Graphics and Framebuffers

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)

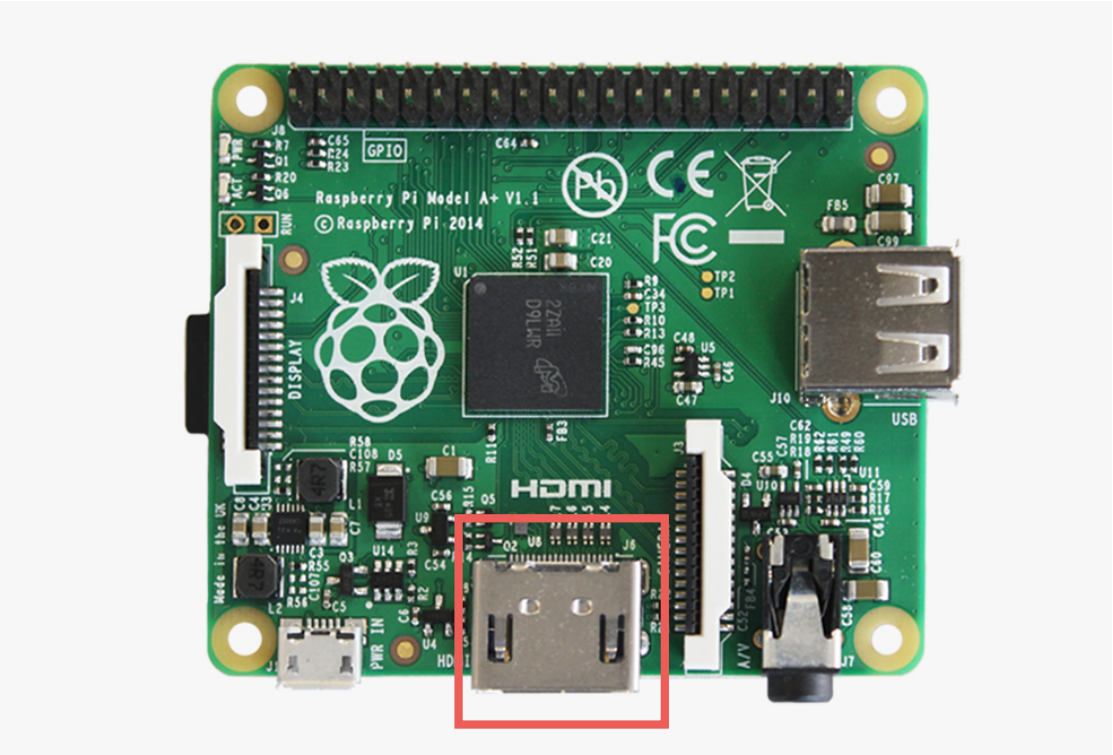
Memory managements

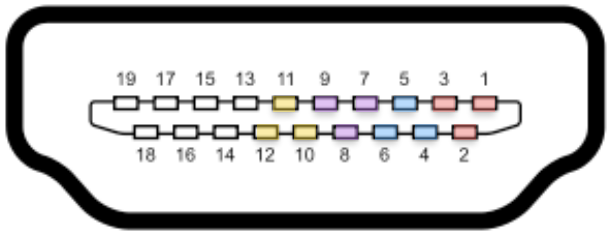
Tools (git, bash, make, brew)

The Force Awakens in You

gpio
timer
uart
printf
malloc
keyboard
fb
gl
console
shell

HDMI





- Clock
- Data 0
- Data 2
- Control

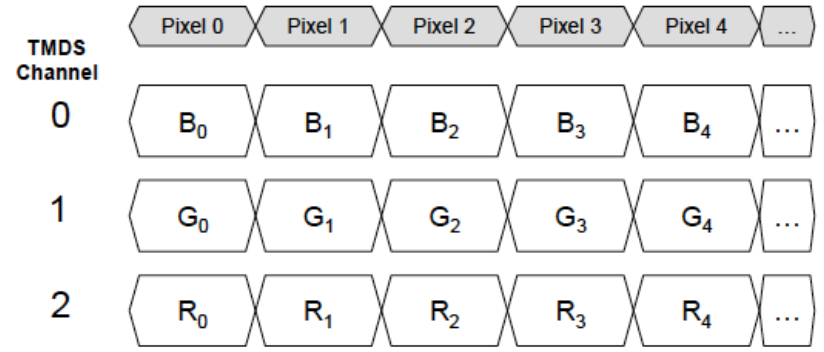
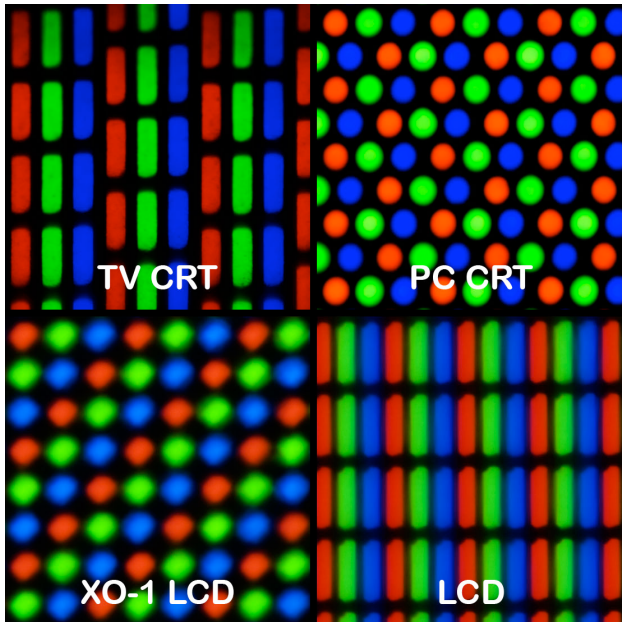


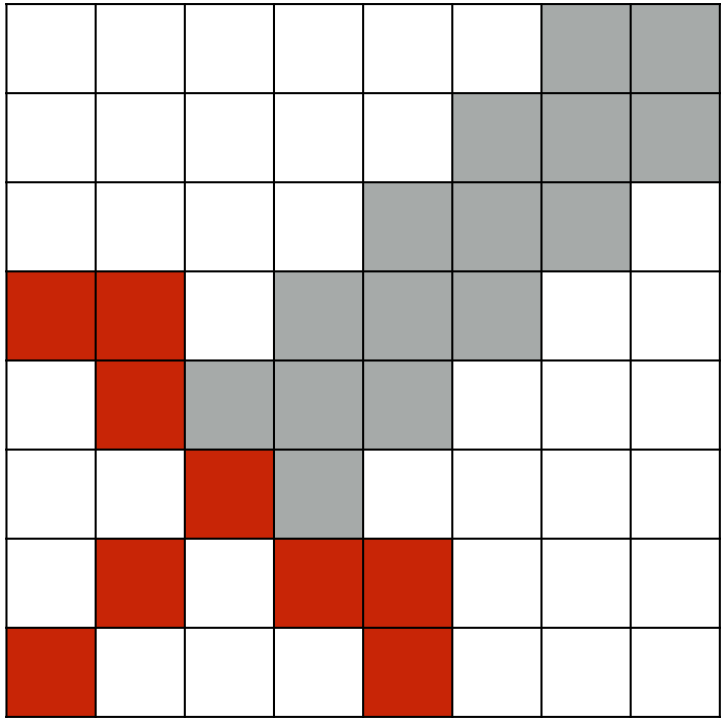
Figure 6-1 Default pixel encoding: RGB 4:4:4, 8 bits/component

