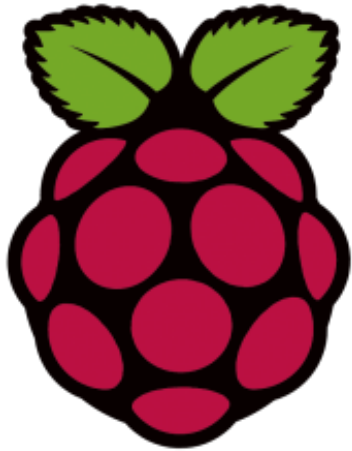
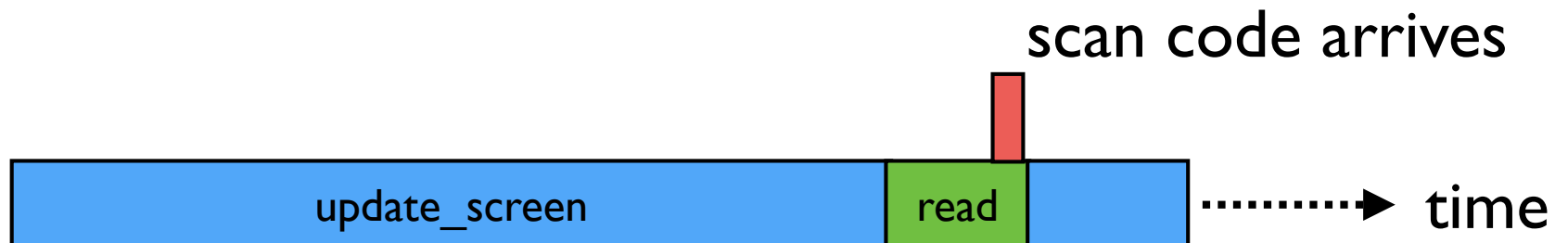


Interrupts and Concurrency



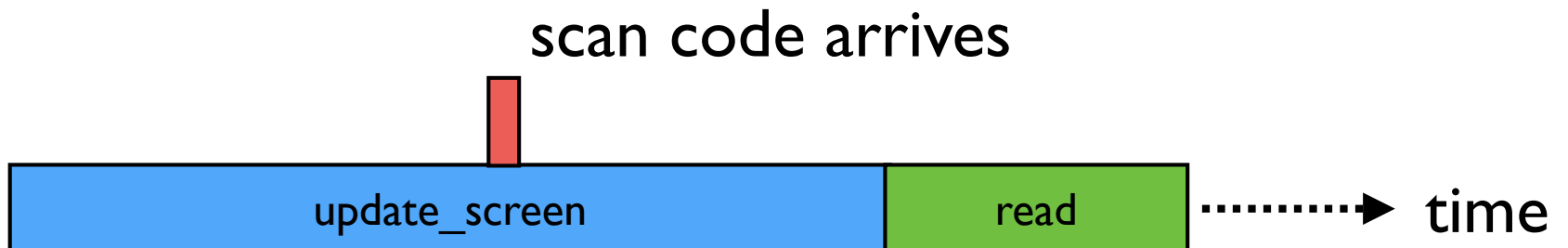
Blocking I/O

```
while (1) {  
    read_char_to_screen();  
    update_screen();  
}
```



Problem!

```
while (1) {  
    read_char_to_screen();  
    update_screen();  
}
```



Interrupts, Redux

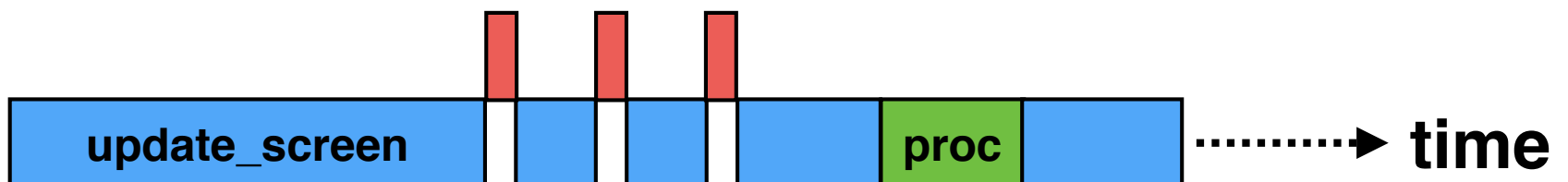
Cause processor to pause what it's doing and immediately execute interrupt code, returning to original code when done

