Trap handling

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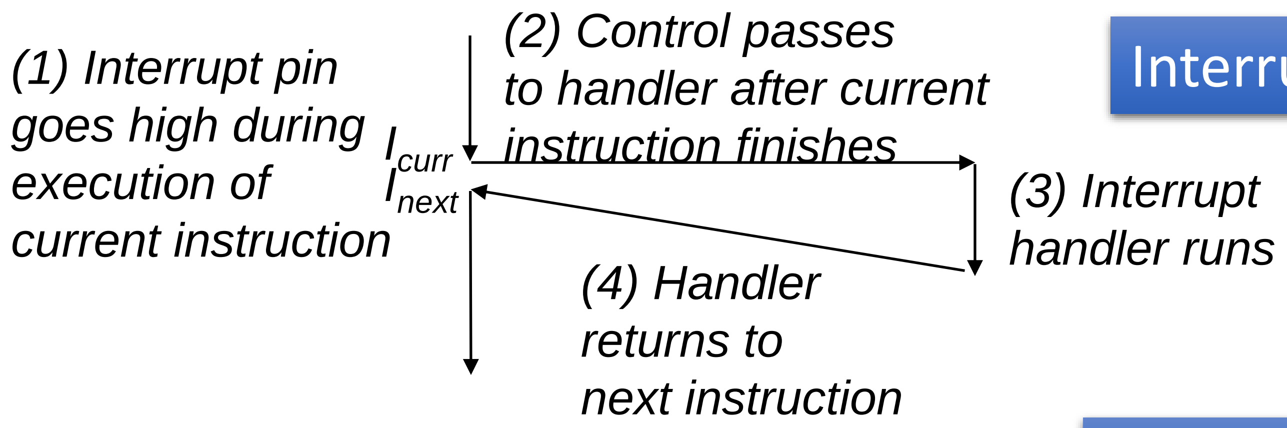
Recap: OS runs processes

- OS manages multiple active processes concurrently
- What is a process?
  - Memory image in RAM = compiled code, data (compile-time, run-time)
  - CPU context (in CPU registers when running, else saved in PCB)
  - Other things like I/O connections, ..
- Processes created by fork from parent processes
- Periodically, OS scheduler loops over ready processes
  - Find a suitable process to run, save old process context, restore new context
- Once process is context switched in, OS is out of picture, CPU in user mode, runs user code directly
- When does the OS run again?

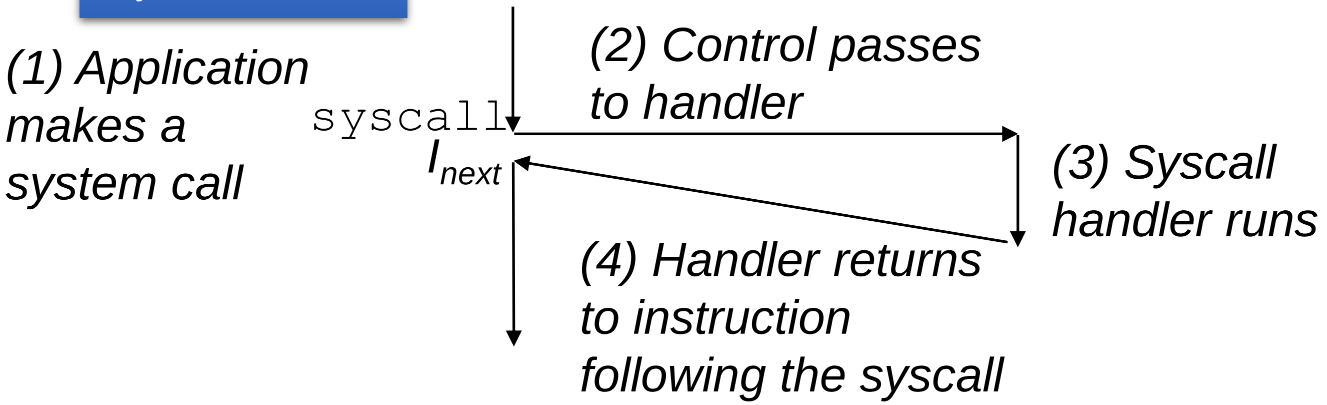
User mode vs. Kernel mode of a process

- CPU runs user code in user mode (low privilege) most of the time
- CPU switches to kernel mode execution when
  - Process makes system call, needs OS services
  - External device needs attention, raises interrupt
  - Some fault has happened during program execution
- All such events are called traps: CPU "traps" into OS code
  - CPU shifts to high privilege level (kernel mode), runs OS code to handle event
  - Later, CPU switches to low privilege level, back to user code in user mode
- Process P goes to kernel mode to run OS code, but it is still process P itself that is in running state
- OS not a separate process, runs in kernel mode of existing processes

Interrupt


(1) Interrupt pin goes high during execution of current instruction
I_{curr}
I_{next}
(2) Control passes to handler after current instruction finishes
(3) Interrupt handler runs
(4) Handler returns to next instruction

