Memory Management Basics

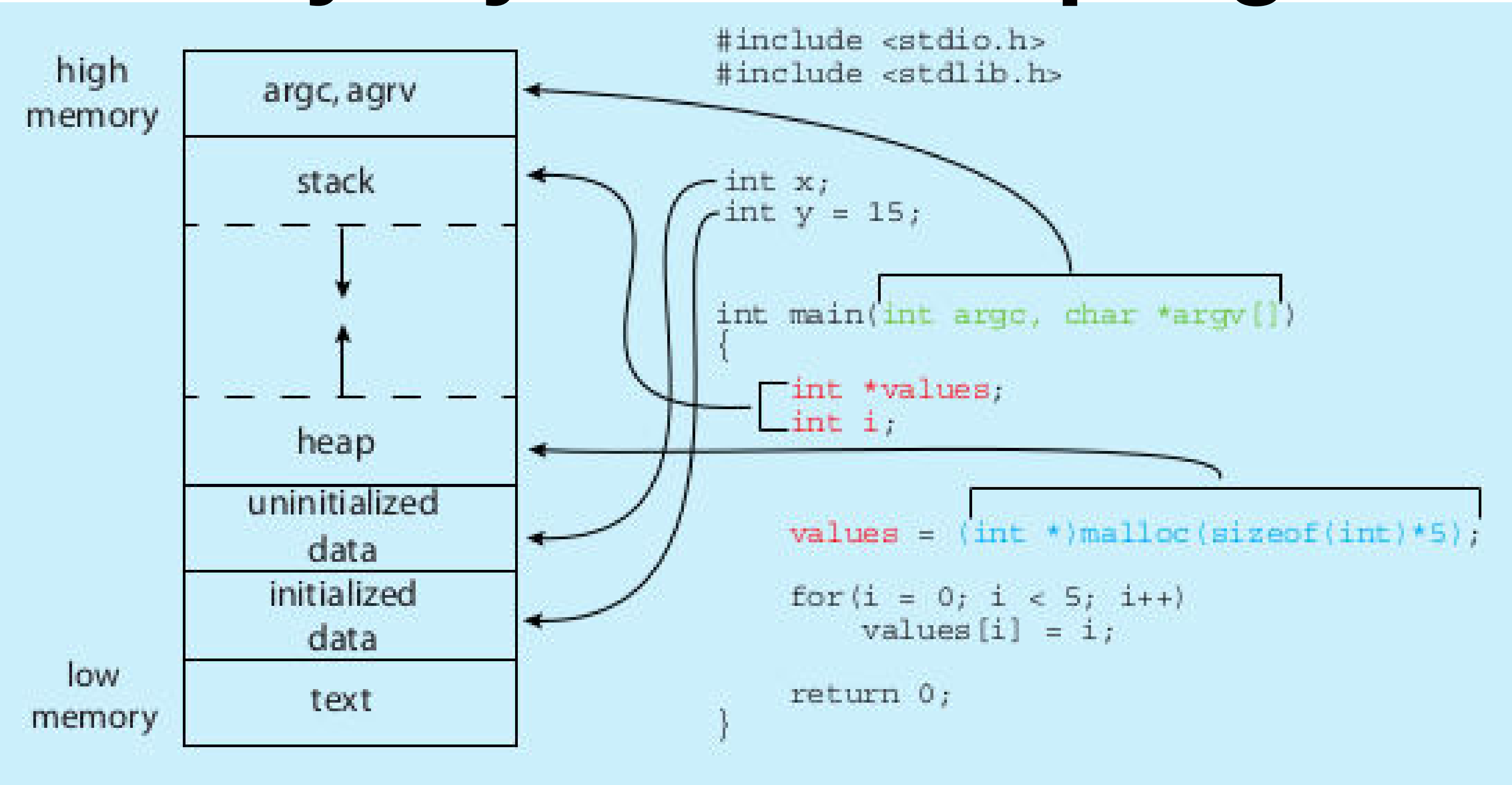
Summary

- Understanding how the processor architecture drives the memory management features of OS and system programs (compilers, linkers)
- Understanding how different hardware designs lead to different memory management schemes by operating systems

Addresses issued by CPU

- During the entire ‘on’ time of the CPU
  - Addresses are “issued” by the CPU on address bus
  - One address to fetch instruction from location specified by PC
  - Zero or more addresses depending on instruction
    - e.g. mov $0x300, r1 # move contents of address 0x300 to r1 --> one extra address issued on address bus

Memory layout of a C program



$ size /bin/ls
text data bss dec hexfilename
128069 4688 4824 137581 2196d/bin/ls

Desired from a multi-tasking system

- Multiple processes in RAM at the same time (multi-programming)
- Processes should not be able to see/touch each other’s code, data (globals), stack, heap, etc.
- Further advanced requirements
  - Process could reside anywhere in RAM
  - Process need not be continuous in RAM
  - Parts of process could be moved anywhere in RAM

Different ‘times’

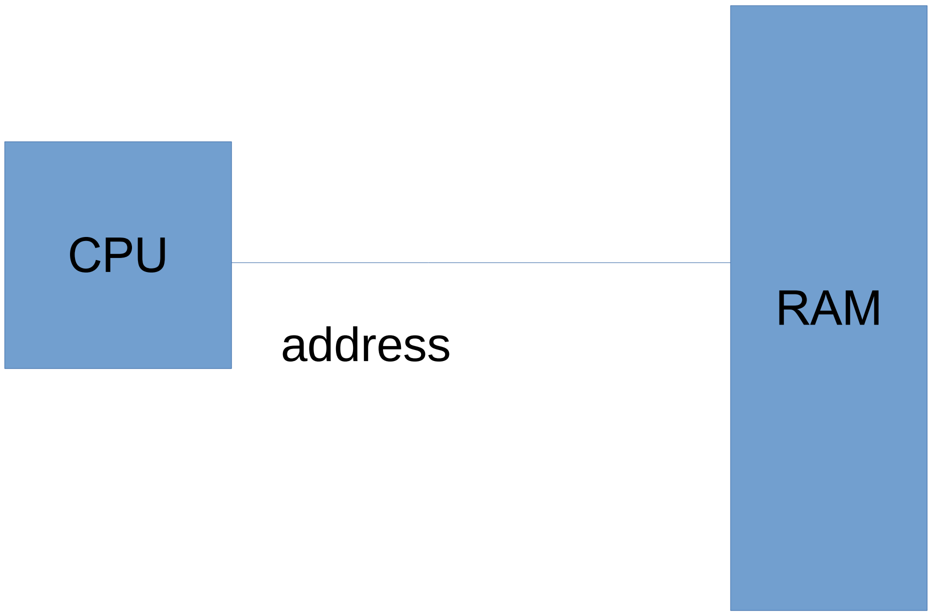
- Different actions related to memory management for a program are taken at different times. So let’s know the different ‘times’
- Compile time
  - When compiler is compiling your C code
- Load time
  - When you execute “./myprogram” and it’s getting loaded in RAM by loader i.e. exec()
- Run time
  - When the process is alive, and getting scheduled by the OS

Different types of Address binding

Which binding is actually used, is mandated by processor features + OS

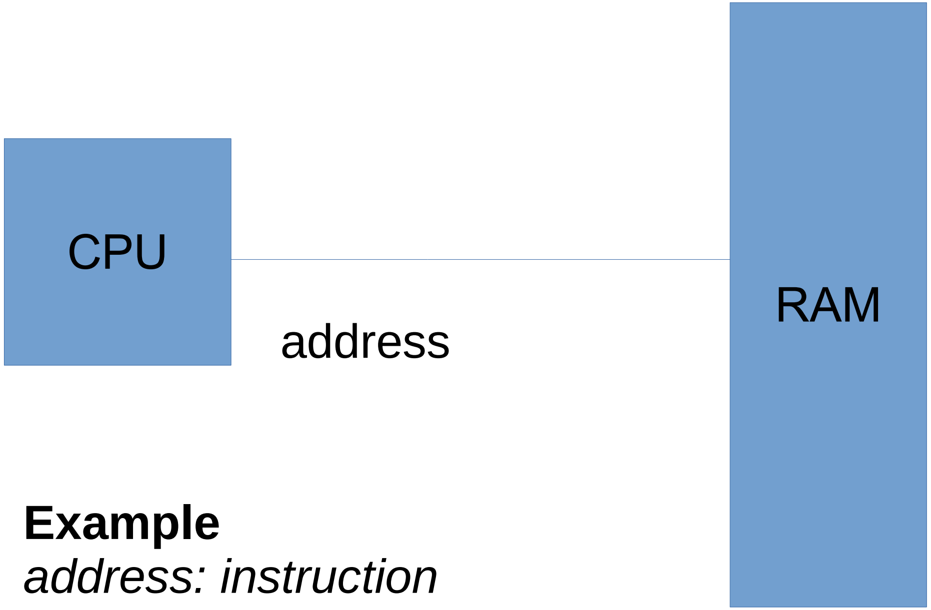
- Compile time address binding
  - Address of code/variables is fixed by compiler
  - Very rigid scheme
  - Location of process in RAM can not be changed ! Non-relocatable code.
- Load time address binding
  - Address of code/variables is fixed by loader
  - Location of process in RAM is decided at load time, but can’t be changed later
  - Flexible scheme, relocatable code
- Run time address binding
  - Address of code/variables is fixed at the time of executing the code
  - Very flexible scheme , highly relocatable code
  - Location of process in RAM is decided at load time, but CAN be changed later also

Simplest case



- Suppose the address issued by CPU reaches the RAM controller directly

Simplest case

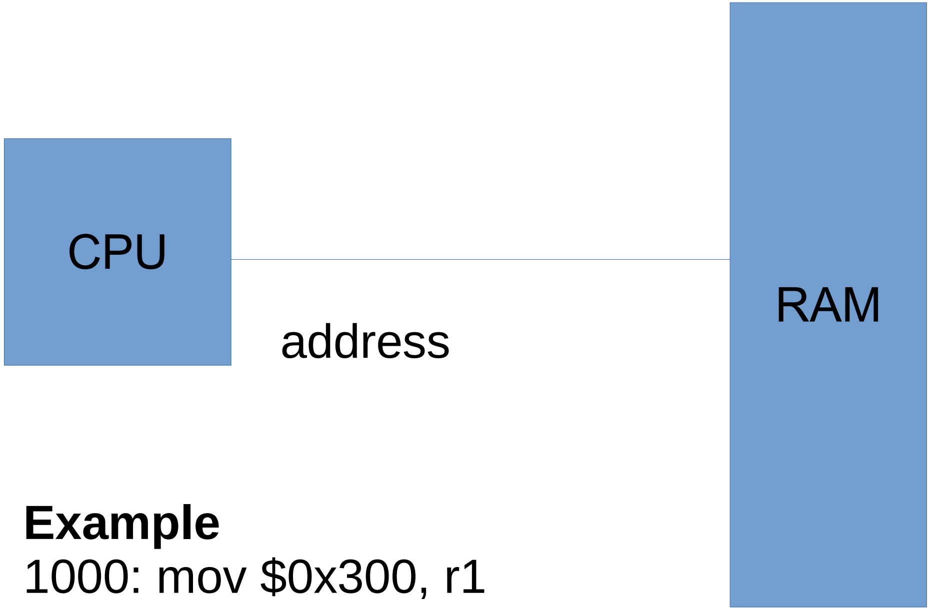


- How does this impact the compiler and OS ?
- When a process is running the addresses issued by it, will reach the RAM directly
- So exact addresses of globals, addresses in “jmp” and “call” must be part the machine instructions generated by compiler
  - How will the compiler know the addresses, at “compile time” ?

Example
address: instruction
1000: mov $0x300, r1
1004: add r1, -3
1008: jnz 1000

Sequence of addressed sent by CPU: 1000, 0x300, 1004, 1008, 1000, 0x300, ...

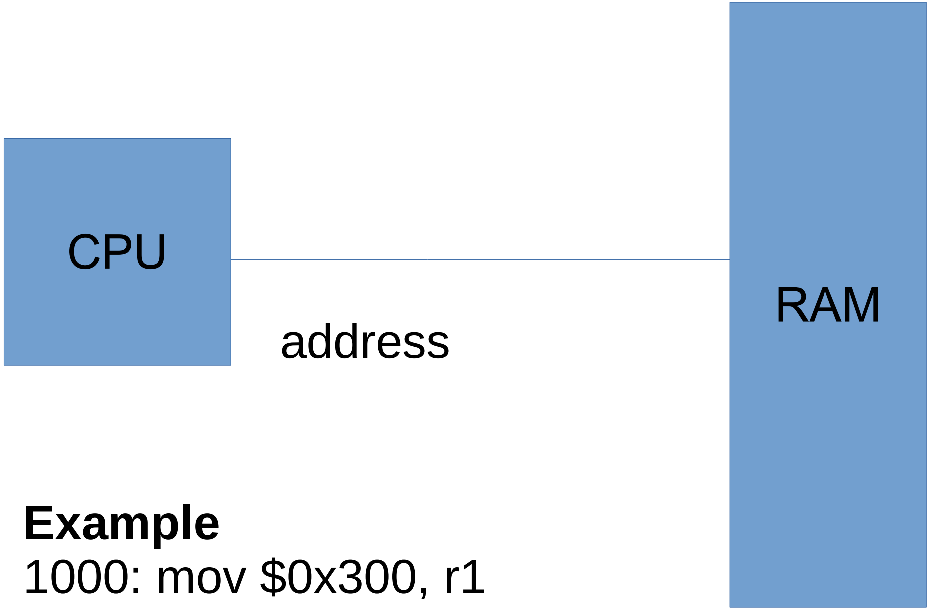
Simplest case



Example
1000: mov $0x300, r1
1004: add r1, -3
1008: jnz 1000

- Solution: compiler assumes some fixed addresses for globals, code, etc.
- OS loads the program exactly at the same addresses specified in the executable file. **Non-relocatable code.**
- Now program can execute properly.

Simplest case



Example
1000: mov $0x300, r1
1004: add r1, -3
1008: jnz 1000

- Problem with this solution
  - Programs once loaded in RAM must stay there, can't be moved
  - What about 2 programs?
    - Compilers being "programs", will make same assumptions and are likely to generate same/overlapping addresses for two different programs
    - Hence only one program can be in memory at a time !
    - No need to check for any memory boundary violations – all memory belongs to one process
- Example: DOS

Base/Relocation + Limit scheme

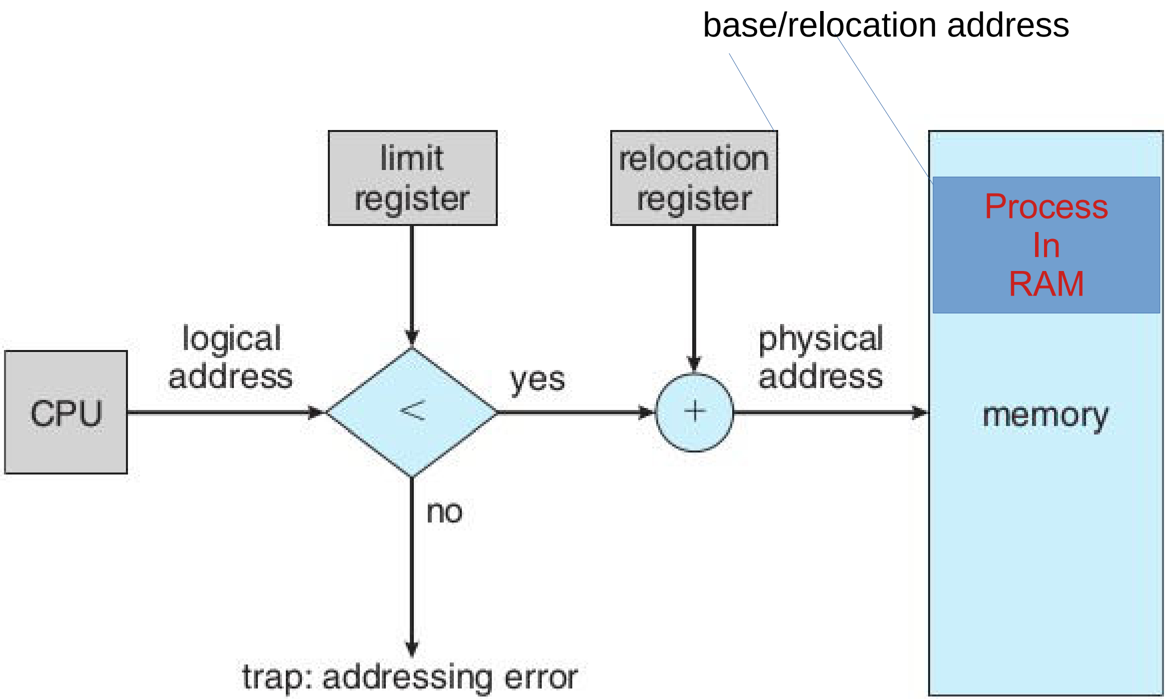


Figure 9.6 Hardware support for relocation and limit registers.

- Base and Limit are two registers inside CPU's Memory Management Unit
- 'base' is added to the address generated by CPU
- The result is compared with base+limit and if less passed to memory, else hardware interrupt is raised

Memory Management Unit (MMU)

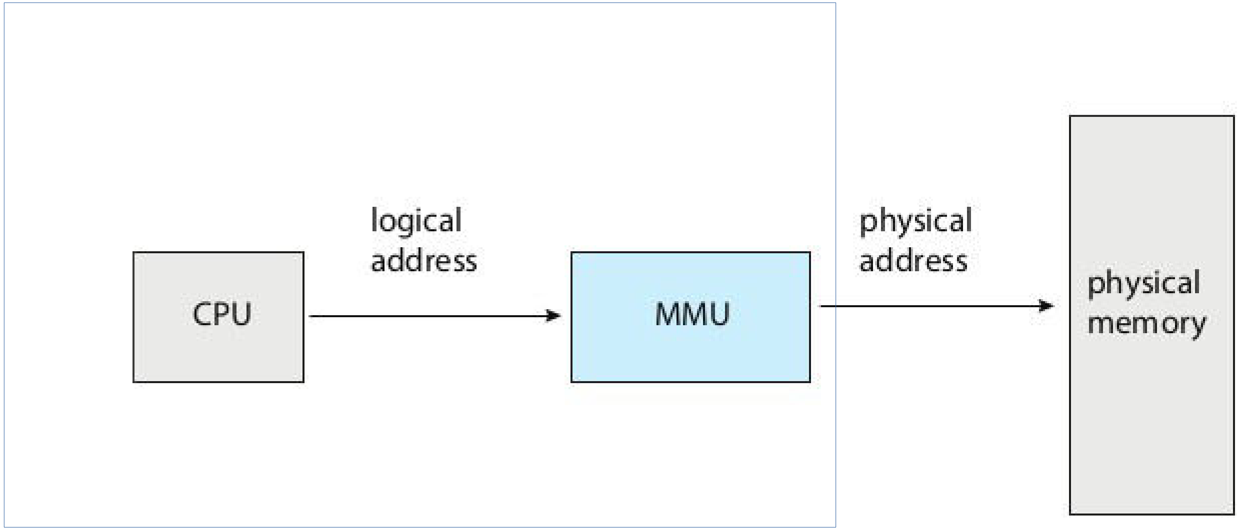
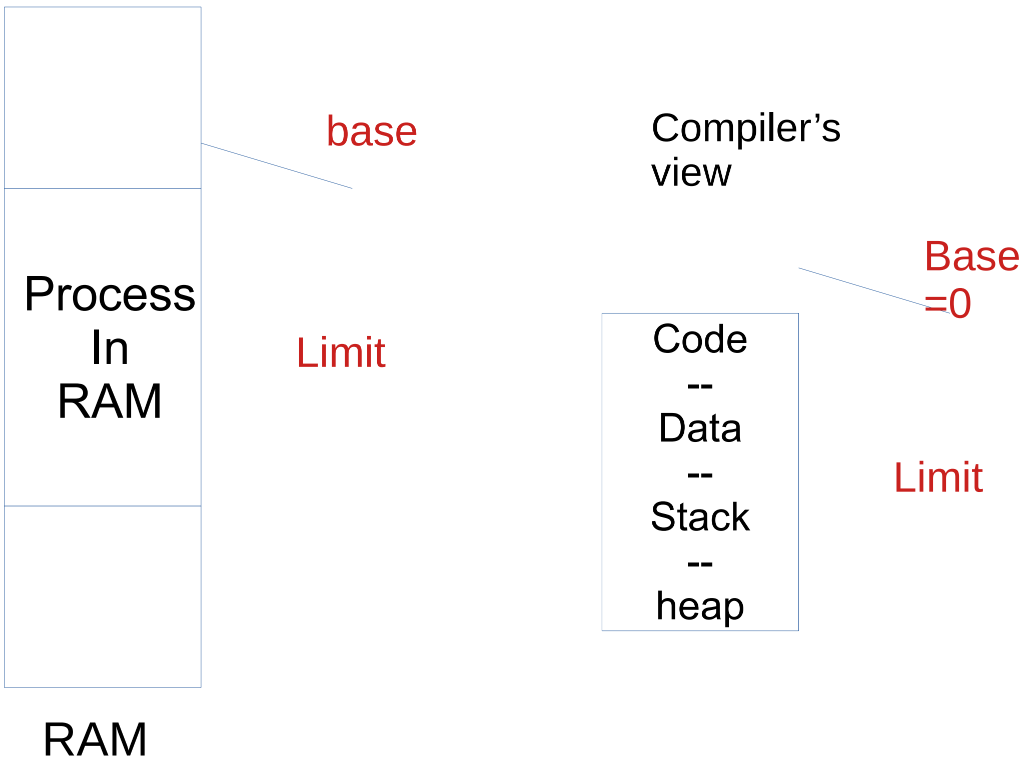


Figure 9.4 Memory management unit (MMU).

- Is part of the CPU chip, acts on every memory address issue by execution unit of the CPU
- In the scheme just discussed, the base, limit calculation parts are part of MMU

Base/Relocation + Limit scheme



- Compiler's work
  - Assume that the process is one continous chunk in memory, with a size limit
  - Assume that the process starts at address zero (!) and calculate addresses for globals, code, etc. And accordingly generate machine code

Base/Relocation + Limit scheme

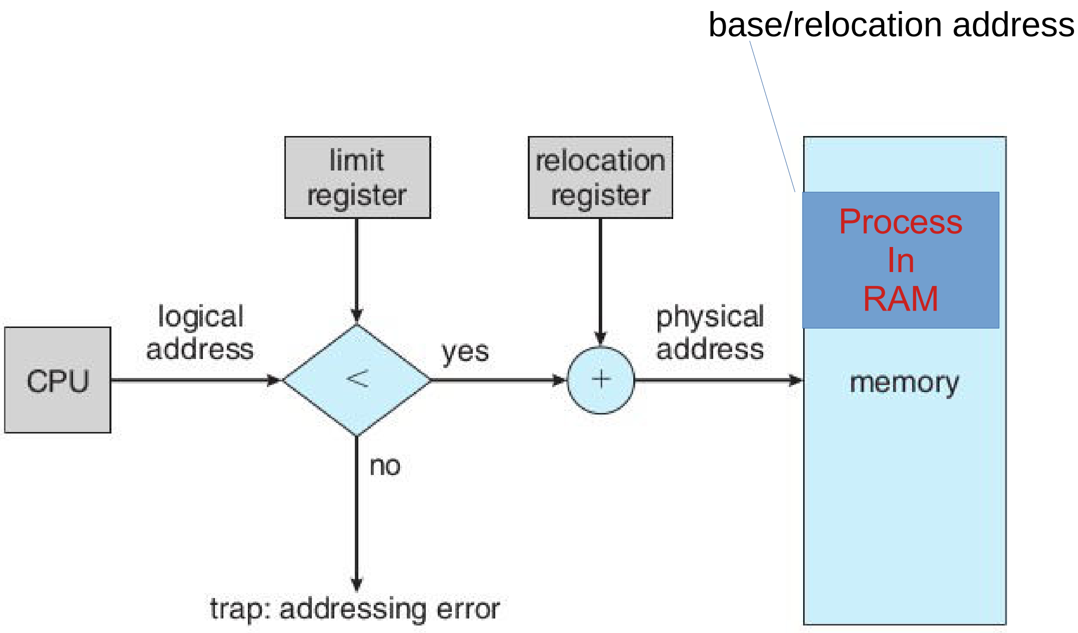


Figure 9.6 Hardware support for relocation and limit registers.

- OS's work
  - While loading the process in memory – must load as one continous segment
  - Fill in the 'base' register with the actual address of the process in RAM.
  - Setup the limit to be the size of the process as set by compiler in the executable file. *Remember the base+limit in OS's own data structures.*

Base/Relocation + Limit scheme

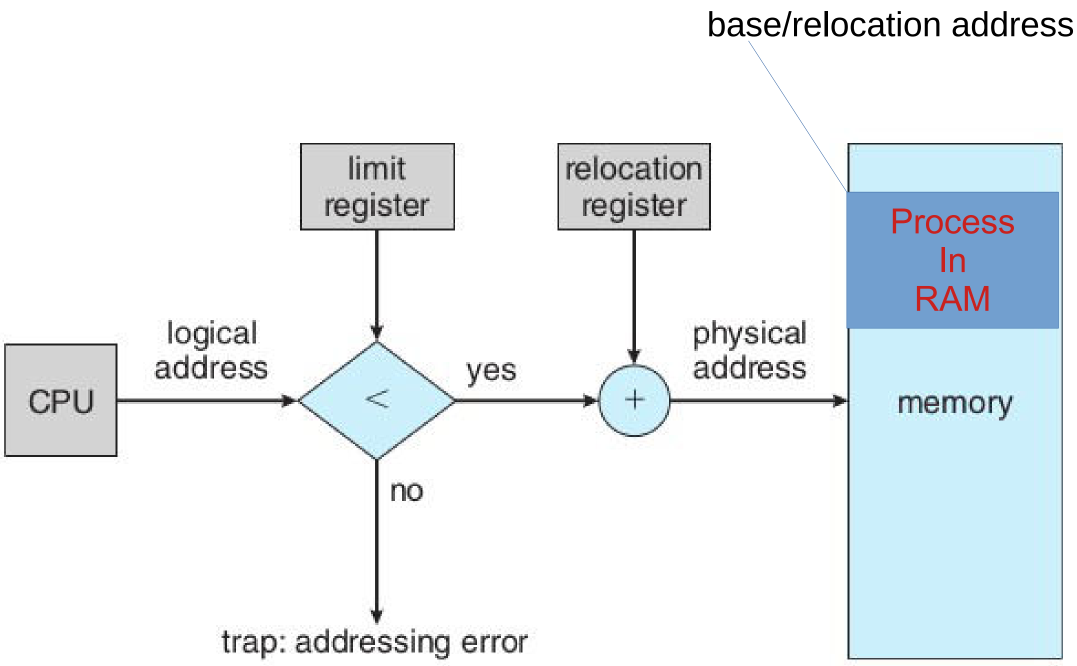
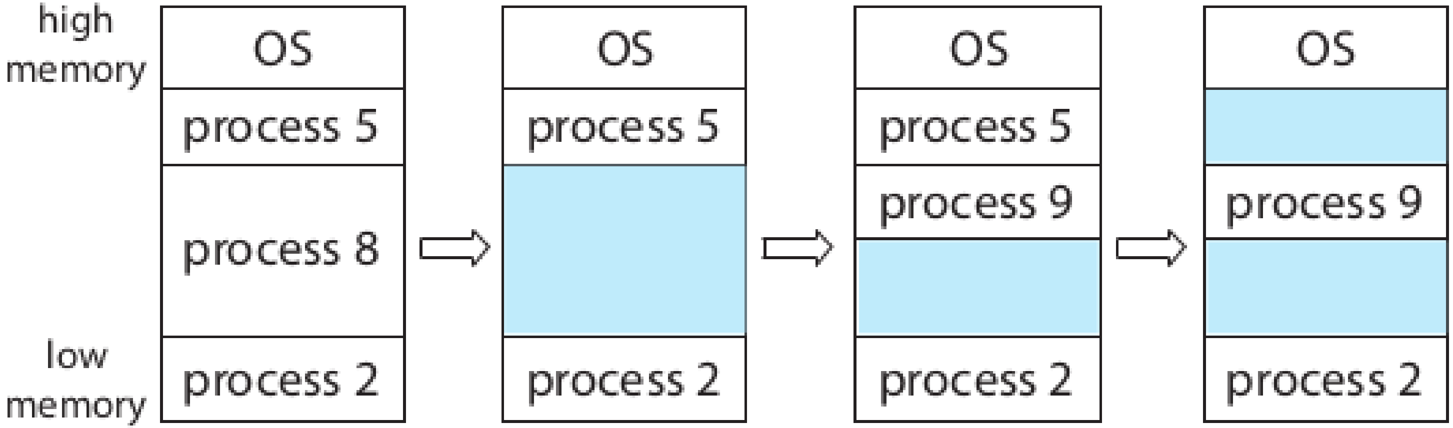


Figure 9.6 Hardware support for relocation and limit registers.

- Combined effect
  - **“Relocatable code”** – the process can go anywhere in RAM at the time of loading
  - Some memory violations can be detected – a memory access beyond base+limit will raise interrupt, thus running OS in turn, which may take action against the process

Example scenario of memory in base+limit scheme



Process 8 called exit()

Process 9 forked

Process 5 terminated

It should be possible to have relocatable code even with “simplest case”

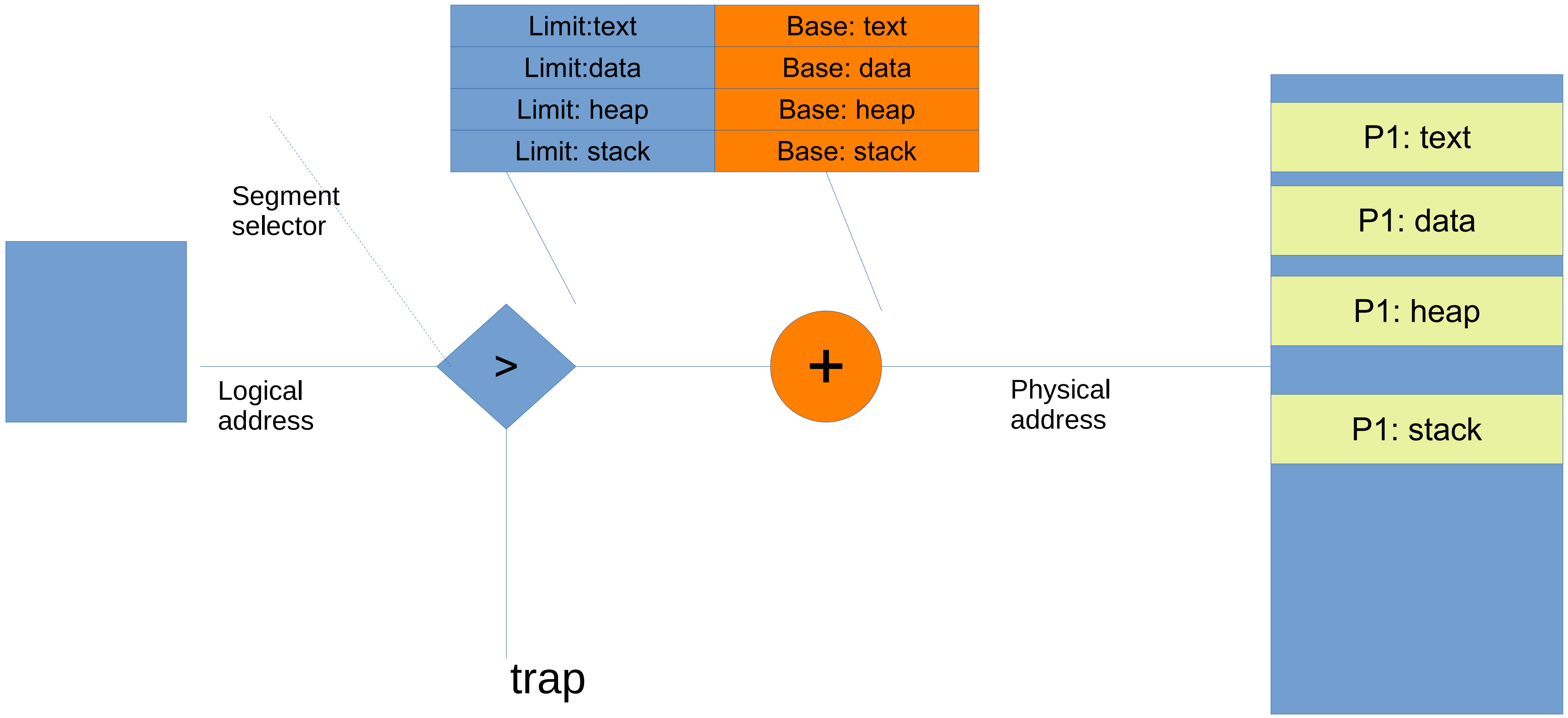
By doing extra work during “loading”.

How?

Next scheme: Segmentation Multiple base +limit pairs

- Multiple sets of base + limit registers
- Whenever an address is issued by execution unit of CPU, it will also include reference to some base register
  - And hence limit register paired to that base register will be used for error checking
- Compiler: can assume a separate chunk of memory for code, data, stack, heap, etc. And accordingly calculate addresses . Each “segment” starting at address 0.
- OS: will load the different ‘sections’ in different memory regions and accordingly set different ‘base’ registers

Next scheme:
Multiple base +limit pairs



Next scheme: Multiple base +limit pairs, with further indirection

- Base + limit pairs can also be stored in some memory location (not in registers). Question: how will the cpu know where it’s in memory?
  - One CPU register to point to the location of table in memory
- Segment registers still in use, they give an index in this table
- This is x86 segmentation
  - Flexibility to have lot more “base+limits” in the array/table in memory

Next scheme:
Multiple base +limit pairs, with further indirection

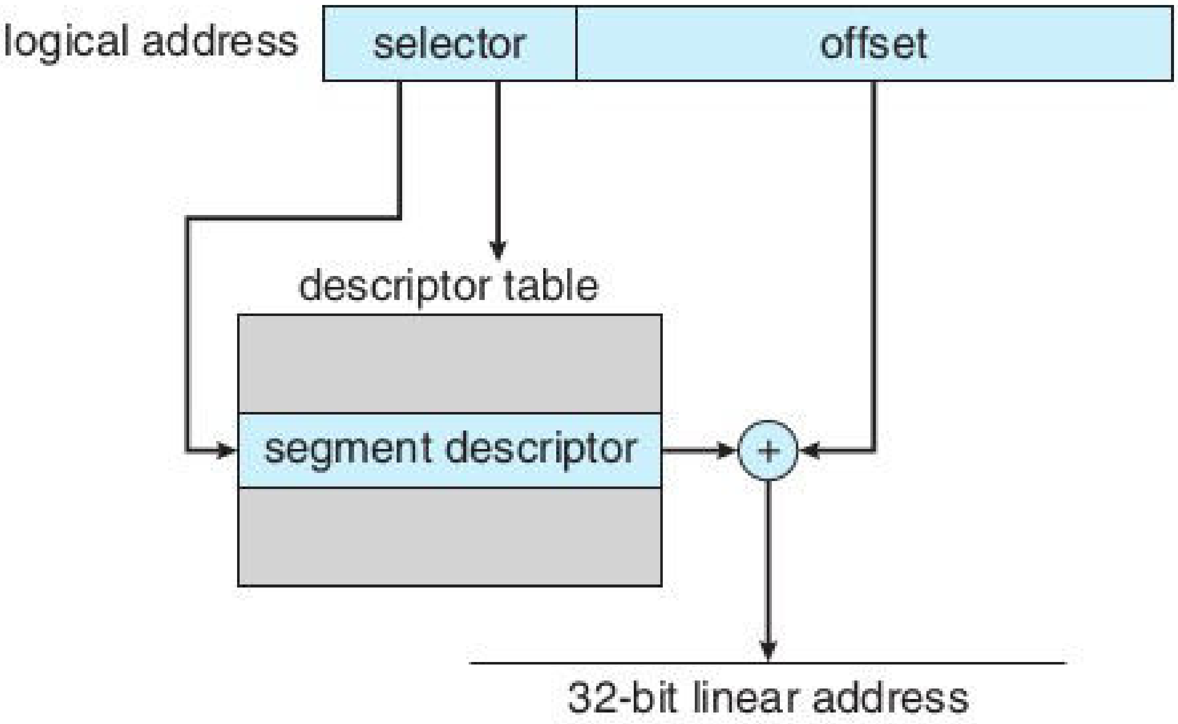


Figure 9.22 IA-32 segmentation.

Problems with segmentation schemes

- OS needs to find a continuous free chunk of memory that fits the size of the "segment"
  - If not available, your exec() can fail due to lack of memory
- Suppose 50k is needed
  - Possible that mong 3 free chunks total 100K may be available, but no single chunk of 50k!
  - **External fragmentation**
- Solution to external fragmentation: **compaction** – move the chunks around and make a continous big chunk available. Time consuming, tricky.

Solving external fragmentation problem

- Process should not be continous in memory!
- Divide the continuous process image in smaller chunks (let’s say 4k each) and locate the chunks anywhere in the physical memory
  - Need a way to map the *logical* memory addresses into *actual physical memory addresses*

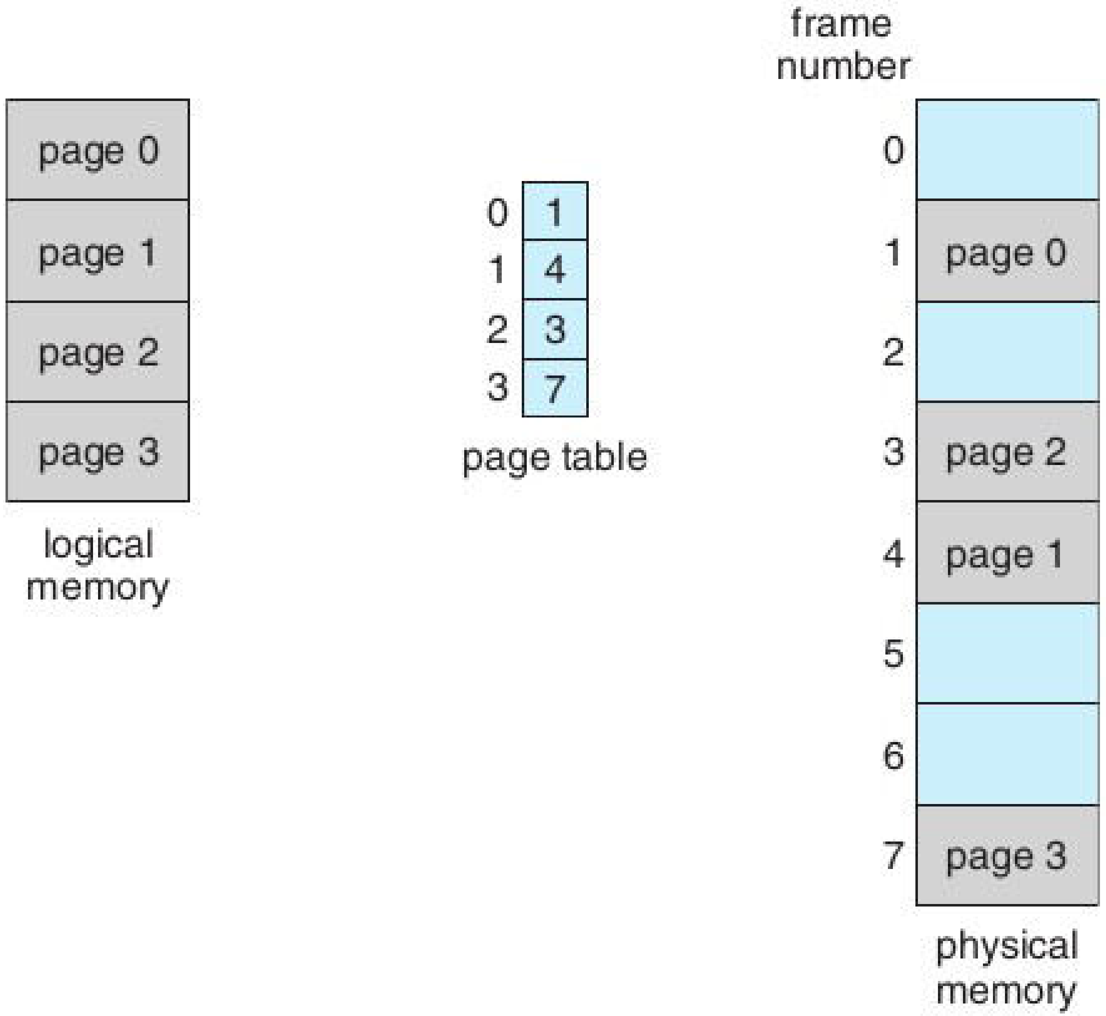


Figure 9.9 Paging model of logical and physical memory.

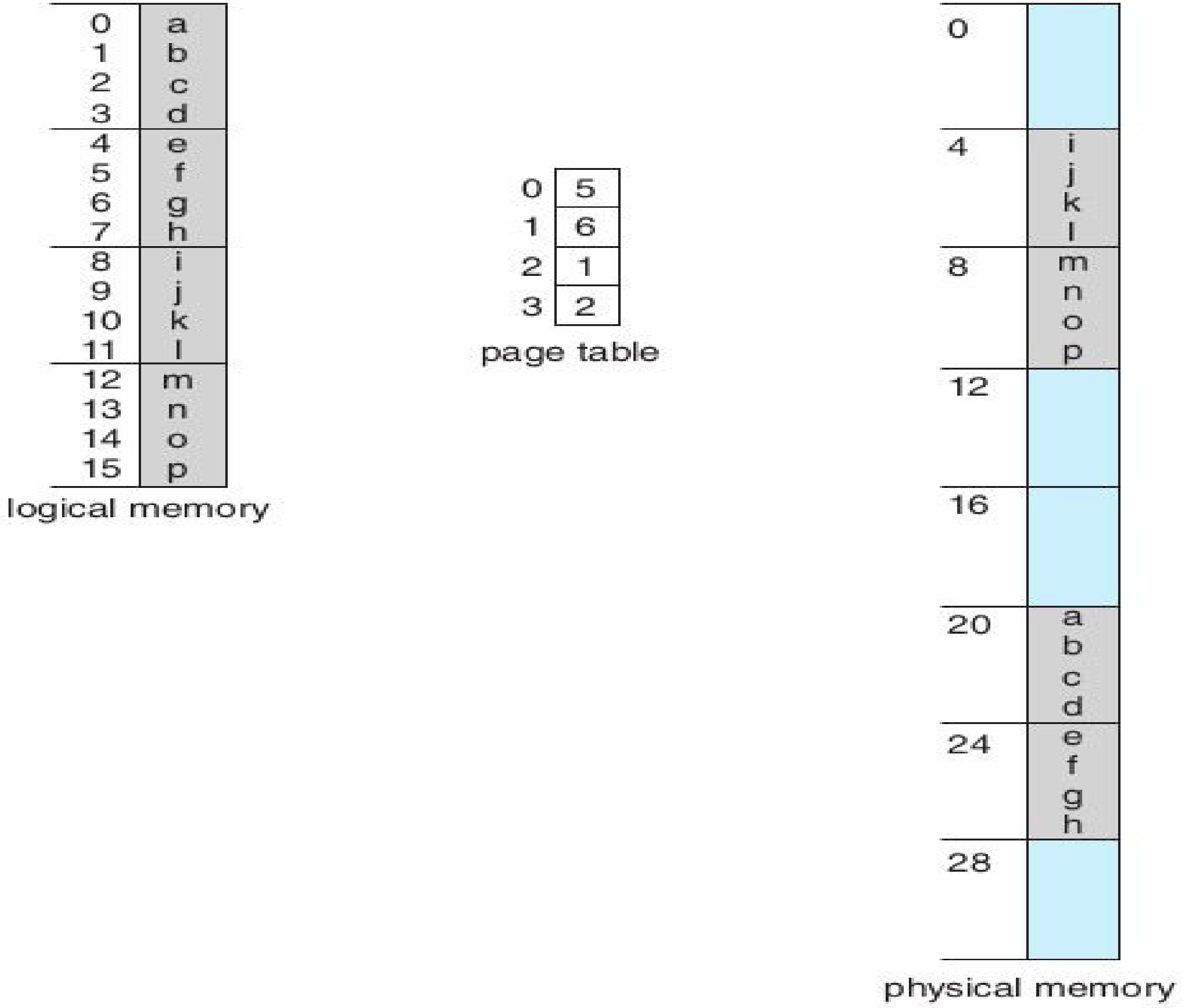


Figure 9.10 Paging example for a 32-byte memory with 4-byte pages.

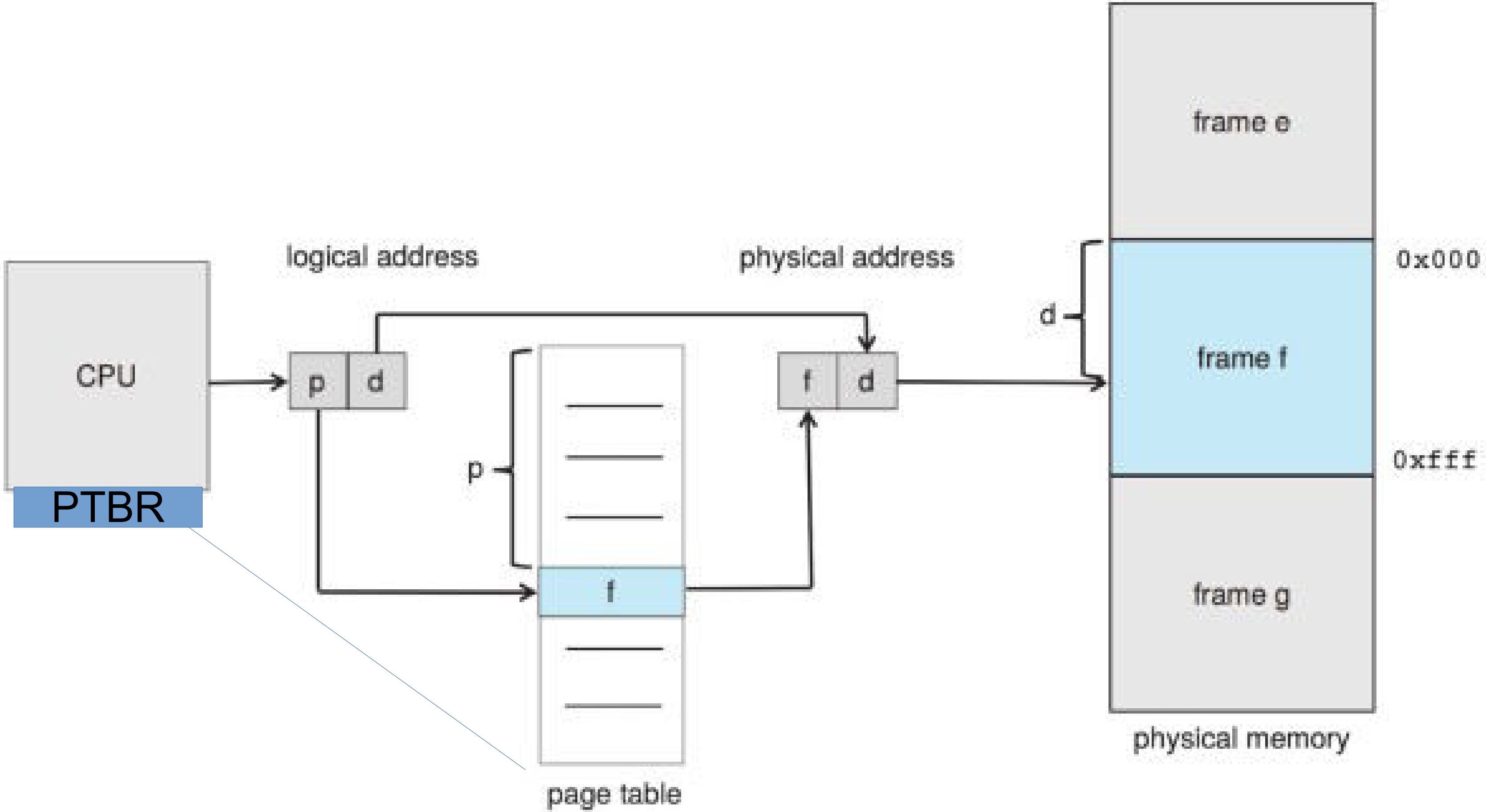


Figure 9.8 Paging hardware.

Paging

- Process is assumed to be composed of equally sized “pages” (e.g. 4k page)
- Actual memory is considered to be divided into page “frames”.
- CPU generated logical address is split into a page number and offset
- A page table base register inside CPU will give location of an in memory table called page table
- Page number used as offset in a table called page table, which gives the physical page frame number
- Frame number + offset are combined to get physical memory address

Paging

- Compiler: assume the process to be one continous chunk of memory (!) . Generate addresses accordingly
- OS: at exec() time – allocate different frames to process, allocate a page table(!), setup the page table to map page numbers with frame numbers, setup the page table base register, start the process
- Now hardware will take care of all translations of logical addresses to physical addresses

X86 memory management

Figure 9.21 Logical to physical address translation in IA-32.

Segmentation in x86

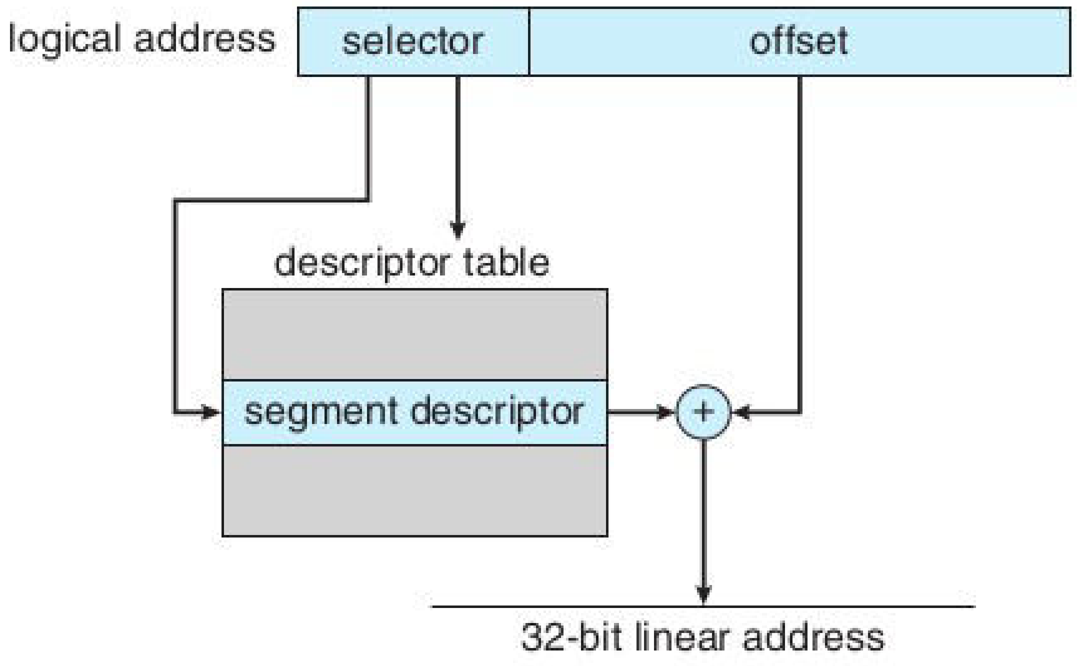


Figure 9.22 IA-32 segmentation.

