

Graphics and Framebuffers

Response to Mid-Quarter Feedback

Thanks for all the feedback!

Some changes

- Do a better job rotating time between students at OH
- Push back on "I just have a quick question"

One tradeoff

- Office hours spread across many times vs. multiple CAs at office hours

gpio
timer
uart
printf
malloc
keyboard
fb
gl
console
shell





Baremetal on the Pi

Raspberry Pi A+

ARM processor and memory

Peripherals: GPIO, timers, UART (gpio, uart), keyboard

Assembly and machine language (as)

C and pointers (gcc)

Functions and the stack (gdb)

Serial communication and strings (uart, printf)

Linking and the memory map (ld, memmap, objcopy)

Loading using the bootloader (rpi-install.py, bootloader)

Starting (start.s, cstart.c)

Memory managements

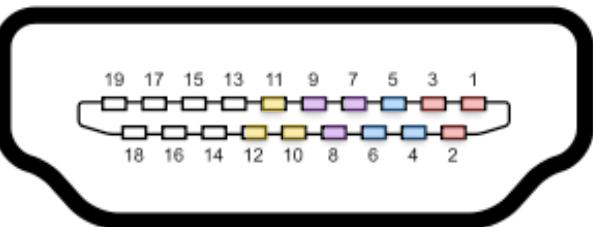
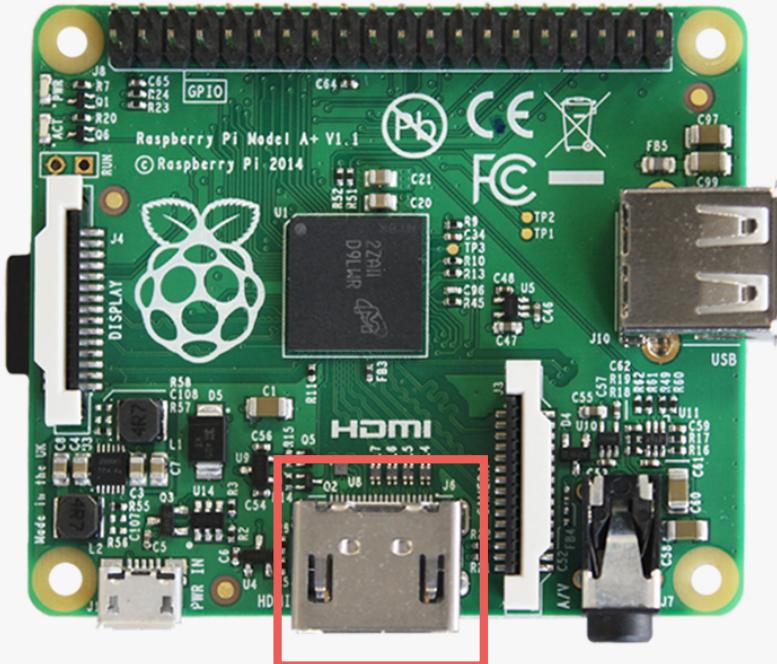
Tools (git, bash, make, brew)

A close-up photograph of a person's hand gripping a lightsaber hilt. The hilt is primarily black with silver-colored accents on the handle and the top cylindrical section. A bright blue energy blade is extended from the hilt, glowing intensely at the tip. The background is dark and out of focus, creating a dramatic effect.

The Force Awakens in You



HDMI



Clock
Data 0
Data 1
Data 2
Control

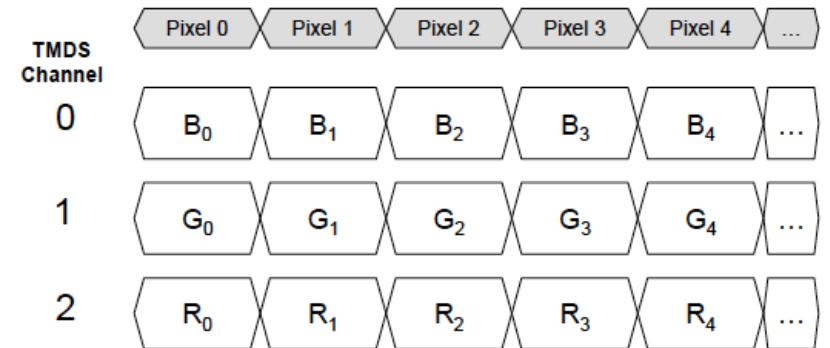
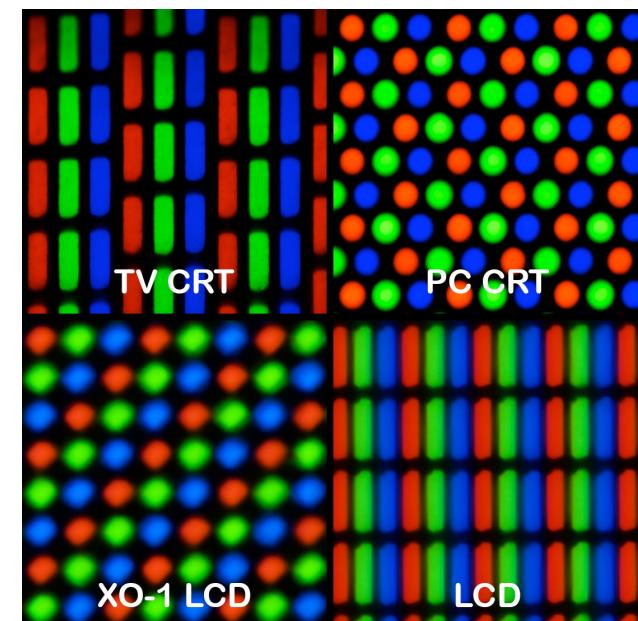


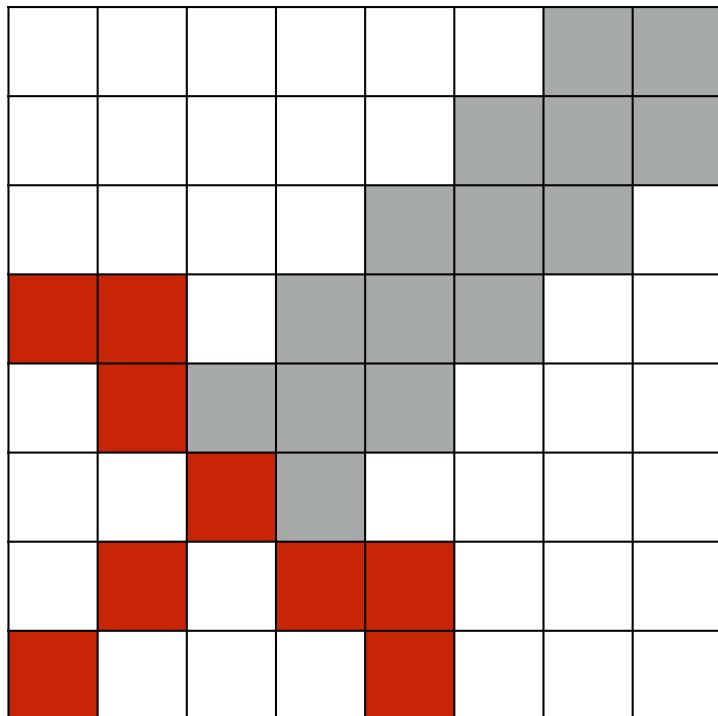
Figure 6-1 Default pixel encoding: RGB 4:4:4, 8 bits/component

