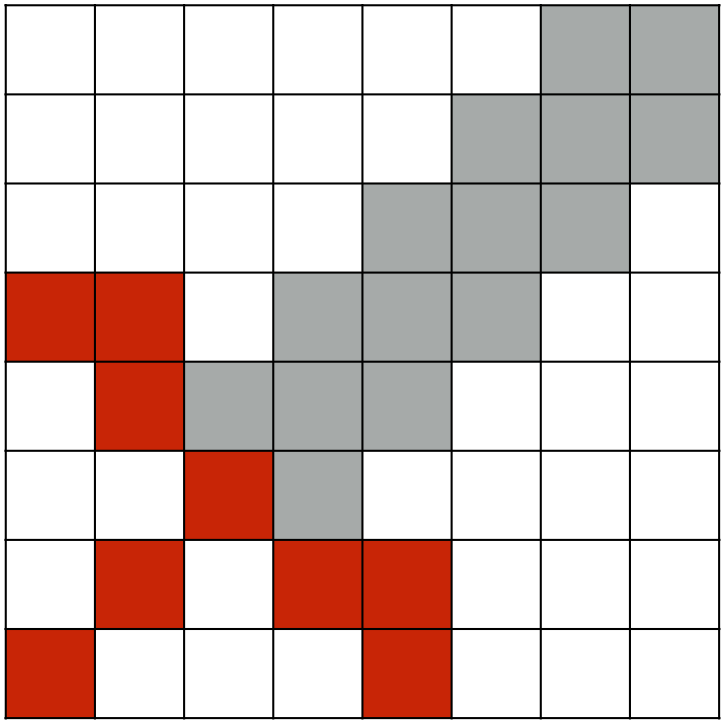
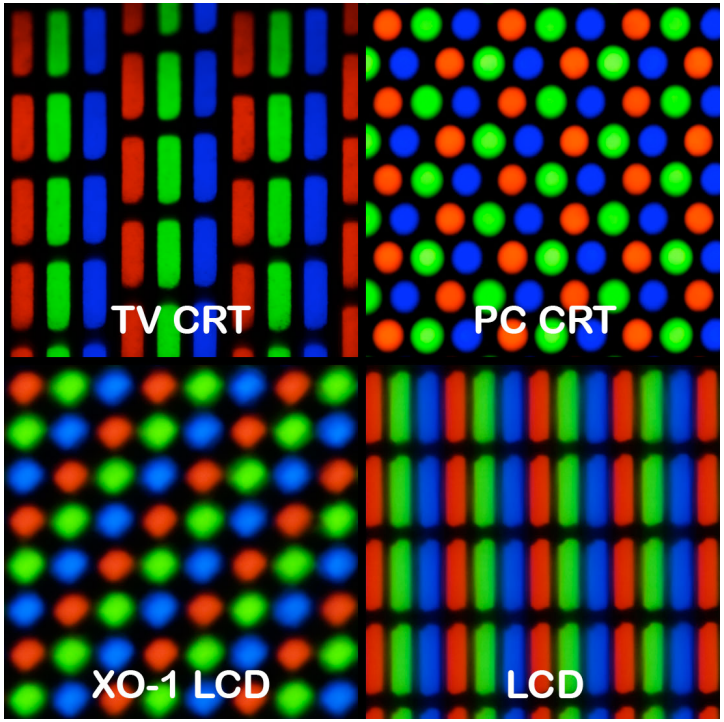
Graphics and Framebuffers