- The selector is automatically chosen using Code Segment (CS) register, or Data Segment (DS) register depending on which type of memory address is being fetched
- Descriptor table is in memory
- The location of Descriptor table (Global DT- GDT or Local DT – LDT) is given by a GDT-register i.e. GDTR or LDT-register i.e. LDTR

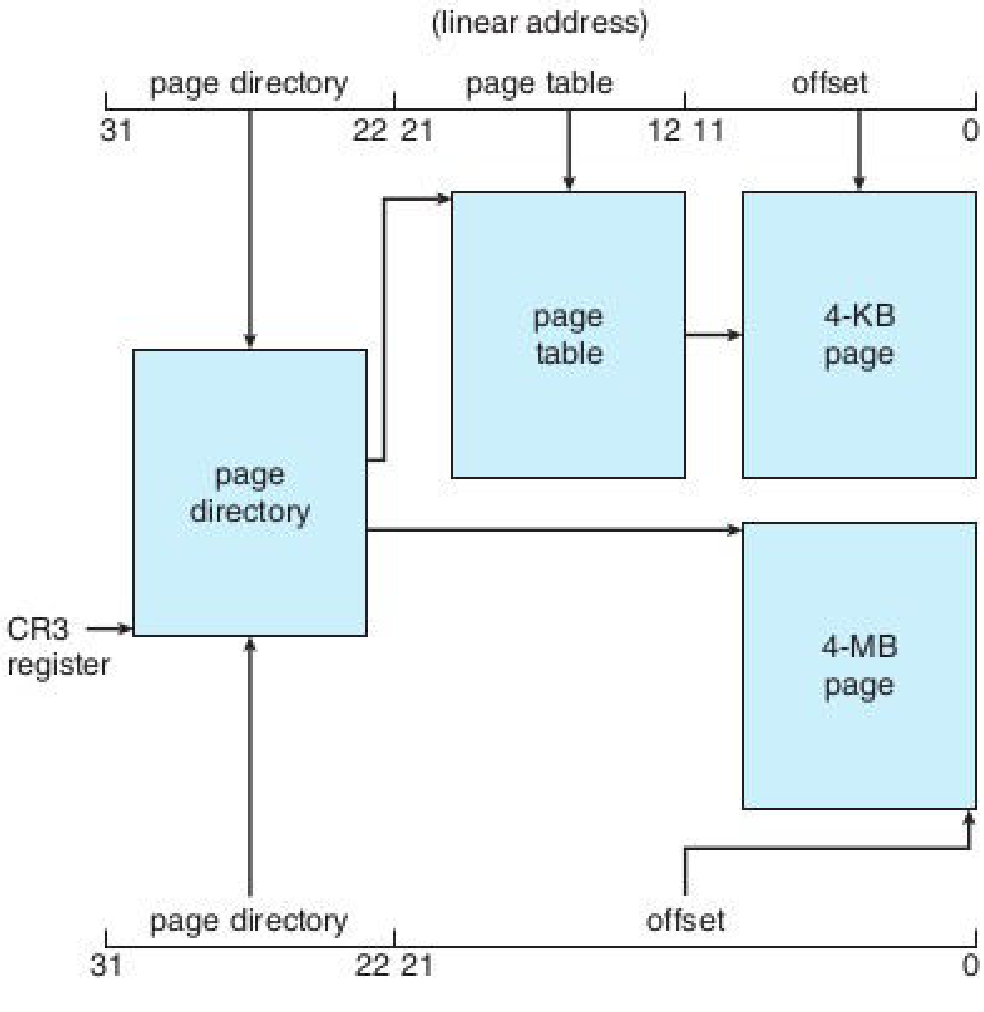


Figure 9.23 Paging in the IA-32 architecture.

Paging in x86

- Depending on a flag setup in CR3 register, either 4 MB or 4 KB pages can be enabled
- Page directory, page table are both in memory

Processes

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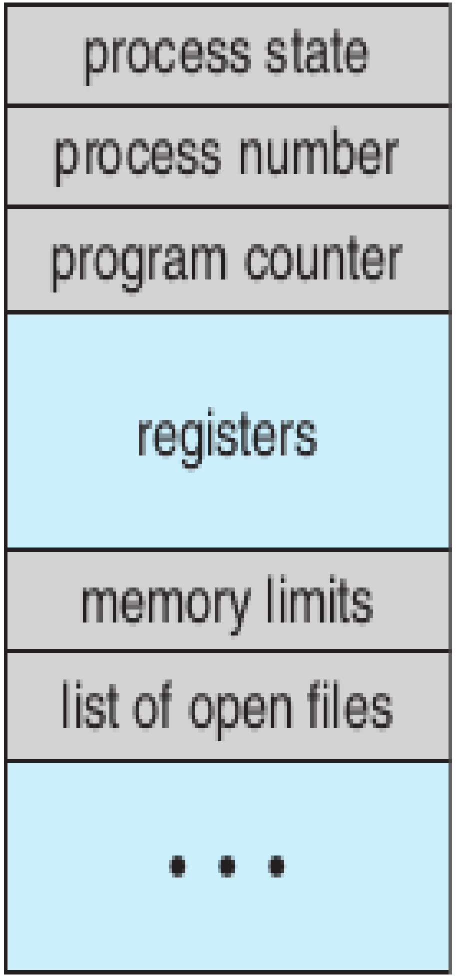
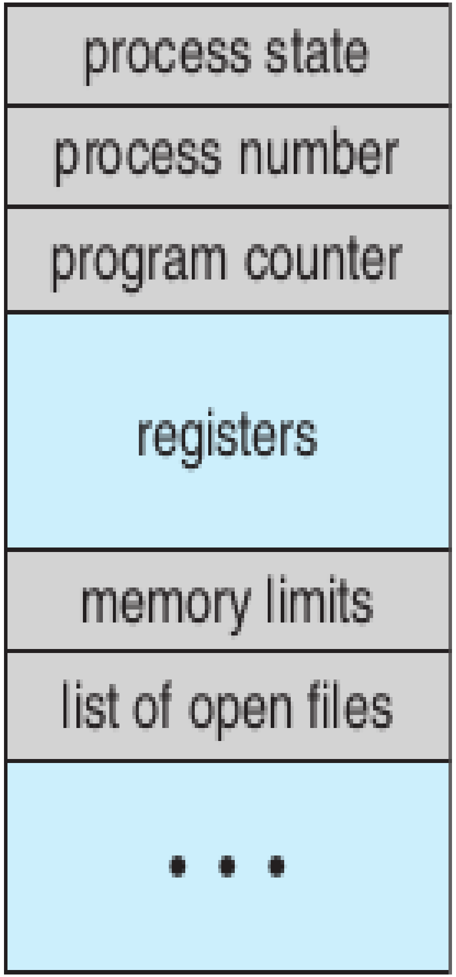
Process related data structures in kernel code

- 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,

Process Control Block



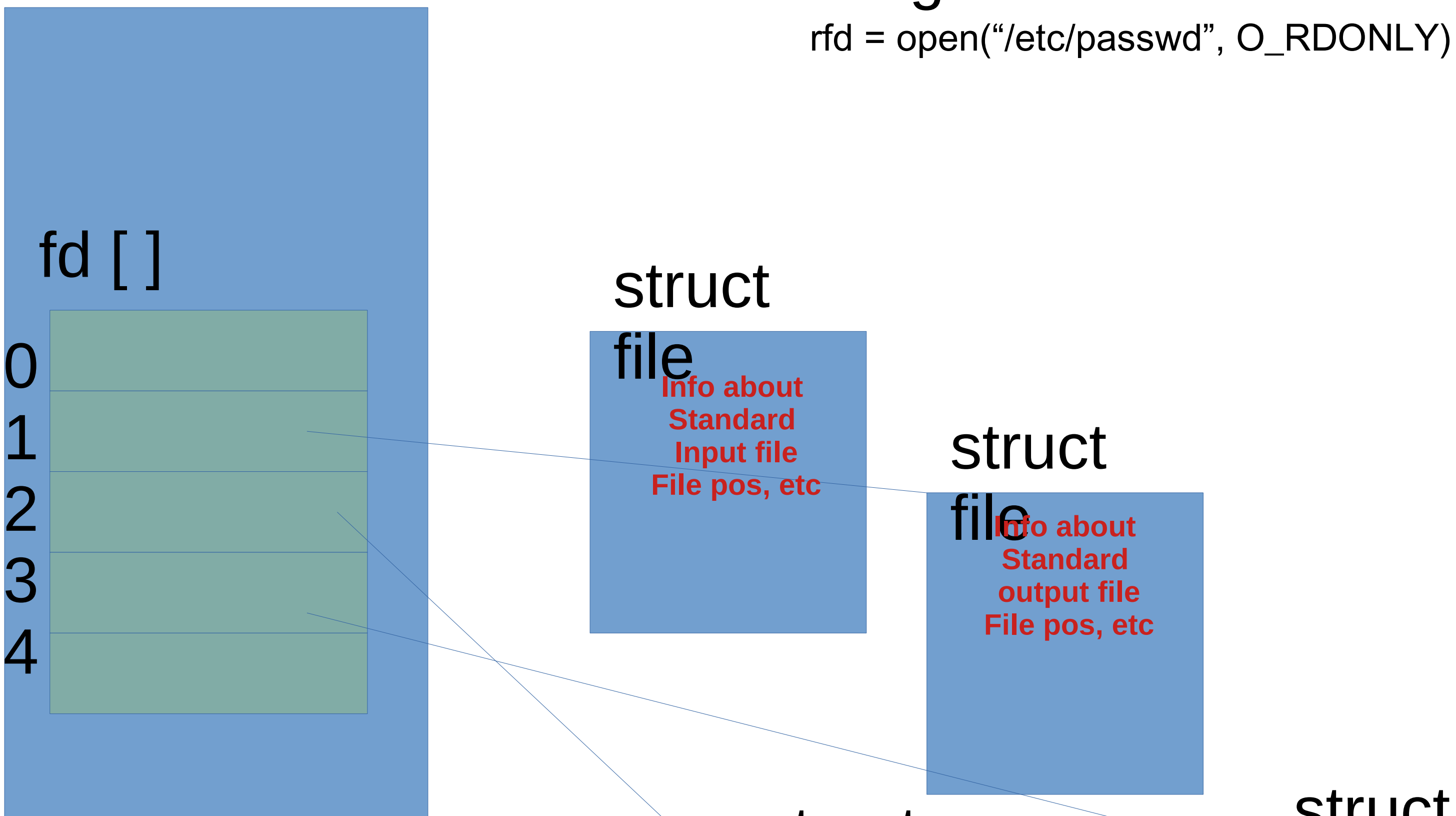
Fields in PCB



List of open files

Program did

rfd = open(“/etc/passwd”, O_RDONLY)



List of open files

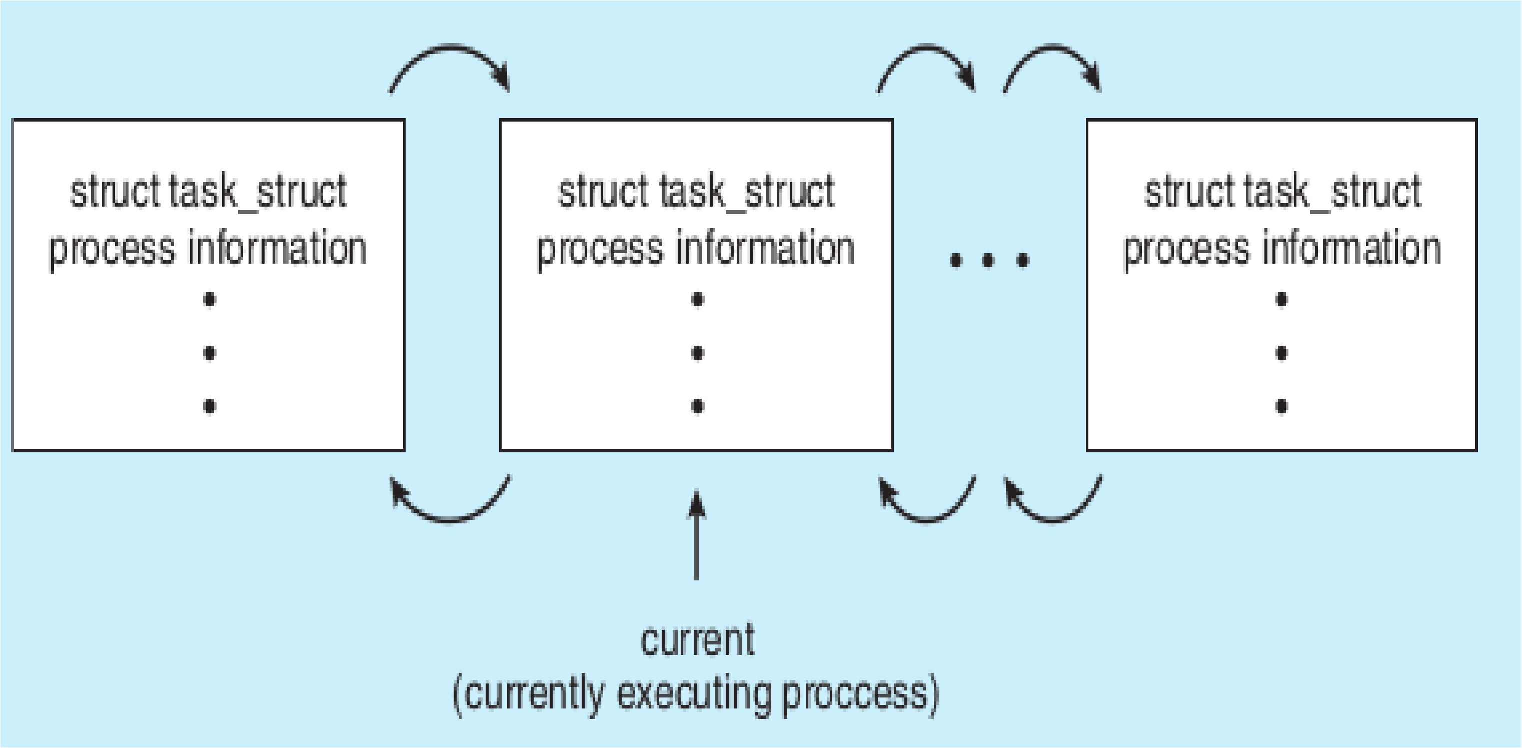
- The PCB contains an array of pointers, called file descriptor array (fd[ ]), pointers to structures representing files
- When open() system call is made
  - A new file structure is created and relevant information is stored in it
  - Smallest available of fd [ ] pointers is made to point to this new struct file
  - The index of this fd [ ] pointer is returned by open
- When subsequent calls are made to read(fd, ...) or write(fd, ...) , etc.
  - The kernel gets the “fd” as an index in the fd[ ] array and is able to

```
// 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;
};
```

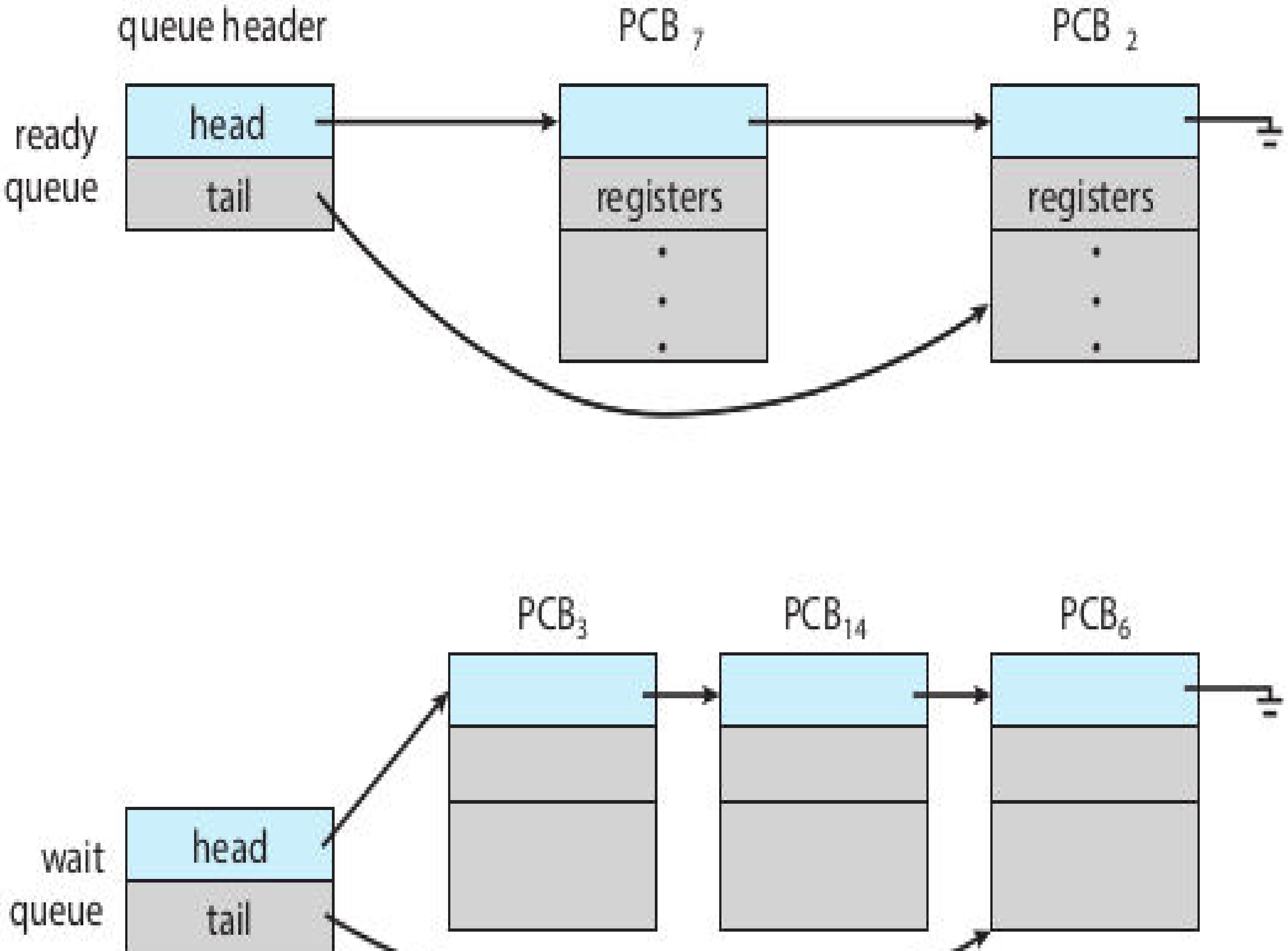
Process Queues/Lists inside OS

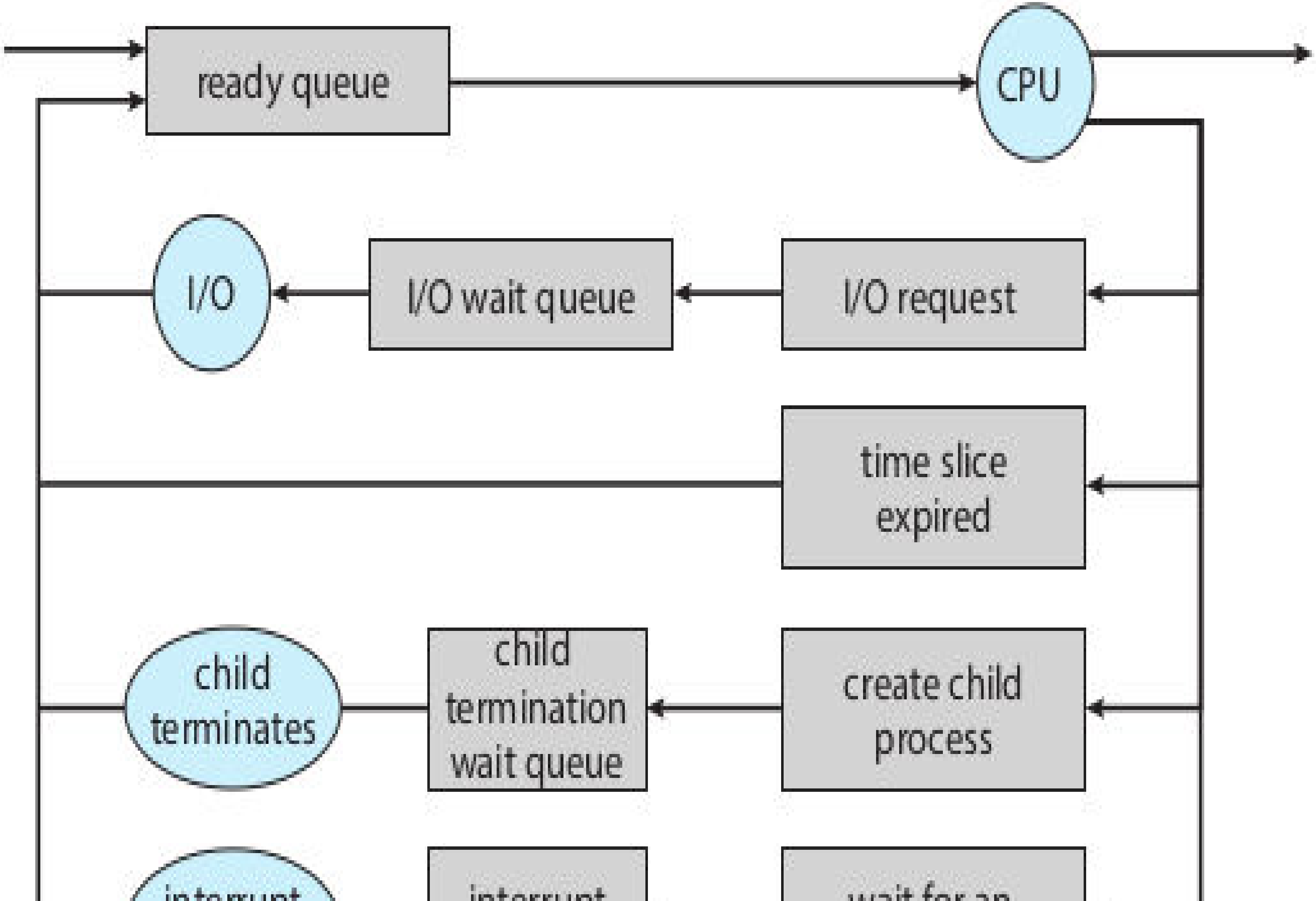
- Different types of queues/lists can be maintained by OS for the processes
  - A queue of processes which need to be scheduled
  - A queue of processes which have requested input/output to a device and hence need to be put on hold/wait
  - List of processes currently running on multiple CPUs




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


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


ready queue
CPU
I/O
I/O wait queue
I/O request
time slice expired
child terminates
child termination wait queue
create child process

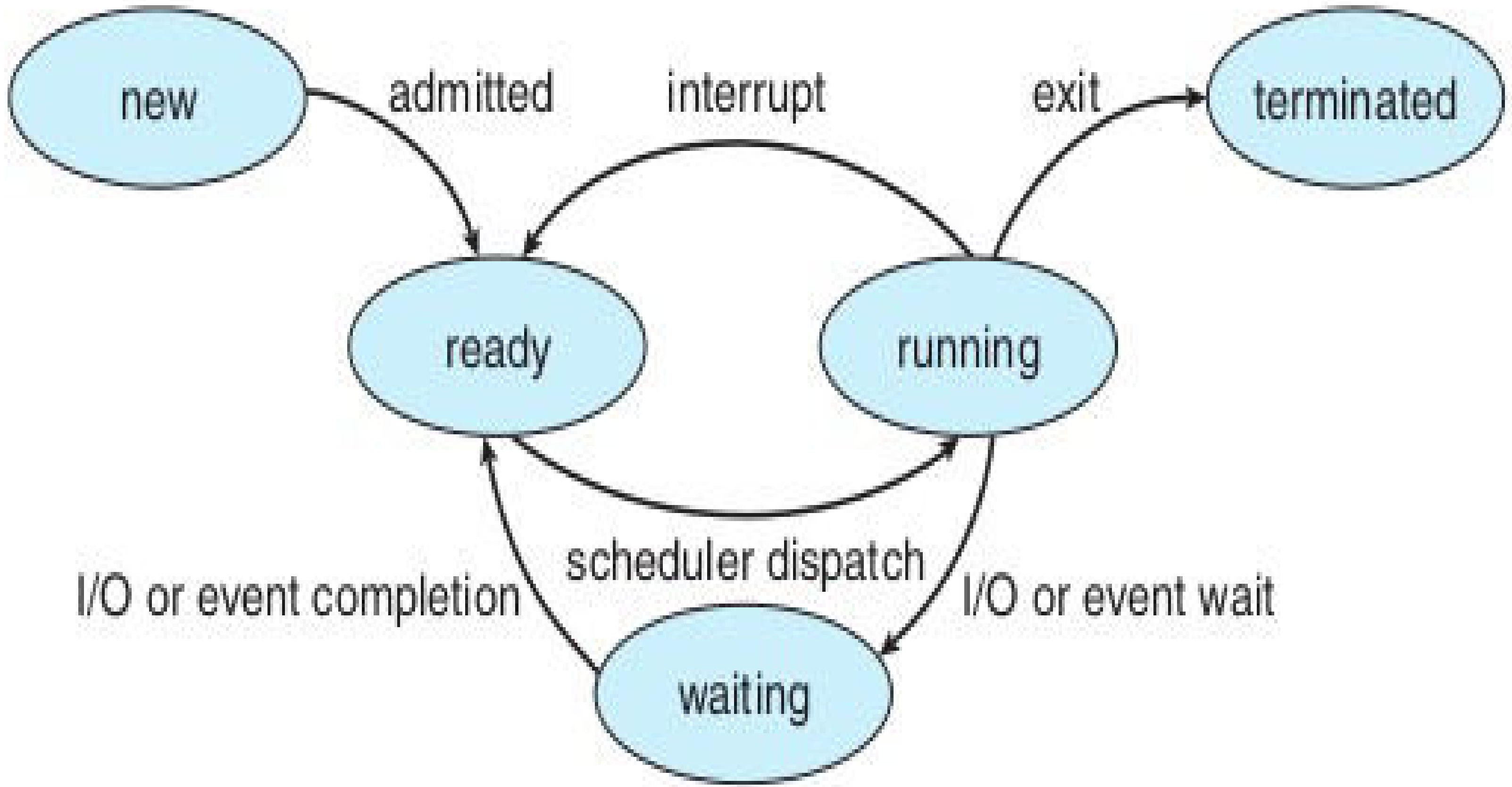


Figure 3.2 Diagram of process state.

“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) {
```

OS Syscall

```
sys_read(int fd, char *buf, int len) {
  file f = current->fdarray[fd];
  int offset = f->position;
  ...
  disk_read(..., offset, ...);
  // Do what now?
  //asynchronous read
  //Interrupt will occur when the disk read is complete
  // Move the process from ready queue to a wait queue and call scheduler!
  // This is called "blocking"
  Return the data read ;
```

“Giving up” CPU by a process or blocking

The relevant code in xv6 is in

Sleep()

The wakeup code is in wakeup() and wakeup1()

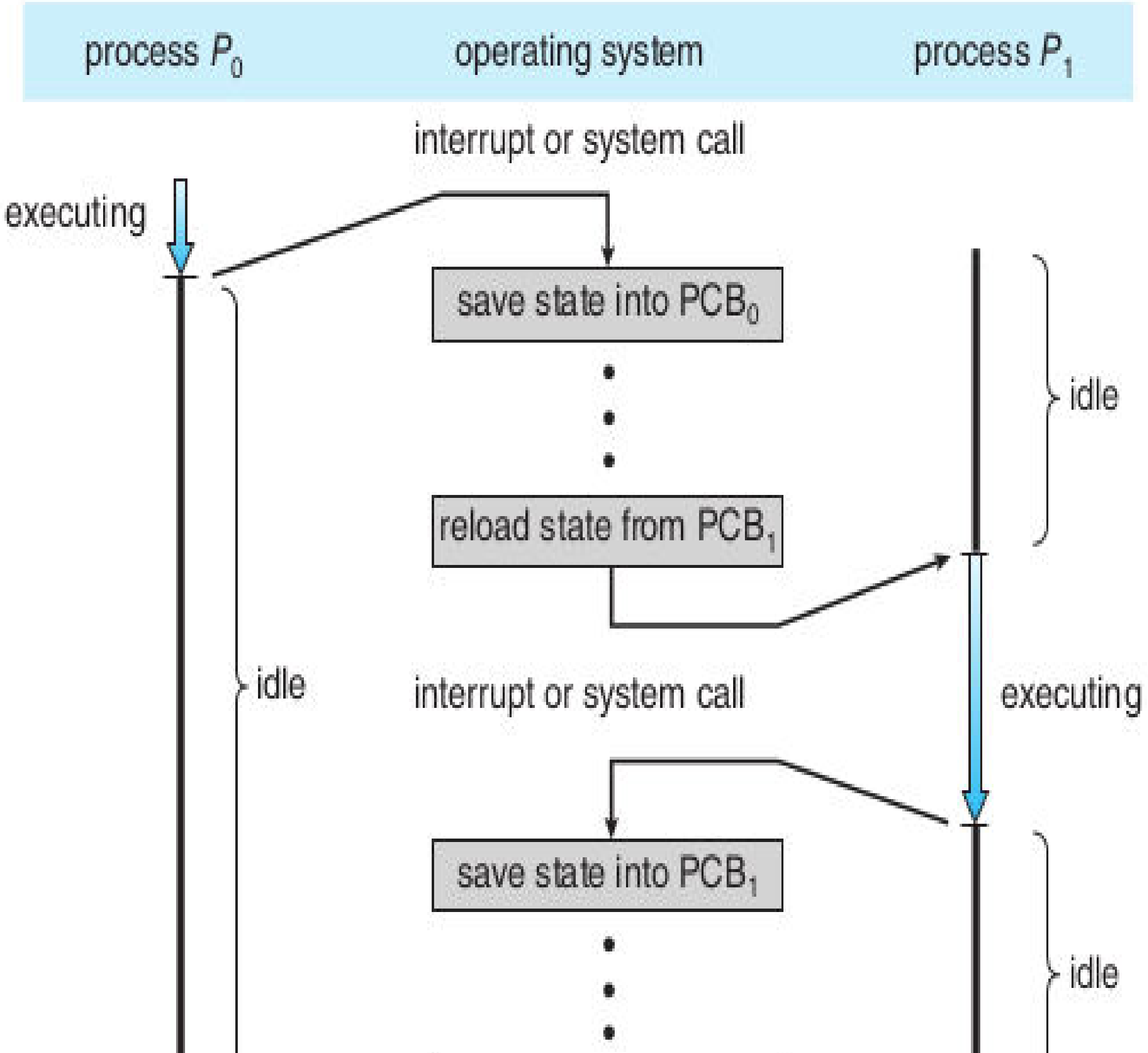
To be seen later

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

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


process P_0
operating system
process P_1
interrupt or system call
executing
save state into PCB_0
idle
reload state from PCB_1
idle
interrupt or system call
executing
save state into PCB_1
idle

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

NEXT: XV6 code overview

1. Understanding how traps are handled

2. How timer interrupt goes to scheduler

3. How scheduling takes place

4. How a “blocking” system call (e.g. read()) “blocks”

Inter Process Communication

Revision of process related concepts

- PCB, struct proc
- Process lifecycle – different states
- Memory layout
- Memory management
- Interrupts handling, system call handling, code from xv6
- Scheduler, code of scheduler in xv6

IPC: Inter Process Communication

- **Processes within a system may be independent or cooperating**
- **Cooperating process can affect or be affected by other processes, including sharing data**
- **Reasons for cooperating processes:**
  - Information sharing, e.g. copy paste
  - Computation speedup, e.g. matrix multiplication
  - Modularity, e.g. chrome – separate process for display, separate for fetching data
  - Convenience,
- **Cooperating processes need interprocess communication (IPC)**
- **Two models of IPC**
  - Shared memory
  - Message passing

Shared Memory Vs Message Passing

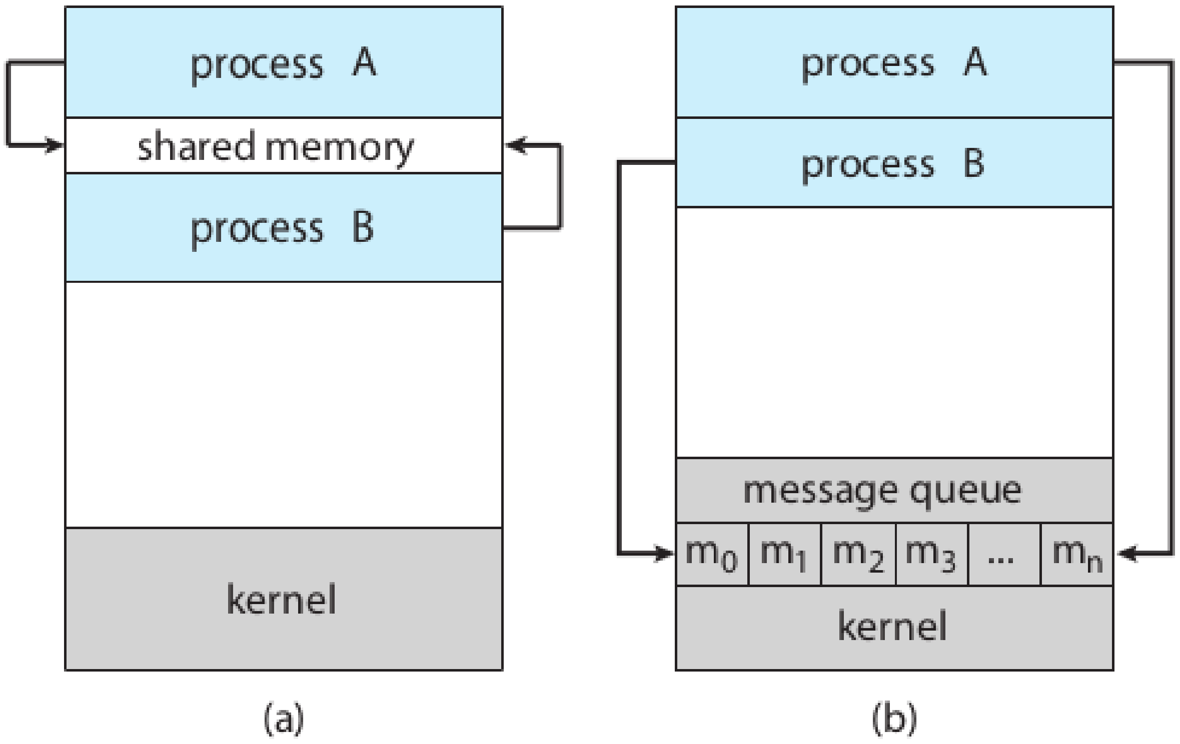


Figure 3.11 Communications models. (a) Shared memory. (b) Message passing.

Each requires OS to provide system calls for

- Creating the IPC mechanism
- To read/write using the IPC mechanism
- Delete the IPC mechanism

Note: processes communicating with each other with the help of OS!

Example of co-operating processes: Producer Consumer Problem

- **Paradigm for cooperating processes, producer process produces information that is consumed by a consumer process**
  - unbounded-buffer places no practical limit on the size of the buffer
  - bounded-buffer assumes that there is a fixed buffer size

Example of co-operating processes: Producer Consumer Problem

- Shared data

```
#define BUFFER_SIZE 10
typedef struct {
. . .
} item;
item buffer[BUFFER_SIZE];
int in = 0;
int out = 0;
```

- Can only use BUFFER_SIZE-1 elements

Example of co-operating processes: Producer Consumer Problem

- **Code of Producer**

```
while (true) {
      /* Produce an item */

while (((in = (in + 1) % BUFFER SIZE count) == out)

; /* do nothing -- no free buffers */

buffer[in] = item;

in = (in + 1) % BUFFER SIZE;

}
```

Example of co-operating processes: Producer Consumer Problem

- **Code of Consumer**

```
while (true) {
while (in == out)
; // do nothing -- nothing to consume
// remove an item from the buffer
item = buffer[out];
out = (out + 1) % BUFFER SIZE;
return item;
}
```

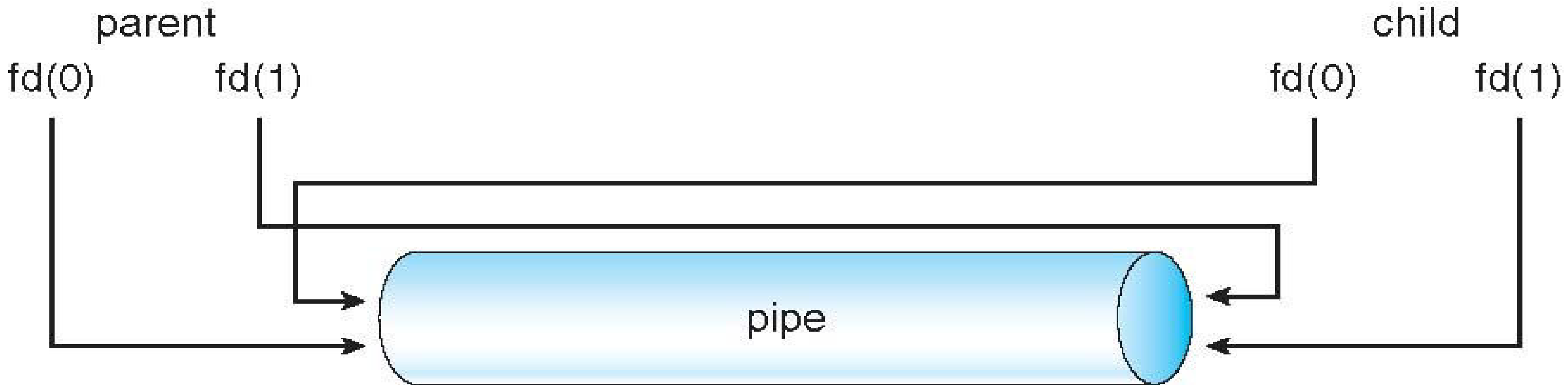
Pipes

Pipes for IPC

- **Two types**
  - Unnamed Pipes or ordinary pipes
  - Named Pipe

Ordinary pipes

- Ordinary Pipes allow communication in standard producer-consumer style
- Producer writes to one end (the write-end of the pipe)
- Consumer reads from the other end (the read-end of the pipe)
- Ordinary pipes are therefore unidirectional
- Requires a parent-child (or sibling, etc) kind of relationship between communicating processes


parent
fd(0)
fd(1)
child
fd(0)
fd(1)
pipe

Named pipes

- Also called FIFO
- Processes can create a “file” that acts as pipe. Multiple processes can share the file to read/write as a FIFO
- Named Pipes are more powerful than ordinary pipes
- Communication is bidirectional
- No parent-child relationship is necessary between the communicating processes
- Several processes can use the named pipe for communication
- Provided on both UNIX and Windows systems
- Is not deleted automatically by OS

Named pipes

- int mkfifo(const char *pathname, mode_t mode);
- Example

Shared Memory

System V shared memory

- Process first creates shared memory segment
- Process wanting access to that shared memory must attach to it
- Now the process could write to the shared memory
- When done, a process can detach the shared memory from its address space

Example of Shared memory POSIX Shared Memory

- **What is POSIX?**
  - Portable Operating System Interface (POSIX)
  - family of standards
  - specified by the IEEE Computer Society
  - for maintaining compatibility between operating systems.
  - API (system calls), shells, utility commands for compatibility among UNIXes and variants

POSIX Shared Memory

- shm_open
- ftruncate
- Mmap
- See the example in Textbook

Message passing

Message Passing

- **Message system – processes communicate with each other using send(), receive() like syscalls given by OS**
- **IPC facility provides two operations:**
  - send(message) – message size fixed or variable
  - Receive(message)
- **If P and Q wish to communicate, they need to:**
  - establish a communication link between them
  - exchange messages via send/receive
- **Communication link can be implemented in a variety of ways**

Message Passing using "Naming"

- **Pass a message by "naming" the receiver**
  - A) Direct communication with receiver
    - Receiver is identified by sender directly using it's name
  - B) Indirect communication with receiver
    - Receiver is identified by sender in-directly using it's 'location of receipt'

Message passing using direct communication

- **Processes must name each other explicitly:**
  - send (P, message) – send a message to process P
  - receive(Q, message) – receive a message from process Q
- **Properties of communication link**
  - Links are established automatically
  - A link is associated with exactly one pair of communicating processes
  - Between each pair there exists exactly one link
  - The link may be unidirectional, but is usually bi-directional

Message passing using IN-direct communication

- **Messages are directed and received from mailboxes (also referred to as ports)**
  - Each mailbox has a unique id
  - Processes can communicate only if they share a mailbox
- **Properties of communication link**
  - Link established only if processes share a common mailbox
  - A link may be associated with many processes
  - Each pair of processes may share several communication links
  - Link may be unidirectional or bi-directional

Message passing using IN-direct communication

- **Operations**
  - create a new mailbox
  - send and receive messages through mailbox
  - destroy a mailbox
- **Primitives are defined as:**
  - send(A, message) – send a message to mailbox A
  - receive(A, message) – receive a message from mailbox A

Message passing using IN-direct communication

- **Mailbox sharing**
  - P1, P2, and P3 share mailbox A
  - P1, sends; P2 and P3 receive
  - Who gets the message?
- **Solutions**
  - Allow a link to be associated with at most two processes
  - Allow only one process at a time to execute a receive operation
  - Allow the system to select arbitrarily the receiver. Sender is notified who the receiver was.

Message Passing implementation: Synchronization issues

- **Message passing may be either blocking or non-blocking**
- **Blocking is considered synchronous**
  - Blocking send has the sender block until the message is received
  - Blocking receive has the receiver block until a message is available
- **Non-blocking is considered asynchronous**
  - Non-blocking send has the sender send the message and continue
  - Non-blocking receive has the receiver receive a valid message or null

Producer consumer using blocking send and receive

Producer

```
message next produced;
while (true) {
/* produce an item in
next_produced */
send(next_produced);
}
```

Consumer