System call


(1) Application makes a system call
syscall
I_{next}
(2) Control passes to handler
(3) Syscall handler runs
(4) Handler returns to instruction following the syscall

Program fault

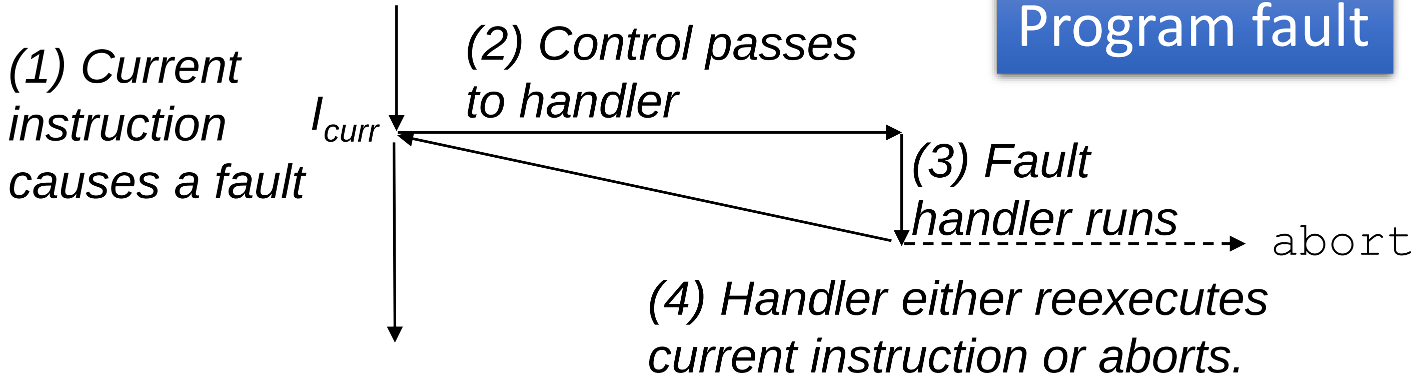
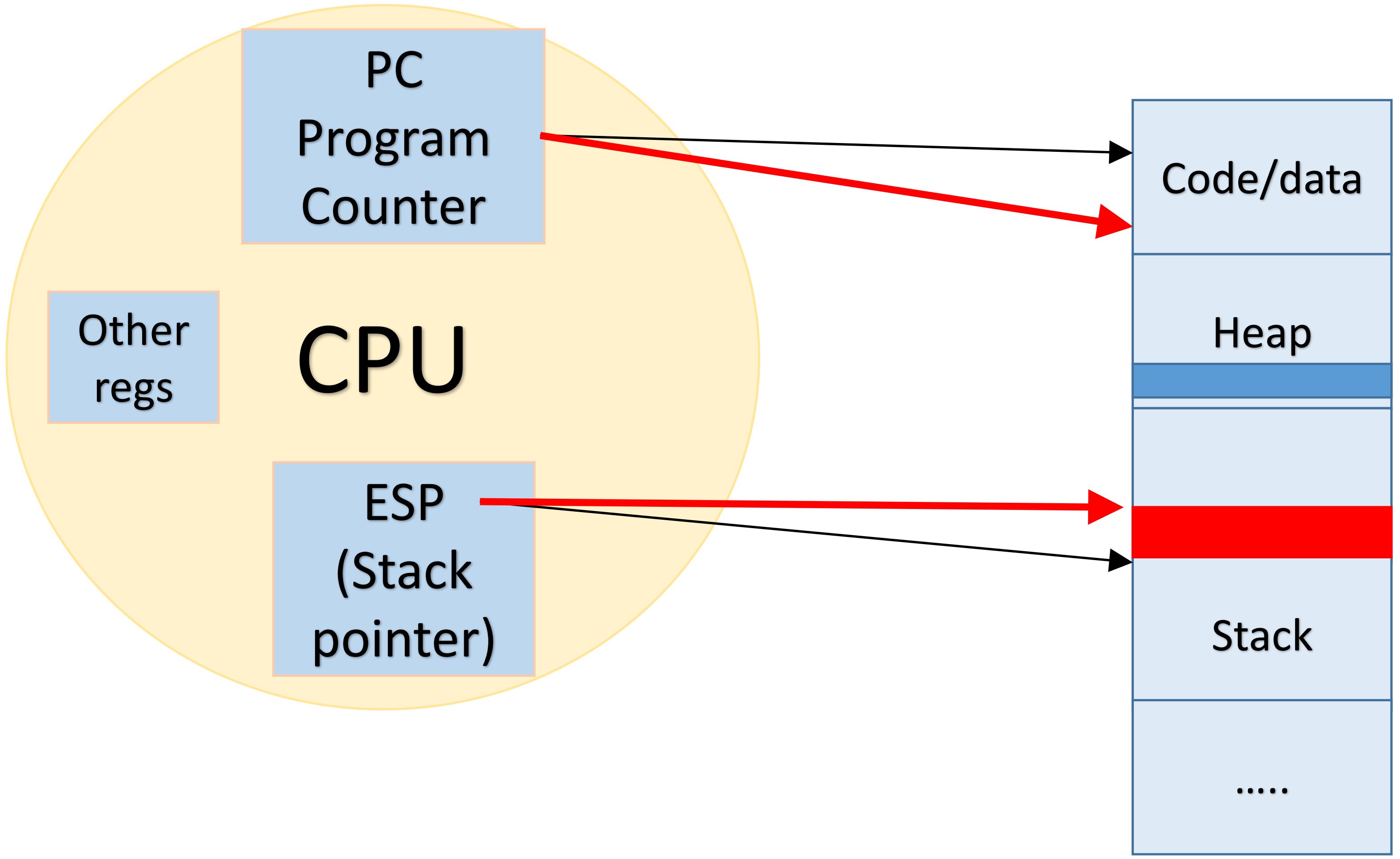