Figure from High-Definition Multimedia Interface Specification Version 1.3a

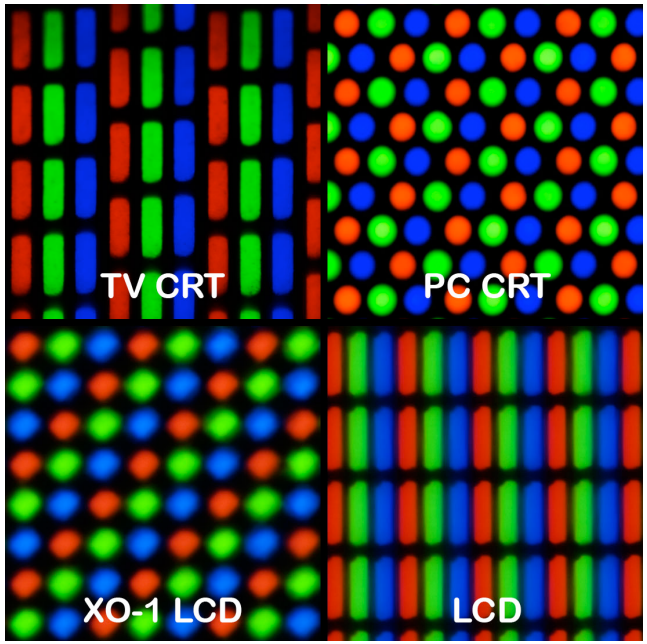


Displays

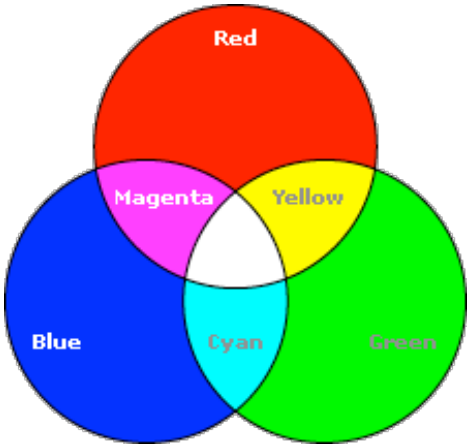
Pixels



Displays



Light



The framebuffer is an image

An image is a 2D array of pixels

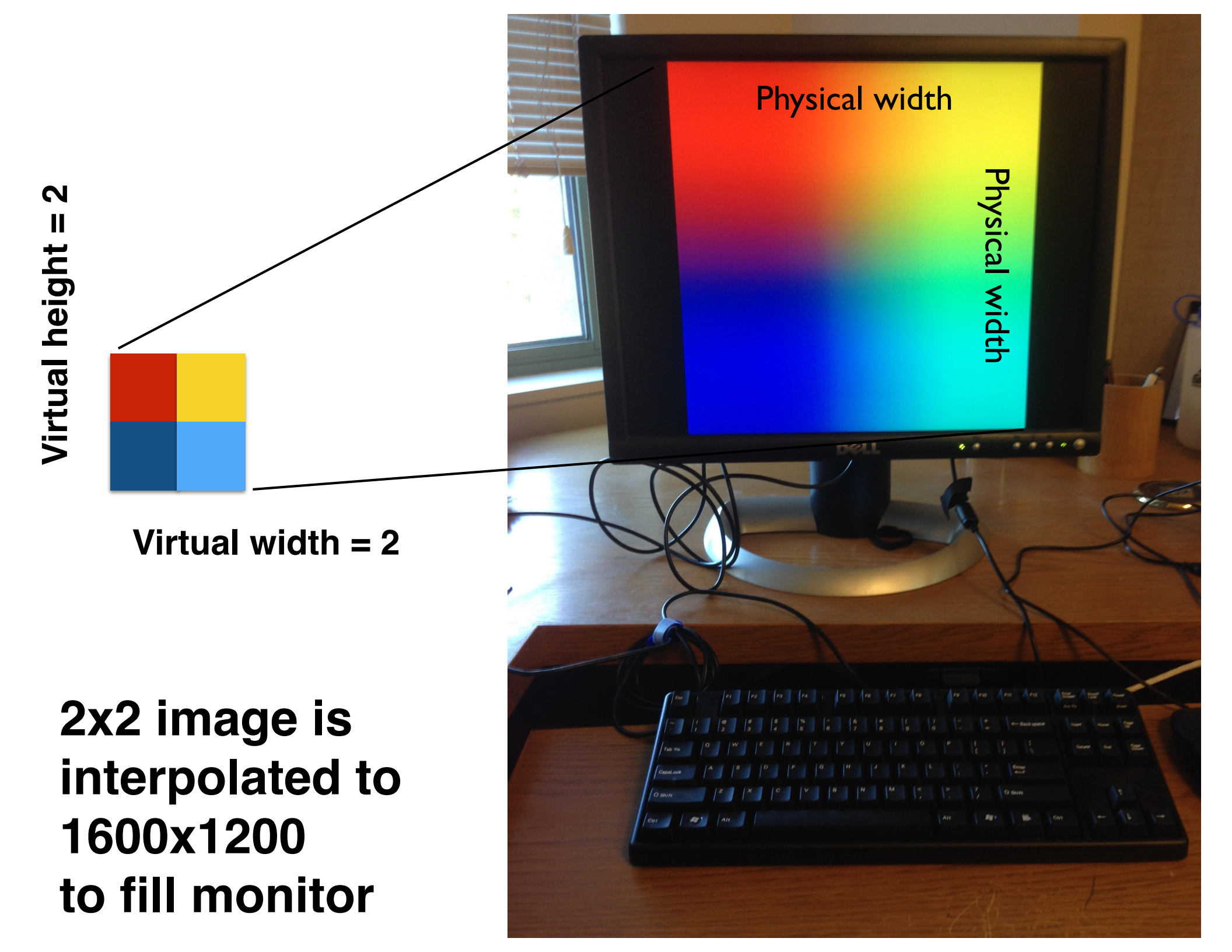
RGBA pixel (depth=32 bits)