```
message
next_consumed;
while (true) {
receive(next_consumed);
}
```

Message Passing implementation: choice of Buffering

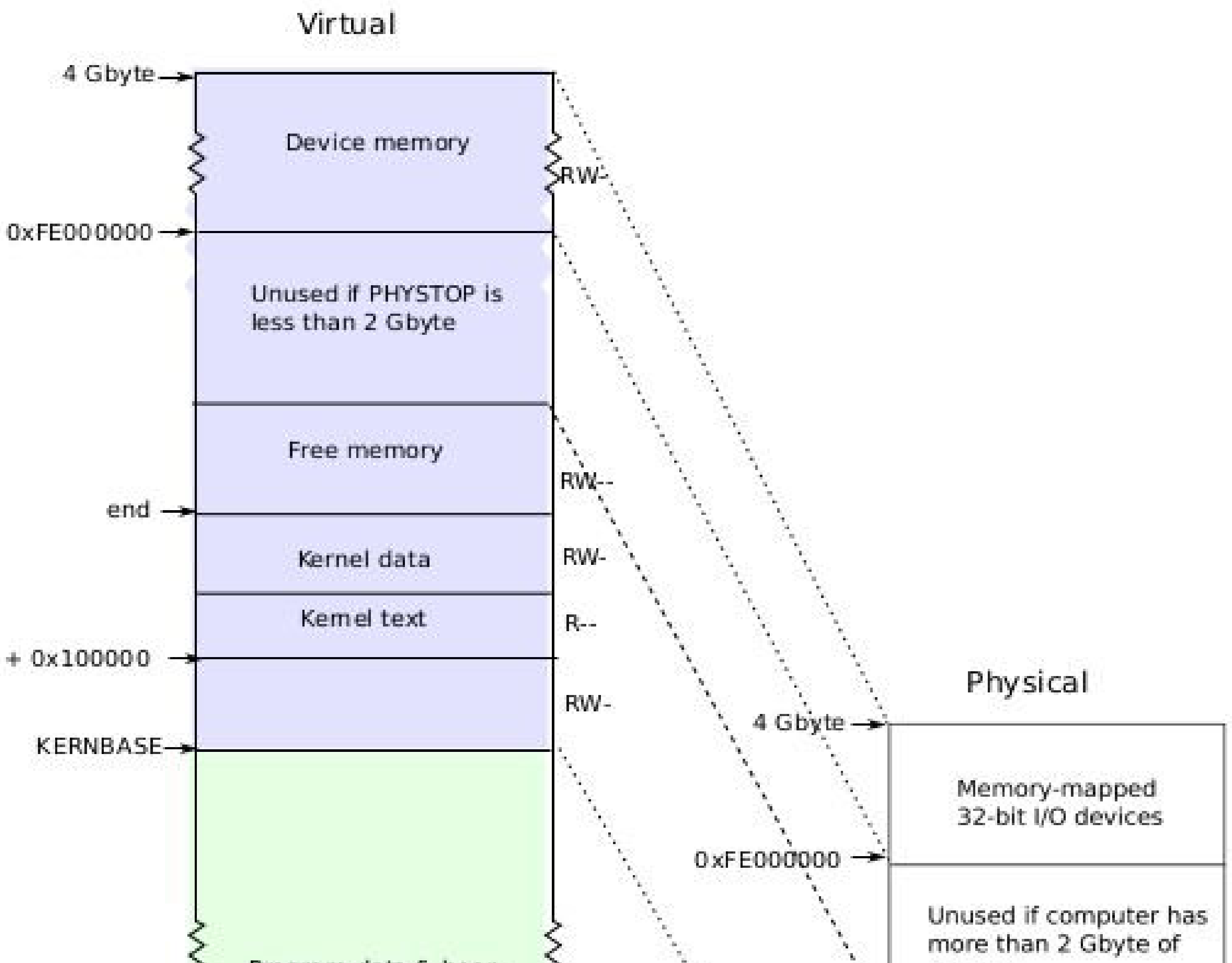
- Queue of messages attached to the link; implemented in one of three ways

Processes in xv6 code

Process Table

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

- One single global array of processes
- Protected by
- **ptable.lock**

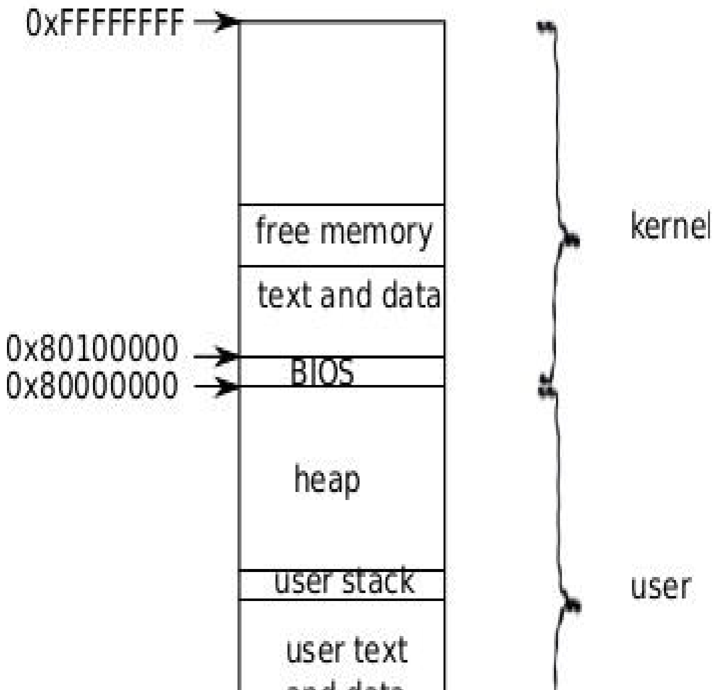


Layout of process's VA space

xv6 schema!

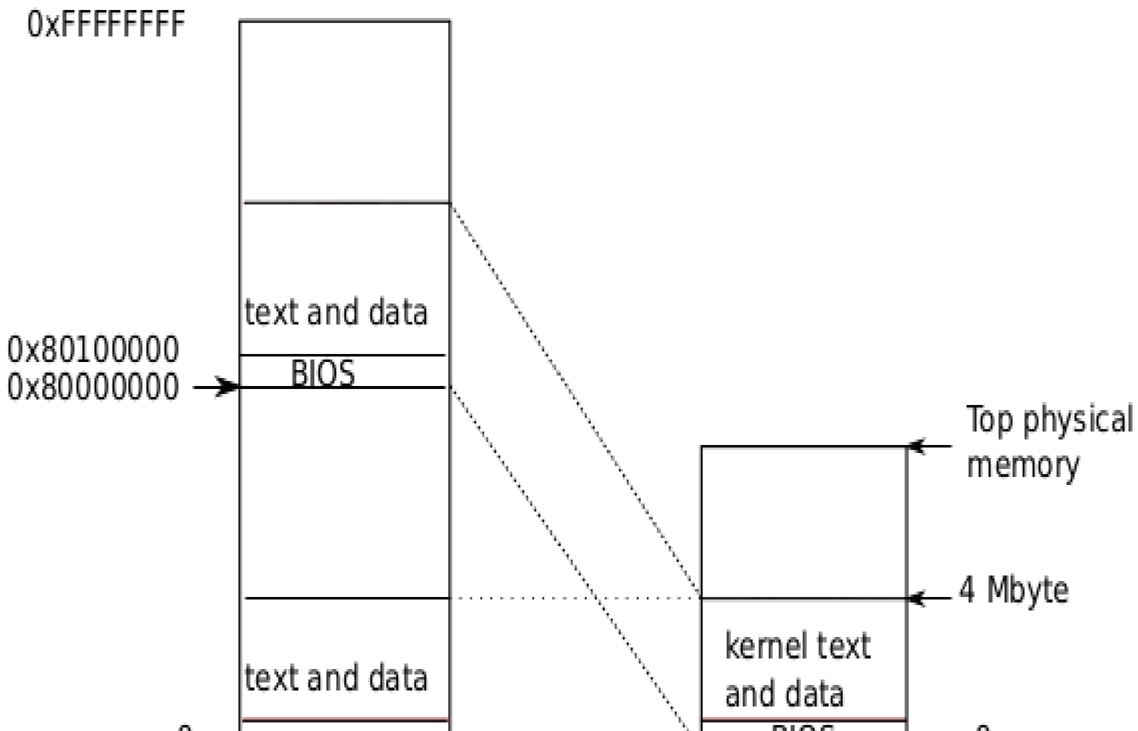
different from Linux

Logical layout of memory for a process



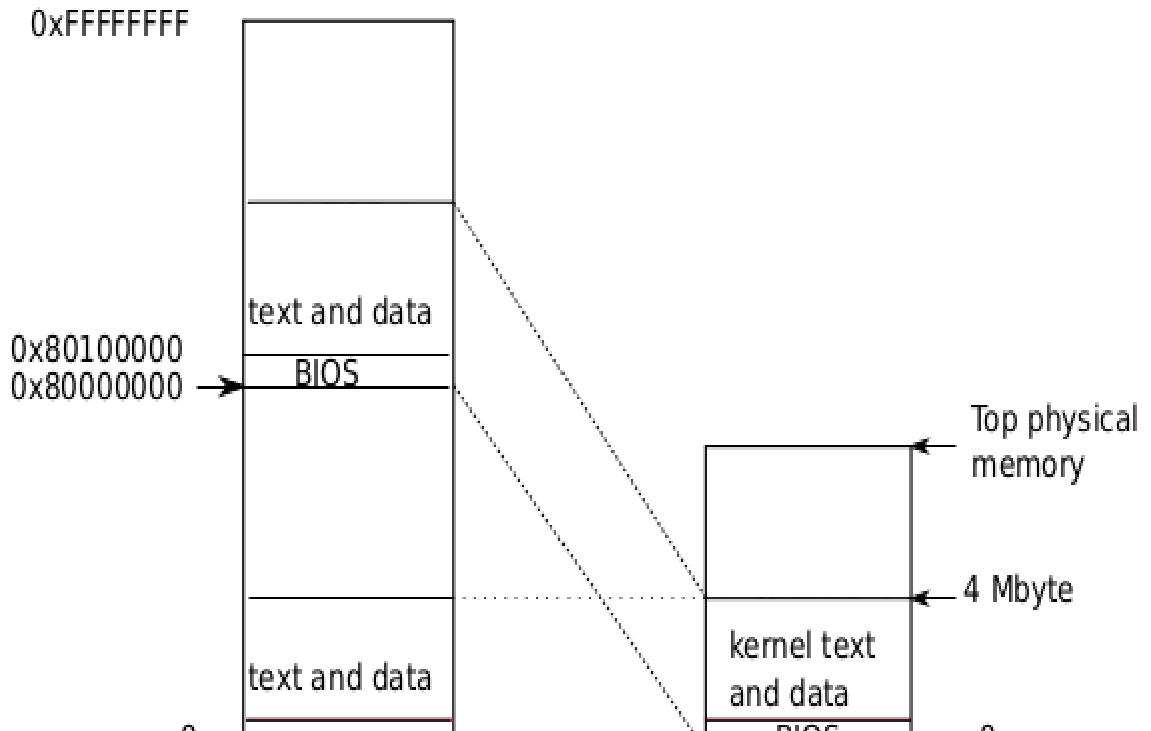
- Address 0: code
- Then globals
- Then stack
- Then heap
- Each processe's address space maps kernel's text, data also --> so that system calls run with these mappings
- Kernel code can directly

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

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**

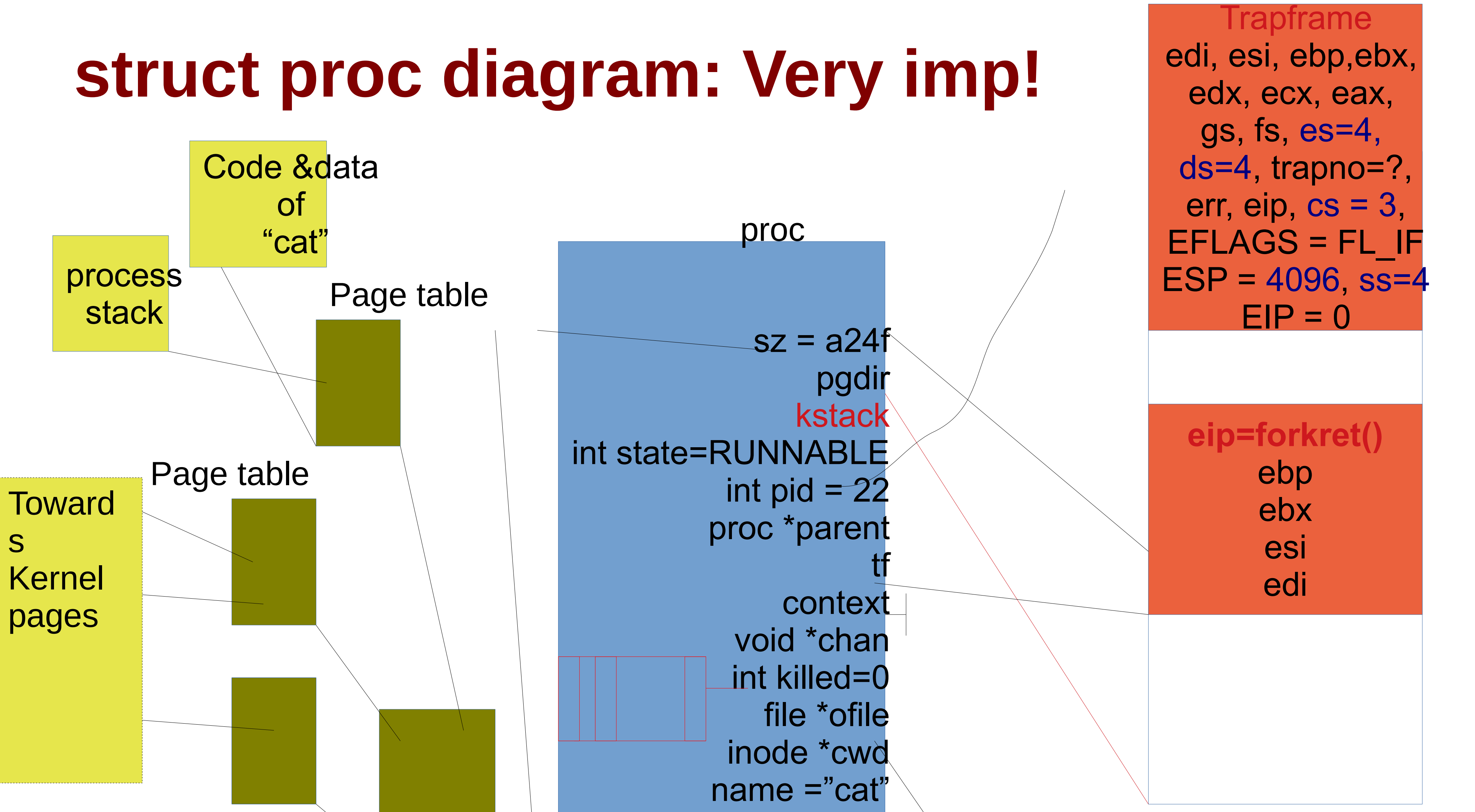
Imp Concepts

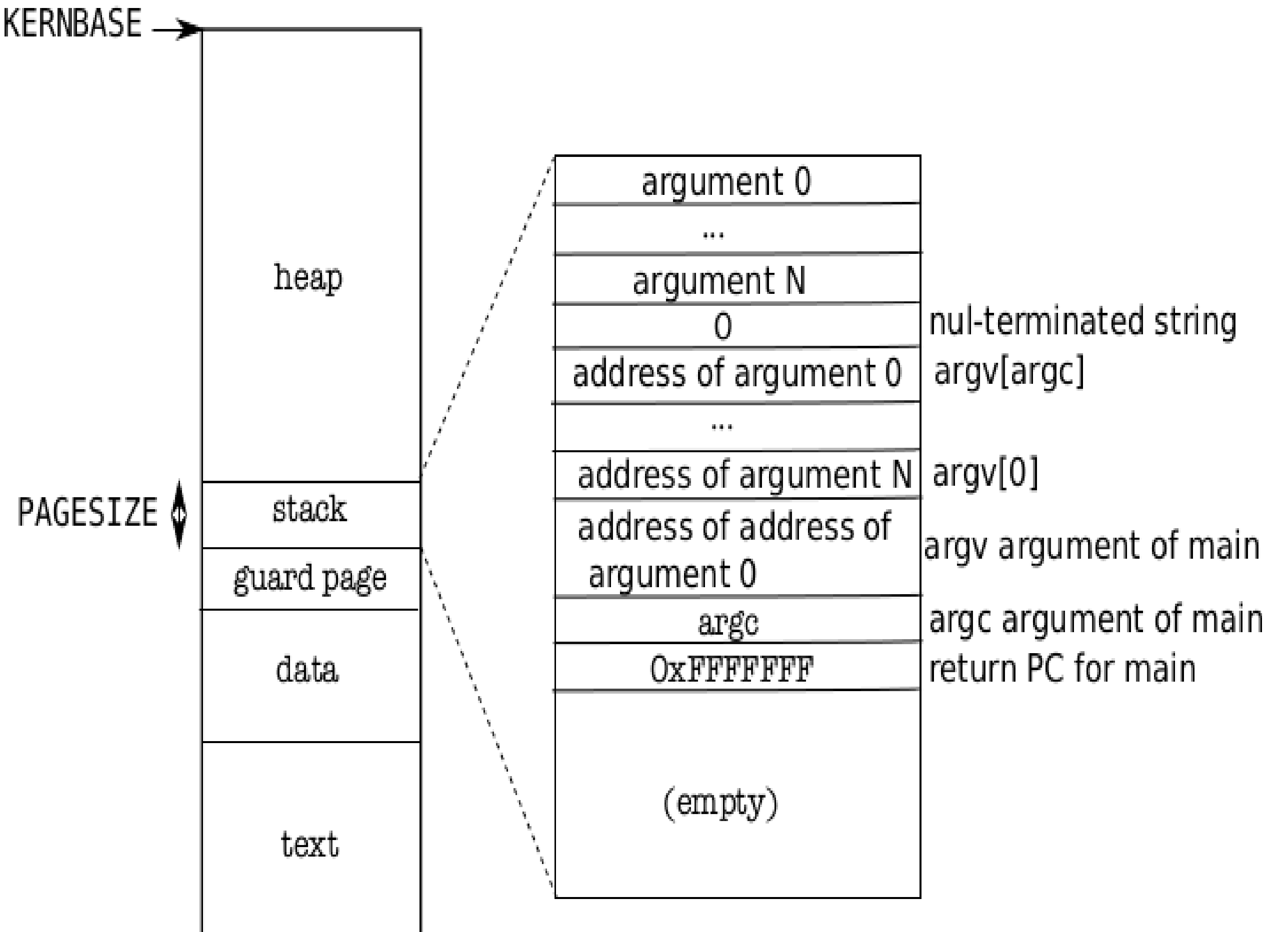
- **A process has two stacks**
  - user stack: used when user code is running
  - kernel stack: used when kernel is running on behalf of a process
- **Note: there is a third stack also!**
  - The kernel stack used by the scheduler itself

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 proc diagram: Very imp!





Memory Layout of a user process

Memory Layout of a user process

After exec()

Note the argc, argv on stack

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

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

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,

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

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**

Interrupt Descriptor Table (IDT) entries

```
// Gate descriptors for interrupts and traps
struct gatedesc {
uint off_15_0 : 16; // low 16 bits of offset in segment
uint cs : 16; // code segment selector
uint args : 5; // # args, 0 for interrupt/trap gates
uint rsv1 : 3; // reserved(should be zero I guess)
uint type : 4; // type(STS_{IG32,TG32})
uint s : 1; // must be 0 (system)
```

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);
```

Setting IDT entries

```
#define SETGATE(gate, istrap, sel, off, d) \
{ \
(gate).off_15_0 = (uint)(off) & 0xffff; \
(gate).cs = (sel); \
(gate).args = 0; \
(gate).rsv1 = 0; \
(gate).type = (istrap) ? STS_TG32 : STS_IG32; \
(gate).s = 0; \
```

Setting IDT entries

Vectors.S

```
# generated by vectors.pl - do not edit
# handlers
.globl alltraps
.globl vector0
vector0:
pushl $0
pushl $0
jmp alltraps
.globl vector1
```

trapasm.S

```
#include "mmu.h"
# vectors.S sends all traps here.
.globl alltraps
alltraps:
# Build trap frame.
pushl %ds
pushl %es
pushl %fs
```

How will interrupts be handled?

On intinstruction/interrupt the CPU does this:

- **Fetch the n'th descriptor from the IDT, where n is the argument of int.**
- **Check that CPL in %cs is <= DPL, where DPL is the privilege level in the descriptor.**
- **Save %esp and %ss in CPU-internal registers, but only if the target segment selector's PL < CPL.**
  - Switching from user mode to kernel mode. Hence save user code's SS and ESP
- **Push %ss. // optional**
- **Push %esp. // optional (also changes ss,esp using TSS)**
- **Push %eflags.**
- **Push %cs.**
- **Push %eip.**
- **Clear the IF bit in %eflags, but only on an interrupt.**
- **Set %cs and %eip to the**

After “int” ‘s job is done

- **IDT was already set**
  - Remember vectors.S
- **So jump to 64th entry in vector’s**
  - So now stack has ss, esp,eflags, cs, eip, 0 (for error code), 64
  - Next run alltraps from trapasm.S

alltraps:

```
# Build trap frame.
pushl %ds
pushl %es
pushl %fs
pushl %gs
pushal // push all gen purpose regs
# Set up data segments.
movw $(SEG_KDATA<<3), %ax
movw %ax, %ds
movw %ax, %es
# Call trap(tf), where tf=%esp
```

- Now stack contains
- ss, esp,eflags, cs, eip, 0 (for error code), 64, ds, es, fs, gs, eax, ecx, edx, ebx, oesp, ebp, esi, edi
  - This is the struct trapframe !
  - So the kernel stack now contains the trapframe
  - Trapframe is a part of kernel stack

trap()

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

- **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

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?**

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

- 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

Memory Management – Continued

More on Linking, Loading, Paging

Review of last class

- **MMU : Hardware features for MM**
- **OS: Sets up MMU for a process, then schedules process**
- **Compiler : Generates object code for a particular OS + MMU architecture**
- **MMU: Detects memory violations and raises interrupt --> Effectively passing control to OS**

More on Linking and Loading

- Static Linking: All object code combined at link time and a big object code file is created
- Static Loading: All the code is loaded in memory at the time of exec()
- Problem: Big executable files, need to load functions even if they do not execute
- Solution: Dynamic Linking and Dynamic Loading

Dynamic Linking

- **Linker is normally invoked as a part of compilation process**
  - Links
    - function code to function calls
    - references to global variables with “extern” declarations
- **Dynamic Linker**
  - Does not combine function code with the object code file
  - Instead introduces a “stub” code that is indirect reference to actual code
  - At the time of “loading” (or executing!) the program in memory, the “link-loader” (part of OS!) will pick up the relevant code from the library machine code file (e.g. libc.so.6)

Dynamic Linking on Linux

```
#include <stdio.h>
int main() {
int a, b;
scanf("%d%d", &a, &b);
printf("%d %d\n", a, b);
return 0;
}
```

PLT: Procedure Linkage Table
used to call external procedures/functions whose address is to be resolved by the dynamic linker at run time.

Output of objdump -x -D

Disassembly of section .text:

0000000000001189 <main>:

11d4: callq 1080 <printf@plt>

Disassembly of section .plt.got:

0000000000001080 <printf@plt>:

1080: endbr64

1084: bnd jmpq *0x2f3d(%rip) # 3fc8 <printf@GLIBC_2.2.5>

108b: nopl 0x0(%rax,%rax,1)

Dynamic Loading

- **Loader**
  - Loads the program in memory
  - Part of exec() code
  - Needs to understand the format of the executable file (e.g. the ELF format)
- **Dynamic Loading**
  - Load a part from the ELF file only if needed during execution
  - Delayed loading
  - Needs a more sophisticated memory management by operating system – to be seen during this series of lectures

Dynamic Linking, Loading

- **Dynamic linking necessarily demands an advanced type of loader that understands dynamic linking**
  - Hence called ‘link-loader’
  - Static or dynamic loading is still a choice
- **Question: which of the MMU options will alllow for which type of linking, loading ?**

Continous memory management

What is Continous memory management?

- **Entire process is hosted as one continous chunk in RAM**
- **Memory is typically divided into two partitions**
  - One for OS and other for processes
  - OS most typically located in “high memory” addresses, because interrupt vectors map to that location (Linux, Windows) !

Hardware support needed: base + limit (or relocation + limit)

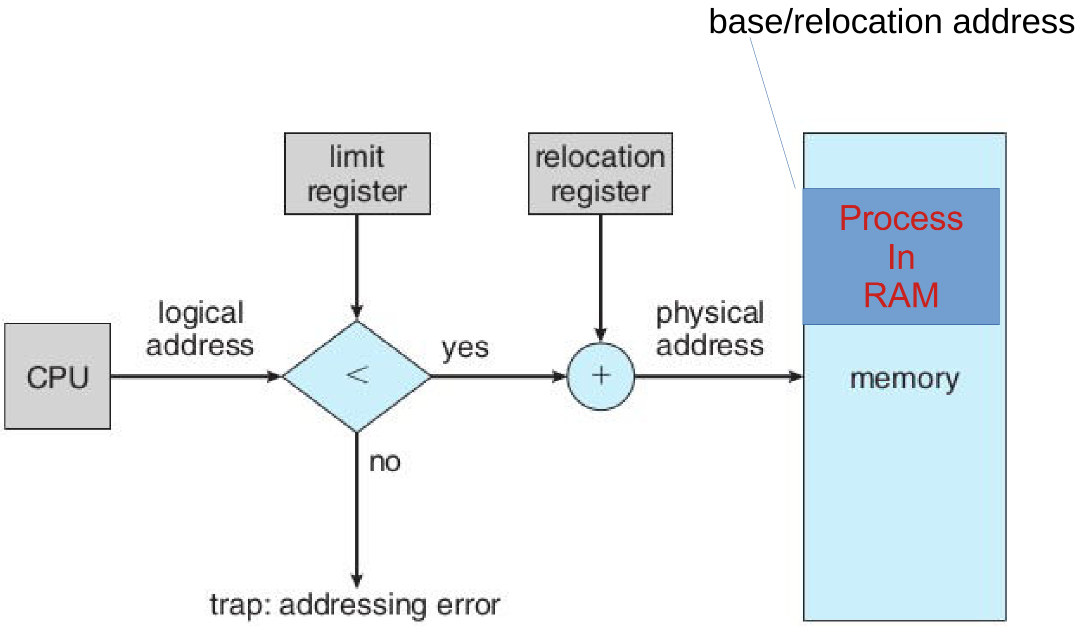


Figure 9.6 Hardware support for relocation and limit registers.

Problems faced by OS

- **Find a continuous chunk for the process being forked**
- **Different processes are of different sizes**
  - Allocate a size parameter in the PCB
- **After a process is over – free the memory occupied by it**
- **Maintain a list of free areas, and occupied areas**
  - Can be done using an array, or linked list

Variable partition scheme

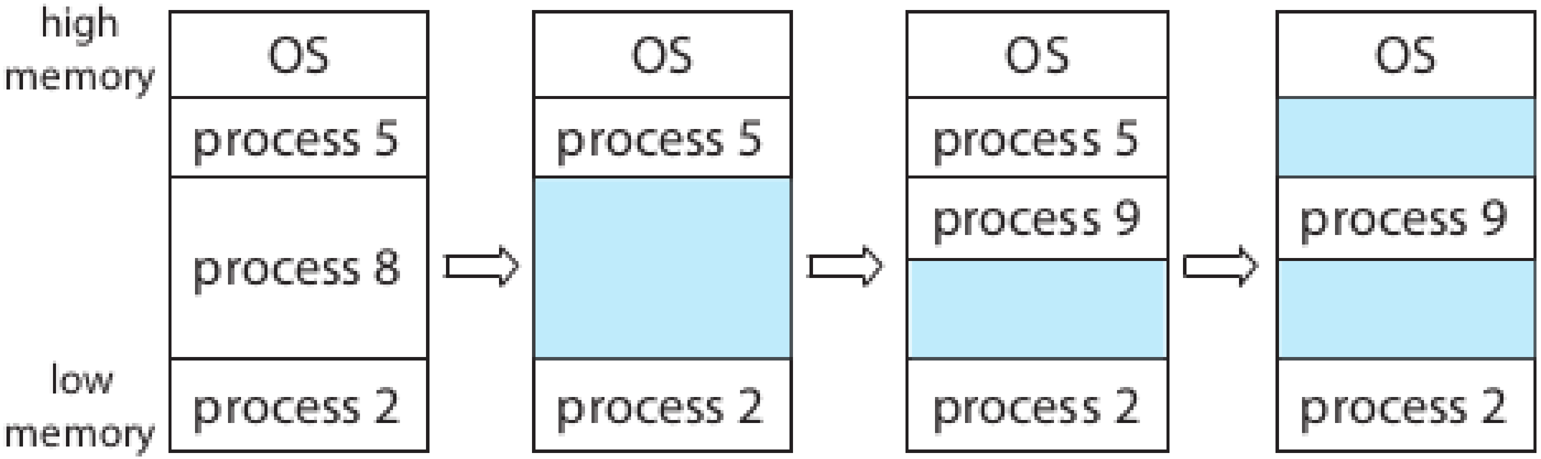


Figure 9.7 Variable partition.

Problem: how to find a “hole” to fit in new process

- Suppose there are 3 free memory regions of sizes 30k, 40k, 20k
- The newly created process (during fork() + exec()) needs 15k
- Which region to allocate to it ?

Strategies for finding a free chunk

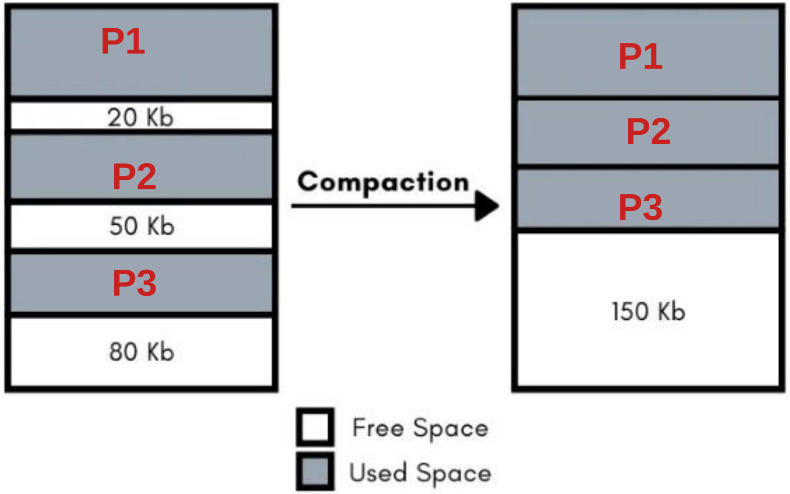
- 6k, 17k, 16k, 40k holes . Need 15k.
- Best fit: Find the smallest hole, larger than process. Ans: 16k
- Worst fit: Find the largest hole. Ans: 40k
- First fit: Find the "first" hole larger than the process. Ans: 17k

Problem : External fragmentation

- **Free chunks: 30k, 40k, 20k**
- **The newly created process (during fork() + exec()) needs 50k**
- **Total free memory: 30+40+20 = 90k**
  - But can’t allocate 50k !

Solution to external fragmentation

- **Compaction !**
- **OS moves the process chunks in memory to make available continous memory region**
  - Then it must update the memory management information in PCB (e.g. base of the process) of each process
- **Time consuming**
- **Possible only if the relocation+limit scheme of MMU is available**



Another solution to external fragmentation: Fixed size partitions

- **Fixed partition scheme**
- **Memory is divided by OS into chunks of equal size: e.g., say, 50k**
  - If total 1M memory, then 20 such chunks
- **Allocate one or more chunks to a process, such that the total size is >= the size of the process**
  - E.g.if request is 50k, allocate 1 chunk
  - If request is 40k, still allocate 1 chunk
  - If request is 60k, then allocate 2 chunks
- **Leads to internal fragmentation**
  - space wasted in the case of 40k or 60k requests above

Fixed partition scheme

- **OS needs to keep track of**
  - Which partition is free and which is used by which process
  - Free partitions can simply be tracked using a bitmap or a list of numbers
  - Each process's PCB will contain list of partitions allocated to it

Solution to internal fragmentation

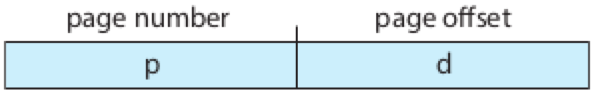
- **Reduce the size of the fixed sized partition**
- **How small then ?**
  - Smaller partitions mean more overhead for the operating system in allocating deallocating

Paging

An extended version of fixed size partitions

- **Partition = page**
  - Process = logically continuous sequence of bytes, divided in ‘page’ sizes
  - Memory divided into equally sized page ‘frames’
- **Important distinction**
  - Process need not be continous in RAM
  - Different page sized chunks of process can go in any page frame
  - Page table to map pages into frames

Logical address seen as



Paging hardware

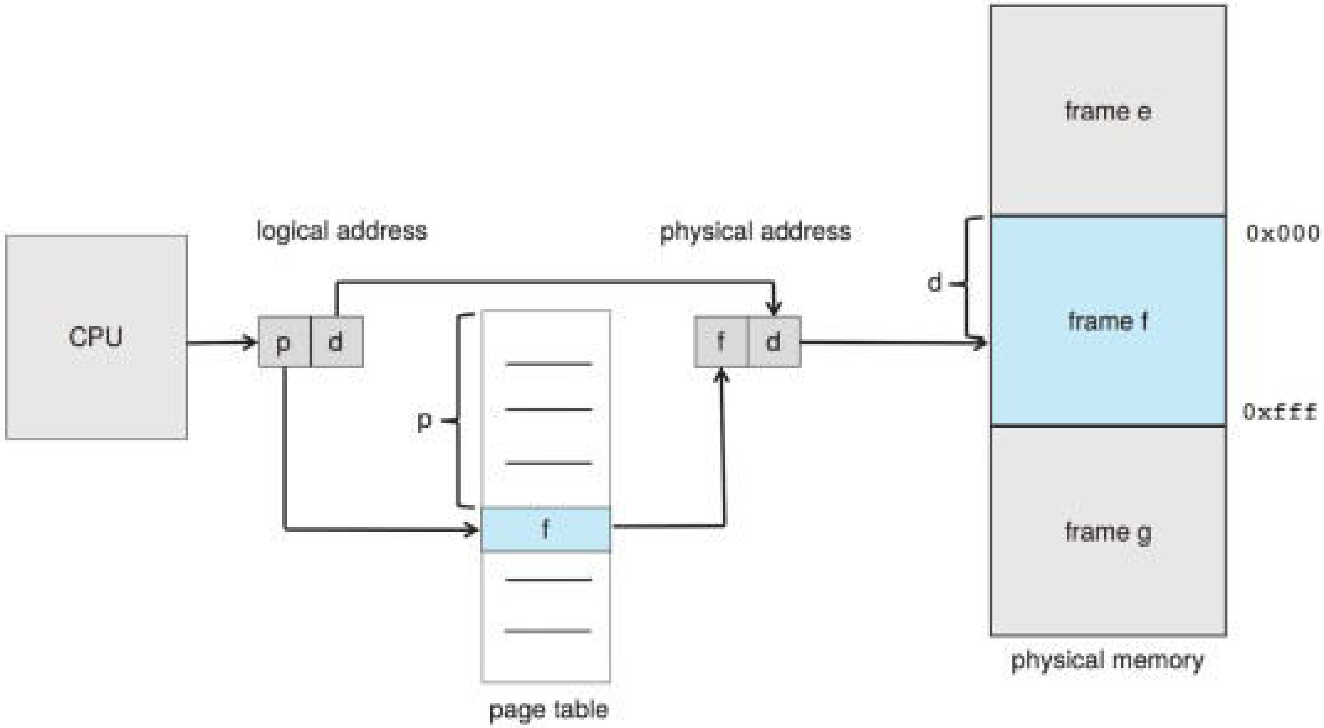


Figure 9.8 Paging hardware.

MMU's job

To translate a logical address generated by the CPU to a physical address:

1. Extract the page number p and use it as an index into the page table.

(Page table location is stored in a hardware register

Also stored in PCB of the process, so that it can be used to load the hardware register on a context switch)

2. Extract the corresponding frame number f from the page table.

3. Replace the page number p in the logical address with the frame number f .

Job of OS

- **Allocate a page table for the process, at time of fork()/exec()**
  - Allocate frames to process
  - Fill in page table entries
- **In PCB of each process, maintain**
  - Page table location (address)
  - List of pages frames allocated to this process
- **During context switch of the process, load the PTBR using the PCB**

Job of OS

- **Maintain a list of all page frames**
  - Allocated frames
  - Free Frames (called frame table)
  - Can be done using simple linked list
  - Innovative data structures can also be used to maintain free and allocated frames list (e.g. xv6 code)

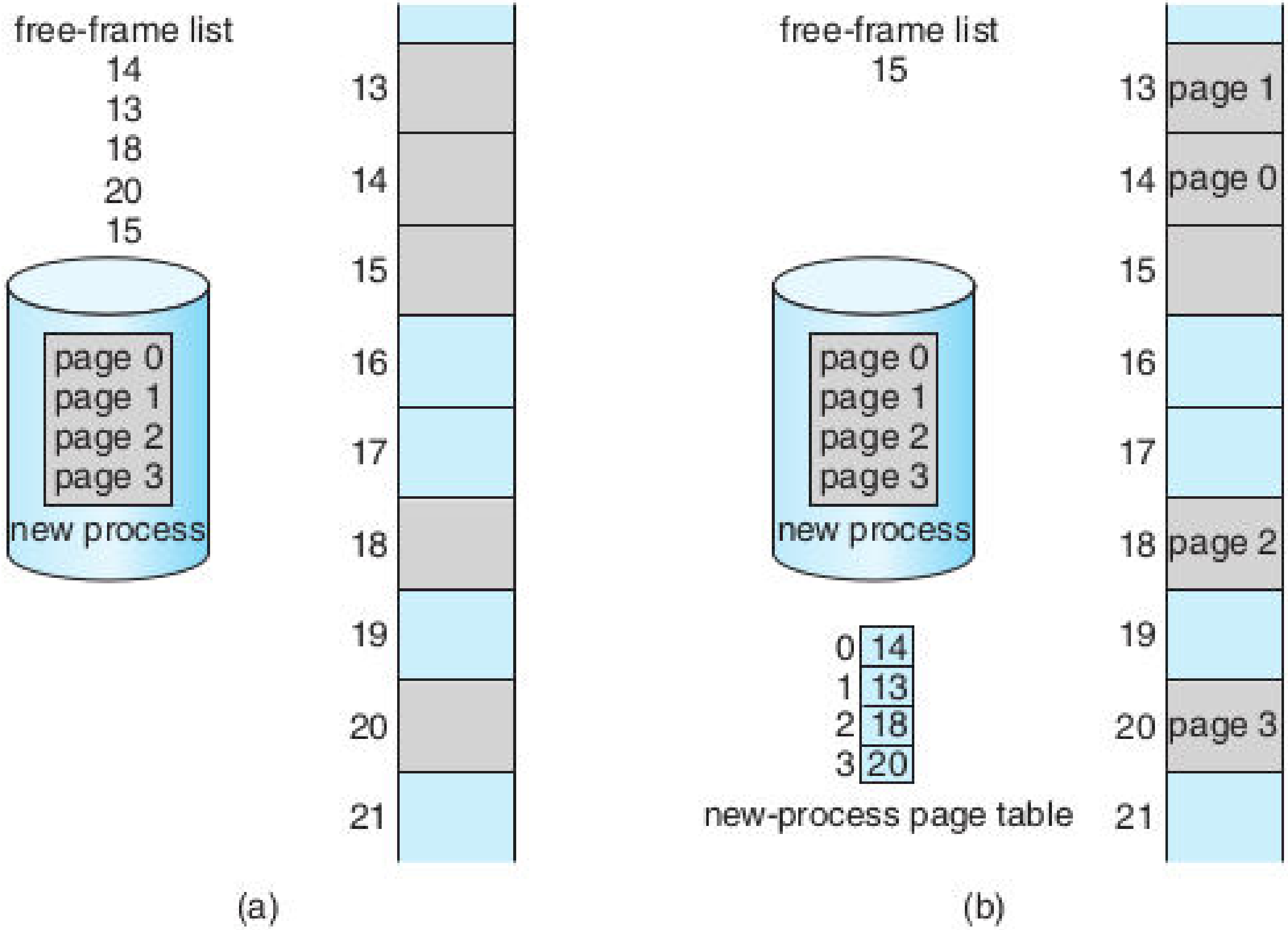


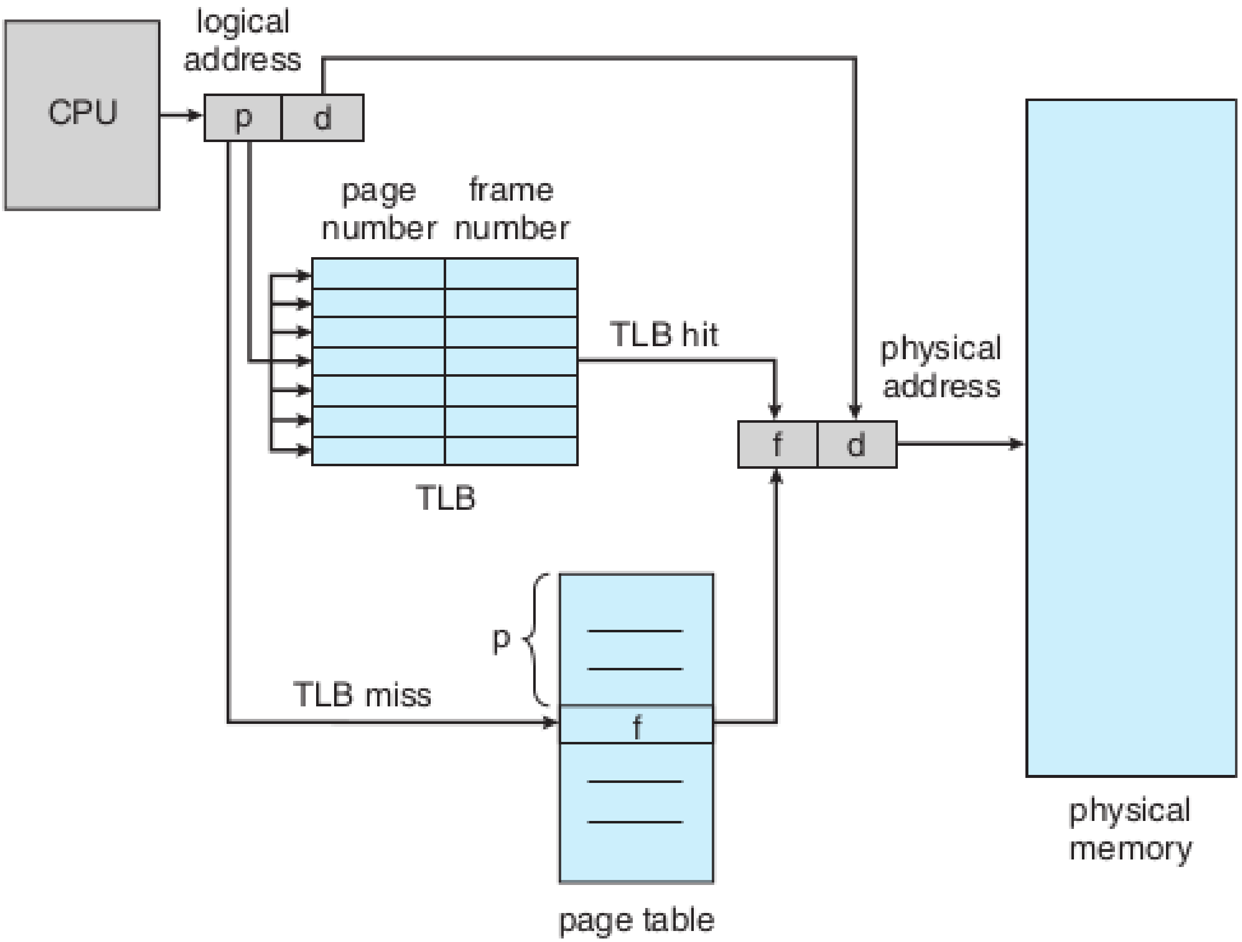
Figure 9.11 Free frames (a) before allocation and (b) after allocation.

Disadvantage of Paging

- **Each memory access results in two memory accesses!**
  - One for page table, and one for the actual memory location !
  - Done as part of execution of instruction in hardware (not by OS!)
  - Slow down by 50%

Speeding up paging

- **Translation Lookaside Buffer (TLB)**
- **Part of CPU hardware**
- **A cache of Page table entries**
- **Searched in parallel for a page number**



Speedup due to TLB

- Hit ratio
- Effective memory access time
- Example: memory access time 10ns, hit ratio = 0.8, then

Memory protection with paging

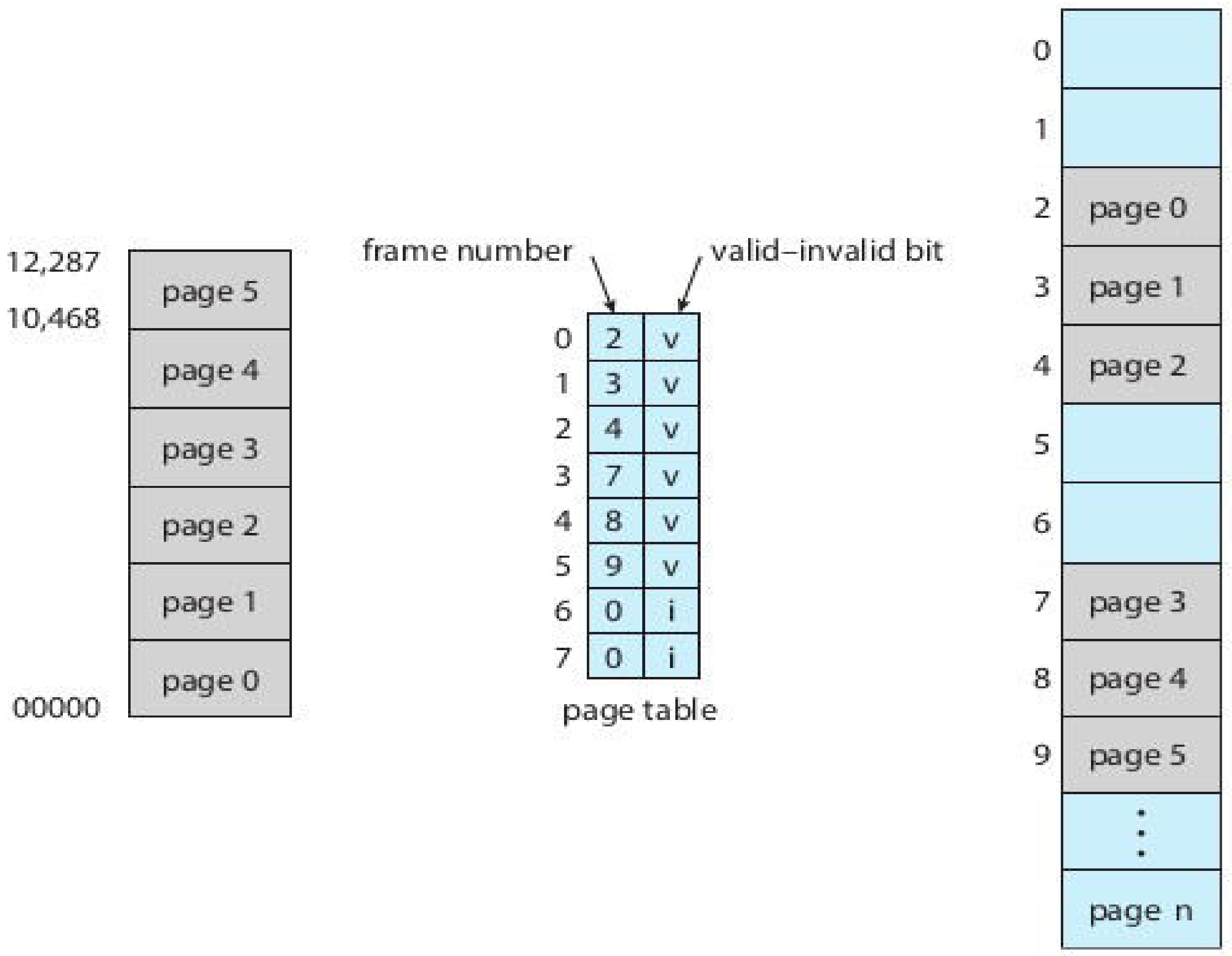
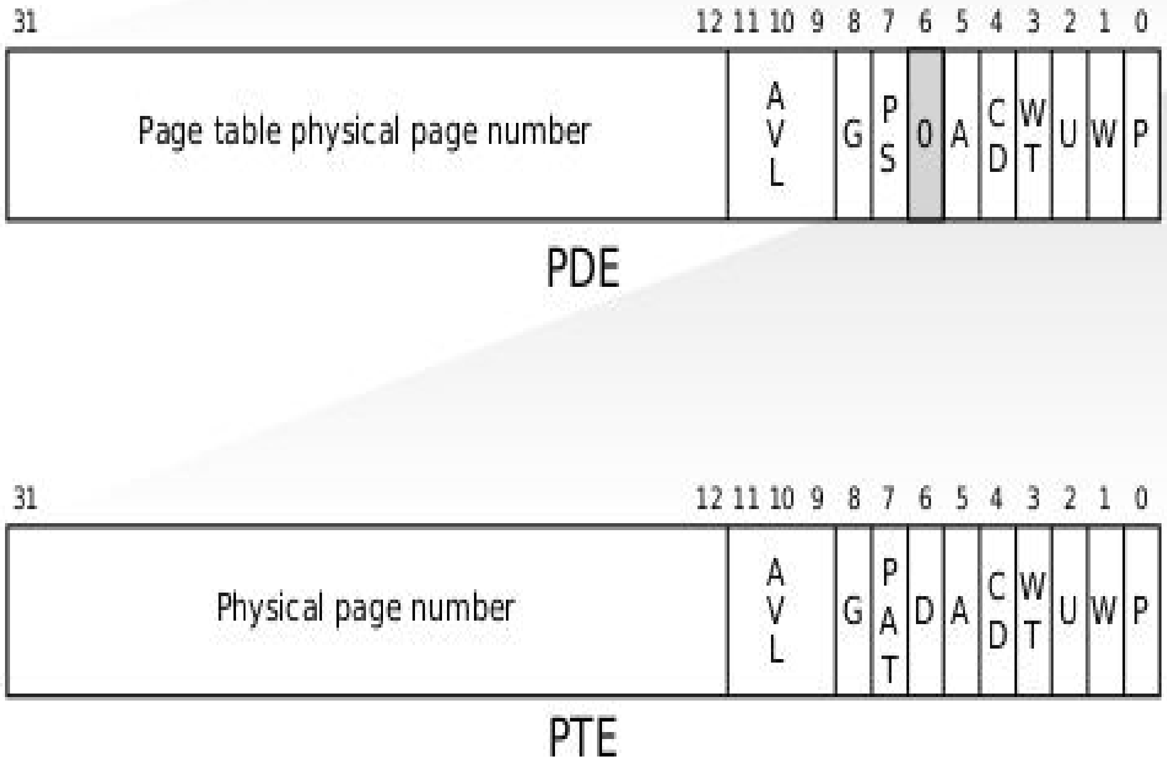


Figure 9.13 Valid (v) or invalid (i) bit in a page table.

X86 PDE and 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

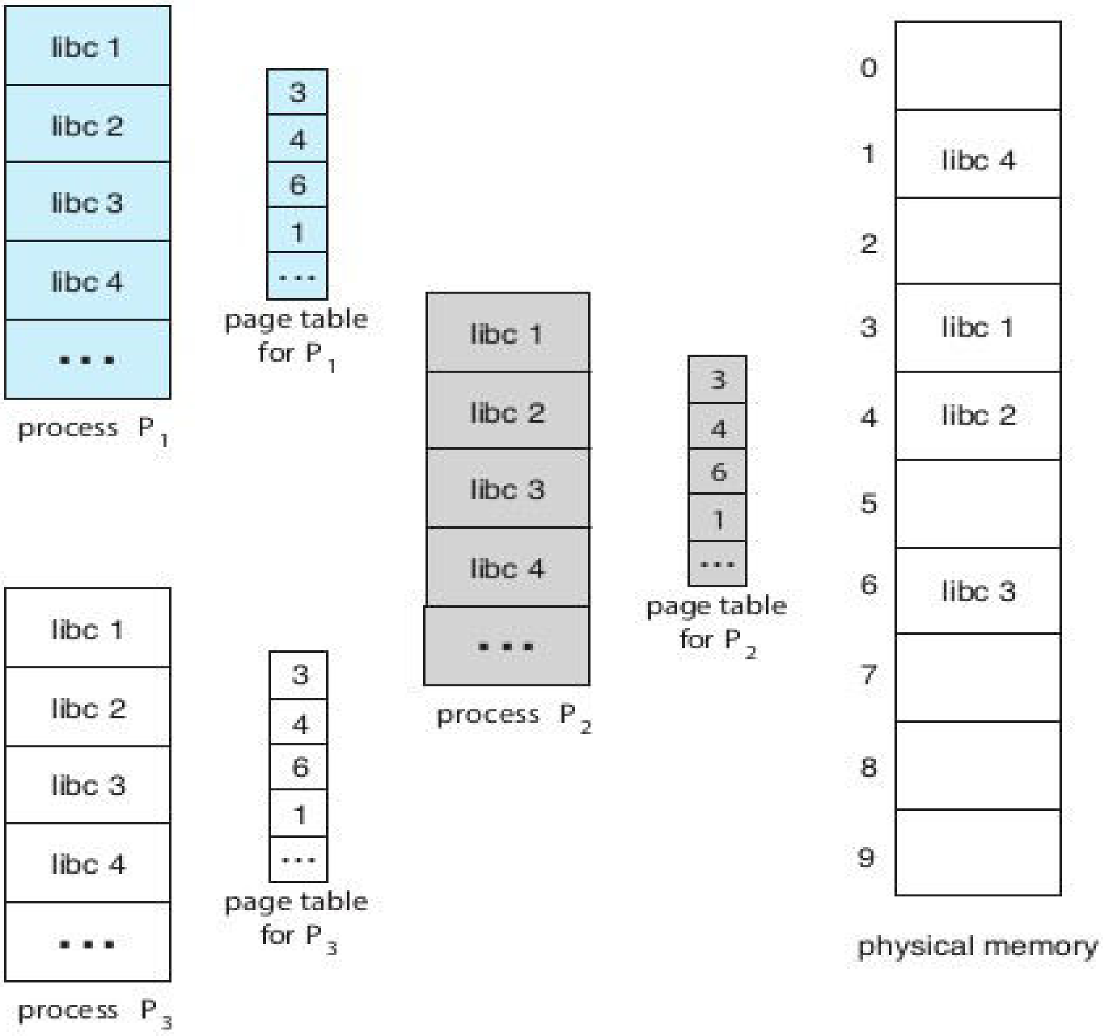


Figure 9.14 Sharing of standard C library in a paging environment.

Shared pages (e.g. library) with paging

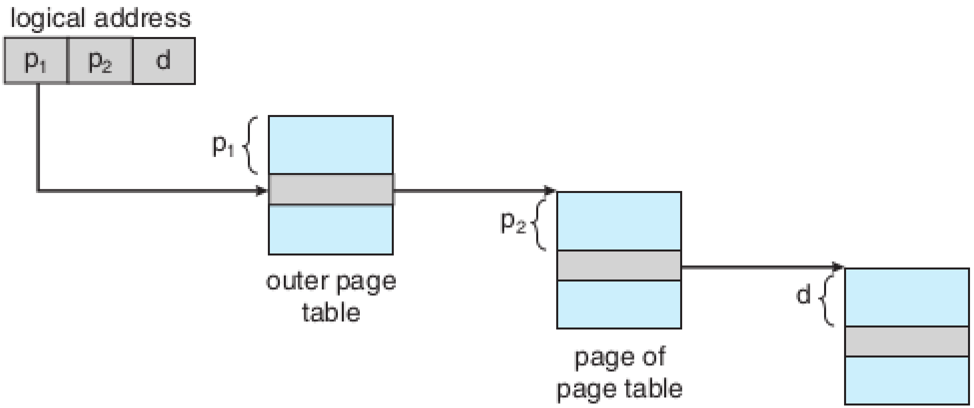
Paging: problem of large PT

- **64 bit address**
- **Suppose 20 bit offset**
  - That means 2^20 = 1 MB pages
  - 44 bit page number: 2^44 that is trillion sized page table!
  - Can’t have that big continuous page table!

Paging: problem of large PT

- **32 bit address**
- **Suppose 12 bit offset**
  - That means 2^12 = 4 KB pages
  - 20 bit page number: 2^20 that is a million entries
  - Can't always have that big continuous page table as well, for each process!