gpio
timer
uart
printf
malloc
keyboard
shell
fb
gl
console

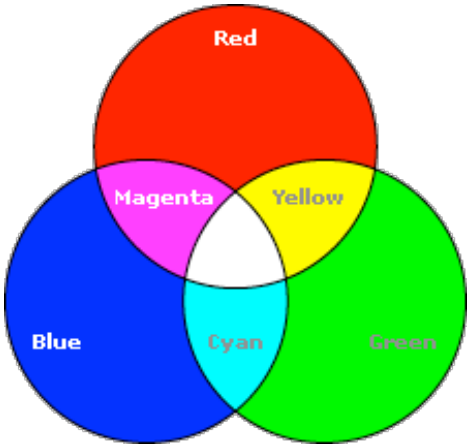
Pixels



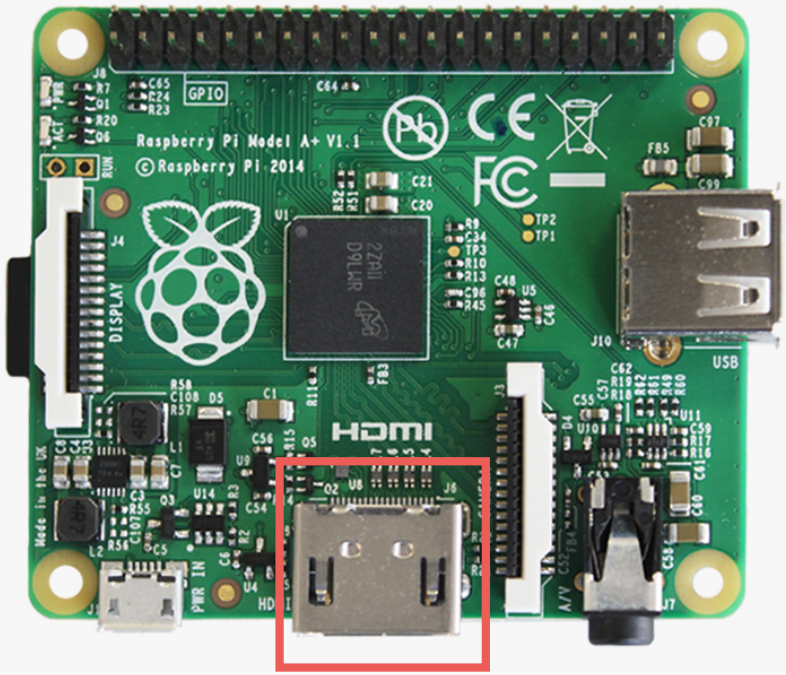
Displays

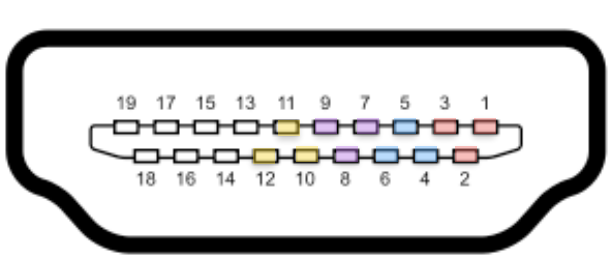


Light



HDMI





Clock

Data 0

Data 1

Data 2

Control

Figure from
High-Definition Multimedia Interface
Specification Version 1.3a

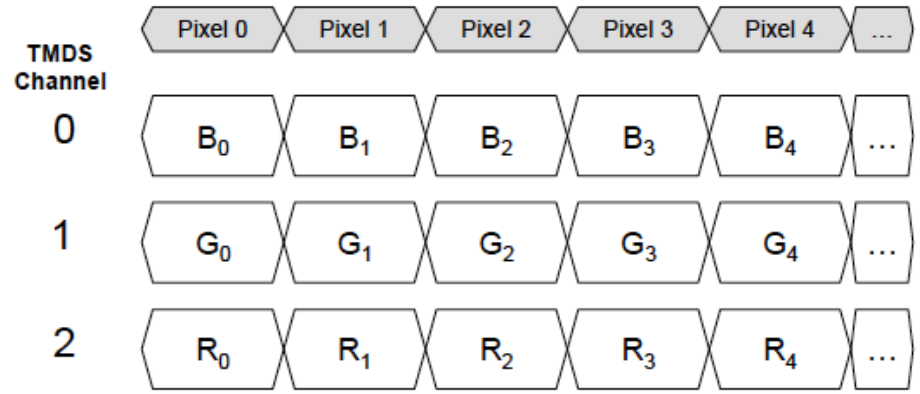


Figure 6-1 Default pixel encoding: RGB 4:4:4, 8 bits/component

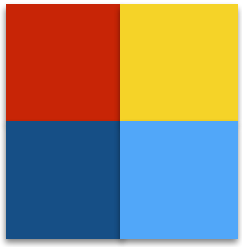
The framebuffer stores an image

An image is a 2D array of pixels

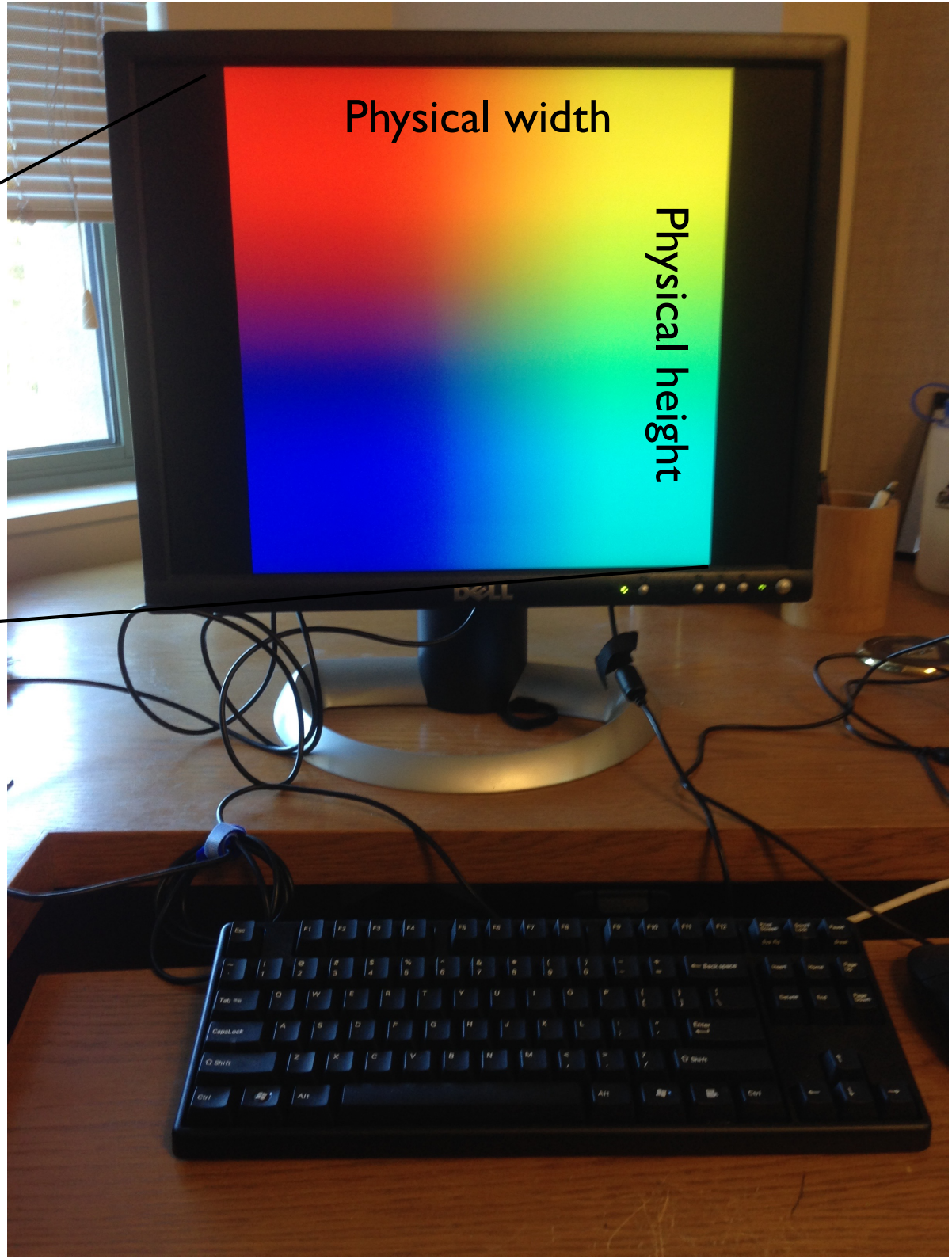
RGBA pixel (depth=32 bits)