- External events (reset, timer, GPIO)
- Internal events (bad memory access, bad instruction)
 - *Sometimes called "exceptions;" different in that they imply code has to do something about the instruction that was interrupted*

Concurrency

```
when a scan code arrives {  
    add_scan_code_to_buffer();  
}
```

```
while (1) {  
    while (read_chars_from_buffer()) {}  
    update_screen();  
}
```



Last Lecture

Processor support for interrupts

- Registers to configure and enable/disable interrupts
- Interrupt mode with private sp, lr, and CPSR registers
- 8 different interrupt cases (we only care about one)
- Processor expects table of instruction (one per interrupt) starting at address 0x0

When an interrupt is raised

- Processor switches to interrupt mode (lr remembers where your program was interrupted)
- Processor jumps to one of 8 instruction in the table at address 0x0
- At that point, everything is software's responsibility

Interrupts are extremely valuable and seem simple, but getting them right requires using everything you've learned: assembly, linking, C, memory

Challenge

Processor specifies location (0x0) where it expects table of instructions, one per interrupt

- When an interrupt occurs, processor jumps to the corresponding instruction
- At that point, everything is software's responsibility

Writing code that can be safely copied to this location requires very careful assembly

- Have to make sure addresses are all absolute, and you know where they are stored

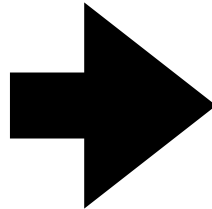
code/vectors

Explicitly Embedded Absolute Addresses

```
.globl _vectors
```

```
_vectors:
```

```
ldr pc, =abort_asm  
ldr pc, =abort_asm  
ldr pc, =abort_asm  
ldr pc, =abort_asm  
ldr pc, =abort_asm  
ldr pc, =abort_asm  
ldr pc, =interrupt_asm  
ldr pc, =abort_asm
```



```
.globl _vectors
```

```
_vectors:
```

```
ldr pc, =_abort_asm  
ldr pc, =_abort_asm  
ldr pc, =_abort_asm  
ldr pc, =_abort_asm  
ldr pc, =_abort_asm  
ldr pc, =_abort_asm  
ldr pc, =_abort_asm  
ldr pc, =_interrupt_asm  
ldr pc, =_abort_asm
```


```
_abort_asm:          .word abort_asm  
_interrupt_asm:      .word interrupt_asm
```

Now we know the constants will follow the code.
This works!!!

Explicitly Embedded Absolute Addresses

8 instructions starting
at 0x0

CPU jumps to instr[6]
on a peripheral
interrupt



```
.globl _vectors
```

```
_vectors:
```

```
ldr pc, =_abort_asm
```

```
ldr pc, =_abort_asm
```

```
ldr pc, =_abort_asm
```

```
ldr pc, =_abort_asm
```

```
ldr pc, =_abort_asm
```

```
ldr pc, =_abort_asm
```

```
ldr pc, =_interrupt_asm
```

```
ldr pc, =_abort_asm
```

```
_abort_asm: .word abort_asm
```

```
_interrupt_asm: .word interrupt_asm
```

Now we know the constants will follow the code.
This works!!!

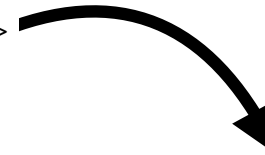
C Code

```
#define RPI_VECTOR_START 0x0
```

```
int* vectorsdst = (int*)RPI_VECTOR_START;
int* vectors = &_vectors;
int* vectors_end = &_vectors_end;
while (vectors < vectors_end)
    *vectorsdst++ = *vectors++;
```

```
0000807c <_vectors>:
```

807c:	e59ff018	ldr	pc, [pc, #24]	; 809c <abort_addr>
8080:	e59ff014	ldr	pc, [pc, #20]	; 809c <abort_addr>
8084:	e59ff010	ldr	pc, [pc, #16]	; 809c <abort_addr>
8088:	e59ff00c	ldr	pc, [pc, #12]	; 809c <abort_addr>
808c:	e59ff008	ldr	pc, [pc, #8]	; 809c <abort_addr>
8090:	e59ff004	ldr	pc, [pc, #4]	; 809c <abort_addr>
8094:	e59ff004	ldr	pc, [pc, #4]	; 80a0 <interrupt_addr>
8098:	e51ff004	ldr	pc, [pc, #-4]	; 809c <abort_addr>
809c:	000080a4	.word	0x000080a4	
80a0:	000080a8	.word	0x000080a8	



```
00000000 <_vectors>:
```