Hierarchical paging



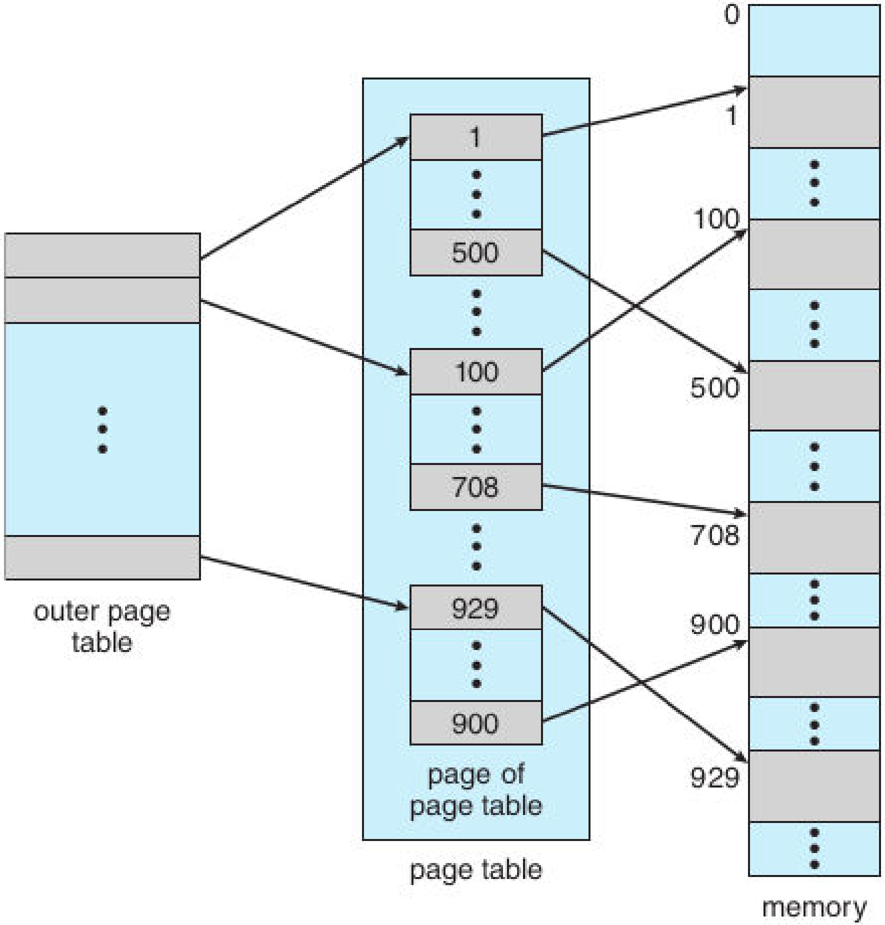
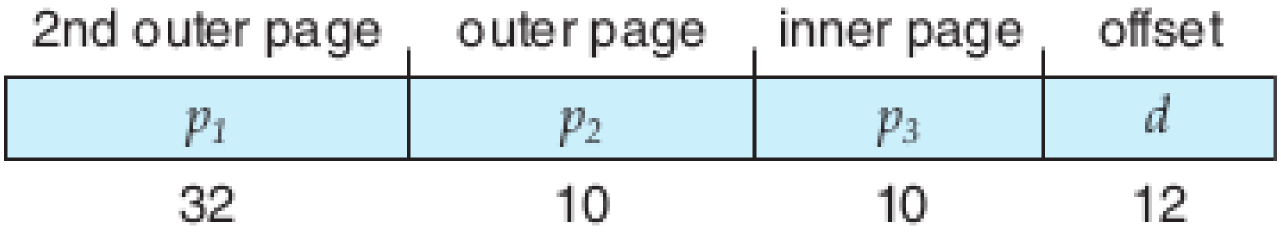


Figure 9.15 A two-level page-table scheme.

outer page	inner page	offset
p_1	p_2	d
42	10	12

More hierarchy



Problems with hierarchical paging

- **More number of memory accesses with each level !**
  - Too slow !
- **OS data structures also needed in that proportion**

Hashed page table

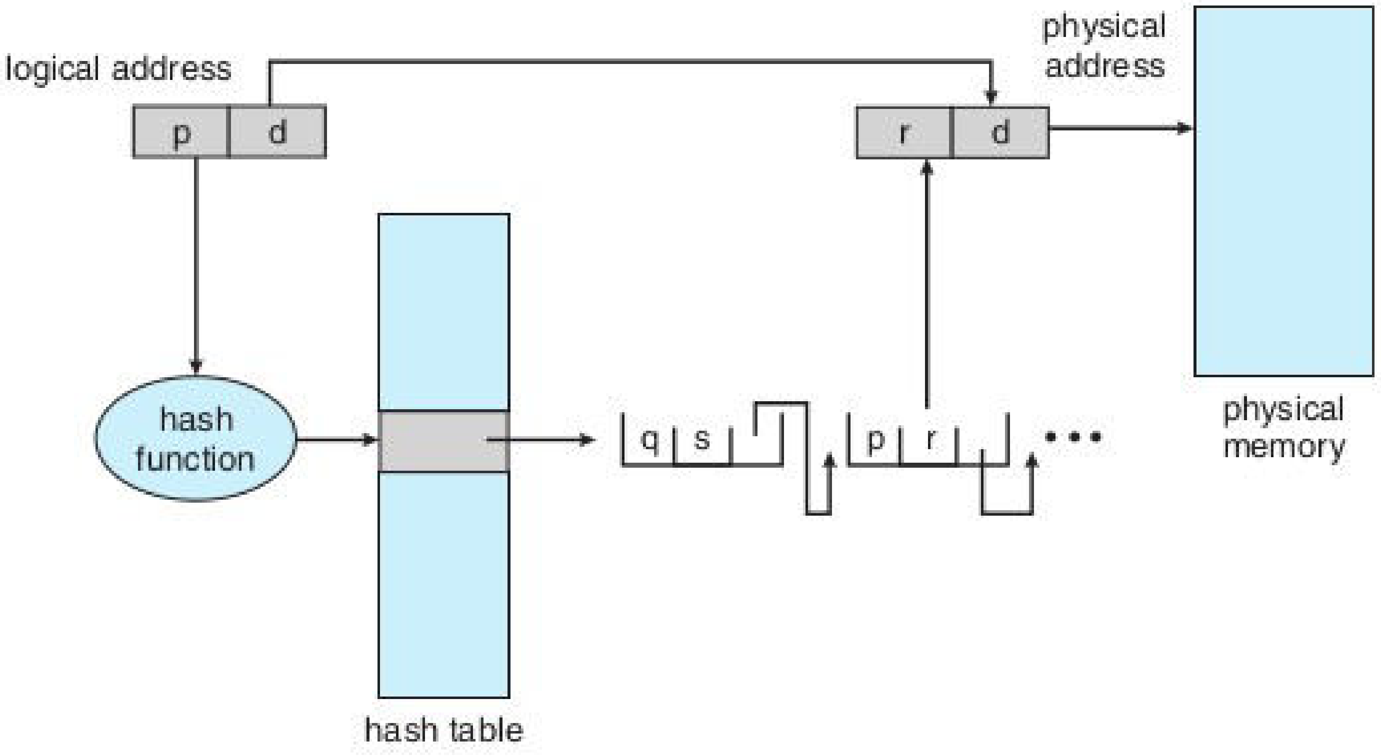


Figure 9.17 Hashed page table.

Inverted page table

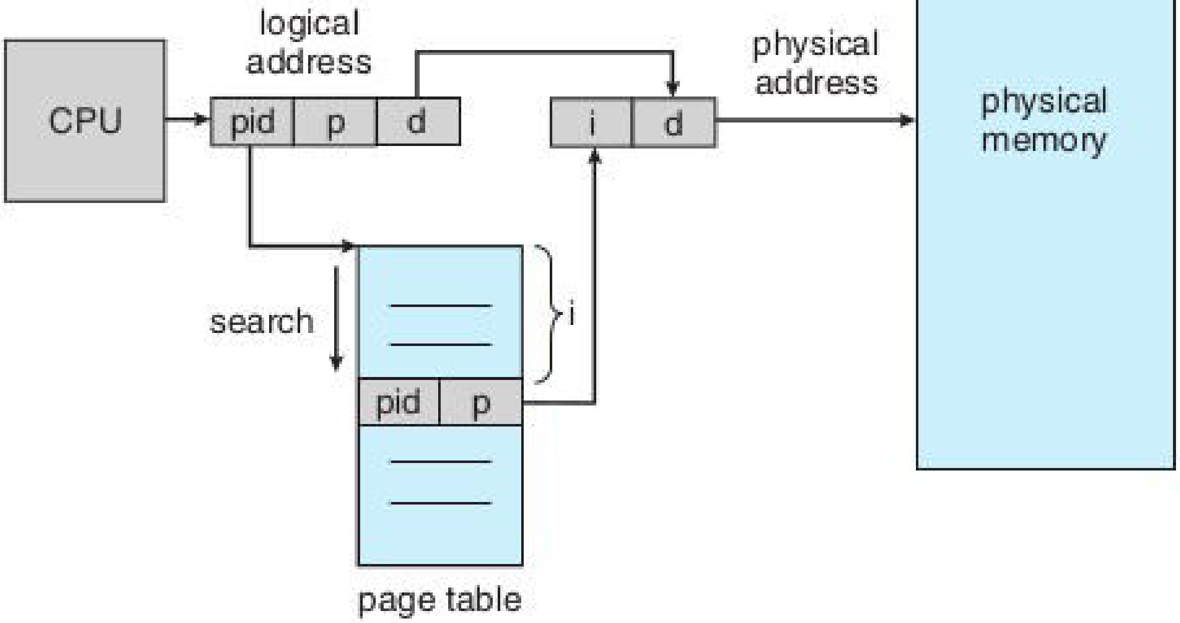


Figure 9.18 Inverted page table.

Normal page table – one per process --> Too much memory consumed

Inverted page table : global table – only one

Needs to store PID in the table entry

Examples of systems using inverted page

tables include the 64-bit Ultra SPARC and Power PC

virtual address

consists of a triple:

<process-id, page-number, offset>

Case Study: Oracle SPARC Solaris

- **64 bit SPARC processor , 64 bit Solaris OS**
- **Uses Hashed page tables**
  - one for the kernel and one for all user processes.
  - Each hash-table entry : base + span (#pages)
    - Reduces number of entries required

Case Study: Oracle SPARC Solaris

- **Cashing levels: TLB (on CPU), TSB(in Memory), Page Tables (in Memory)**
  - CPU implements a TLB that holds translation table entries (TTE s) for fast hardware lookups.
  - A cache of these TTEs resides in a in-memory translation storage buffer (TSB), which includes an entry per recently accessed page
  - When a virtual address reference occurs, the hardware searches the TLB for a translation.
  - If none is found, the hardware walks through the in memory TSB looking for the TTE that corresponds to the virtual address that caused the lookup

Case Study: Oracle SPARC Solaris

- If a match is found in the TSB , the CPU copies the TSB entry into the TLB , and the memory translation completes.
- If no match is found in the TSB , the kernel is interrupted to search the hash table.
- The kernel then creates a TTE from the appropriate hash table and stores it in the TSB for automatic loading into the TLB by the CPU memory-management unit.
- Finally, the interrupt handler returns control to the MMU , which completes the address translation and retrieves the requested byte or word from main memory.

Swapping

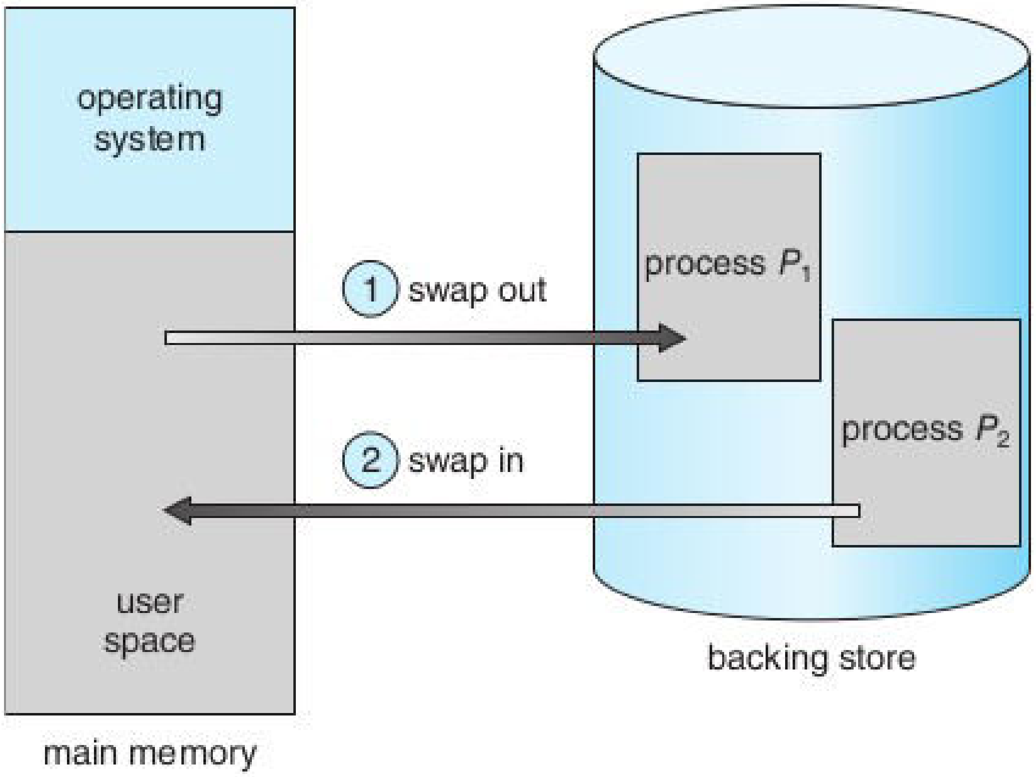


Figure 9.19 Standard swapping of two processes using a disk as a backing store.

Swapping

- **Standard swapping**
  - Entire process swapped in or swapped out
  - With continous memory management
- **Swapping with paging**
  - Some pages are “paged out” and some “paged in”
  - Term “paging” refers to paging with swapping now

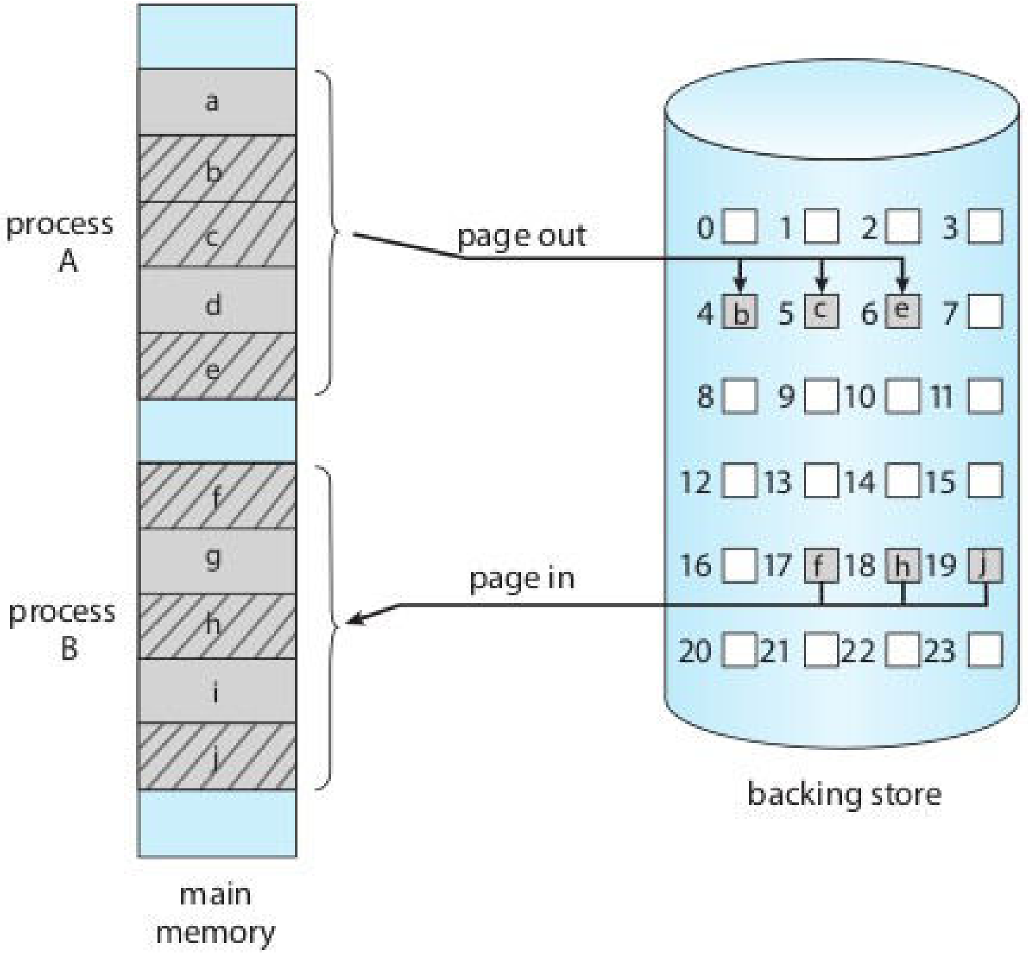


Figure 9.20 Swapping with paging.

Words of caution about ‘paging’

- **Not as simple as it sounds when it comes to implementation**
  - Writing OS code for this is challenging

Virtual Memory

Introduction

- Virtual memory != Virtual address

  Virtual address is address issued by CPU’s execution unit, later converted by MMU to physical address

  Virtual memory is a memory management technique employed by OS (with hardware support, of course)

Unused parts of program

```
int a[4096][4096]
int f(int m[][4096]) {
int i, j;
for(i = 0; i < 1024; i++)
m[0][i] = 200;
}
int main() {
int i, j;
for(i = 0; i < 1024; i++)
a[1][i] = 200;
if(random() == 10)
f(a);
}
```

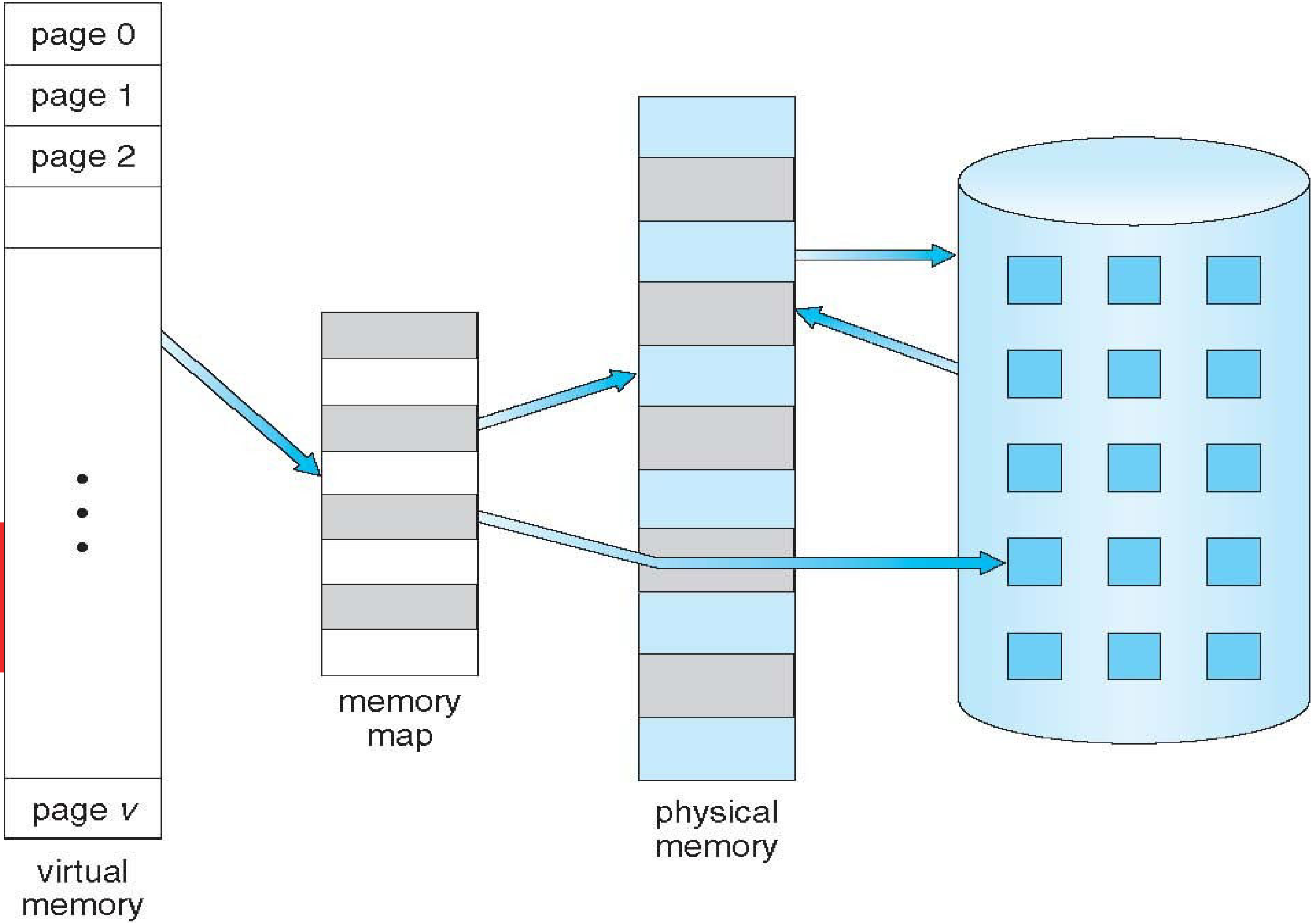
All parts of array a[] not accessed
Function f() may not be called

Some problems with schemes discussed so far

- Code needs to be in memory to execute, But entire program rarely used
    - Error code, unusual routines, large data structures are rarely used
- So, entire program code, data not needed at same time
- So, consider ability to execute partially-loaded program
    - One Program no longer constrained by limits of physical memory
    - One Program and collection of programs could be larger than physical memory

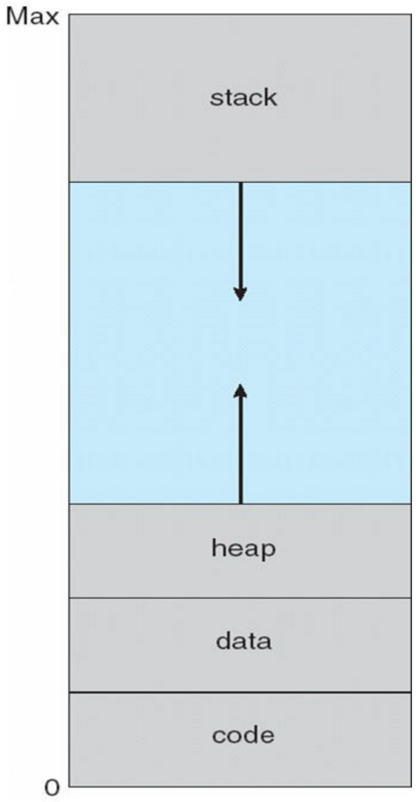
What is virtual memory?

- Virtual memory – separation of user logical memory from physical memory
  - Only part of the program needs to be in memory for execution
  - Logical address space can therefore be much larger than physical address space
  - Allows address spaces to be shared by several processes
  - Allows for more efficient process creation
  - More programs running concurrently
  - Less I/O needed to load or swap processes
- Virtual memory can be implemented via:
  - Demand paging
  - Demand segmentation

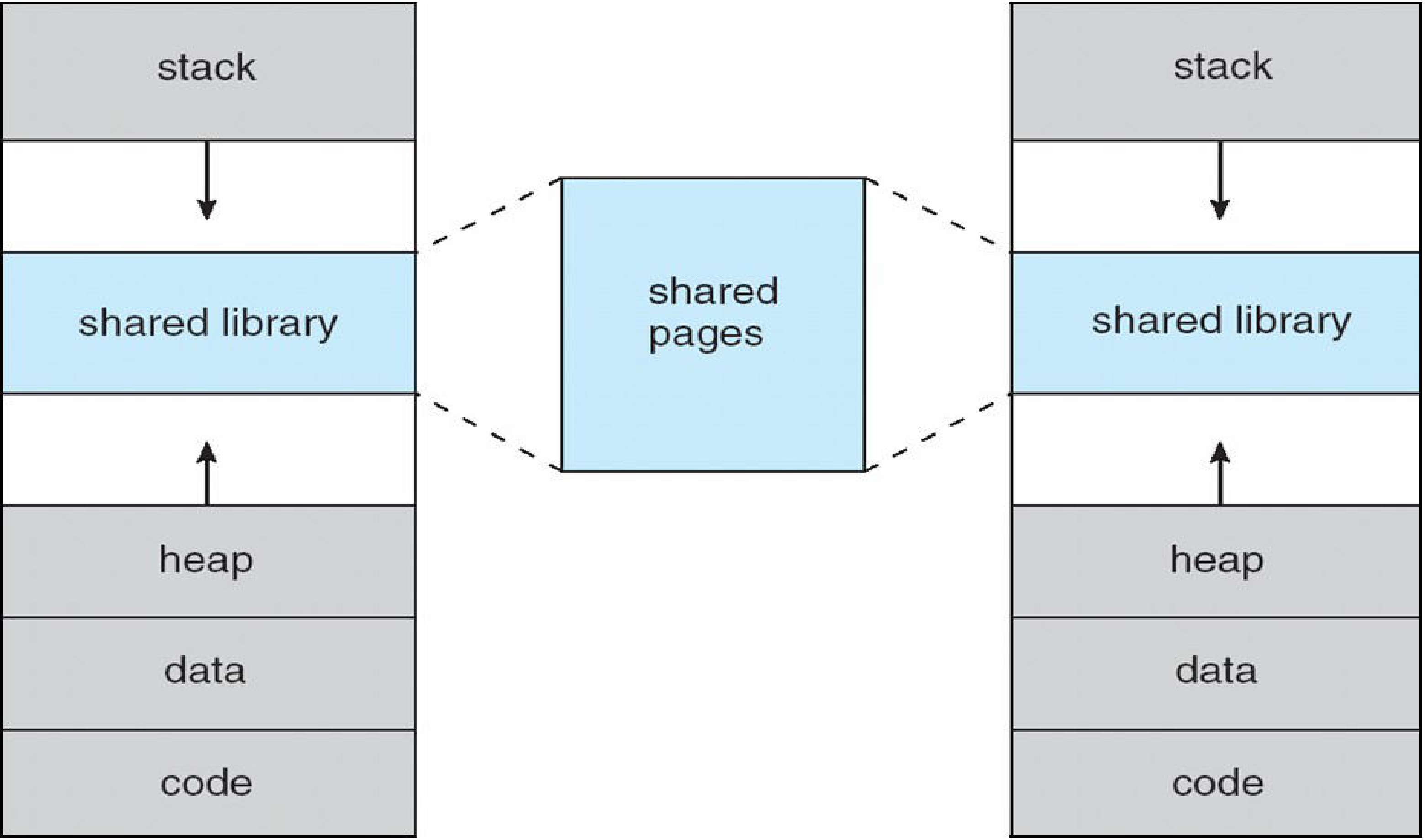


Virtual Memory Larger Than Physical Memory

Virtual Address space



Enables **sparse** address spaces with holes left for growth, dynamically linked libraries, etc



Shared pages Using Virtual Memory

System libraries shared via mapping into virtual address space

Shared memory by mapping same page-frames into page tables of involved processes

Pages can be shared during fork(), speeding process creation (more later)

Demand Paging

Demand Paging

- Load a “page” to memory when it’s neded (on demand)

    Less I/O needed, no unnecessary I/O

    Less memory needed

    Faster response

    More users

Demand Paging

- Options:
  - Load entire process at load time : achieves little
  - Load some pages at load time: good
  - Load no pages at load time: pure demand paging

New meaning for valid/invalid bits in page table

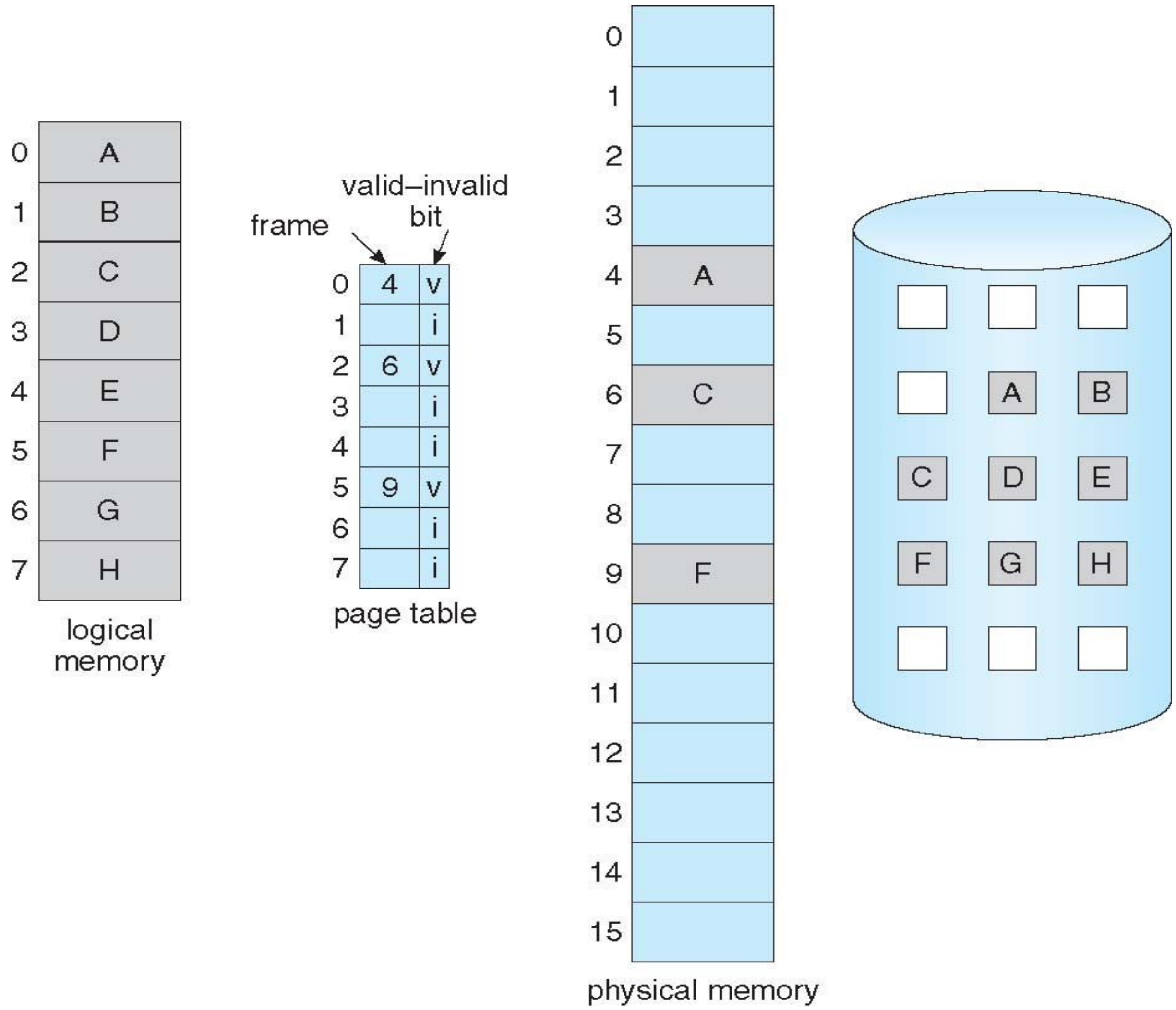
Frame #	valid-invalid bit
	v
	v
	v
	v
	i
….	
	i
	i

- With each page table entry a valid–invalid bit is associated

  v: in-memory – memory resident

  i : not-in-memory or illegal

- During address translation, if valid–invalid bit in page table entry is I : **raises trap called page fault**



Page

Table

With

Some pages

Not

In memory

Page fault

Page fault

- Page fault is a hardware interrupt
- It occurs when the page table entry corresponding to current memory access is “i”
- All actions that a kernel takes on a hardware interrupt are taken!

    Change of stack to kernel stack

    Saving the context of process

    Switching to kernel code

On a Page fault

1) Operating system looks at another data structure (table), most likely in PCB itself, to decide:

    If it's Invalid reference -> abort the process (segfault)

    Just not in memory -> Need to get the page in memory

2) Get empty frame (this may be complicated!)

3) Swap page into frame via scheduled disk/IO operation

4) Reset tables to indicate page now in memory.

5) Set validation bit = v

6) Restart the instruction that caused the page fault

Additional problems

- Extreme case – start process with *no* pages in memory
    - OS sets instruction pointer to first instruction of process, non-memory-resident -> page fault
    - And for every other process pages on first access
    - **Pure demand paging**
- Actually, a given instruction could access multiple pages -> multiple page faults
    - Pain decreased because of **locality of reference**
- Hardware support needed for demand paging
    - Page table with valid / invalid bit
    - Secondary memory (swap device with **swap space**)
    - Instruction restart

Instruction restart

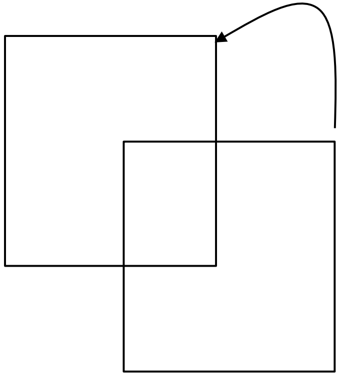
- A critical Problem
- Consider an instruction that could access several different locations

movarray 0x100, 0x200, 20

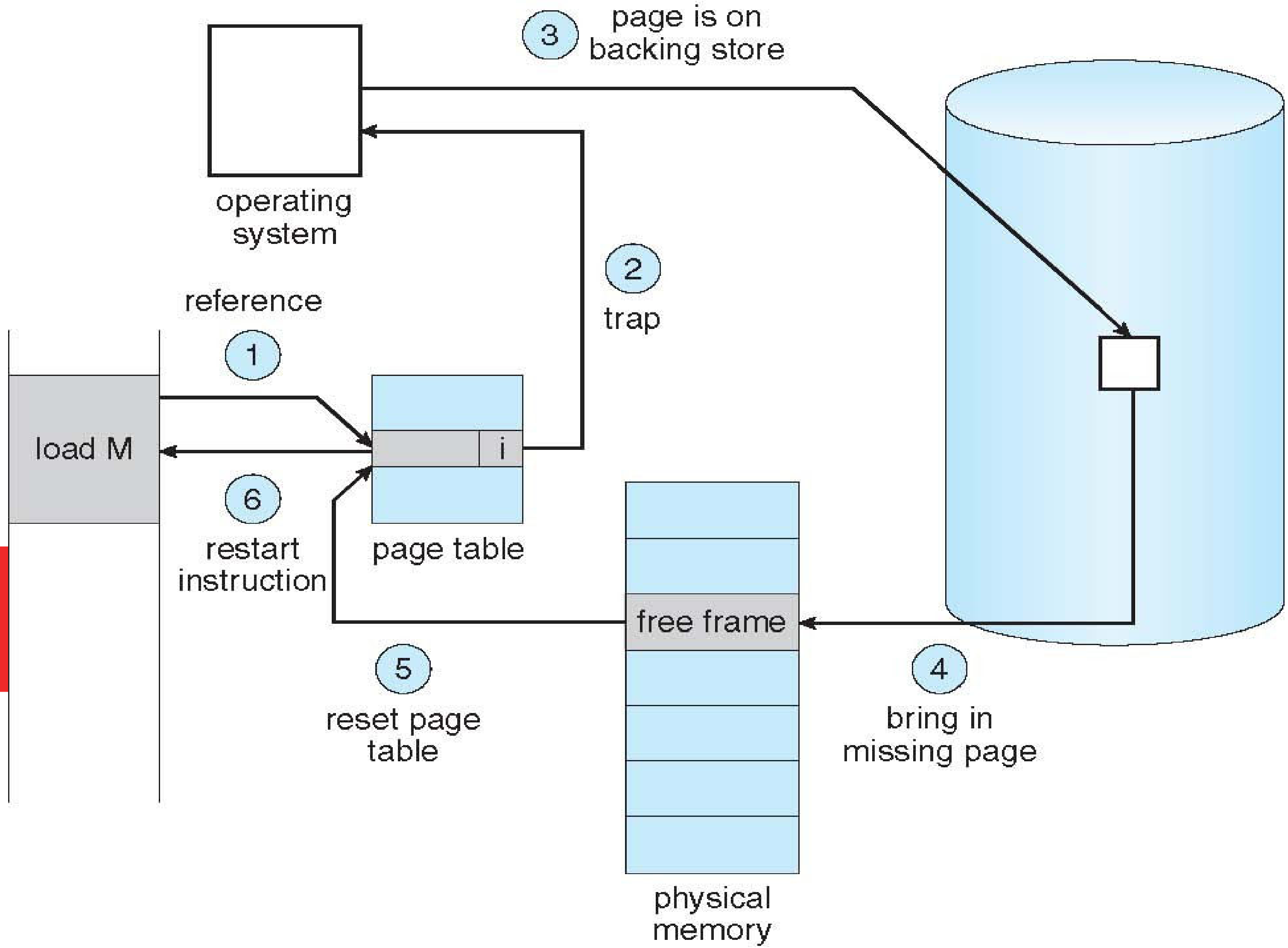
copy 20 bytes from address 0x100 to address 0x200

movarray 0x100, 0x110, 20

what to do in this case?



Handling A Page Fault



Page fault handling

1) Trap to the operating system
2) Default trap handling():

    Save the process registers and process state

    Determine that the interrupt was a page fault. Run page fault handler.

3) Page fault handler(): Check that the page reference was legal and determine the location of the page on the disk. If illegal, terminate process.
4) Find a free frame. Issue a read from the disk to a free frame:

    Process waits in a queue for disk read. Meanwhile many processes may get scheduled.

    Disk DMA hardware transfers data to the free frame and raises interrupt in end

Page fault handling

6) (as said on last slide) While waiting, allocate the CPU to some other process
7) (as said on last slide) Receive an interrupt from the disk I/O subsystem (I/O completed)
8) Default interrupt handling():
   - Save the registers and process state for the other user
   - Determine that the interrupt was from the disk
9) Disk interrupt handler():
   - Figure out that the interrupt was for our waiting process
   - Make the process runnable
10) Wait for the CPU to be allocated to this process again
   - Kernel restores the page table of the process, marks entry as “v”
   - Restore the user registers, process state, and new page table, and then resume the interrupted instruction

Performance of demand paging

Page Fault Rate 0 <= p <= 1

if p = 0 no page faults

if p = 1, every reference is a fault

Effective (memory) Access Time (EAT)

EAT = (1 – p) * memory access time +

p * (page fault overhead // Kernel code execution time

+ swap page out // time to write an occupied frame to disk

+ swap page in // time to read data from disk into free frame

+ restart overhead) // time to reset process context, restart it

Performance of demand paging

Memory access time = 200 nanoseconds

Average page-fault service time = 8 milliseconds
EAT = (1 – p) x 200 + p (8 milliseconds)

= (1 – p x 200 + p x 8,000,000

= 200 + p x 7,999,800

If one access out of 1,000 causes a page fault, then

EAT = 8.2 microseconds.

This is a slowdown by a factor of 40!!

If want performance degradation < 10 percent

220 > 200 + 7,999,800 x p
20 > 7,999,800 x p

p < .0000025

< one page fault in every 400,000 memory accesses

An optimization: Copy on write

The problem with fork() and exec(). Consider the case of a shell

```
scanf("%s", cmd);
if(strcmp(cmd, "exit") == 0)
return 0;
pid = fork(); // A->B
if(pid == 0) {
ret = execl(cmd, cmd, NULL);
if(ret == -1) {
perror("execution failed");
exit(errno);
}
} else {
wait(0);
}
```

- During fork()
  - Pages of parent were duplicated
  - Equal amount of page frames were allocated
  - Page table for child differed from parent (as it has another set of frames)
- In exec()
  - The page frames of child were taken away and new frames were allocated
  - Child’s page table was rebuilt!
- Waste of time during fork() if the exec() was to be called immediately

An optimization: Copy on write

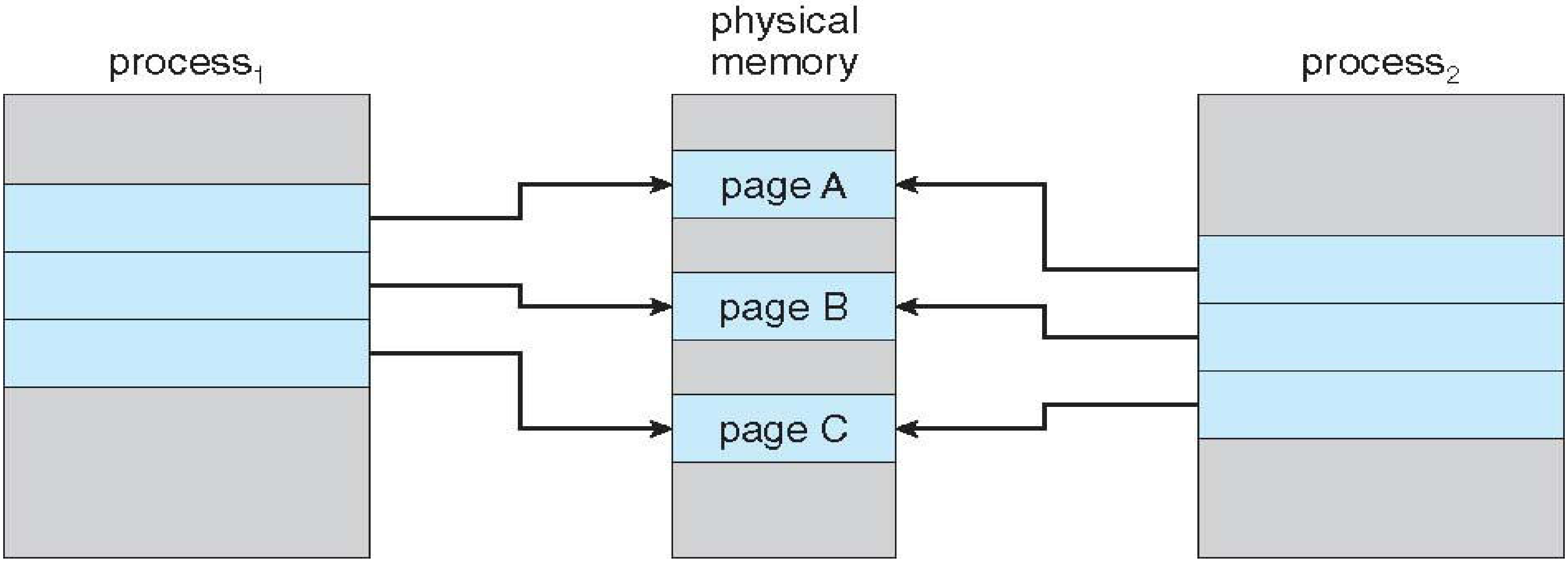
- Copy-on-Write (COW) allows both parent and child processes to initially share the same pages in memory

    If either process modifies a shared page, only then is the page copied

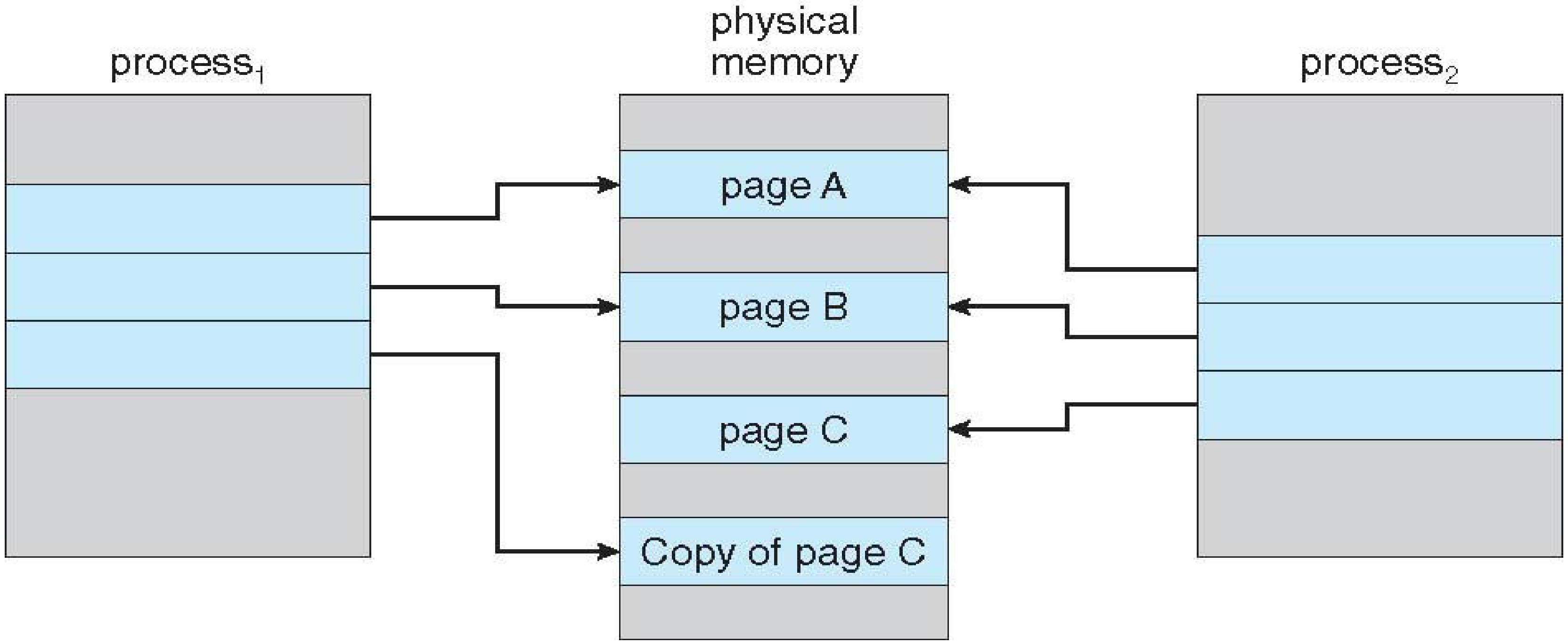
- COW allows more efficient process creation as only modified pages are copied
- vfork() variation on fork() system call has parent suspend and child using copy-on-write address space of parent

    Designed to have child call exec()

    Very efficient



Before Process 1 Modifies Page C



After Process 1 Modifies Page C

Challenges and improvements in implementation

- Choice of backing store

    For stack, heap pages: on swap partition

    For code, shared library? : swap partition or the actual executable file on the file-system?

    If the choice is file-system for code, then the page-fault handler needs to call functions related to file-system

- Is the page table itself pagable?

    If no, good

    If Yes, then there can be page faults in accessing the page tables themselves! More complicated!

- Is the kernel code pagable?

    If no, good

    If yes, life is very complicated ! Page fault in running kernel code, interrupt handlers, system calls, etc.

Page replacement

Review

- Concept of virtual memory, demand paging.
- Page fault
- Performance degradation due to page fault: Need to reduce #page faults to a minimum
- Page fault handling process, broad steps: (1) Trap (2) Locate on disk (3) find free frame (4) schedule disk I/O (5) update page table (6) resume
- More on (3) today

List of free frames

- Kernel needs to maintain a list of free frames
- At the time of loading the kernel, the list is created
- Frames are used for allocating memory to a process

  But may also be used for managing kernel’s own data structures also
- More processes --> more demand for frames

What if no free frame found on page fault?

- Page frames in use depends on “Degree of multiprogramming”
    - More multiprogramming -> overallocation of frames
    - Also in demand from the kernel, I/O buffers, etc
    - How much to allocate to each process? How many processes to allow?
- Page replacement – find some page(frame) in memory, but not really in use, page it out
    - Questions : terminate process? Page out process? replace the page?
    - For performance, need an algorithm which will result in minimum number of page faults
- Bad choices may result in same page being brought into memory several times

Need for Page Replacement

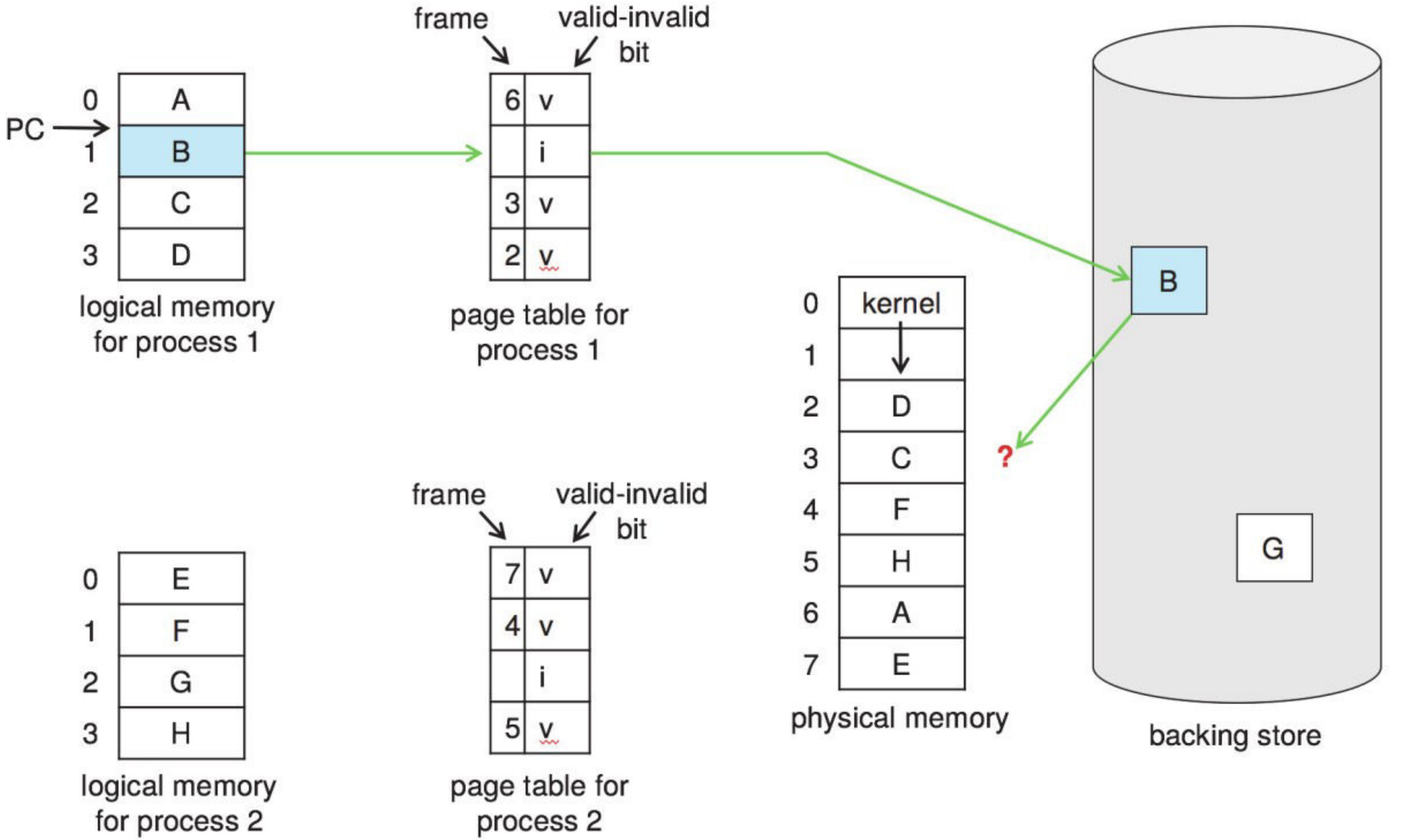


Figure 10.9 Need for page replacement.