(1) Current instruction causes a fault
I_{curr}
(2) Control passes to handler
(3) Fault handler runs
abort
(4) Handler either reexecutes current instruction or aborts.

Image credit: CSAPP

Function call vs. system call

- What happens when a user program makes a function call?
  - Allocate memory on user stack for function arguments, local variables, ..
  - Push return address, PC jumps to function code
  - Push register context (to resume execution when function returns)
  - Execute function code
  - When returning from function, pop return address, pop register context
- System call also must
  - Use a stack to push register context
  - Save old PC, change PC to point to OS code to handle system call
  - Run system call, restore context back to user code

Understanding a function call



from compiled executable
(machine instructions, static/global data)

Address of this memory
returned by malloc

New stack frame pushed by function call
Contains args, local vars, return addr, …
Popped when function returns

Changes on a function call

Located at some memory addresses in RAM

What is different for a system call?

- Changing PC in function call vs. system call
  - In function call, address of function code known in executable, can jump to function code directly using a CPU instruction ("call" in x86)
  - For system call, cannot trust user to jump to correct OS code (what if user jumps to inappropriate privileged code?)
- Saving register context on stack in function call vs. system call
  - In function call, register context is saved and restored from user stack
  - For system call, OS does not wish to use user stack (what if user has setup malicious values on the stack?)
- We require: a secure stack, a secure way of jumping to OS code