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

Virtual height = 2



Virtual width = 2

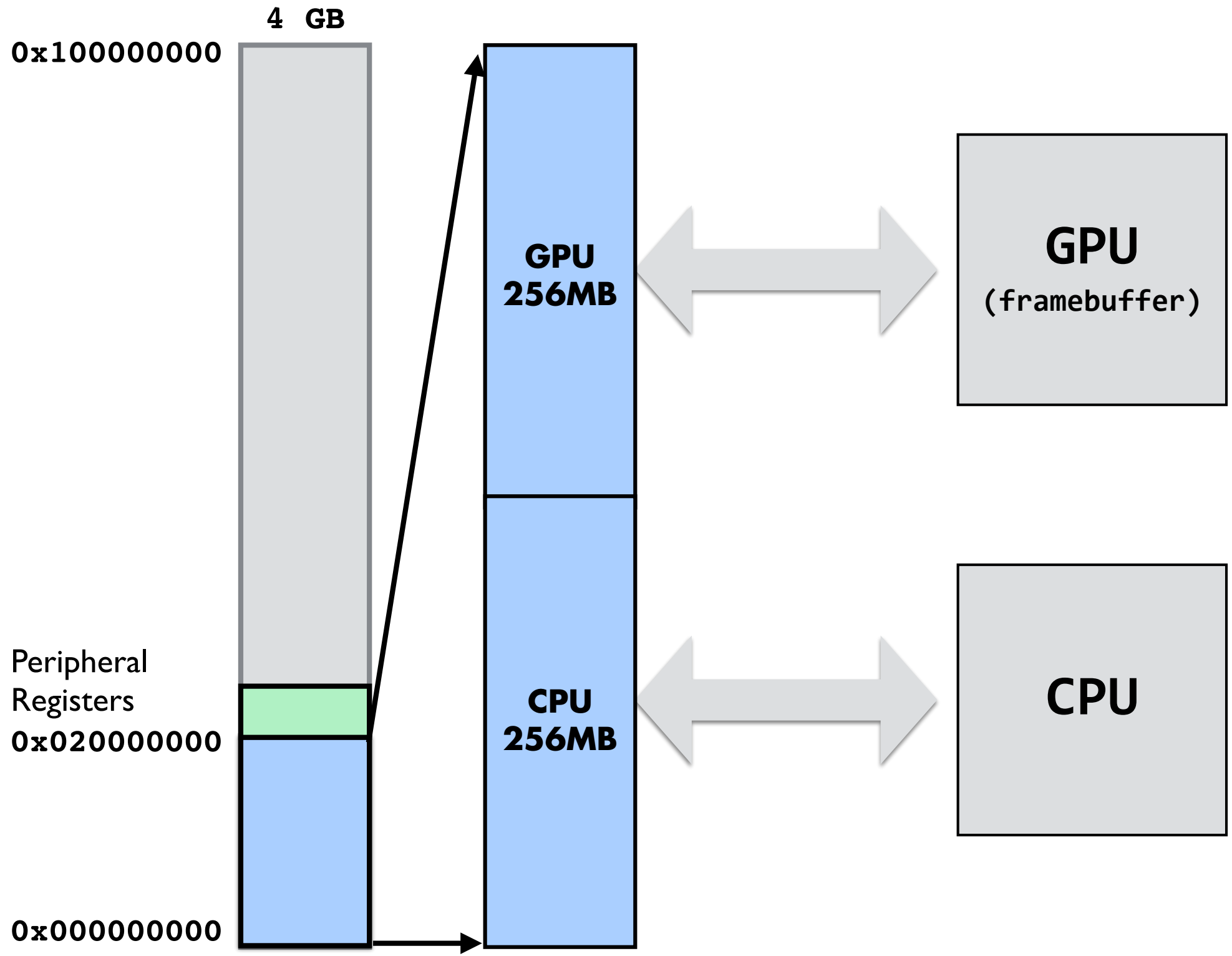


2x2 image is interpolated to 1600x1200 to fill monitor

Framebuffer Resolution

read CPU and GPU memory
read fb physical size
read fb virtual size
read fb pixel depth

