Performance (finish) / Exceptions

Changelog

Changes made in this version not seen in first lecture:

- 9 November 2017: an infinite loop: correct infinite loop code
- 9 November 2017: move sync versus async slide earlier

alternate vector interfaces

intrinsics functions/assembly aren't the only way to write vector code

e.g. GCC vector extensions: more like normal C code

- types for each kind of vector
- write + instead of `_mm_add_epi32`

e.g. CUDA (GPUs): looks like writing multithreaded code, but each thread is vector "lane"

other vector instructions

multiple extensions to the X86 instruction set for vector instructions

this class: SSE, SSE2, SSE3, SSSE3, SSE4.1, SSE4.2

- supported on lab machines
- 128-bit vectors

latest X86 processors: AVX, AVX2, AVX-512

- 256-bit and 512-bit vectors

other vector instructions features

AVX2/AVX/SSE pretty limiting

other vector instruction sets often more featureful:

(and require more sophisticated HW support)

better conditional handling

better variable-length vectors

ability to load/store non-contiguous values

addressing efficiency

```
for (int i = 0; i < N; ++i) {
  for (int j = 0; j < N; ++j) {
    float Bij = B[i * N + j];
    for (int k = kk; k < kk + 2; ++k) {
      Bij += A[i * N + k] * A[k * N + j];
    }
    B[i * N + j] = Bij;
  }
}
```

tons of multiplies by N??

isn't that slow?

addressing transformation

```
for (int kk = 0; k < N; kk += 2 )
  for (int i = 0; i < N; ++i) {
    for (int j = 0; j < N; ++j) {
      float Bij = B[i * N + j];
      float *Akj_pointer = &A[kk * N + j];
      for (int k = kk; k < kk + 2; ++k) {
        // Bij += A[i * N + k] * A[k * N + j~];
        Bij += A[i * N + k] * Akj_pointer;
        Akj_pointer += N;
      }
      B[i * N + j] = Bij;
    }
  }
```

transforms loop to iterate with pointer

compiler will usually do this!

increment/decrement by N ($\times$ sizeof(float))

addressing transformation

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for (int kk = 0; k < N; kk += 2 )
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      }
      B[i * N + j] = Bij;
    }
  }
```

transforms loop to iterate with pointer

compiler will usually do this!

increment/decrement by N ($\times$ sizeof(float))

addressing efficiency

compiler will usually eliminate slow multiplies

doing transformation yourself often slower if so

`i * N; ++i` into `i_times_N; i_times_N += N`

way to check: see if assembly uses lots multiplies in loop

if it doesn't — do it yourself

optimizing real programs

spend effort where it matters

e.g. 90% of program time spent reading files, but optimize computation?

e.g. 90% of program time spent in routine A, but optimize B?

profilers

first step — tool to determine where you spend time

tools exist to do this for programs

example on Linux: `perf`

perf usage

sampling profiler

stops periodically, takes a look at what's running

`perf record OPTIONS program`

example OPTIONS:

`-F 200` — record 200/second

`--call-graph=dwarf` — record stack traces

`perf report` or `perf annotate`

children/self

"children" — samples in function or things it called

"self" — samples in function alone

demo

other profiling techniques

count number of times each function is called

not sampling — exact counts, but higher overhead

- might give less insight into amount of time

tuning optimizations

biggest factor: how fast is it actually

setup a benchmark

- make sure it's realistic (right size? uses answer? etc.)

compare the alternatives

an infinite loop

```
int main(void) {
    while (1) {
        /* waste CPU time */
    }
}
```

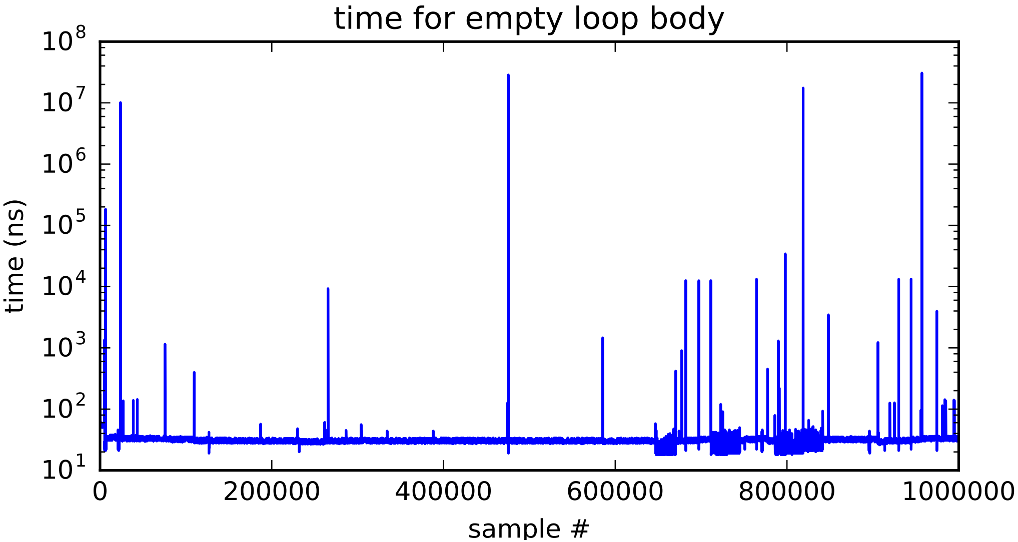
If I run this on a lab machine, can you still use it?
...if the machine only has one core?

timing nothing

