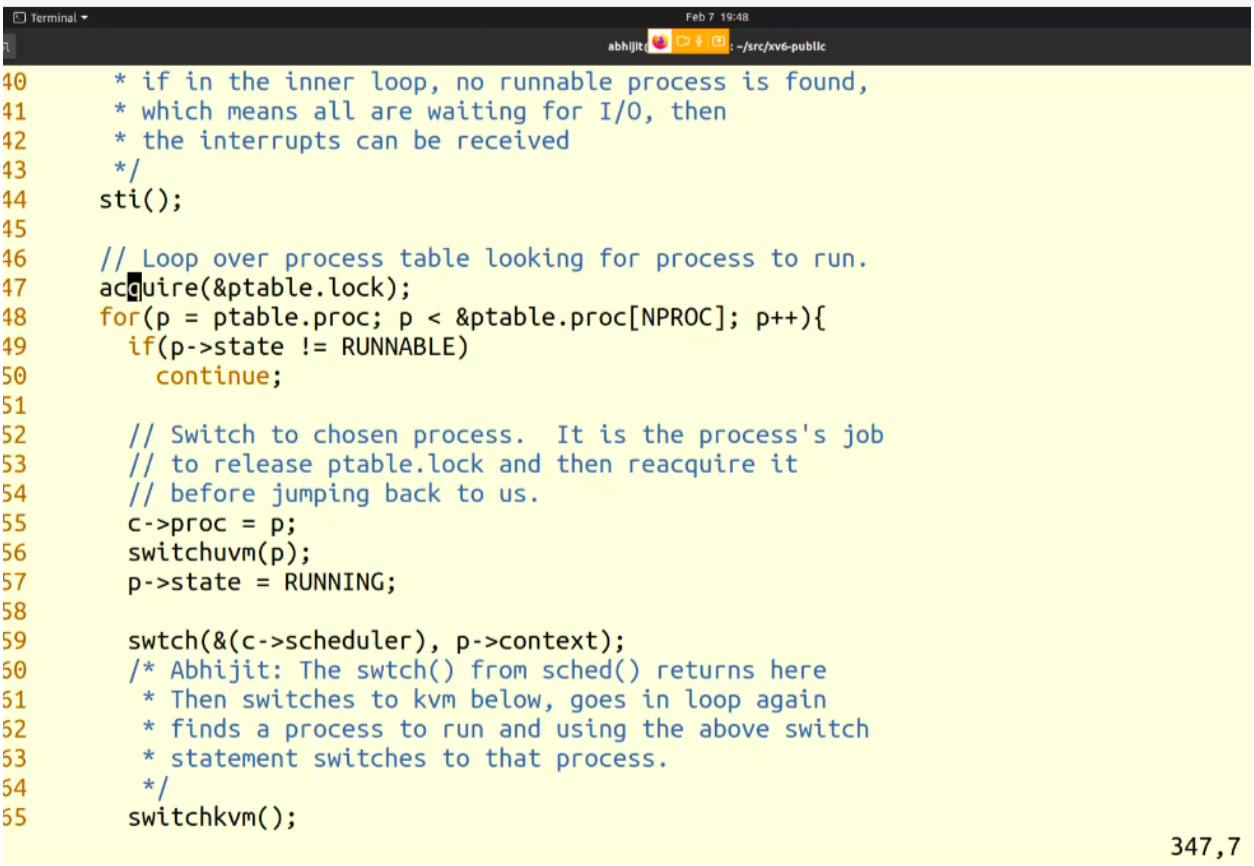


it should array for proc,(a global variable ptable contains array of this proc) iterate over those processes that are ready and then allocate them.

this C code will be compiled according to calling conventions

sti() is using the gcc directive asm to embed assembly code in C code, to enable interrupts