Figure from High-Definition Multimedia Interface Specification Version 1.3a

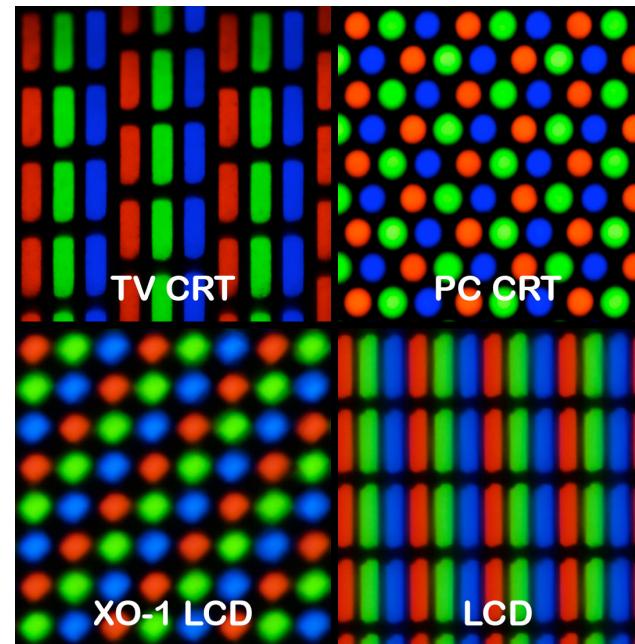


Displays

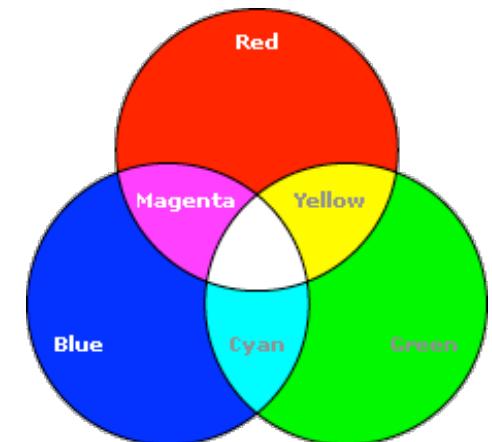
Pixels

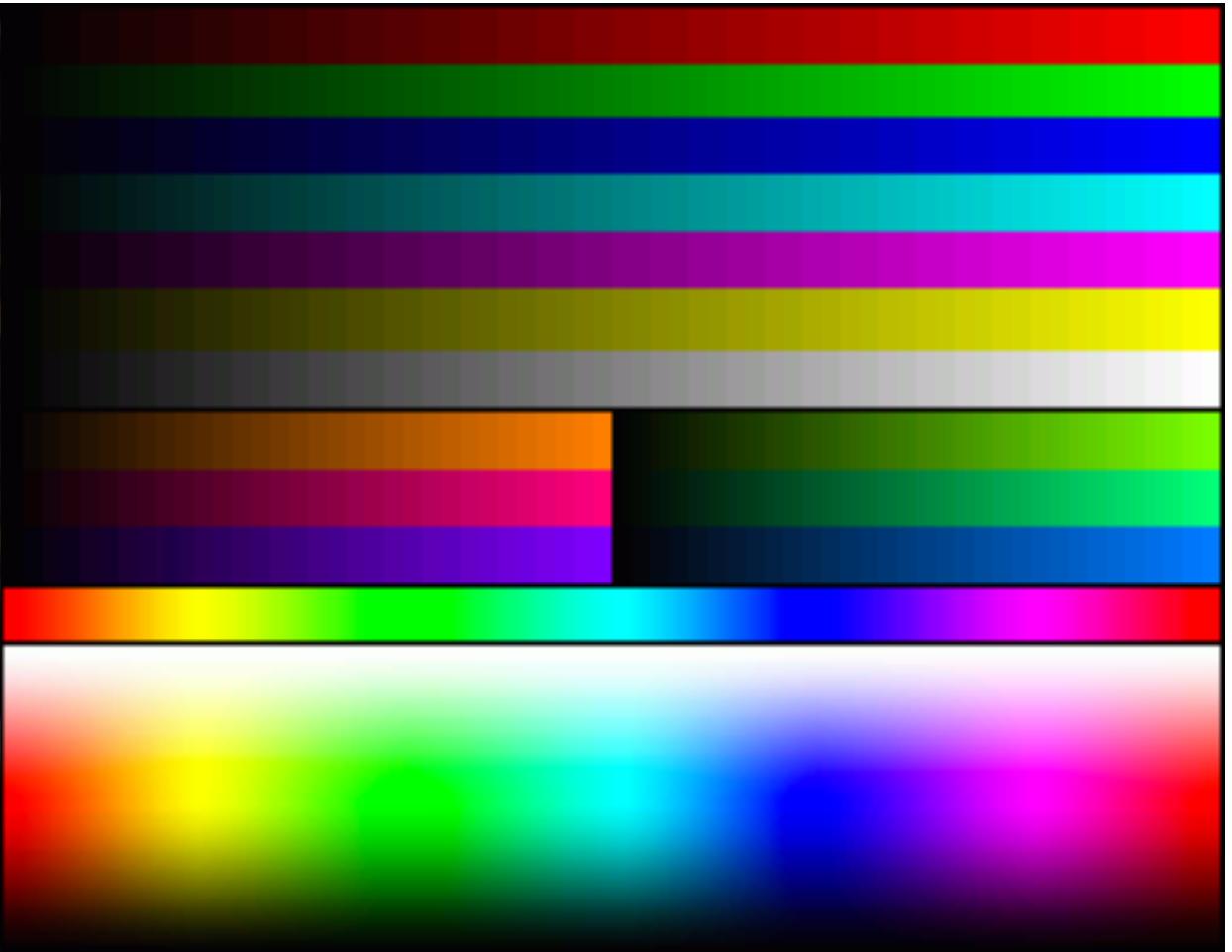


Displays



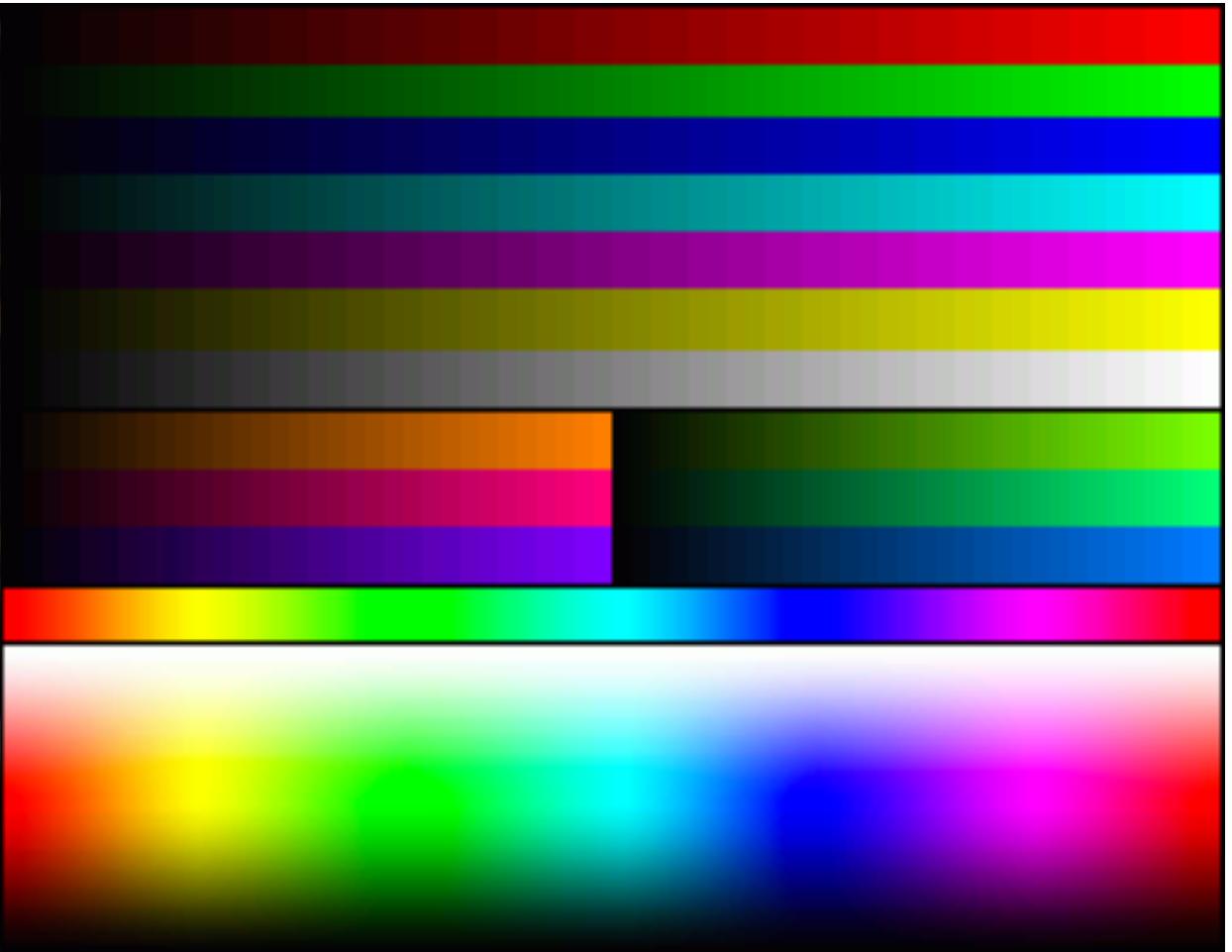
Light





The framebuffer is an image

An image is a 2D array of pixels



RGBA pixel (depth=32 bits)

Red = 8 bits
Green = 8 bits
Blue = 8 bits
Alpha = 8 bits

Framebuffer Resolution

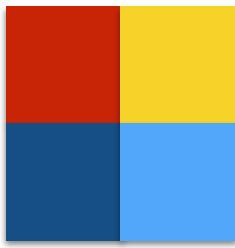
read physical size

read virtual size

read pixel depth

code/video

Virtual height = 2



Virtual width = 2

2x2 image is
interpolated to
1600x1200
to fill monitor



FB Config Structure

40 bytes long, specifies 10 parameters

| Field | CPU | GPU | Description |
|----------------|-------|-------|-----------------------------------|
| width | write | read | Width of physical screen |