Page replacement

- Strategies for performance

  Prevent over-allocation of memory by modifying page-fault service routine to include page replacement

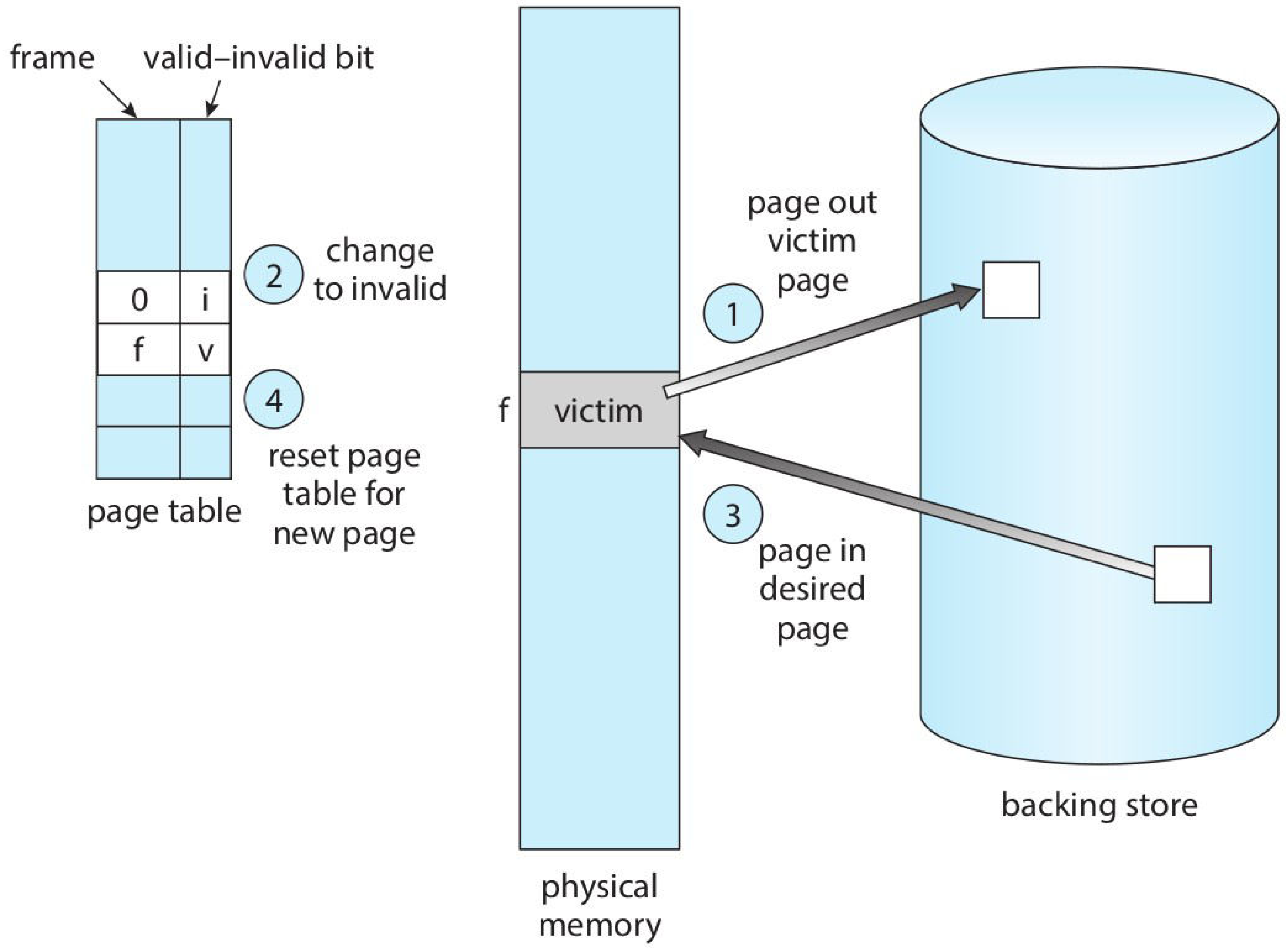
  Use modify (dirty) bit in page table. To reduce overhead of page transfers – only modified pages are written to disk. If page is not modified, just reuse it (a copy is already there in backing store)

Basic Page replacement

1) Find the location of the desired page on disk
2) Find a free frame:
3) - If there is a free frame, use it
4) - If there is no free frame, use a page replacement algorithm to select a victim frame & write victim frame to disk if dirty
5) Bring the desired page into the free frame; update the page table of process and global frame table/list
6) Continue the process by restarting the instruction that caused the trap

- Note now potentially 2 page transfers for page fault – increasing EAT

Page Replacement

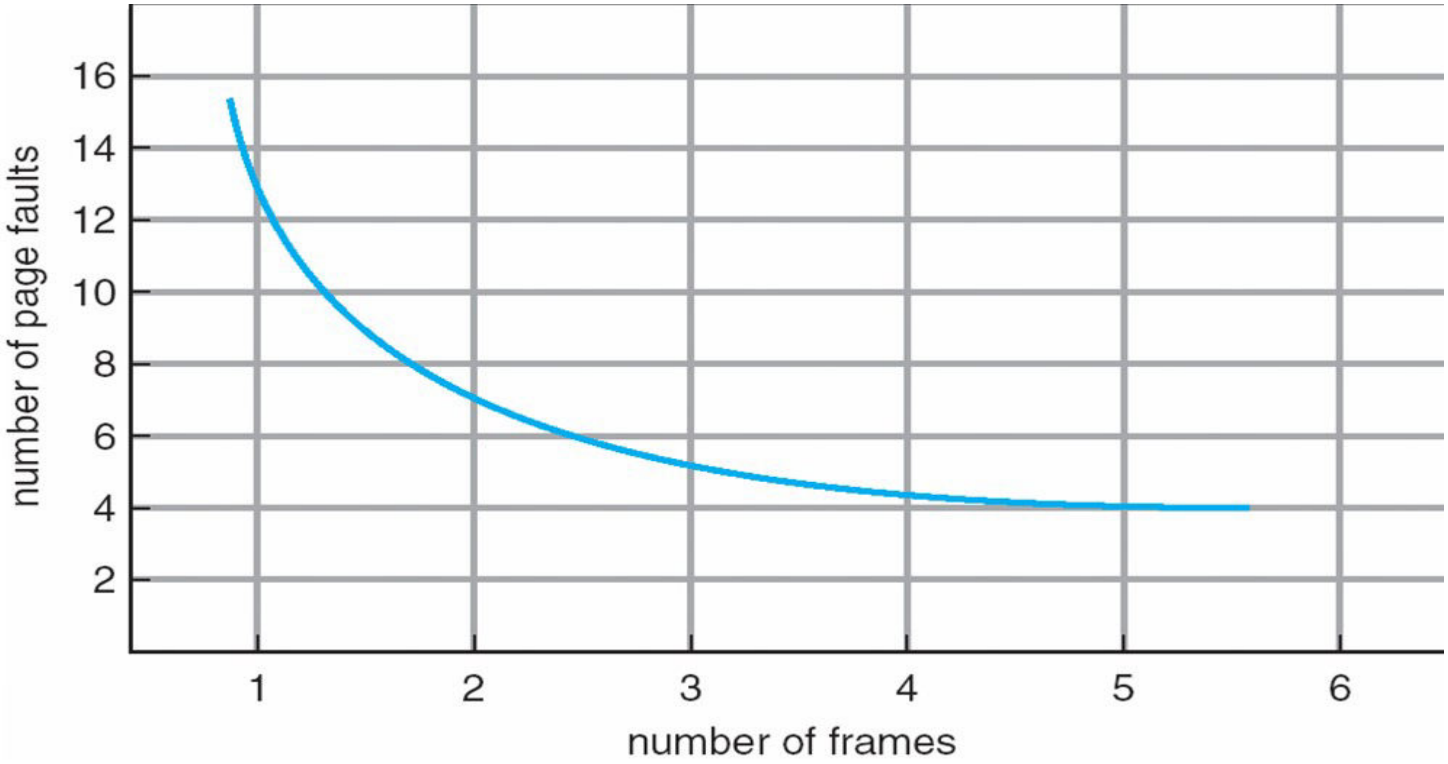


Two problems to solve

- Frame-allocation algorithm determines
  - How many frames to give each process
  - Which frames to replace
- Page-replacement algorithm
  - Want lowest page-fault rate on both first access and re-access

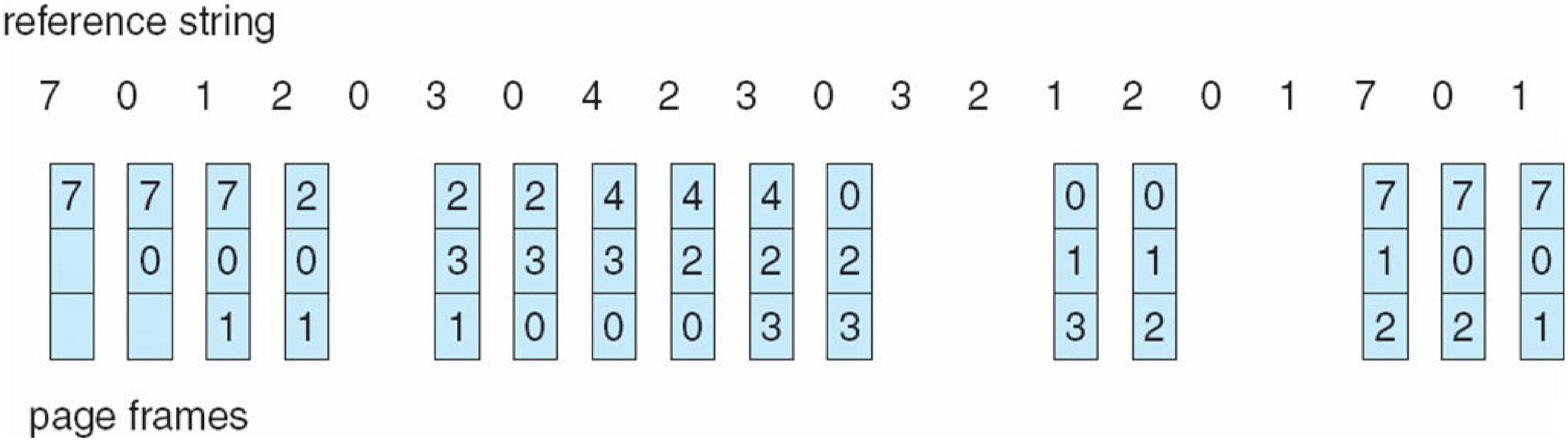
Evaluating algorithm: Reference string

- Evaluate algorithm by running it on a particular string of memory references (reference string) and computing the number of page faults on that string
  - String is just page numbers, not full addresses
  - Repeated access to the same page does not cause a page fault
- In all our examples, the reference string is 7,0,1,2,0,3,0,4,2,3,0,3,0,3,2,1,2,0,1,7,0,1



An Expectation More page Frames Means less faults

FIFO Algorithm



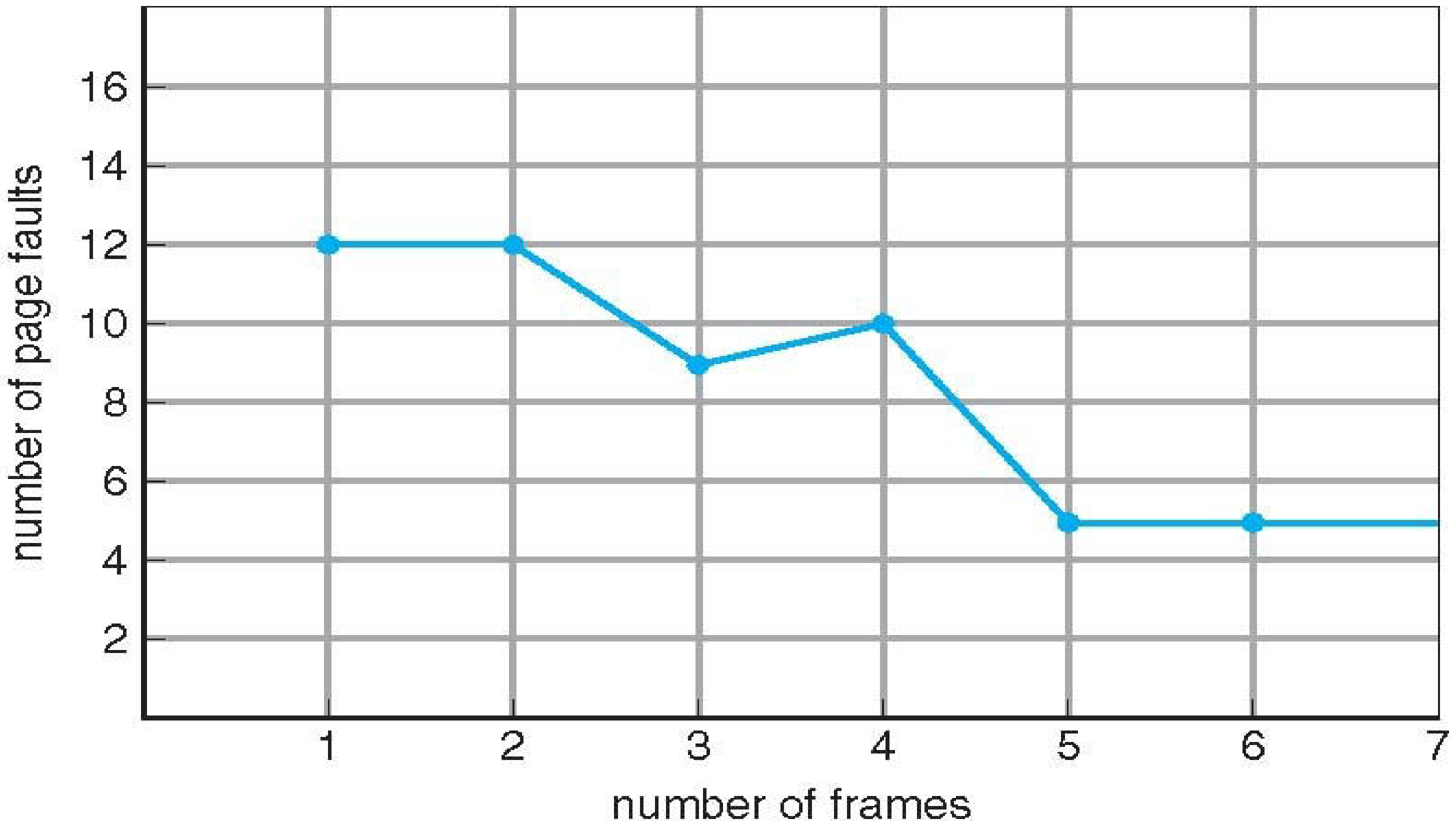
FIFO Algorithm

1	7	2 4 0 7
2	0	3 2 1 0
3	1	0 3 2 1

15 page faults

- Reference string: 7,0,1,2,0,3,0,4,2,3,0,3,0,3,2,1,2,0,1, 7,0,1
- 3 frames (3 pages can be in memory at a time per process)
- **Belady's Anomaly**
- Adding more frames can cause more page faults!
- Can vary by reference string: consider 1,2,3,4,1,2,5,1,2,3,4,5

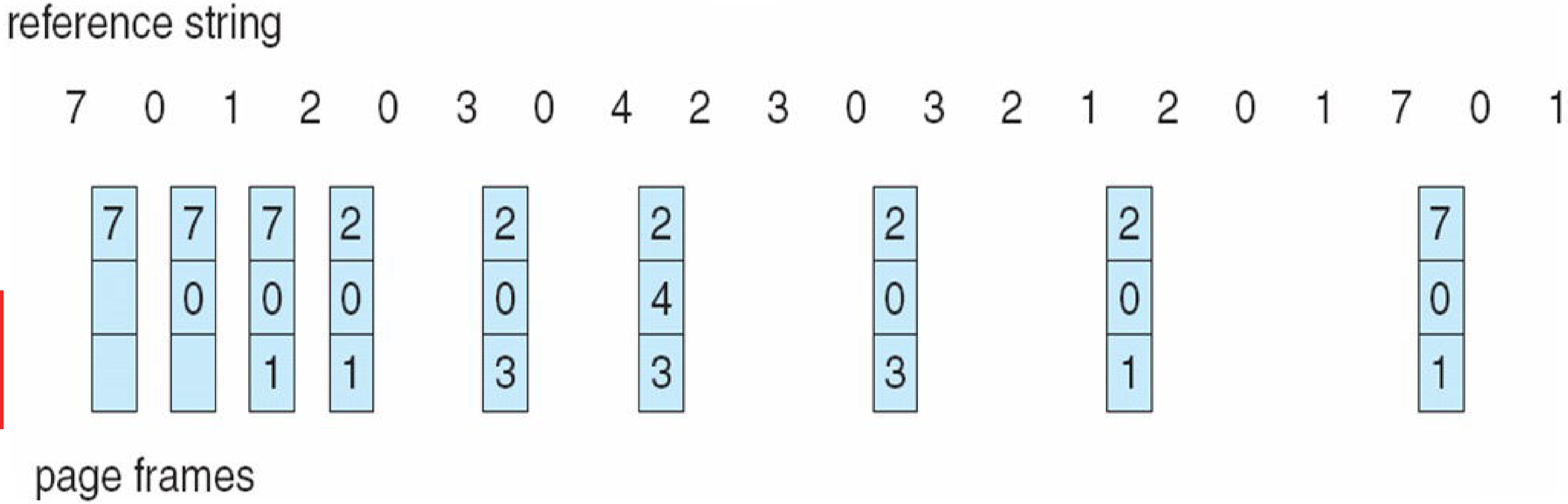
FIFO Algorithm: Balady’s anamoly



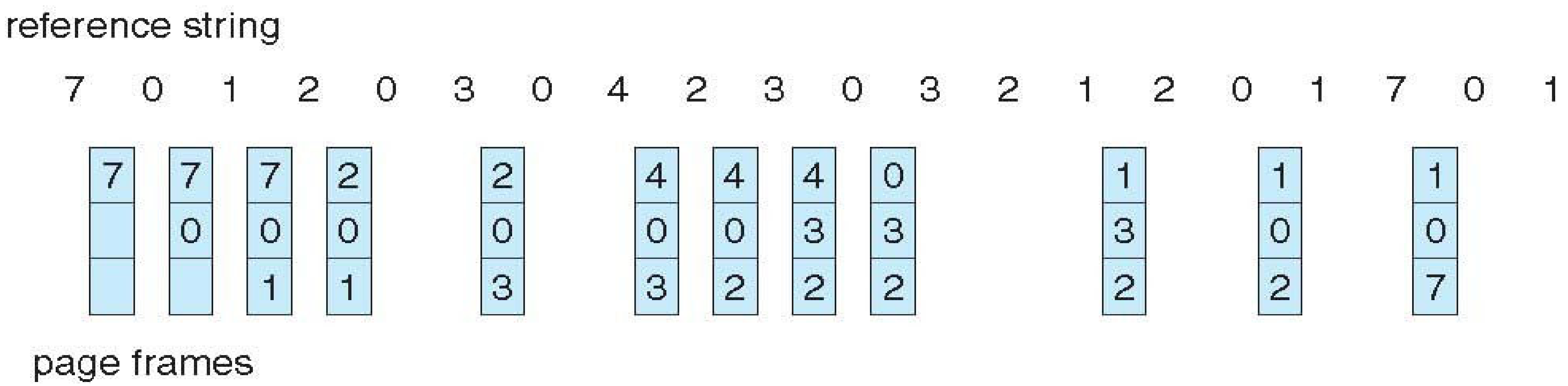
Optimal Algorithm

- Replace page that will not be used for longest period of time
  - 9 is optimal #replacements for the example on the next slide
- How do you know this?
  - Can’t read the future
- Used for measuring how well your algorithm performs

Optimal page replacement



Least Recently Used: an approximation of optimal



Use past knowledge rather than future
Replace page that has not been used in the most amount of time
Associate time of last use with each page
12 faults – better than FIFO but worse than OPT
Generally good algorithm and frequently used
But how to implement?

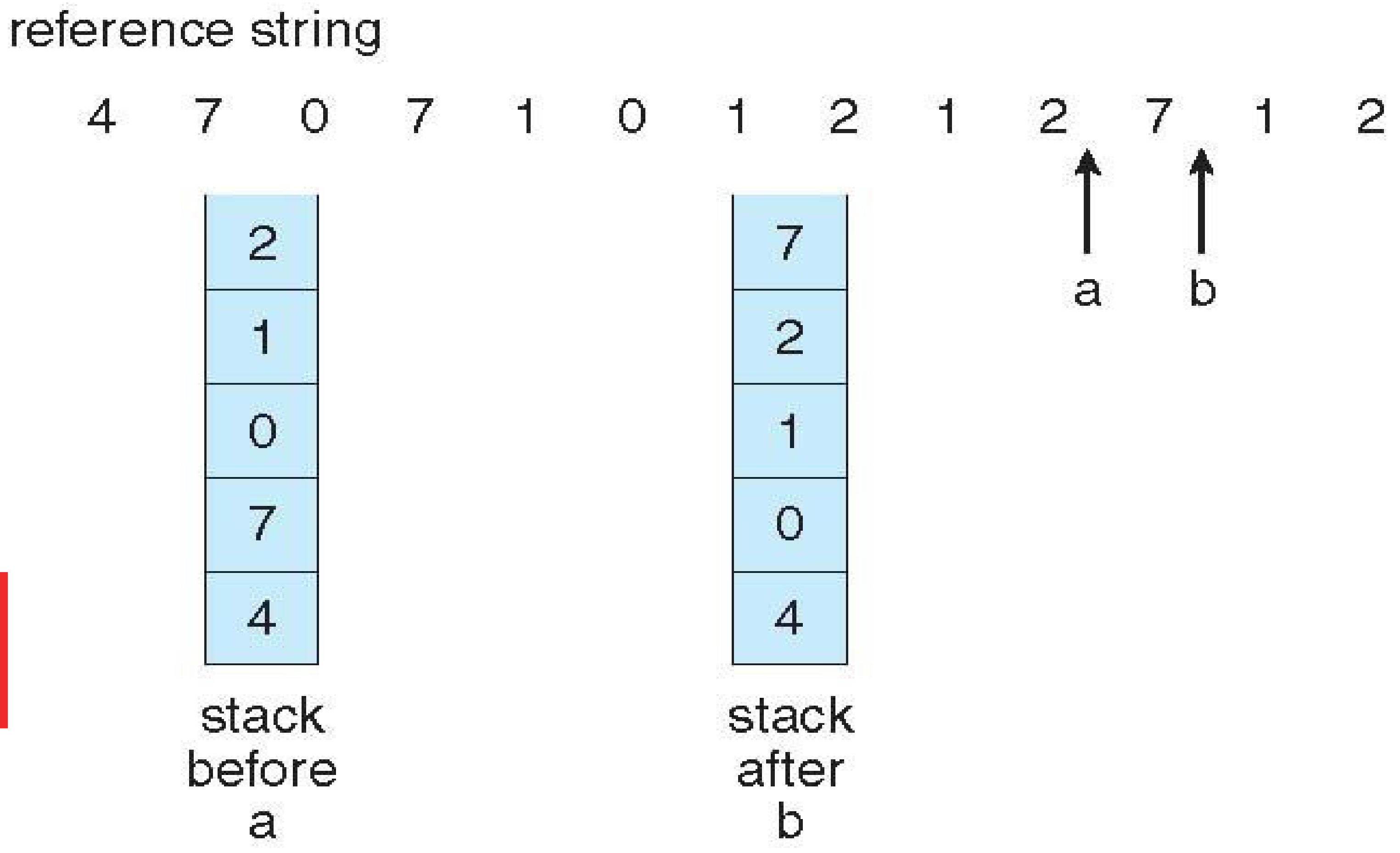
LRU: Counter implementation

- **Counter implementation**
  - Every page entry has a counter; every time page is referenced through this entry, copy the clock into the counter
  - When a page needs to be changed, look at the counters to find smallest value
    - Search through table needed

LRU: Stack implementation

- Keep a stack of page numbers in a double link form:
- Page referenced: move it to the top
  - requires 6 pointers to be changed and
  - each update more expensive
  - But no need of a search for replacement

Use Of A Stack to Record The Most Recent Page References



Stack algorithms

- An algorithm for which it can be shown that the set of pages in memory for n frames is always a subset of the set of pages that would be in memory with n + 1 frames
- Do not suffer from Balady’s anamoly
- For example: Optimal, LRU

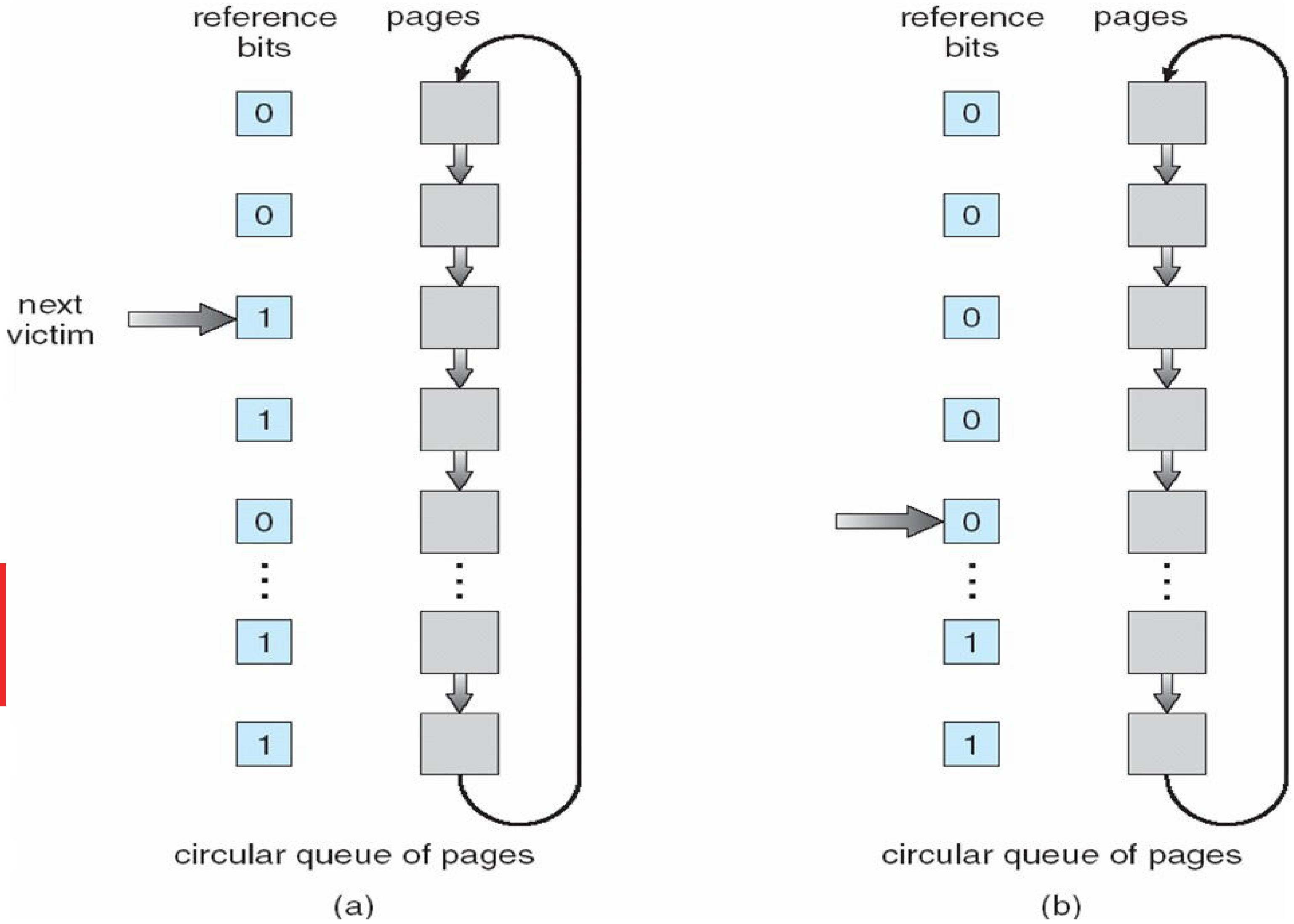
LRU: Approximation algorithms

- LRU needs special hardware and still slow
- **Reference bit**
  - With each page associate a bit, initially = 0
  - When page is referenced bit set to 1
  - Replace any with reference bit = 0 (if one exists)
  - We do not know the order, however

LRU: Approximation algorithms

- **Second-chance algorithm**
  - FIFO + hardware-provided reference bit. If bit is 0 select, if bit is 1, then set it to 0 and move to next one.
- **An implementation of second-chance: Clock replacement**
  - If page to be replaced has
  - Reference bit = 0 -> replace it
  - reference bit = 1 then:
    - set reference bit 0, leave page in memory
    - replace next page, subject to same rules

Second-Chance (clock) Page-Replacement Algorithm



Counting Algorithms

- Keep a counter of the number of references that have been made to each page
  - Not common
- **LFU Algorithm**: replaces page with smallest count
- **MFU Algorithm**: based on the argument that the page with the smallest count was probably just brought in and has yet to be used

Page buffering algorithms

- Keep a pool of free frames, always
  - Then frame available when needed, not found at fault time
  - Read page into free frame and select victim to evict and add to free pool
  - When convenient, evict victim
- Possibly, keep list of modified pages
  - When backing store otherwise idle, write pages there and set to non-dirty
- Possibly, keep free frame contents intact and note what is in them
  - If referenced again before reused, no need to load contents again from disk
  - Generally useful to reduce penalty if wrong victim frame selected

Major and Minor page faults

- Most modern OS refer to these two types
- Major fault
  - Fault + page not in memory
- Minor fault
  - Fault, but page is in memory
  - For example shared memory pages; second instance of fork(), page already on free-frame list,
- On Linux run
  - $ ps -eo min_flt,maj_flt,cmd

Special rules for special applications

- All of earlier algorithms have OS guessing about future page access
- But some applications have better knowledge – e.g. databases
- Memory intensive applications can cause double buffering
  - OS keeps copy of page in memory as I/O buffer
  - Application keeps page in memory for its own work
- Operating system can given direct access to the disk, getting out of the way of the applications
  - Raw disk mode
- Bypasses buffering, locking, etc

Allocation of frames

- Each process needs *minimum* number of frames
- Example: IBM 370 – 6 pages to handle SS MOVE instruction:
  - instruction is 6 bytes, might span 2 pages
  - 2 pages to handle *from*
  - 2 pages to handle *to*
- Maximum of course is total frames in the system
- Two major allocation schemes
  - fixed allocation
  - priority allocation
- Many variations

Fixed allocation of frames

- Equal allocation – For example, if there are 100 frames (after allocating frames for the OS) and 5 processes, give each process 20 frames

    Keep some as free frame buffer pool

- Proportional allocation – Allocate according to the size of process

    Dynamic as degree of multiprogramming, process sizes change

$$s_i = \text{size of process } p_i$$
$$S = \sum s_i$$
$$m = \text{total number of frames}$$
$$a_i = \text{allocation for } p_i = \frac{s_i}{S} \times m$$

$$m = 64$$
$$s_1 = 10$$
$$s_2 = 127$$
$$a_1 = \frac{10}{137} \times 64 \approx 5$$
$$a_2 = \frac{127}{137} \times 64 \approx 59$$

Priority Allocation of frames

- Use a proportional allocation scheme using priorities rather than size
- If process Pi generates a page fault,
  - select for replacement one of its frames
  - select for replacement a frame from a process with lower priority number

Global Vs Local allocation

- **Global replacement –** process selects a replacement frame from the set of all frames; one process can take a frame from another
  - But then process execution time can vary greatly
  - But greater throughput so more common
- **Local replacement –** each process selects from only its own set of allocated frames
  - More consistent per-process performance
  - But possibly underutilized memory

Virtual Memory – Remaining topics

Agenda

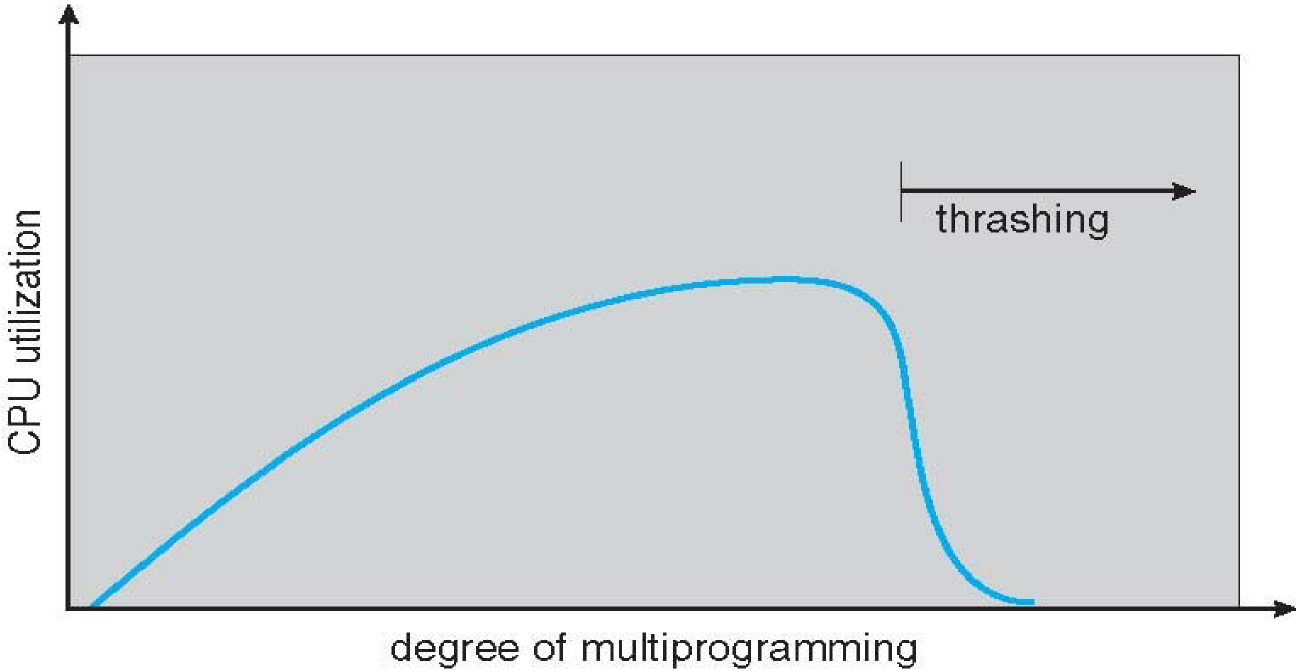
- Problem of Thrashing and possible solutions
- Mmap(), Memory mapped files
- Kernel Memory Management
- Other Considerations

Thrashing

Thrashing

- If a process does not have “enough” pages, the page-fault rate is very high
  - Page fault to get page
  - Replace existing frame
  - But quickly need replaced frame back
- This leads to:
  - Low CPU utilization
  - Operating system thinking that it needs to increase the degree of multiprogramming
  - Another process added to the system
- Thrashing : a process is busy swapping pages in and out

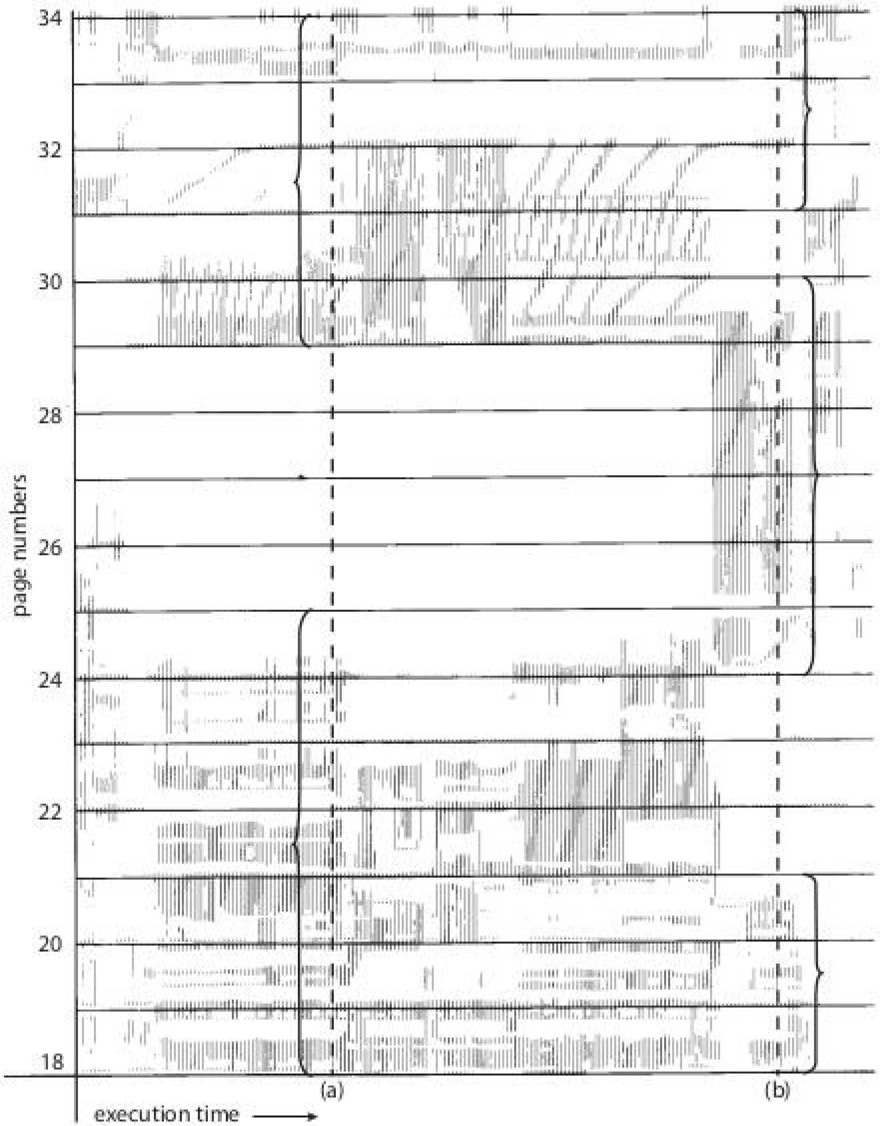
Thrashing



Demand paging and thrashing

- Why does demand paging work?
  - Locality model
  - Process migrates from one locality to another
  - Localities may overlap
- Why does thrashing occur?
  - size of locality > total memory size
  - Limit effects by using local or priority page replacement

Locality In A Memory-Reference Pattern

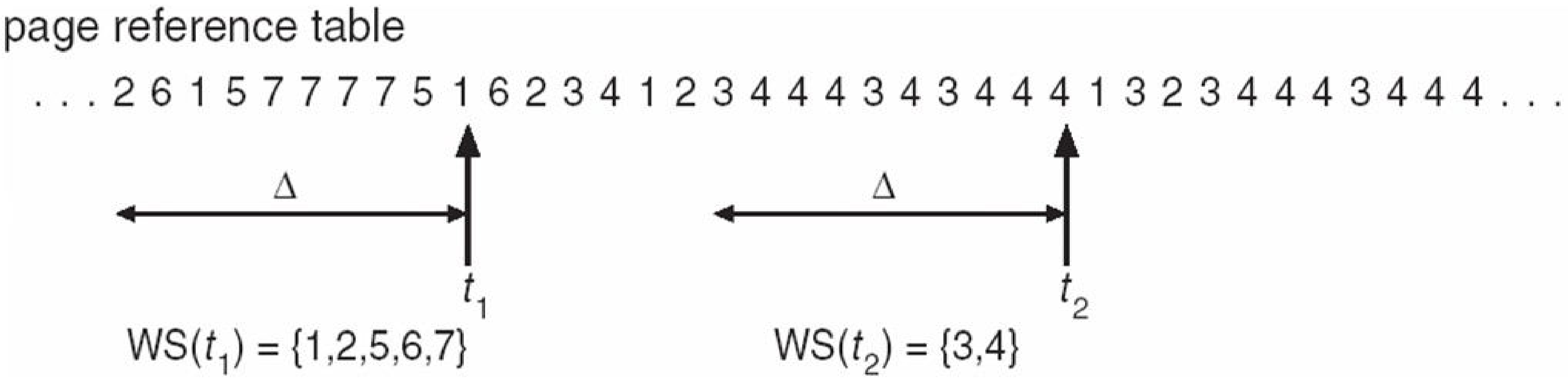


Working set model

- $\Delta \equiv$ working-set window $\equiv$ a fixed number of page references
  - Example: 10,000 instructions
- Working Set Size, WSS_i (working set of Process P_i) =
  - total number of pages referenced in the most recent Δ (varies in time)
  - if Δ too small will not encompass entire locality
  - if Δ too large will encompass several localities
  - if $\Delta = \infty \Rightarrow$ will encompass entire program

Working set model

- $D = \Sigma\ WSS_i \equiv$ total demand frames
  - Approximation of locality
- if $D > m$ (total available frames) $\Rightarrow$ Thrashing
- Policy if $D > m$, then suspend or swap out one of the processes



Keeping Track of the Working Set

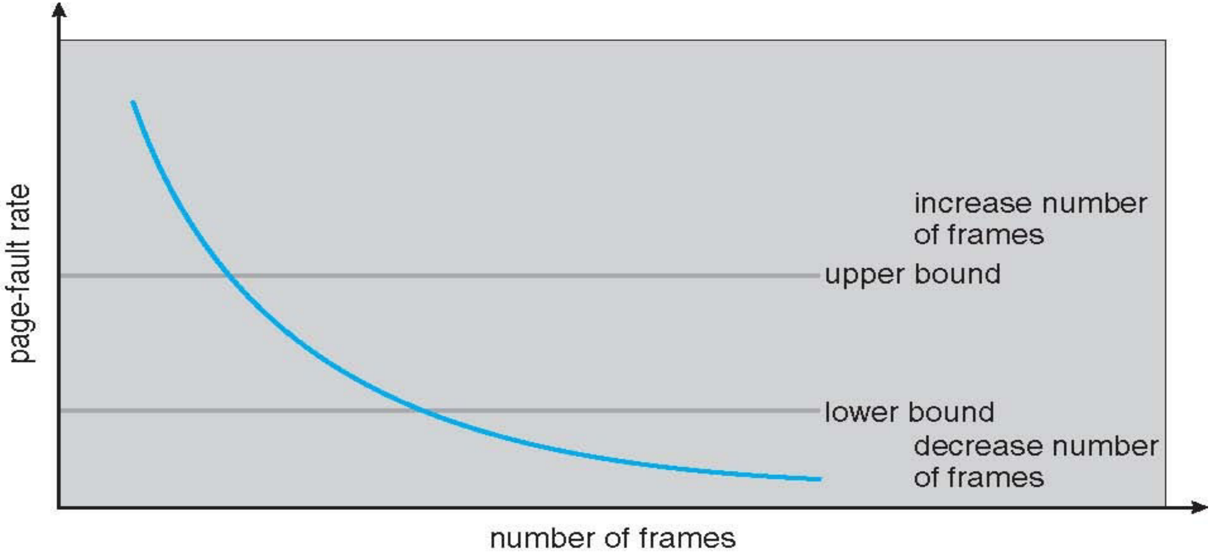
- Approximate with interval timer + a reference bit
- Example: $\Delta = 10{,}000$
  - Timer interrupts after every 5000 time units
  - Keep in memory 2 bits for each page
  - Whenever a timer interrupts copy (to memory) and sets the values of all reference bits to 0
  - If one of the bits in memory = 1 $\Rightarrow$ page in working set
- Why is this not completely accurate?
- Improvement = 10 bits and interrupt every 1000 time units

Page fault frequency

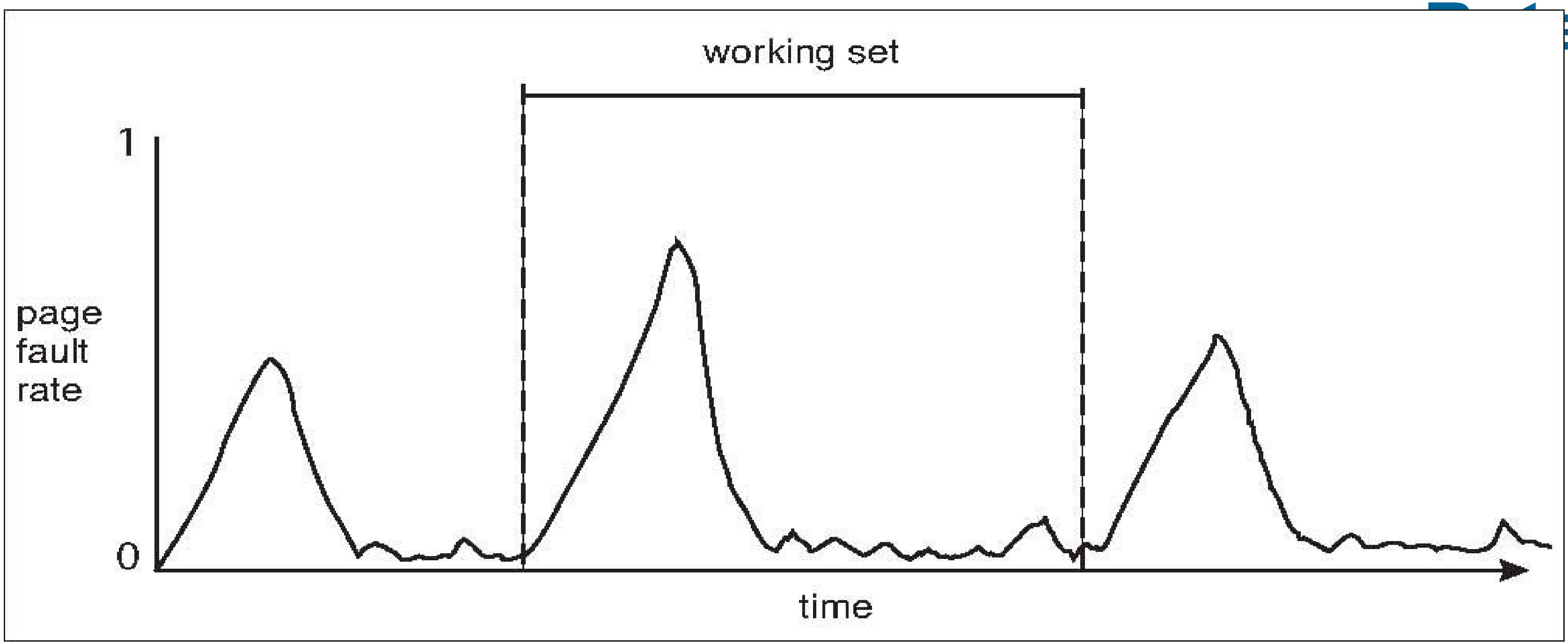
- More direct approach than WSS
- Establish “acceptable” page-fault frequency rate and use local replacement policy

    If actual rate too low, process loses frame

    If actual rate too high, process gains frame



Working Sets and Page Fault Rates

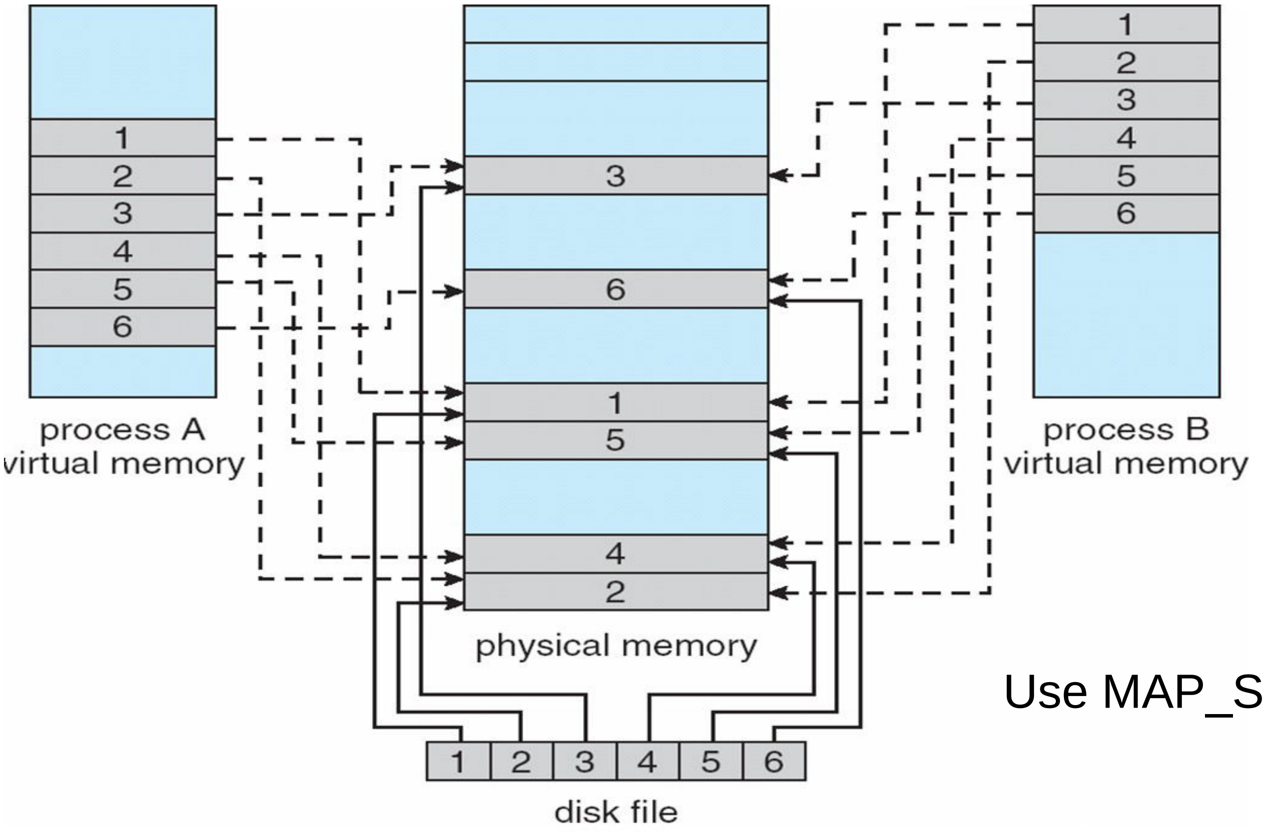


Memory Mapped Files

Memory-Mapped Files

- First, let’s see a demo of using mmap()

Memory-Mapped Files



Use MAP_SHARED flag

Memory-Mapped Files

- Memory-mapped file I/O allows file I/O to be treated as routine memory access by mapping a disk block to a page in memory
- A file is initially read using demand paging
  - A page-sized portion of the file is read from the file system into a physical page
  - Subsequent reads/writes to/from the file are treated as ordinary memory accesses
- Simplifies and speeds file access by driving file I/O through memory rather than read() and write() system calls
- Also allows several processes to map the same file allowing the pages in memory to be shared
- But when does written data make it to disk?
  - Periodically and / or at file close() time
  - For example, when the pager scans for dirty pages

Memory-Mapped Files

- Some OSes uses memory mapped files for standard I/O
- Process can explicitly request memory mapping a file via mmap() system call
  - Now file mapped into process address space
- For standard I/O (open(), read(), write(), close()), mmap anyway
  - But map file into kernel address space
  - Process still does read() and write()
    - Copies data to and from kernel space and user space
  - Uses efficient memory management subsystem
    - Avoids needing separate subsystem
- COW can be used for read/write non-shared pages
- Memory mapped files can be used for shared memory (although again via separate system calls)

Allocating Kernel Memory

Allocating kernel memory

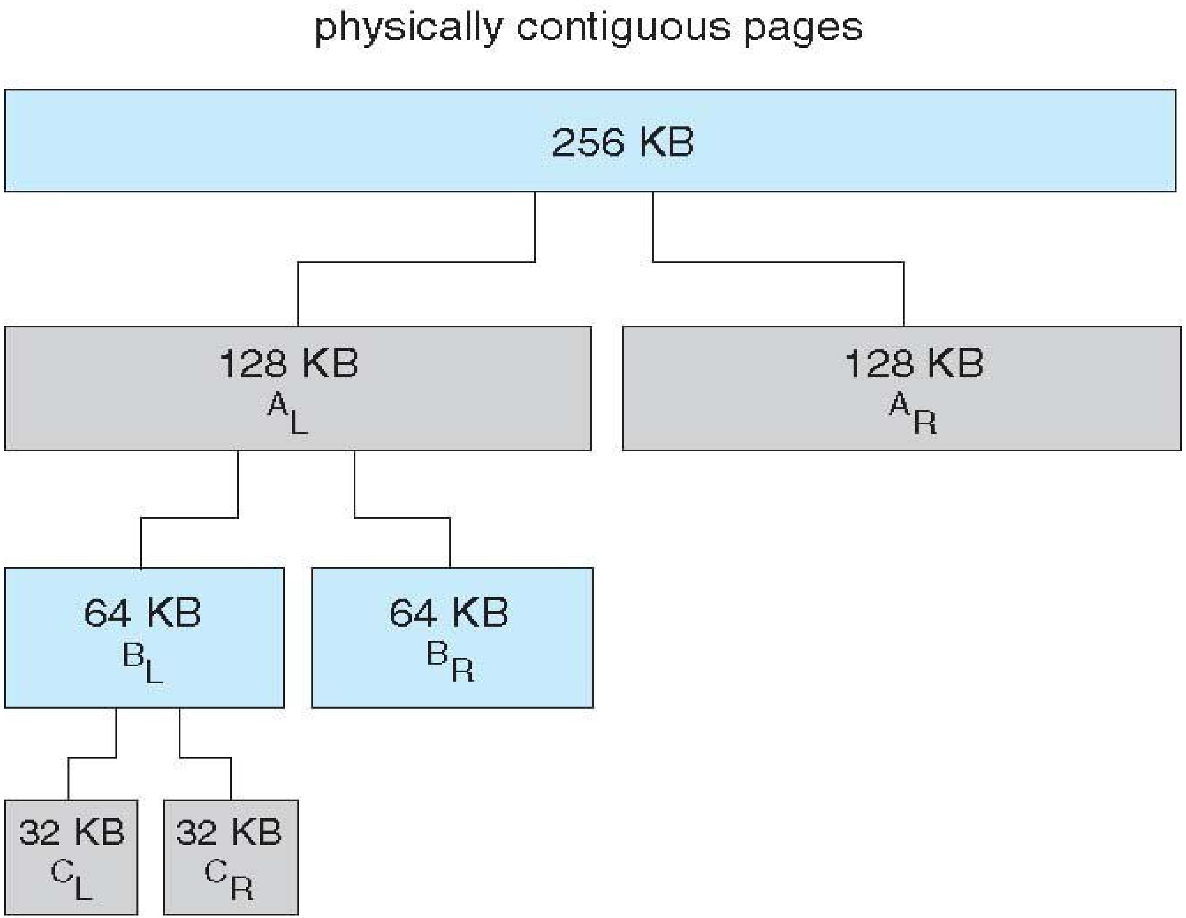
- Treated differently from user memory
- Often allocated from a free-memory pool

    Kernel requests memory for structures of varying sizes

    Some kernel memory needs to be contiguous

    I.e. for device I/O

Buddy Allocator



Buddy Allocator

- Allocates memory from fixed-size segment consisting of physically-contiguous pages
- Memory allocated using power-of-2 allocator

    Satisfies requests in units sized as power of 2

    Request rounded up to next highest power of 2

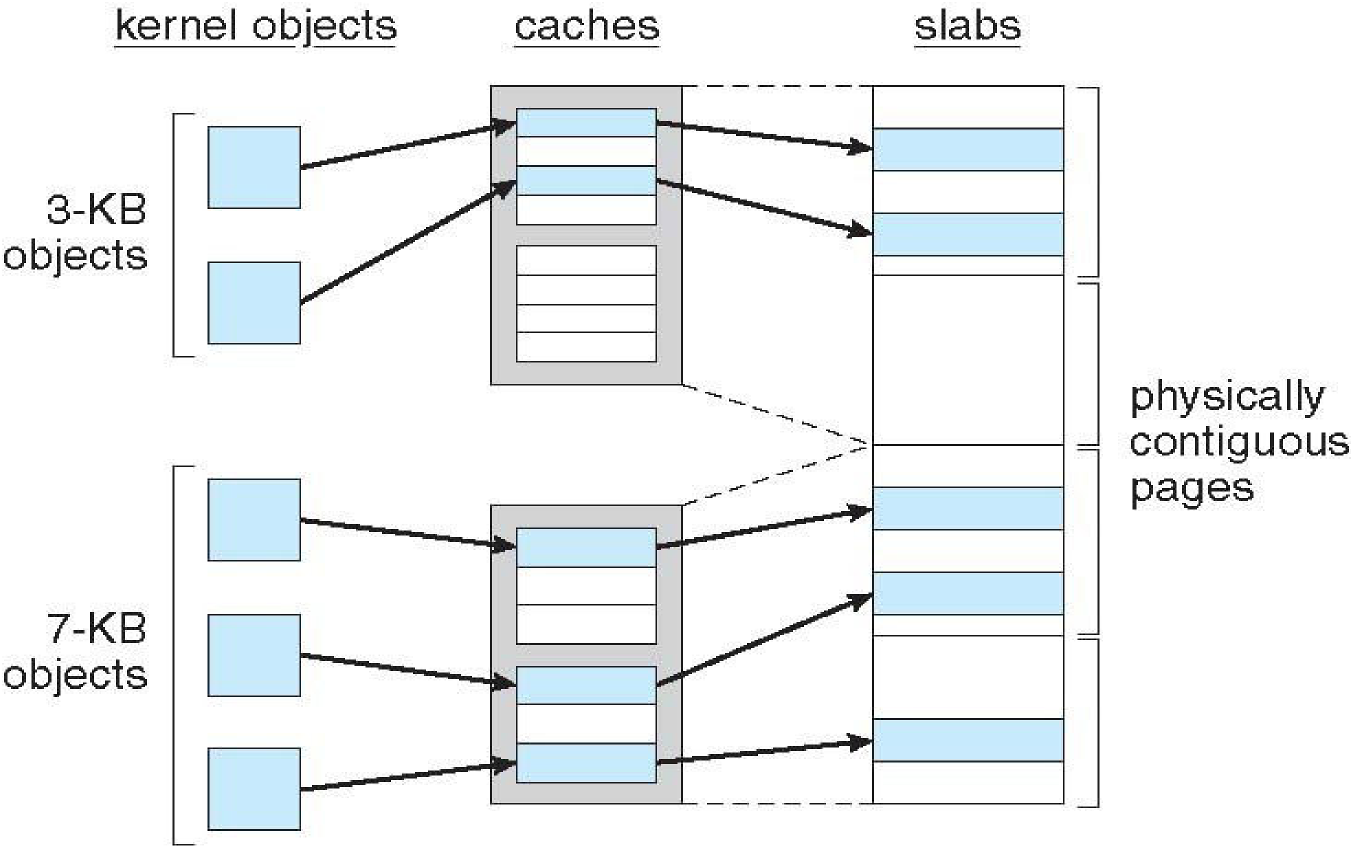
    When smaller allocation needed than is available, current chunk split into two buddies of next-lower power of 2

    Continue until appropriate sized chunk available

Buddy Allocator

- Continue until appropriate sized chunk available
- For example, assume 256KB chunk available, kernel requests 21KB
    - Split into AL and Ar of 128KB each
        - One further divided into BL and BR of 64KB
            - One further into CL and CR of 32KB each – one used to satisfy request
- Advantage – quickly coalesce unused chunks into larger chunk
- Disadvantage - fragmentation

Slab Allocator



Slab Allocator

- Alternate strategy
- **Slab** is one or more physically contiguous pages
- **Cache** consists of one or more slabs
- Single cache for each unique kernel data structure
  - Each cache filled with **objects** – instantiations of the data structure
- When cache created, filled with objects marked as **free**
- When structures stored, objects marked as **used**
- If slab is full of used objects, next object allocated from empty slab
  - If no empty slabs, new slab allocated
- Benefits include no fragmentation, fast memory request satisfaction

Other considerations

Other Considerations -- Prepaging

- To reduce the large number of page faults that occurs at process startup
- Prepage all or some of the pages a process will need, before they are referenced
- But if prepaged pages are unused, I/O and memory was wasted
- Assume s pages are prepaged and α of the pages is used

  Is cost of $s * \alpha$ save pages faults > or < than the cost of prepaging $s * (1- \alpha)$ unnecessary pages?

