Why do we need interrupts?

Remember:
hardware interface is designed to help OS
Why do we need interrupts?

- Two main use cases:
  - **Synchronous**: Something bad happened and OS needs to fix it
    - Program tries to access an unmapped page (OS maps the page if it's on disk)
  - **Asynchronous**: Notifications from external devices
    - Network packet arrived (OS will copy the packet from temporary buffer in memory (to avoid overflowing) and may switch to a process waiting on that packet)
    - Timer interrupt (OS may switch to another process)

- A third, special, use-case
  - **It's also synchronous**: For a while an interrupt, i.e., int 0xXX instruction, was used as a mechanism to transfer control flow from user-level to kernel in a secure manner
    - In other words, to implement system calls
    - Now, a faster mechanism is available (sysenter)
How do we handle an interrupt?
Handling interrupts and exceptions

- In both synchronous and asynchronous cases the CPU follows the **same procedure**
  - Stop execution of the current program
  - Start execution of a handler
  - Processor accesses the handler through an entry in the Interrupt Descriptor Table (IDT)
- Each interrupt is defined by a number
  - E.g., 14 is pagefault, 3 debug
  - This number is an index into the interrupt table (IDT)
There might be two cases

- **Interrupt requires no change of privilege level**
  - i.e., the CPU runs kernel code (privilege level 0) when
    - a timer interrupt arrives, or
    - kernel tries to access an unmapped page

- **Interrupt changes privilege level**
  - i.e., the CPU runs **user** code (privilege level 3) when
    - a timer interrupt arrives, or
    - User code tries to access an unmapped page
Case #1: Interrupt path no change in privilege level

- e.g., we're already running in the kernel
Interrupt descriptor table (IDT)

- Is pointed by the IDTR register
- Virtual address

- OS configures the value and loads it into the register (normally during boot)
Interrupt descriptor

 Interrupt Gate

<table>
<thead>
<tr>
<th>31</th>
<th>16 15 14 13 12</th>
<th>8 7 5 4</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Offset 31..16</td>
<td>P</td>
<td>D</td>
<td>PL</td>
</tr>
</tbody>
</table>

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<tr>
<th>31</th>
<th>16 15</th>
<th>0</th>
</tr>
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<tbody>
<tr>
<td>Segment Selector</td>
<td>Offset 15..0</td>
<td>0</td>
</tr>
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</table>
Interrupt descriptor

- We will walk through these fields gradually
  - For now we care about vector offset
  - Pointer to the interrupt handler
Interrupt handlers

- Just plain old code in the kernel
- The IDT stores a pointer to the right handler routine
Interrupt path

Interrupt Vector 

Timer:IRQ0 -> vector 32

Kernel stack

Last stack frame

EBP

Argument 1
Argument 2
Calling EIP ++
Old EBP
Local variables
Saved local values, e.g. push EAX, etc

IDT

... 
CS: HANDLER ADDR
...
...

Kernel code

CS: #1  EIP: <kernel>
SS: #2  ESP: <kernel>
GDT: gdt  TSS: tss
IDT: idt  CR3: pt

vector32
Processing of interrupt (same PL)

1. Push the current contents of the EFLAGS, CS, and EIP registers (in that order) on the stack.
2. Push an error code (if appropriate) on the stack.
3. Load the segment selector for the new code segment and the new instruction pointer (from the interrupt gate or trap gate) into the CS and EIP registers.
4. If the call is through an interrupt gate, clear the IF flag in the EFLAGS register (disable further interrupts).
5. Begin execution of the handler.
### Stack Usage with No Privilege-Level Change

**Interrupted Procedure’s and Handler’s Stack**

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<th>EFLAGS</th>
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<tr>
<td>EIP</td>
</tr>
<tr>
<td>Error Code</td>
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ESP Before Transfer to Handler

ESP After Transfer to Handler
Interrupt path

- EBP
- Argument 1
- Argument 2
- Calling EIP ++
- Old EBP
- Local variables
- Saved local values, e.g., push EAX, etc
- EFLAGS
- CS
- EIP
- Error code

- Interrupt Vector #
- Timer: IRQ0 -> vector 32
- ... CS : HANDLER ADDR
- ... ...