code/video


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

Configure Framebuffer

write physical size
write virtual size
write depth
write offset of upper left

read fb pointer, size, pitch

`code/fb`

`fb_config_t` Structure

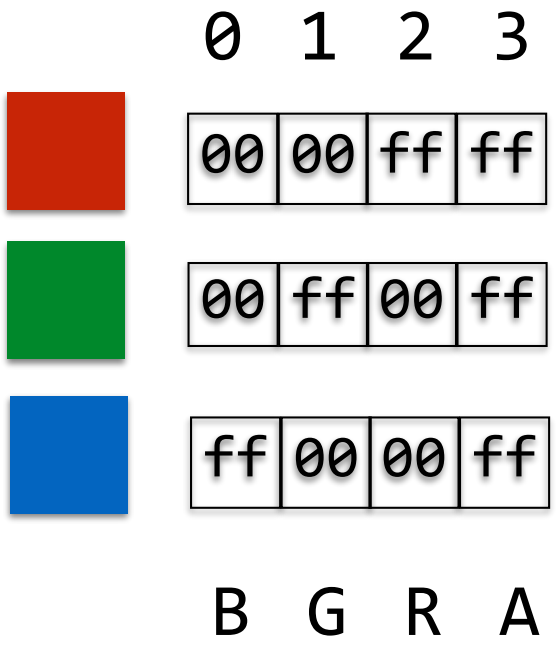
10 parameters

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

CPU writes/reads to/from GPU

RGBA (BGRA) Pixel/Color

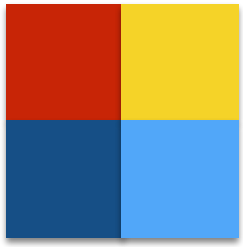
RGBA (BGRA) pixels are four bytes

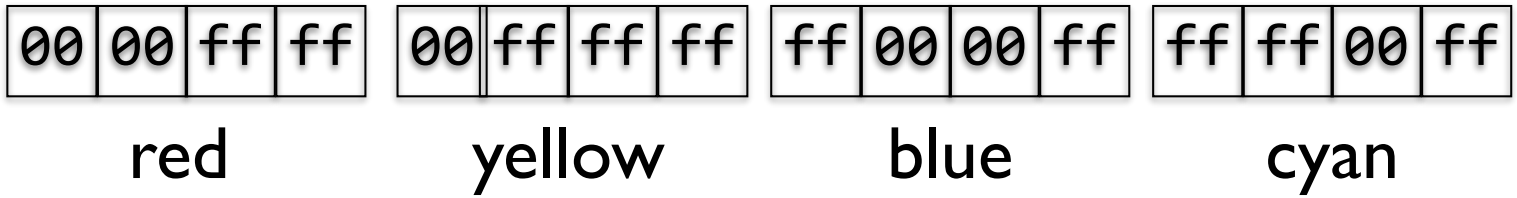


Beware: blue is the first

Framebuffer is an Array

```
#define DEPTH 4
#define WIDTH 2
#define HEIGHT 2
unsigned char fb[HEIGHT*WIDTH*DEPTH];

fb[DEPTH*(WIDTH*y+x)+bgra] = component
```





Note:

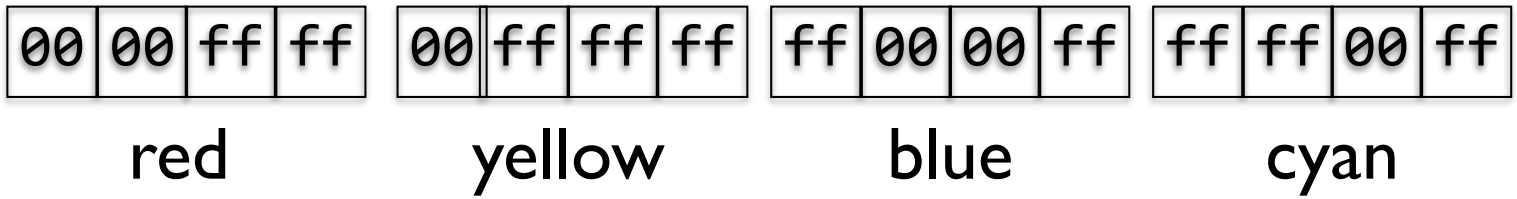
- **(0,0) is at the upper left corner of the display**
- **The order of pixels is** `y` **then** `x` **then** `bgra`

Drawing

`code/clear`

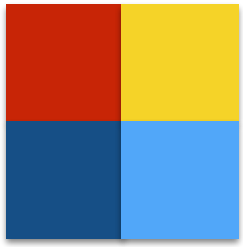
Array of unsigned char

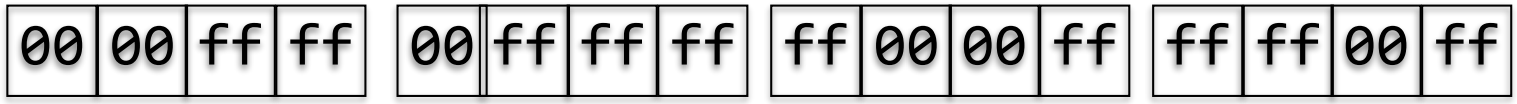
```
unsigned char fb[HEIGHT*WIDTH*DEPTH];
// fb[DEPTH*(WIDTH*y+x)+bgra] = component

fb[0] = 0x00; // x=0, y=0, bgra=b
fb[1] = 0x00; // x=0, y=0, bgra=g
fb[2] = 0xff; // x=0, y=0, bgra=r
fb[3] = 0xff; // x=0, y=0, bgra=a
fb[4] = 0x00; // x=1, y=0, bgra=b
…
```