```
long times[NUM_TIMINGS];
int main(void) {
    for (int i = 0; i < N; ++i) {
        long start, end;
        start = get_time();
        /* do nothing */
        end = get_time();
        times[i] = end - start;
    }
    output_timings(times);
}
```

same instructions — same difference each time?

doing nothing on a busy system



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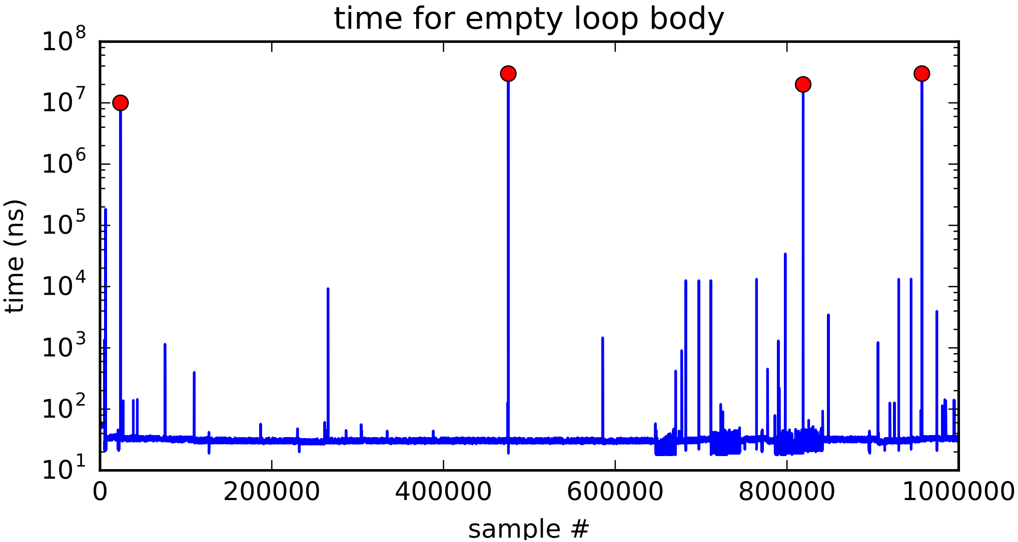


time multiplexing

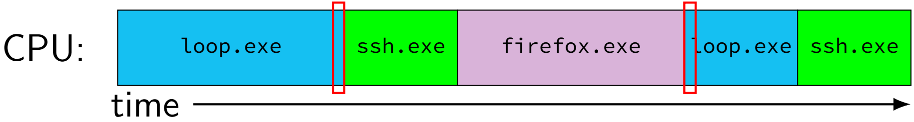
time multiplexing


```
...
call get_time
    // whatever get_time does
movq %rax, %rbp
```

million cycle delay

```
call get_time
    // whatever get_time does
subq %rbp, %rax
...
```

time multiplexing




```
...
call get_time
    // whatever get_time does
movq %rax, %rbp
```

—— million cycle delay ——