  α near zero --> prepaging loses

Page Size

- Sometimes OS designers have a choice
  - Especially if running on custom-built CPU
- Page size selection must take into consideration:
  - Fragmentation
  - Page table size
  - **Resolution**
  - I/O overhead
  - Number of page faults
  - Locality
  - TLB size and effectiveness
- Always power of 2, usually in the range 2^{12} (4,096 bytes) to 2^{22} (4,194,304 bytes)
- On average, growing over time

TLB Reach

- TLB Reach - The amount of memory accessible from the TLB
- TLB Reach = (TLB Size) X (Page Size)
- Ideally, the working set of each process is stored in the TLB

  Otherwise there is a high degree of page faults

- Increase the Page Size

  This may lead to an increase in fragmentation as not all applications require a large page size

- Provide Multiple Page Sizes

  This allows applications that require larger page sizes the opportunity to use them without an increase in fragmentation

Program Structure

- Program structure
- Int[128,128] data;
- Each row is stored in one page
- Program 1

```
for (j = 0; j <128; j++)
        for (i = 0; i < 128; i++)
        data[i,j] = 0;
```

128 x 128 = 16,384 page faults

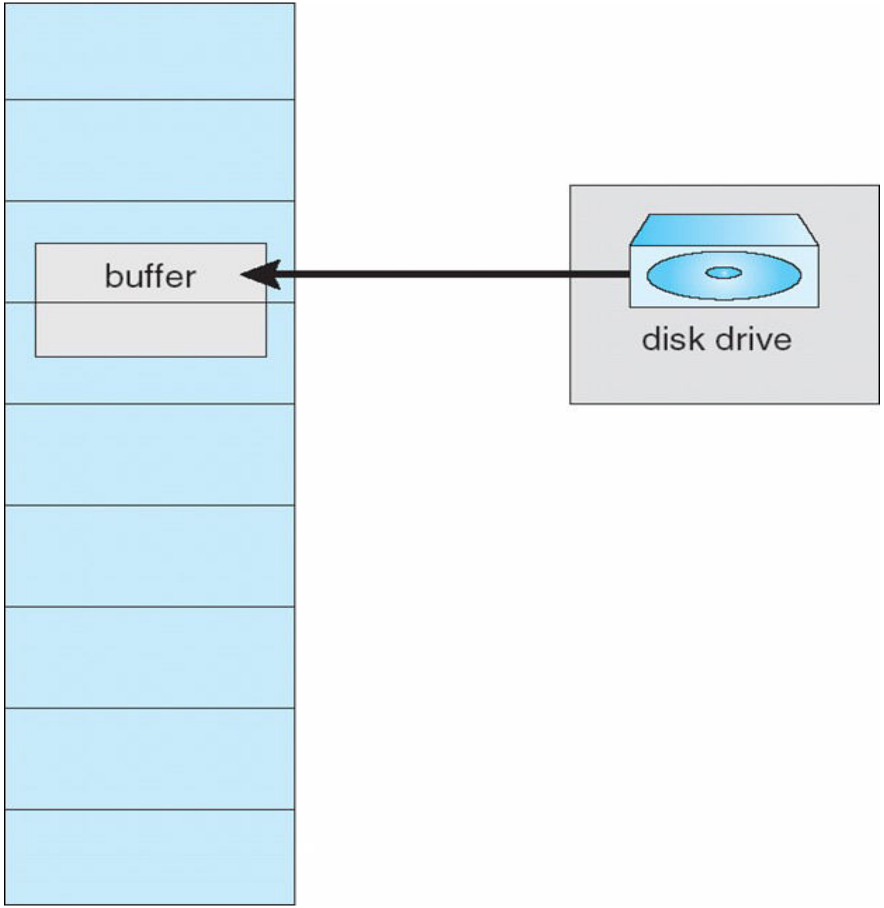
- Program 2

```
for (i = 0; i < 128; i++)
        for (j = 0; j < 128; j++)
        data[i,j] = 0;
```

128 page faults

I/O Interlock

- **I/O Interlock** – Pages must sometimes be locked into memory
- Consider I/O - Pages that are used for copying a file from a device must be locked from being selected for eviction by a page replacement algorithm



Threads, Signals

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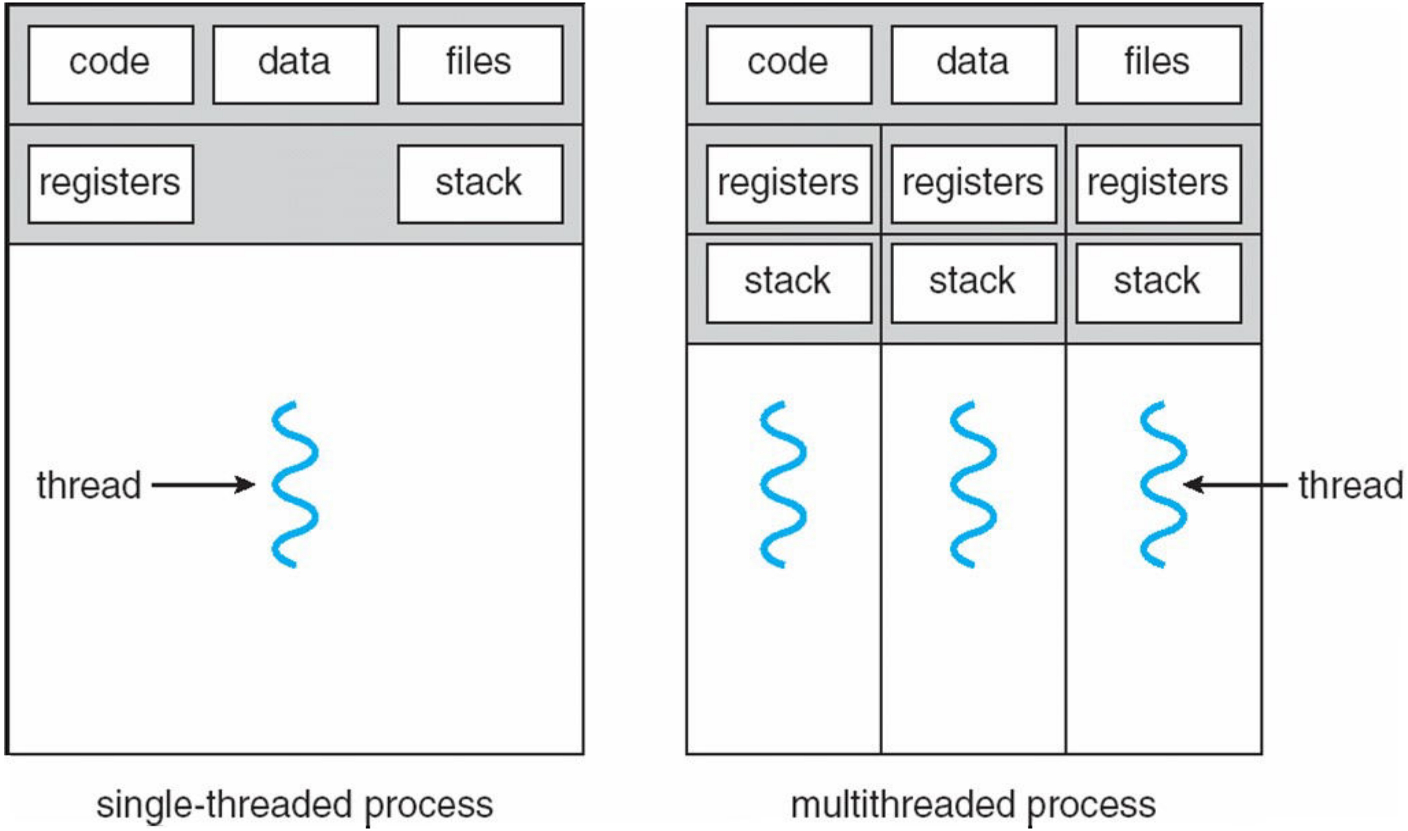
Threads

- **thread — a fundamental unit of CPU utilization**
  - A separate control flow within a program
  - set of instructions that execute “concurrently” with other parts of the code
  - Note the difference: Concurrency: progress at the same time, Parallel: execution at the same time
- **Threads run within application**
  - An application can be divided into multiple parts
  - Each part may be written to execute as a threads
- **Let’s see an example**

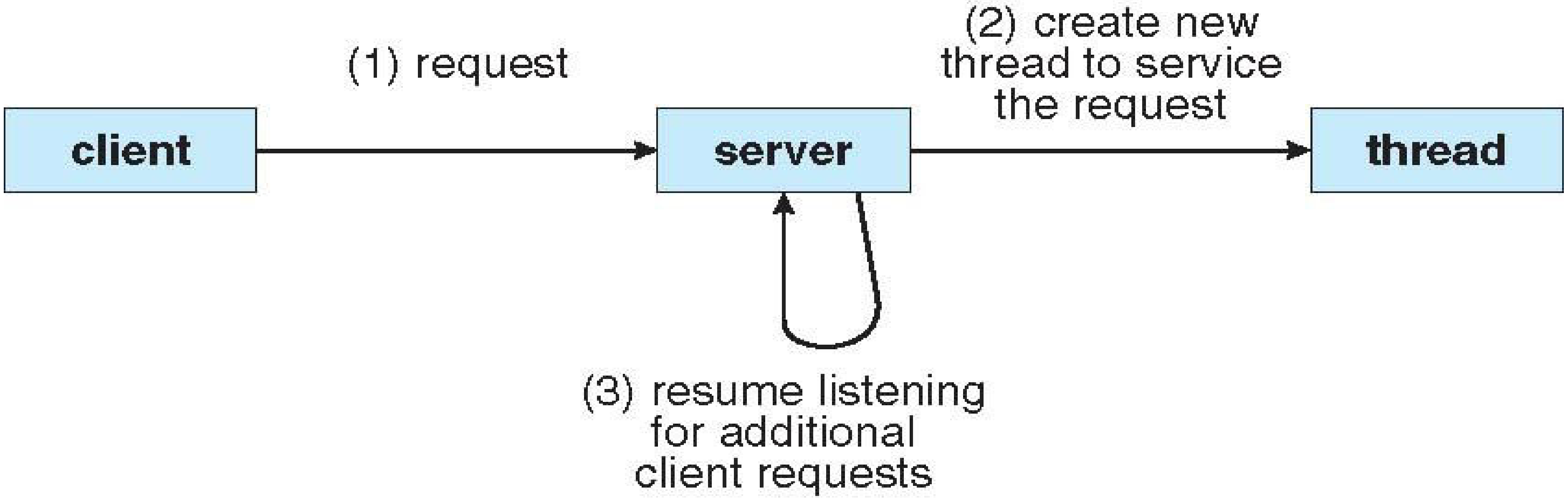
Threads

- **Multiple tasks with the application can be implemented by separate threads**
    - Update display
    - Fetch data
    - Spell checking
    - Answer a network request
- **Process creation is heavy-weight while thread creation is light-weight, due to the very nature of threads**
- **Can simplify code, increase efficiency**
- **Kernels are generally multithreaded**

Single vs Mulththreaded process



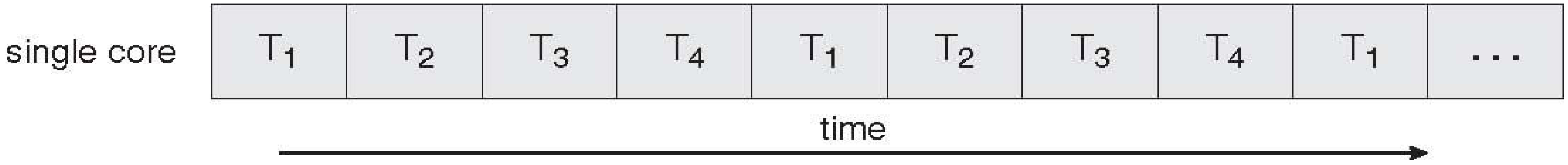
A mulththreaded server



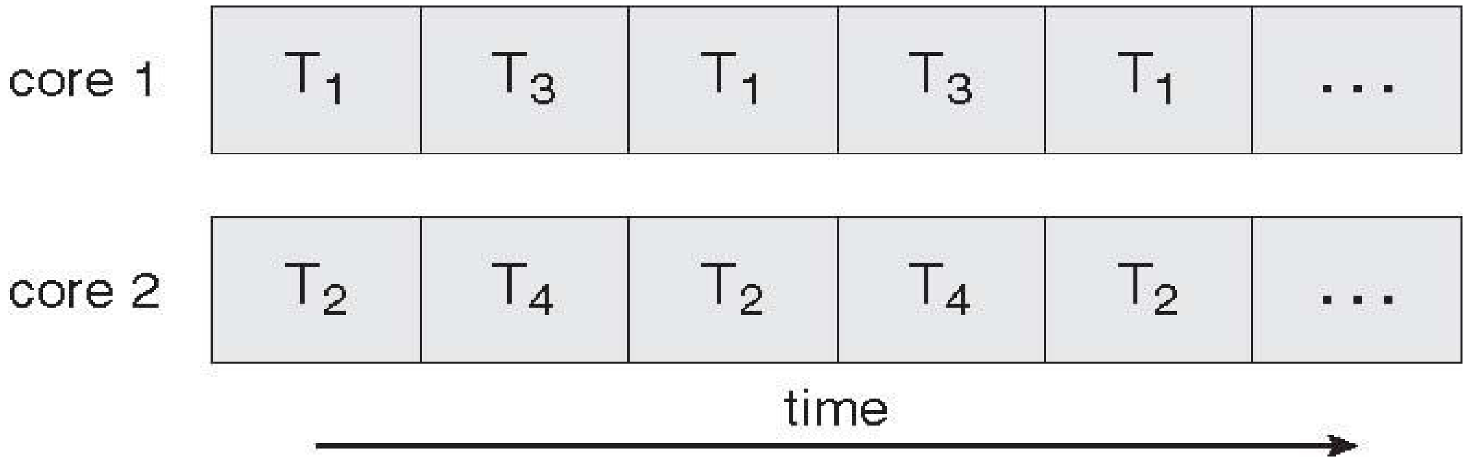
Benefits of threads

- Responsiveness
- Resource Sharing
- Economy
- Scalability

Single vs Multicore systems



Single core : Concurrency possible
Multicore : parallel execution possible



Multicore programming

- **Multicore systems putting pressure on programmers, challenges include:**
  - Dividing activities
  - Balance
  - Data splitting
  - Data dependency
  - Testing and debugging

User vs Kernel Threads

- **User Threads: Thread management done by user-level threads library**
- **Three primary thread libraries:**
  - POSIX Pthreads
  - Win32 threads
  - Java threads
- **Kernel Threads: Supported by the Kernel**
- **Examples**
  - Windows XP/2000
  - Solaris
  - Linux
  - Tru64 UNIX
  - Mac OS X

User threads vs Kernel Threads

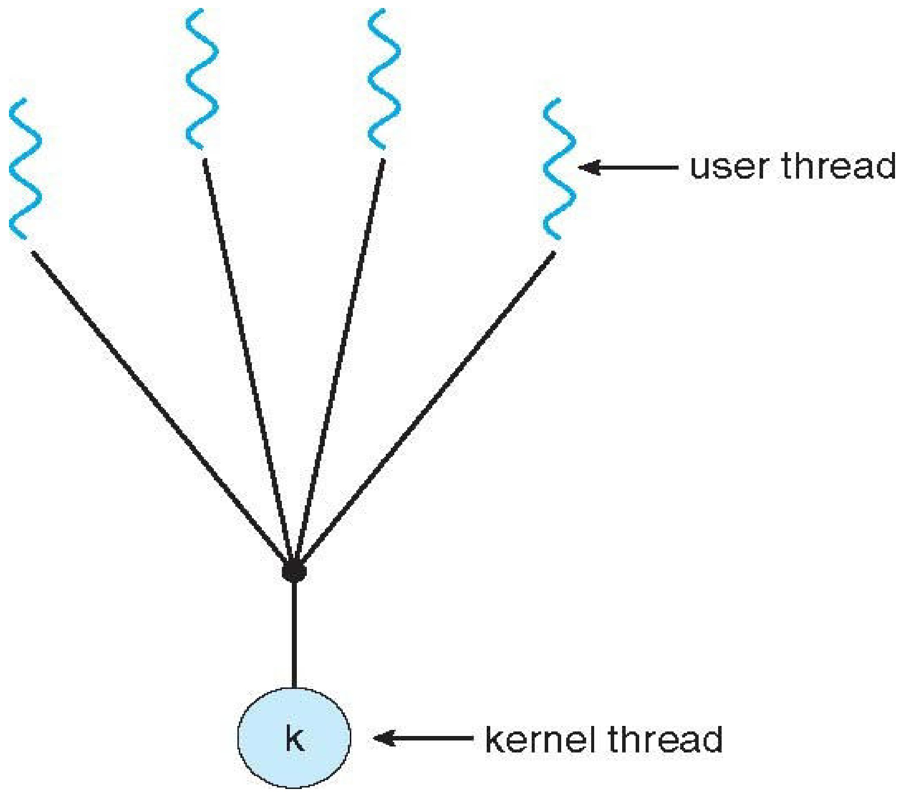
- **User threads**
  - User level library provides a “typedef” called threads
  - The scheduling of threads needs to be implemented in the user level library
  - Need some type of timer handling functionality at user level execution of CPU
    - OS needs to provide system calls for this
  - Kernel does not know that there are threads!

- **Kernel Threads**
  - Kernel implements concept of threads
  - Still, there may be a user level library, that maps kernel concept of threads to “user concept” since applications link with user level libraries
  - Kernel does scheduling!

Mulththreading models

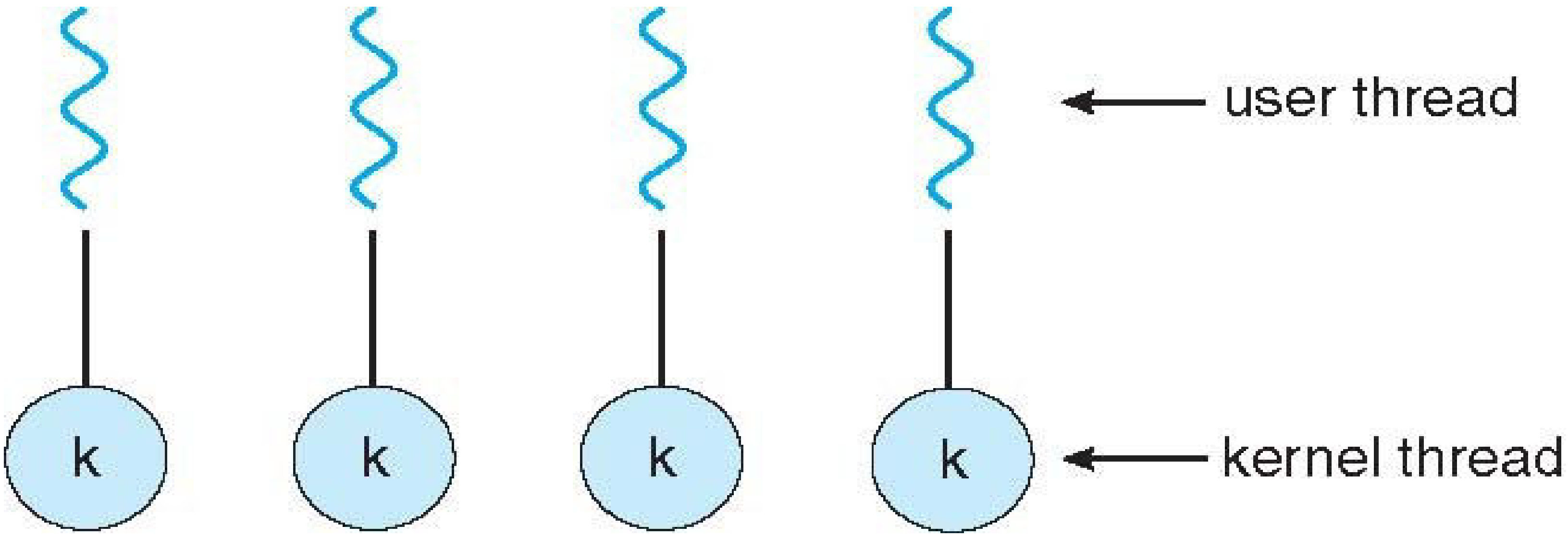
- **How to map user threads to kernel threads?**
  - Many-to-One
  - One-to-One
  - Many-to-Many
- **What if there are no kernel threads?**
  - Then only “one” process. Hence many-one mapping possible, to be done by user level thread library
  - Is One-One possible?

Many-One Model



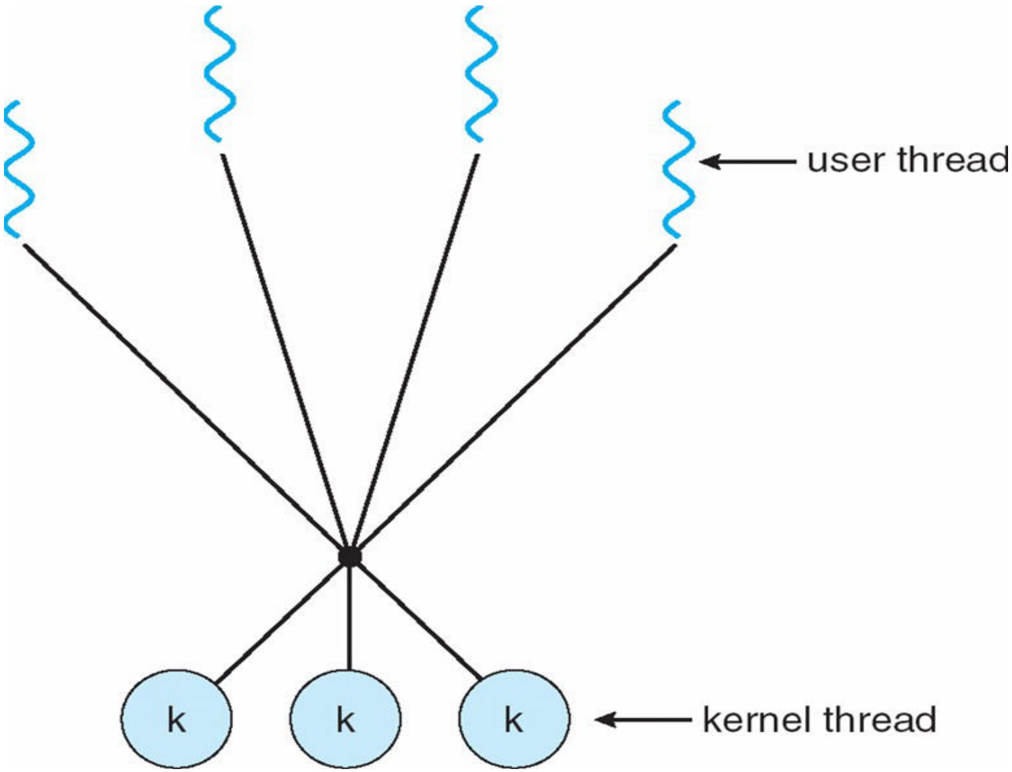
- **Many user-level threads mapped to single kernel thread**
- **Examples:**
  - Solaris Green Threads
  - GNU Portable Threads

One-One Model



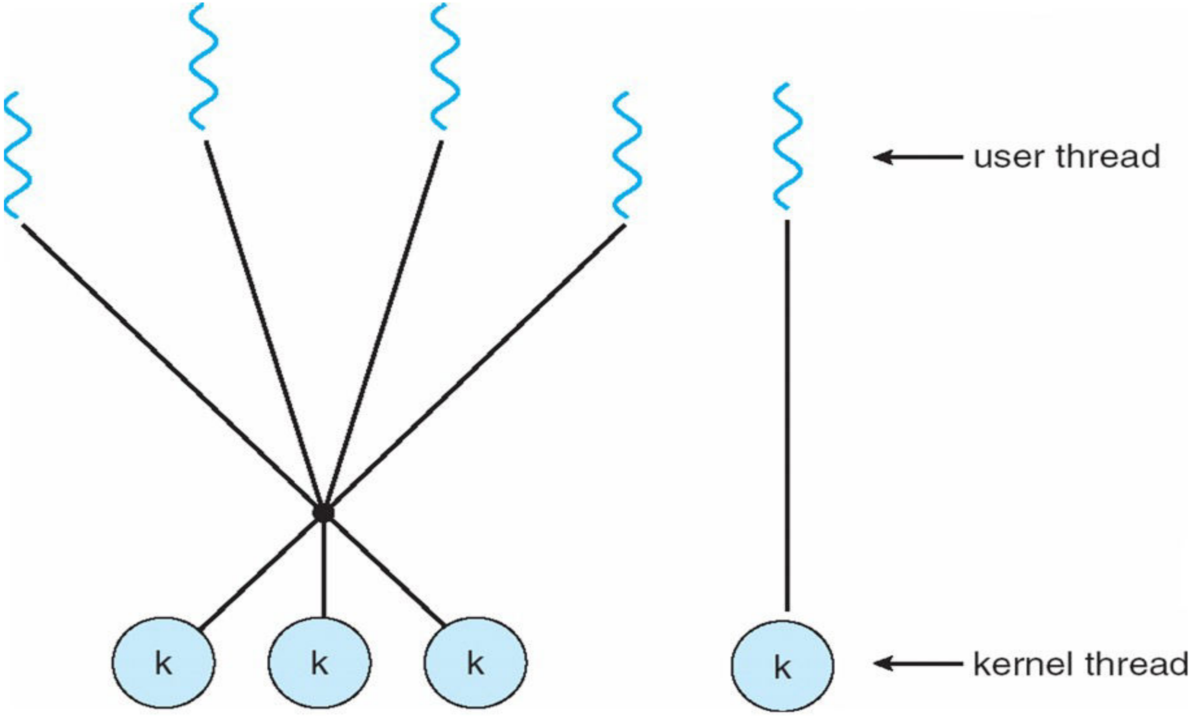
- **Each user-level thread maps to kernel thread**
- **Examples**
  - Windows NT/XP/2000
  - Linux
  - Solaris 9 and later

Many-Many Model



- Allows many user level threads to be mapped to many kernel threads
- Allows the operating system to create a sufficient number of kernel threads
- Solaris prior to version 9
- Windows NT/2000 with the ThreadFiber package

Two Level Model



- **Similar to M:M, except that it allows a user thread to be bound to kernel thread**
- **Examples**
  - IRIX
  - HP-UX
  - Tru64 UNIX
  - Solaris 8 and earlier

Thread Libraries

Thread libraries

- **Thread library provides programmer with API for creating and managing threads**
- **Two primary ways of implementing**
  - Library entirely in user space
  - Kernel-level library supported by the OS

pthreads

- May be provided either as user-level or kernel-level
- A POSIX standard (IEEE 1003.1c) API for thread creation and synchronization
- API specifies behavior of the thread library, implementation is up to development of the library
- Common in UNIX operating systems (Solaris, Linux, Mac OS X)

Demo of pthreads code

Demonstration on Linux – see the code, compile and execute it.

Other libraries

- **Windows threading API**
  - CreateThread(...)
  - WaitForSingleObject(...)
  - CloseHandle(...)
- **Java Threads**
  - The Threads class
  - The Runnable Interface

Issues with threads

- **Semantics of fork() and exec() system calls**
  - Does fork() duplicate only the calling thread or all threads?
- **Thread cancellation of target thread**
  - Terminating a thread before it has finished
  - Two general approaches:
    - Asynchronous cancellation terminates the target thread immediately.
    - Deferred cancellation allows the target thread to periodically check if it should be cancelled.

More on threads

Thread pools

- **Some kernels/libraries can provide system calls to : Create a number of threads in a pool where they await work, assign work/function to a waiting thread**
- **Advantages:**
  - Usually slightly faster to service a request with an existing thread than create a new thread
  - Allows the number of threads in the application(s) to be bound to the size of the pool

Thread Local Storage (TLS)

- **Thread-specific data, Thread Local Storage (TLS)**
  - Not local, but global kind of data for all functions of a thread, more like “static” data
  - Create Facility needed for data private to thread
  - Allows each thread to have its own copy of data
  - Useful when you do not have control over the thread creation process (i.e., when using a thread pool)
  - gcc compiler provides the storage class keyword thread for declaring TLS data

```
int arr[16];
int f() {
a(); b(); c();
}
int g() {
x(); y();
}
int main() {
th_create(...,f,...);
th_create(...,g,...);
}
//arr is visible to all of them!
//need data for only f,a,b,c
//need data for only g,x,y
```

Scheduler activations for threads

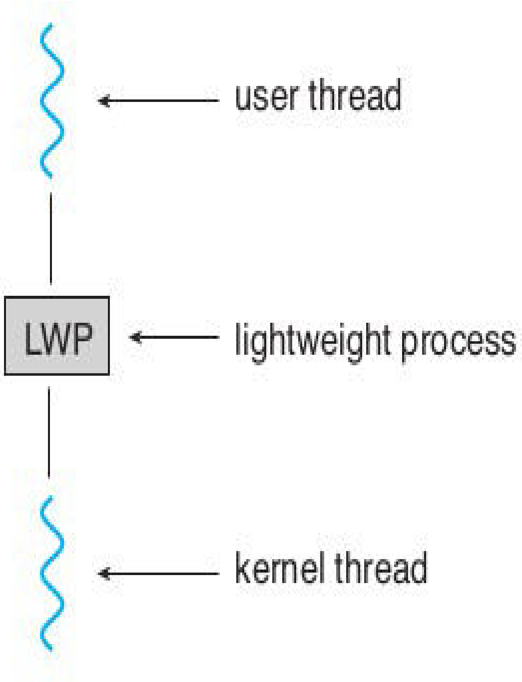
```
Library
--
th_setup(int n) {
max_threads = n;
curr_threads = 0;
}
th_create(...., fn,....) {
if(curr_threads < max_threads)
create kernel thread;
schedule fn on one of the kernel threads;
}
```

```
application
---
f() {
scanf();
}
g() {
recv();
}
h() {...}; i() {...}
main()
th_setup(2);
th_create(...,f,...);
th_create(...,g,...);
th_create(...,h,...);
th_create(...,i,...);
}
```

Scheduler activations for threads

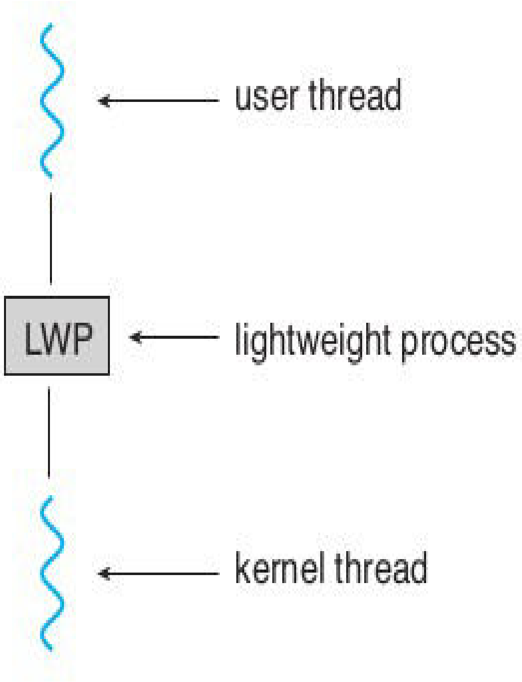
- **Scheduler Activations**
  - Both M:M and Two-level models require communication to maintain the appropriate number of kernel threads allocated to the application
  - Scheduler activations provide upcalls - a communication mechanism from the kernel to the thread library
  - This communication allows an application to maintain the correct number kernel threads

Issues with threads



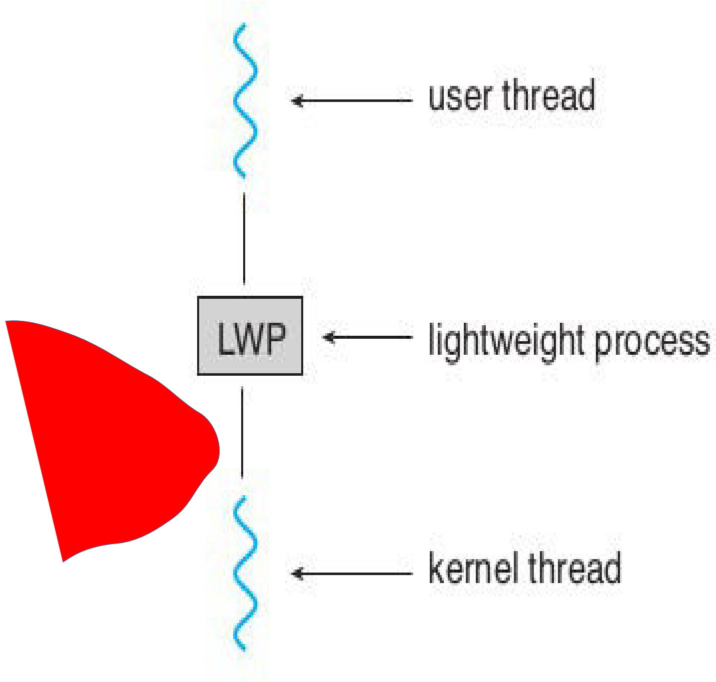
- **Scheduler Activations: LWP approach**
  - An intermediate data structure LWP
  - appears to be a virtual processor on which the application can schedule a user thread to run.
  - Each LWP attached to a kernel thread
  - Typically one LWP per blocking call, e.g. 5 file I/Os in one process, then 5 LWPs needed

Issues with threads



- **Scheduler Activations: LWP approach**
  - Kernel needs to inform application about events like: a thread is about to block, or wait is over
  - This will help application relinquish the LWP or request a new LWP

Issues with threads



- **The actual upcalls**

Linux threads

- Only threads (called task), no processes!
- Process is a thread that shares many particular resources with the parent thread
- Clone() system call to create a thread

Linux threads

- clone() takes options to determine sharing on process create
- struct task_struct points to process data structures (shared or unique depending on clone options)
- fork() is a wrapper on top of clone()

flag	meaning
CLONE_FS	File-system information is shared.
CLONE_VM	The same memory space is shared.
CLONE_SIGHAND	Signal handlers are shared.
CLONE_FILES	The set of open files is shared.

Issues in implementing threads project

- How to implement a user land library for threads?
- How to handle 1-1, many-one, many-many implementations?
- Identifying the support required from OS and hardware
- Identifying the libraries that will help in implementation

Issues in implementing threads project

- **Understand the clone() system call completely**
  - Try out various possible ways of calling it
  - Passing different options
  - Passing a user-land buffer as stack
- **How to save and restore context?**
  - C: setjmp, longjmp
  - Setcontext, getcontext(), makecontext(), swapcontext() functions
- **Sigaction is more powerful than signal**
  - Learn SIGALRM handling for timer and scheduler, timer_create() & timer_stop() system calls
- **Customized data structure to store threads, and manage thread-lists for scheduling**

Signals

Signals

- **Signals are used in UNIX systems to notify a process that a particular event has occurred.**
- **Signal handling**
  - Synchronous and asynchronous
- **A signal handler (a function) is used to process signals**
  - Signal is generated by particular event
  - Signal is delivered to a process
  - Then, signal is “handled” by the handler

Signals

- **More about signals**
  - Different signals are typically identified as different numbers
  - Operating systems provide system calls like kill() and signal() to enable processes to deliver and receive signals
  - Signal() - is used by a process to specify a “signal handler” – a code that should run on receiving a signal
  - Kill() is used by a process to send another process a signal
  - There are restrictions on which process can send which signal to other processes

Demo

- **Let's see a demo of signals with respect to processes**
- **Let's see signal.h**
  - /usr/include/signal.h
  - /usr/include/asm-generic/signal.h
  - /usr/include/linux/signal.h
  - /usr/include/sys/signal.h
  - /usr/include/x86_64-linux-gnu/asm/signal.h
  - /usr/include/x86_64-linux-gnu/sys/signal.h
- **man 7 signal**
- **Important signals: SIGKILL, SIGUSR1, SIGSEGV, SIGALRM, SIGCLD, SIGINT, SIGPIPE, ...**

Signal handling by OS

Process 12323 {

signal(19, abcd);

}

OS: sys_signal {

Note down that process 12323 wants to handle signal number 19 with function abcd

}

Process P1 {

kill (12323, 19) ;

}

OS: sys_kill {

Note down in PCB of process 12323 that signal number 19 is pending for you.

}

When process 12323 is scheduled, at that time the OS will check for pending signals, and invoke the appropriate signal handler for a pending signal.

Threads and Signals

- **Signal handling Options:**
  - Deliver the signal to the thread to which the signal applies
  - Deliver the signal to every thread in the process
  - Deliver the signal to certain threads in the process
  - Assign a specific thread to receive all signals for the process

Creation of first process by kernel

Why first process needs ‘special’ treatment?

- **Normally process is created using fork()**
  - and typically followed by a call to exec()
- **Fork will use the PCB of existing process to create a new process**
  - as a clone
- **The first process has nothing to copy from!**
- **So it’s PCB needs to “built” by kernel code**

Why first process needs 'special' treatment?

- **XV6 approach**
  - Create the process as if it was created by "fork"
  - Ensure that the process starts in a call to "exec"
  - Let "Exec" do the rest of the JOB as expected
  - In this case exec() will call
    - exec("/init", NULL);
- **See the code of init.c**
  - opens console() device for I/O; dups 0 on 1 and 2!
    - Same device file for I/O
  - forks a process and execs ("sh") on it.

Why first process needs ‘special’ treatment?