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`



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

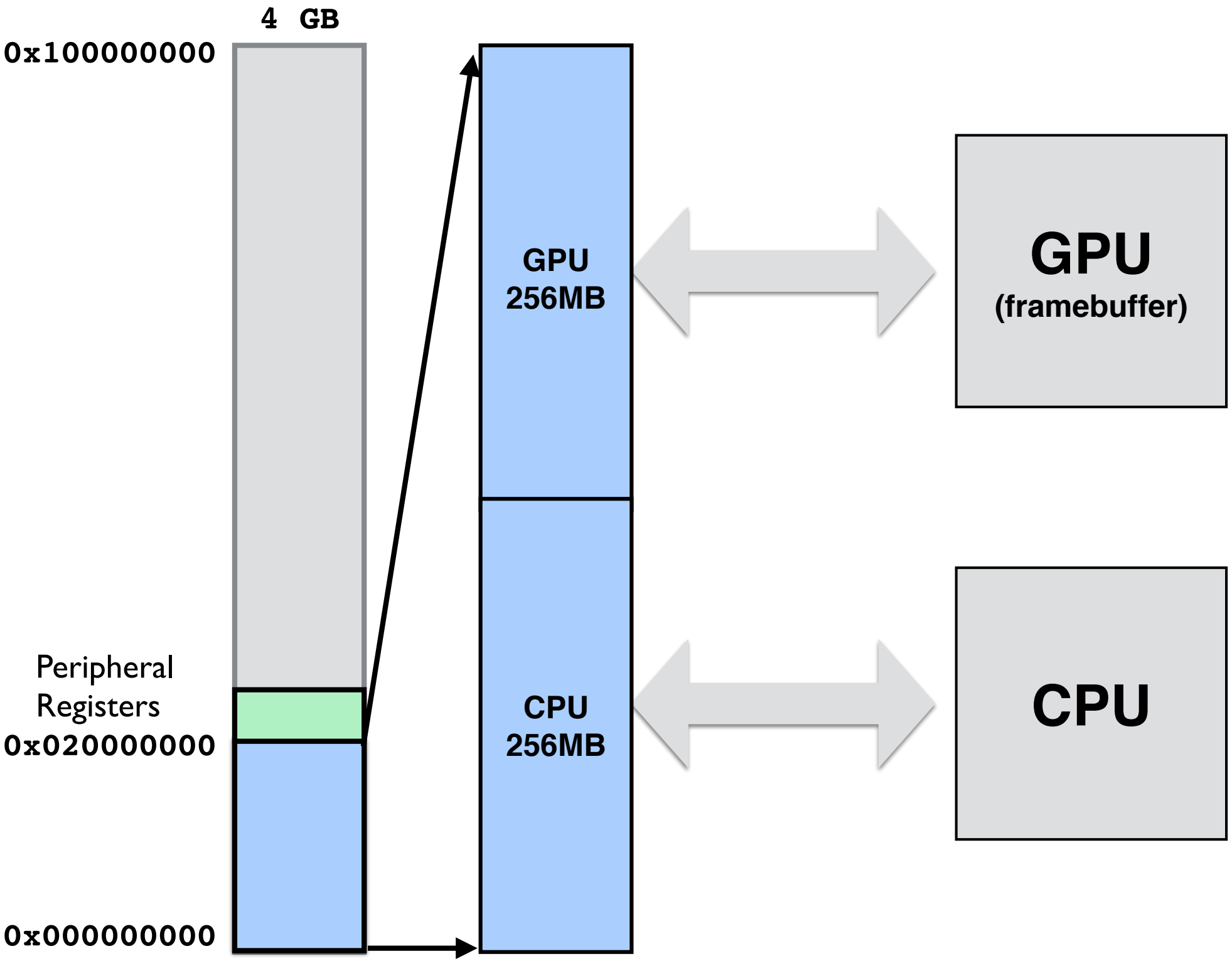
read pitch, size, fb pointer

`code/fb`

Shared Memory

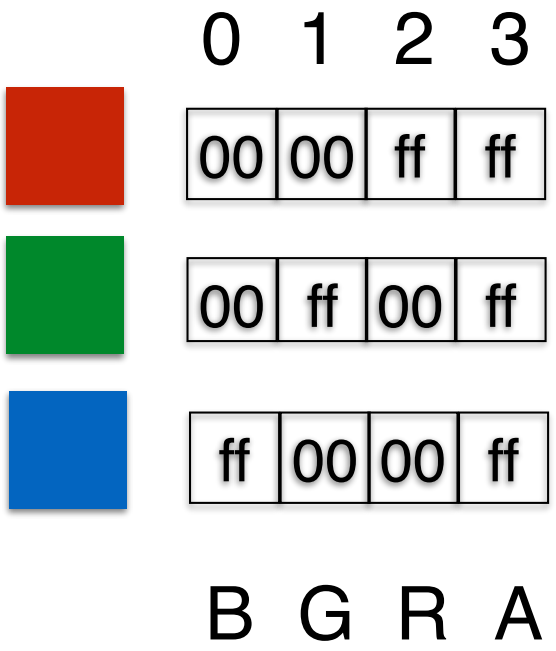
frame buffer memory
split between cpu & gpu

code/video


4 GB
0x100000000
GPU
256MB
GPU
(framebuffer)
Peripheral
Registers
0x020000000
CPU
256MB
CPU
0x000000000

RGBA (BGRA) Pixel/Color

RGBA (BGRA) pixels are four bytes

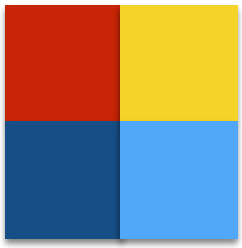


Beware: blue is the first byte (lowest address)

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

red

00	ff	ff	ff

yellow

ff	00	00	ff

blue

ff	ff	00	ff

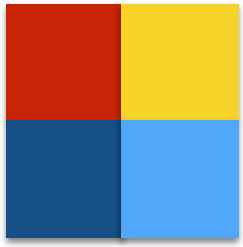
cyan

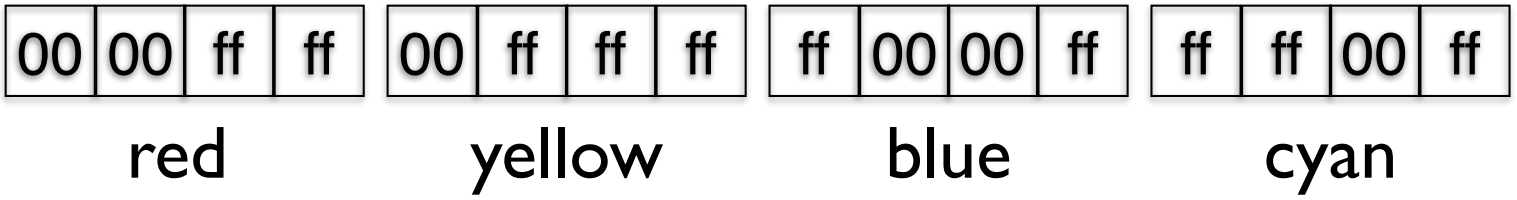
Note: (0,0) is at the upper left corner of the monitor

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
```

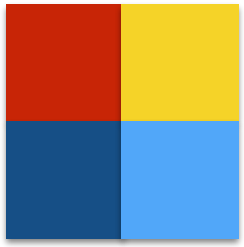




Array of unsigned char

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] = 0xffffff00; // 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][0] = 0xffff0000; // x=0, y=0
fb[1][0] = 0xffffff00; // x=1, y=0
fb[0][1] = 0xff0000ff; // x=0, y=1
fb[1][1] = 0xff00ffff; // x=1, y=1
```

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

cdecl.org

Demo

draw a 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

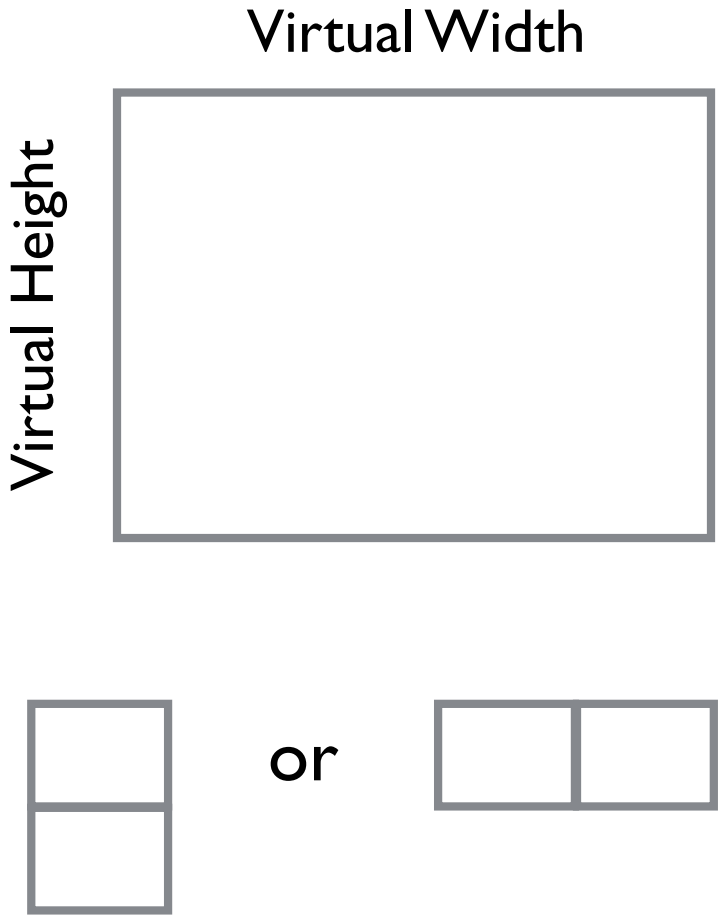
Single Buffer

Drawing directly to framebuffer lets you see the graphics as it is draw (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.