```
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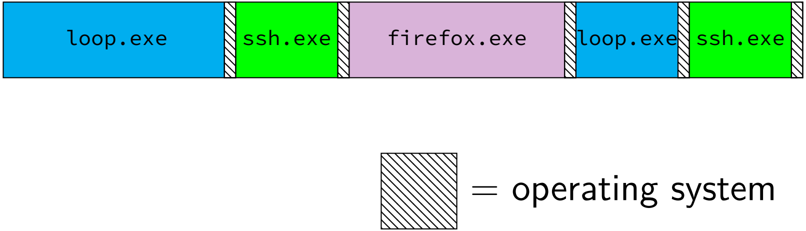
```

time multiplexing really



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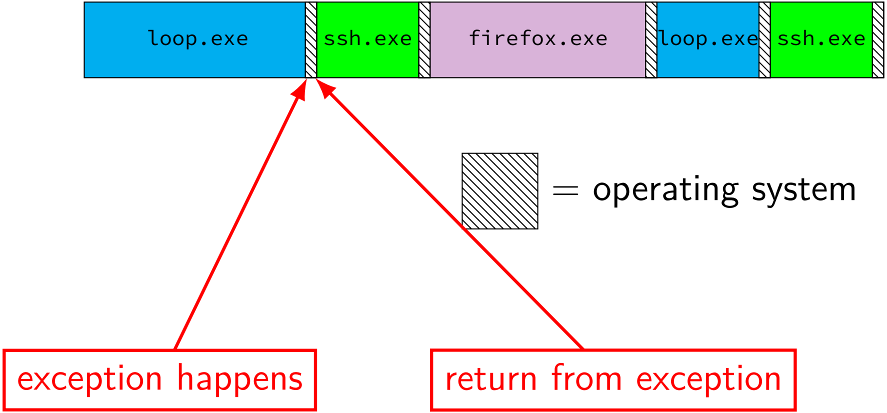


OS and time multiplexing

starts running instead of normal program

- mechanism for this: exceptions (later)

saves old program counter, registers somewhere

sets new registers, jumps to new program counter

called context switch

- saved information called context

context

all registers values

`%rax %rbx, ..., %rsp, ...`

condition codes

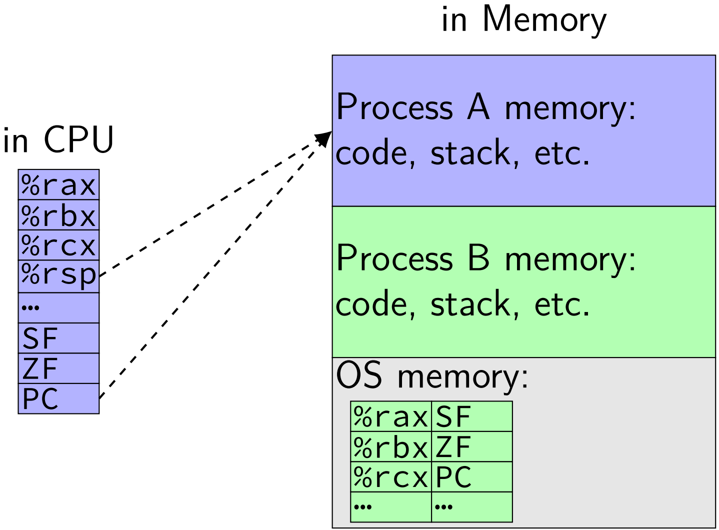
program counter

i.e. all visible state in your CPU except memory

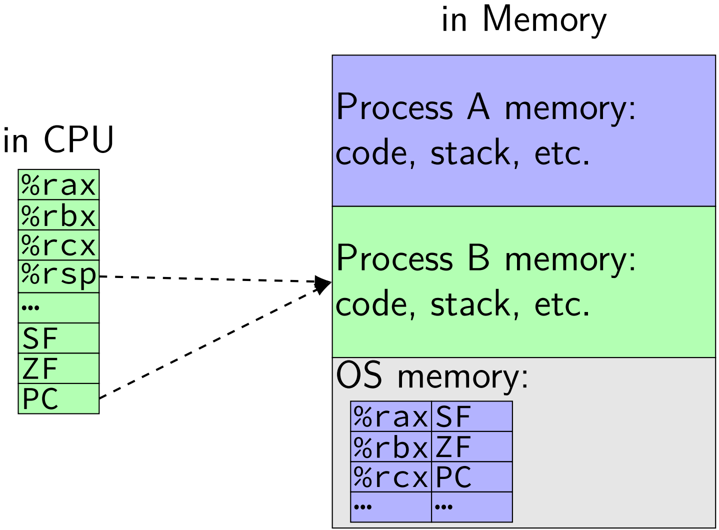
context switch pseudocode

