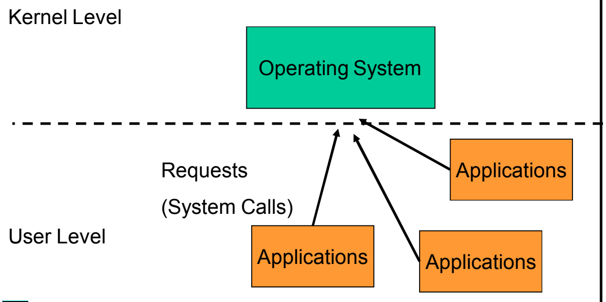
System Calls

Learning Outcomes

- A high-level understanding of System Calls
  - Mostly from the user's perspective
    - From textbook (section 1.6)
- Exposure architectural details of the MIPS R3000
  - Detailed understanding of the of exception handling mechanism
    - From "Hardware Guide" on class web site
- Understanding of the existence of compiler function calling conventions
  - Including details of the MIPS 'C' compiler calling convention
- Understanding of how the application kernel boundary is crossed with system calls in general
    - Including an appreciation of the relationship between a case study (OS/161 system call handling) and the general case.

Operating System System Calls



System Calls

- Can be viewed as special procedure calls
  - Provides for a controlled entry into the kernel
  - While in kernel, they perform a privileged operation
  - Returns to original caller with the result
- The system call interface represents the abstract machine provided by the operating system.

A Brief Overview of Classes System Calls

- From the user's perspective
  - Process Management
  - File I/O
  - Directories management
  - Some other selected Calls
  - There are many more
    - On Linux, see `man syscalls` for a list

Some System Calls For Process Management

Process management

Call	Description
pid = fork( )	Create a child process identical to the parent
pid = waitpid(pid, &statloc, options)	Wait for a child to terminate
s = execve(name, argv, environp)	Replace a process' core image
exit(status)	Terminate process execution and return status

Some System Calls For File Management

File management

Call	Description
fd = open(file, how, ...)	Open a file for reading, writing or both
s = close(fd)	Close an open file
n = read(fd, buffer, nbytes)	Read data from a file into a buffer
n = write(fd, buffer, nbytes)	Write data from a buffer into a file
position = lseek(fd, offset, whence)	Move the file pointer
s = stat(name, &buf)	Get a file's status information

Some System Calls For Directory Management

Directory and file system management

Call	Description
s = mkdir(name, mode)	Create a new directory
s = rmdir(name)	Remove an empty directory
s = link(name1, name2)	Create a new entry, name2, pointing to name1
s = unlink(name)	Remove a directory entry
s = mount(special, name, flag)	Mount a file system
s = umount(special)	Unmount a file system

Some System Calls For Miscellaneous Tasks

Miscellaneous

Call	Description
s = chdir(dirname)	Change the working directory
s = chmod(name, mode)	Change a file's protection bits
s = kill(pid, signal)	Send a signal to a process
seconds = time(&seconds)	Get the elapsed time since Jan. 1, 1970

System Calls

- A stripped down shell:

```
while (TRUE) {                                  /* repeat forever */
    type_prompt( );                             /* display prompt */
    read_command (command, parameters)          /* input from terminal */

if (fork() != 0) {                              /* fork off child process */
    /* Parent code */
    waitpid( -1, &status, 0);                   /* wait for child to exit */
} else {
    /* Child code */
    execve (command, parameters, 0);            /* execute command */
 }
}
```


System Calls

UNIX	Win32	Description
fork	CreateProcess	Create a new process
waitpid	WaitForSingleObject	Can wait for a process to exit
execve	(none)	CreateProcess = fork + execve
exit	ExitProcess	Terminate execution
open	CreateFile	Create a file or open an existing file
close	CloseHandle	Close a file
read	ReadFile	Read data from a file
write	WriteFile	Write data to a file
lseek	SetFilePointer	Move the file pointer
stat	GetFileAttributesEx	Get various file attributes
mkdir	CreateDirectory	Create a new directory
rmdir	RemoveDirectory	Remove an empty directory
link	(none)	Win32 does not support links
unlink	DeleteFile	Destroy an existing file
mount	(none)	Win32 does not support mount
umount	(none)	Win32 does not support mount
chdir	SetCurrentDirectory	Change the current working directory
chmod	(none)	Win32 does not support security (although NT does)
kill	(none)	Win32 does not support signals
time	GetLocalTime	Get the current time

Some Win32 API calls

The MIPS R2000/R3000

- Before looking at system call mechanics in some detail, we need a basic understanding of the MIPS R3000

MIPS R3000

- Load/store architecture
  - No instructions that operate on memory except load and store
  - Simple load/stores to/from memory from/to registers
    - Store word: `sw r4, (r5)`
      - Store contents of r4 in memory using address contained in register r5
    - Load word: `lw r3,(r7)`
      - Load contents of memory into r3 using address contained in r7
      - Delay of one instruction after load before data available in destination register
        - » Must always an instruction between a load from memory and the subsequent use of the register.
  - `lw, sw, lb, sb, lh, sh`,....