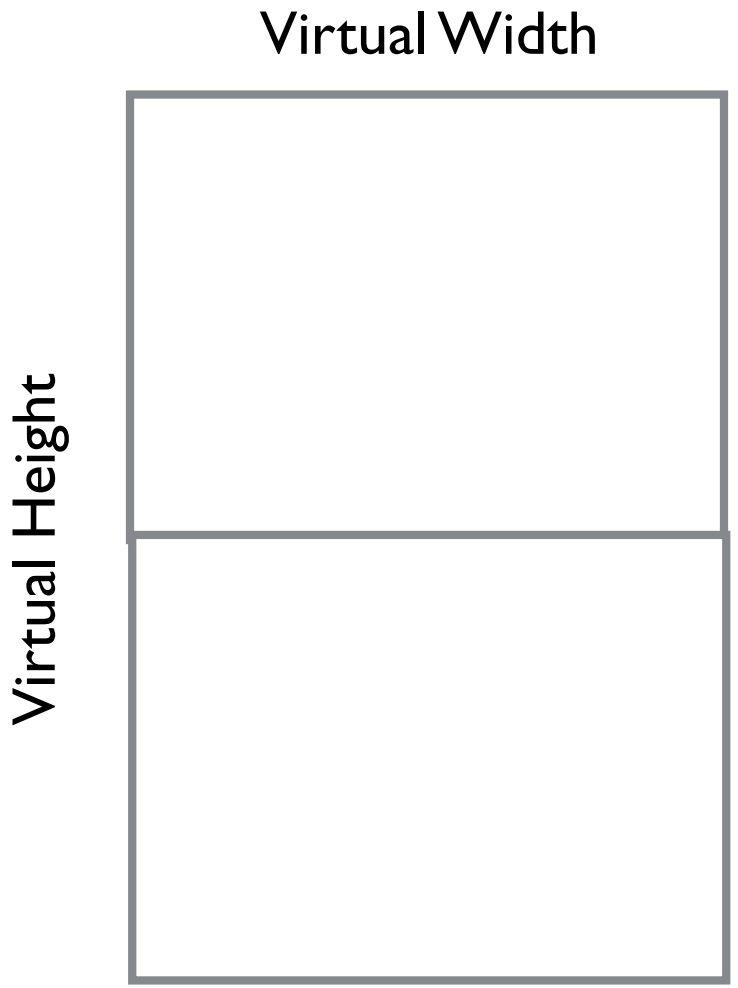
Which arrangement is better?



Double Buffer

Double buffering:

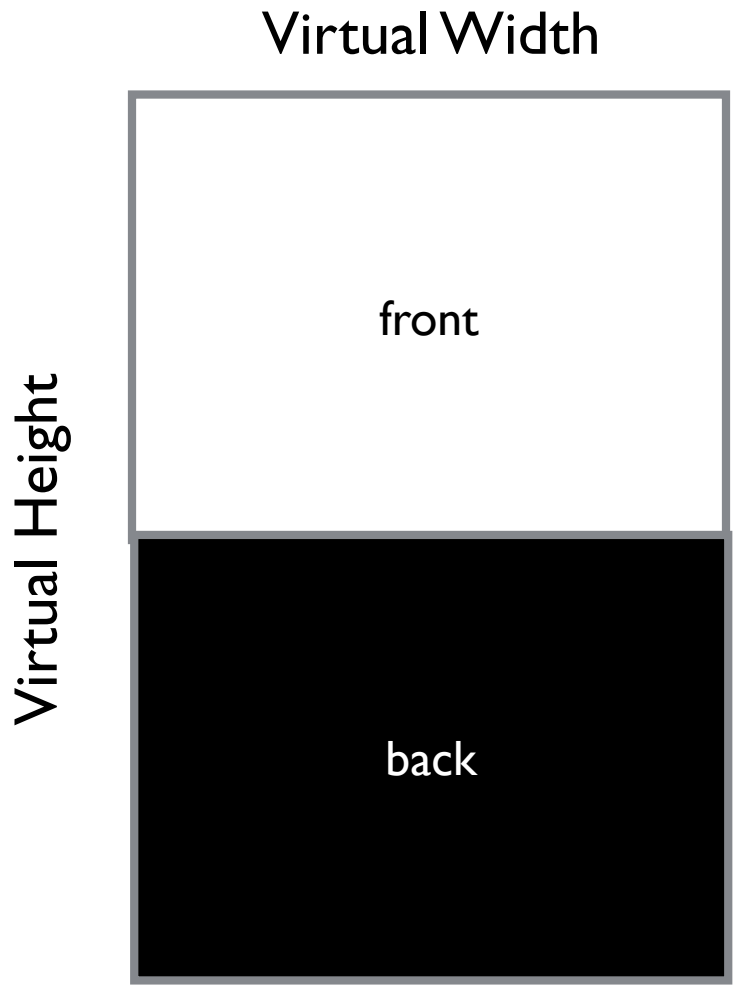
- Display the "front"-buffer
- Draw into the "back"-buffer
- Swap front and back when you are done drawing
- Requires 2 frame buffers



Double Buffer

Double buffering:

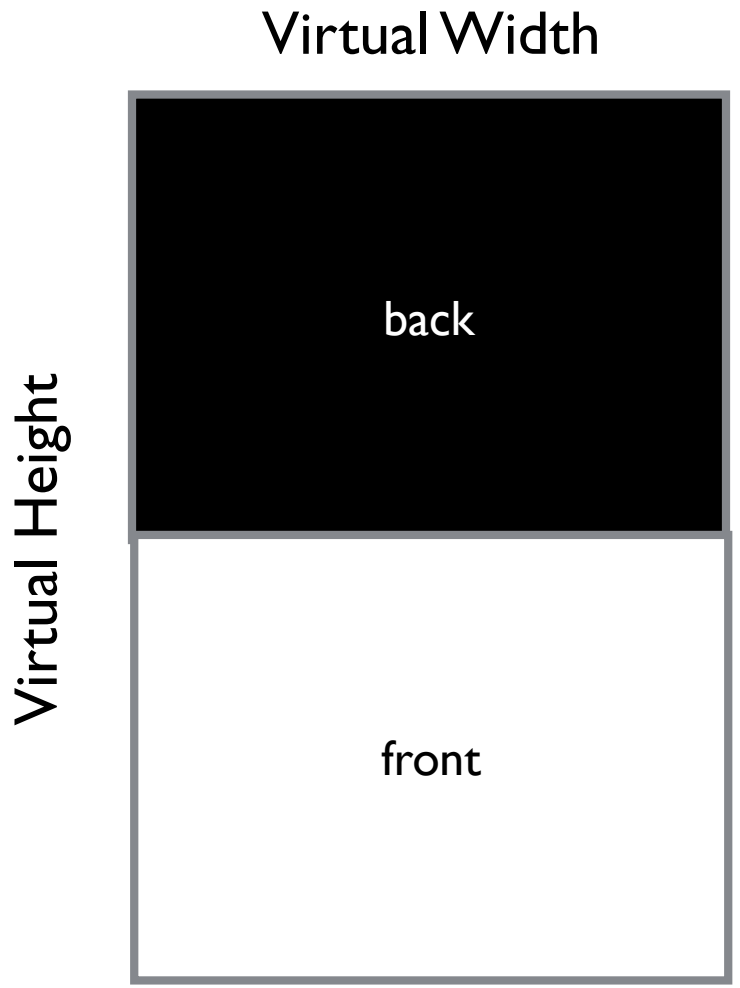
- Display the "front"-buffer
- Draw into the "back"-buffer
- Swap front and back when you are done drawing
- Requires 2 frame buffers