- Kernel code
- CS : #1
- SS : #2
- GDT: gdt
- IDT: idt
- EIP: <kernel>
- ESP: <kernel>
- TSS: tss
- CR3: pt
- vector32
Processing of interrupt (cross PL)

• Need to change privilege level...
Detour:
What are those privilege levels?
Recap: Can a process overwrite kernel memory?
Privilege levels

- Each segment has a privilege level
  - DPL (descriptor privilege level)
  - 4 privilege levels ranging 0-3
Logical Address (or Far Pointer) → Segment Selector → Offset → Linear Address Space → Global Descriptor Table (GDT) → Segment Selector → Segment Base Address → Linear Address → Segment → Page Directory → Page Table → Entry → Page → Physical Address Space
Privilege levels

- Each segment has a privilege level
  - DPL (descriptor privilege level)
  - 4 privilege levels ranging 0-3
Privilege levels

- Currently running code also has a privilege level
  - “Current privilege level” (CPL): 0-3
  - It is saved in the %cs register
    - It was loaded there when the descriptor for the currently running code was loaded into %cs
Privilege level transitions

• CPL can access only less privileged segments
  – E.g., 0 can access 1, 2, 3

• Some instructions are “privileged”
  • Can only be invoked at CPL = 0
  • Examples:
    – Load GDT
    – MOV <control register>
      • E.g. reload a page table by changing CR3
Xv6 example: started boot (no CPL yet)
Xv6 example: prepare to load GDT entry #1

ljmp 1, $start32
Privilege levels

- Each segment has a privilege level
  - DPL (descriptor privilege level)
  - 4 privilege levels ranging 0-3
Now CPL=0. We run in the kernel.
iret: return to user, load GDT #4
Run in user, CPL=3
Real world

- Only two privilege levels are used in modern OSes:
  - OS kernel runs at 0
  - User code runs at 3
- This is called “flat” segment model
  - Segments for both 0 and 3 cover entire address space
- But then... how the kernel is protected?
Real world

- Only two privilege levels are used in modern OSes:
  - OS kernel runs at 0
  - User code runs at 3
- This is called “flat” segment model
  - Segments for both 0 and 3 cover entire address space
- But then... how the kernel is protected?
  - Page tables
Page table: user bit

- Each entry (both Level 1 and Level 2) has a bit
  - If set, code at privilege level 3 can access
  - If not, only levels 0-2 can access
- Note, only 2 levels, not 4 like with segments
- All kernel code is mapped with the user bit clear
  - This protects user-level code from accessing the kernel
End of detour:
Back to handling interrupts
Recap: interrupt path, no PL change
Processing of an interrupt when change of a privilege level is required
Processing of interrupt (cross PL)

- Assume we're at CPL = 3 (user)
Interrupt descriptor (an entry in the IDT)

- Interrupt is allowed if...
  - current privilege level (CPL) is less or equal to descriptor privilege level (DPL)
  - The kernel protects device interrupts from user
Interrupt descriptor (an entry in the IDT)

- Note that this new segment can be more privileged
  - E.g., CPL = 3, DPL = 3, new segment can be PL = 0
  - This is how user-code (PL=3) transitions into kernel (PL=0)
Interrupt path

Process

User stack of a process (can grow up to 2GBs)

Code, data, heap

Interrupt Vector #

Timer: IRQ0 -> vector 32

GDT

IDT

Page table
Level 1

Level 2

Kernel code

vector 32

EBP

Argument 1
Argument 2
Calling EIP ++
Old EBP
Local variables
Saved local values, e.g. push EAX, etc

Last stack frame

CS : #4 (user) EIP: <user>
SS : #5 (user) ESP: <user>
GDT: gdt TSS: tss
IDT: idt CR3: pt
**Stack**

- Can we continue on the same stack?
But how hardware knows where it is?
TSS: Task State Segment (yet another table)

User stack of a process (can grow up to 2GBs)

Interrupt Vector #

Timer: IRQ0 -> vector 32

Kernel Stack of a process (4K)

GDT
NULL: 0x0
KCODE: 0 - 4GB
KDATA: 0 - 4GB
K_CPU: 4 bytes
CODE: 0 - 4GB
DATA: 0 - 4GB
TSS: sizeof(ts)

IDT
CS : HANDLER ADDR
...
...