Array of unsigned int

```
unsigned int fb[WIDTH*HEIGHT];
// fb[WIDTH*y+x] = color

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
```



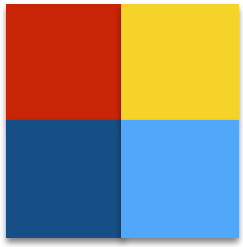


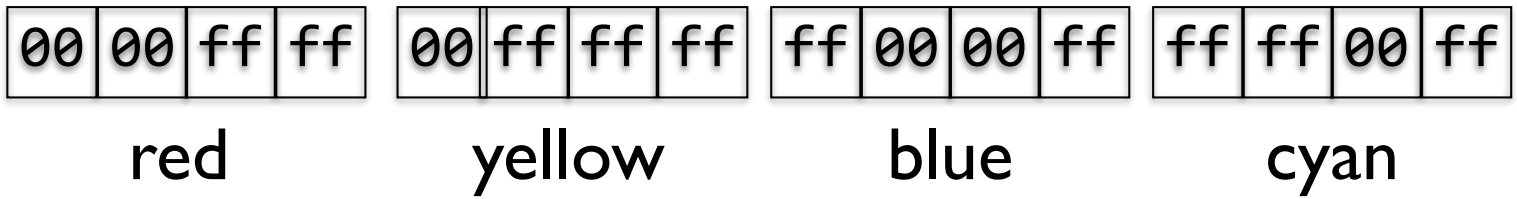
red yellow blue cyan

Same size and layout as `unsigned char` version

Casting to a 2D Array

```
unsigned int (*fb)[WIDTH] =
    (unsigned int (*)[WIDTH])fb.framebuffer;
// fb[y][x] = color
fb[0][0] = 0xffff0000;
fb[0][1] = 0xffffff00;
fb[1][0] = 0xff0000ff;
fb[1][1] = 0xff00ffff;
```





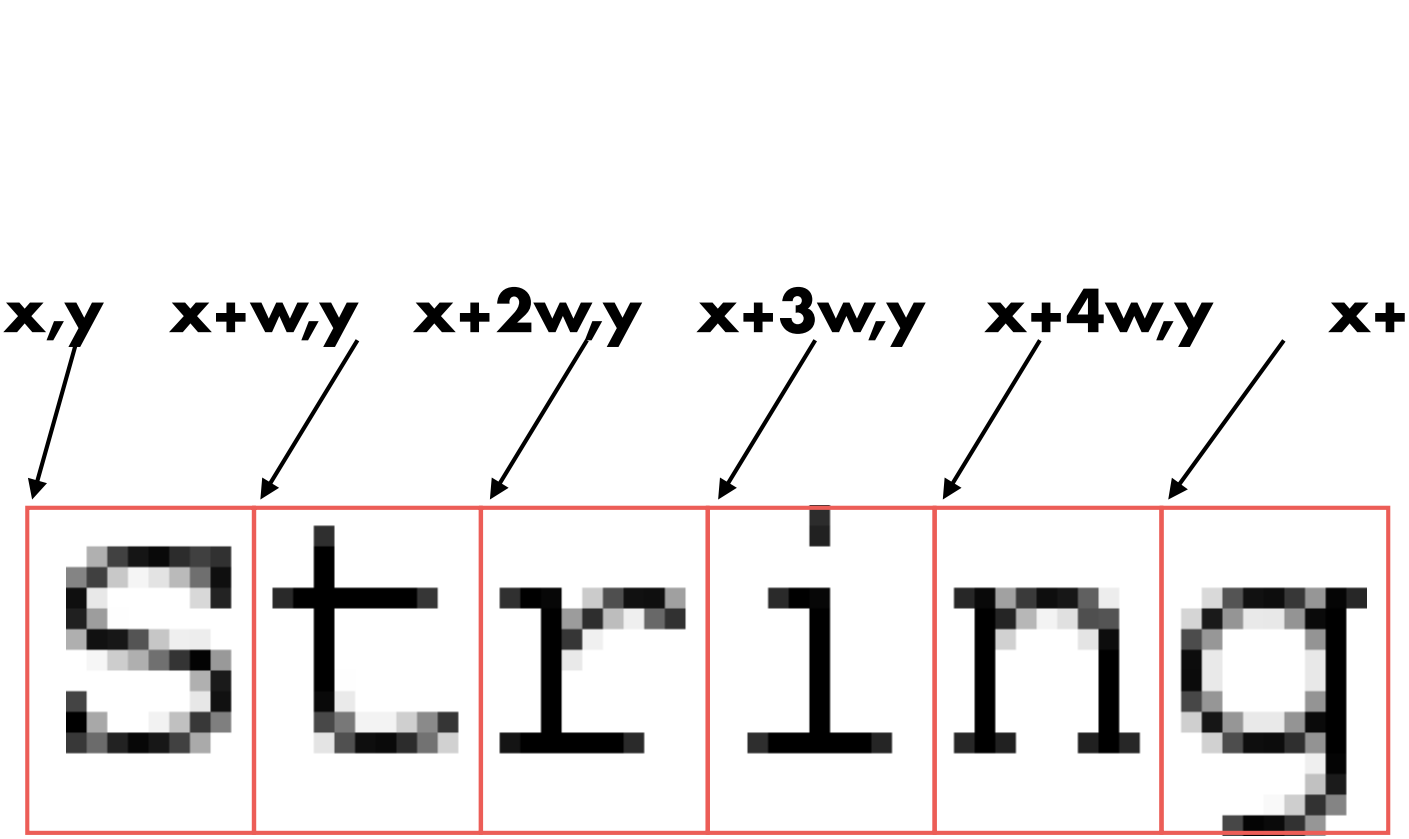
What is `unsigned *fb[WIDTH], (*fb)[WIDTH]`**?** cdecl.org