0000:	e59ff018	ldr	pc, [pc, #24]	; 809c <abort_addr>
0004:	e59ff014	ldr	pc, [pc, #20]	; 809c <abort_addr>
0008:	e59ff010	ldr	pc, [pc, #16]	; 809c <abort_addr>
000c:	e59ff00c	ldr	pc, [pc, #12]	; 809c <abort_addr>
0010:	e59ff008	ldr	pc, [pc, #8]	; 809c <abort_addr>
0014:	e59ff004	ldr	pc, [pc, #4]	; 809c <abort_addr>
0018:	e59ff004	ldr	pc, [pc, #4]	; 80a0 <interrupt_addr>
001c:	e51ff004	ldr	pc, [pc, #-4]	; 809c <abort_addr>
0020:	000080a4	.word	0x000080a4	
0024:	000080a8	.word	0x000080a8	

interrupts_asm.s

```
interrupt_asm:
    mov     sp, #0x8000
    sub     lr, lr, #4
    push    {r0-r12, lr}
    mov     r0, lr
    bl      interrupt_dispatch
    ldm     sp!, {r0-r12, pc}^
```

Today

1. Set up the interrupt stack.
2. Install interrupt handler code.
3. Tell CPU when to trigger interrupts.
 - When PS/2 clock line has a falling edge
4. Enable interrupts!
5. Writing safe interrupt handlers.
 - How do you share state that can be modified at any time?

Three Layers

1. Enable/disable a specific interrupt source

- For example, when we detect a falling clock edge on GPIO_PIN23 (PS/2 CLK)