```
context_switch(last, next):
  copy_preexception_pc last->pc
  mov rax,last->rax
  mov rcx, last->rcx
  mov rdx, last->rdx
  ...
  mov next->rdx, rdx
  mov next->rcx, rcx
  mov next->rax, rax
  jmp next->pc
```

contexts (A running)



contexts (B running)



memory protection

reading from another program's memory?

Program A	Program B

`0x10000: .word 42`
`    // ...`
`    // do work`
`    // ...`
`    movq 0x10000, %rax`
	`// while A is working:`
	`movq $99, %rax`
	`movq %rax, 0x10000`
	`...`

memory protection

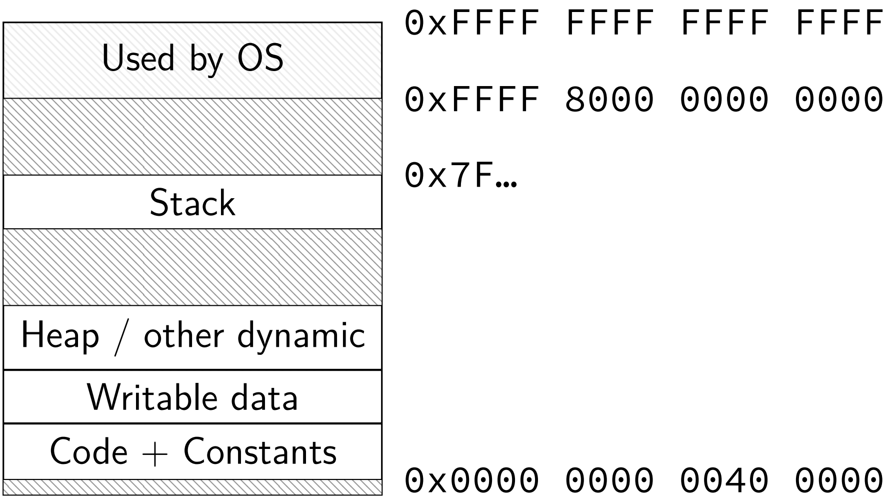
reading from another program's memory?

Program A	Program B

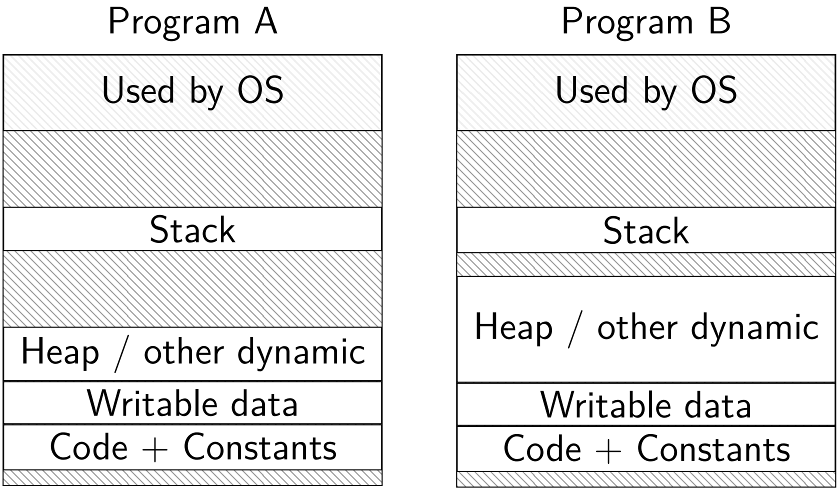
`0x10000: .word 42`
`    // ...`
`    // do work`
`    // ...`
`    movq 0x10000, %rax`
	`// while A is working:`
	`movq $99, %rax`
	`movq %rax, 0x10000`
	`...`

result: `%rax` is 42 (always)	result: might crash

program memory



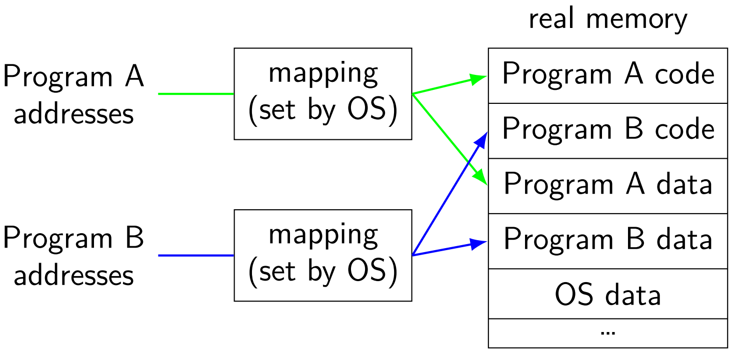
program memory (two programs)



address space

programs have illusion of own memory

called a program's address space



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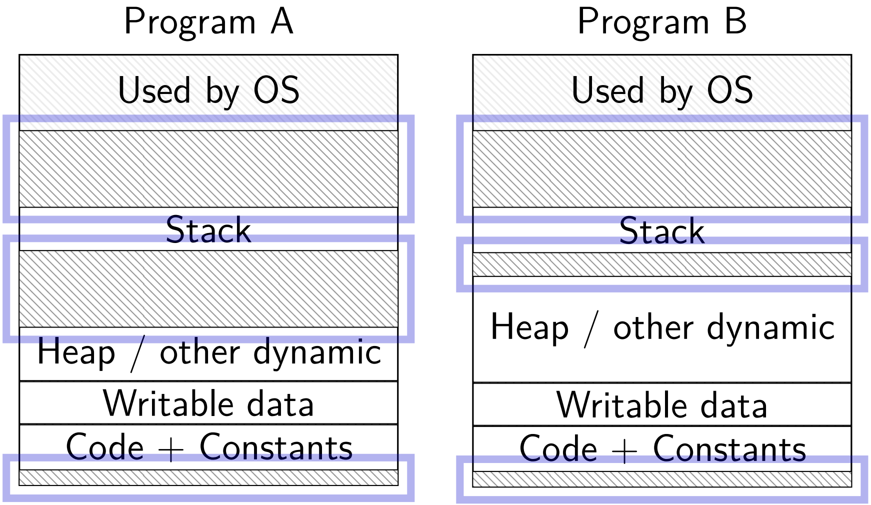

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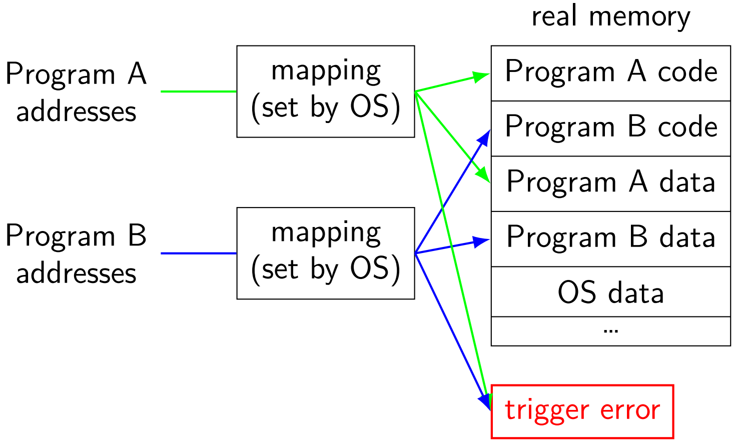

address space mechanisms

next week's topic

called virtual memory

mapping called page tables

mapping part of what is changed in context switch

context

all registers values

`%rax %rbx, ..., %rsp, ...`

condition codes

program counter

~~i.e. all visible state in your CPU except memory~~

address space: map from program to real addresses

The Process

process = thread(s) + address space

illusion of dedicated machine:

- thread = illusion of own CPU
- address space = illusion of own memory

synchronous versus asynchronous

synchronous — triggered by a particular instruction

- traps and faults

asynchronous — comes from outside the program

- interrupts and aborts
- timer event
- keypress, other input event