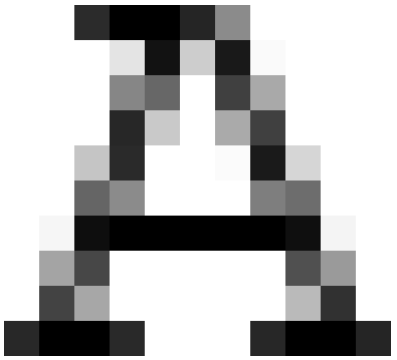
Demo

`code/grid`

Drawing Text

Fonts: monospaced vs. proportional





Font a set of "glyphs"

Apple II Font (7x8)

Single and Double Buffering

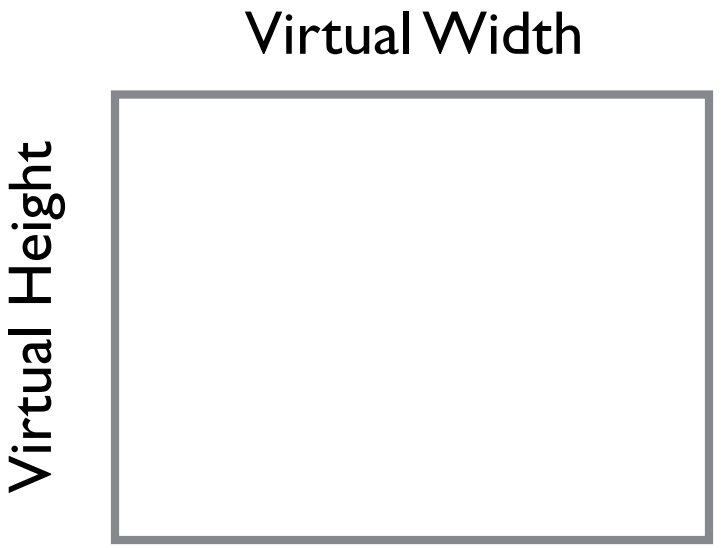
code/singlebuffer
code/doublebuffer

Single Buffer

Draw directly into the framebuffer

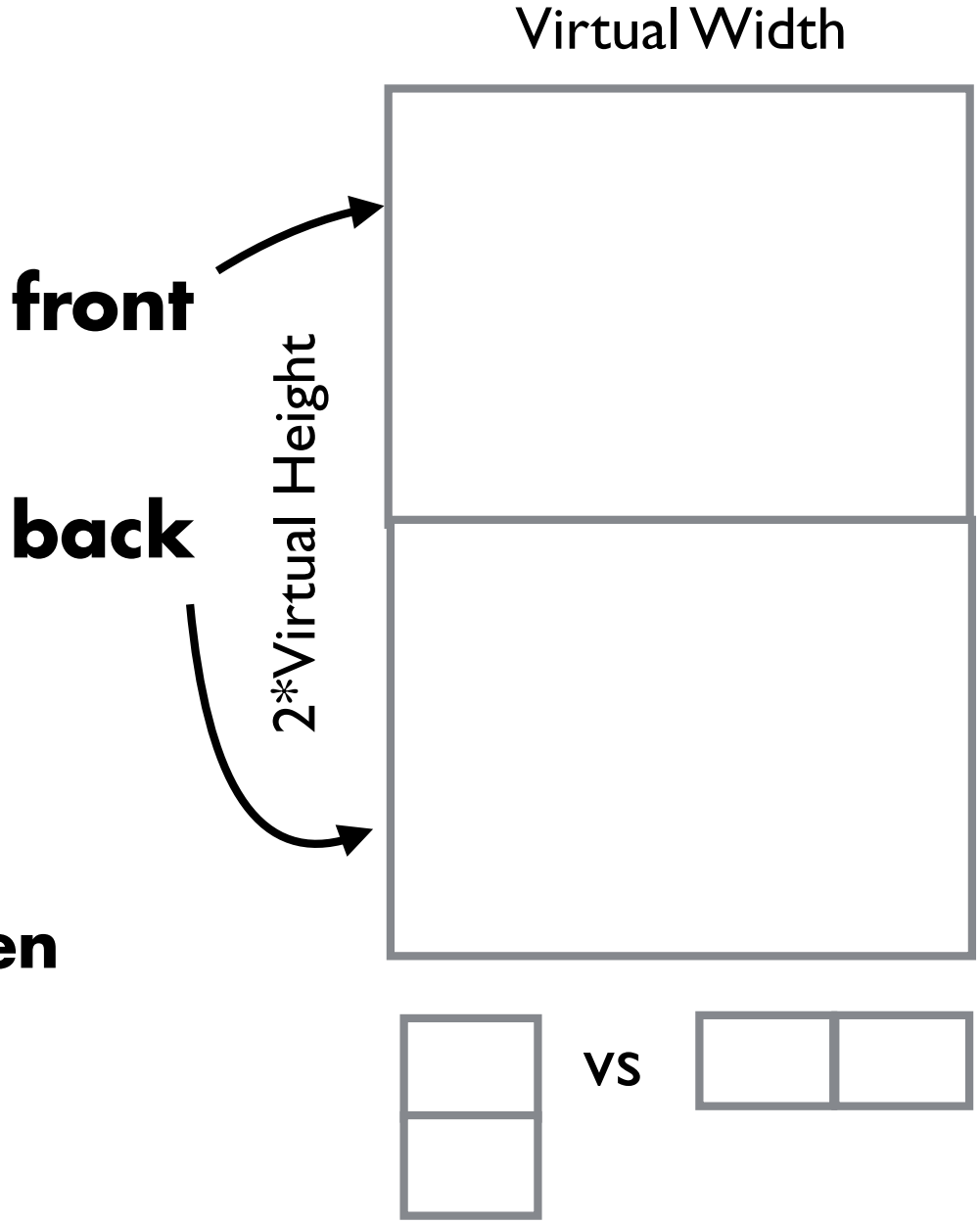
Lets you see the graphics as it is drawn (good for debugging!)