2. Enable/disable type of interrupts

- E.g., GPIO interrupts

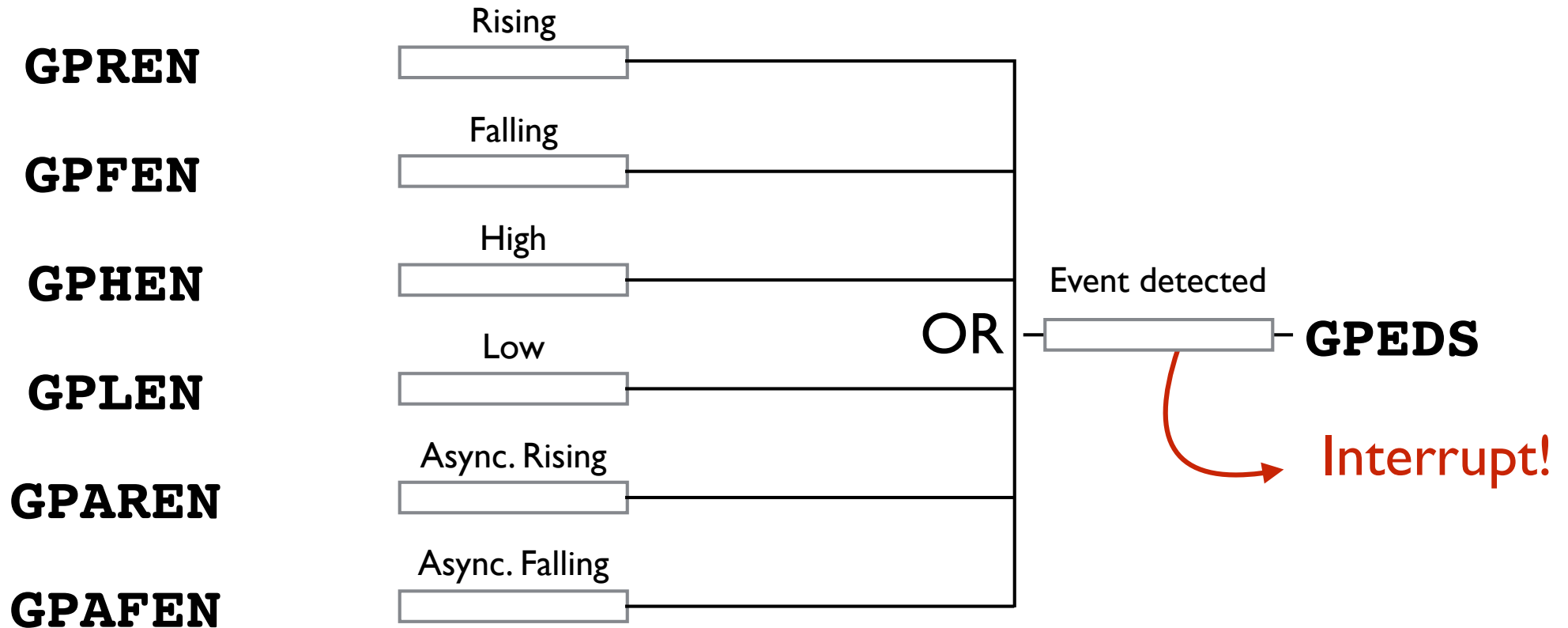
3. Global interrupt enable/disable

Interrupt fires if and only if all three are enabled

Forgetting to enable one is a common bug

GPIO Events

Peripheral Registers



See `gpioextra.h` and `gpioextra.c`

GPIO Interrupts (pg. 96-98)

Goal: Trigger interrupt on falling edge of clock, read data line in interrupt handler.

Falling edge detect enable register (GPFEN_n)

- Lots of other options! High level, low level, rising edge, etc.

Event detect status register (GPEDS_n)

- Bit is set when an event on the given pin occurs
- Clear event by writing 1 to position, or will re-trigger an interrupt!

Interrupt sources



BCM2835 ARM Peripherals

ARM peripherals interrupts table.

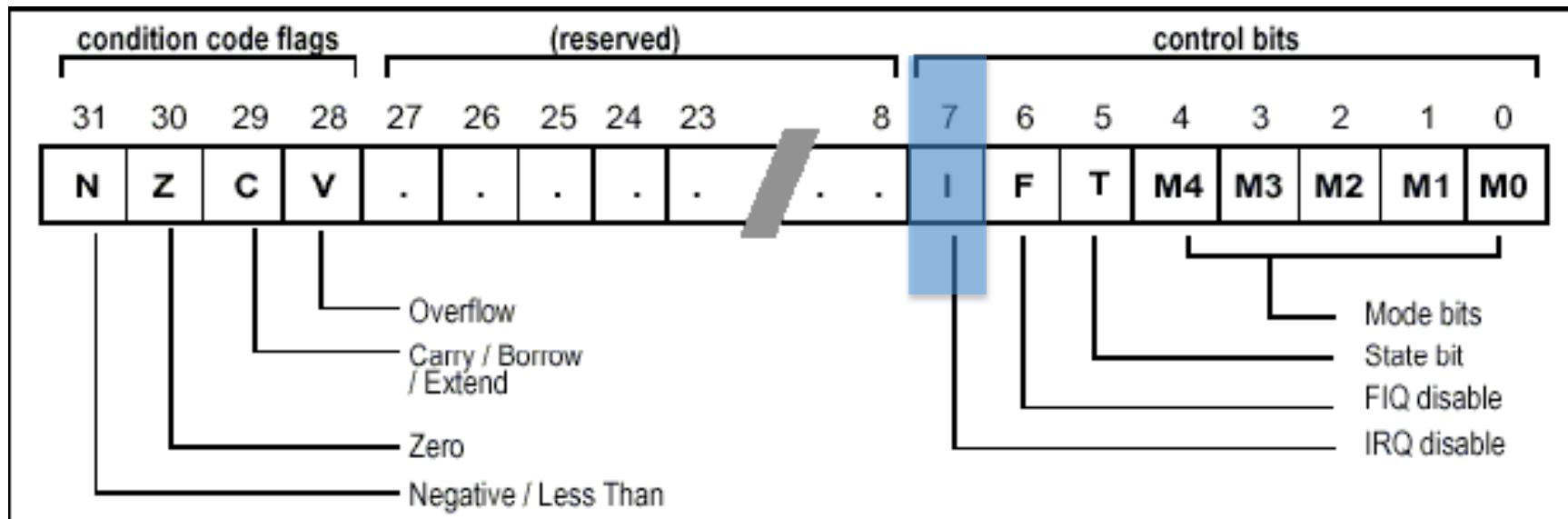
#	IRQ 0-15	#	IRQ 16-31	#	IRQ 32-47	#	IRQ 48-63
0		16		32		48	smi
1		17		33		49	gpio_int[0]
2		18		34		50	gpio_int[1]
3		19		35		51	gpio_int[2]
4		20		36		52	gpio_int[3]
5		21		37		53	i2c_int
6		22		38		54	spi_int
7						55	pcm_int
8		24		40		56	
9		25		41		57	uart_int
10		26		42		58	
11		27		43	i2c_spi_slv_int	59	
12		28		44		60	
13		29	Aux int	45	pwa0	61	
14		30		46	pwa1	62	
15		31		47		63	