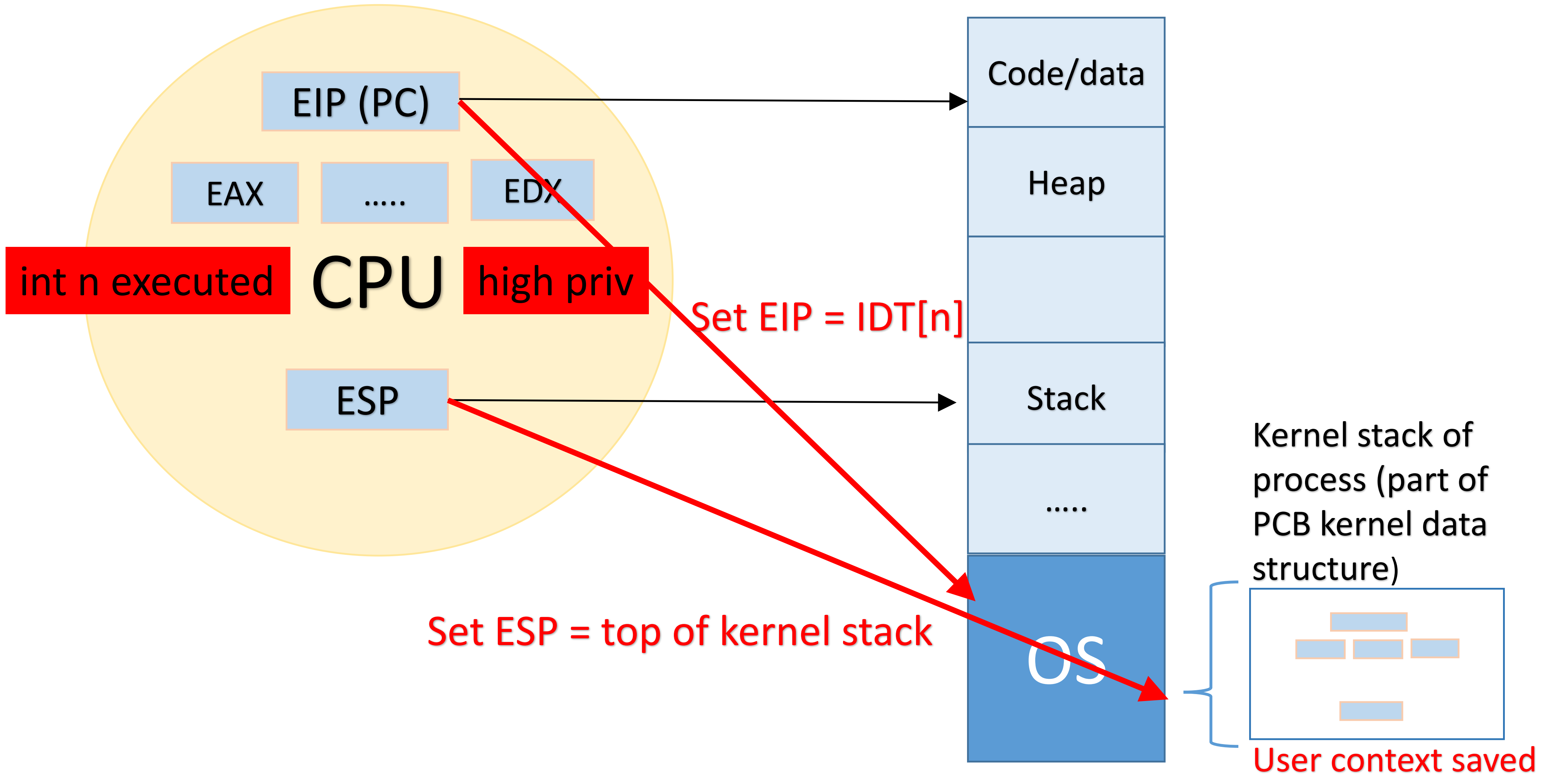
Kernel stack and IDT

- Every process uses a separate kernel stack for running kernel code
  - Part of PCB of process, in OS memory, not accessible in user mode
  - Used like user stack, but for kernel mode execution
  - Context pushed on kernel stack during system call, popped when done
- To set PC, CPU accesses Interrupt Descriptor Table (IDT)
  - Data structure with addresses of kernel code to jump to for events
  - Setup by OS during bootup, not accessible in user mode
  - CPU uses IDT to locate address of OS code to jump to
- Together: secure way of locating OS code, secure stack for OS to run

Hardware trap instruction

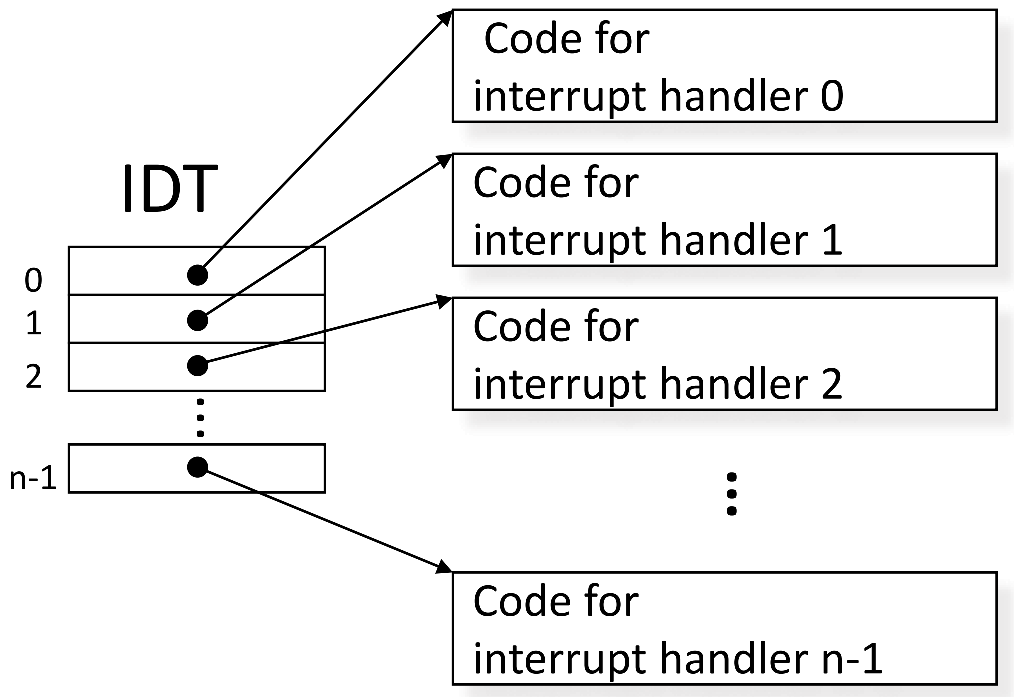
- When user code wants to make system call, it invokes special "trap instruction" with an argument
  - Example: "int n" in x86, argument "n" indicates type of trap (syscall, interrupt)
  - The value of "n" specifies index into IDT array, which OS function to jump to
- When CPU runs the trap instruction:
  - CPU moves to higher privilege level
  - CPU shifts stack pointer register to kernel stack of process
  - Register context is saved on kernel stack (part of PCB)
  - Address of OS code to jump to is obtained from IDT, PC points to OS code
  - OS code starts to run, on a secure stack