Double Buffer

Double buffering:

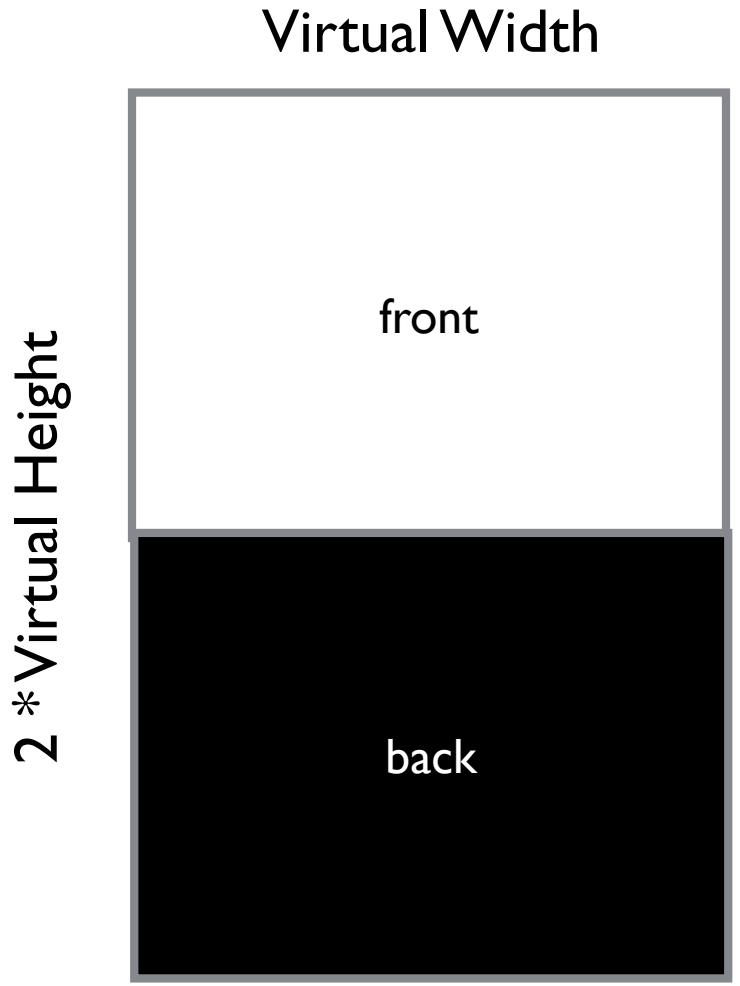
- Display the "front"-buffer
- Draw into the "back"-buffer
- Swap front and back when you are done drawing
- Requires 2 frame buffers



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

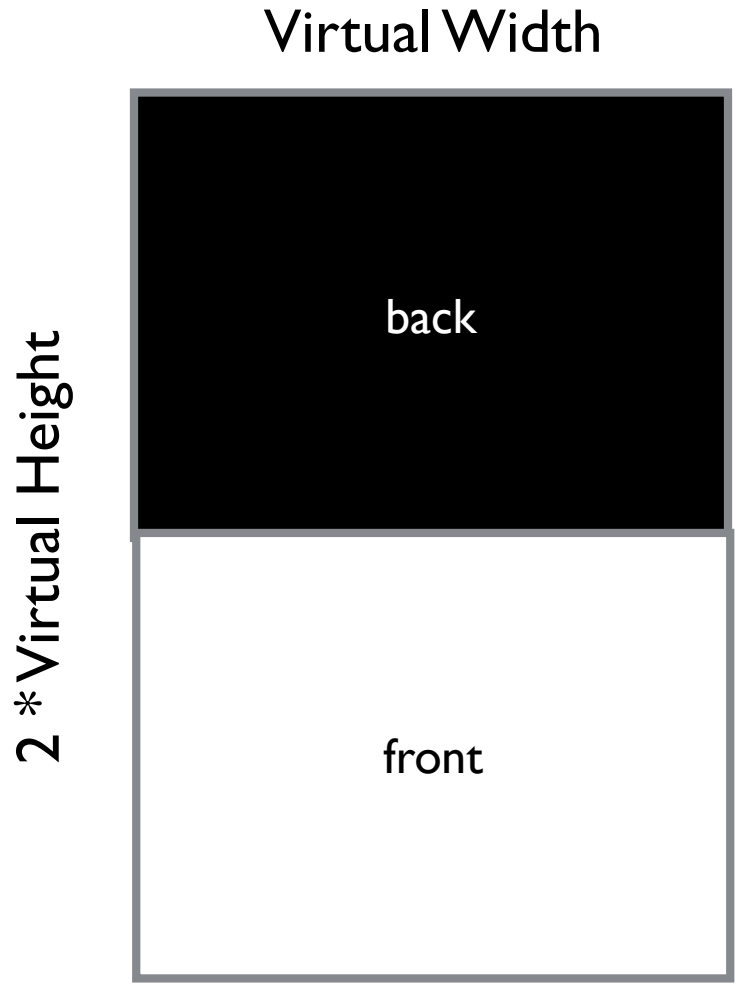



```
x_offset = 0;
y_offset = 0;
```

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



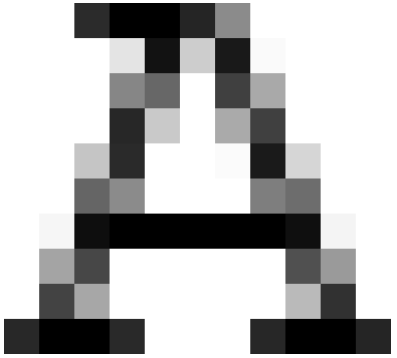

```
x_offset = 0;
y_offset = vheight;
```

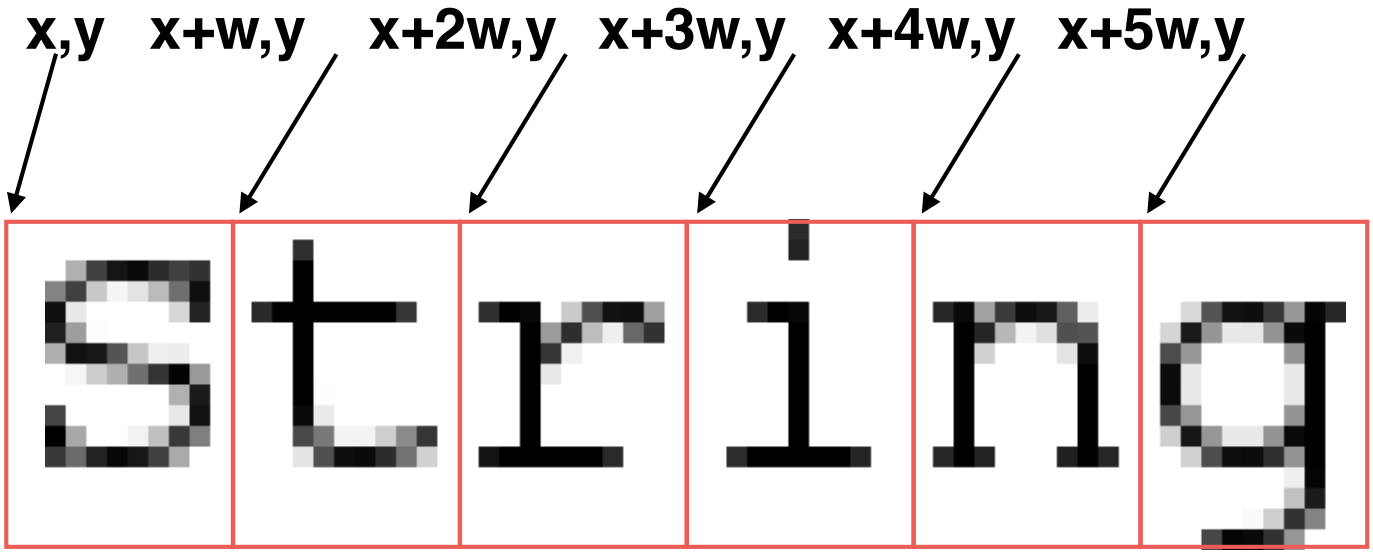
code/singlebuffer
code/doublebuffer

Drawing Text

Fonts: monospaced vs. proportional

Font a set of "glyphs"