| height | write | read | Height of physical screen |
| virtual_width | write | read | Width of framebuffer |
| virtual_height | write | read | Height of framebuffer |
| pitch | read | write | Bytes/row of framebuffer |
| depth | write | read | Bits/pixel of framebuffer |
| x_offset | write | read | X offset of screen in framebuffer |
| y_offset | write | read | Y offset of screen in framebuffer |
| pointer | read | write | Pointer to framebuffer |
| size | read | write | Size of framebuffer in bytes |

Configure Framebuffer Resolution

set physical size

set virtual size

set depth

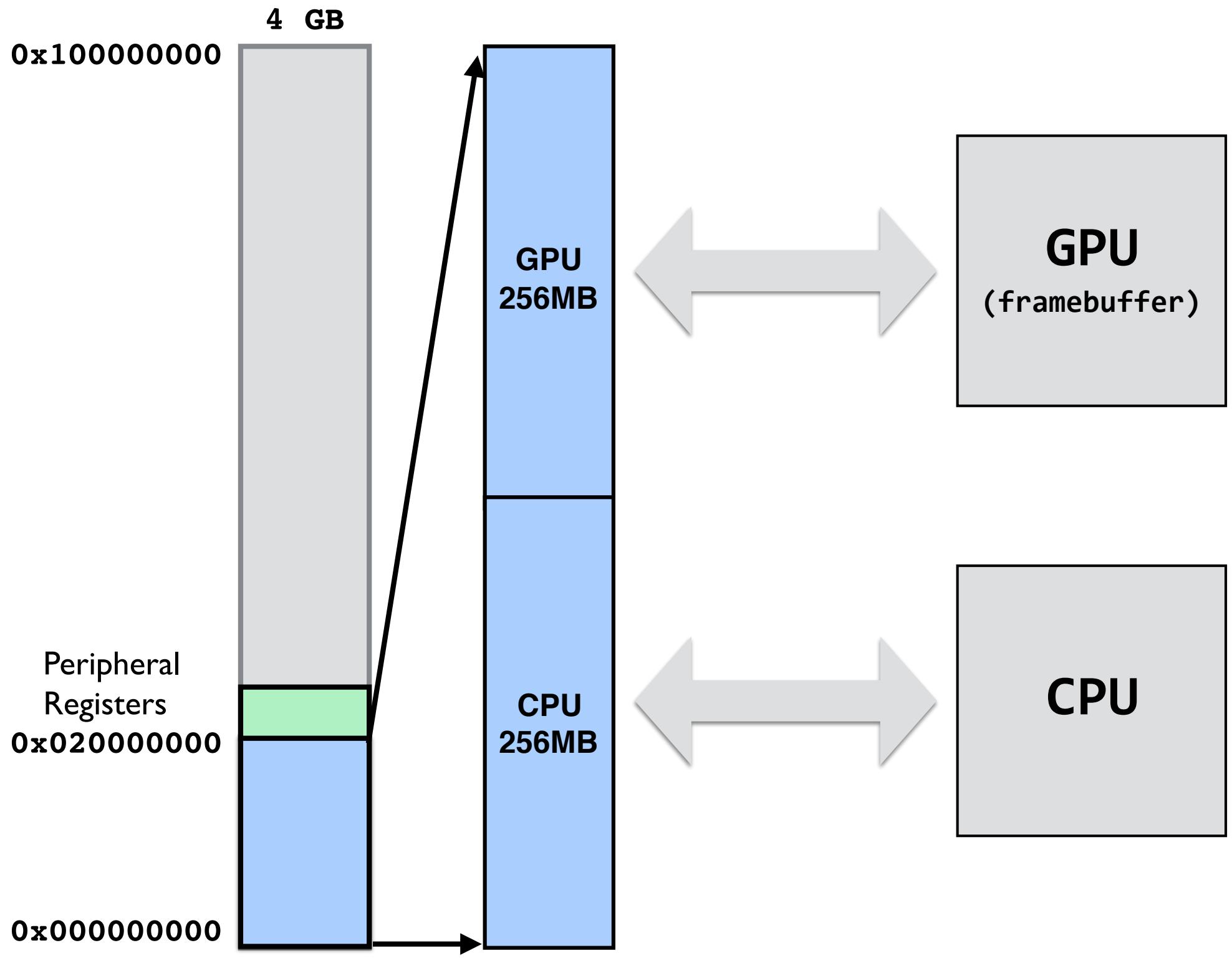
read pitch, size, fb pointer

code/fb

Shared Memory

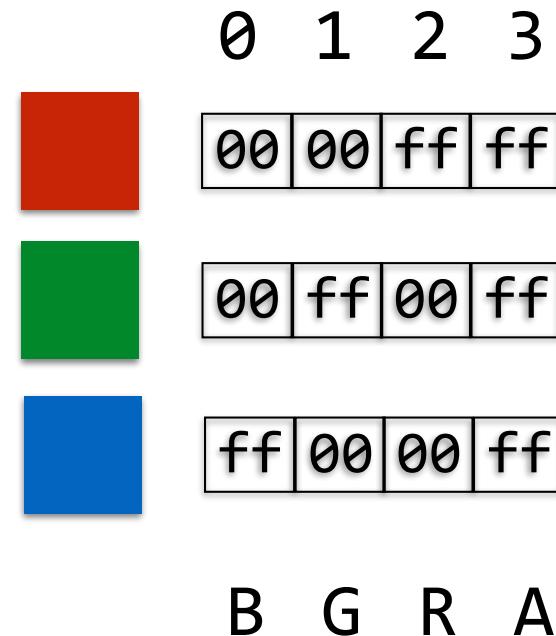
**frame buffer memory
split between cpu & gpu**

code/video



RGBA (BGRA) Pixel/Color

RGBA (BGRA) pixels are four bytes

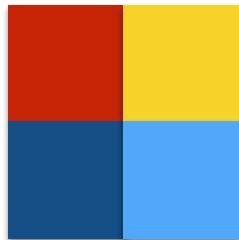


Beware: blue is the first byte (lowest address)