MIPS R3000

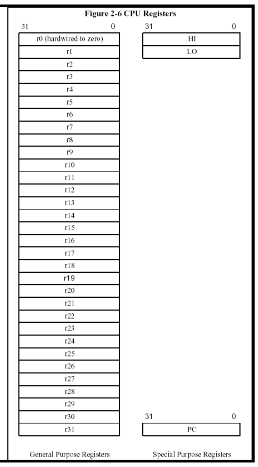
- Arithmetic and logical operations are register to register operations
  - E.g., add r3, r2, r1
  - No arithmetic operations on memory
- Example
  - `add r3, r2, r1` ⇒ r3 = r2 + r1
- Some other instructions
  - `add, sub, and, or, xor, sll, srl`

MIPS R3000

- All instructions are encoded in 32-bit
- Some instructions have *immediate* operands
  - Immediate values are constants encoded in the instruction itself
  - Only 16-bit value
  - Examples
    - Add Immediate: `addi r2, r1, 2048`
      - ⇒ r2 = r1 + 2048
    - Load Immediate : `li r2, 1234`
      - ⇒ r2 = 1234

MIPS Registers

- User-mode accessible registers
  - 32 general purpose registers
    - r0 hardwired to zero
    - r31 the *link* register for jump-and-link (JAL) instruction
  - HI/LO
    - 2 * 32-bits for multiply and divide
  - PC
    - Not directly visible
    - Modified implicitly by jump and branch instructions



Branching and Jumping

- Branching and jumping have a *branch delay slot*
  - The instruction following a branch or jump is always executed prior to destination

```
    li   r2, 1
    sw r0,(r3)
    j    1f
    li   r2, 2
    li   r2, 3
1:  sw r2, (r3)
```


Jump and Link Instruction

- JAL is used to implement function calls
  - r31 = PC+8
- Return Address register (RA) is used to return from function call

```
    :
    jal  1f
    nop
    lw r4,(r6)
    :
1:  sw r2, (r3)
    :
    jr r31
    nop
```

MIPS R3000

- RISC architecture – 5 stage pipeline

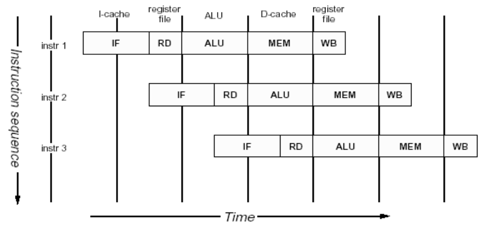


Figure 1.1. MIPS 5-stage pipeline

Coprocessor 0

- The processor control registers are located in CP0
  - Exception management registers
  - Translation management registers
- CP0 is manipulated using mtc0 (move to) and mfc0 (move from) instructions
  - mtc0/mfc0 are only accessible in kernel mode.

CP0 Registers

- Exception Management
  - c0_cause
    - Cause of the recent exception
  - c0_status
    - Current status of the CPU
  - c0_epc
    - Address of the instruction that caused the exception
  - c0_badvaddr
    - Address accessed that caused the exception
- Miscellaneous
  - c0_prid
    - Processor Identifier
- Memory Management
  - c0_index
  - c0_random
  - c0_entryhi
  - c0_entrylo
  - c0_context
  - More about these later in course

c0_status

31	30	29	28	27–26	25	24–23	22	21	20	19	18	17	16
CU3	CU2	CU1	CU0	0	RE	0	BEV	TS	PE	CM	PZ	SwC	IsC

15–8	7–6	5	4	3	2	1	0
IM	0	KUo	IEo	KUp	IEp	KUc	IEc

Figure 3.2. Fields in status register (SR)

- For practical purposes, you can ignore most bits
  - Green background is the focus

c0_status

31	30	29	28	27–26	25	24–23	22	21	20	19	18	17	16
CU3	CU2	CU1	CU0	0	RE	0	BEV	TS	PE	CM	PZ	SwC	IsC

15–8	7–6	5	4	3	2	1	0
IM	0	KUo	IEo	KUp	IEp	KUc	IEc

Figure 3.2. Fields in status register (SR)

- IM
  - Individual interrupt mask bits
  - 6 external
  - 2 software
- KU
  - 0 = kernel
  - 1 = user mode
- IE
  - 0 = all interrupts masked
  - 1 = interrupts enable
    - Mask determined via IM bits
- c, p, o = current, previous, old

c0_cause

31	30	29–28	27–16	15–8	7	6–2	1–0
BD	0	CE	0	IP	0	ExcCode	0

Figure 3.3. Fields in the Cause register

- IP
  - Interrupts pending
    - 8 bits indicating current state of interrupt lines
- CE
  - Coprocessor error
    - Attempt to access disabled Copro.
- BD
  - If set, the instruction that caused the exception was in a branch delay slot
- ExcCode
  - The code number of the exception taken