types of exceptions

interrupts — externally-triggered

- timer — keep program from hogging CPU
- I/O devices — key presses, hard drives, networks, ...

faults — errors/events in programs

- memory not in address space ("Segmentation fault")
- divide by zero
- invalid instruction

traps — intentionally triggered exceptions

- system calls — ask OS to do something

aborts

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timer interrupt

(conceptually) external timer device

(usually on same chip as processor)

OS configures before starting program

sends signal to CPU after a fixed interval

types of exceptions

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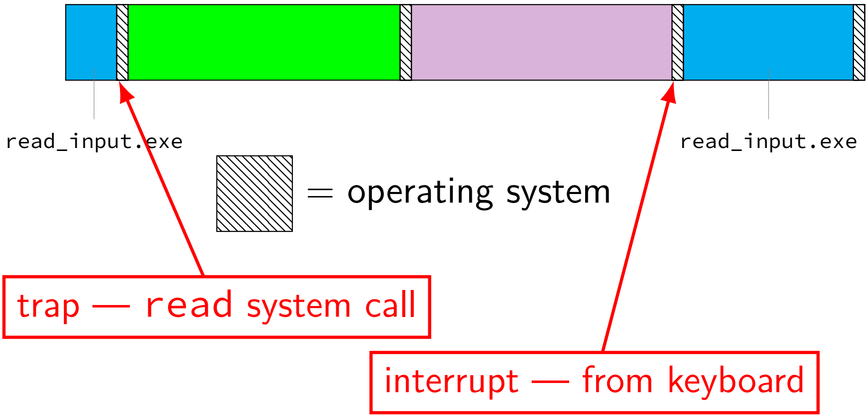
keyboard input timeline



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exception implementation

detect condition (program error or external event)

save current value of PC somewhere

jump to exception handler (part of OS)

- jump done without program instruction to do so

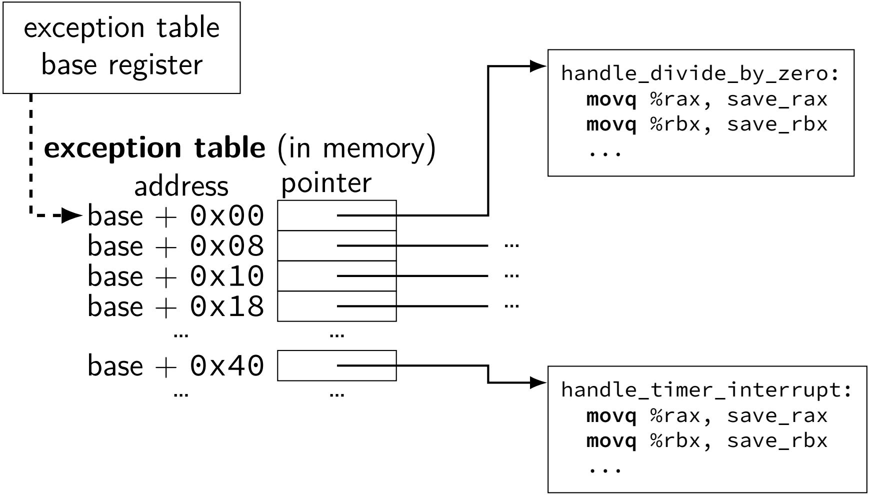
exception implementation: notes

I/textbook describe a simplified version

real x86/x86-64 is a bit more complicated

(mostly for historical reasons)

locating exception handlers



running the exception handler

hardware saves the old program counter (and maybe more)

identifies location of exception handler via table

then jumps to that location

OS code can save anything else it wants to , etc.

added to CPU for exceptions

new instruction: set exception table base

new logic: jump based on exception table

new logic: save the old PC (and maybe more)
- to special register or to memory

new instruction: return from exception
- i.e. jump to saved PC

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why return from exception?

reasons related to protection (later)

not just ret — can't modify process's stack

- would break the illusion of dedicated CPU/memory
- program could use stack in weird way