Clearing followed by drawing causes flickering

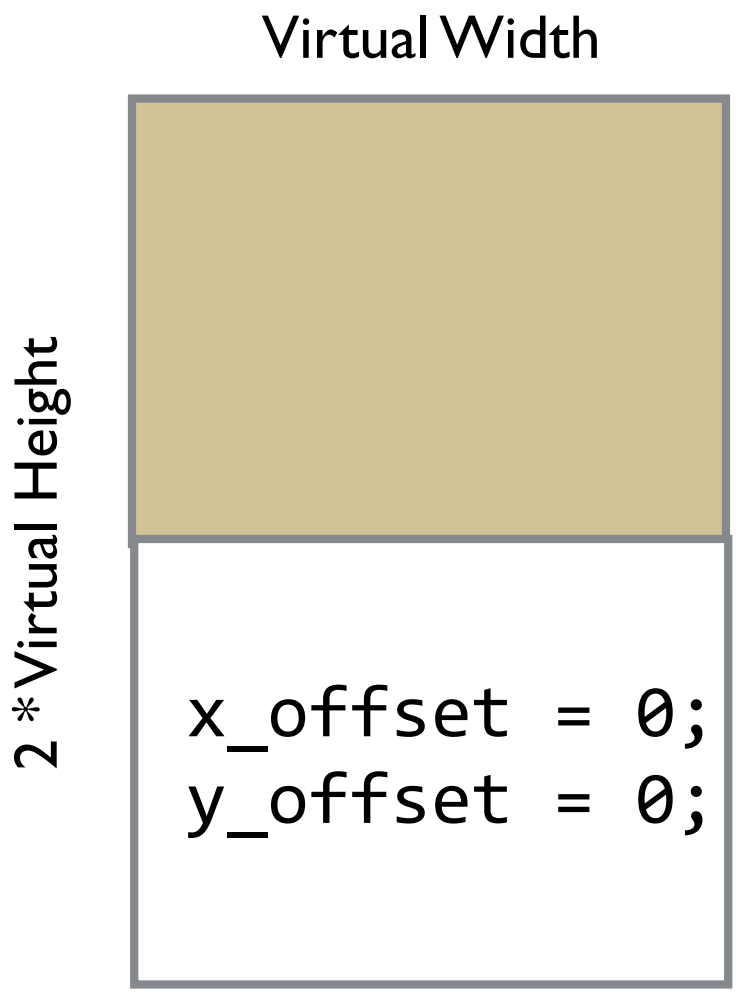


Double Buffer

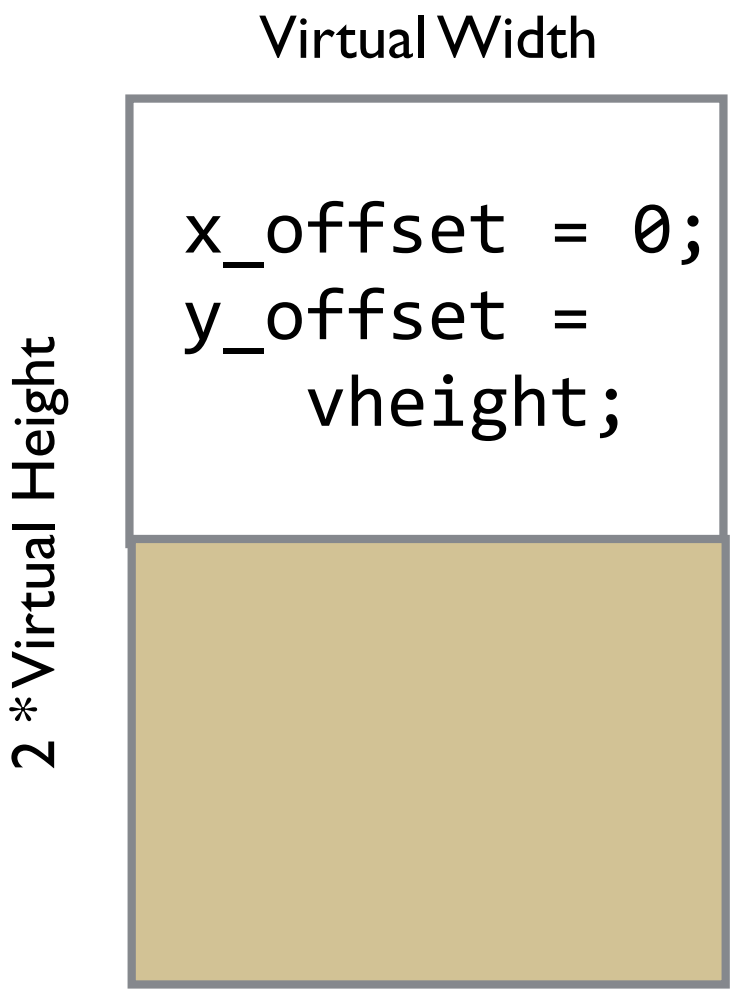
- Requires two images
  - Front-buffer
  - Back-buffer
- Display the "front"-buffer
- Draw into the "back"-buffer
- Swap front and back when you are done drawing to complete the "frame"