Exception Codes

ExcCode Value	Mnemonic	Description
0	Int	Interrupt
1	Mod	"TLB modification"
2	TLBL	"TLB load/TLB store"
3	TLBS	
4	AdEL	Address error (on load/I-fetch or store respectively). Either an attempt to access outside kuseg when in user mode, or an attempt to read a word or half-word at a misaligned address.
5	AdES	

Table 3.2. ExcCode values: different kinds of exceptions

Exception Codes

ExcCode Value	Mnemonic	Description
6	IBE	Bus error (instruction fetch or data load, respectively). External hardware has signalled an error of some kind; proper exception handling is system-dependent. The R30xx family CPUs can't take a bus error on a store; the write buffer would make such an exception "imprecise".
7	DBE	
8	Syscall	Generated unconditionally by a *syscall* instruction.
9	Bp	Breakpoint - a *break* instruction.
10	RI	"reserved instruction"
11	CpU	"Co-Processor unusable"
12	Ov	"arithmetic overflow". Note that "unsigned" versions of instructions (e.g. *addu*) never cause this exception.
13-31	-	reserved. Some are already defined for MIPS CPUs such as the R6000 and R4xxx

Table 3.2. ExcCode values: different kinds of exceptions

c0_epc

- The Exception Program Counter
  - Points to address of where to restart execution after handling the exception or interrupt
  - Example
    - Assume `sw r3,(r4)` causes a fault exception

Aside: We are ignore BD-bit in c0_cause which is also used in reality on rare occasions.

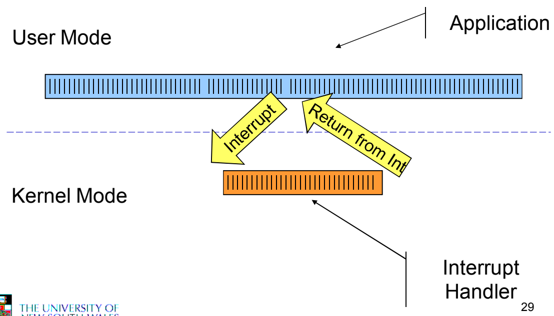
```
nop
sw r3 (r4)   <-- c0_epc
nop
```


Exception Vectors

Program address	"segment"	Physical Address	Description
0x8000 0000	kseg0	0x0000 0000	TLB miss on *kuseg* reference only.
0x8000 0080	kseg0	0x0000 0080	All other exceptions.
0xbfc0 0100	kseg1	0x1fc0 0100	Uncached alternative *kuseg* TLB miss entry point (used if *SR* bit BEV set).
0xbfc0 0180	kseg1	0x1fc0 0180	Uncached alternative for all other exceptions, used if *SR* bit BEV set).
0xbfc0 0000	kseg1	0x1fc0 0000	The "reset exception".

Table 4.1. Reset and exception entry points (vectors) for R30xx family

Simple Interrupt Walk-through

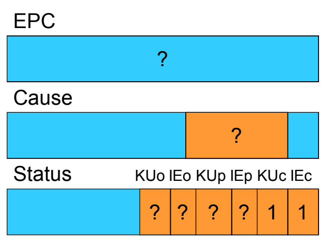


Hardware exception handling

PC

0x12345678

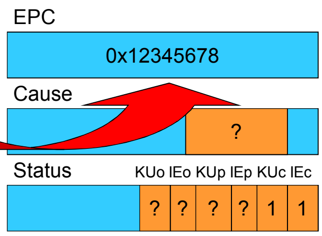
- Let's now walk through an exception
  - Assume an interrupt occurred as the previous instruction completed
  - Note: We are in user mode with interrupts enabled



Hardware exception handling

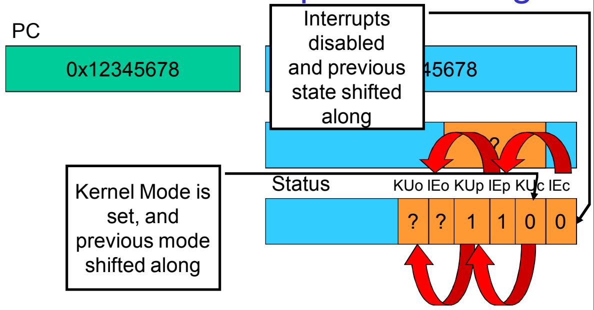
PC

0x12345678

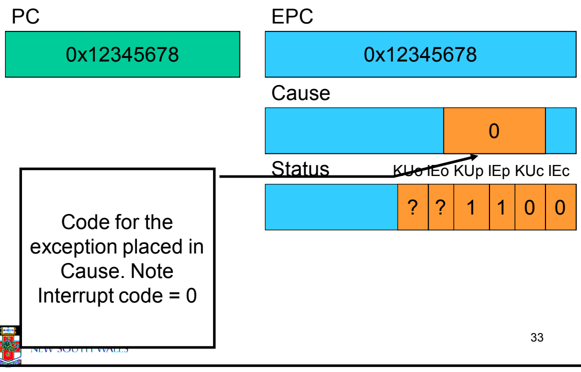


- Instruction address at which to restart after the interrupt is transferred to EPC