Array of unsigned char

The framebuffer is an array

```
unsigned char fb[2*2*4];  
fb[0] = 0x00; // b  
fb[1] = 0x00; // g  
fb[2] = 0xff; // r  
fb[3] = 0xff; // a
```



| | | | | | | | | | | | | | | | |
|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| 00 | 00 | ff | ff | 00 | ff | ff | ff | ff | 00 | 00 | ff | ff | ff | 00 | ff |
|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|

red

yellow

blue

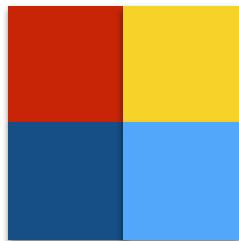
cyan

Note: (0,0) is at the upper left corner of the monitor

Array of unsigned char

The framebuffer is an array

```
unsigned char fb[2*2*4];  
fb[bgra + 4*(x + 2*y)] = ...  
bra = 0, 1, 2, or 3
```

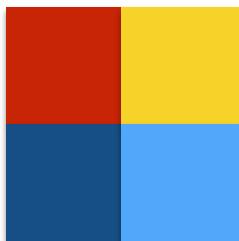


| | | | |
|-------------|-------------|-------------|-------------|
| 00 00 ff ff | 00 ff ff ff | ff 00 00 ff | ff ff 00 ff |
| red | yellow | blue | cyan |

Array of unsigned char

The display is a block of memory

```
#define DEPTH 2
#define WIDTH 2
#define HEIGHT 2
unsigned char fb[WIDTH*HEIGHT*DEPTH];
fb[bgra + DEPTH*(x + WIDTH*y)] = ...
```



Array of unsigned

The display is a block of memory

```
#define DEPTH 2
#define WIDTH 2
#define HEIGHT 2
unsigned char fb[WIDTH*HEIGHT*DEPTH];
fb[rgba + DEPTH*(x + WIDTH*y)] = ...

unsigned fb[WIDTH*HEIGHT];
fb[0] = 0xffff0000; // x=0, y=0
fb[1] = 0xfffffff0; // x=1, y=0
fb[2] = 0xff0000ff; // x=0, y=1
fb[3] = 0xff00ffff; // x=1, y=1
```

Drawing

code/clear

2D Array of unsigned

The display is a block of memory

```
#define DEPTH 2
#define WIDTH 2
#define HEIGHT 2
unsigned char fb[WIDTH*HEIGHT*DEPTH];
fb[rgba + DEPTH*(x + WIDTH*y)] = ...

unsigned (*fb)[2] = (unsigned (* )[2])frame;
fb[0] = 0xffff0000; // x=0, y=0
fb[1] = 0xfffffff0; // x=1, y=0
fb[2] = 0xff0000ff; // x=0, y=1
fb[3] = 0xff00ffff; // x=1, y=1
```



What is `unsigned *fb[2]`, `(*fb)[2]`?

Demo

code/grid

Double- Buffering

Double Buffering

Writing directly to screen can cause flickering

Solution: Double buffering

- Two buffers: back-buffer and front-buffer
- Front-buffer is being display
- Draw into back-buffer
- Swap buffers to update display

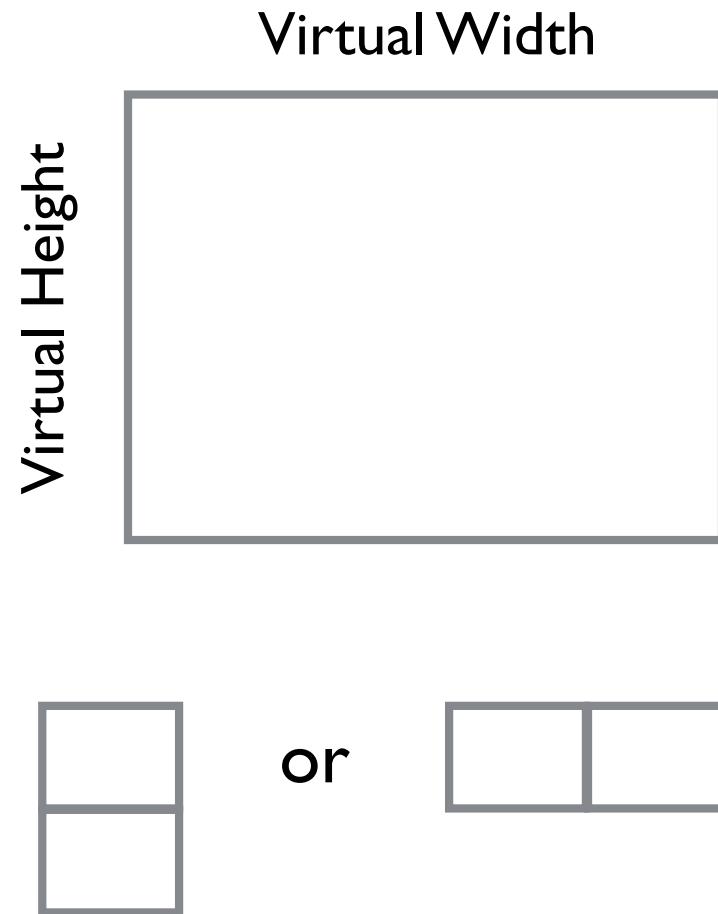
Single Buffer

Drawing directly to framebuffer lets you see the graphics as it is drawn (good for debugging!)

Normally we just show the result.
Don't see the drawing process

Double buffering: display "front-buffer" while drawing into "back"-buffer. Swap buffers when you are done drawing.

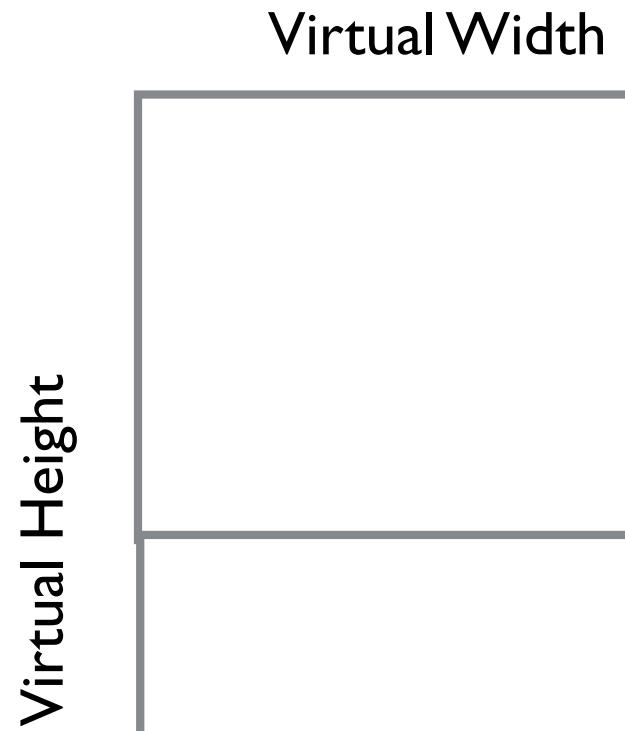
Which arrangement is better?