TSS
...
SS: 0
ESP:...

Page table
Level 1
0 - 4MB
4 - 8MB
...

Level 2
2GB - 2GB + 4MB
...

Kernel code

vector32

CS : #1
EIP: <kernel>
SS : #2
ESP: <kernel>
GDT: gdt
TSS: tss
IDT: idt
CR3: pt

EBP →

Process

Last stack frame

Code, data, heap
Task State Segment

- Another magic control block
  - Pointed to by special task register (TR)
- Lots of fields for rarely-used features
- A feature we care about in a modern OS:
  - Location of kernel stack (fields SS/ESP)
    - Stack segment selector
    - Location of the stack in that segment
Processing of interrupt (cross PL)

1. Save ESP and SS in a CPU-internal register

2. Load SS and ESP from TSS

3. Push user SS, user ESP, user EFLAGS, user CS, user EIP onto new stack (kernel stack)

4. Set CS and EIP from IDT descriptor's segment selector and offset

5. If the call is through an interrupt gate clear some EFLAGS bits

6. Begin execution of a handler
Stack Usage with Privilege-Level Change

Interrupted Procedure’s Stack

ESP Before Transfer to Handler

Handler’s Stack

SS
ESP
EFLAGS
CS
EIP
Error Code

ESP After Transfer to Handler
Interrupted Procedure’s and Handler’s Stack

- EFLAGS
- CS
- EIP
- Error Code

ESP Before Transfer to Handler

ESP After Transfer to Handler

Stack Usage with No Privilege-Level Change
Complete interrupt path

User stack of a process (can grow up to 2GBs)

Code, data, heap

Timer: IRQ0 -> vector 32

Interrupt Vector #

User state (saved by hardware)

Kernel Stack of a process (4K)

Process

Last stack frame

Argument 1
Argument 2
Calling EIP ++
Old EBP
Local variables
Saved local values, e.g. push EAX, etc

EBP →

ESP →

CS : #1
SS : #2
GDT: gdt
IDT: idt
EIP: <kernel>
ESP: <kernel>
TSS: tss
CR3: pt

null: 0x0
kcode: 0 - 4GB
kdata: 0 - 4GB
K_CPU: 4 bytes
code: 0 - 4GB
data: 0 - 4GB
TSS: sizeof(ts)

IDT

Page table
Level 1

IDT: handler addr

TSS

Level 2

Kernel code

vector32
Return from an interrupt

• Starts with IRET

1. Restore the CS and EIP registers to their values prior to the interrupt or exception
2. Restore EFLAGS
3. Restore SS and ESP to their values prior to interrupt
   – This results in a stack switch
4. Resume execution of interrupted procedure
Interrupt descriptor table (IDT)
x86 interrupt descriptor table

Device IRQs

Reserved for the CPU

Software Configurable
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<th>Mnemonic</th>
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<td>DIV and IDIV instructions.</td>
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<td>Debug</td>
<td>Any code or data reference.</td>
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<tr>
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<td>Breakpoint</td>
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<td>BOUND Range Exceeded</td>
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<td>Invalid Opcode (UnDefined Opcode)</td>
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Interrupts

- Each type of interrupt is assigned an index from 0—255.
  - 0—31 are for processor interrupts fixed by Intel
  - E.g., 14 is always for page faults
- 32—255 are software configured
  - 32—47 are often used for device interrupts (IRQs)
  - Most device IRQ lines can be configured
  - Look up APICs for more info (Ch 4 of Bovet and Cesati)
  - 0x80 issues system call in Linux
    - Xv6 uses 0x40 (64) for the system call
Disabling interrupts

- Delivery of interrupts can be disabled with IF (interrupt flag) in EFLAGS register
- There is a couple of exceptions
  - Synchronous interrupts cannot be disabled
    - It doesn't make sense to disable a page fault
    - INT n – cannot be masked as it is synchronous
  - Non-maskable interrupts (see next slide)
    - Interrupt #2 in the IDT
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Nonmaskable interrupts (NMI)