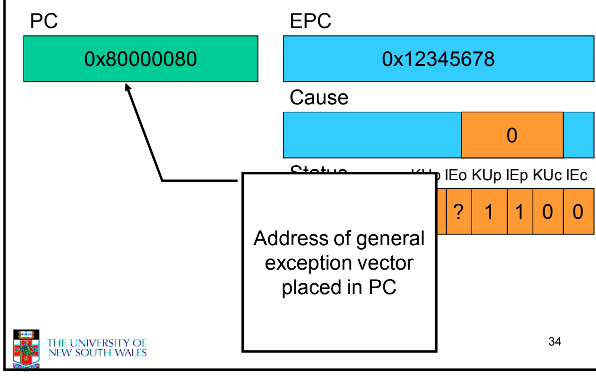
Hardware exception handling



Hardware exception handling



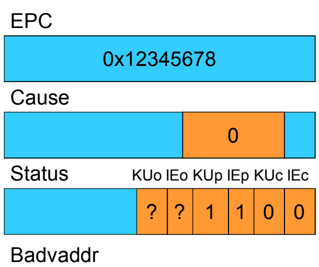
Hardware exception handling



Hardware exception handling

PC

0x80000080



- CPU is now running in kernel mode at 0x80000080, with interrupts disabled
- All information required to
  - Find out what caused the exception
  - Restart after exception handling

  is in coprocessor registers

Returning from an exception

- For now, lets ignore
  - how the exception is actually handled
  - how user-level registers are preserved
- Let's simply look at how we return from the exception

Returning from an exception

PC: 0x80001234

EPC: 0x12345678

Cause: 0

Status: KUo IEo KUp IEp KUc IEc

- This code to return is

```
lw   r27, saved_epc
nop
jr   r27
rfe
```

Load the contents of EPC which is usually moved earlier to somewhere in memory by the exception handler

Returning from an exception

PC: 0x12345678

EPC: 0x12345678

Cause: 0

Status: KUo IEo KUp IEp KUc IEc — 1 1 0 0

- This code to return is

```
lw   r27, saved_epc
nop
jr   r27
rfe
```

Store the EPC back in the PC

Returning from an exception

PC: 0x12345678

Cause: 0

Status: KUo IEo KUp IEp KUc IEc — ? ? ? ? 1 1

- This code to retur

```
lw   r27, saved_ep
nop
jr   r27
rfe
```

In the *branch delay slot*, execute a *restore from exception* instruction

Returning from an exception

PC: 0x12345678

EPC: 0x12345678

Cause: 0

Status: KUo IEo KUp IEp KUc IEc — ? ? ? ? 1 1

- We are now back in the same state we were in when the exception happened

Function Stack Frames

- Each function call allocates a new stack frame for local variables, the return address, previous frame pointer etc.
- Example: assume f1() calls f2(), which calls f3().

Stack

Frame Pointer → f1() stack frame

Stack Pointer →

Function Stack Frames

- Each function call allocates a new stack frame for local variables, the return address, previous frame pointer etc.
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Stack

f1() stack frame

Frame Pointer → f2() stack frame

Stack Pointer →

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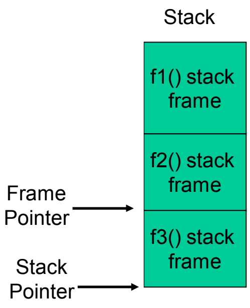


Software Register Conventions

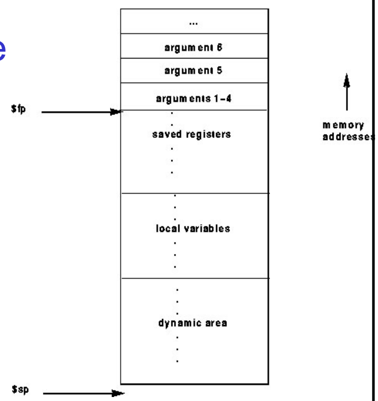
- Given 32 registers, which registers are used for
  - Local variables?
  - Argument passing?
  - Function call results?
  - Stack Pointer?

Software Register Conventions

Reg No	Name	Used for
0	zero	Always returns 0
1	at	(assembler temporary) Reserved for use by assembler
2-3	v0-v1	Value (except FP) returned by subroutine
4-7	a0-a3	(arguments) First four parameters for a subroutine
8-15	t0-t7	(temporaries) subroutines may use without saving
24-25	t8-t9	
16-23	s0-s7	Subroutine "register variables"; a subroutine which will write one of these must save the old value and restore it before it exits, so the *calling* routine sees their values preserved.
26-27	k0-k1	Reserved for use by interrupt/trap handler - may change under your feet
28	gp	global pointer - some runtime systems maintain this to give easy access to (some) "static" or "extern" variables.
29	sp	stack pointer
30	s8/fp	9th register variable. Subroutines which need one can use this as a "frame pointer".
31	ra	Return address for subroutine