Double Buffer

Double buffering:

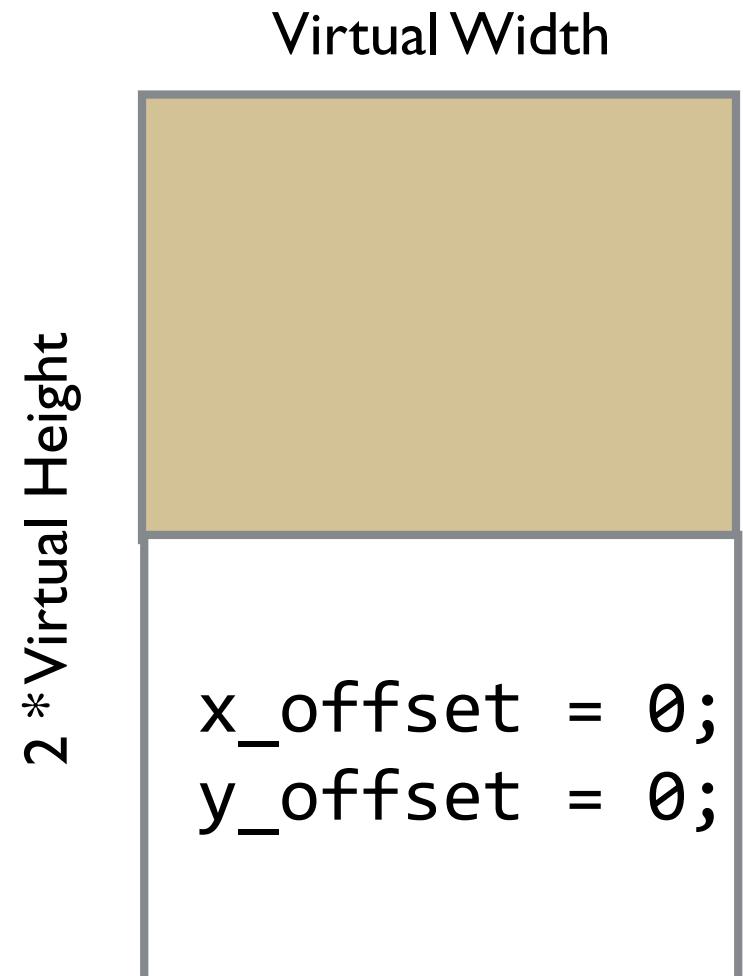
- Display the "front"-buffer
- Draw into the "back"-buffer
- Swap front and back when you are done drawing
- Requires 2 frame buffers



Display Top Buffer

Double buffering:

- Display the "front"-buffer
- Draw into the "back"-buffer
- Swap front and back when you are done drawing
- Requires 2 frame buffers



Display Bottom Buffer

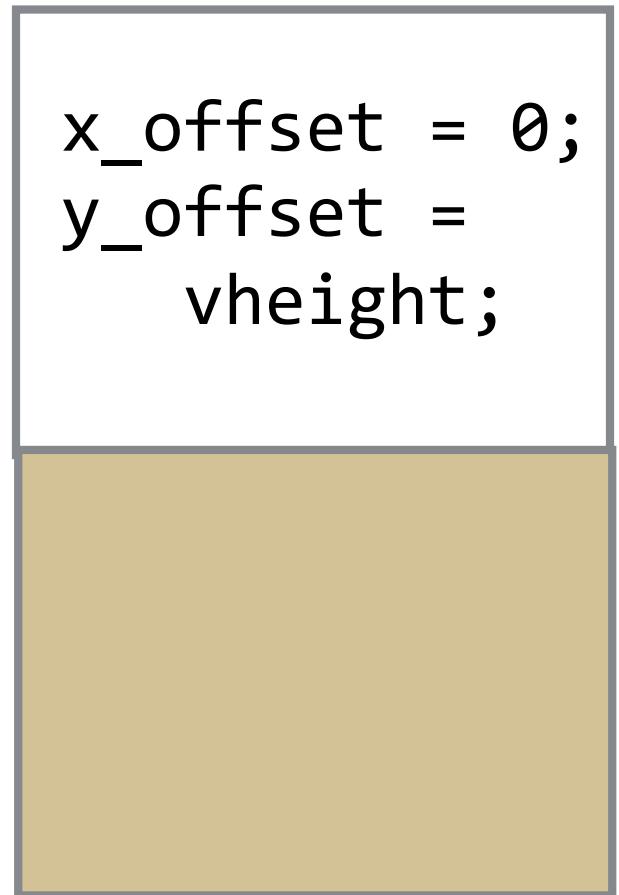
Double buffering:

- Display the "front"-buffer
- Draw into the "back"-buffer
- Swap front and back when you are done drawing
- Requires 2 frame buffers

Virtual Width

```
x_offset = 0;  
y_offset =  
vheight;
```

2 * Virtual Height

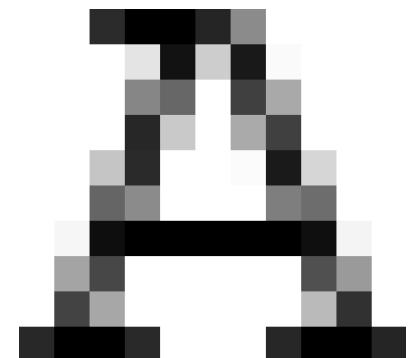
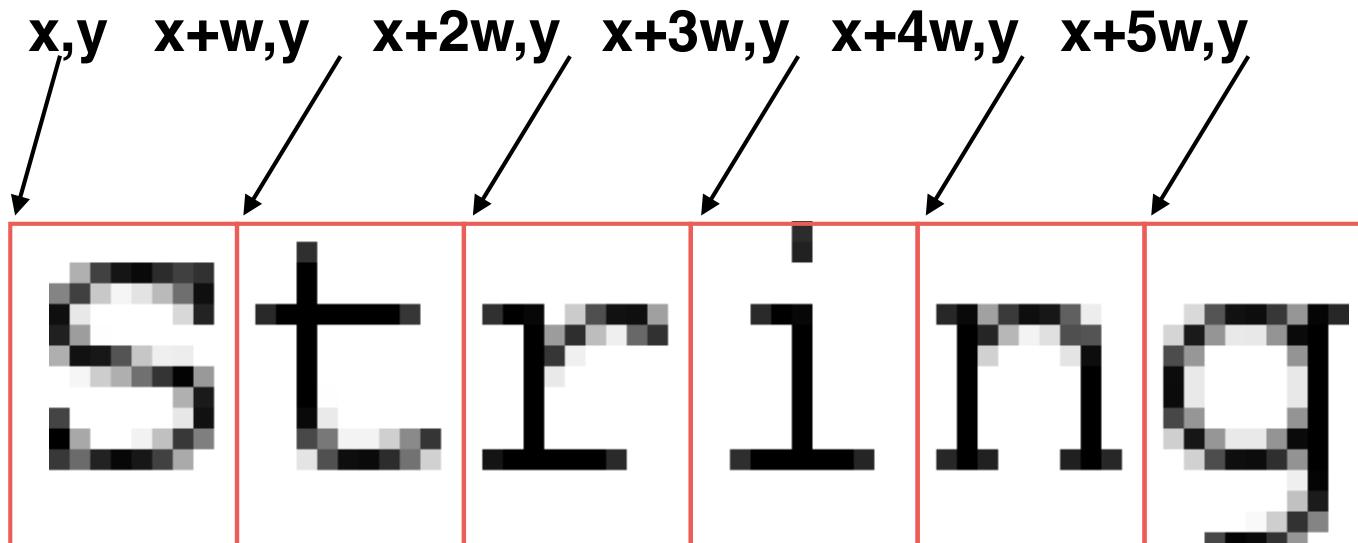