Documentation is sparse ...

what we
want

The table above has many empty entries. These should not be enabled as they will interfere with the GPU operation.

Enabling Global Interrupts



```
.global interrupts_global_enable
interrupts_global_enable:
    mrs r0,cpsr
    bic r0,r0,#0x80
    // I=0 enables interrupts
    msr cpsr_c,r0
    bx lr
```

```
.global interrupts_global_disable
interrupts_global_disable:
    mrs r0,cpsr
    orr r0,r0,#0x80
    // I=1 disables interrupts
    msr cpsr_c,r0
    bx lr
```

code/button-interrupts

We're done!

We now can write correct and safe interrupt code

- Assembly to save all registers
- Call into C code
- Assembly to restore registers, return to interrupted code

We can install the interrupt code table to 0x0

- Embed addresses of assembly routines so jumps are absolute
- Copy interrupt table to 0x0 in cstart

Enable and disable interrupts

- Specific interrupts, per-peripheral interrupts, global interrupts

Not Quite

Need to be able to specify what code to run

- Interrupts are bottom-up
- The library implements the calling function: we implement the handlers that should run on different interrupts
- Need API to be able to do this

Need to write code that can be safely interrupted

- Interrupt handler may put a PS/2 scan code in a buffer
- Could do so at any time: in the middle of when main() code is trying to pull a scan code out of the buffer
- Need to make sure the interrupt doesn't corrupt the buffer

Interrupt API Goals

Speed!

- Minimize number of cycles spent in library: imagine if the handler is just a few instructions because we want to be able to run it very often

Avoid runtime failures (i.e., debugging)

- You should always be able to register one handler for each interrupt: whether you can register it should be independent of how many modules there are

Flexible

- Allow you to easily add new modules that handle interrupts

Basic API

```
bool interrupts_enable_source(unsigned int source);
bool interrupts_disable_source(unsigned int source);

typedef bool (*handler_fn_t)(unsigned int);
handler_fn_t interrupts_register_handler(unsigned int source, handler_fn_t fn);

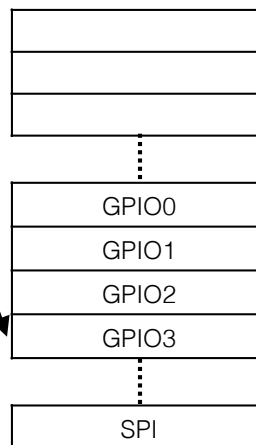
enum interrupt_source {
    INTERRUPTS_SHARED_START = 29,
    INTERRUPTS_AUX = 29,
    INTERRUPTS_I2CSPISLV = 43,
    ...
    INTERRUPTS_GPIO0 = 49,
    INTERRUPTS_GPIO1 = 50,
    INTERRUPTS_GPIO2 = 51,
    INTERRUPTS_GPIO3 = 52,
    INTERRUPTS_VC_I2C = 53,
    INTERRUPTS_VC_SPI = 54,
    INTERRUPTS_VC_I2SPCM = 55,
    INTERRUPTS_VC_UART = 57,
    ...
};
```

Implementation

Array of function pointers, mirrors structure of interrupts

```
static struct {  
    handler_fn_t fn;  
} handlers[INTERRUPTS_COUNT];  
  
void interrupt_dispatch(unsigned int pc) {  
    int next_interrupt = interrupts_get_next();  
    if (next_interrupt < INTERRUPTS_COUNT) {  
        handlers[next_interrupt].fn(pc);  
    }  
}
```

