Announcements

Upcoming schedule ...

Start thinking about final project; form teams of 2 people (1-3 ok)

Final 2 labs will be devoted to working on your project (work on proposal as team; check-in)

Late days apply through Assign7, not final project

Single and double buffering review

font_get_char demonstration

Single and Double Buffering Review

font_get_char

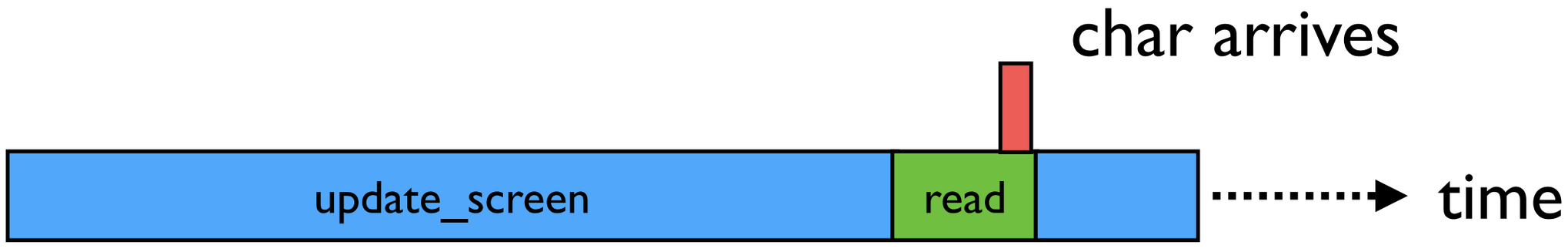
demonstration

Interrupts

Blocking I/O

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

Read fn loops until char is received - blocking



Blocking I/O

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

How long does it take to send a scan code?
- 11kHz, 11 bits/scan code

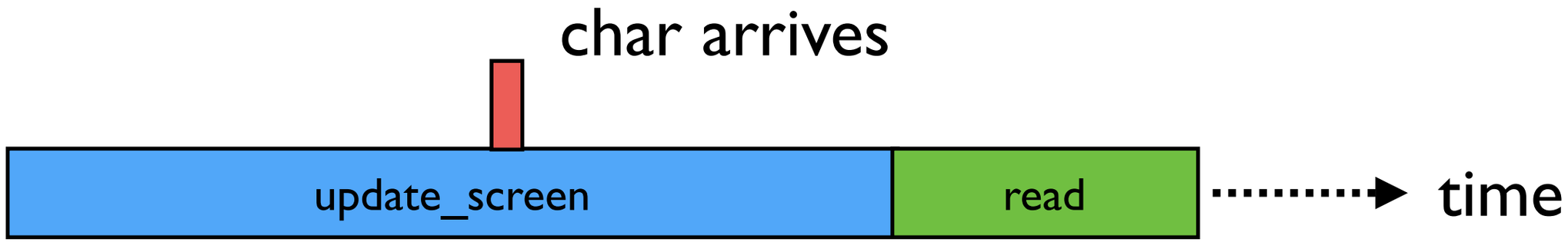
How long does it take to update the screen?

What could go wrong?

code/glkeyboard

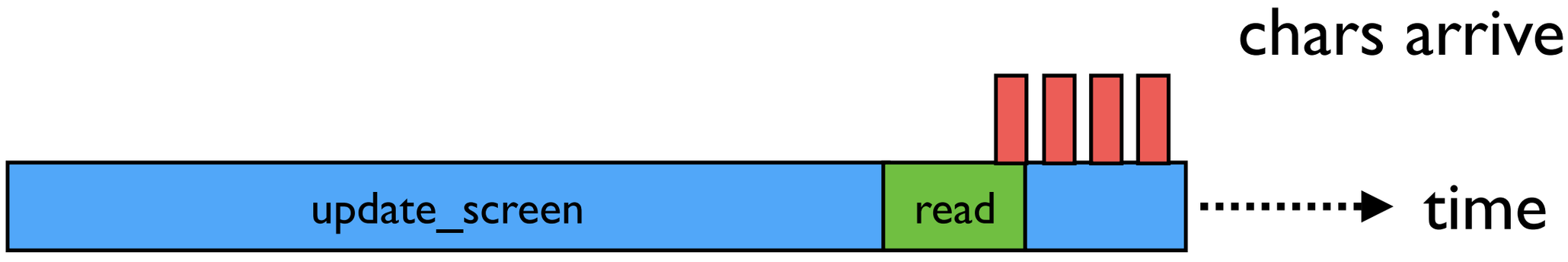
Blocking I/O

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



Blocking I/O

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



The Problem

Need long-running computations (graphics, computations, applications, etc.).