Trap handling



IDT lookup

- IDT configured by OS
- Base address of IDT stored in CPU register
- Upon trap, CPU looks up IDT to find address of interrupt handler


IDT
0
1
2
n-1
Code for interrupt handler 0
Code for interrupt handler 1
Code for interrupt handler 2
Code for interrupt handler n-1

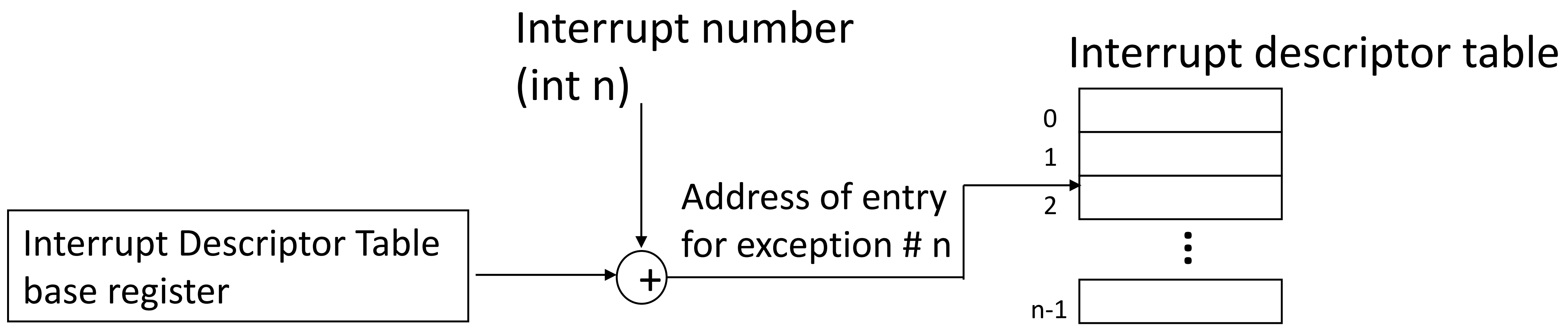

Interrupt number (int n)
Interrupt descriptor table
0
1
2
n-1
Interrupt Descriptor Table base register
Address of entry for exception # n

Image credit: CSAPP

Why trap instruction?

- Need a secure way of jumping to OS code to handle traps
  - User code cannot be trusted to jump to correct OS code
  - Only CPU can be trusted to handover control from user to OS securely
- Who calls trap instruction?
  - System call code in a language library (printf invokes system call via int n)
  - External hardware raises interrupt, causes CPU to execute “int n”
  - Argument “n” indicates whether system call /IRQ number of hardware device
- Across all cases, the mechanism is: save context on kernel stack, switch to OS address in IDT, run OS code to handle trap

Return from trap

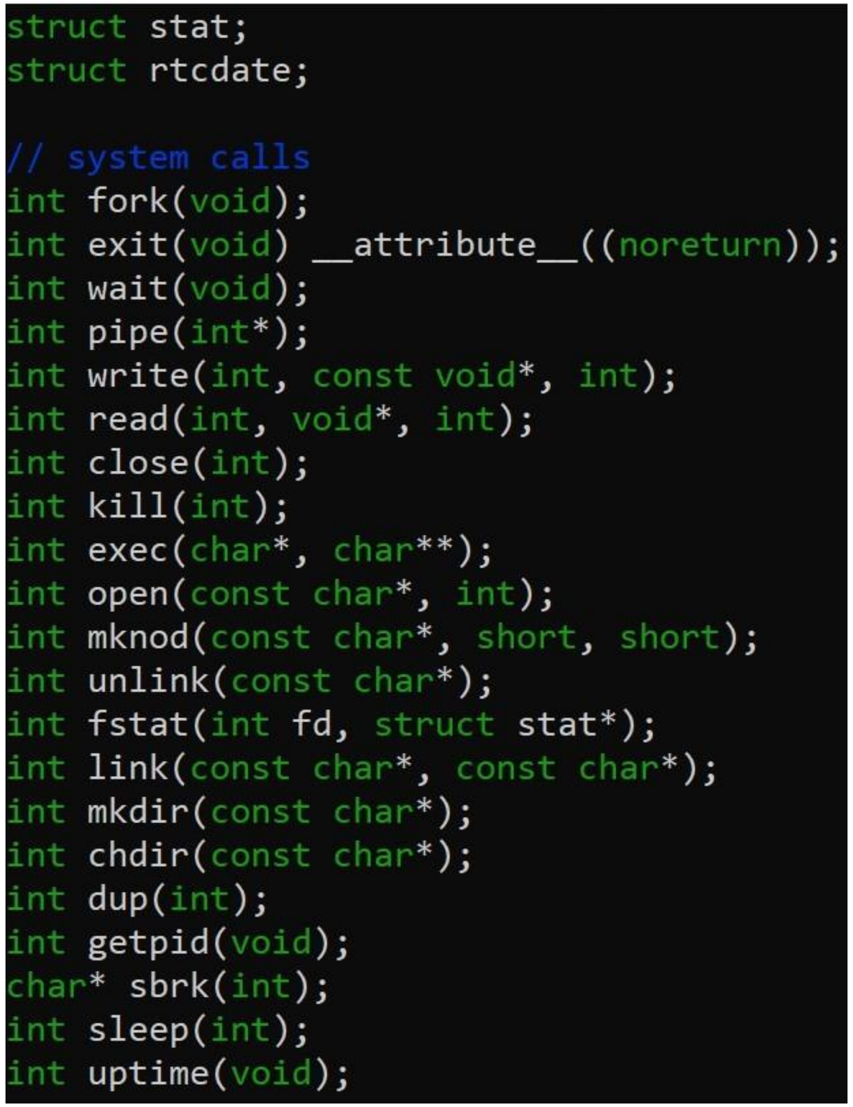
- When OS is done handling syscall or interrupt, it calls a special instruction return-from-trap
  - Restore context of CPU registers from kernel stack
  - Change CPU privilege from kernel mode to user mode
  - Restore PC and jump to user code after trap
- User process unaware that it was suspended, resumes execution at the point it stopped before
- Always return to the same user process from kernel mode? No
  - Before returning to user mode, OS checks if it must switch to another process