code/singlebuffer
code/doublebuffer

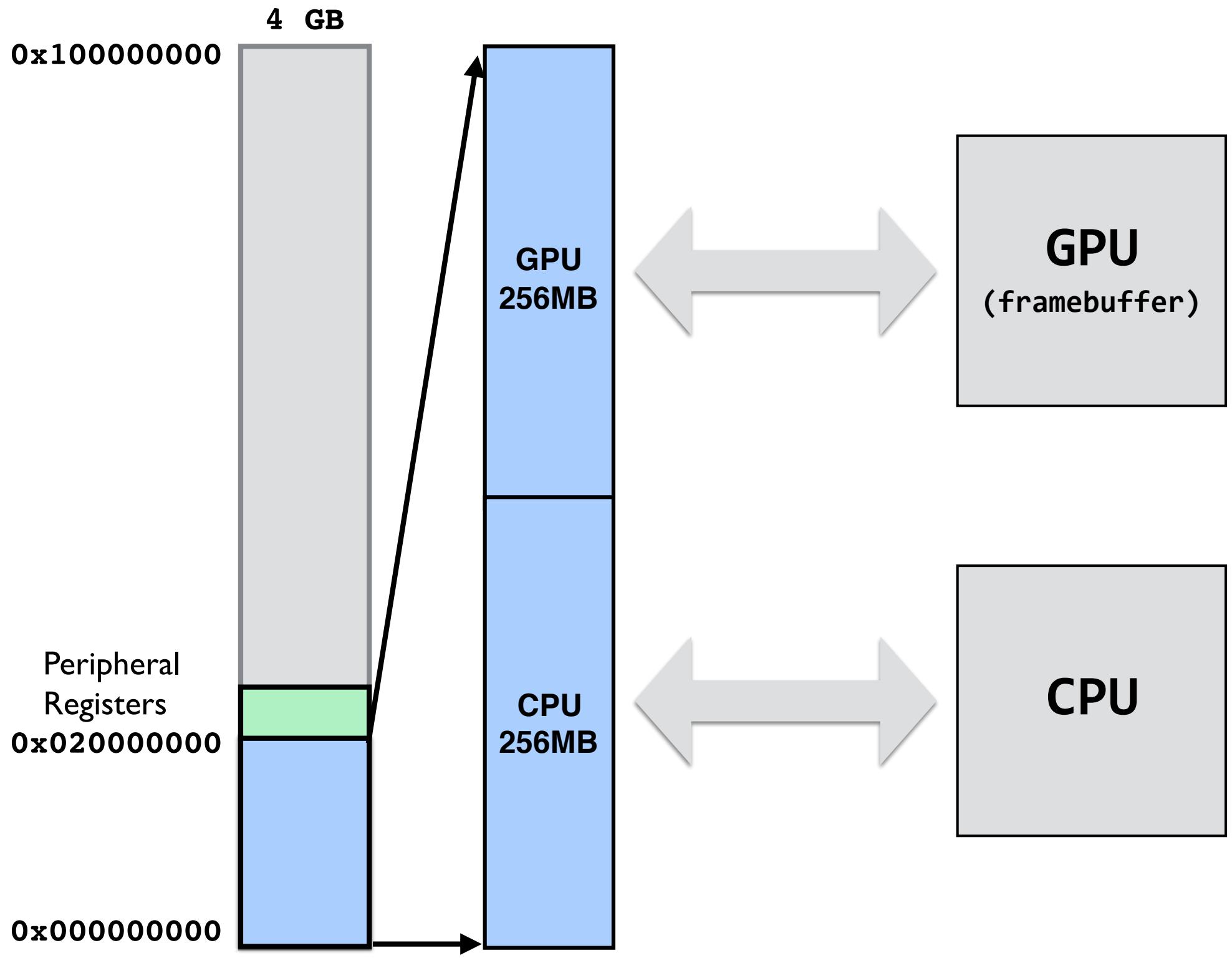
Drawing Text

Fonts: monospaced vs. proportional

Font a set of "glyphs"