• Delivered even if IF is clear, e.g. interrupts disabled
  • CPU blocks subsequent NMI interrupts until IRET

• Sources
  • External hardware asserts the NMI pin
  • Processor receives a message on the system bus, or the APIC serial bus with NMI delivery mode

• Delivered via vector #2
System calls
Software interrupts can be used to implement system calls

- The int N instruction provides a secure mechanism for kernel invocation
  - i.e., user can enter the kernel
  - But through a well-defined entry point
    - System call handler

- Xv6 uses vector 0x40 (or 64)
  - You can choose any other unused vector
  - Linux uses 0x80
    - Well now it uses sysenter instead of int 0x80 as it is faster
System call path

User stack of a process (can grow up to 2GBs)

Code, data, heap

Interrupt Vector #

Timer: IRQ0 -> vector 32

Kernel code

vector32

Kernel Stack of a process (4K)

User state (saved by hardware)

ESI →

Argument 1
Argument 2
Calling EIP ++
Old EBP
Local variables
Saved local values, e.g. push EAX, etc

Process

EBP →

Last stack frame

SS
ESP
EFLAGS
CS
EIP

Level 1

0 - 4KB
4 - 32KB
...
2GB - 2GB + 4MB

Level 2

0 - 4K
4K - 8K
...
(4MB-4K) - 4MB

Page table

GDT

NULL: 0x0
KCODE: 0 - 4GB
KBDA: 0 - 4GB
K_CPU: 4 bytes
CODE: 0 - 4GB
DATA: 0 - 4GB
TSS: sizeof(tss)

IDT

TSS

CS : HANDLER ADDR
...
...
...
SS9:
...
ESPR:

CS : #1
SS : #2
GDT: gdt
TSS: tss
IDT: idt
CR3: pt

CPU
3316 void
tvinit(void)
3318 {
3319   int i;
3320
3321   for(i = 0; i < 256; i++)
3322     SETGATE(idt[i], 0, SEG_KCODE<<3, vectors[i], 0);
3323   SETGATE(idt[T_SYSCALL], 1, SEG_KCODE<<3,
3324       vectors[T_SYSCALL], DPL_USER);
3325   initlock(&tickslock, "time");
3326 }

Initialize IDT

- tvinit() is called from main()
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);

    initlock(&tickslock, "time");
}
Protection

• Generally user code cannot invoke int X
  • i.e., can't issue int 14 (a page fault)
  • OS configures the IDT in such a manner that invocation of all int X instructions besides 0x40 triggers a general protection fault exception
    – Interrupt vector 13
Remember this slide: interrupt descriptor (an entry in the IDT)

- Interrupt is allowed if...
  - current privilege level (CPL) is less or equal to descriptor privilege level (DPL)
  - The kernel protects device interrupts from user
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);

  initlock(&tickslock, "time");
}

Initialize IDT

- A couple of important details
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);

  initlock(&tickslock, "time");
}

Initialize IDT

- Only int T_SYSCALL can be called from user-level
3316  void
tvinit(void)
3318  {
3319    int i;
3320
3321    for(i = 0; i < 256; i++)
3322      SETGATE(idt[i], 0, SEG_KCODE<<3, vectors[i], 0);
3323    SETGATE(idt[T_SYSCALL], 1, SEG_KCODE<<3, vectors[T_SYSCALL], DPL_USER);
3324
3325    initlock(&tickslock, "time");
3326  }

Initialize IDT

- Syscall is a “trap”
- i.e., doesn't disable interrupts
Interrupt path through the xv6 kernel
Where does IDT (entry 64) point to?

vector64:

    pushl $0    // error code
    pushl $64   // vector #
    jmp alltraps

• Automatically generated
• From vectors.pl
• vector.S
Kernel stack after interrupt

User state (saved by hardware)

vector32

ESP

Kernel Stack of a process (4K)

int 0x64

vector64

Call stack: vector32()
Kernel stack after interrupt

User state (saved by hardware)
- SS
- ESP
- EFLAGS
- CS
- EIP
- 0
- 32
- DS
- ES
- FS
- GS
- All registers
- ESP

Kernel Stack of a process (4K)