Stack Frame

- MIPS calling convention for gcc
  - Args 1-4 have space reserved for them



Example Code

```
main ()
{
  int i;

  i =
  sixargs(1,2,3,4,5,6);
}
```

```
int sixargs(int a, int b,
  int c, int d, int e,
  int f)
{
  return a + b + c + d
       + e + f;
}
```



```
0040011c <main>:
  40011c:     27bdffd8      addiu   sp,sp,-40
  400120:     afbf0024      sw      ra,36(sp)
  400124:     afbe0020      sw      s8,32(sp)
  400128:     03a0f021      move    s8,sp
  40012c:     24020005      li      v0,5
  400130:     afa20010      sw      v0,16(sp)
  400134:     24020006      li      v0,6
  400138:     afa20014      sw      v0,20(sp)
  40013c:     24040001      li      a0,1
  400140:     24050002      li      a1,2
  400144:     24060003      li      a2,3
  400148:     0c10002c      jal     4000b0 <sixargs>
  40014c:     24070004      li      a3,4
  400150:     afc20018      sw      v0,24(s8)
  400154:     03c0e821      move    sp,s8
  400158:     8fbf0024      lw      ra,36(sp)
  40015c:     8fbe0020      lw      s8,32(sp)
  400160:     03e00008      jr      ra
  400164:     27bd0028      addiu   sp,sp,40
   ...
```

```
004000b0 <sixargs>:
  4000b0:       27bdfff8        addiu   sp,sp,-8
  4000b4:       afbe0000        sw      s8,0(sp)
  4000b8:       03a0f021        move    s8,sp
  4000bc:       afc40008        sw      a0,8(s8)
  4000c0:       afc5000c        sw      a1,12(s8)
  4000c4:       afc60010        sw      a2,16(s8)
  4000c8:       afc70014        sw      a3,20(s8)
  4000cc:       8fc30008        lw      v1,8(s8)
  4000d0:       8fc2000c        lw      v0,12(s8)
  4000d4:       00000000        nop
  4000d8:       00621021        addu    v0,v1,v0
  4000dc:       8fc30010        lw      v1,16(s8)
  4000e0:       00000000        nop
  4000e4:       00431021        addu    v0,v0,v1
  4000e8:       8fc30014        lw      v1,20(s8)
  4000ec:       00000000        nop
  4000f0:       00431021        addu    v0,v0,v1
  4000f4:       8fc30018        lw      v1,24(s8)
  4000f8:       00000000        nop
```



```
  4000fc:       00431021        addu    v0,v0,v1
  400100:       8fc3001c        lw      v1,28(s8)
  400104:       00000000        nop
  400108:       00431021        addu    v0,v0,v1
  40010c:       03c0e821        move    sp,s8
  400110:       8fbe0000        lw      s8,0(sp)
  400114:       03e00008        jr      ra
  400118:       27bd0008        addiu   sp,sp,8
```


System Calls

Continued

User and Kernel Execution

- Simplistically, execution state consists of
  - Registers, processor mode, PC, SP
- User applications and the kernel have their own execution state.
- System call mechanism safely transfers from user execution to kernel execution and back.

System Call Mechanism in Principle

- Processor mode
  - Switched from user-mode to kernel-mode
    - Switched back when returning to user mode
- SP
  - User-level SP is saved and a kernel SP is initialised
    - User-level SP restored when returning to user-mode
- PC
  - User-level PC is saved and PC set to kernel entry point
    - User-level PC restored when returning to user-level
  - Kernel entry via the designated entry point must be strictly enforced

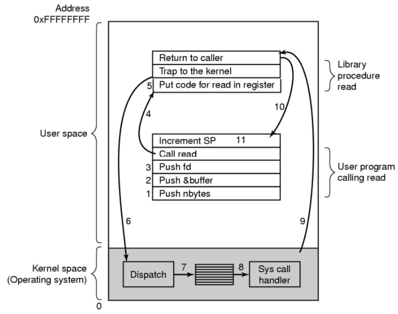
System Call Mechanism in Principle

- Registers
  - Set at user-level to indicate system call type and its arguments
    - A convention between applications and the kernel
  - Some registers are preserved at user-level or kernel-level in order to restart user-level execution
    - Depends on language calling convention etc.
  - Result of system call placed in registers when returning to user-level
    - Another convention

Why do we need system calls?