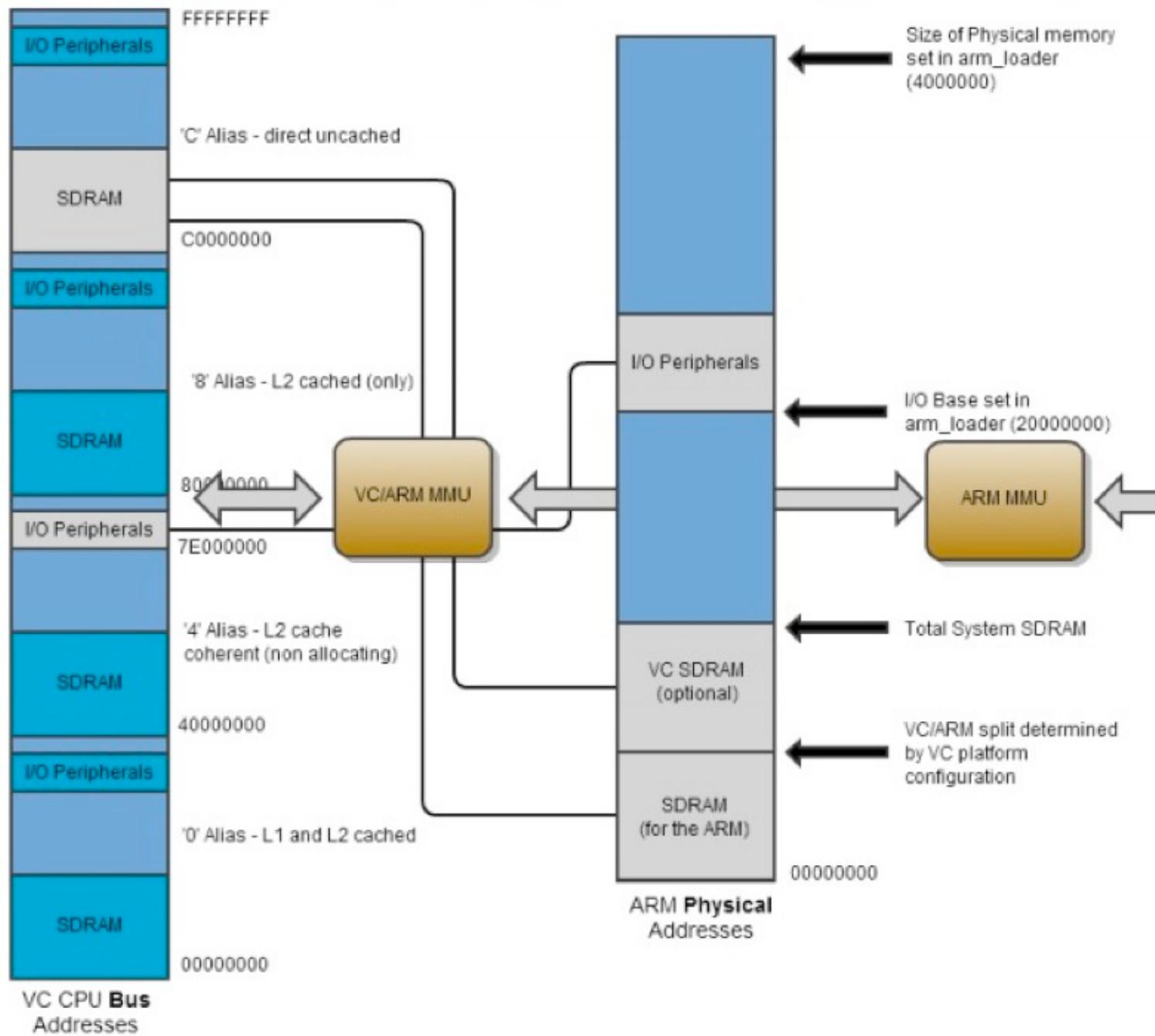


Mailbox





BCM2835 ARM Peripherals



Coordinating CPU+GPU

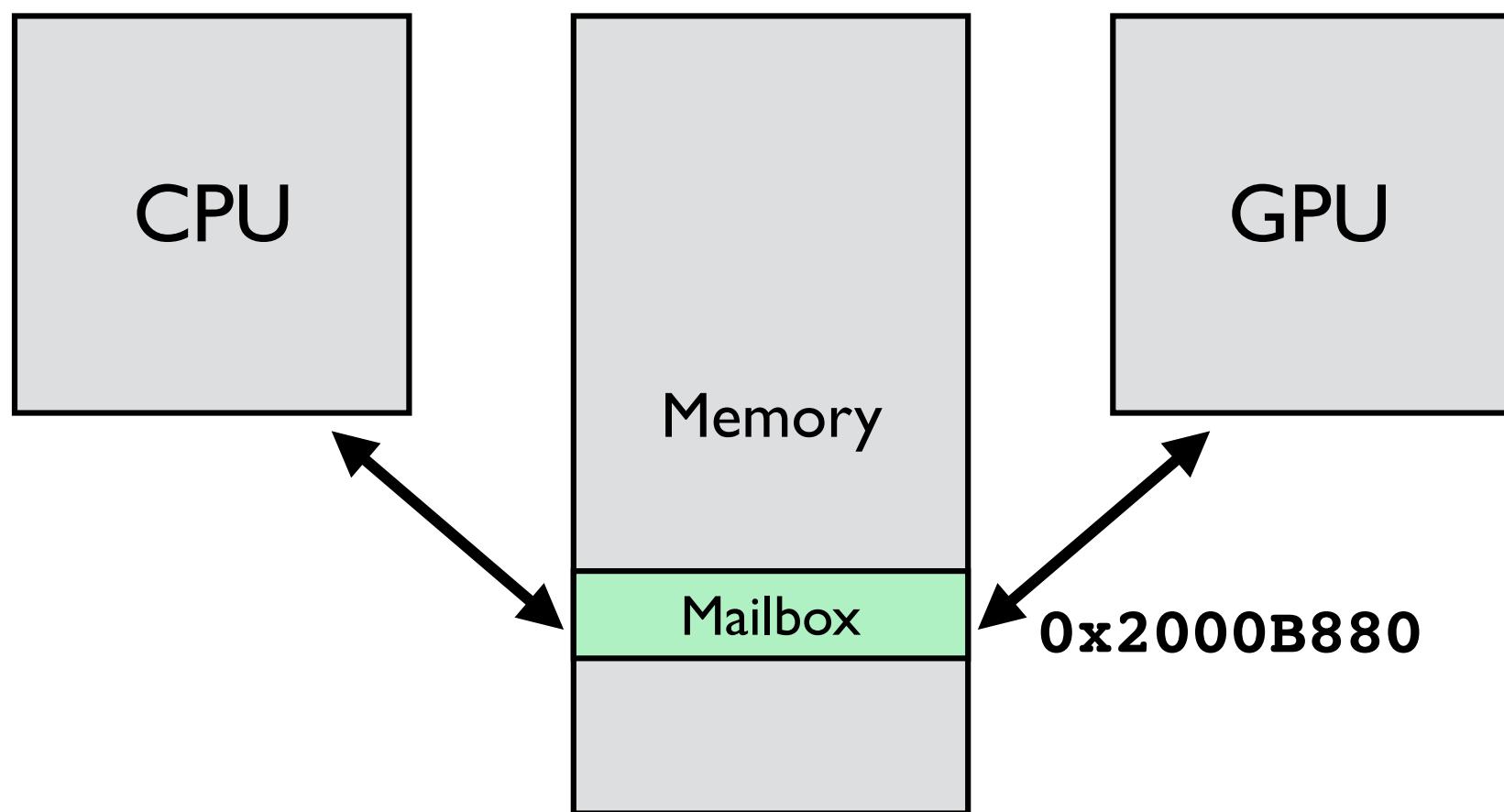
CPU and GPU need to communicate

- CPU code wants to set/change screen settings
- GPU and CPU need to agree where frame buffer is

Danger: reading incomplete/partial data

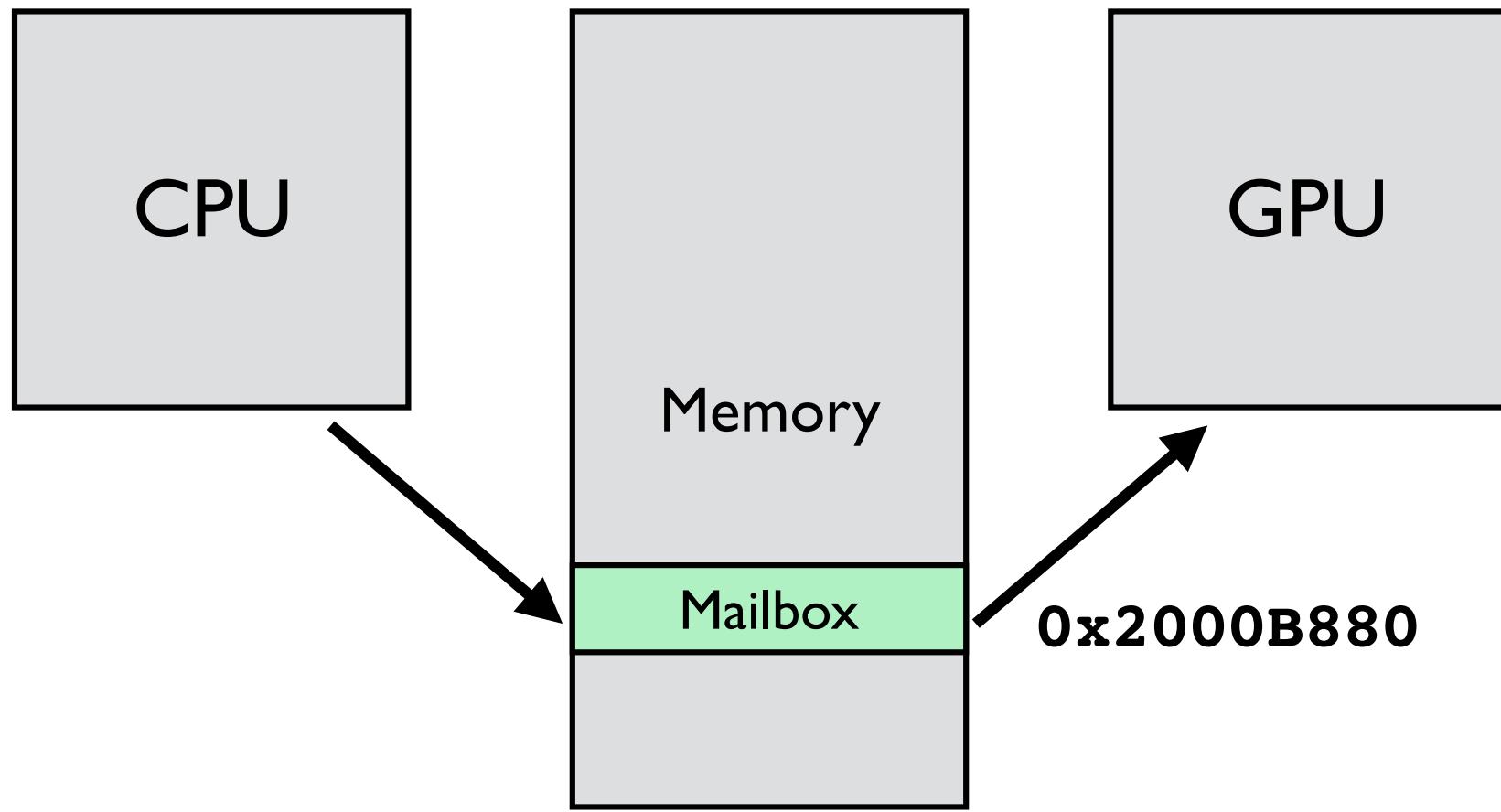
- They are two processors, running at different speeds, C compiler has no knowledge of this
- Need a simple handshake that depends on a single bit
 - "*I've set this bit, which means I have sent some data to you.*"
 - "*I've cleared the bit, which means I've read the data.*"