Trap frame

Call stack:
- vector32()
- alltraps()

int 0x64
- vector64
- alltraps
Syscall number

• System call number is passed in the %eax register
  • To distinguish which syscall to invoke,
    - e.g., sys_read, sys_exec, etc.
• alltrap() saves it along with all other registers
alltraps:
# Build trap frame.
pushl %ds
pushl %es
pushl %fs
pushl %gs
pushal

# Set up data and per-cpu segments.
movw $(SEG_KDATA<<3), %ax
movw %ax, %ds
movw %ax, %es
movw $(SEG_KCPU<<3), %ax
movw %ax, %fs
movw %ax, %gs

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

- An assembler instruction that saves all registers on the stack

- https://c9x.me/x86/html/file_module_x86_id_270.html

  Temporary = ESP;
  Push(EAX);
  Push(ECX);
  Push(EDX);
  Push(EBX);
  Push(Temporary);
  Push(Temporary);
  Push(EBP);
  Push(ESI);
  Push(EDI);
alltraps:
# Build trap frame.
pushl %ds
pushl %es
pushl %fs
pushl %gs
pushal

# Set up data and per-cpu segments.
movw $(SEG_KDATA<<3), %ax
movw %ax, %ds
movw %ax, %es
movw $(SEG_KCPU<<3), %ax
movw %ax, %fs
movw %ax, %gs

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

The end result: call trap()
All interrupts, e.g. timer interrupt end up in a single function: trap()

```c
3351 trap(struct trapframe *tf) {
    ... switch(tf->trapno){
3363       case T_IRQ0 + IRQ_TIMER:
3364           if(cpu->id == 0){
3365               acquire(&tickslock);
3366               ticks++;
3367               wakeup(&ticks);
3368               release(&tickslock);
3369           }
3370       } break;
3372  ... break;
3423  if(proc && proc->state == RUNNING
            && tf->trapno == T_IRQ0+IRQ_TIMER)
3424       yield();
```
3351 trap(struct trapframe *tf)  
3352 {  
3353   if(tf->trapno == T_SYSCALL){  
3354     if(proc->killed)  
3355       exit();  
3356     proc->tf = tf;  
3357     syscall();  
3358     if(proc->killed)  
3359       exit();  
3360     return;  
3361   }  
3362  
3363   switch(tf->trapno){  
3364     case T_IRQ0 + IRQ_TIMER:
3365       Same for syscalls
syscall(void) {
  int num;

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

    num = proc->tf->eax;
    if(num > 0 && num < NELEM(syscalls) && syscalls[num])
    {
        proc->tf->eax = syscalls[num]();
    } else {
        cprintf("%d %s: unknown sys call %d\n", proc->pid, proc->name, num);
        proc->tf->eax = -1;
    }
}
static int (*syscalls[])(void) = {
    [SYS_fork] sys_fork,
    [SYS_exit] sys_exit,
    [SYS_wait] sys_wait,
    [SYS_pipe] sys_pipe,
    [SYS_read] sys_read,
    [SYS_kill] sys_kill,
    [SYS_exec] sys_exec,
    [SYS_fstat] sys_fstat,
    [SYS_chdir] sys_chdir,
    [SYS_dup] sys_dup,
    [SYS_getpid] sys_getpid,
    [SYS_sbrk] sys_sbrk,
    [SYS_sleep] sys_sleep,
    [SYS_uptime] sys_uptime,
    [SYS_open] sys_open,
    [SYS_write] sys_write,
    [SYS_mknod] sys_mknod,
    [SYS_unlink] sys_unlink,
    [SYS_link] sys_link,
    [SYS_mkdir] sys_mkdir,
    [SYS_close] sys_close,
};
How do user programs access system calls?