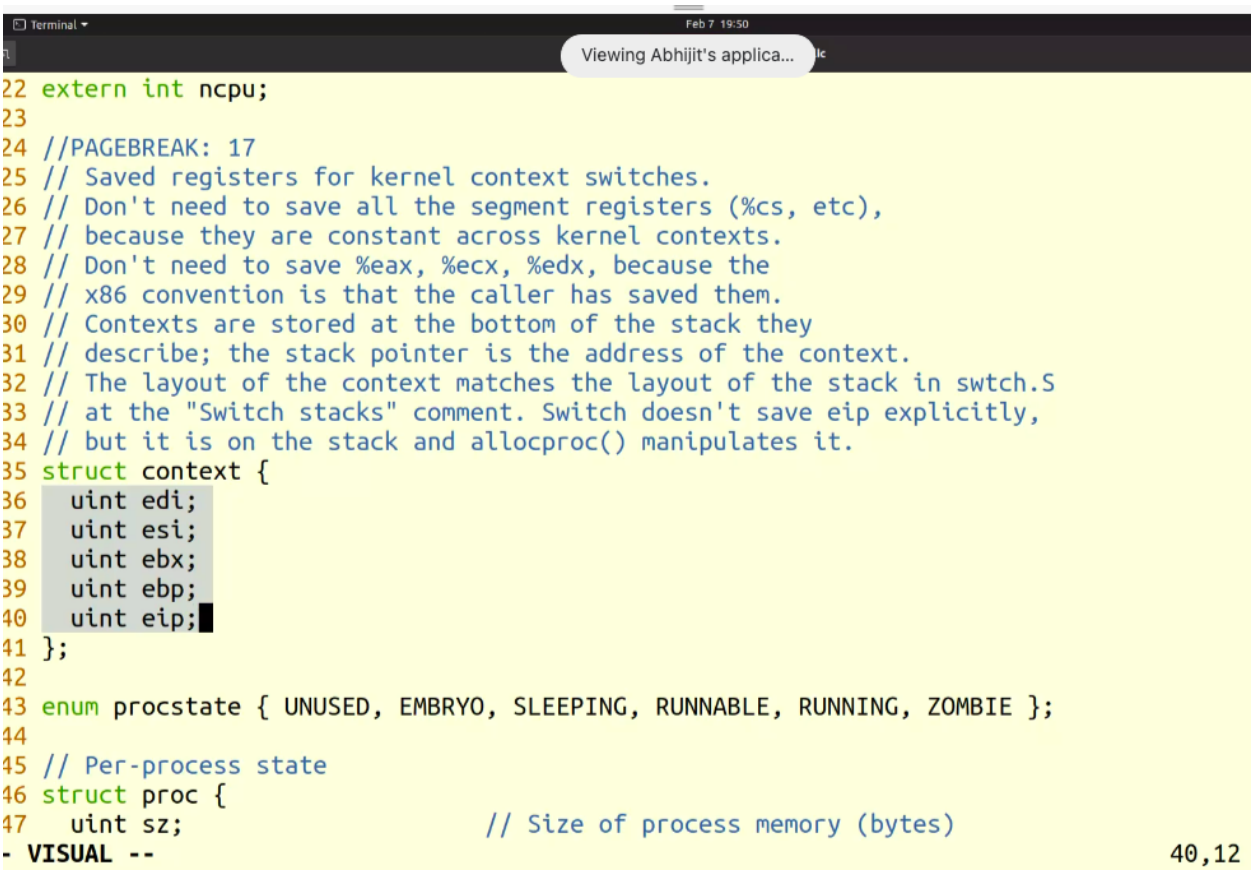

Terminal
Feb 7 19:47
~/src/xv6-public
}
/* Abhijit: Clear Interrupt Flag */
static inline void
cli(void)
{
asm volatile("cli");
}
/* Abhijit: Set Interrupt Flag */
static inline void
sti(void)
{
asm volatile("sti");
}
/* Abhijit: Atomic Compare and Swap */
static inline uint
xchg(volatile uint *addr, uint newval)
{
uint result;
// The + in "+m" denotes a read-modify-write operand.
asm volatile("lock; xchgl %0, %1" :
"+m" (*addr), "=a" (result) :
"1" (newval) :
145,0-



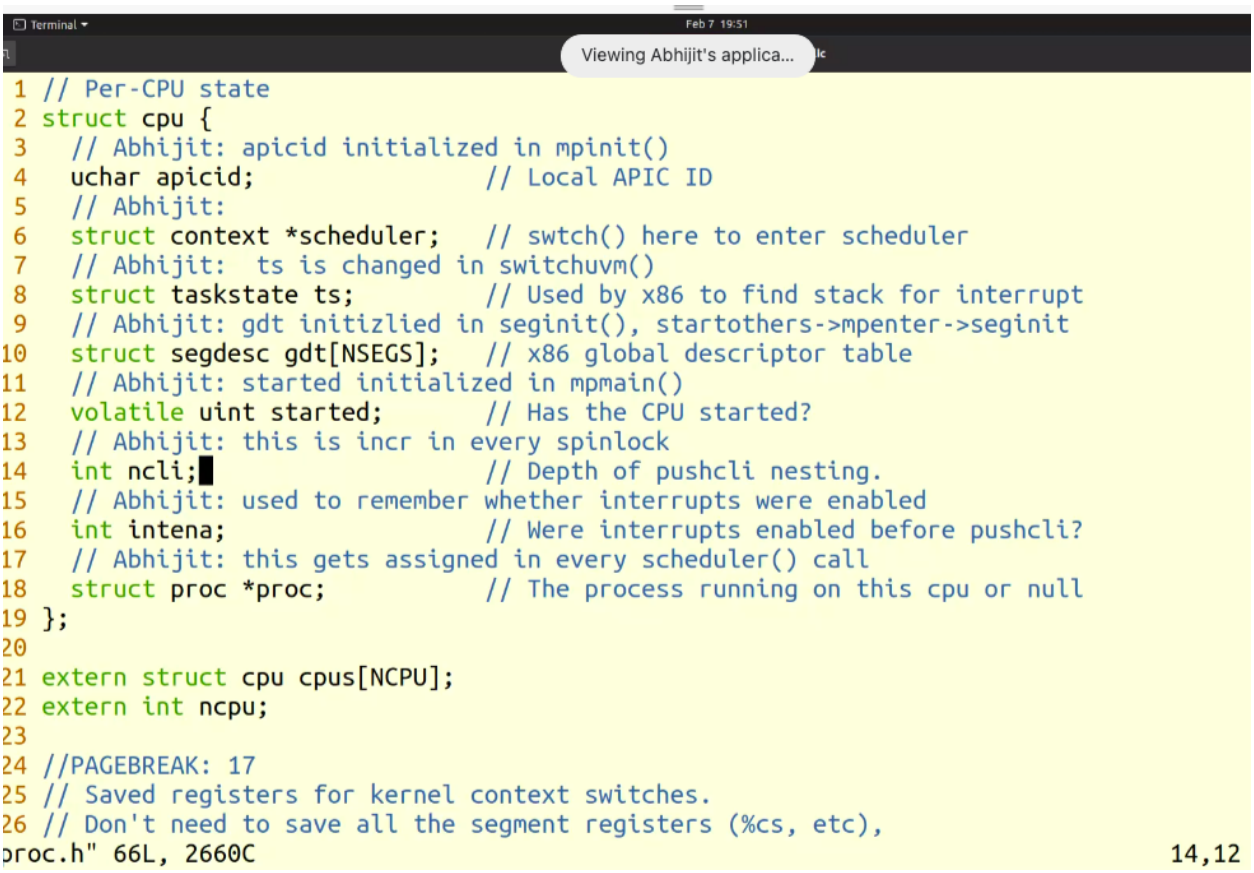
RUNNABLE==READY, if process not ready skip, if RUNNABLE, it initializes c→proc =p; (storing pointer to currently running process)

which was a cpu pointer.we are passing address to swtch() of c→scheduler, since we are likely to change it. scheduler is instance of type struct context only