Trap handling in xv6

- The following events in xv6 cause a user process to “trap” into the kernel
  - System calls (requests by user for OS services)
  - Interrupts (external device wants attention)
  - Program fault (illegal action by program)
- When above events happen, CPU executes the special “int” instruction
  - Example seen in usys.S, “int” invoked to handle system calls
  - For hardware interrupts, device sends a signal to CPU, and CPU executes int
- Trap instruction has a parameter (int n), indicating type of interrupt
  - E.g., syscall has a different value of n from keyboard interrupt
  - The value of “n” is used to index into IDT, get address of kernel code to run
- xv6 trap handling code saves register context, handles trap, returns

xv6 system calls

- In xv6, system calls available to user programs are defined in user library header “user.h”
  - Equivalent to C library headers (xv6 doesn’t use standard C library)
- These system call functions invoked in user programs after including “user.h”
- The actual invoking of system call is done in usys.S

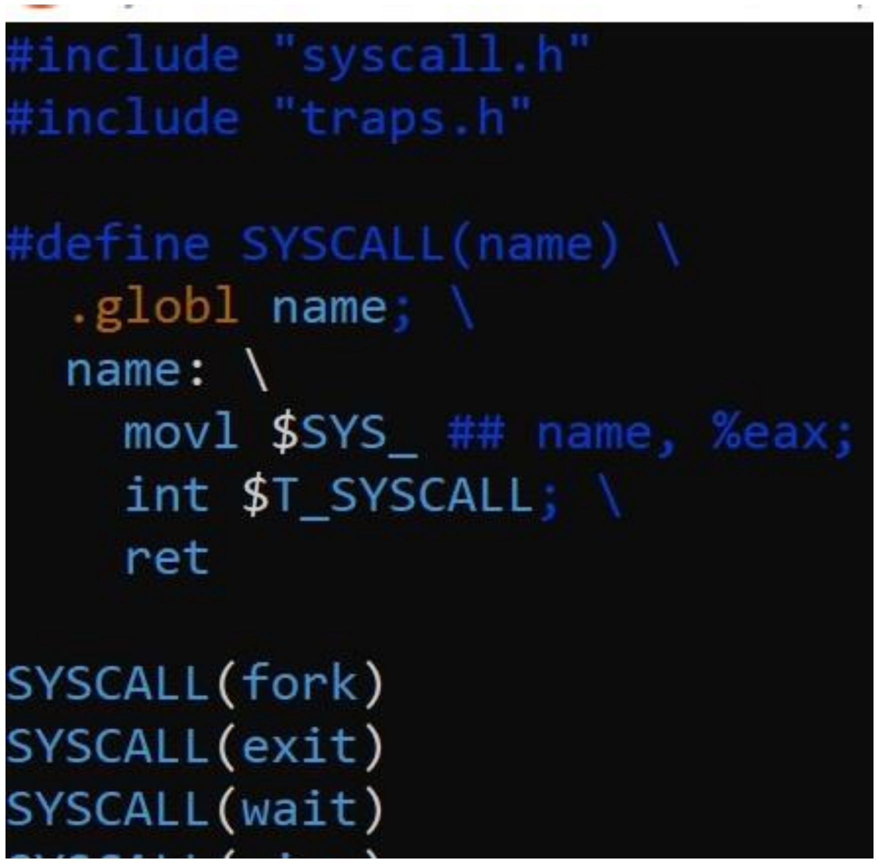


```
struct stat;
struct rtcdate;

// system calls
int fork(void);
int exit(void) __attribute__((noreturn));
int wait(void);
int pipe(int*);
int write(int, const void*, int);
int read(int, void*, int);
int close(int);
int kill(int);
int exec(char*, char**);
int open(const char*, int);
int mknod(const char*, short, short);
int unlink(const char*);
int fstat(int fd, struct stat*);
int link(const char*, const char*);
int mkdir(const char*);
int chdir(const char*);
int dup(int);
int getpid(void);
char* sbrk(int);
int sleep(int);
int uptime(void);
```

xv6 system calls

- The user library makes the actual system call to invoke OS code
- User library invokes trap instruction to make system call, code seen in usys.S
  - Defined using a macro
  - Move system call number to eax
  - Invoke int n where n is T_SYSCALL
- The trap (int) instruction causes a jump to kernel code that handles the system call