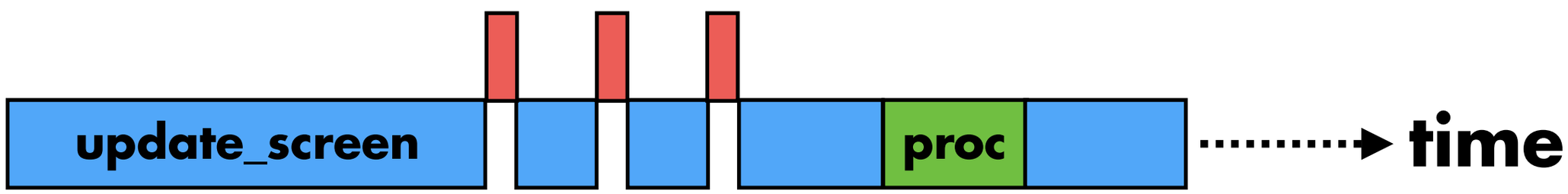
Need to respond to external events quickly.

How could we change this code?

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

Interrupts

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

while (1) {
   // Doesn't block
   while (read_chars_from_buffer()) {}
   update_screen();
}
```



Interrupts to the Rescue

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, software trigger)**

Critical for responsive systems.

Using interrupts exercises everything you've learned so far.

- **Architecture, assembly, linking, memory, C, peripherals**

They'll complete your interactive graphics console.

code/blink

`blink.c`

Timer causes an interrupt once per second

`while()` loop in `main()` is interrupted

Interrupt handler increments `counter`

`while()` checks for counter change

Toggles `ACT_LED` and prints `counter`

Why is `counter` declared `volatile`?

How is `interrupt_handler` called?

Interrupt Vectors

8 Kinds of Interrupts

```
_vectors:
  ldr pc, _reset_asm
  ldr pc, _undefined_instruction_asm
  ldr pc, _software_interrupt_asm
  ldr pc, _prefetch_abort_asm
  ldr pc, _data_abort_asm
  ldr pc, _reset_asm
  ldr pc, _interrupt_asm
  ldr pc, _fast_asm

_reset_asm:                     .word impossible_asm
_undefined_instruction_asm:     .word impossible_asm
_software_interrupt_asm:        .word impossible_asm
_prefetch_abort_asm:            .word impossible_asm
_data_abort_asm:                .word impossible_asm
_interrupt_asm:                 .word interrupt_asm
_fast_asm:                      .word impossible_asm

_vectors_end
```

Interrupt Vectors

```
_vectors:
  ldr pc, _reset_asm
  ldr pc, _undefined_instruction_asm
  ldr pc, _software_interrupt_asm
  ldr pc, _prefetch_abort_asm
  ldr pc, _data_abort_asm
  ldr pc, _reserved_asm
  ldr pc, _interrupt_asm:
  ldr pc, _fast_asm

_reset_asm:                         .word impossible_asm
_undefined_instruction_asm:         .word impossible_asm
_software_interrupt_asm:            .word impossible_asm
_prefetch_abort_asm:                .word impossible_asm
_data_abort_asm:                    .word impossible_asm
_interrupt_asm:                     .word interrupt_asm
_fast_asm:                          .word impossible_asm

_vectors_end
```

branch to `interrupt_asm`

How is `interrupt_asm` is called?
What is the difference between `interrupt_asm` and `_interrupt_asm`?

Interrupt Vectors

```
_vectors:
  ldr pc, _reset_asm
  ldr pc, _undefined_instruction_asm
  ldr pc, _software_interrupt_asm
  ldr pc, _prefetch_abort_asm
  ldr pc, _data_abort_asm
  ldr pc, _reset_asm
  ldr pc, _interrupt_asm:
  ldr pc, _fast_asm