- Why not simply jump into the kernel via a function call????
  - Function calls do not
    - Change from user to kernel mode
      - and eventually back again
    - Restrict possible entry points to secure locations

Steps in Making a System Call



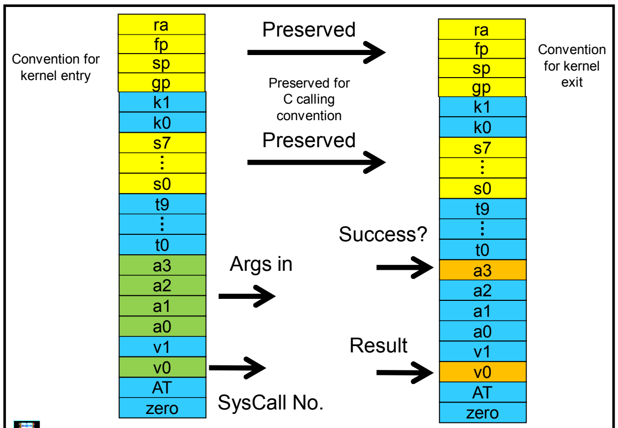
There are 11 steps in making the system call read (fd, buffer, nbytes)

MIPS System Calls

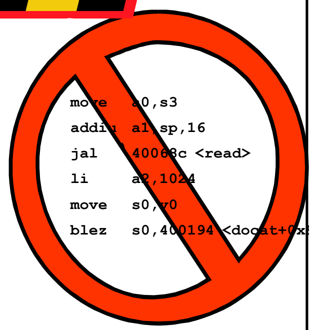
- System calls are invoked via a *syscall* instruction.
  - The *syscall* instruction causes an exception and transfers control to the general exception handler
  - A convention (an agreement between the kernel and applications) is required as to how user-level software indicates
    - Which system call is required
    - Where its arguments are
    - Where the result should go

OS/161 Systems Calls

- OS/161 uses the following conventions
  - Arguments are passed and returned via the normal C function calling convention
  - Additionally
    - Reg v0 contains the system call number
    - On return, reg a3 contains
      - 0: if success, v0 contains successful result
      - not 0: if failure, v0 has the errno.
        - » v0 stored in errno
        - » -1 returned in v0



- Seriously low-level code follows
- This code is not for the faint hearted



User-Level System Call Walk Through

```
int read(int filehandle, void *buffer, size_t size)
```

- Three arguments, one return value
- Code fragment calling the read function

```
400124:   02602021    move   a0,s3
400128:   27a50010    addiu  a1,sp,16
40012c:   0c1001a3    jal    40068c <read>
400130:   24060400    li     a2,1024
400134:   00408021    move   s0,v0
400138:   1a000016    blez   s0,400194 <docat+0x94>
```

- Args are loaded, return value is tested

The read() syscall function part 1

```
0040068c <read>:
  40068c: 08100190  j    400640 <__syscall>
  400690: 24020005  li   v0,5
```

- Appropriate registers are preserved
  - Arguments (a0-a3), return address (ra), etc.
- The syscall number (5) is loaded into v0
- Jump (not jump and link) to the common syscall routine

The read() syscall function part 2

Generate a syscall exception

```
00400640 <__syscall>:
  400640:   0000000c    syscall
  400644:   10e00005    beqz  a3,40065c <__syscall+0x1c>
  400648:   00000000    nop
  40064c:   3c011000    lui   at,0x1000
  400650:   ac220000    sw    v0,0(at)
  400654:   2403ffff    li    v1,-1
  400658:   2402ffff    li    v0,-1
  40065c:   03e00008    jr    ra
  400660:   00000000    nop
```


The read() syscall function part 2

Test success, if yes, branch to return from function

```
00400640 <__syscall>:
  400640:   0000000c    syscall
  400644:   10e00005    beqz  a3,40065c <__syscall+0x1c>
  400648:   00000000    nop
  40064c:   3c011000    lui   at,0x1000
  400650:   ac220000    sw    v0,0(at)
  400654:   2403ffff    li    v1,-1
  400658:   2402ffff    li    v0,-1
  40065c:   03e00008    jr    ra
  400660:   00000000    nop
```


The read() syscall function part 2

If failure, store code in *errno*

```
00400640 <__syscall>:
  400640:   0000000c    syscall
  400644:   10e00005    beqz  a3,40065c
  400648:   00000000    nop
  40064c:   3c011000    lui   at,0x1000
  400650:   ac220000    sw    v0,0(at)
  400654:   2403ffff    li    v1,-1
  400658:   2402ffff    li    v0,-1
  40065c:   03e00008    jr    ra
  400660:   00000000    nop
```


The read() syscall function part 2

Set read() result to -1

```
00400640 <__syscall>:
  400640:   0000000c    syscall
  400644:   10e00005    beqz  a3,40065c
  400648:   00000000    nop
  40064c:   3c011000    lui   at,0x1000
  400650:   ac220000    sw    v0,0(at)
  400654:   2403ffff    li    v1,-1
  400658:   2402ffff    li    v0,-1
  40065c:   03e00008    jr    ra
  400660:   00000000    nop
```

The read() syscall function part 2

```
00400640 <__syscall>:
  400640:    0000000c     syscall
  400644:    10e00005     beqz  a3,40065c
  400648:    00000000     nop
  40064c:    3c011000     lui   at,0x1000
  400650:    ac220000     sw    v0,0(at)
  400654:    2403ffff     li    v1,-1
  400658:    2402ffff     li    v0,-1
  40065c:    03e00008     jr    ra
  400660:    00000000     nop
```

Return to location after where read() was called

Summary

- From the caller's perspective, the read() system call behaves like a normal function call
  - It preserves the calling convention of the language
- However, the actual function implements its own convention by agreement with the kernel
  - Our OS/161 example assumes the kernel preserves appropriate registers(s0-s8, sp, gp, ra).
- Most languages have similar *support libraries* that interface with the operating system.

