

Notes

The book uses “exception” as a general term for all interrupts ...
... in these notes interrupt is used as the general term ...
... and a narrower definition is used for exception.

The definitions of trap, interrupt, and exception given here ...
... are not explicitly provided in the text ...
... but are widely used.

Interrupt:

Event that requires OS attention.

Operating system “takes over” computer ...

... attends to whatever caused the interrupt ...

... and (most of the time) resumes interrupted program.

Interrupt Terminology

Handler:

The OS program that “takes over” in response to interrupt.

Privileged Mode:

A state in which the CPU controller and memory system ...

... do not restrict instructions that can be executed ...

... or memory that can be accessed.

Processor switches into privileged mode in response to interrupt ...

... and out of privileged mode when resuming the program.

Three Types:

- *Trap:*
Sort of a subroutine call to OS.
- *Exception:*
Something went wrong, triggered by an executing instruction.

Exception has both a general and this specific meaning.
- *Hardware Interrupt:*
Something outside the CPU is trying to get the computer's attention.

Interrupt has both a general and this specific meaning.

Trap

A type of instruction that switches processor to privileged mode...
... and jumps to an address pre-arranged by the OS or other software.

Uses For Traps

System Calls

Some Exception Causes

Unrecognized Opcode.

Division by Zero

Insufficient privilege level for insn.

Insufficient privilege level for memory address.

Load to misaligned memory address.

Load to illegal memory address.

Memory system needs updating. (TLB miss, page fault, etc.)

Trap:

- (1) An instruction intended for user programs that transfers control to the operating system (privileged code).
- (2) The execution of such an instruction.

Sort of a subroutine call to OS.

Trap causes branch to OS code and a switch to *privileged mode*.

Privileged Mode: a.k.a. System Mode and Supervisor Mode

A processor mode in which there are fewer restrictions on instruction execution.

Some instructions can only be executed in privileged mode.

When in privileged mode a *trap handler* is executed to service request.

Trap Handler:

A program, running in privileged mode that responds to a trap.

Traps typically used for I/O, memory allocation, etc.

Example, SPARC V8 trap instruction:

`ta <rs1>,<imm>.`

ISA has a *trap base register (TBR)* that is used to construct the trap address.

Trap handler starts in *trap table*, each entry holds first four instructions of trap handler.

Trap Address Construction:

OS initializes TBR with upper 20 bits of trap table base.

When, say, `ta r1,3` executed, bits 4-10 set to low seven bits of `r1+3`.

Low four bits of TBR always zero.

System Calls

read(2)

NAME

read, readv, pread - read from file

SYNOPSIS

```
#include <unistd.h>
ssize_t read(int fildes, void *buf, size_t nbyte);
```

DESCRIPTION

The read() function attempts to read nbyte bytes from the file associated with the open file descriptor, fildes, into the buffer pointed to by buf.

```
! Read System Call.
! Parameters placed in %o0, %o1, %o2.
! %o0: File descriptor (fildes)
! %o1: Buffer pointer (buf, address where read data copied to).
! %o2: Number of bytes to read. (nbyte)
```

```
mov SYS_read, %g1 ! Argument for trap.
ta %g0, ST_SYSCALL ! Call trap.
```

Some SPARC Trap Codes

```
/* Copyright (c) 1989 by Sun Microsystems, Inc. */
/* Software traps (ticc instructions). */
/* In sys/trap.h */
#define ST_OSYSYSCALL 0x00
#define ST_BREAKPOINT 0x01
#define ST_SYSCALL 0x08
#define ST_GETCC 0x20 // Move condition code to reg.
#define ST_SETCC 0x21 // Move condition code from reg.

/* In sys/syscall.h */
#define SYS_syscall 0
#define SYS_exit 1
#define SYS_fork 2
#define SYS_read 3
#define SYS_write 4
#define SYS_open 5
#define SYS_close 6

mov SYS_read, %g1 ! Argument for trap.
ta %g0, ST_SYSCALL ! Call trap.
```

Exception:

An interruption in normal execution triggered by an instruction that could not complete execution.