- **What needs to be done ?**
  - Build struct proc by hand
  - How data structures (proc, stack, etc) are hand-crafted so that when kernel returns, the process starts in code of init

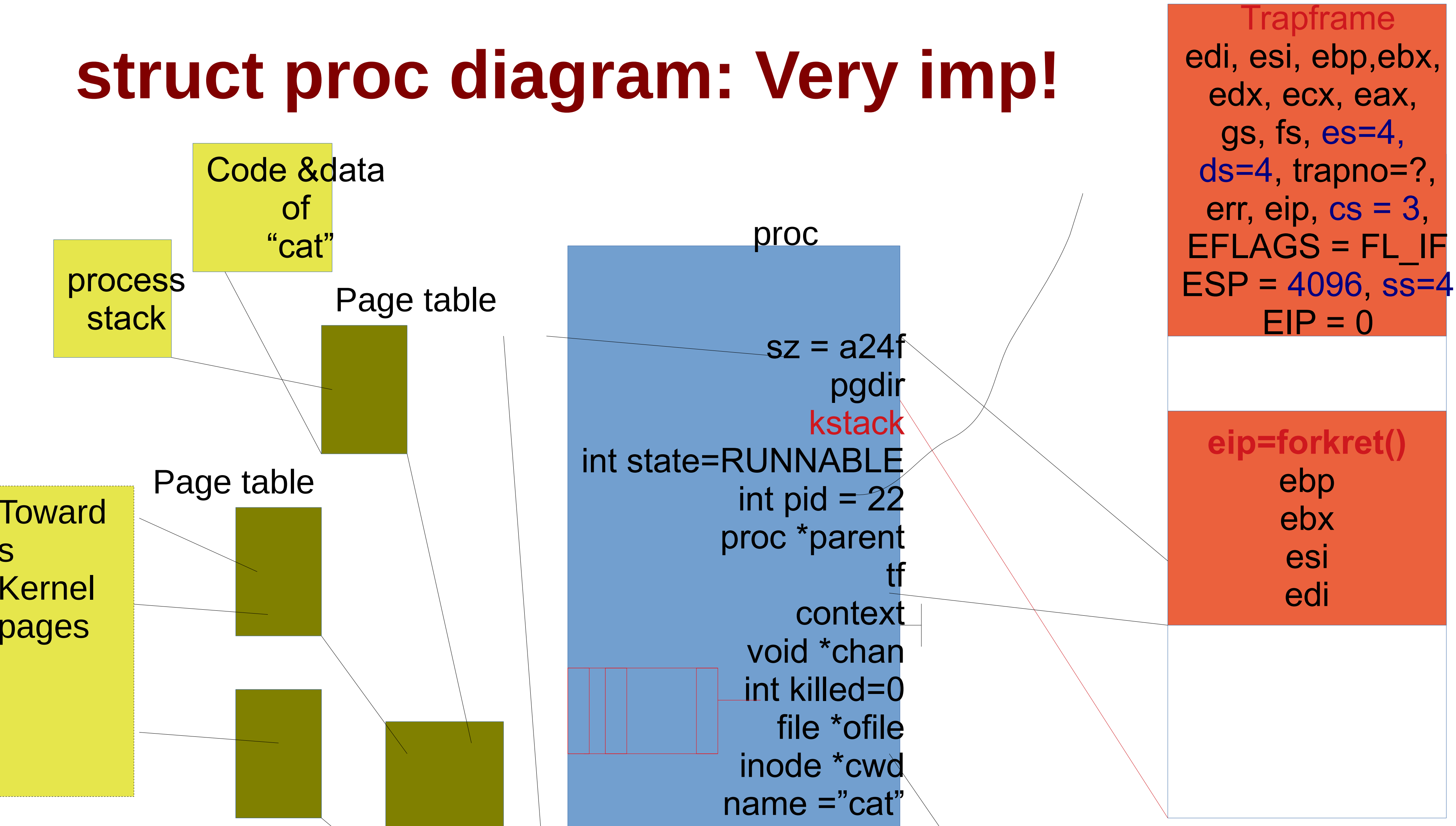
Imp Concepts

- **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

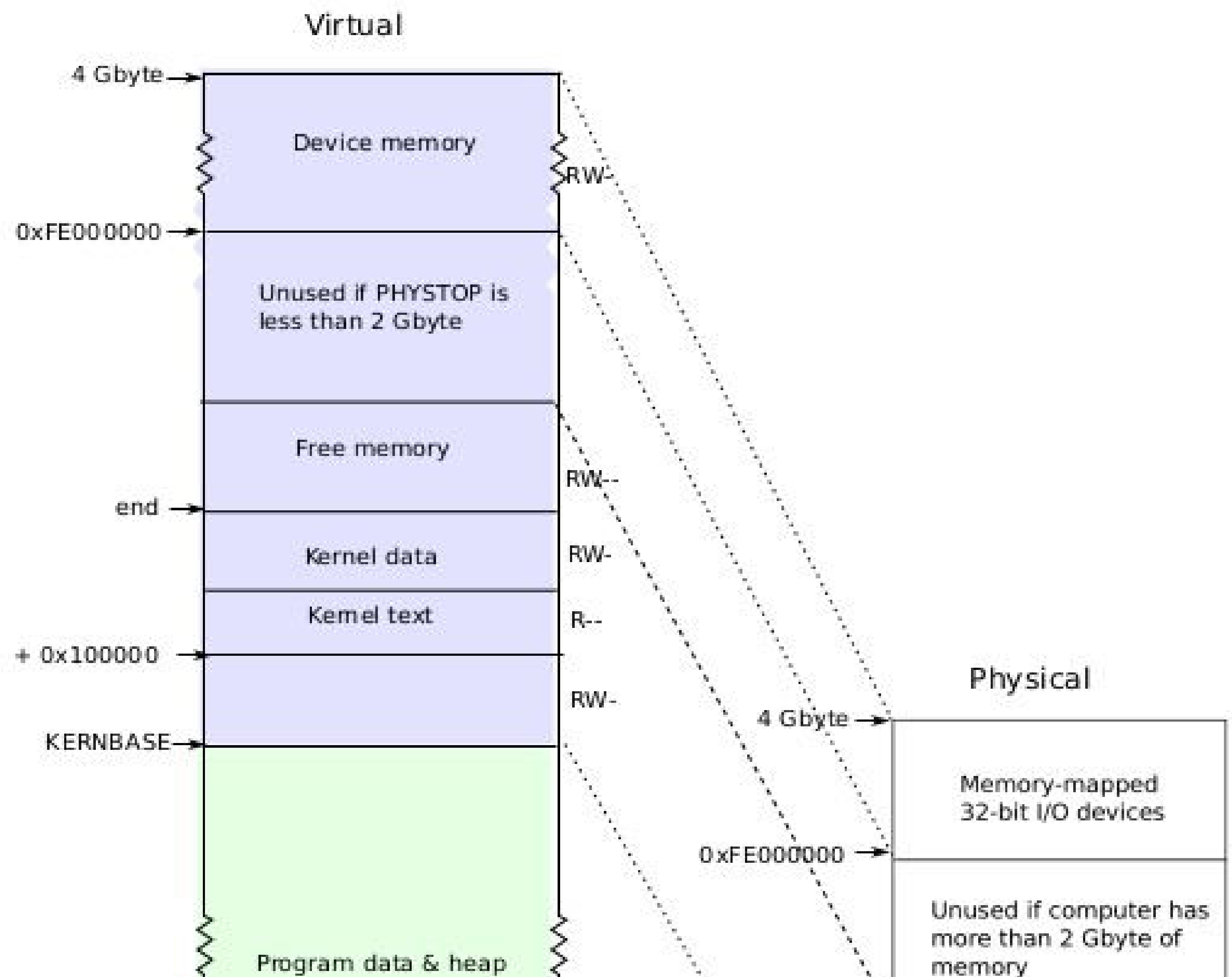
Imp Concepts

```
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
```

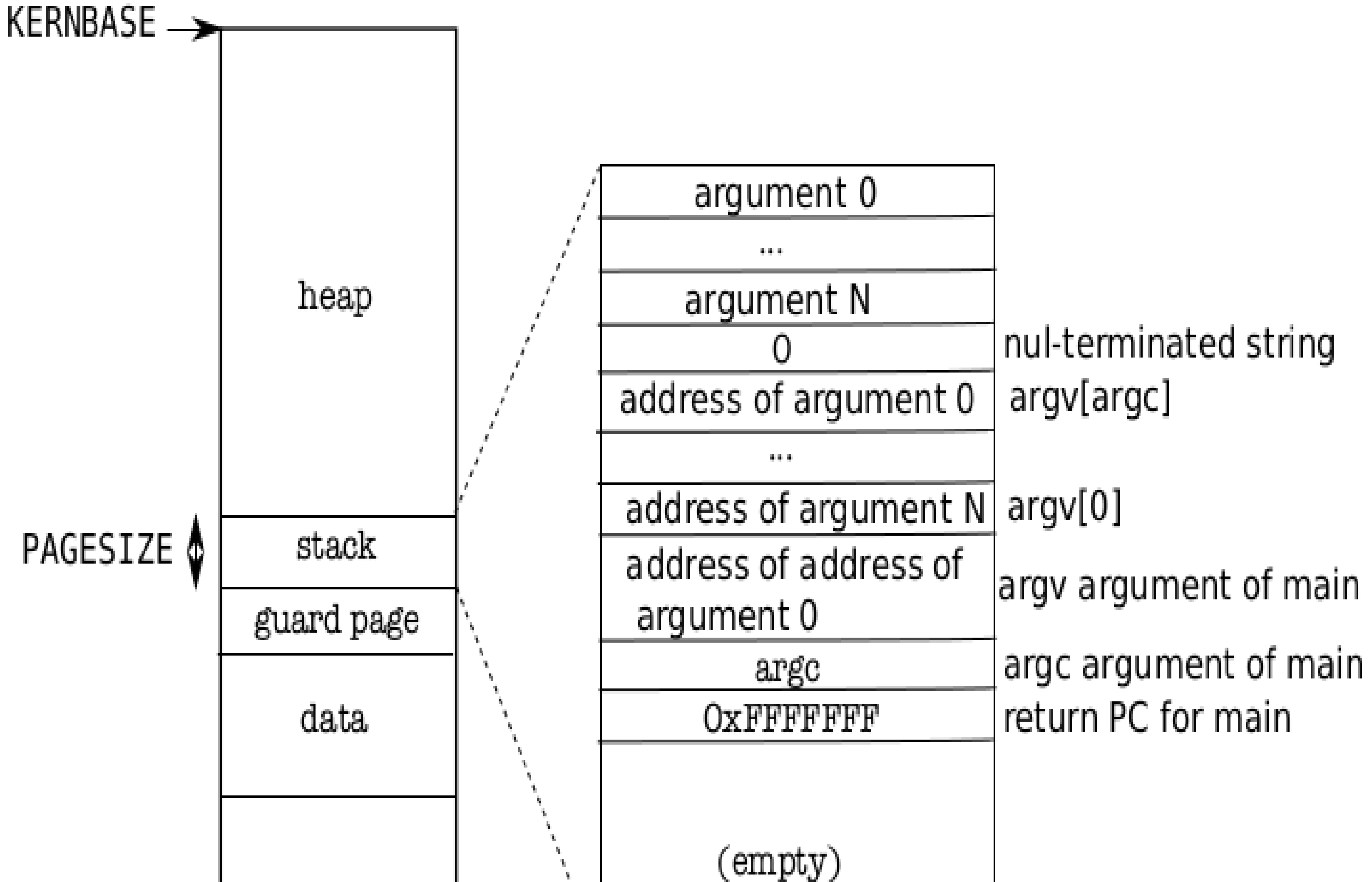
struct proc diagram: Very imp!



setupkvm()
does this mapping



These mappings



Memory Layout of a user process After exec()

Note the argc, argv on stack stack is just one page. size of text and data is derived from ELF file

main()->userinit()
Creating first process by hand

- **Code of the first process**
  - initcode.S and init.c
  - init.c is compiled into “/init” file
    - During make !
  - Trick:
    - Use initcode.S to “exec(“/init”)”
    - And let exec() do rest of the job
  - But before you do exec()

main()->userinit()
Creating first process by hand

```
void
userinit(void)
{
struct proc *p;
extern char _binary_initcode_start[], _binary_initcode_size[];
// Abhijit: obtain proc 'p', with stack initialized
// and trapframe created and eip set to 'forkret'
p = allocproc();
```

First process creation
Let’s revisit 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

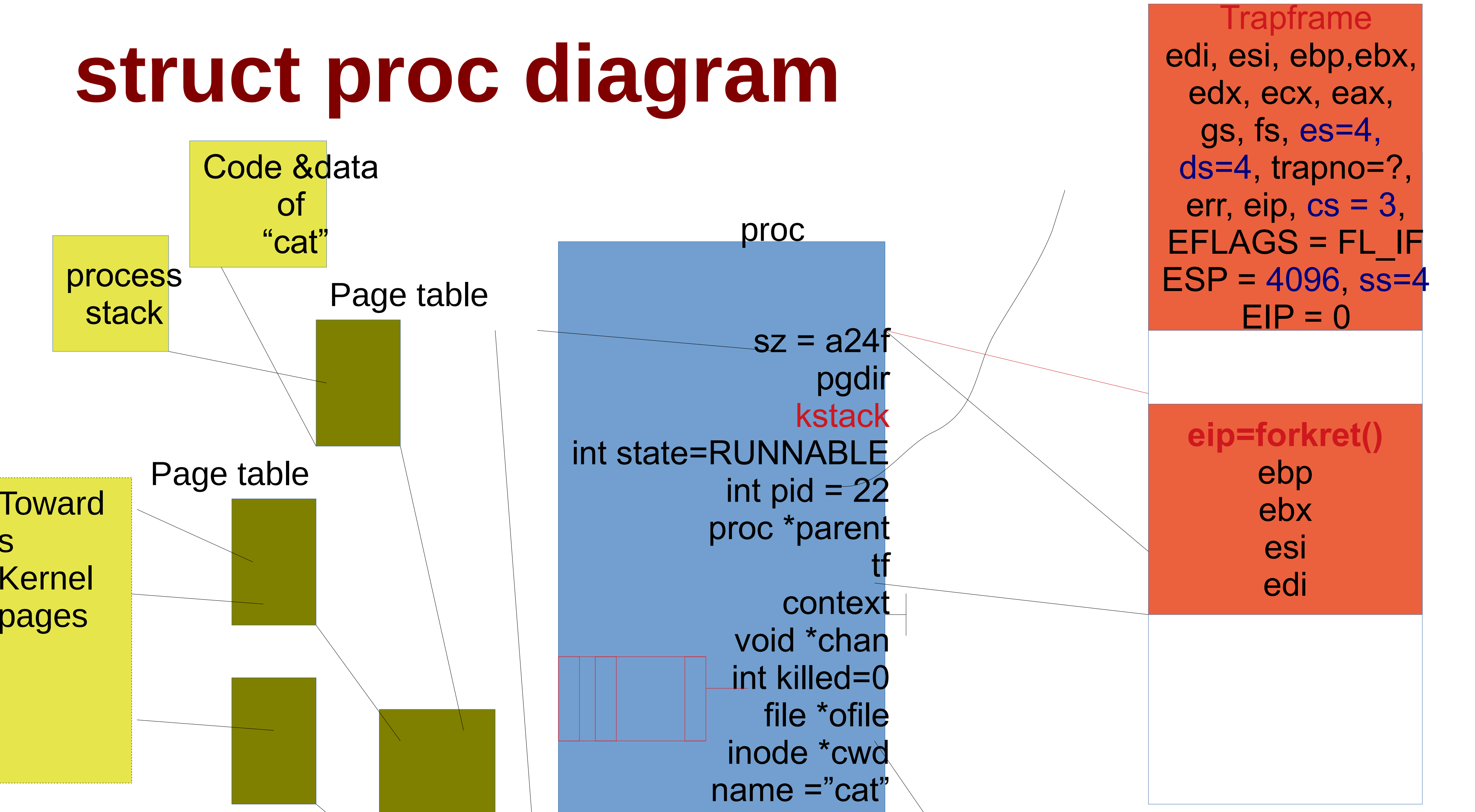
struct proc *parent; // Parent process

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

struct proc diagram



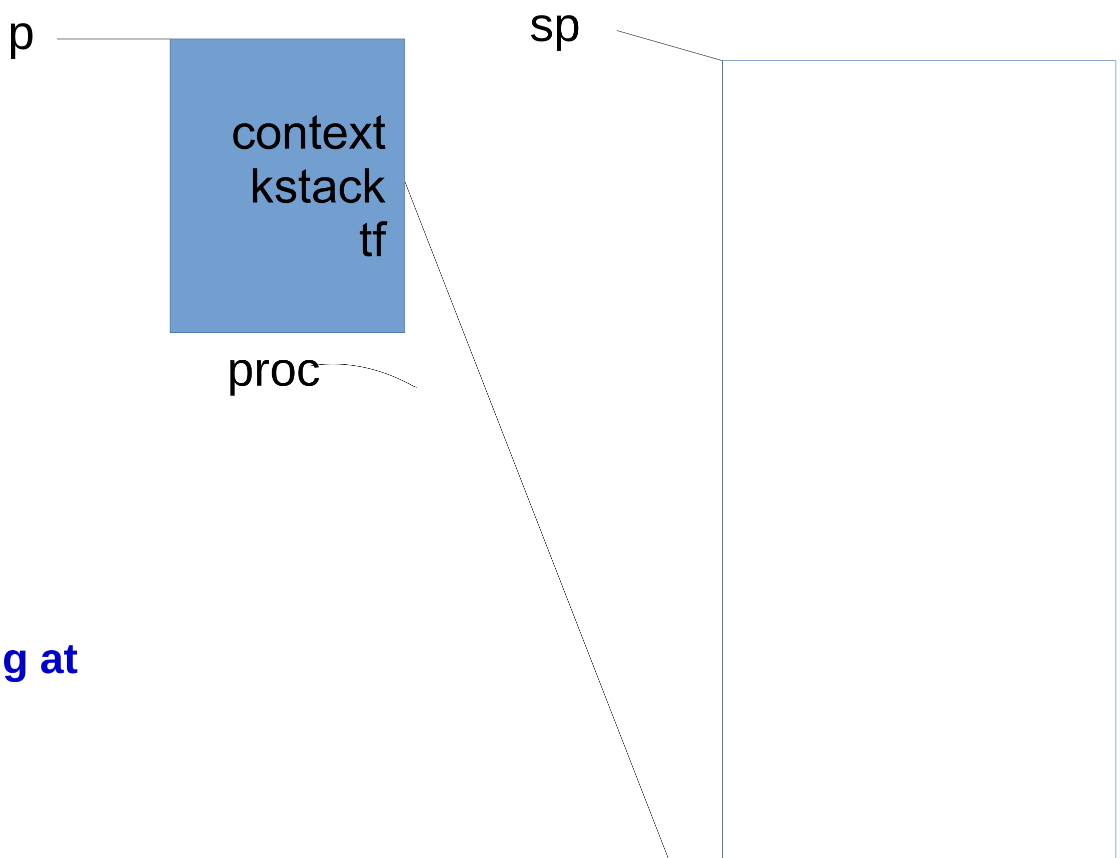
allocproc()

```
static struct proc*
allocproc(void)
{
struct proc *p;
char *sp;
acquire(&ptable.lock);
for(p = ptable.proc; p <
&ptable.proc[NPROC]; p++)
if(p->state == UNUSED)
goto found;
release(&ptable.lock);
```

```
found:
p->state = EMBRYO;
p->pid = nextpid++;
release(&ptable.lock);
```

allocproc() setting up stack

```
if((p->kstack = kalloc()) == 0){
p->state = UNUSED;
return 0;
}
sp = p->kstack + KSTACKSIZE;
// Abhijit KSTCKSIZE = PGSIZE
// Leave room for trap frame.
sp -= sizeof *p->tf;
p->tf = (struct trapframe*)sp;
// Set up new context to start executing at forkret,
// which returns to trapret.
sp -= 4;
```



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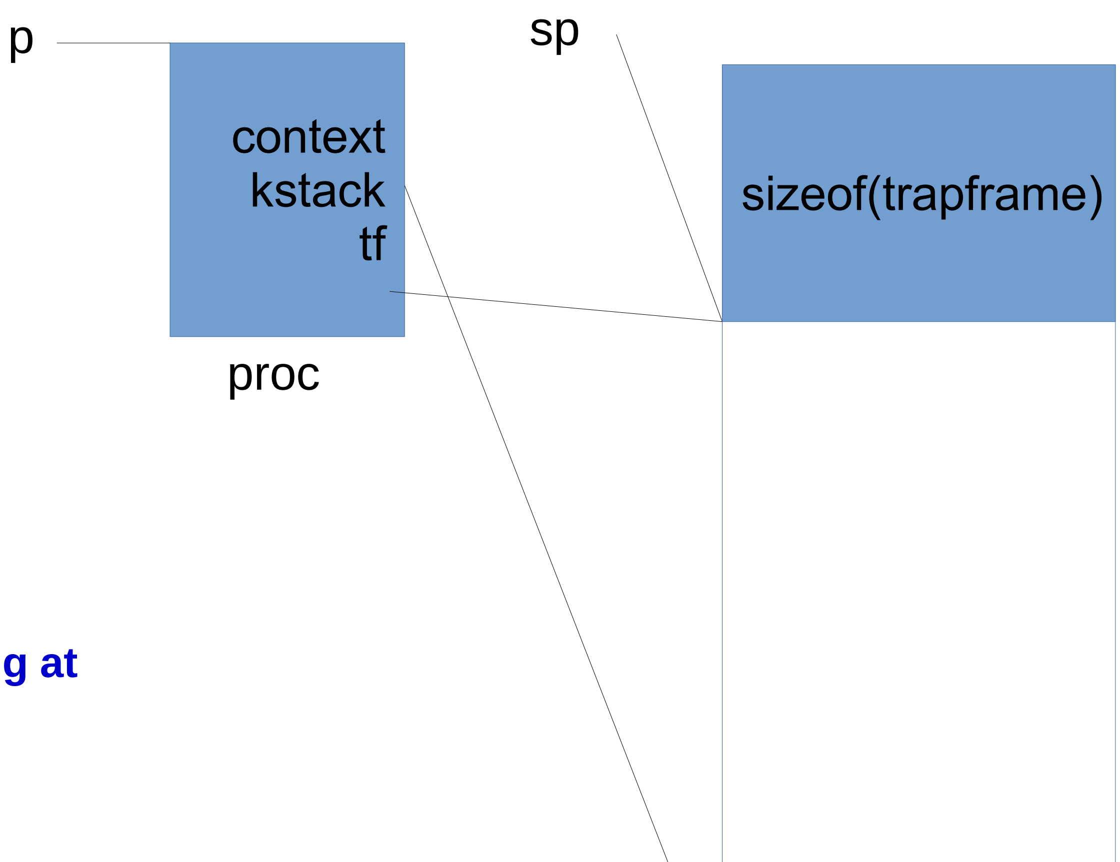
// Set up new context to start executing at forkret,
// which returns to trapret.
sp -= 4;
```



allocproc() setting up stack

```
if((p->kstack = kalloc()) == 0){
p->state = UNUSED;
return 0;
}
sp = p->kstack + KSTACKSIZE;
// Abhijit KSTCKSIZE = PGSIZE
// Leave room for trap frame.
sp -= sizeof *p->tf;
p->tf = (struct trapframe*)sp;
// Set up new context to start executing at forkret,
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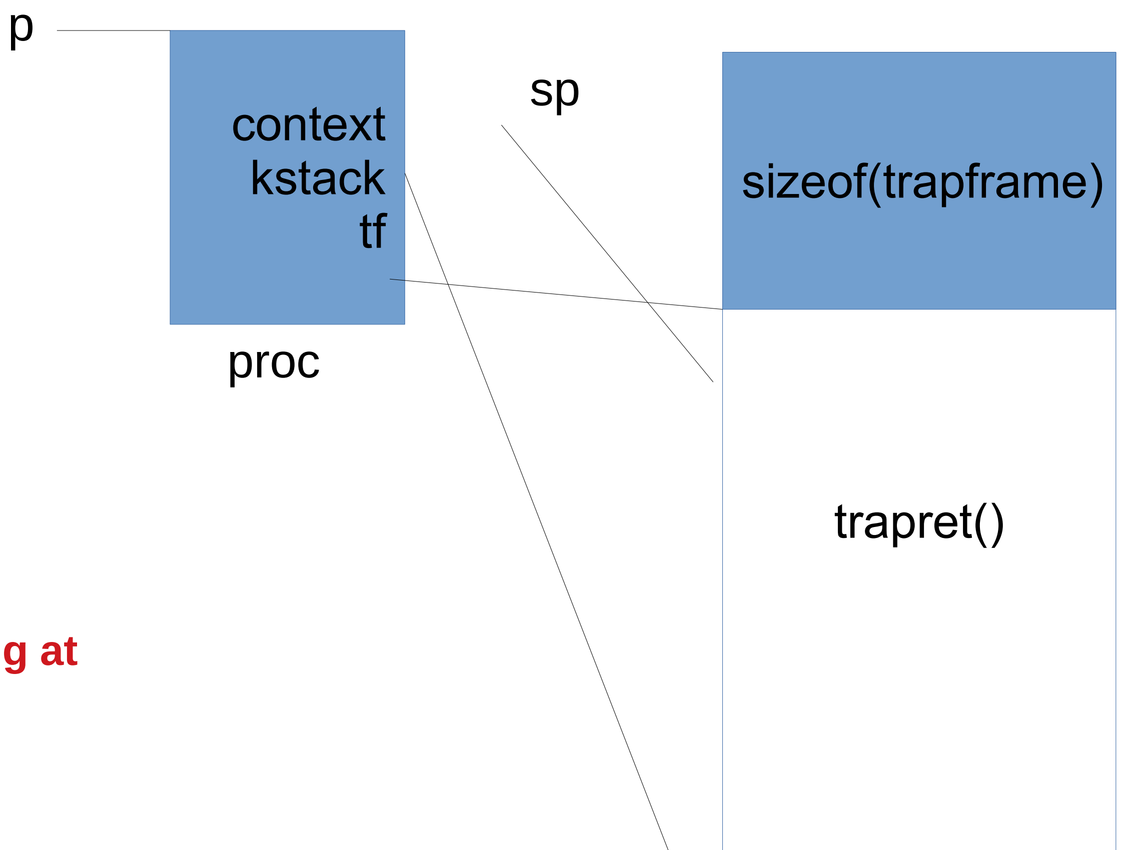
sp -= 4;
```



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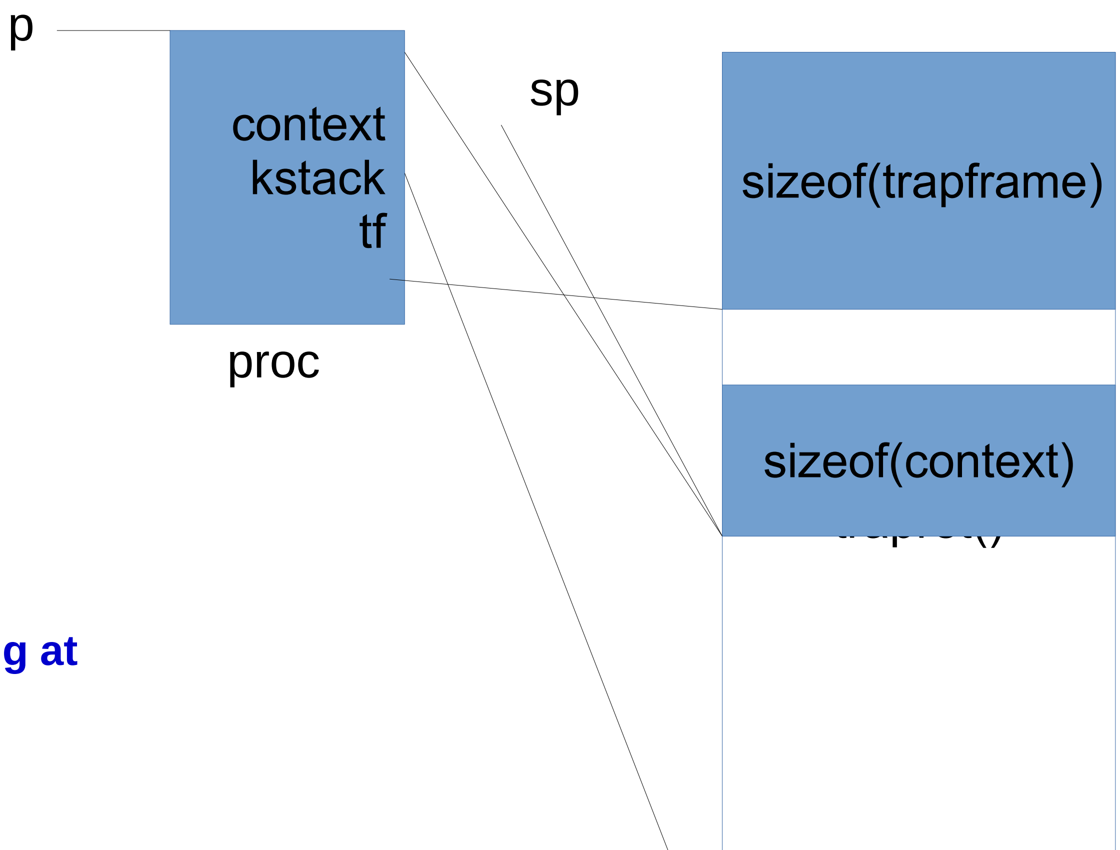

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forkret,
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sp -= 4;
```
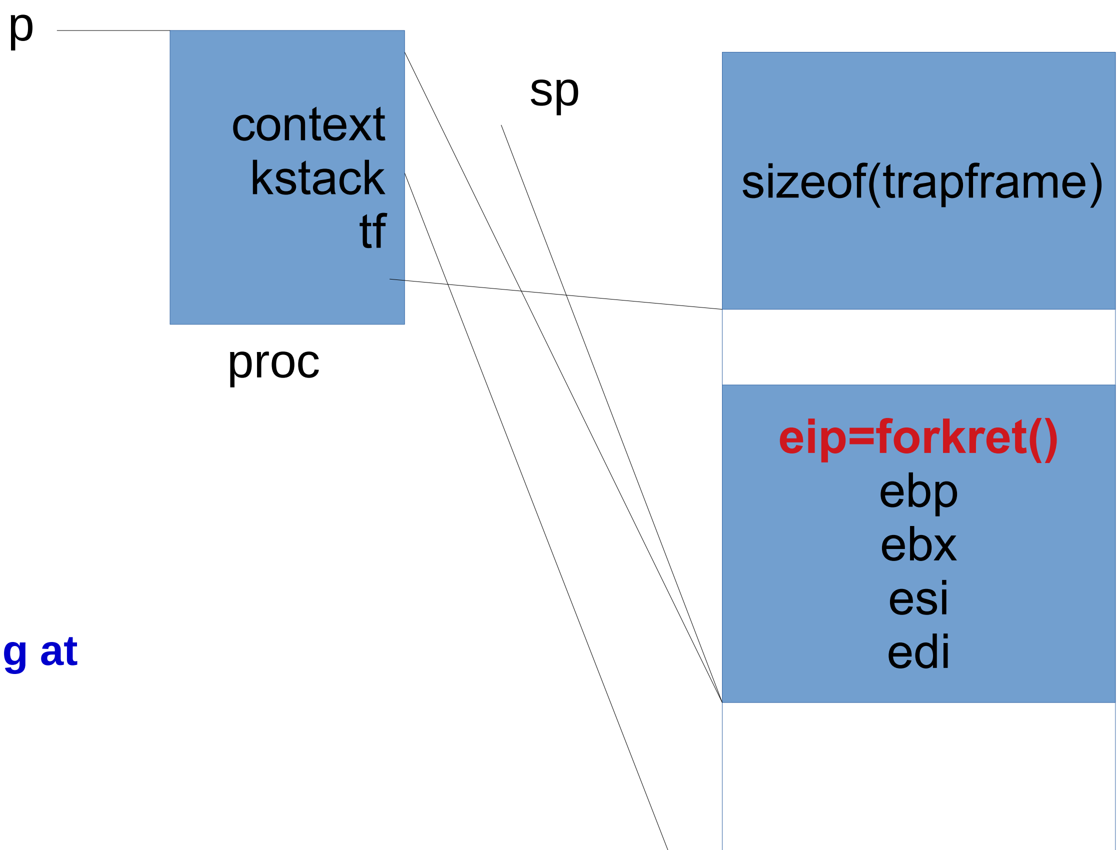
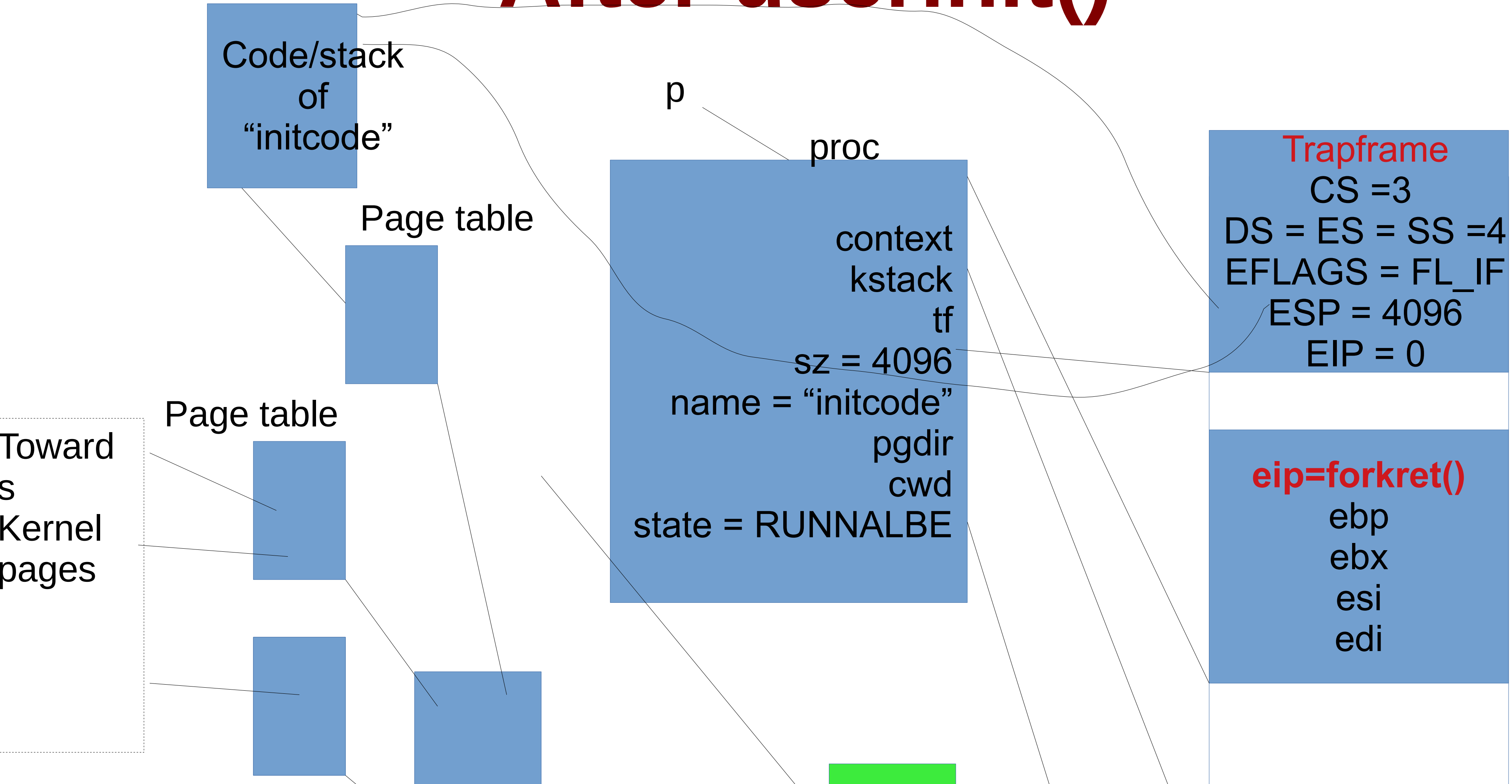



Next in userinit()

```
initproc = p;
if((p->pgdir = setupkvm()) == 0)
panic("userinit: out of memory?");
inituvm(p->pgdir, _binary_initcode_start, (int)_binary_initcode_size);
p->sz = PGSIZE;
memset(p->tf, 0, sizeof(*p->tf));
p->tf->cs = (SEG_UCODE << 3) | DPL_USER;
p->tf->ds = (SEG_UDATA << 3) |
```

```
p->tf->eflags = FL_IF;
p->tf->esp = PGSIZE;
p->tf->eip = 0; // beginning of initcode.S
safestrcpy(p->name, "initcode", sizeof(p->name));
p->cwd = namei("/");
acquire(&ptable.lock);
p->state = RUNNABLE;
release(&ptable.lock);
```

After userinit()



main()->mpmain()

```
static void
mpmain(void)
{
cprintf("cpu%d: starting %d\n", cpuid(), cpuid());
idtinit(); // load idt register
xchg(&(mycpu()->started), 1); // tell startothers() we're up
scheduler(); // start running processes
```

- **Load IDT register**
  - Copy from idt[] array into IDTR
- **Call scheduler()**
  - One process has already been made runnable
  - Let’s enter scheduler

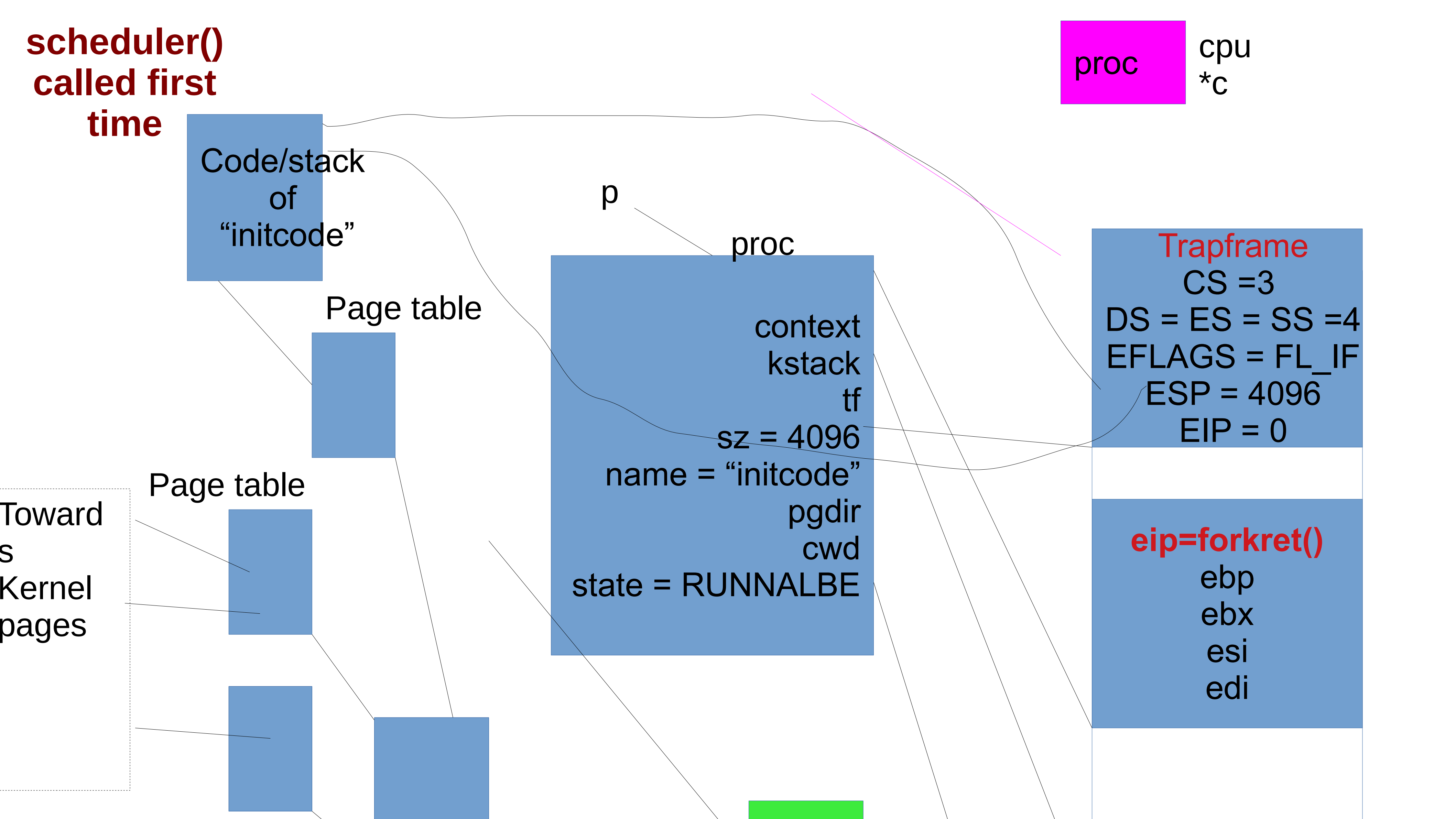
Before reading scheduler(): Note

- **The esp is still pointing to the stack which was allocated in entry.S !**
  - this is the kernel only stack
  - Not the per process kernel stack.
- **CR3 points to kpgdir**
- **Struct cpu[ ] has been setup up already**
  - apicid – in mpinit()
  - segdesc gdt – in seginit()

- **Fields in cpu[] not yet set**
  - context * scheduler --> will be setup in sched()
  - taskstate ts --> large structure, only parts used in switchuvm()
  - ncli, intena --> used while locking
  - proc *proc -> set during

scheduler()

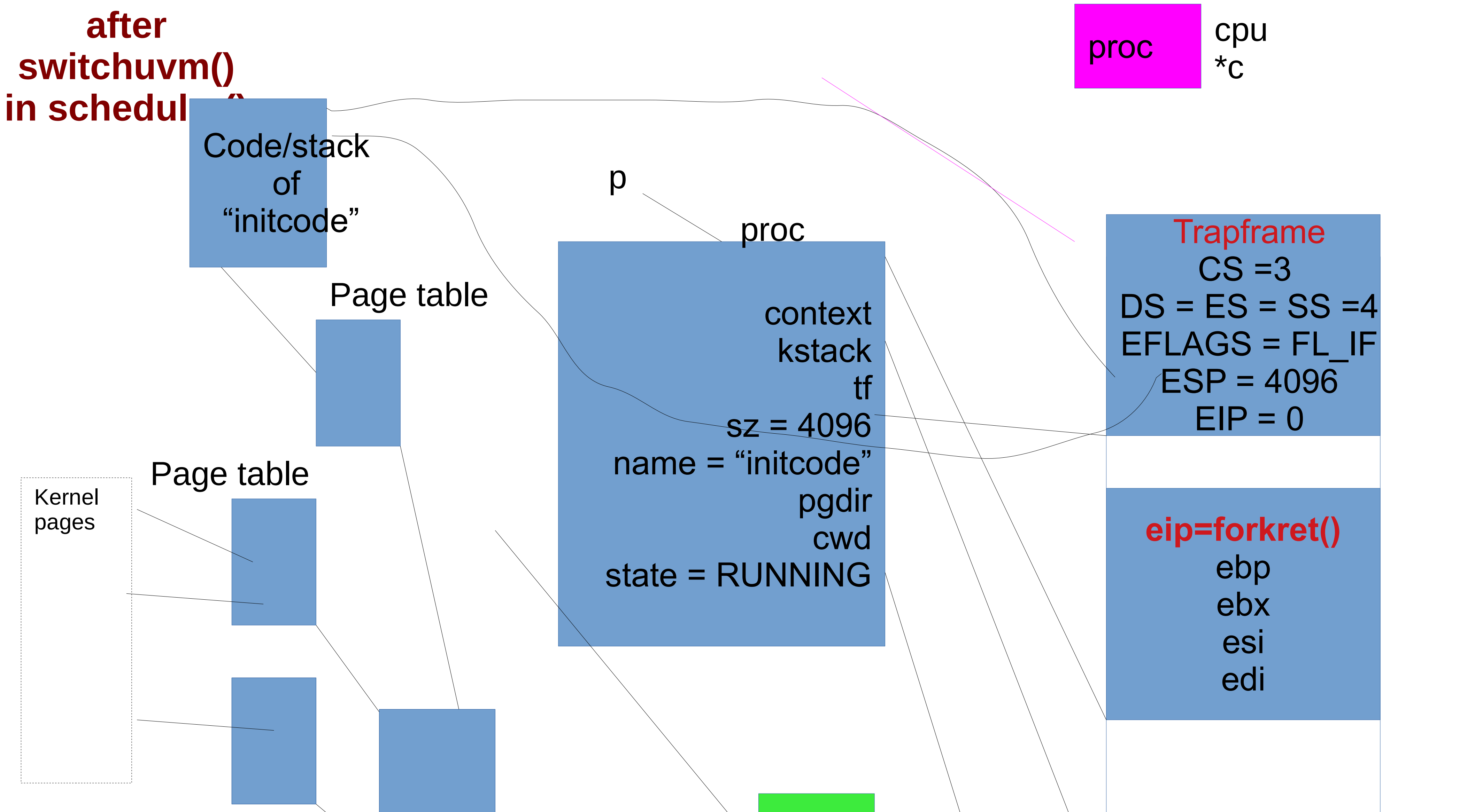
```
void
scheduler(void)
{
struct proc *p;
struct cpu *c = mycpu();
c->proc = 0;

for(;;){
sti();
// Loop over process table looking for process to run.
acquire(&ptable.lock);
for(p = ptable.proc; p < &ptable.proc[NPROC]; p++){
if(p->state != RUNNABLE)
continue;
// Switch to chosen process. It is the process's job
```



scheduler()
called first
time
proc
cpu
*c
Code/stack
of
“initcode”
p
proc
Page table
context
kstack
tf
sz = 4096
name = “initcode”
pgdir
cwd
state = RUNNALBE
Trapframe
CS =3
DS = ES = SS =4
EFLAGS = FL_IF
ESP = 4096
EIP = 0
eip=forkret()
ebp
ebx
esi
edi
Page table
Towards
Kernel
pages

scheduler()

```
acquire(&ptable.lock);
for(p = ptable.proc; p < &ptable.proc[NPROC]; p++){
if(p->state != RUNNABLE)
continue;
// Switch to chosen process. It is the process's job
// to release ptable.lock and then reacquire it
// before jumping back to us.
c->proc = p;
switchuvm(p);
p->state = RUNNING;
```

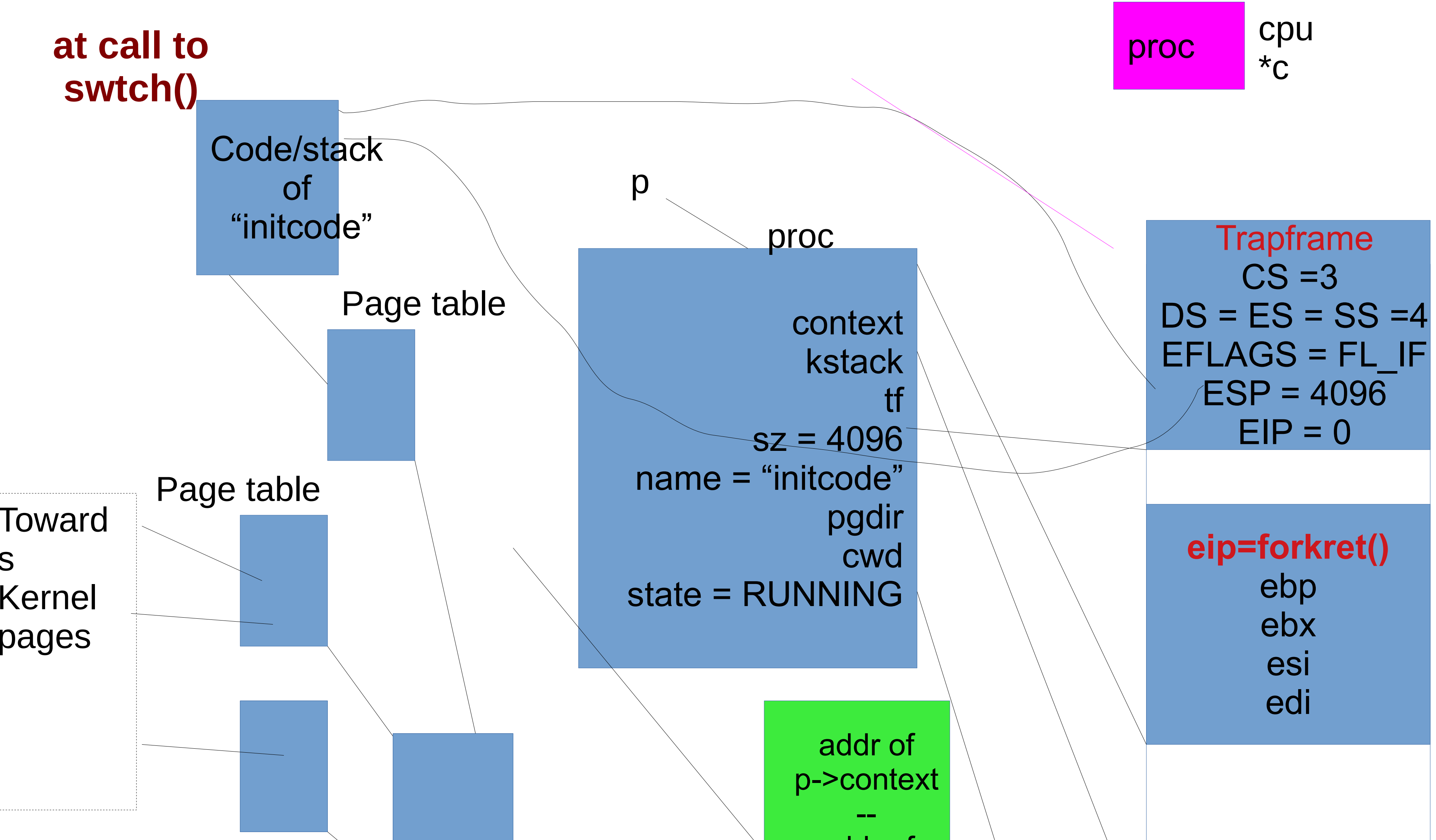


after
switchuvm()
in schedul...()
proc
cpu
*c
Code/stack
of
“initcode”
p
proc
Trapframe
CS =3
DS = ES = SS =4
EFLAGS = FL_IF
ESP = 4096
EIP = 0
Page table
context
kstack
tf
sz = 4096
name = “initcode”
pgdir
cwd
state = RUNNING
Page table
Kernel
pages
eip=forkret()
ebp
ebx
esi
edi

scheduler()

```
acquire(&ptable.lock);
for(p = ptable.proc; p < &ptable.proc[NPROC]; p++){
if(p->state != RUNNABLE)
continue;
// Switch to chosen process. It is the process's job
// to release ptable.lock and then reacquire it
// before jumping back to us.
c->proc = p;
switchuvm(p);
p->state = RUNNING
swtch(&(c->scheduler), p->context);
.
```