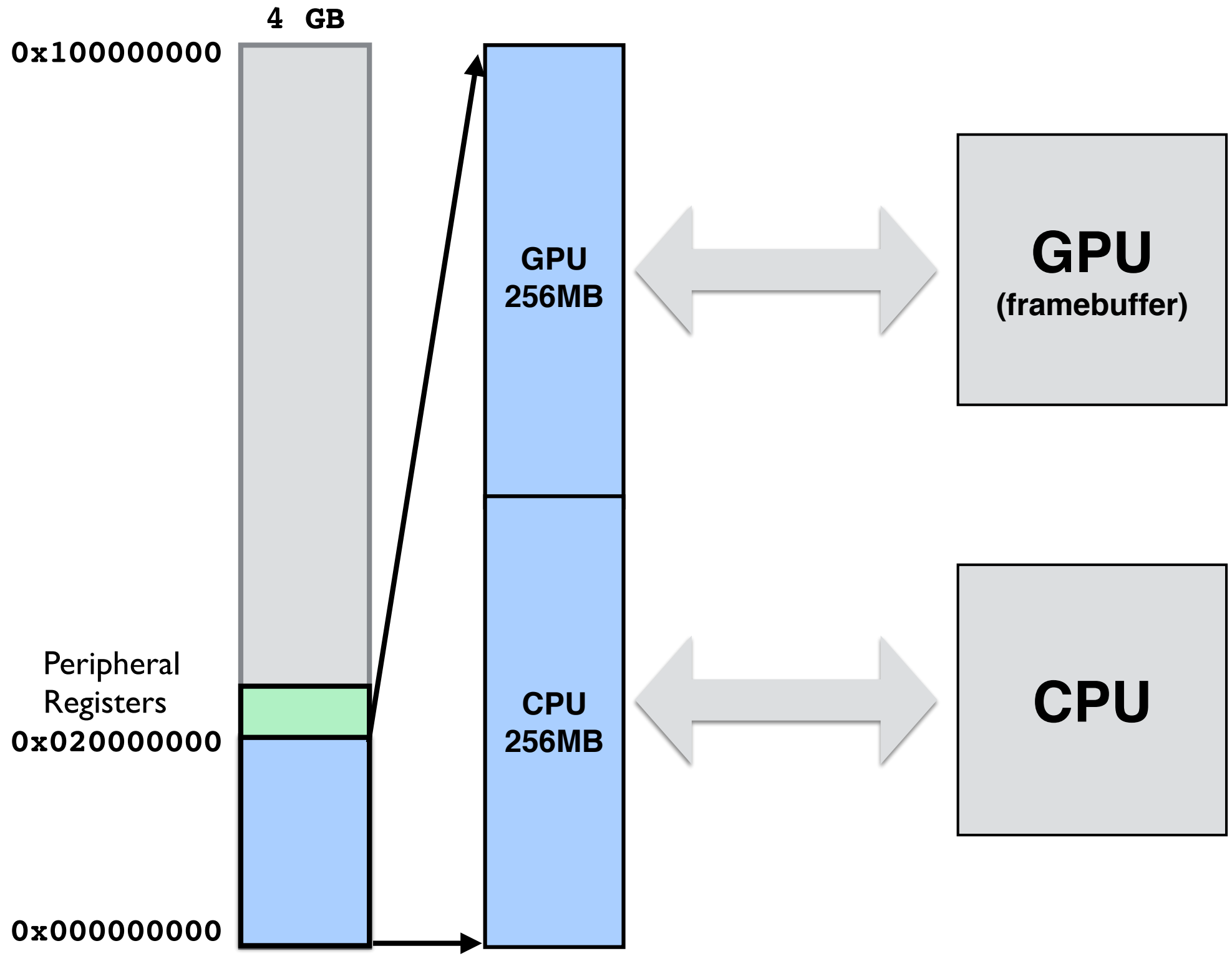




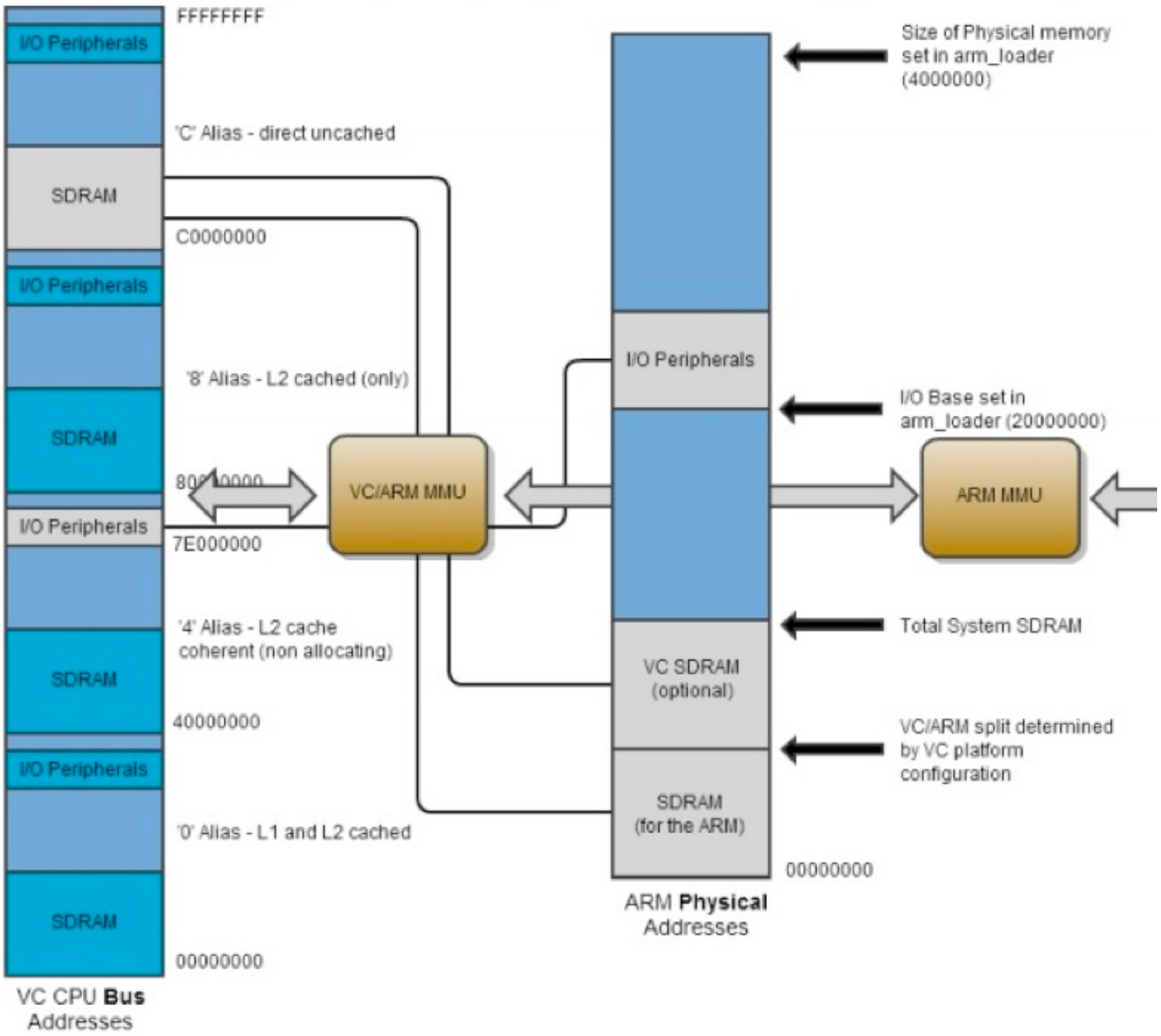
Font a set of "glyphs"