An exception occurs when an instruction cannot fully execute.

Faulting Instruction:

Instruction that caused an exception.

Some Exception Causes

- Access to unallocated memory, a segmentation fault.
- Access to memory that's paged out (on disk), a page fault.
- Division by zero.
- Unimplemented instruction.

In response to an exception ...

... OS fixes problem and re-tries the faulting instruction ...

... or OS fixes problem and skips the faulting instruction ...

... or OS terminates program.

Exception in ME stage of `lw`, indicated with an asterisk.

Cycle:		0	1	2	3	4	5	...		99	100	...		
	<code>add r1, r2, r3</code>	IF	ID	EX	ME	WB								
	<code>lw r6, 0(r1)</code>		IF	ID	EX	ME*x				IF	ID			
	<code>sub r5, r6, r7</code>			IF	ID	EXx					IF			
	<code>xor r10, r11, r12</code>				IF	IDx								
	<code>and r20, r21, r22</code>					IFx								
	...													
Handler:														
	<code>sw ...</code>							IF ...						
	...													
	<code>eret (exception return)</code>									IF	ID	EX	ME	WB

Cycle 4: `lw` raises a page-fault exception, ...

... `lw` and following instructions are squashed, ...

... and address of handler routine computed and sent to `PC`.

Cycle 5: handler fetched.

When handler returns at 99, execution resumes with `lw` (its second try).

Two faults, ID stage of `ant` and ME stage of `lw`, indicated asterisks.

Cycle:		0	1	2	3	4	5	...		99	100	...		
	<code>add r1, r2, r3</code>	IF	ID	EX	ME	WB								
	<code>lw r6, 0(r1)</code>		IF	ID	EX	ME*x				IF	ID	EX	ME	WB
	<code>ant r5, r6, r7</code>			IF	ID*EXx					IF	ID*EX	MEx		
	<code>xor r10, r11, r12</code>				IF	IDx					IF	ID	EXx	
	<code>and r20, r21, r22</code>					IFx						IF	IDx	
	...													
Handler:														
	<code>sw ...</code>						IF ...					IF ...		
	...													
	<code>eret (exception return)</code>									IF	ID	EX	ME	WB

Cycle 3: `ant` raises an illegal instruction exception.

Cycle 4: `lw` raises an illegal instruction exception.