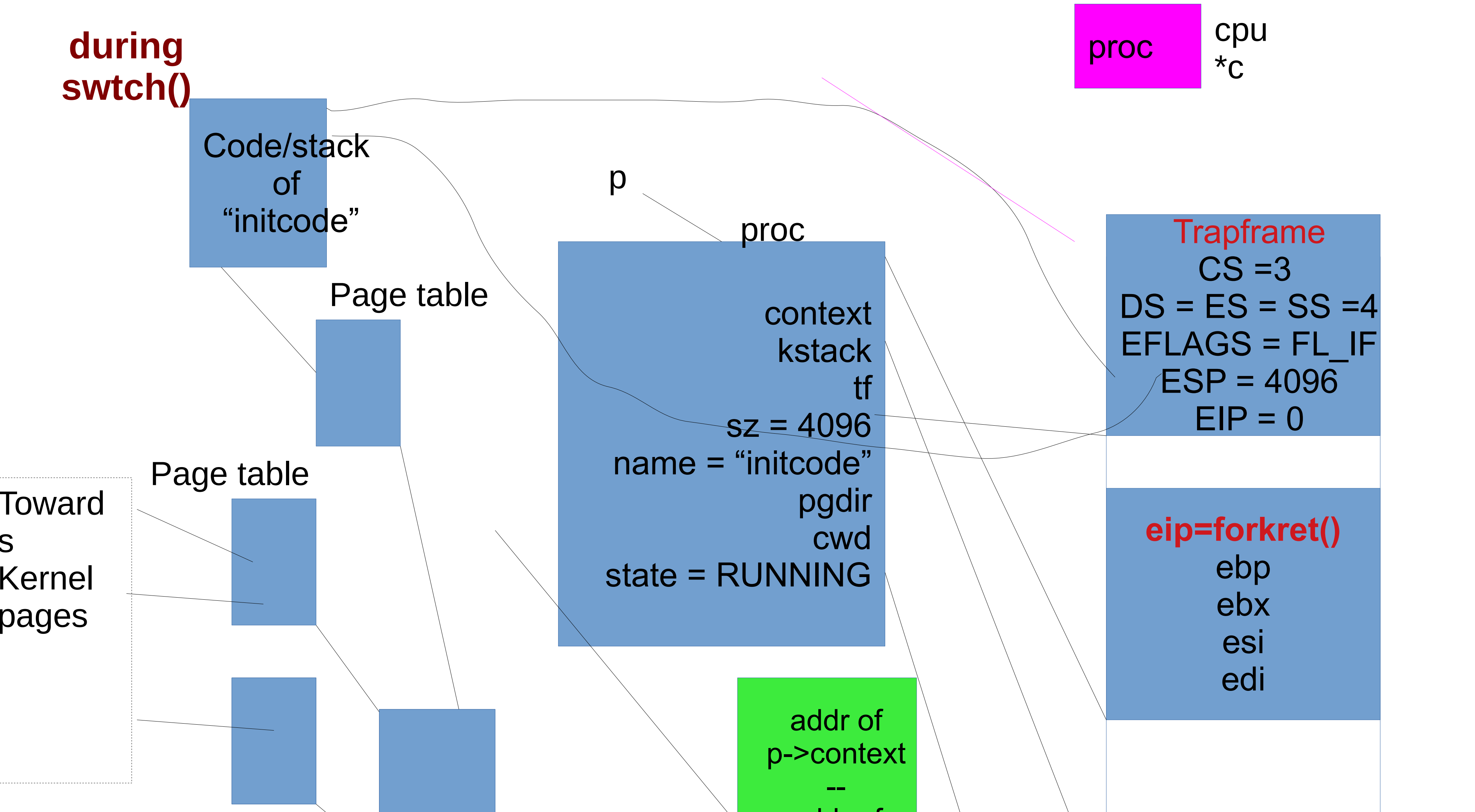
at call to swtch()



swtch

```
swtch:
#Abhijit: swtch was called through a function call.
#So %eip was saved on stack already
movl 4(%esp), %eax # Abhijit: eax = old
movl 8(%esp), %edx # Abhijit: edx = new
```

during swtch()



swtch

```
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#So %eip was saved on stack already
movl 4(%esp), %eax # Abhijit: eax = old
movl 8(%esp), %edx # Abhijit: edx = new
# Save old callee-saved registers
pushl %ebp
pushl %ebx
pushl %esi
pushl %edi # Abhijit: esp = esp + 16
```
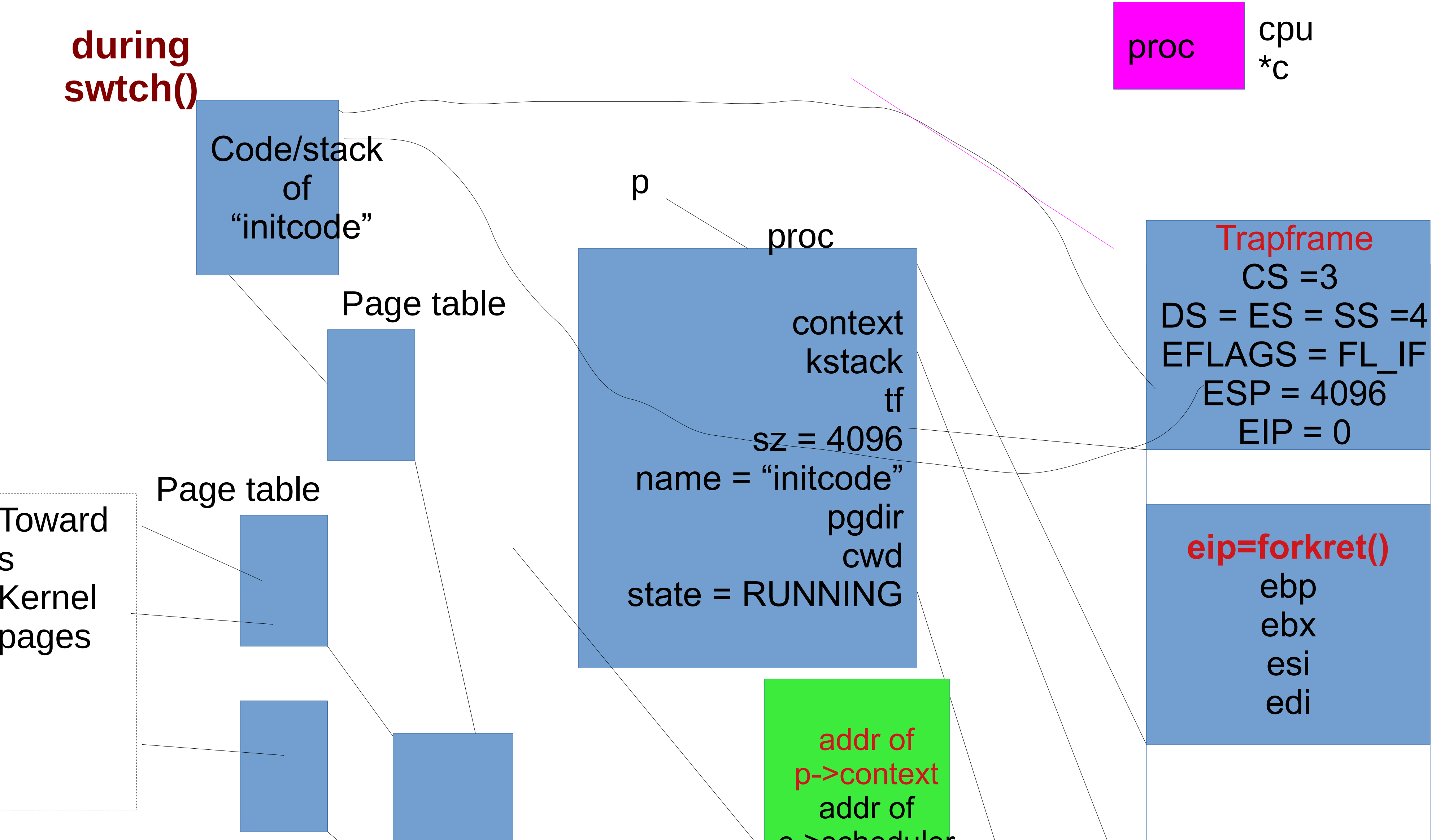

during swtch()



swtch

```
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movl 8(%esp), %edx # Abhijit: edx = new
# Save old callee-saved registers
pushl %ebp
pushl %ebx
pushl %esi
pushl %edi # Abhijit: esp = esp + 16
# Switch stacks
movl %esp, (%eax) # Abhijit: *old = updated old stack
```
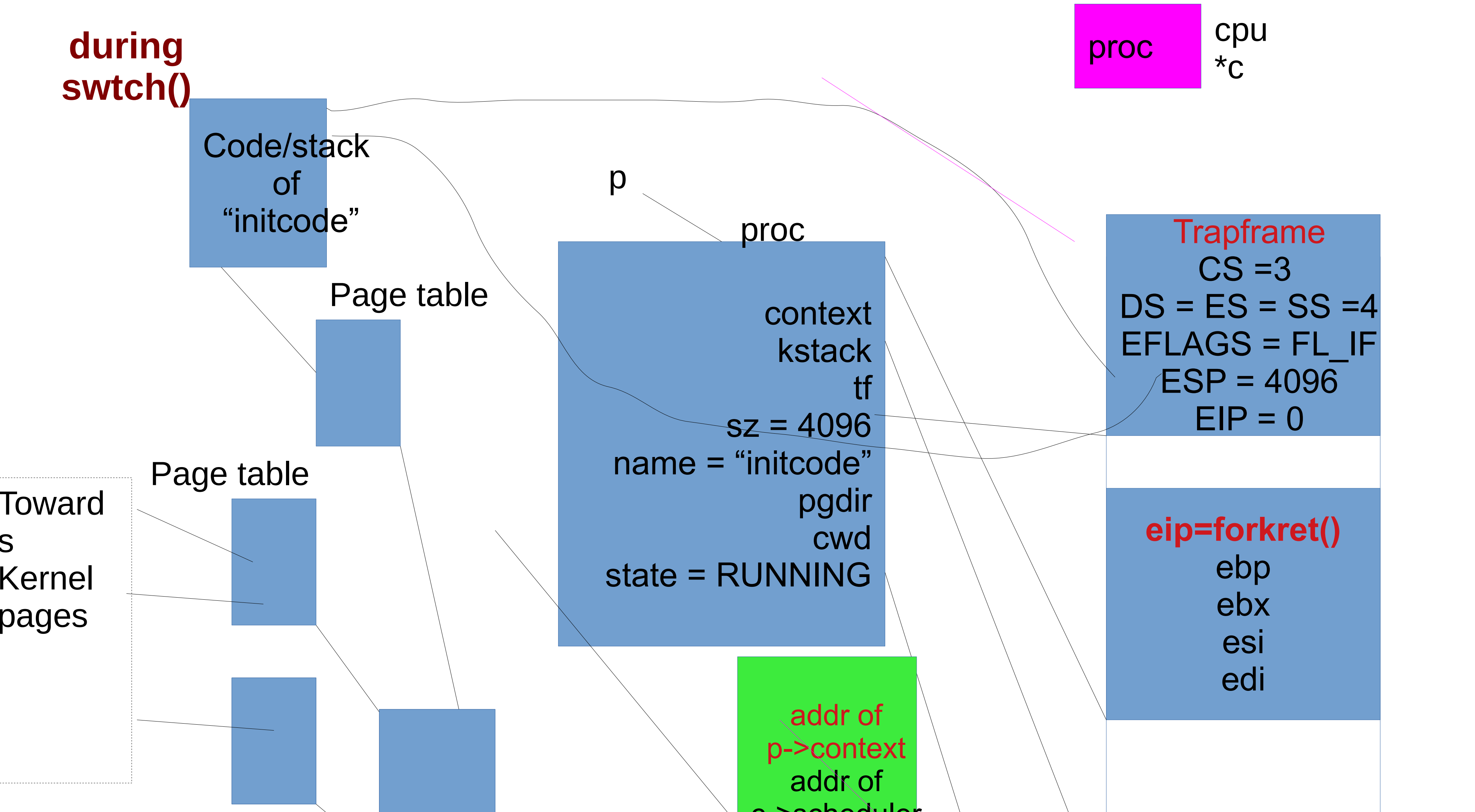

during swtch()



swtch

```
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# Save old callee-saved registers
pushl %ebp
pushl %ebx
pushl %esi
pushl %edi # Abhijit: esp = esp + 16
# Switch stacks
movl %esp, (%eax) # Abhijit: *old = updated old stack
movl %edx, %esp # Abhijit: esp = new
# Load new callee-saved registers
popl %edi
```
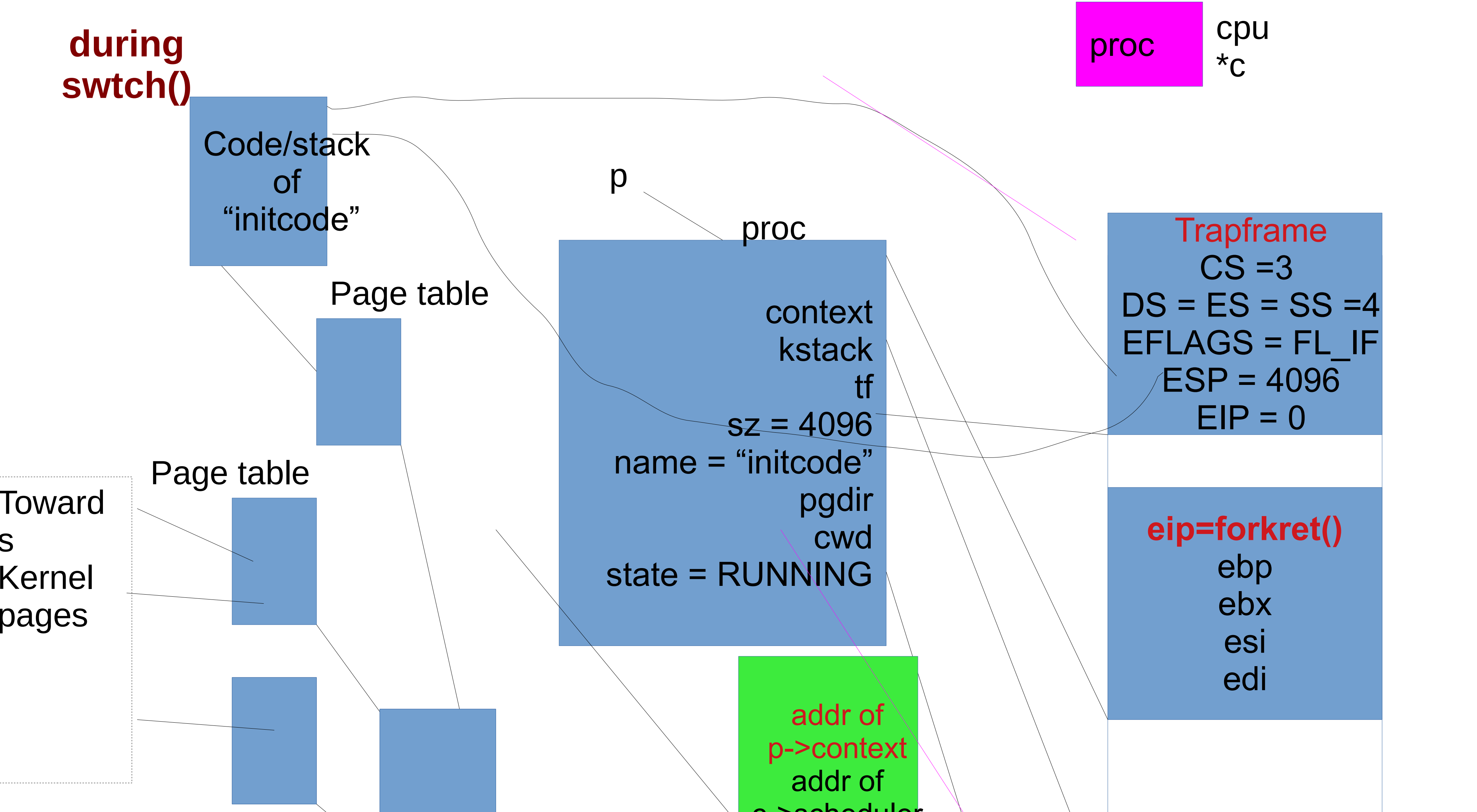

during swtch()



swtch

```
swtch:
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movl 4(%esp), %eax # Abhijit: eax = old
movl 8(%esp), %edx # Abhijit: edx = new
# Save old callee-saved registers
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pushl %ebx
pushl %esi
pushl %edi # Abhijit: esp = esp + 16
# Switch stacks
movl %esp, (%eax) # Abhijit: *old = updated old stack
movl %edx, %esp # Abhijit: esp = new
# Load new callee-saved registers
popl %edi
```
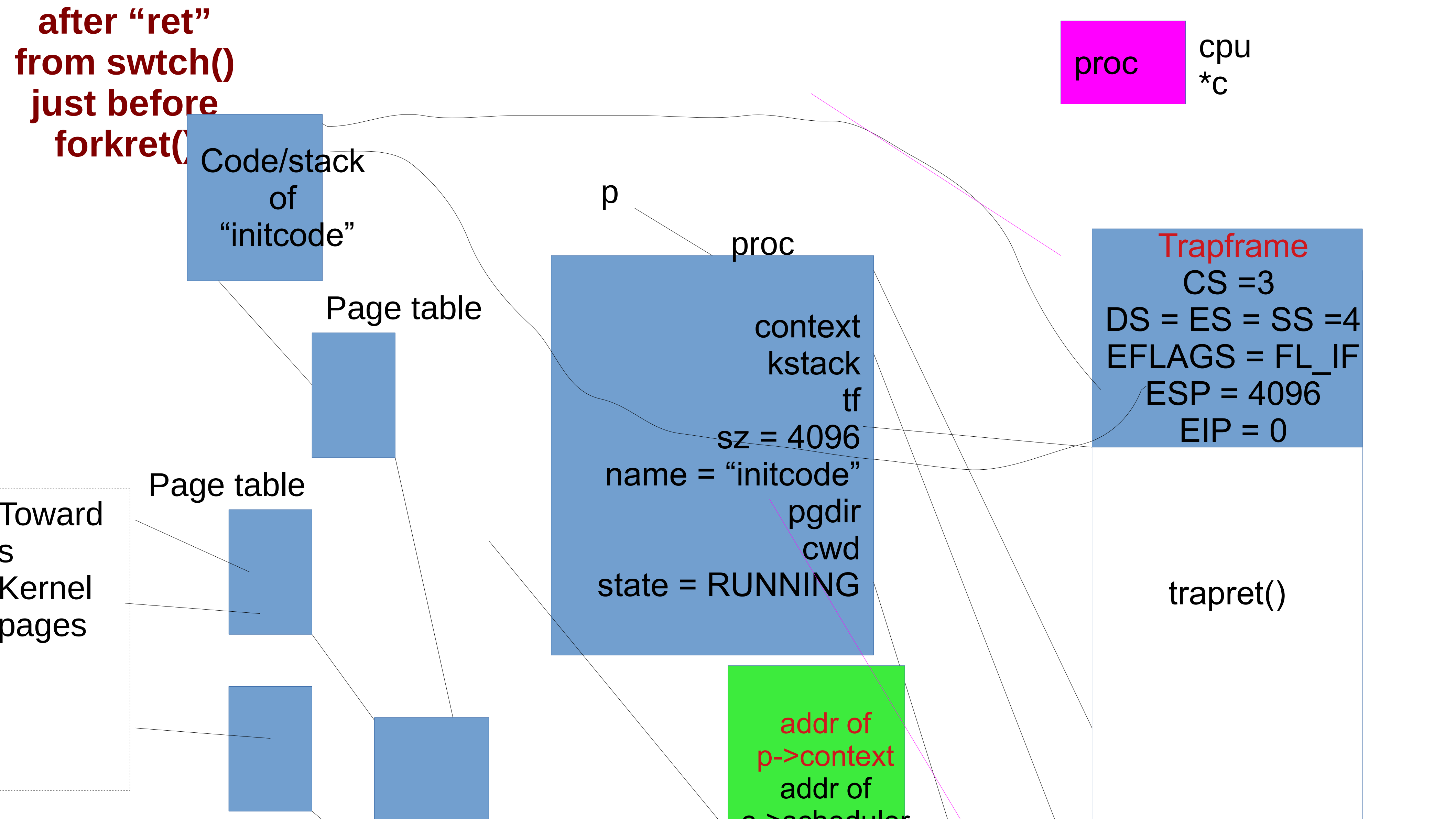
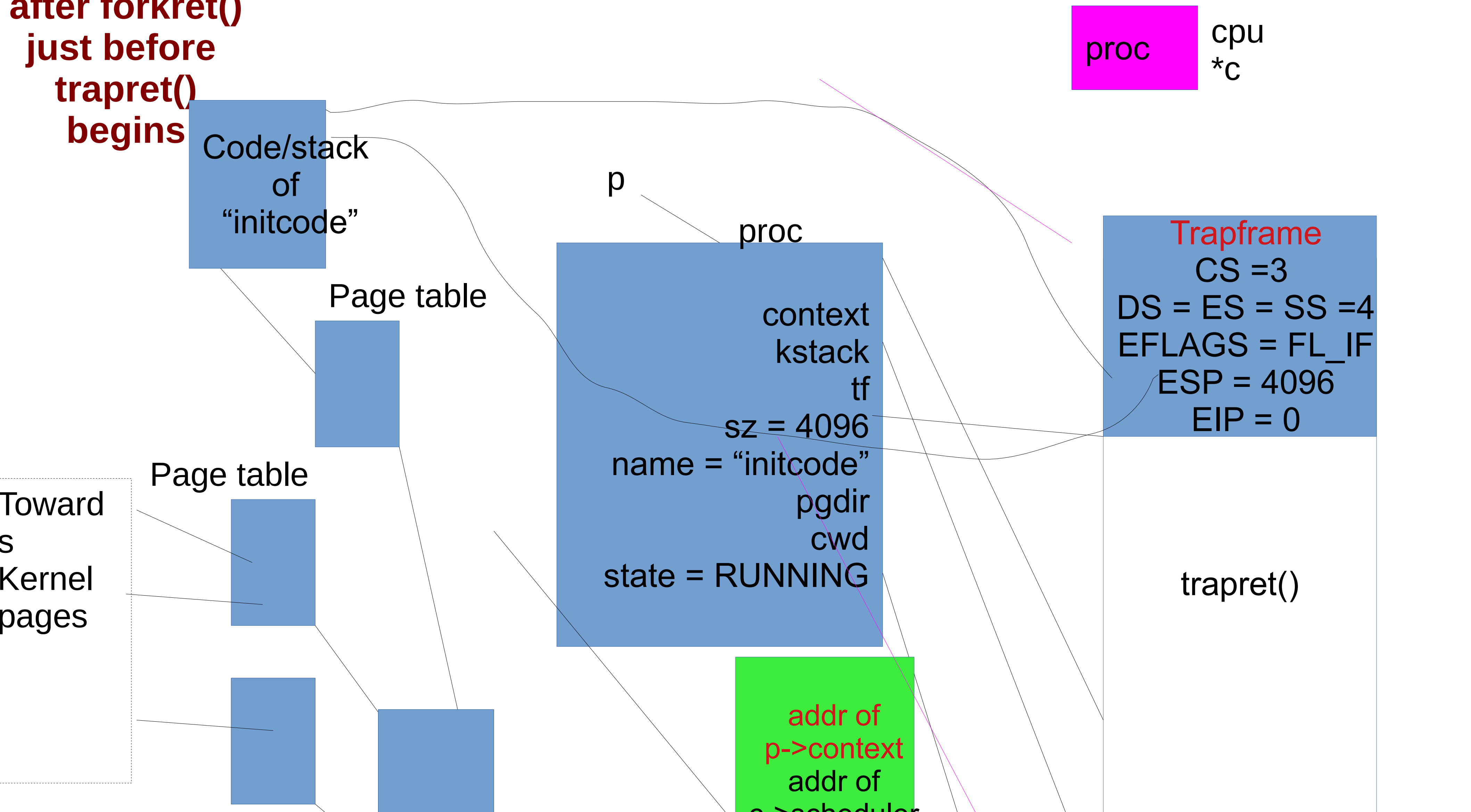


after “ret” from swtch() just before forkret()
proc
cpu *c
Code/stack of “initcode”
p
proc
context
kstack
tf
sz = 4096
name = “initcode”
pgdir
cwd
state = RUNNING
Trapframe
CS =3
DS = ES = SS =4
EFLAGS = FL_IF
ESP = 4096
EIP = 0
trapret()
Page table
Page table
Towards Kernel pages
addr of p->context
addr of

After swtch()

- **Process is running in forkret()**
- **c->cscheduler has saved the old kernel stack**
  - with the context of p, return value in scheduler, ebp, ebx, esi, edi on stack
  - remember {edi, esi, ebx, ebp, ret-value } = context
  - The c->scheduler is pointing to old context
- **CR3 is pointing to process pgdir**

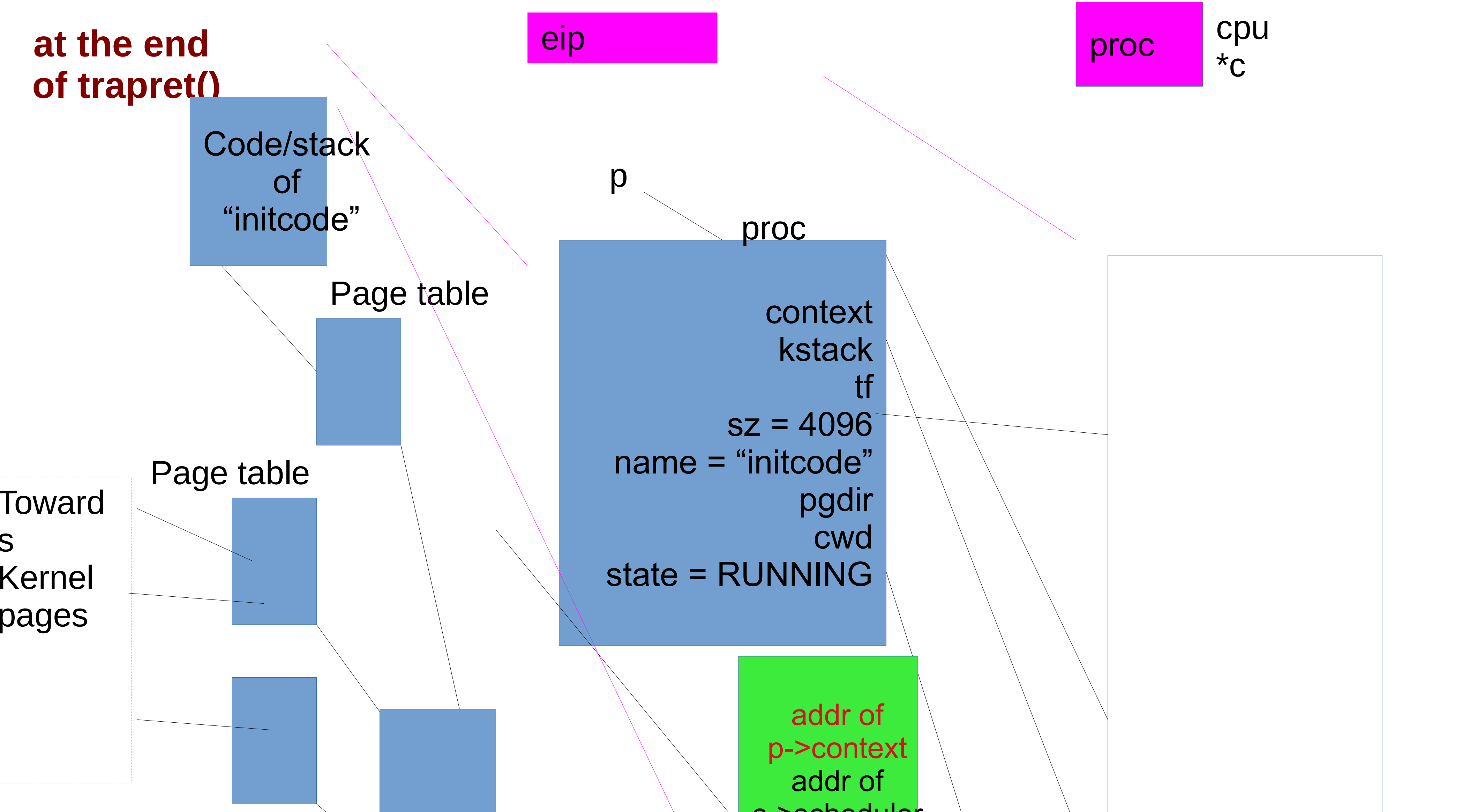
after forkret() just before trapret() begins



After iret in trapret

- **The CS, EIP, ESP will be changed**
  - to values already stored on trapframe
  - this is done by iret
- **Hence after this user code will run**
  - On user stack!
- **Hence code of *initcode* will run now**

at the end of trapret()



initcode

```
# char init[] = "/init\0";
init:
.string "/init\0"
# char *argv[] = { init, 0 };
.p2align 2
argv:
.long init
```

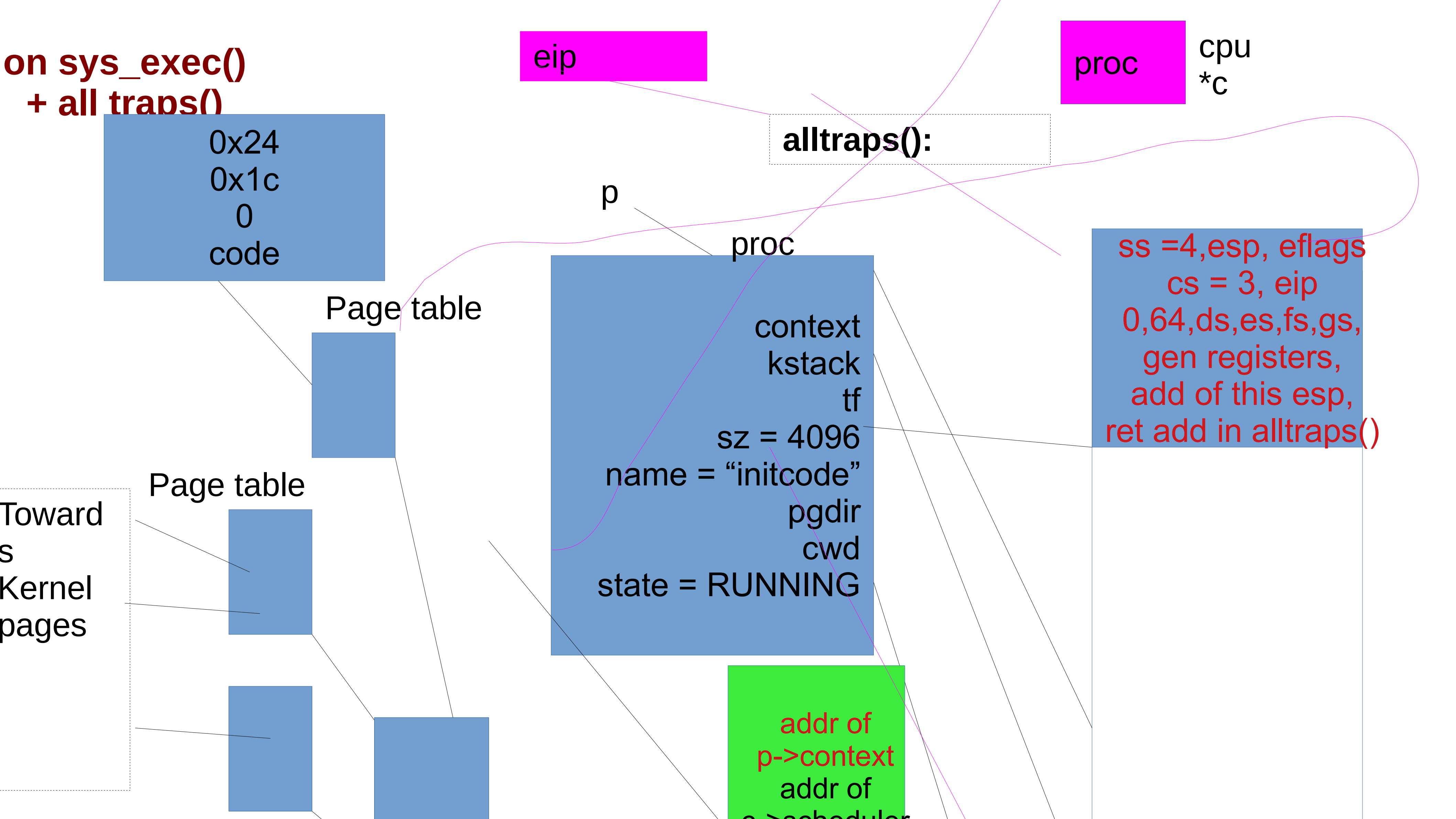
```
start:
pushl $argv
pushl $init
pushl $0 // where caller pc would be
movl $SYS_exec, %eax
int $T_SYSCALL
# for(;;) exit();
exit:
```

esp

0x24 = addr of argv
0x1c = addr of init
0x0

```
00000000 <start>:
0:68 24 00 00 00 push $0x24
5:68 1c 00 00 00 push $0x1c
a:6a 00 push $0x0
c:b8 07 00 00 00 mov $0x7,%eax
11:cd 40 int $0x40
00000013 <exit>:
13:b8 02 00 00 00 mov $0x2,%eax
18:cd 40 int $0x40
1a:eb f7 jmp 13 <exit>
0000001c <init>:
```

on sys_exec()
+ all traps()



Understanding fork() and exec()
First, revising some concepts already learnt
then code of fork(), exec()

First process creation
Let's revisit 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

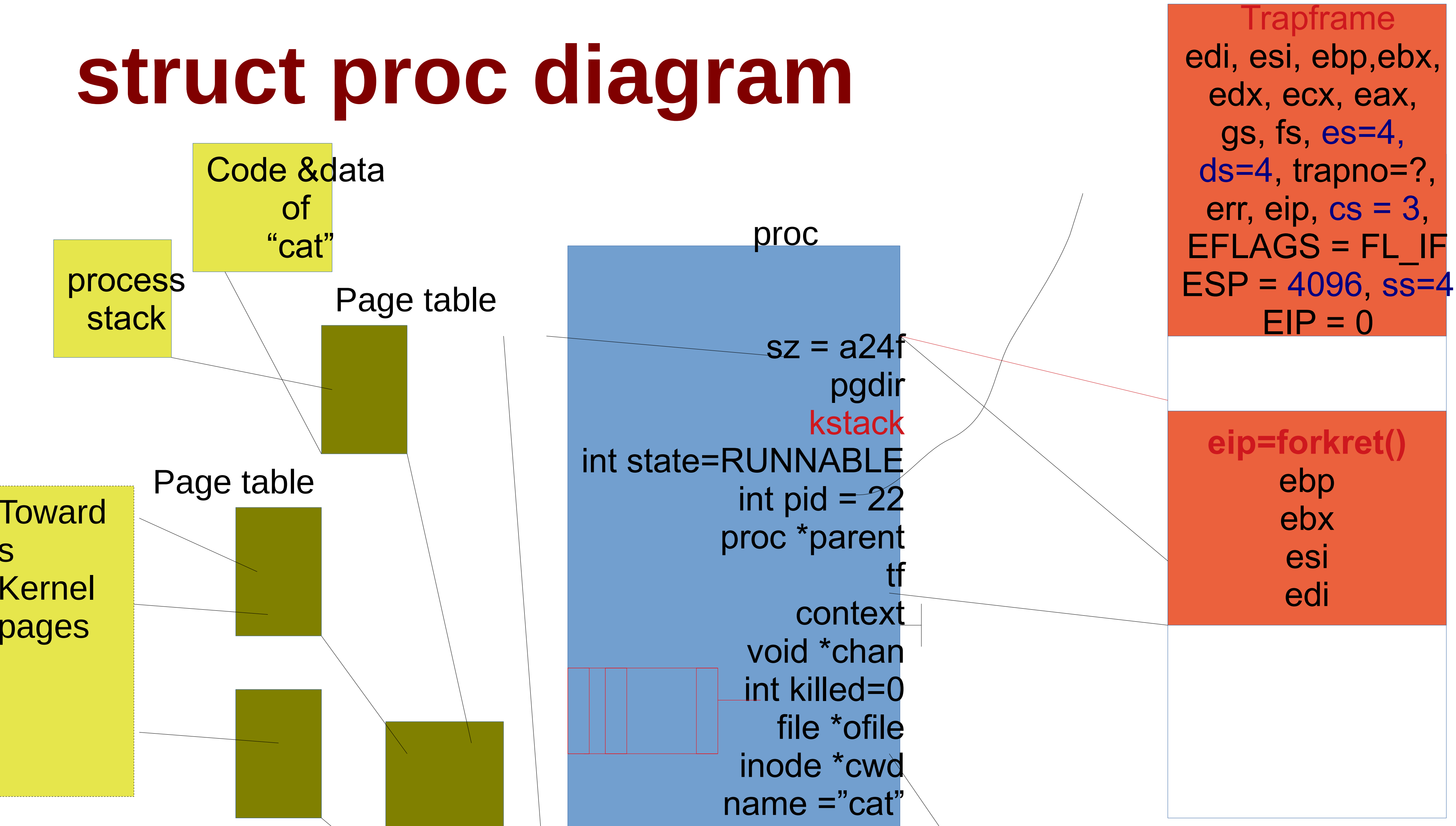
struct proc *parent; // Parent process

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

struct proc diagram



fork()/exec() are syscalls. On every syscall this happens

- **Fetch the n’th descriptor from the IDT, where n is the argument of int.**
- **Check that CPL in %cs is <= DPL, where DPL is the privilege level in the descriptor.**
- **Save %esp and %ss in CPU-internal registers, but only if the target segment selector’s PL < CPL.**
  - Switching from user mode to kernel mode. Hence save user code’s SS and ESP
- **Push %ss. // optional**
- **Push %esp. // optional (also changes ss,esp using TSS)**
- **Push %eflags.**
- **Push %cs.**
- **Push %eip.**
- **Clear the IF bit in %eflags, but only on an interrupt.**
- **Set %cs and %eip to the**

After “int” ‘s job is done

- **IDT was already set, during idtinit()**
  - Remember vectors.S – gives jump locations for each interrupt
- **“int 64” ->jump to 64th entry in vector table**
  - So now stack has ss, esp,eflags, cs, eip, 0 (for error code), 64
  - Next run alltraps from trapasm.S

alltraps:

```
# Build trap frame.
pushl %ds
pushl %es
pushl %fs
pushl %gs
pushal // push all gen purpose regs
# Set up data segments.
movw $(SEG_KDATA<<3), %ax
movw %ax, %ds
movw %ax, %es
# Call trap(tf), where tf=%esp
```

- Now stack contains
- ss, esp,eflags, cs, eip, 0 (for error code), 64, ds, es, fs, gs, eax, ecx, edx, ebx, oesp, ebp, esi, edi
  - This is the struct trapframe !
  - So the kernel stack now contains the trapframe
  - Trapframe is a part of kernel stack

trap()

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

- **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

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?**

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

- 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

understanding fork()

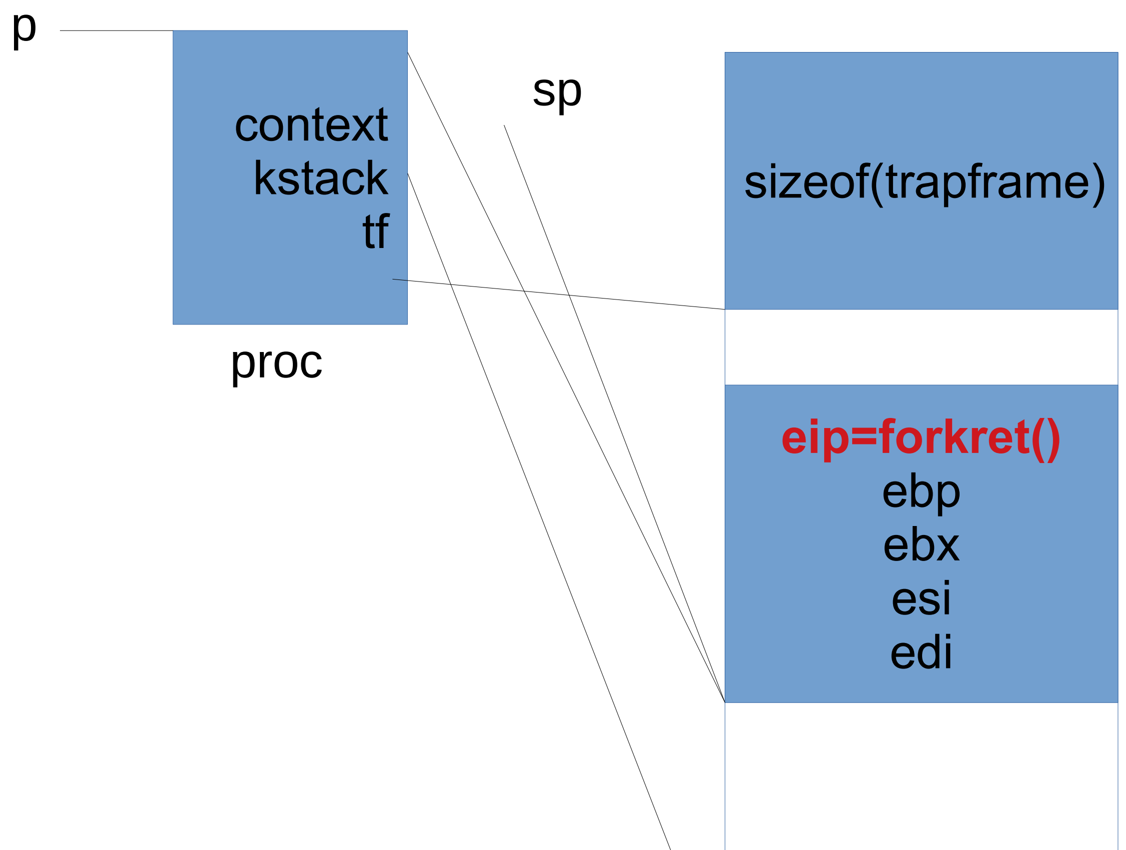
- **What should fork do?**
  - Create a copy of the existing process
  - child is same as parent, except pid, parent-child relation, return value (pid or 0)
  - Please go through every member of struct proc, understand it’s meaning to appreciate what fork() should do
  - create a struct proc, and
    - duplicate pages, page directory, sz, state,trapframe,context, ofile (and files!), cwd, name
    - modify: pid, parent, trapframe, state

understanding fork()

```
int
sys_fork(void)
{
return fork();
}
```

```
int
fork(void)
{
int i, pid;
struct proc *np;
struct proc *curproc = myproc();
// Allocate process.
if((np = allocproc()) == 0){
return -1;
```

after allocproc()
-- we studied this -- same as creation of first process



understanding fork()

```
// Copy process state from proc.
if((np->pgdir = copyuvm(curproc->pgdir, curproc->sz)) == 0){
kfree(np->kstack);
np->kstack = 0;
np->state = UNUSED;
return -1;
}
np->sz = curproc->sz;
np->parent = curproc;
```

- **copy the pages, page tables, page directory**
  - no copy on write here!
  - Rewind if operation of copyuvm() fails
- **copy size**
- **set parent of child**
- **copy trapframe**

```
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;
memmove(mem, (char*)P2V(pa), PGSIZE);
if(mappages(d, (void*)i, PGSIZE, V2P(mem), flags) < 0) {
kfree(mem);
goto bad;
}
```

understanding fork()->copyuvm()

- **Map kernel pages**
- **for every page in parent's VM address space**
  - allocate a PTE for child
  - set flags
  - copy data
  - map pages in child's

understanding fork()

```
np->tf->eax = 0;
for(i = 0; i < NOFILE; i++)
if(curproc->ofile[i])
np->ofile[i] = filedup(curproc->ofile[i]);
np->cwd = idup(curproc->cwd);
safestrcpy(np->name, curproc->name, sizeof(curproc->name));
pid = np->pid;
acquire(&ptable.lock);
np->state = RUNNABLE;
```

- set return value of child to 0
  - eax contains return value, it’s on TF
- copy each struct file
- copy current working dir inode
- copy name
- set pid of child

exec() - different prototype

- int exec(char*, char**);
  - usage: to print README and test.txt using “cat”

```
int main(int argc, char *argv[])
{
char *cmd = "/cat";
char *argstr[4] = { "/cat", "README", "test.txt", 0};
exec(cmd, argstr);
```

sys_exec()

```
int
sys_exec(void)
{
char *path, *argv[MAXARG];
int i;
uint uargv, uarg;
if(argstr(0, &path) < 0 || argint(1, (int*)&uargv) < 0){
return -1;
}
memset(argv, 0, sizeof(argv));
for(i=0;; i++){
if(i >= NELEM(argv))
return -1;
if(fetchint(uargv+4*i, (int*)&uarg) < 0)
return -1;
if(uarg == 0){
argv[i] = 0;
break;
}
```

- **argstr(n,), argint(n,)**
  - Fetch the n'th argument from *process stack* using p->tf->esp + offset
  - Again: revise calling conventions
  - 0'th argument: name of executable file
  - 1st Argument: address of the array of arguments

sys_exec()

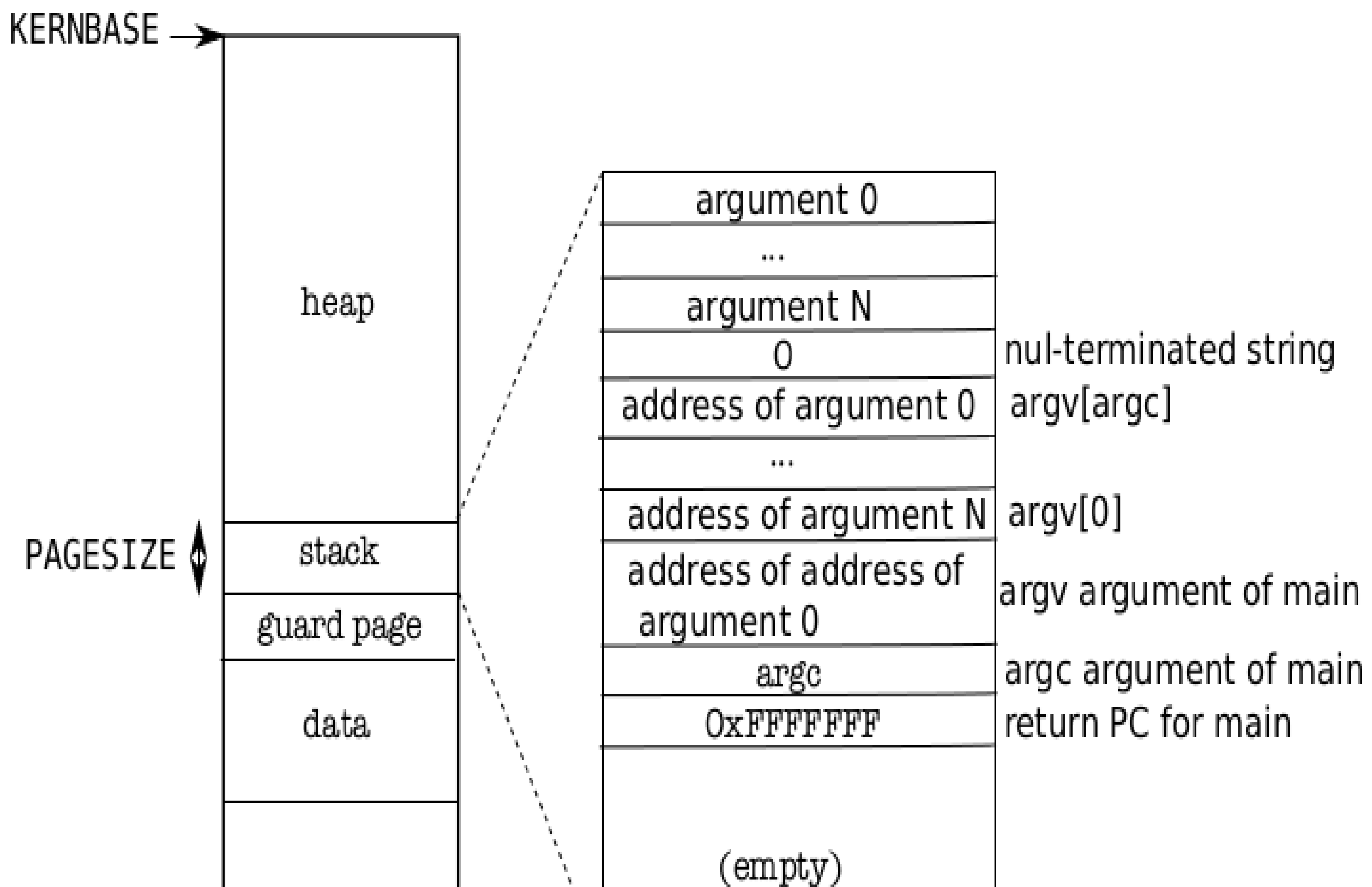
```
int sys_exec(void)
{
char *path, *argv[MAXARG];
int i; uint uargv, uarg;
if(argstr(0, &path) < 0 || argint(1,
(int*)&uargv) < 0){
return -1;
}
memset(argv, 0, sizeof(argv));
for(i=0;; i++){
if(i >= NELEM(argv)) return -1;
if(fetchint(uargv+4*i, (int*)&uarg) < 0)
return -1;
if(uarg == 0){
argv[i] = 0; break;
}
if(fetchstr(uarg, &argv[i]) < 0)
```

- the local array argv[] (allocated on kernel stack, obviously) set to 0
- fetch every next argument from array of arguments
  - Sets the address of argument in argv[1]
- call exec
  - beware: mistake to assume that this exec() is the exec()

What should exec() do?

- **Remember, it came from fork()**
  - so proc & within it tf, context, kstack, pgdir-tables-pages, all exist.
  - Code, stack pages exist, and mappings exist through proc->pgdir
- **Hence**
  - read the ELF executable file (argv[0])
  - create a new page dir – create mappings for kernel and user code+data; copy data from ELF to these pages (later discard old pagedir)
  - Copy the argv onto the user stack – so that when new process starts it has it's main(argc, argv[]) built

User stack after call to exec() is over



exec()

```
int
exec(char *path, char **argv)
{
...
uint argc, sz, sp,
ustack[3+MAXARG+1];
...
if((ip = namei(path)) == 0){
end_op();
cprintf("exec: fail\n");
return -1;
```

- **ustack**
  - used to build the arguments to be pushed on user-stack
- **namei**
  - get the inode of the executable file

exec()

```
// Check ELF header
if(readi(ip, (char*)&elf, 0, sizeof(elf)) != sizeof(elf))
goto bad;
if(elf.magic != ELF_MAGIC)
goto bad;
if((pgdir = setupkvm()) == 0)
```

- **readi**
  - read ELF header
- **setupkvm()**
  - creating a *new* page directory and mapping kernel pages

exec()

```
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;
```

- Read ELF program headers from ELF file
- Map the code/data into pagedir-pagetable-pages
- Copy data from ELF file into the pages

exec()

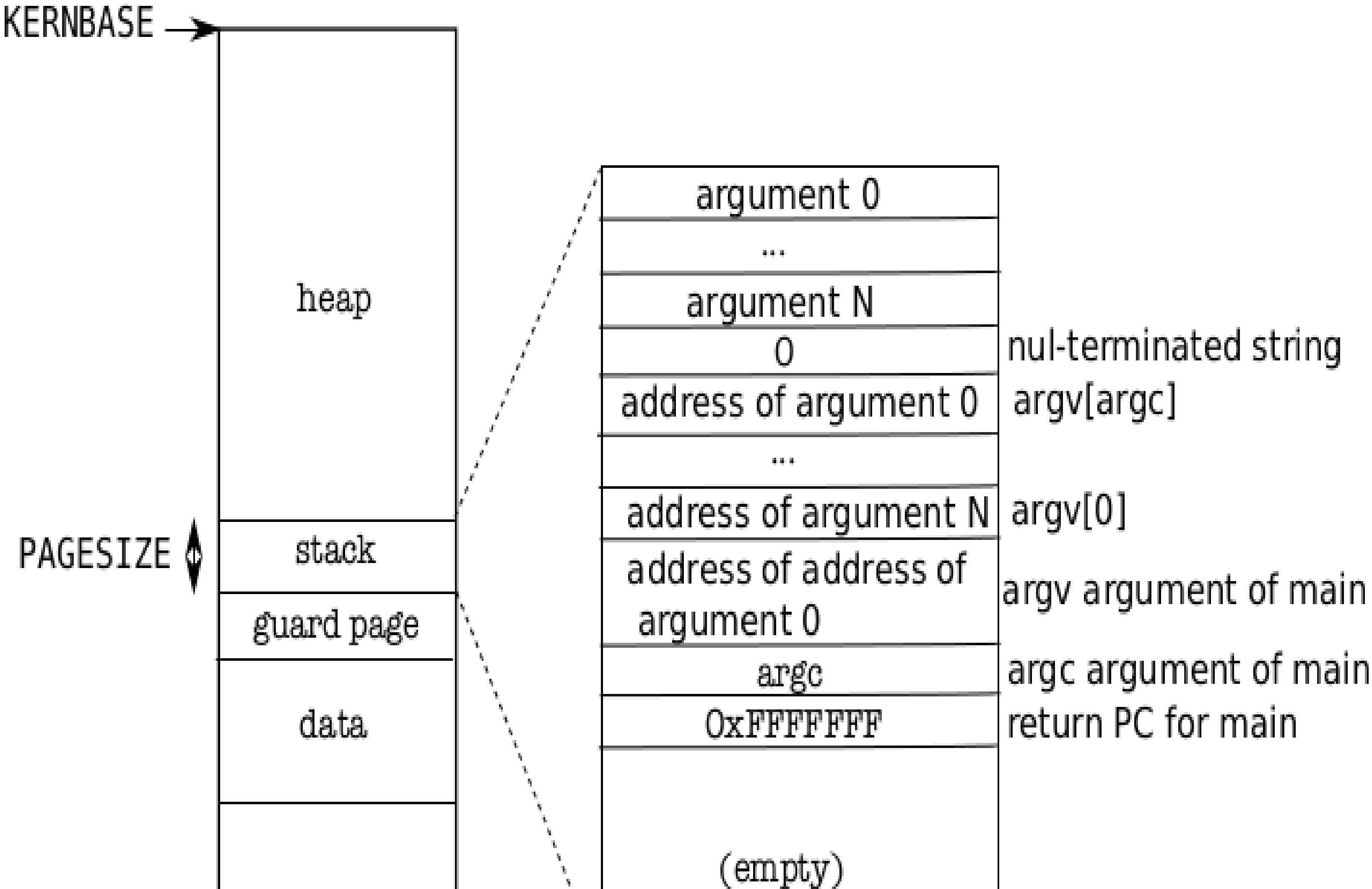
```
sz = PGROUNDUP(sz);
if((sz = allocuvm(pgdir, sz, sz + 2*PGSIZE)) == 0)
goto bad;
clearpteu(pgdir, (char*)(sz - 2*PGSIZE));
sp = sz;
```

- Allocate 2 pages on top of proc->sz
- One page for stack
- one page for guard page
- Clear the valid flag on

exec()

```
// Push argument strings, prepare rest of stack
in ustack.
for(argc = 0; argv[argc]; argc++) {
if(argc >= MAXARG)
goto bad;
sp = (sp - (strlen(argv[argc]) + 1)) & ~3;
if(copyout(pgdir, sp, argv[argc],
strlen(argv[argc]) + 1) < 0)
goto bad;
ustack[3+argc] = sp;
}
ustack[3+argc] = 0;
ustack[0] = 0xffffffff; // fake return PC
ustack[1] = argc;
ustack[2] = sp - (argc+1)*4; // argv pointer
```

- For each entry in argv[]
  - copy it on user-stack
  - remember it's location on user stack in ustack
- add extra entries (to be copied to user stack) to ustack
- copy argc, argv pointer
- take sp to bottom
- copy ustack to user stack



This is what the code on earlier slide did

```
// Save program name for debugging.
for(last=s=path; *s; s++)
if(*s == '/')
last = s+1;
safestrcpy(curproc->name, last,
sizeof(curproc->name));
// Commit to the user image.
oldpgdir = curproc->pgdir;
curproc->pgdir = pgdir;
curproc->sz = sz;
curproc->tf->eip = elf.entry; // main
curproc->tf->esp = sp;
```

exec()

- copy name of new process in proc->name
- change to new page directory
- change new size
- tf->eip will be used when we return from exec() to jump to user code. Set to to first instruction of code, given by elf.entry
- Set user stack pointer to “sp” (bottom of stack

return 0 from exec()?

- **We know exec() does not return !**
- **This was exec() function !**
  - Returns to sys_exec()
- **sys_exec() also returns , where?**
  - Remember we are still in kernel code, running on kernel stack. p->kstack has the trapframe setup
  - There is context struct on stack. Why?
  - sys_exec() returns to trapret(), the trap frame will be popped !
    - with “iret” jump into new program !
  - New program is not old program , which could have accessed return