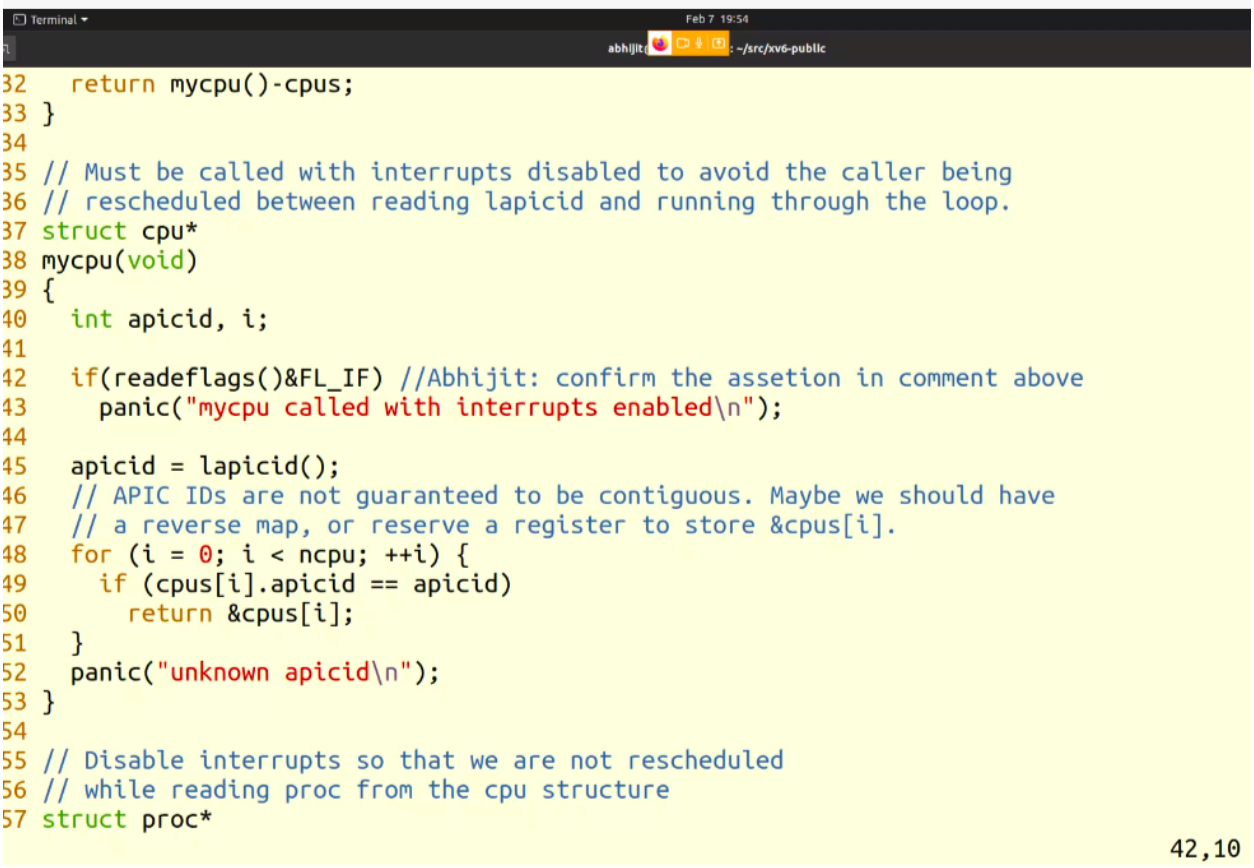
then calls switchuvm, changes state, and then calls swtch() with a argument p→context, p is the process to be scheduled



what is c? c is struct cpu



it has a pointer scheduler of context struct, lets see mycpu()



it is assumed here, whichever process is to be scheduled its context is already present,while calling swtch

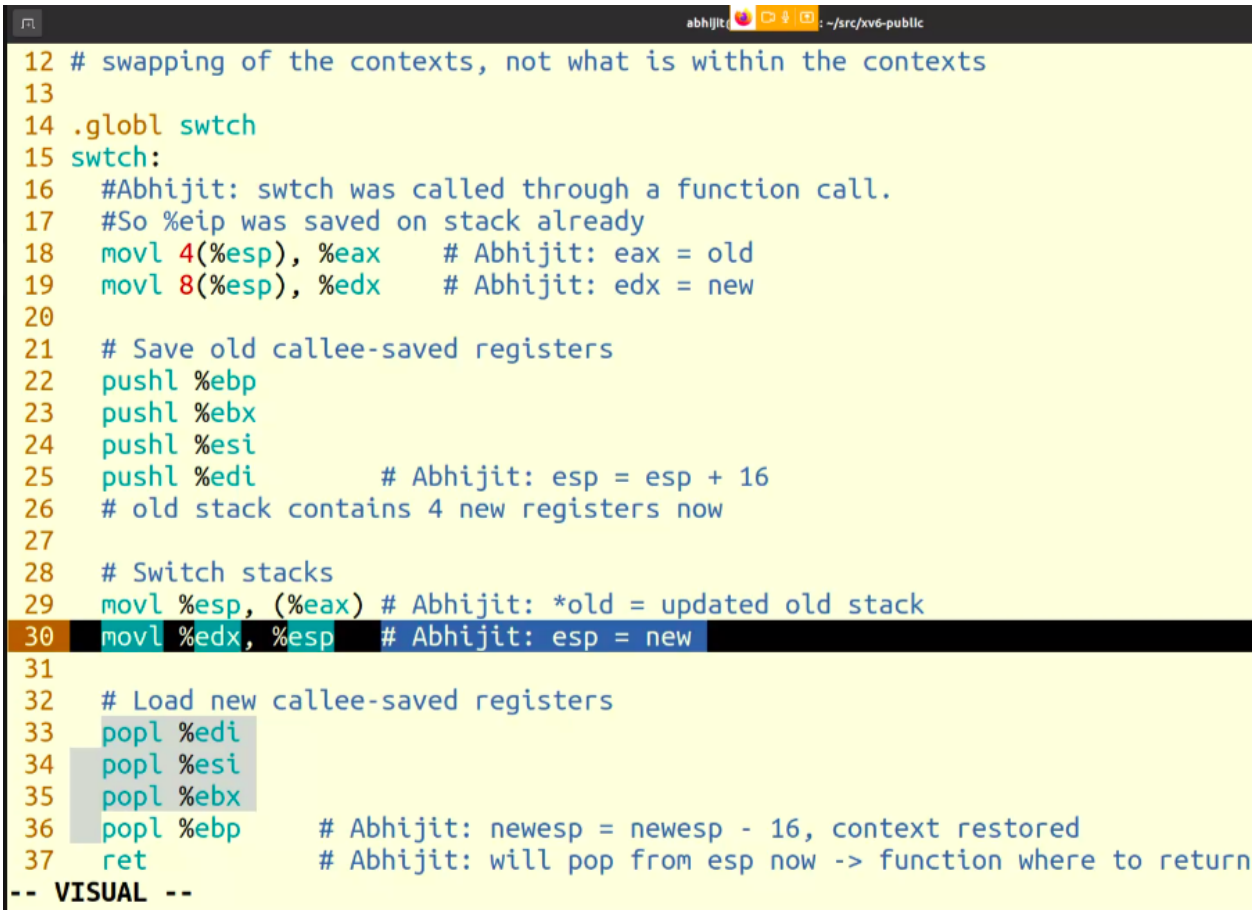
lets jump to switch which is defined into Switch.S

```
 1 # Context switch
 2 #
 3 #   void swtch(struct context **old, struct context *new);
 4 #
 5 # Save the current registers on the stack, creating
 6 # a struct context, and save its address in *old.
 7 # Switch stacks to new and pop previously-saved registers.
 8
 9 # Abhijit: remember you dont' change anything in the contexts,
10 # i.e. **old is not changed
11 # old *old is changed and *new is changed
12 # swapping of the contexts, not what is within the contexts
13
14 .globl swtch
15 swtch:
16   #Abhijit: swtch was called through a function call.
17   #So %eip was saved on stack already
18   movl 4(%esp), %eax    # Abhijit: eax = old
19   movl 8(%esp), %edx    # Abhijit: edx = new
20
21   # Save old callee-saved registers
22   pushl %ebp
23   pushl %ebx
24   pushl %esi
25   pushl %edi        # Abhijit: esp = esp + 16
26   # old stack contains 4 new registers now
                                                              3,53
```