• It would be weird to write

    8410  pushl $argv
    8411  pushl $init
    8412  pushl $0 // where caller pc would be
    8413  movl $SYS_exec, %eax
    8414  int $T_SYSCALL

• ... every time we want to invoke a system call
• This is an example for the exec() system call
// system calls
int fork(void);
int exit(void) __attribute__((noreturn));
int wait(void);
int pipe(int*);
int write(int, void*, int);
int read(int, void*, int);
int close(int);
int kill(int);
int exec(char*, char**);
int open(char*, int);
int mknod(char*, short, short);
int unlink(char*);
int fstat(int fd, struct stat*);
int link(char*, char*);
...
Example

• From cat.asm

• if (write(1, buf, n) != n)

  A3:  53          push    ebx
  a4:  68 00 0b 00 00  push    0xb00
  a9:  6a 01          push    0x1
  ab:  e8 c2 02 00 00  call    372     <write>
• Note, different versions of gcc
  • and different optimization levels
• Will generate slightly different code
Example

- From cat.asm

```asm
if (write(1, buf, n) != n)

a0:   89 5c 24 08   mov    %ebx,0x8(%esp)

a4:   c7 44 24 04 00 0b 00   movl   $0xb00,0x4(%esp)

ab:   00

ac:   c7 04 24 01 00 00 00 00   movl   $0x1,(%esp)

b3:   e8 aa 02 00 00   call   362 <write>
```
Example

- From cat.asm

- if (write(1, buf, n) != n)

  a0: 89 5c 24 08  mov    %ebx,0x8(%esp)
  a4: c7 44 24 04 00 0b 00  movl   $0xb00,0x4(%esp)
  ab: 00
  ac: c7 04 24 01 00 00 00  movl   $0x1,(%esp)
  b3: e8 aa 02 00 00  call   362 <write>
Example

• From cat.asm

• if (write(1, buf, n) != n)

  a0: 89 5c 24 08  mov    %ebx,0x8(%esp)
  a4: c7 44 24 04 00 0b 00  movl   $0xb00,0x4(%esp)
  ab: 00
  ac: c7 04 24 01 00 00 00  movl   $0x1,(%esp)
  b3: e8 aa 02 00 00  call   362 <write>
Still not clear...

- The header file allows compiler to generate a call side invocation,
  - e.g., push arguments on the stack
- But where is the system call invocation itself
  - e.g., int $T_SYSCALL
Xv6 uses a SYSCALL macro to define a function for each system call invocation.

- E.g., fork() to invoke the “fork” system call.
Example

- Write system call from cat.asm

000000362 <write>:

SYSCALL(write)

362: b8 10 00 00 00  mov    $0x10,%eax
367: cd 40         int    $0x40
369: c3            ret
System call arguments

- Where are the system call arguments?
- How does kernel access them?
  - And returns results?
Example

- Write system call
  - `if (write(1, buf, n) != n)`

```c
5876 int
5877 sys_write(void)
5878 {
5879   struct file *f;
5880   int n;
5881   char *p;
5882
5883   if(argfd(0, 0, &f) < 0 || argint(2, &n) < 0 || argptr(1, &p, n) < 0)
5884     return -1;
5885   return filewrite(f, p, n);
5886 }
```
Example

• Write system call

  • if (write(1, buf, n) != n)

    5876 int
    5877 sys_write(void)
    5878 {
    5879   struct file *f;
    5880   int n;
    5881   char *p;
    5882
    5883   if(argfd(0, 0, &f) < 0 || argint(2, &n) < 0 || argptr(1, &p, n) < 0)
    5884     return -1;
    5885   return filewrite(f, p, n);
    5886 }
3543 // Fetch the nth 32-bit system call argument.
3544 int argint(int n, int *ip)
3545 {
3546     return fetchint(proc->tf->esp + 4 + 4*n, ip);
3547 }

3515 // Fetch the int at addr from the current process.
3516 int fetchint(uint addr, int *ip)
3517 {
3518     if(addr >= proc->sz || addr+4 > proc->sz)
3519         return -1;
3520     *ip = *(int*)(addr);
3521     return 0;
3522 }

argint(int n, int *ip)
3543 // Fetch the nth 32-bit system call argument.
3544 int
3545 argint(int n, int *ip)
3546 {
3547     return fetchint(proc->tf->esp + 4 + 4*n, ip);
3548 }