_reset_asm:                     .word impossible_asm
_undefined_instruction_asm:     .word impossible_asm
_software_interrupt_asm:        .word impossible_asm
_prefetch_abort_asm:            .word impossible_asm
_data_abort_asm:                .word impossible_asm
_interrupt_asm:                 .word interrupt_asm
_fast_asm:                      .word impossible_asm

_vectors_end
```

branch to `interrupt_asm`

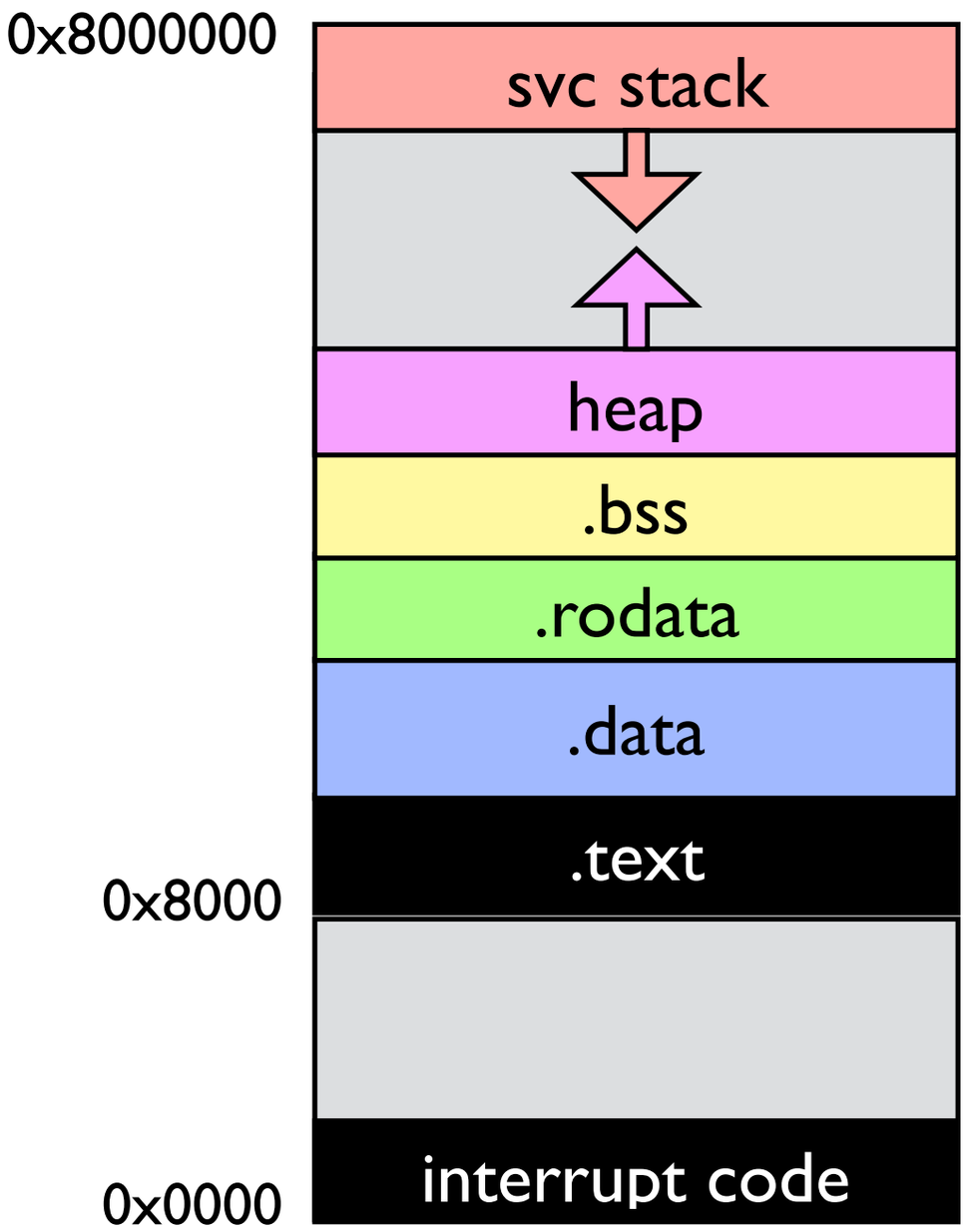
How does the system know what to call when an interrupt occurs?

cstart.c

```
static int * const RPI_INTERRUPT_VECTOR_BASE = 0x0;

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

Where do we put the interrupt vectors?
Why do we need to copy them?
Where are `_vectors` and `_vectors_end` defined?