Apple II Font (7x8)

Mailbox


4 GB
0x100000000
Peripheral
Registers
0x020000000
0x000000000
GPU
256MB
CPU
256MB
GPU
(framebuffer)
CPU

BCM2835 ARM Peripherals



Coordinating CPU+GPU

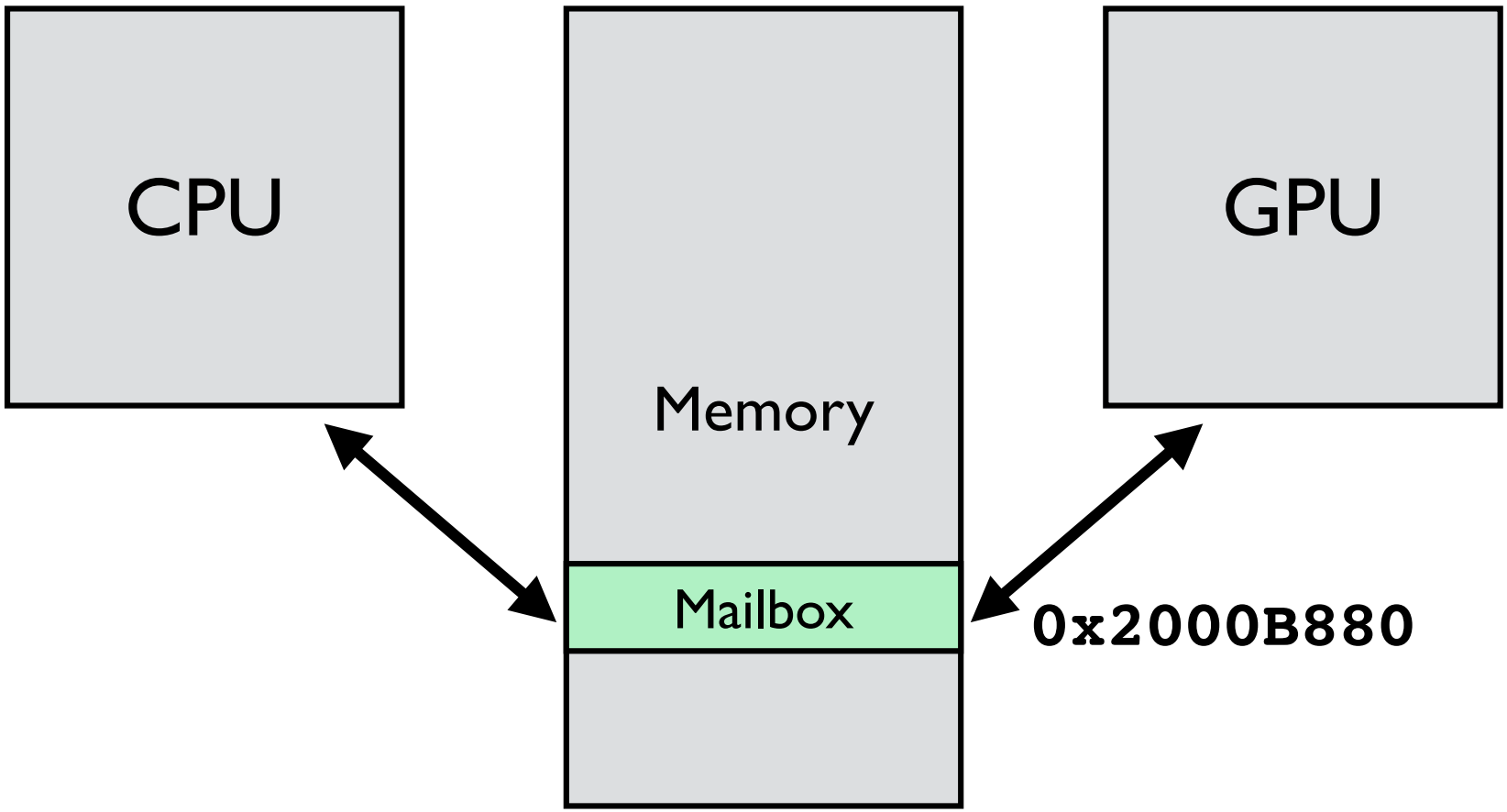
CPU and GPU need to communicate

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

Danger: reading incomplete/partial data

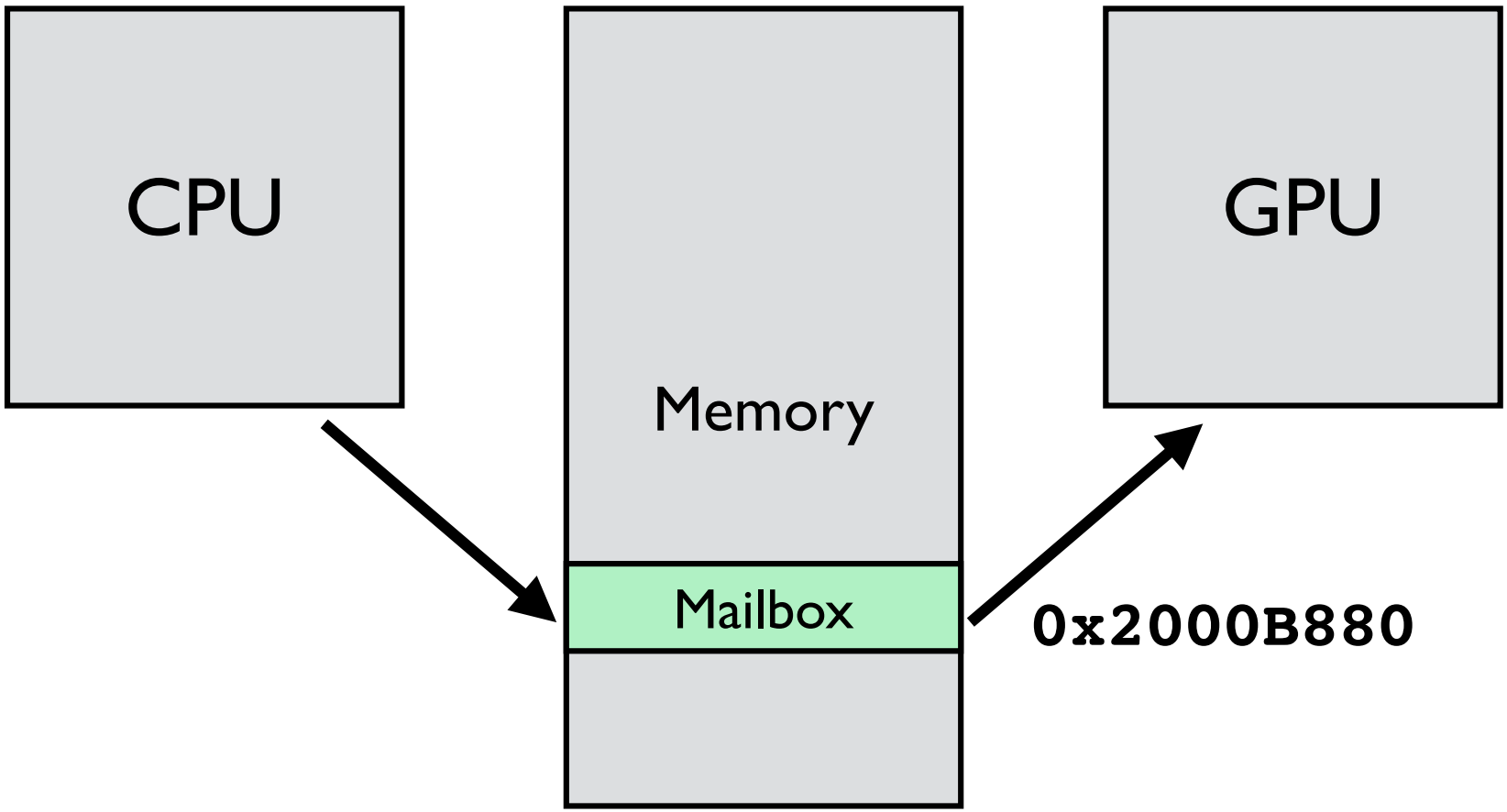
- They are two processors, running at different speeds, C compiler has no knowledge of this
- Need a simple handshake that depends on a single bit
  - *"I've set this bit, which means I have sent some data to you."*
  - *"I've cleared the bit, which means I've read the data."*