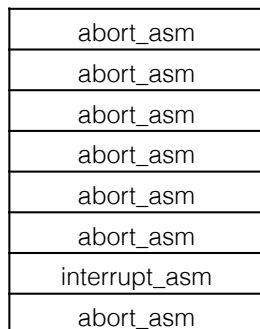
handlers



GPIO module

SPI module

ARM



```
interrupt_asm:  
    mov    sp, #0x8000  
    sub    lr, lr, #4  
    push   {r0-r12, lr}  
    mov    r0, lr  
    bl     interrupt_dispatch  
    ldm    sp!, {r0-r12, pc}^
```


Not Quite

Need to be able to specify what code to run

- Interrupts are bottom-up
- The library implements the calling function: we implement the handlers that should run on different interrupts
- Need API to be able to do this

Need to write code that can be safely interrupted

- Interrupt handler may put a PS/2 scan code in a buffer
- Could do so at any time: in the middle of when main() code is trying to pull a scan code out of the buffer
- Need to make sure the interrupt doesn't corrupt the buffer

code/race

One Problem

main code

```
extern int a;
```

```
a = a + 1;
```

interrupt

```
extern int a;
```

```
a = a - 1;
```

One Problem

main code

```
extern int a;
```

```
a = a + 1;
```

interrupt

```
extern int a;
```

```
a = a - 1;
```

<inc>:

```
8000: e52db004 push {fp}
8004: e28db000 add fp, sp, #0
8008: e59f3018 ldr r3, [pc, #24]
800c: e5933000 ldr r3, [r3]
8010: e2832001 add r2, r3, #1
8014: e59f300c ldr r3, [pc, #12]
8018: e5832000 str r2, [r3]
801c: e24bd000 sub sp, fp, #0
8020: e49db004 pop {fp}
8024: e12fff1e bx lr
8028: 00010070 .word 0x00010070
```

<dec>:

```
802c: e52db004 push {fp}
8030: e28db000 add fp, sp, #0
8034: e59f3018 ldr r3, [pc, #24]
8038: e5933000 ldr r3, [r3]
803c: e2432001 sub r2, r3, #1
8040: e59f300c ldr r3, [pc, #12]
8044: e5832000 str r2, [r3]
8048: e24bd000 sub sp, fp, #0
804c: e49db004 pop {fp}
8050: e12fff1e bx lr
8054: 00010070 .word 0x00010070
```

One Problem

main code

```
extern int a;
```

```
a = a + 1;
```


interrupt

```
extern int a;
```

```
a = a - 1;
```

<inc>:

```
8000: e52db004  push {fp}
8004: e28db000  add fp, sp, #0
8008: e59f3018  ldr r3, [pc, #24]
800c: e5933000  ldr r3, [r3]
8010: e2832001  add r2, r3, #1
8014: e59f300c  ldr r3, [pc, #12]
8018: e5832000  str r2, [r3]
801c: e24bd000  sub sp, fp, #0
8020: e49db004  pop {fp}
8024: e12fff1e  bx  lr
8028: 00010070  .word 0x00010070
```



<dec>:

```
802c: e52db004  push {fp}
8030: e28db000  add fp, sp, #0
8034: e59f3018  ldr r3, [pc, #24]
8038: e5933000  ldr r3, [r3]
803c: e2432001  sub r2, r3, #1
8040: e59f300c  ldr r3, [pc, #12]
8044: e5832000  str r2, [r3]
8048: e24bd000  sub sp, fp, #0
804c: e49db004  pop {fp}
8050: e12fff1e  bx  lr
8054: 00010070  .word 0x00010070
```

Why will a decrement be lost if interrupt occurs here?

One Problem

main code

```
extern int a;
```

```
a = a + 1;
```


interrupt

```
extern int a;
```

```
a = a - 1;
```

<inc>:

```
8000: e52db004 push {fp}
8004: e28db000 add fp, sp, #0
8008: e59f3018 ldr r3, [pc, #24]
800c: e5933000 ldr r3, [r3]
8010: e2832001 add r2, r3, #1
8014: e59f300c ldr r3, [pc, #12]
8018: e5832000 str r2, [r3]
801c: e24bd000 sub sp, fp, #0
8020: e49db004 pop {fp}
8024: e12fff1e bx lr
8028: 00010070 .word 0x00010070
```



<dec>:

```
802c: e52db004 push {fp}
8030: e28db000 add fp, sp, #0
8034: e59f300c ldr r3, [pc, #12]
8038: e5832000 str r2, [r3]
803c: e24bd000 sub sp, fp, #0
8040: e49db004 pop {fp}
8044: e12fff1e bx lr
8048: 00010070 .word 0x00010070
```

code uses copy of a in r3, not a; decrement is lost

Will volatile solve this?