CPU Address Space



```
_vectors:
  ldr pc, _reset_asm
  ldr pc, _undefined_instruction_asm
  ldr pc, _software_interrupt_asm
  ldr pc, _prefetch_abort_asm
  ldr pc, _data_abort_asm
  ldr pc, _reset_asm
  ldr pc, _interrupt_asm:
  ldr pc, _fast_asm

_reset_asm:                    .word impossible_asm
_undefined_instruction_asm:    .word impossible_asm
_software_interrupt_asm:       .word impossible_asm
_prefetch_abort_asm:           .word impossible_asm
_data_abort_asm:               .word impossible_asm
_interrupt_asm:                .word interrupt_asm
_fast_asm:                     .word impossible_asm

_vectors_end
```

branch to `interrupt_asm`

Why does this code work if it is copied to address 0?

Position independent code

pc-relative addressing

```
% cd ../vector
% make main.list
% cat main.list
…
00008040 <_vectors>:
    8040:   ldr pc, [pc, #24]   ; 8060 <_impossible_asm>
    8044:   ldr pc, [pc, #20]   ; 8060 <_impossible_asm>
    8048:   ldr pc, [pc, #16]   ; 8060 <_impossible_asm>
    804c:   ldr pc, [pc, #12]   ; 8060 <_impossible_asm>
    8050:   ldr pc, [pc, #8]    ; 8060 <_impossible_asm>
    8054:   ldr pc, [pc, #4]    ; 8060 <_impossible_asm>
    8058:   ldr pc, [pc, #4]    ; 8064 <_interrupt_asm>
    805c:   ldr pc, [pc, #-4]   ; 8060 <_impossible_asm>

00008060 <_impossible_asm>:
    8060:   .word   0x00008084
00008064 <_interrupt_asm>:
    8064:   .word   0x00008068
. . .
00008084 <impossible_asm>:
. . .
00008068 <interrupt_asm>:
```