System Calls - Kernel Side

- Things left to do
  - Change to kernel stack
  - Preserve registers by saving to memory (the stack)
  - Leave saved registers somewhere accessible to
    - Read arguments
    - Store return values
  - Do the "read()"
  - Restore registers
  - Switch back to user stack
  - Return to application


```
exception:
   move k1, sp               /* Save previous stack pointer in k1 */
   mfc0 k0, c0_status        /* Get status register */
   andi k0, k0, CST_     /* Check the we-were-in-user-mode bit */
   beq k0, $0, 1f /* I      ear, from kernel, already have stack */
   nop                       /* delay slot */

   /* Coming from user mode                      nto sp */
   la k0, curkstack                              rkstack" */
   lw sp, 0(k0)                                  lue */
   nop                                           load */

1:
   mfc0 k0, c0_cause    /* N                     ause. */
   j common_exception                            de */
   nop
```

Note k0, k1 registers available for kernel use


```
exception:
   move k1, sp               /* Save previous stack pointer in k1 */
   mfc0 k0, c0_status        /* Get status register */
   andi k0, k0, CST_Kup /* Check the we-were-in-user-mode bit */
   beq  k0, $0, 1f /* If clear, from kernel, already have stack */
   nop                       /* delay slot */

   /* Coming from user mode - load kernel stack into sp */
   la k0, curkstack          /* get address of "curkstack" */
   lw sp, 0(k0)                      /* get its value */
   nop                       /* delay slot for the load */

1:
   mfc0 k0, c0_cause   /* Now, load the exception cause. */
   j common_exception        /* Skip to common code */
   nop                       /* delay slot */
```



```
common_exception:

   /*
    * At this point:
    *       Interrupts are off. (The processor did this for us.)
    *       k0 contains the exception cause value.
    *       k1 contains the old stack pointer.
    *       sp points into the kernel stack.
    *       All other registers are untouched.
    */

   /*
    * Allocate stack space for 37 words to hold the trap frame,
    * plus four more words for a minimal argument block.
    */
   addi sp, sp, -164
```

```
/* The order here must match mips/include/trapframe.h. */

   sw ra, 160(sp)      /* dummy for gdb */
   sw s8, 156(sp)      /* save s8 */
   sw sp, 152(sp)      /* dummy for gdb */
   sw gp, 148(sp)      /* save gp */
   sw k1, 144(sp)      /* dummy for gdb */
   sw k0, 140(sp)      /* dummy for gdb */

   sw k1, 152(sp)      /* real saved sp */
   nop                 /* delay slot for store */

   mfc0 k1, c0_epc     /* Copr.0 reg 13 == PC for
   sw k1, 160(sp)      /* real saved PC */
```

These six stores are a "hack" to avoid confusing GDB
You can ignore the details of why and how


```
/* The order here must match mips/include/trapframe.h. */

   sw ra, 160(sp)      /* dummy for gdb */
   sw s8, 156(sp)      /* save s8 */
   sw sp, 152(sp)      /* dummy for gdb */
   sw gp, 148(sp)      /* save gp */
   sw k1, 144(sp)      /* dummy for gdb */
   sw k0, 140(sp)      /* dummy for gdb */

   sw k1, 152(sp)      /* real saved sp */
   nop                 /* delay slot for store */

   mfc0 k1, c0_epc     /* Copr.0 reg 13 == PC for exception */
   sw k1, 160(sp)      /* real saved PC */
```

The real work starts here


```
   sw t9, 136(sp)
   sw t8, 132(sp)
   sw s7, 128(sp)
   sw s6, 124(sp)
   sw s5, 120(sp)
   sw s4, 116(sp)
   sw s3, 112(sp)
   sw s2, 108(sp)
   sw s1, 104(sp)
   sw s0, 100(sp)
   sw t7, 96(sp)
   sw t6, 92(sp)
   sw t5, 88(sp)
   sw t4, 84(sp)
   sw t3, 80(sp)
   sw t2, 76(sp)
   sw t1, 72(sp)
   sw t0, 68(sp)
   sw a3, 64(sp)
   sw a2, 60(sp)
   sw a1, 56(sp)
   sw a0, 52(sp)
   sw v1, 48(sp)
   sw v0, 44(sp)
   sw AT, 40(sp)
   sw ra, 36(sp)
```