first argument is old(pointer to pointer of c→scheduler), 2nd is new(pointer to process context that is to be scheduled)

at top of stack %esp we have return value of function, at 4(esp) we have old(1st argument) and at 8(esp) we have 2nd argument new

ebp,ebx,esi,edi are the callee saved registers, which are pushed to stack, which stack? scheduler stack, in assemby .comm wala stack



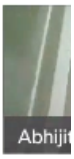
then line 29 does *old= esp's current value after pushing registers, then we now point esp to new stack i.e. p→ context 's value, so now the stack is pointing to the kernel stack of new process, then we do pop i.e loading context of new process from stack to actual registers, then we call ret, which will pop value into eip, when this return happens it jumps into new process, we are pushing edi,esi,ebx and ebp explicitly while eip is being pushed and poped implicitly.(hence it aligns with defination of struct context)

the ret will pop eip of new process, so we will go into new process. So switching of context is not like function call, we never return to swtch() after its call

to know how is line 30 swtiching stacks, see diagram of struct proc.

NOTE:SCHEDULER ENABLES INTERRUPTS, not disable (sti instruction)

scheduler()



- Disable interrupts
- Find a RUNNABLE process. Simple round-robin!
- c->proc = p
- switchuvm(p) : Save TSS of scheduler's stack and make CR3 to point to new process pagedir
- p->state = RUNNING
- swtch(&(c->scheduler), p->context)

scheduler()

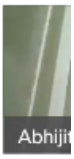
- swtch(&(c->scheduler), p->context)
- Note that when scheduler() was called, when P1 was running
- After call to swtch() shown above
  - The call does NOT return!
  - The new process P2 given by ‘p’ starts running !
  - Let’s review swtch() again

swtch(old, new)

- The magic function in swtch.S
- Saves callee-save registers of old context
- Switches esp to new-context's stack
- Pop callee-save registers from new context
- ret
  - where? in the case of first process – returns to forkret() because stack was setup like that !
  - in case of other processes, return where?
    - Return address given on kernel stack. But what's that?
    - The EIP in p->context
    - When was EIP set in p->context ?

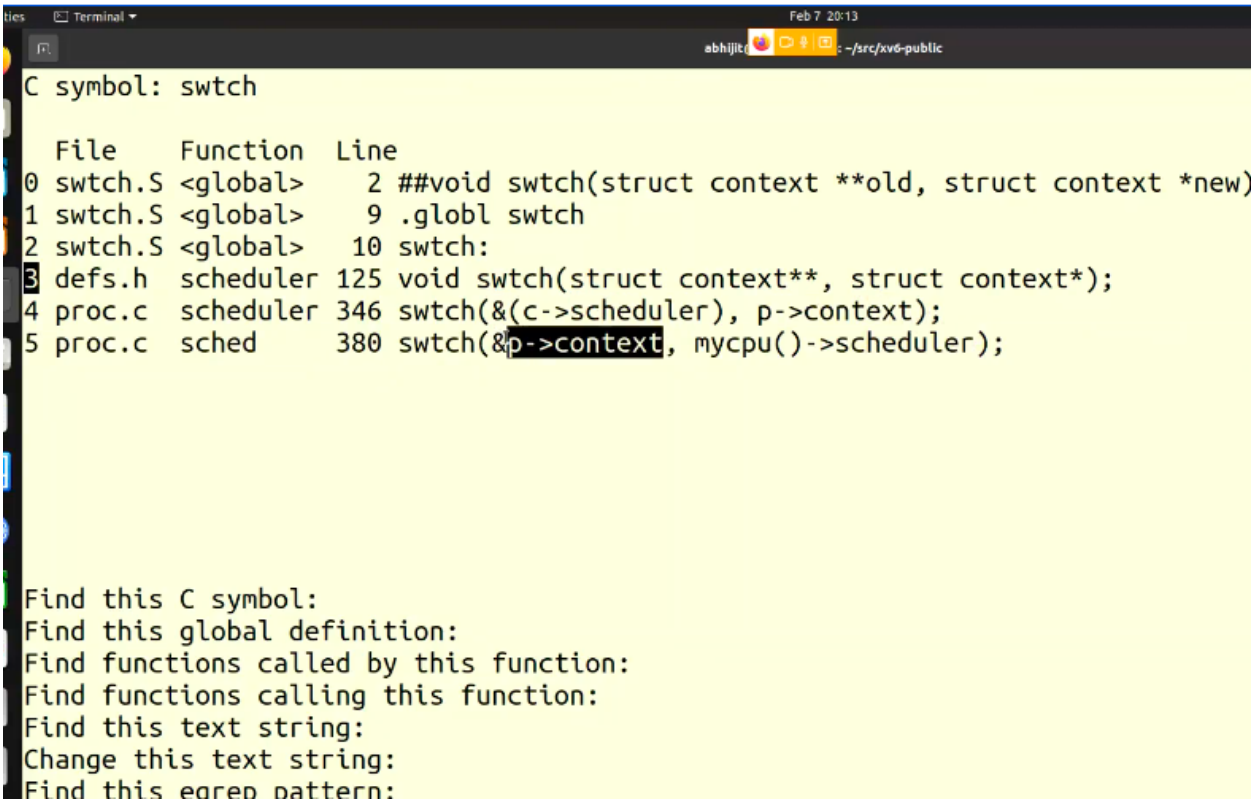
so the ret will return to eip in p→context, when was eip set in p→context, so to find that we try to look where was scheduler called, it is only called once in mpmain, but interestingly there is another sched() which is also a scheduler