Disabling Interrupts

main

interrupt handler

```
interrupts_global_disable();
```

```
a++;
```

```
b++;;
```

```
interrupts_global_enable();
```

```
a++;
```

```
b++;
```

Preemption and Safety

Very hard, lots of bugs.

You'll learn more in CS110/CS140.

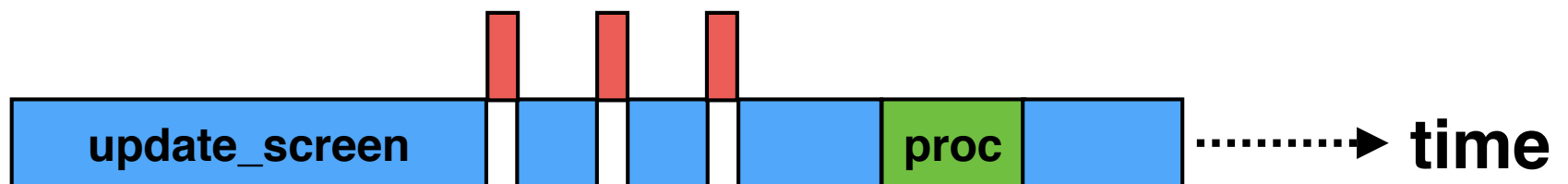
Two simple answers

1. Use simple, safe data structures
 - write once, but not always possible
2. Otherwise, temporarily disable interrupts
 - always works, but easy to forge
 - hard to compose (calling functions)

Concurrency

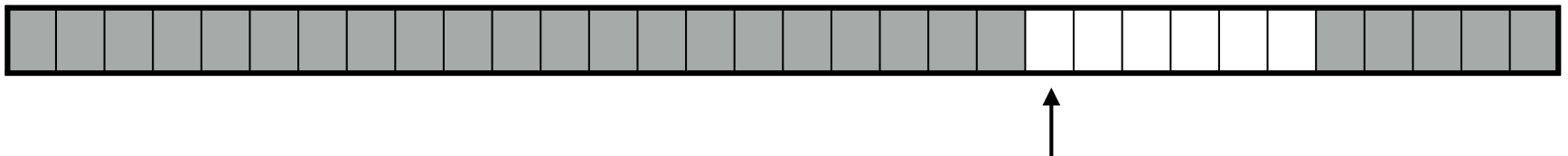
```
when a scan code arrives {  
    add_scan_code_to_buffer();  
}
```

```
while (1) {  
    while (read_chars_from_buffer()) {}  
    update_screen();  
}
```



Safe Ring Buffer

```
bool rb_enqueue(rb_t *rb, int elem) {  
    if (rb_full(rb)) {  
        return false;  
    } else {  
        rb->entries[rb->tail] = elem;  
        rb->tail = (rb->tail + 1) % LENGTH; // only writes tail  
        return true;  
    }  
}  
} ringbuffer
```



```
bool rb_dequeue (rb_t *rb, int *elem) {  
    if (rb_empty(rb)) {  
        return false;  
    }  
    *elem = rb->entries[rb->head];  
    rb->head = (rb->head + 1) % LENGTH; // only writes head  
    return true;  
}
```

This Lecture

Writing the code that runs in interrupts

- Assembly code needed to change to processor models and special registers
- Interrupt table copied to 0x0 in `cstart.c`

Setting up the CPU to issue interrupts

- 3 levels: cause, type, global

Writing code that can be safely interrupted

- Race conditions though interrupt-safe ring buffer

Summary

Interrupts allow external events to preempt what's executing and run code immediately

- Needed for responsiveness, e.g., do not miss PS/2 scan codes from keyboard when drawing
- Without interrupts, most computers do nothing: they deliver keystrokes, network packets, disk reads, timers, etc.

Simple goal, but working correctly is very tricky!

- Deals with many of the hardest issues in systems

Assignment 7: update keyboard to use interrupts