Mailbox



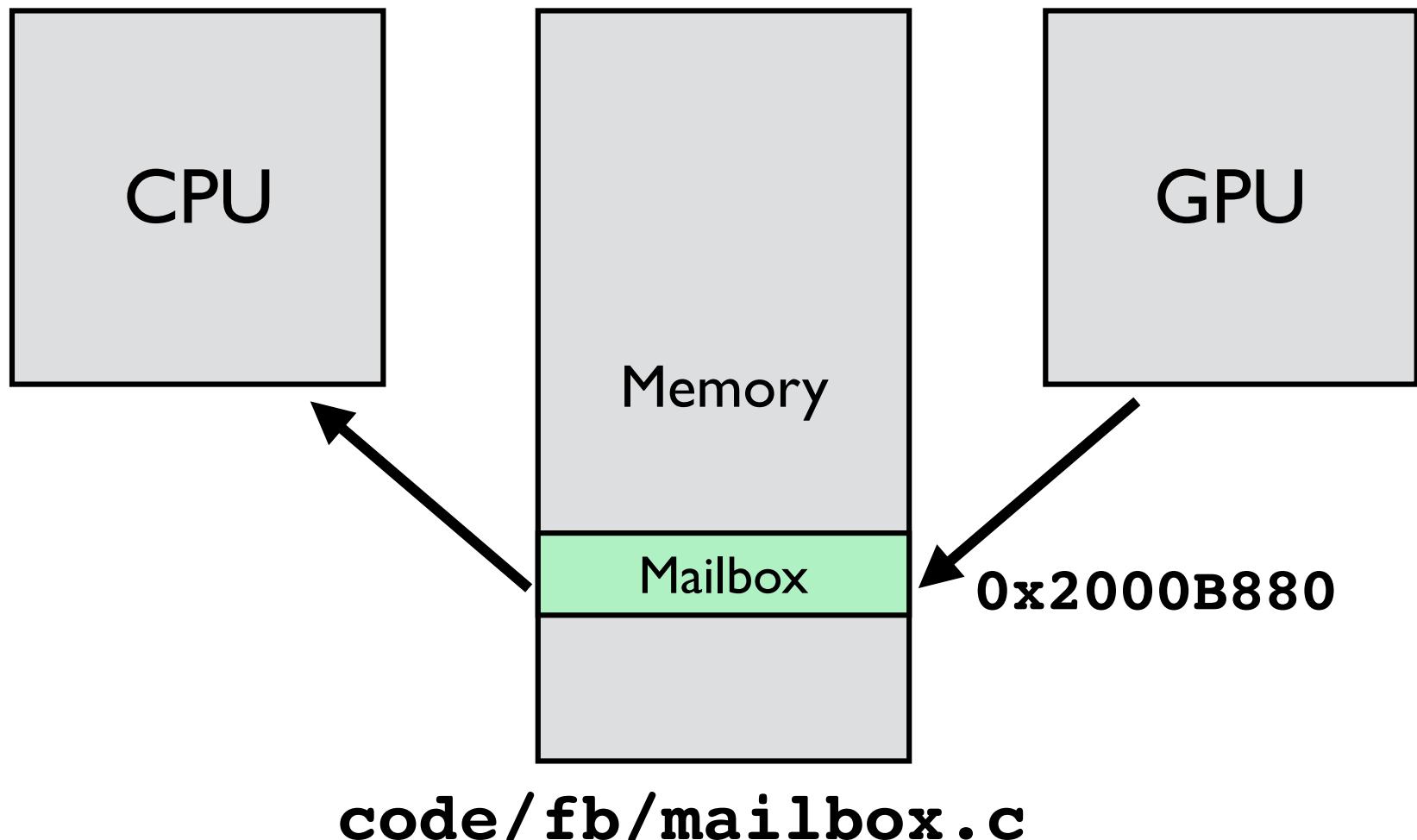
code/clear/mailbox.c

CPU "Mails" Message to GPU



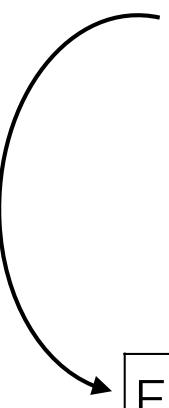
`code/fb/mailbox.c`

GPU Mails Reply to CPU



Mailbox Format

| Register | Offset | R/W | Use |
|---------------|--------|-----|----------------------------------|
| Read | 0x00 | R | Destructively read value |
| Peek | 0x10 | R | Read without removing data |
| Sender | 0x14 | R | Sender ID (bottom 2 bits) |
| Status | 0x18 | R | Status bits |
| Configuration | 0x1C | RW | Configuration bits |
| Write | 0x20 | W | Address to write data (GPU addr) |

F | E

undocumented/unused?

F = Full

E = Empty

code/fb/mailbox.c

Mailbox Format

```
#define MAILBOX_BASE    0x2000B880
#define MAILBOX_FULL     (1<<31)
#define MAILBOX_EMPTY    (1<<30)
typedef struct {
    unsigned int read;
    unsigned int padding[3]; // note padding to skip 3 words
    unsigned int peek;
    unsigned int sender;
    unsigned int status;
    unsigned int configuration;
    unsigned int write;
} mailbox_t;

void mailbox_write(unsigned channel, unsigned addr) {
    if (channel >= MAILBOX_MAXCHANNEL) {return;}
    if (addr & 0xF) {return;}
    volatile mailbox_t *mailbox = (volatile mailbox_t *)MAILBOX_BASE;
    while (mailbox->status & MAILBOX_FULL) ;
    mailbox->write = addr + channel;
}
```

code/fb/mailbox.c

Framebuffer Overview

GPU refreshes the display using a framebuffer

The size of the image sent to the monitor is called the physical size

The size of the framebuffer image in memory is called the virtual size

The CPU and GPU share the memory, and hence the frame buffer

The CPU and GPU exchange messages using a mailbox

Put It All Together

graphical shell