scheduler()



- Called from?
  - mpmain()
  - No where else!
- sched() is another scheduler function !
  - Who calls sched() ?
    - exit() - a process exiting calls sched ()
    - yield() - a process interrupted by timer calls yield()
    - sleep() - a process going to wait calls sleep()

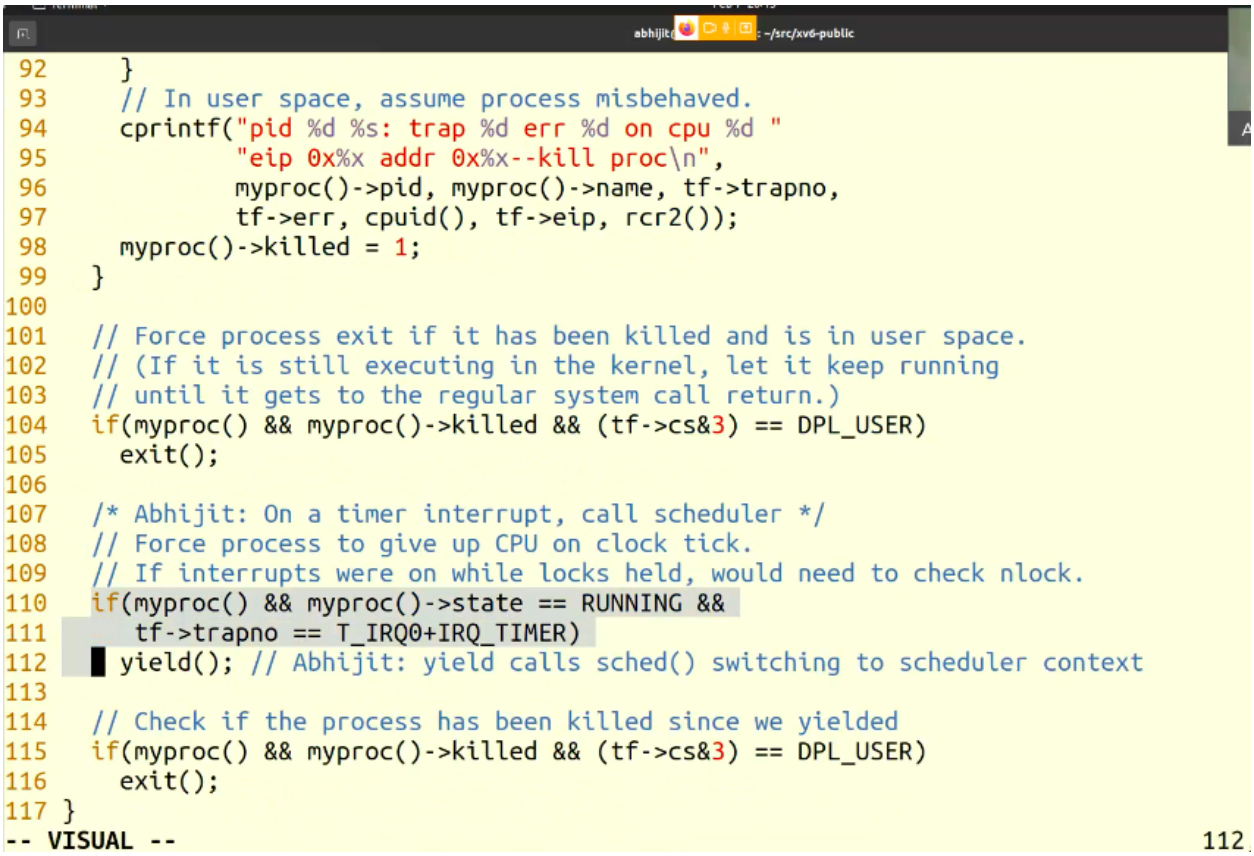
we try to find where swtch was called,and find that it was called inside sched and that the arguments are reversed, just see 4th and 5th entry in the below image