```
movq $100, −8(%rsp)
...
movq −8(%rsp), %rax
```

(even though this wouldn't be following calling conventions)

need to restart program undetectably!

exception handler structure

1. save process's state somewhere
2. do work to handle exception
3. restore a process's state (maybe a different one)
4. jump back to program

```
handle_timer_interrupt:
  mov_from_saved_pc save_pc_loc
  movq %rax, save_rax_loc
  ... // choose new process to run here
  movq new_rax_loc, %rax
  mov_to_saved_pc new_pc
  return_from_exception
```

exceptions and time slicing

timer interrupt

exception table lookup

```
handle_timer_interrupt:
    ...
    ...
    set_address_space ssh_address_space
    mov_to_saved_pc saved_ssh_pc
    return_from_exception
```

defeating time slices?

```
my_exception_table:
    ...
my_handle_timer_interrupt:
    // HA! Keep running me!
    return_from_exception

main:
    set_exception_table_base my_exception_table
loop:
    jmp loop
```

defeating time slices?

wrote a program that tries to set the exception table:

```
my_exception_table:
    ...

main:
    // "Load Interrupt
    //  Descriptor Table"
    // x86 instruction to set exception table
    lidt my_exception_table
    ret
```

result: `Segmentation fault` (exception!)

privileged instructions

can't let any program run some instructions

allows machines to be shared between users (e.g. lab servers)

examples:

- set exception table
- set address space
- talk to I/O device (hard drive, keyboard, display, …)
- …

processor has two modes:

- kernel mode — privileged instructions work
- user mode — privileged instructions cause exception instead

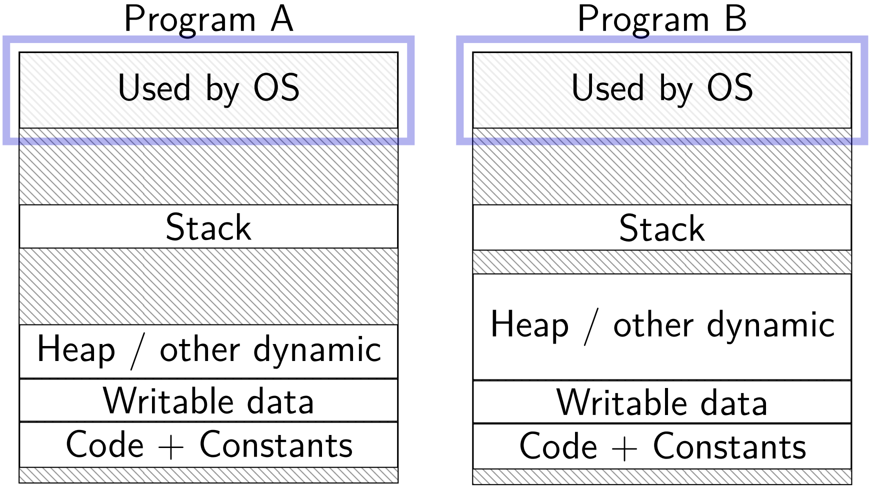
kernel mode

extra one-bit register: "are we in kernel mode"

exceptions enter kernel mode

return from exception instruction leaves kernel mode

program memory (two programs)



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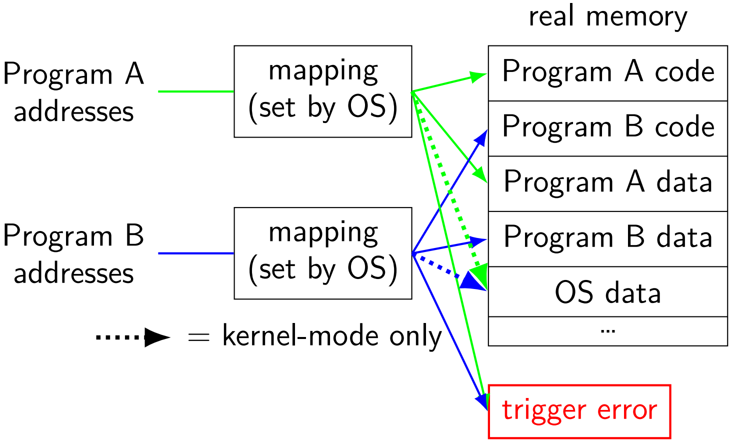

types of exceptions

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aborts

protection fault

when program tries to access memory it doesn't own

e.g. trying to write to bad address

when program tries to do other things that are not allowed

e.g. accessing I/O devices directly

e.g. changing exception table base register

OS gets control — can crash the program

or more interesting things

types of exceptions

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kernel services

allocating memory? (change address space)

reading/writing to file? (communicate with hard drive)

read input? (communicate with keyborad)

all need privileged instructions!

need to run code in kernel mode

Linux x86-64 system calls

special instruction: `syscall`

triggers trap (deliberate exception)

Linux syscall calling convention

before `syscall`:

`%rax` — system call number

`%rdi`, `%rsi`, `%rdx`, `%r10`, `%r8`, `%r9` — args

after `syscall`:

`%rax` — return value

on error: `%rax` contains -1 times “error number”

almost the same as normal function calls

Linux x86-64 hello world