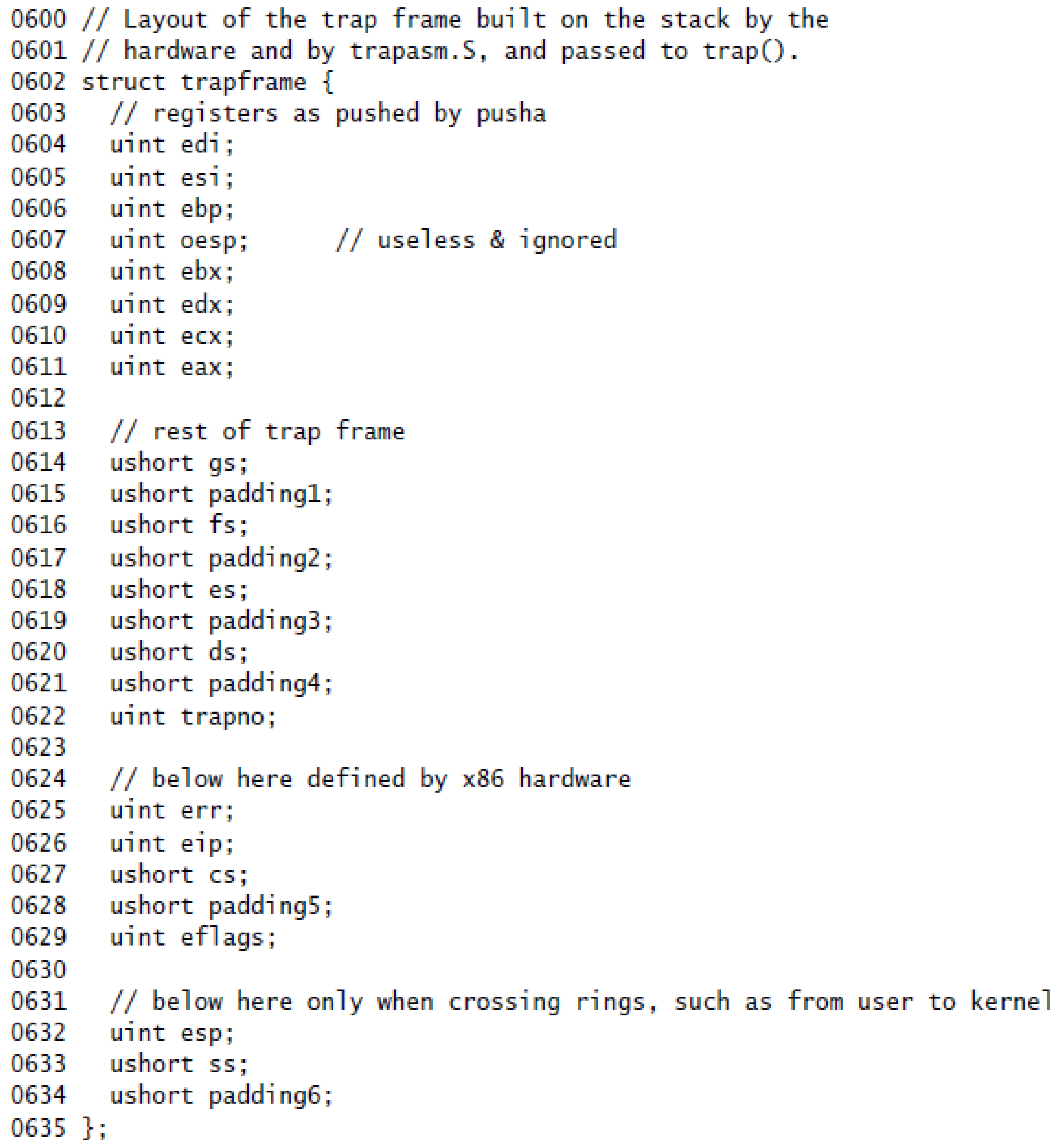
```
#include "syscall.h"
#include "traps.h"

#define SYSCALL(name) \
  .globl name; \
  name: \
    movl $SYS_ ## name, %eax;
    int $T_SYSCALL; \
    ret

SYSCALL(fork)
SYSCALL(exit)
SYSCALL(wait)
```