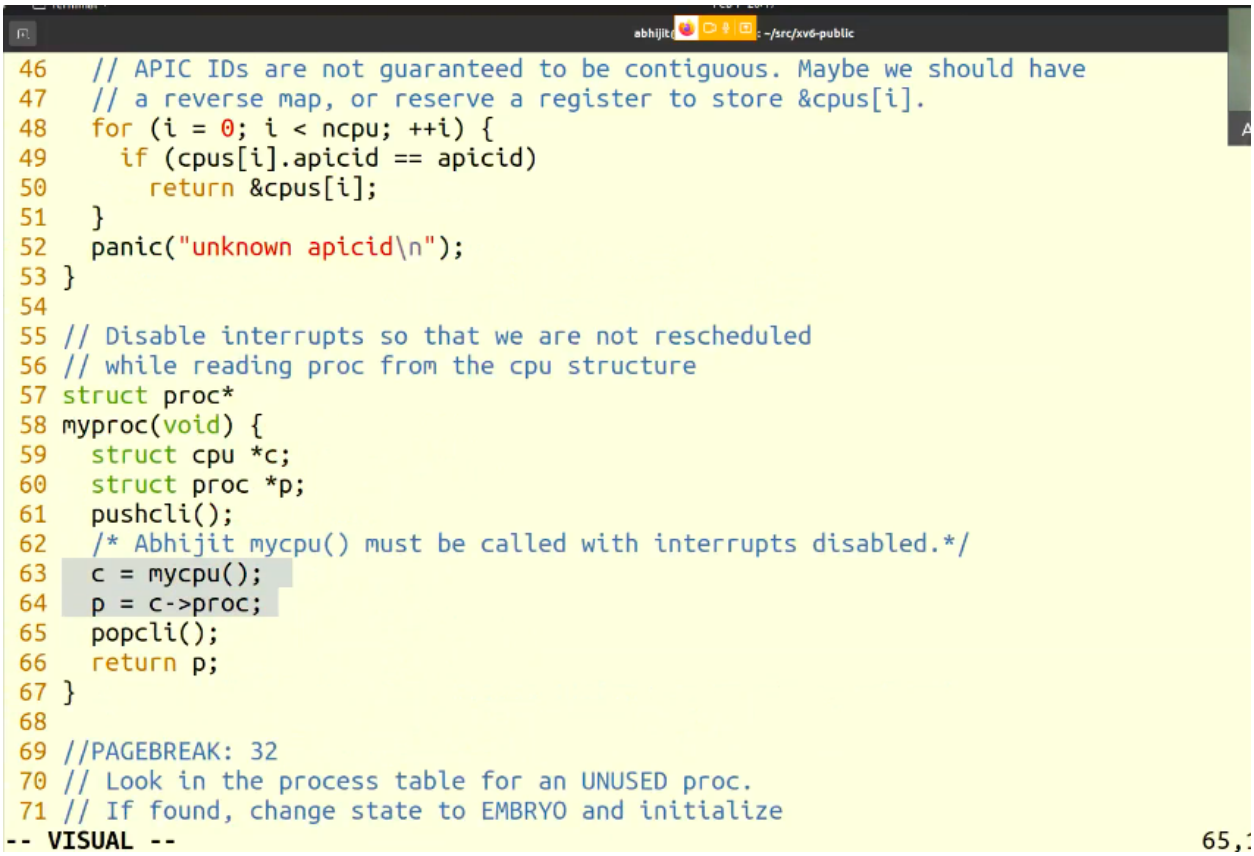


exit() calls sched, which is obvious, since when process ends, it has to pass control back to kernel

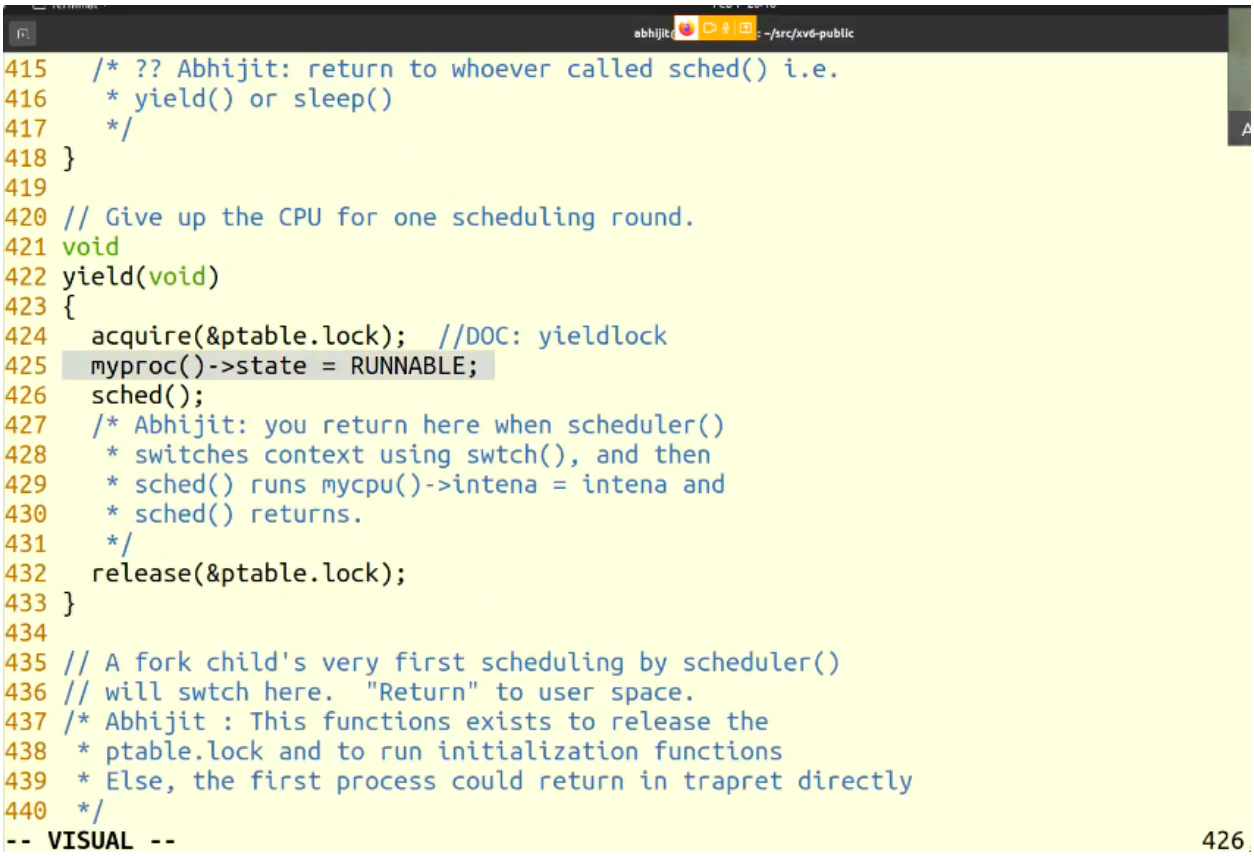
sleep() when is sleep called, when it is above to be blocking for i/o operations

so our interest lies in yield, lets see who calls yield(). it is called in trap.c