```
.globl _start
.data
hello_str: .asciz "Hello,␣World!\n"
.text
_start:
  movq $1, %rax # 1 = "write"
  movq $1, %rdi # file descriptor 1 = stdout
  movq $hello_str, %rsi
  movq $15, %rdx # 15 = strlen("Hello, World!\n")
  syscall

  movq $60, %rax # 60 = exit
  movq $0, %rdi
  syscall
```

approx. system call handler

```
sys_call_table:
    .quad handle_read_syscall
    .quad handle_write_syscall
    // ...

handle_syscall:
    ... // save old PC, etc.
    pushq %rcx // save registers
    pushq %rdi
    ...
    call *sys_call_table(,%rax,8)
    ...
    popq %rdi
    popq %rcx
    return_from_exception
```

Linux system call examples

`mmap`, `brk` — allocate memory

`fork` — create new process

`execve` — run a program in the current process

`_exit` — terminate a process

`open`, `read`, `write` — access files

terminals, etc. count as files, too

system calls and protection

exceptions are only way to access kernel mode

operating system controls what proceses can do

… by writing exception handlers very carefully

careful exception handlers

```
movq $important_os_address, %rsp
```

can't trust user's stack pointer!

need to have own stack in kernel-mode-only memory

need to check all inputs really carefully

protection and sudo

programs always run in user mode

extra permissions from OS do not change this

- sudo, superuser, root, SYSTEM, …

operating system may remember extra privileges

system call wrappers

library functions to not write assembly:

```
open:
    movq $2, %rax // 2 = sys_open
    // 2 arguments happen to use same registers
    syscall
    // return value in %eax
    cmp $0, %rax
    jl has_error
    ret
has_error:
    neg %rax
    movq %rax, errno
    movq $-1, %rax
    ret
```

system call wrappers

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has_error:
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    movq $−1, %rax
    ret
```

system call wrapper: usage

```
/* unistd.h contains definitions of:
    O_RDONLY (integer constant), open() */
#include <unistd.h>
int main(void) {
  int file_descriptor;
  file_descriptor = open("input.txt", O_RDONLY);
  if (file_descriptor < 0) {
      printf("error:␣%s\n", strerror(errno));
      exit(1);
  }
  ...
  result = read(file_descriptor, ...);
  ...
}
```

system call wrapper: usage

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    }
    ...
    result = read(file_descriptor, ...);
    ...
}
```

a note on terminology (1)

real world: inconsistent terms for exceptions

we will follow textbook's terms in this course

the real world won't

you might see:

- 'interrupt' meaning what we call 'exception' (x86)
- 'exception' meaning what we call 'fault'
- 'hard fault' meaning what we call 'abort'
- 'trap' meaning what we call 'fault'
- ... and more

a note on terminology (2)

we use the term “kernel mode”

some additional terms:

- supervisor mode
- privileged mode
- ring `0`

some systems have multiple levels of privilege

- different sets of priviliged operations work

recall: square

```
void square(unsigned int *A, unsigned int *B) {
    for (int k = 0; k < N; ++k)
        for (int i = 0; i < N; ++i)
            for (int j = 0; j < N; ++j)
                B[i * N + j] += A[i * N + k] * A[k *
}
```

square unrolled

```
void square(unsigned int *A, unsigned int *B) {
  for (int k = 0; k < N; ++k) {
    for (int i = 0; i < N; ++i)
      for (int j = 0; j < N; j += 4) {
        /* goal: vectorize this */
        B[i * N + j + 0] += A[i * N + k] * A[k * N + j + 0];
        B[i * N + j + 1] += A[i * N + k] * A[k * N + j + 1];
        B[i * N + j + 2] += A[i * N + k] * A[k * N + j + 2];
        B[i * N + j + 3] += A[i * N + k] * A[k * N + j + 3];
      }
}
```

handy intrinsic functions for square

`_mm_set1_epi32` — load four copies of a 32-bit value into a 128-bit value

- instructions generated vary; one example: `movq` + `pshufd`

`_mm_mullo_epi32` — multiply four pairs of 32-bit values, give lowest 32-bits of results

- generates `pmulld`

vectorizing square