Trap frame in xv6

- Trap frame is the structure pushed on kernel stack before trap handling, popped when returning from trap
- Contains various registers that are saved on kernel stack before trap handling
- The “int n” instruction pushes a few registers (old PC, old SP etc.) and jumps to kernel code to handle trap
- The kernel code that is run next will push remaining registers on kernel stack, and then proceed to handle the trap
- Think: why are EIP, ESP pushed by hardware and not by kernel code?



```
// Layout of the trap frame built on the stack by the
// hardware and by trapasm.S, and passed to trap().
struct trapframe {
  // registers as pushed by pusha
  uint edi;
  uint esi;
  uint ebp;
  uint oesp;      // useless & ignored
  uint ebx;
  uint edx;
  uint ecx;
  uint eax;

  // rest of trap frame
  ushort gs;
  ushort padding1;
  ushort fs;
  ushort padding2;
  ushort es;
  ushort padding3;
  ushort ds;
  ushort padding4;
  uint trapno;

  // below here defined by x86 hardware
  uint err;
  uint eip;
  ushort cs;
  ushort padding5;
  uint eflags;

  // below here only when crossing rings, such as from user to kernel
  uint esp;
  ushort ss;
  ushort padding6;
};
```

xv6 kernel trap handler

- IDT entries for all interrupts will set eip to point to the kernel trap handler “alltraps”
- Alltraps assembly code pushes remaining registers to complete trapframe on kernel stack
- Invokes C trap handling function named “trap”
  - Push pointer to trapframe (current top of stack, esp) as argument to the C function

```
#include "mmu.h"

  # vectors.S sends all traps here.
.globl alltraps
alltraps:
  # Build trap frame.
  pushl %ds
  pushl %es
  pushl %fs
  pushl %gs
  pushal

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

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

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

C trap handler function in xv6

- C trap handler performs different actions based on kind of trap
- Different types of traps identified using value of “n” in “int n”
- For system call, “n” equal to a value T_SYSCALL (in usys.S), indicating this trap is a system call
  - Trap handler invokes common system call function
  - Looks at system call number stored in eax and calls the corresponding function (fork, exec, …)
  - Return value of syscall stored in eax

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

```c
void
syscall(void)
{
  int num;
  struct proc *curproc = myproc();

  num = curproc->tf->eax;
  if(num > 0 && num < NELEM(syscalls) && syscalls[num]) {
    curproc->tf->eax = syscalls[num]();
  } else {
    cprintf("%d %s: unknown sys call %d\n",
            curproc->pid, curproc->name, num);
    curproc->tf->eax = -1;
  }
}
```

- If interrupt from a device, corresponding driver code called
- Timer is special hardware interrupt, generated periodically to trap to kernel

```
switch(tf->trapno){
case T_IRQ0 + IRQ_TIMER:
  if(cpuid() == 0){
    acquire(&tickslock);
    ticks++;
    wakeup(&ticks);
    release(&tickslock);
  }
  lapiceoi();
  break;
case T_IRQ0 + IRQ_IDE:
  ideintr();
  lapiceoi();
  break;
case T_IRQ0 + IRQ_IDE+1:
  // Bochs generates spurious IDE1 interrupts.
  break;
case T_IRQ0 + IRQ_KBD:
  kbdintr();
  lapiceoi();
  break;
  // Force process to give up CPU on clock tick.
  // If interrupts were on while locks held, would need to check nlock.
  if(myproc() && myproc()->state == RUNNING &&
     tf->trapno == T_IRQ0+IRQ_TIMER)
    yield();

```

```
// Give up the CPU for one scheduling round.
void
yield(void)
{
  acquire(&ptable.lock);
  myproc()->state = RUNNABLE;
  sched();
  release(&ptable.lock);
}
```

- On timer interrupt, a process “yields” CPU to scheduler
- Ensures a process does not run for too long

Return from trap

- Assembly code “trapret”
- Pop all state from kernel stack
- Return-from-trap instruction “iret” does the opposite of int
  - Pop values pushed by “int”
  - Change back privilege level
- Execution of pre-trap code can resume

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  popl %ds
  addl $0x8, %esp  # trapno and errcode
  iret
```

xv6 trap handling: the complete story

- System calls, program faults, or hardware interrupts cause CPU to run "int n" instruction and "trap" to OS
- The trap instruction (int n) causes CPU to switch ESP to kernel stack, EIP to kernel trap handling code "alltraps"
- Pre-trap CPU state is saved on kernel stack in the trap frame by int instruction + alltraps code
- Alltraps assembly code calls C trap handling function
- C trap handler handles trap suitably and returns to trapret code
- Trapret pops register context and runs "iret" instruction to return from trap to user mode of process

Summary

A process running in user mode carefree
Encounters a trap that forces it to be
More responsible in the kernel mode
As it traps into the OS code

"Don't panic", says the OS, "I'll handle this"
Saves context on the trap frame and dives right in
To its trap handling code that does what must be done
To handle the trap and bring the process back to run