abhijit: ~/src/xv6-public
92 }
93 // In user space, assume process misbehaved.
94 cprintf("pid %d %s: trap %d err %d on cpu %d "
95 "eip 0x%x addr 0x%x--kill proc\n",
96 myproc()->pid, myproc()->name, tf->trapno,
97 tf->err, cpuid(), tf->eip, rcr2());
98 myproc()->killed = 1;
99 }
100
101 // Force process exit if it has been killed and is in user space.
102 // (If it is still executing in the kernel, let it keep running
103 // until it gets to the regular system call return.)
104 if(myproc() && myproc()->killed && (tf->cs&3) == DPL_USER)
105 exit();
106
107 /* Abhijit: On a timer interrupt, call scheduler */
108 // Force process to give up CPU on clock tick.
109 // If interrupts were on while locks held, would need to check nlock.
110 if(myproc() && myproc()->state == RUNNING &&
111 tf->trapno == T_IRQ0+IRQ_TIMER)
112 yield(); // Abhijit: yield calls sched() switching to scheduler context
113
114 // Check if the process has been killed since we yielded
115 if(myproc() && myproc()->killed && (tf->cs&3) == DPL_USER)
116 exit();
117 }
-- VISUAL --
112

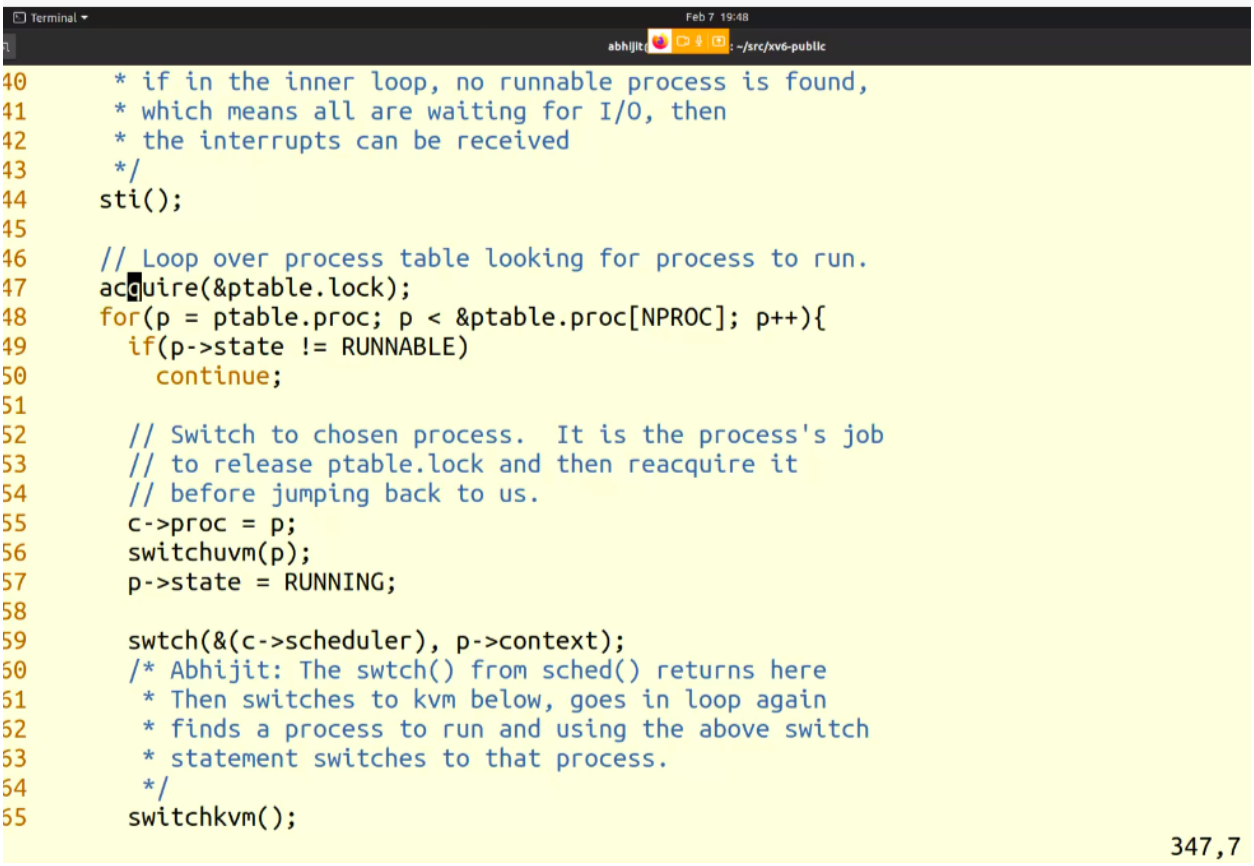


(myproc is shown above,)if current proc, and its state is RUNNING, and timer interrupt occurred, it calls yield(which means to give up), (timer interrupt is a kind of hardware interrupt hence stack changes to kernel stack as a part of int instruction)



it marks current process's state as RUNNABLE from RUNNING(marked in scheduler)

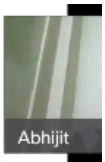
then calls sched, which calls swtch(&p→context,mycpu()→scheduler), currently running process context is pushed on its own kernel stack, when we came to kernel stack, we came to kernel stack of process when int instruction was executed, it will set p→ context pointer to top of stack, after pushing 5 variables, and it will now load context from mycpu→scheduler(),from there it will load context of kernel, this is the same context that was saved when switch was called from scheduler(), the end result of calling this swtch() is that function now returns into the proc.c file scheduler() function, after swtch(), i.e at line 359(seen 59 in below image)



now scheduler function will continue in the infinite loop.