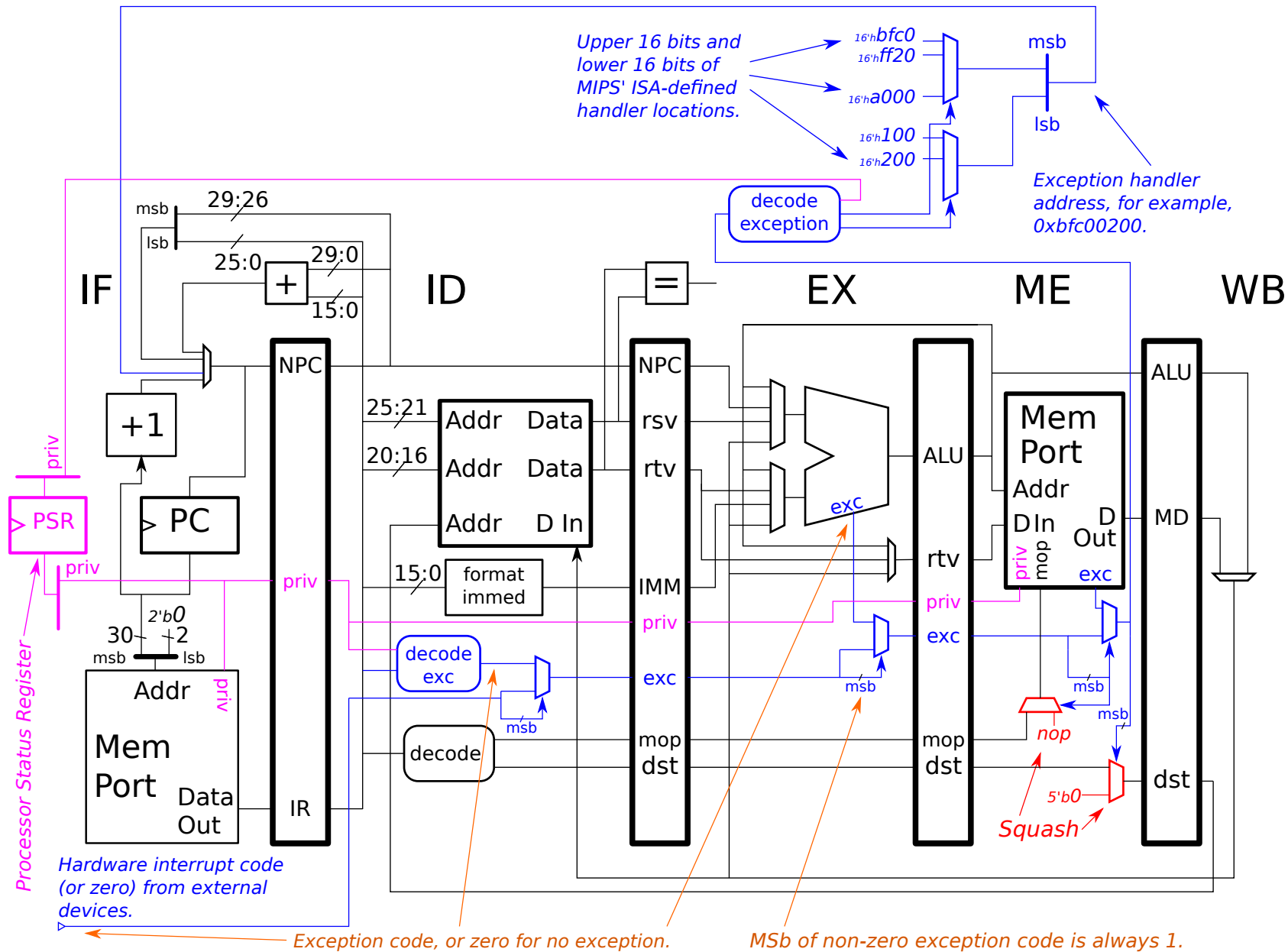
Hardware checks for exceptions in `ME` ...

... to preserve program order ...

... and so `lw` is handled first.

When handler returns at 99, execution resumes with `lw` (its second try).

Possible MIPS Interrupt Hardware



Interrupt

Caused by an external event ...
... which typically needs routine attention.

For example,

- Disk drive has data that was requested 20 ms ago.
- User pressed a key on the keyboard.
- User sneezed, causing mouse to move.
- Timer (used by the OS as an alarm clock) expired.

Example:

```

add  r1, r2, r3    IF  ID  EX  ME  WB
sub  r4, r5, r6          IF  ID  EX  ME  WB
xor  r7, r8, r9          IF  ID  EX  ME  WB

```

As execution reaches code above, *achoooo* (user sneezes) ...
 ... moving mouse, triggering an interrupt.

Based on time of sneeze, hardware completes **add** and **sub** ...
 ... but squashes **xor** (for now).

The handler starts ...
 ... the screen pointer (the little arrow) is moved ...
 ... the handler finishes ...
 ... and execution resumes with **xor**.

Interrupt Mechanisms: Goals and Difficulties

Goals

Exceptions: Handle in program order.

All Interrupts: Ability to resume execution as though nothing happened.

Precise Exception: Must be able to re-start or skip faulting instruction...
... and so last instruction must immediately precede faulting instruction.

Difficulties

Precise exceptions are easy to implement for integer pipeline ...
... because exceptions can be detected before later instructions write.

Much harder with floating point operations (covered in next set).

Actions Initiated by HW Interrupt & Exceptions — Simple Case

Hardware executes up to and including last instruction ...
... and squashes all following instructions.