Mailbox



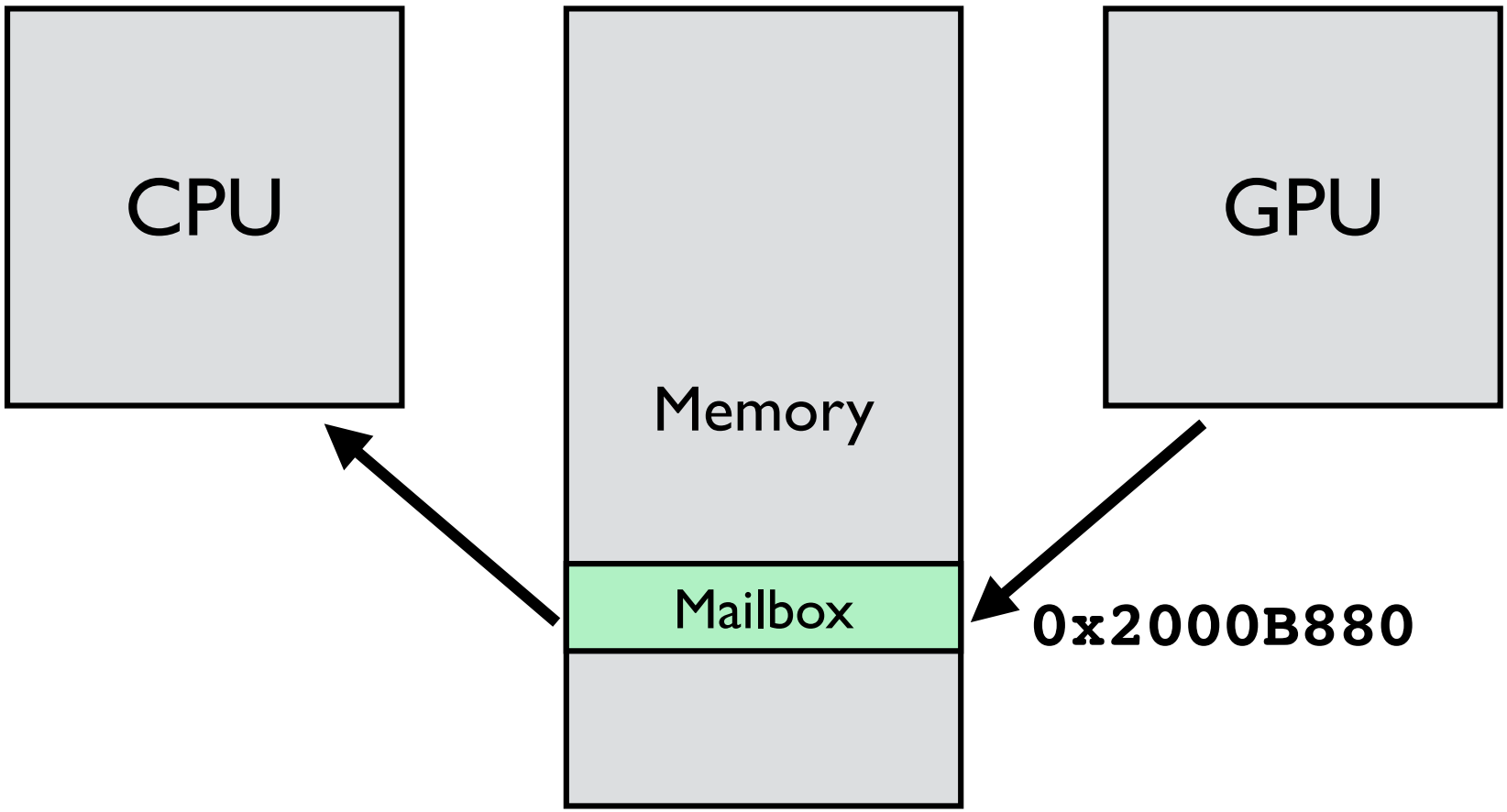
code/clear/mailbox.c

CPU "Mails" Message to GPU



code/fb/mailbox.c

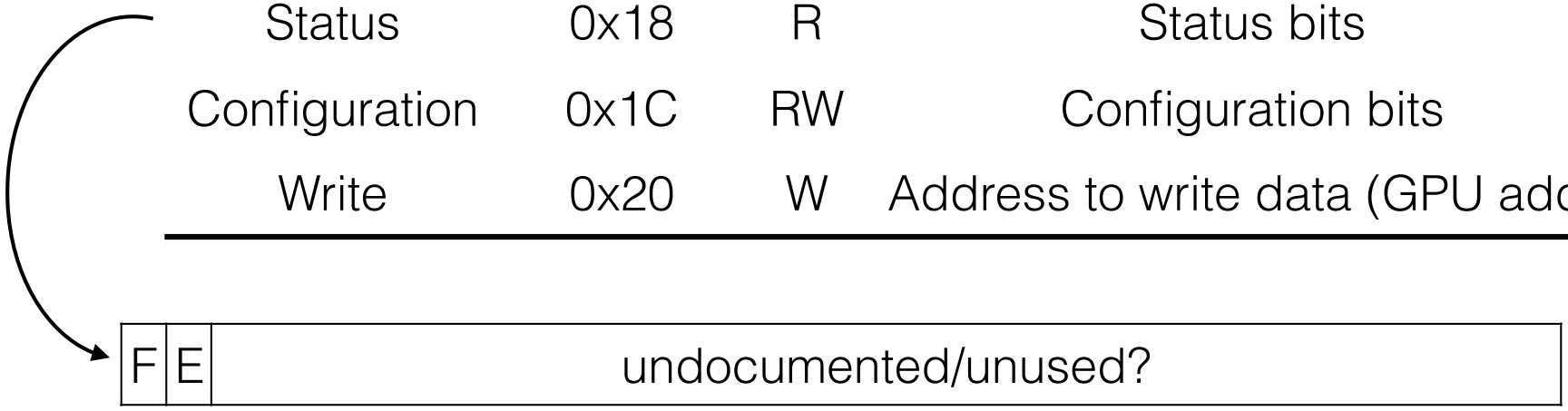
GPU Mails Reply to CPU



code/fb/mailbox.c

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 = 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`