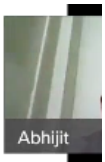
```
void
sched(void)
{
  int intena;
  struct proc *p = myproc();
  if(!holding(&ptable.lock))
    panic("sched ptable.lock");
  if(mycpu()->ncli != 1)
    panic("sched locks");
  if(p->state == RUNNING)
    panic("sched running");
  if(readeflags()&FL_IF)
    panic("sched interruptible");
  intena = mycpu()->intena;
  swtch(&p->context, mycpu()->scheduler);
/*A*/  mycpu()->intena = intena;
}
```

sched()



- get current process
- Error checking code (ignore as of now)
- get interrupt enabled status on current CPU (ignore as of now)
- call to swtch
  - Note the arguments' order
  - p->context first, mycpu()->scheduler second
- swtch() is a function call
  - pushes address of /*A*/ on stack of current process p
  - switches stack to mycpu()->scheduler. Then pops EIP from that stack and jumps there.
  - when was mycpu()->scheduler set? Ans: during scheduler()!

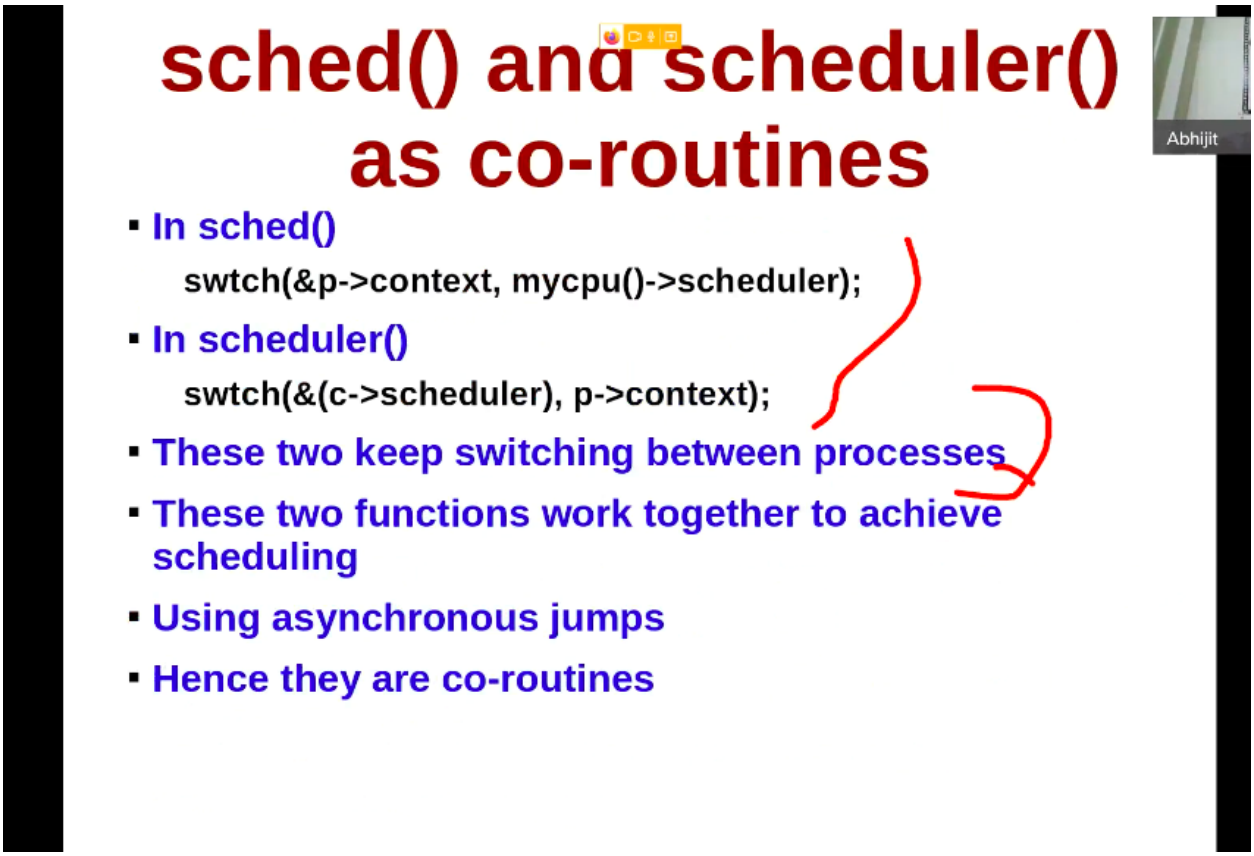
sched() and schduler()




```
sched() {
...
  swtch(&p->context, mycpu()->scheduler); /* X */
}
```

```
scheduler(void) {
...
    swtch(&(c->scheduler), p->context);  / * Y */
}
```

- scheduler() saves context in c->scheduler, sched() saves context in p->context
- after swtch() call in sched(), the control jumps to Y in scheduler
  - Switch from process stack to scheduler's stack
- after swtch() call in scheduler(), the control jumps to X in sched()
  - Switch from scheduler's stack to new process's stack
- Set of co-operating functions



there are other 2 possibilities, that is when sched is called from exit() and sleep()

the above discussion only makes sense if the parameters are passed through stack, in calling conventions(and registers are not used for passing parameters) while calling swtch in sched and scheduler, hence we give a option while compiling the code that it will always pass parameters through stack.

why each process has its own kernel stack?

because each process makes its own syscall, so context of each process is to be stored on kernel stack, it is not accessible to application code, or the application could manipulate it and do illegal things.

how does kernel keeps track of each process's kstack?

there is a pointer inside struct proc for that

SUMMARY (combining traps and scheduler)

when timer interrupt, [as a part of int instruction process's user stack changes to process's kernel stack] occurs,it gets cs and eip from idt table inside gatedesc struct, from there it goes to vectors.S where it pushes 0,trap number, then alltraps which

creates trapframe and calls trap,which checks for timer interrupt and calls yield, which calls sched which switches user process’s stack to scheduler stack,(inside swtch() i.e. in switch.S, that saves the old context and switches stack,loads context into registers[here process’s kernel stack changes to scheduler’s stack]) which returns inside scheduler(), inside that infinite loop, which checks for next RUNNABLE process and then switches scheduler’s stack to new process’s stack,[scheduler’s stack changes to new process’s kernel stack](which inside swtch.S stores scheduler’s context on stack, updates esp, changes esp to process’s stack, load context into registers) and return sched() and returns in yield inside trap, which returns in alltraps. In alltraps, which calls trapret, iret [that will change new process’s kernel stack to process’s user stack],process continues execution, then again a timer interrupt occurs and so on.