Interrupt Handler

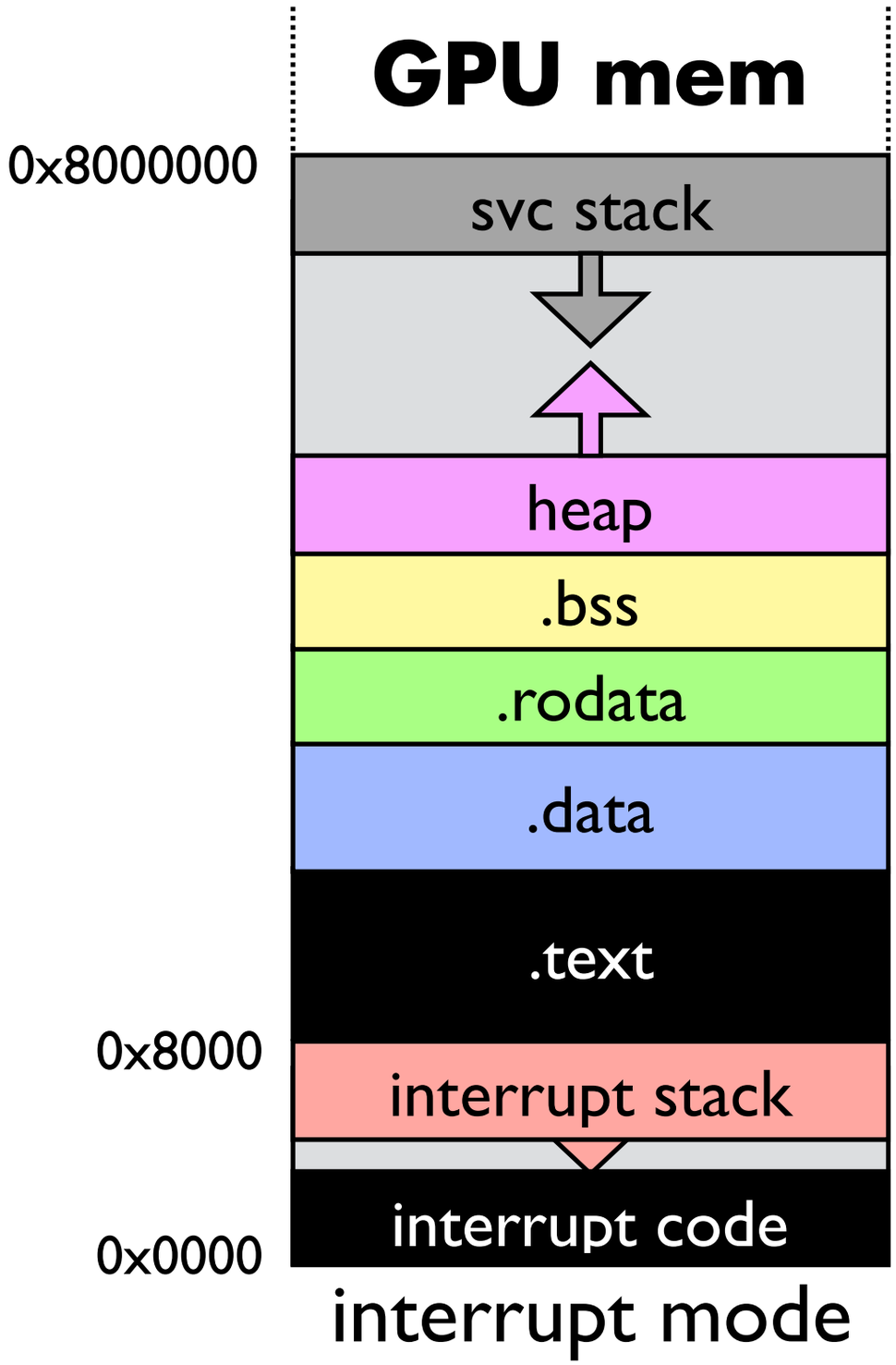
Interrupt Handler

```
interrupt_asm:
    mov sp, #0x8000
    sub lr, lr, #4

    push {r0-r12,lr}

    mov  r0, lr
    bl  interrupt_handler

    pop {r0-r12, lr}
    movs pc, lr
```

```
interrupt_asm:
    mov sp, #0x8000
    sub lr, lr, #4

    push {r0-r12,lr}

    mov  r0, lr
    bl  interrupt_handler

    pop {r0-r12, lr}
    movs pc, lr
```

Why do we save all of the registers?
Where do we save the registers?

Interrupt Stack



Interrupt occurs right before instruction

```
Disassembly of section .text:

00008000 <_start>:
    8000:       e3a0d902        mov     sp, #32768      ; 0x8000
    8004:       eb000001        bl      8010 <_cstart>

00008008 <hang>:
    8008:       eb000039        bl      80f4 <led_on>
    800c:       eafffffe        b       800c <hang+0x4>

00008010 <_cstart>:
    8010:       e92d4800        push    {fp, lr}
```

← **Interrupt!**

What is the pc when the interrupt occurs?
Where can we store that information?

```
interrupt_asm:
    mov sp, #0x8000
    sub lr, lr, #4

    push {r0-r12,lr}

    mov r0, lr
    bl  interrupt_handler

    pop {r0-r12, lr}
    movs pc, lr
```

Why do we subtract 4 from `lr`?
What is the value passed to `interrupt_handler`?