- Type and timing of interrupt determine a *last* instruction.
- The last and all preceding instructions allowed to complete ...
... instructions following last are squashed (nullified).
- Address of handler is determined ...
... based on the type of interrupt and exception.
- Processor jumps to handler (OS code) and switches to privileged mode.
- Handler attends to interrupt.
- If appropriate, state is restored and program resumes ...
... with the instruction following last.

The Last Instruction

The last and all preceding instructions must execute completely ...
... while instructions following the last must have no effect at all ...
... even though they may have already started when the interrupt occurred.

These *squashed* instructions will be executed after the handler completes.

Choice of Last Instruction

Choice depends on type of interrupt.

- For traps, the trap instruction itself is last.

No problem.

- For hardware interrupts, a convenient last instruction can be chosen.

No problem again.

- Precise exception, the instruction preceding faulting instruction.

Problem: exception can occur in any of several stages.

Problem: more than one instruction can raise exception.

Problem: an instruction can raise exception before its *predecessor*.

Problem: despite problems, some exceptions must be precise.

Squashing Instructions

When an interrupt occurs instructions may be squashed.

When the handler finishes and the program resumes ...
it must be as though the squashed instructions never even started.

So ...

... they cannot write registers ...

... they cannot write memory ...

... or set any kind of condition codes ...

... *unless* ...

... the state change can be un-done.

Squashing Instructions in MIPS

In the MIPS implementation it's easy to squash integer instructions ...
... because they only change state in the last two stages (ME & WB).

To squash an instruction in the IF, ID, or EX stages ...
... the opcode is replaced with a NOP ...
... or any control bits that initiate a memory or register write ...
... are set to perform no action.

An instruction in WB cannot easily be squashed ...
... because the following instruction, in ME, ...
... would already be changing state.

Fortunately, there's never a need to squash an instruction in WB ...
... although an already-squashed instruction can enter WB.

An instruction in ME cannot be squashed ...
... *unless* the memory operation fails ...
... which, luckily, is the only reason to squash the instruction.

Implementing Exceptions in MIPS

Each stage has its own hardware to detect exceptions.

IF: Page fault etc on instruction fetch, detected by mem port.

ID: Illegal opcode, detected by decode logic.

EX: Arithmetic exception, detected by ALU.

ME: Page fault on load/store, detected by memory port.

Pipeline latches have exception registers.

Normally set to null.

If exception occurs, written with exception info.

When exception occurs:

- Exception pipeline latch (at faulting instruction) written.
- NOPs written to IRs for following (to the left) instructions.
- Following instructions proceed normally.

In writeback stage:

Exception latch checked (every cycle).

If exception latch non-null ...

... exception latch value written to *cause* register ...

... PC written to *EPC* (exception PC) register ...

... and processor jumps to an entry in the exception table ...

... which contains beginning of handler.

Note

- Exceptions handled in program order because exception register tested at one place in pipeline, in class ME.

Precise Exceptions

Precise Exception:

An exception for which when the handler is called all of the instructions before the faulting instruction finish and none of the instructions after finish.

Deferred Exception:

An exception for which when the handler is called all of the instructions before the faulting instruction finish and a few consecutive instructions after the faulting instruction finish.

Resuming of Interrupted Program

After handler finishes it may **resume** or **terminate** program.

With **precise exceptions** handler can resume **at** or **after** faulting instruction.

With deferred exceptions handler can only resume long after faulting instruction.

Resuming of Program for Precise Exceptions

If an exception is **precise**, handler **can return** to faulting instruction (thereby giving it a second chance).

Handler also **has option to** return to instruction **after** faulting instruction ...
... this is done to emulate instructions that are not implemented in hardware.

Resuming of Program for Deferred Exceptions

Cannot return to faulting instruction if it raises a deferred exception...
... because instructions after faulting instruction would be executed twice!

Need for Precise Exceptions

Precise exceptions are necessary for some instructions ...
... and expensive for others.

They are **necessary** for instructions ...
... such as memory **loads and stores**.

For other instructions they are a **convenience** ...
... for example **FP instructions** ...
... that can write error values instead of numbers ...
... if they don't complete.

In many systems precise exceptions are optional for floating point ...
... but always provided for other instructions.