Save all the registers on the kernel stack


```
   /*
    * Save special registers.
    */
   mfhi t0
   mflo t1
   sw t0, 32(sp)
   sw t1, 28(sp)

   /*
    * Save remaining exception context information.
    */

   sw   k0, 24(sp)            /* k0 was loaded with cause earlier */
   mfc0 t1, c0_status         /* Copr.0 reg 11 == status */
   sw   t1, 20(sp)
   mfc0 t2, c0_vaddr          /* Copr.0 reg 8 == faulting vaddr */
   sw   t2, 16(sp)

   /*
    * Pretend to save $0 for gdb's benefit.
    */
   sw $0, 12(sp)
```

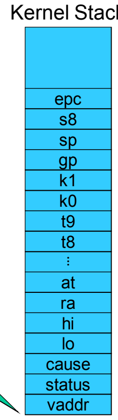
We can now use the other registers (t0, t1) that we have preserved on the stack


```
   /*
    * Prepare to call mips_trap(struct trapframe *)
    */

   addiu a0, sp, 16         /* set argument */
   jal mips_trap            /* call it */
   nop                      /* delay slot */
```

Create a pointer to the base of the saved registers and state in the first argument register


```
struct trapframe {
    u_int32_t tf_vaddr;       /* vaddr register */
    u_int32_t tf_status;      /* status register */
    u_int32_t tf_cause;       /* cause register */
    u_int32_t tf_lo;
    u_int32_t tf_hi;
    u_int32_t tf_ra;/* Saved register 31 */
    u_int32_t tf_at;/* Saved register 1 (AT) */
    u_int32_t tf_v0;/* Saved register 2 (v0) */
    u_int32_t tf_v1;/* etc. */
    u_int32_t tf_a0;
    u_int32_t tf_a1;
    u_int32_t tf_a2;
    u_int32_t tf_a3;
    u_int32_t tf_t0;
    :
    u_int32_t tf_t7;
    u_int32_t tf_s0;
    :
    u_int32_t tf_s7;
    u_int32_t tf_t8;
    u_int32_t tf_t9;
    u_int32_t tf_k0;/* dummy (see exception.S comment
    u_int32_t tf_k1;/* dummy */
    u_int32_t tf_gp;
    u_int32_t tf_sp;
    u_int32_t tf_s8;
    u_int32_t tf_epc;         /* coprocessor 0 epc register
    */
}
```



By creating a pointer to here of type struct trapframe *, we can access the user's saved registers as normal variables within 'C'

Now we arrive in the 'C' kernel

```
/*
 * General trap (exception) handling function for mips.
 * This is called by the assembly-language exception handler once
 * the trapframe has been set up.
 */
void
mips_trap(struct trapframe *tf)
{
   u_int32_t code, isutlb, iskern;
   int savespl;

   /* The trap frame is supposed to be 37 registers long. */
   assert(sizeof(struct trapframe)==(37*4));

   /* Save the value of curspl, which belongs to the old context. */
   savespl = curspl;

   /* Right now, interrupts should be off. */
   curspl = SPL_HIGH;
```

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What happens next?

- The kernel deals with whatever caused the exception
  - Syscall
  - Interrupt
  - Page fault
  - It potentially modifies the *trapframe*, etc
    - E.g., Store return code in v0, zero in a3
- 'mips_trap' eventually returns

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```
exception_return:

   /*     16(sp)            no need to restore tf_vaddr */
   lw t0, 20(sp)         /* load status register value into t0 */
   nop                           /* load delay slot */
   mtc0 t0, c0_status            /* store it back to coprocessor 0 */
   /*     24(sp)            no need to restore tf_cause */

   /* restore special registers */
   lw t1, 28(sp)
   lw t0, 32(sp)
   mtlo t1
   mthi t0

   /* load the general registers */
   lw ra, 36(sp)

   lw AT, 40(sp)
   lw v0, 44(sp)
   lw v1, 48(sp)
   lw a0, 52(sp)
   lw a1, 56(sp)
   lw a2, 60(sp)
   lw a3, 64(sp)
```

THE UNIVERSITY OF NEW SOUTH WALES 81

```
lw t0, 68(sp)
   lw t1, 72(sp)
   lw t2, 76(sp)
   lw t3, 80(sp)
   lw t4, 84(sp)
   lw t5, 88(sp)
   lw t6, 92(sp)
   lw t7, 96(sp)
   lw s0, 100(sp)
   lw s1, 104(sp)
   lw s2, 108(sp)
   lw s3, 112(sp)
   lw s4, 116(sp)
   lw s5, 120(sp)
   lw s6, 124(sp)
   lw s7, 128(sp)
   lw t8, 132(sp)
   lw t9, 136(sp)

   /*     140(sp)          "saved" k0 was dummy garbage anyway */
   /*     144(sp)          "saved" k1 was dummy garbage anyway */
```

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```
   lw gp, 148(sp)          /* restore gp */
   /*     152(sp)             stack pointer - below */
   lw s8, 156(sp)          /* restore s8 */
   lw k0, 160(sp)          /* fetch exception return PC into k0 */

   lw sp, 152(sp)          /* fetch saved sp (must be last) */

   /* done */
   jr k0                   /* jump back */
   rfe                     /* in delay slot */
   .end common_exception
```

Note again that only k0, k1 have been trashed

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