Processor Modes

User - unprivileged mode

IRQ - interrupt mode

FIQ - fast interrupt mode

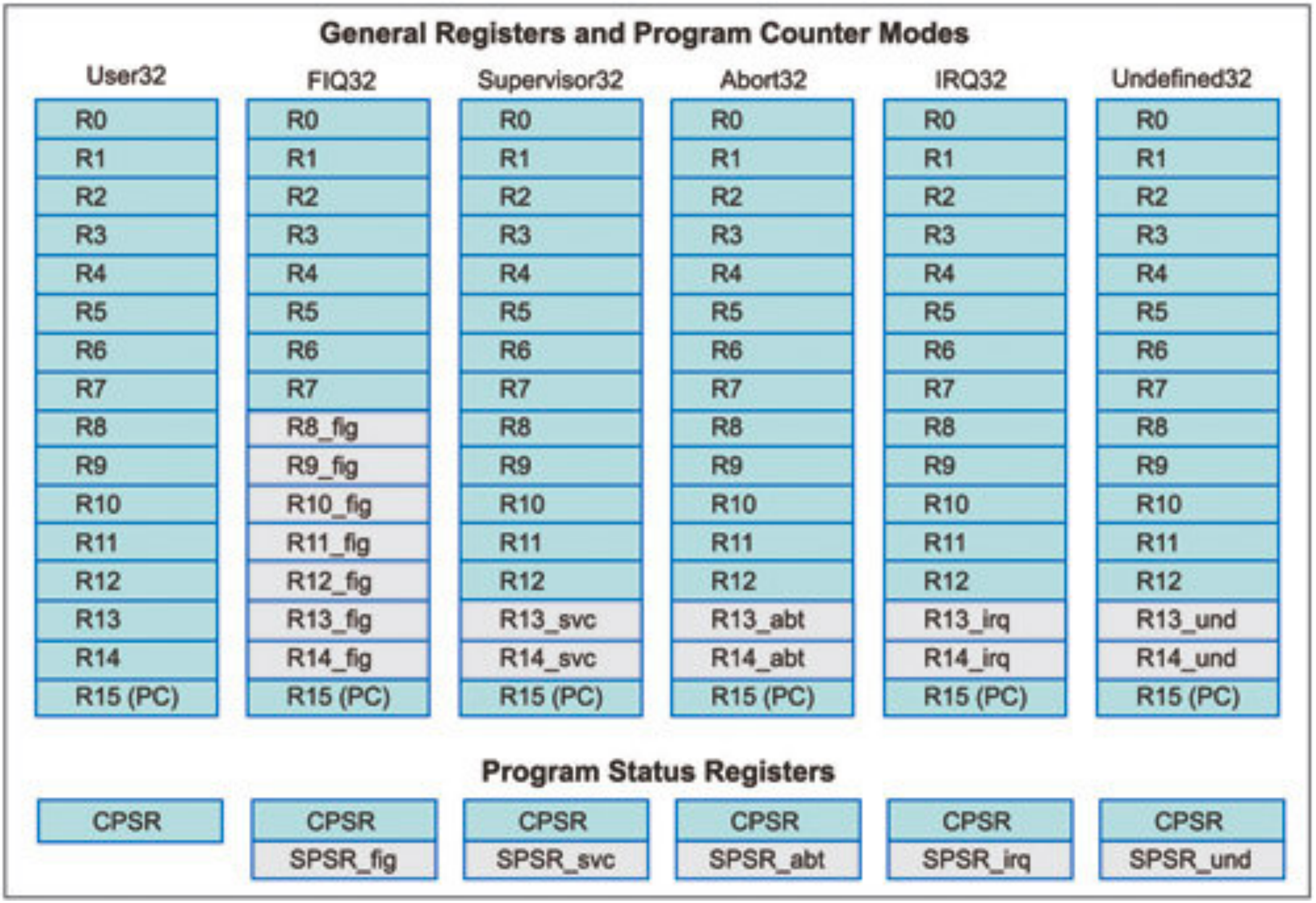
Supervisor - privileged mode, entered on reset

Abort - memory access violation

Undefined - undefined instruction

System - privileged mode that shares user regs

Shared / Unshared Registers



Return from Interrupt

```
interrupt_asm:
    mov sp, #0x8000
    sub lr, lr, #4

    push {r0-r12,lr}

    mov  r0, lr
    bl  interrupt_handler

    pop {r0-r12, lr}
    movs pc, lr
```

Restore the registers
`movs` causes a return from interrupt

Can this code be written in C?

Summary

Interrupts allow external events to trigger code to run with very little delay: responsiveness despite long-running functions

- **They bring together everything you've learned so far**

Running code at arbitrary points is dangerous!

- **Copies of lr and sp, use separate stack**

Interrupt vectors are at `0x0-0x1c`

- **Have to copy them there at boot time**
- **Generating safe assembly requires explicitly embedding addresses**

Next time: using and writing interrupts (the return of GPIO)