```
/* goal: vectorize this */
B[i * N + j + 0] += A[i * N + k] * A[k * N + j + 0];
B[i * N + j + 1] += A[i * N + k] * A[k * N + j + 1];
B[i * N + j + 2] += A[i * N + k] * A[k * N + j + 2];
B[i * N + j + 3] += A[i * N + k] * A[k * N + j + 3];
```

vectorizing square

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B[i * N + j + 2] += A[i * N + k] * A[k * N + j + 2];
B[i * N + j + 3] += A[i * N + k] * A[k * N + j + 3];
```

```
// load four elements from B
Bij = _mm_loadu_si128(&B[i * N + j + 0]);
... // manipulate vector here
// store four elements into B
_mm_storeu_si128((__m128i*) &B[i * N + j + 0], Bij);
```

vectorizing square

```
/* goal: vectorize this */
B[i * N + j + 0] += A[i * N + k] * A[k * N + j + 0];
B[i * N + j + 1] += A[i * N + k] * A[k * N + j + 1];
B[i * N + j + 2] += A[i * N + k] * A[k * N + j + 2];
B[i * N + j + 3] += A[i * N + k] * A[k * N + j + 3];
```

```
// load four elements from A
Akj = _mm_loadu_si128(&A[k * N + j + 0]);
... // multiply each by A[i * N + k] here
```

vectorizing square

```
/* goal: vectorize this */
B[i * N + j + 0] += A[i * N + k] * A[k * N + j + 0];
B[i * N + j + 1] += A[i * N + k] * A[k * N + j + 1];
B[i * N + j + 2] += A[i * N + k] * A[k * N + j + 2];
B[i * N + j + 3] += A[i * N + k] * A[k * N + j + 3];
```

```
// load four elements starting with A[k * n + j]
Akj = _mm_loadu_si128(&A[k * N + j + 0]);
// load four copies of A[i * N + k]
Aik = _mm_set1_epi32(A[i * N + k]);
// multiply each pair
multiply_results = _mm_mullo_epi32(Aik, Akj);
```

vectorizing square

```
/* goal: vectorize this */
B[i * N + j + 0] += A[i * N + k] * A[k * N + j + 0];
B[i * N + j + 1] += A[i * N + k] * A[k * N + j + 1];
B[i * N + j + 2] += A[i * N + k] * A[k * N + j + 2];
B[i * N + j + 3] += A[i * N + k] * A[k * N + j + 3];
```

```
Bij = _mm_add_epi32(Bij, multiply_results);
// store back results
_mm_storeu_si128(..., Bij);
```

square vectorized

```
__m128i Bij, Akj, Aik, Aik_times_Akj;

// Bij = {B_{i,j}, B_{i,j+1}, B_{i,j+2}, B_{i,j+3}}
Bij = _mm_loadu_si128((__m128i*) &B[i * N + j]);
// Akj = {A_{k,j}, A_{k,j+1}, A_{k,j+2}, A_{k,j+3}}
Akj = _mm_loadu_si128((__m128i*) &A[k * N + j]);

// Aik = {A_{i,k}, A_{i,k}, A_{i,k}, A_{i,k}}
Aik = _mm_set1_epi32(A[i * N + k]);

// Aik_times_Akj = {A_{i,k} × A_{k,j}, A_{i,k} × A_{k,j+1}, A_{i,k} × A_{k,j+2}, A_{i,k} × A_{k,j+3}}
Aik_times_Akj = _mm_mullo_epi32(Aij, Akj);

// Bij= {B_{i,j} + A_{i,k} × A_{k,j}, B_{i,j+1} + A_{i,k} × A_{k,j+1}, ...}
Bij = _mm_add_epi32(Bij, Aik_times_Akj);

// store Bij into B
_mm_storeu_si128((__m128i*) &B[i * N + j], Bij);
```

constant multiplies/divides (1)

```
unsigned int fiveEights(unsigned int x) {
    return x * 5 / 8;
}
```

```
fiveEights:
        leal    (%rdi,%rdi,4), %eax
        shrl    $3, %eax
        ret
```

constant multiplies/divides (2)

```
int oneHundredth(int x) { return x / 100; }
```

```
oneHundredth:
        movl    %edi, %eax
        movl    $1374389535, %edx
        sarl    $31, %edi
        imull   %edx
        sarl    $5, %edx
        movl    %edx, %eax
        subl    %edi, %eax
        ret
```

$$\frac{1374389535}{2^{37}} \approx \frac{1}{100}$$

constant multiplies/divides

compiler is very good at handling

...but need to actually use constants