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3516 int
3517 fetchint(uint addr, int *ip)
3518 {
3519     if(addr >= proc->sz || addr+4 > proc->sz)
3520         return -1;
3521     *ip = *(int*)(addr);
3522     return 0;
3523 }

argint(int n, int *ip)
3543 // Fetch the nth 32-bit system call argument.
3544 int
3545 argint(int n, int *ip)
3546 {
3547     return fetchint(proc->tf->esp + 4 + 4*n, ip);
3548 }

3515 // Fetch the int at addr from the current process.
3516 int
3517 fetchint(uint addr, int *ip)
3518 {
3519     if(addr >= proc->sz || addr+4 > proc->sz)
3520         return -1;
3521     *ip = *(int*)(addr);
3522     return 0;
3523 }

• Start with the address where current user stack is (esp)
3543 // Fetch the nth 32-bit system call argument.
3544 int
3545 argint(int n, int *ip)
3546 {
3547   return fetchint(proc->tf->esp + 4 + 4*n, ip);
3548 }

3515 // Fetch the int at addr from the current process.
3516 int
3517 fetchint(uint addr, int *ip)
3518 {
3519   if(addr >= proc->sz || addr+4 > proc->sz)
3520     return -1;
3521   *ip = *(int*)(addr);
3522   return 0;
3523 }

• Skip return eip
3543 // Fetch the nth 32-bit system call argument.
3544 int
3545 argint(int n, int *ip)
3546 {
3547     return fetchint(proc->tf->esp + 4 + 4*n, ip);
3548 }

3515 // Fetch the int at addr from the current process.
3516 int
3517 fetchint(uint addr, int *ip)
3518 {
3519     if(addr >= proc->sz || addr+4 > proc->sz)
3520         return -1;
3521     *ip = *(int*)(addr);
3522     return 0;
3523 }

• Fetch n'th argument
3543 // Fetch the nth 32-bit system call argument.
3544 int
3545 argint(int n, int *ip)
3546 {
3547     return fetchint(proc->tf->esp + 4 + 4*n, ip);
3548 }

3515 // Fetch the int at addr from the current process.
3516 int
3517 fetchint(uint addr, int *ip)
3518 {
3519     if(addr >= proc->sz || addr+4 > proc->sz)
3520         return -1;
3521     *ip = *(int*)(addr);
3522     return 0;
3523 }

fetchint(uint addr, int *ip)
// Fetch the nth 32-bit system call argument.
int argint(int n, int *ip)
{
    return fetchint(proc->tf->esp + 4 + 4*n, ip);
}

// Fetch the int at addr from the current process.
int fetchint(uint addr, int *ip)
{
    if(addr >= proc->sz || addr+4 > proc->sz)
        return -1;
    *ip = *(int*)(addr);
    return 0;
}

fetchint(uint addr, int *ip)
Any idea for what argptr() shall do?

- Write system call
  - if (write(1, buf, n) != n)

```c
5876 int
5877 sys_write(void)
5878 {
5879   struct file *f;
5880   int n;
5881   char *p;
5882
5883   if(argfd(0, 0, &f) < 0 || argint(2, &n) < 0 || argptr(1, &p, n) < 0)
5884     return -1;
5885   return filewrite(f, p, n);
5886 }
```

- Remember, buf is a pointer to a region of memory
  - i.e., a buffer
  - of size n
// Fetch the nth word-sized system call argument as a pointer to a block of memory of size n bytes. Check that the pointer lies within the process address space.

int argptr(int n, char **pp, int size)
{
  int i;

  if(argint(n, &i) < 0)
    return -1;
  if((uint)i >= proc->sz || (uint)i+size > proc->sz)
    return -1;
  *pp = (char*)i;
  return 0;
}

argptr(uint addr, int *ip)
3550 // Fetch the nth word-sized system call argument as a pointer
3551 // to a block of memory of size n bytes. Check that the pointer
3552 // lies within the process address space.
3553 int
3554 argptr(int n, char **pp, int size)
3555 {
3556   int i;
3557
3558   if(argint(n, &i) < 0)
3559     return -1;
3560   if((uint)i >= proc->sz || (uint)i+size > proc->sz)
3561     return -1;
3562   *pp = (char*)i;
3563   return 0;
3564 }

• Check that the buffer is in user memory

argptr(uint addr, int *ip)
Summary

- We've learned how system calls work
Thank you