Swapping Buffers



"Front' is Top

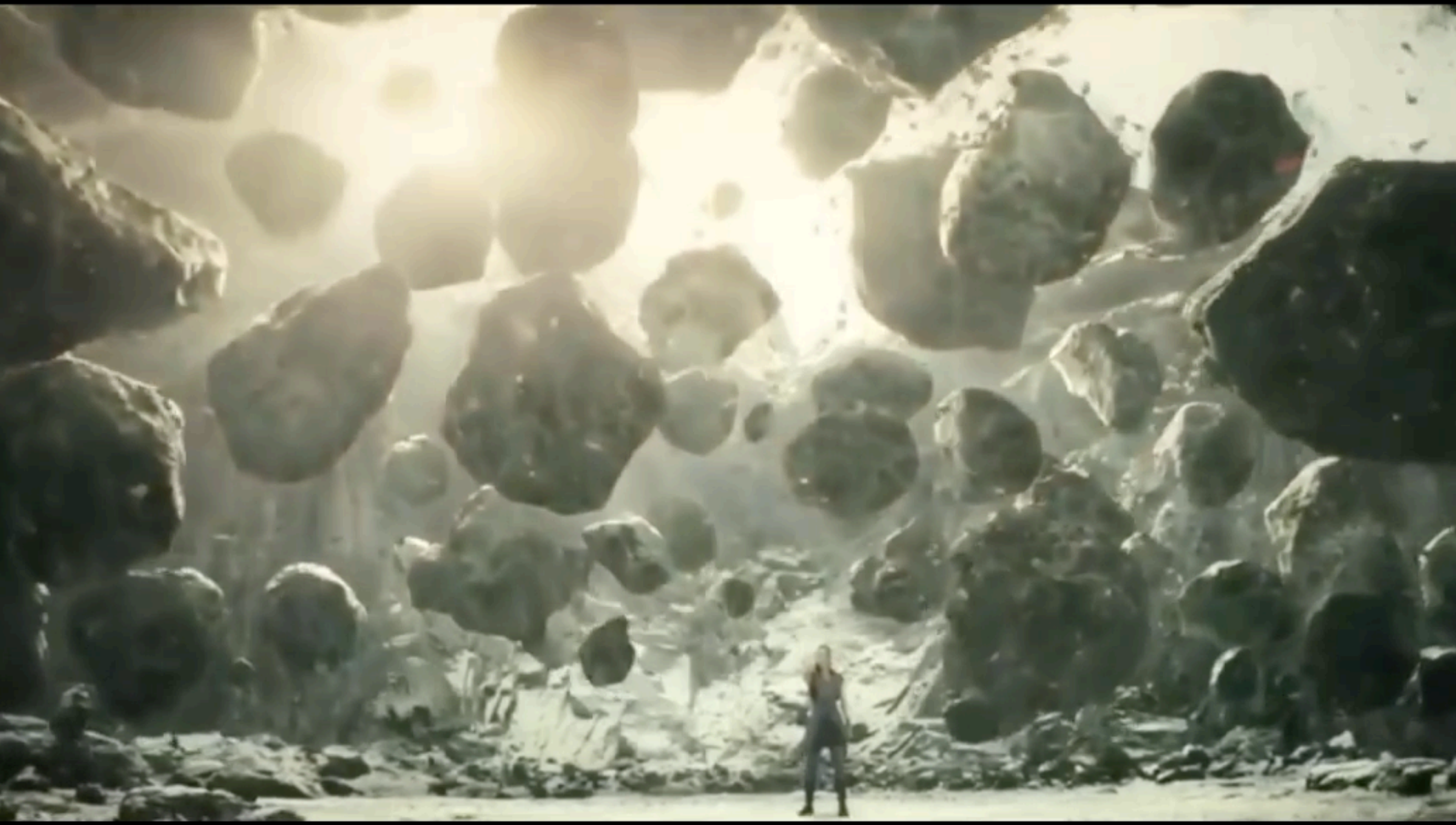


"Front' is Bottom

Put It All Together

graphical shell

The Force Awakens in You



Framebuffer Overview

GPU continuously refreshes the display by sending the pixels in the framebuffer out the HDMI port

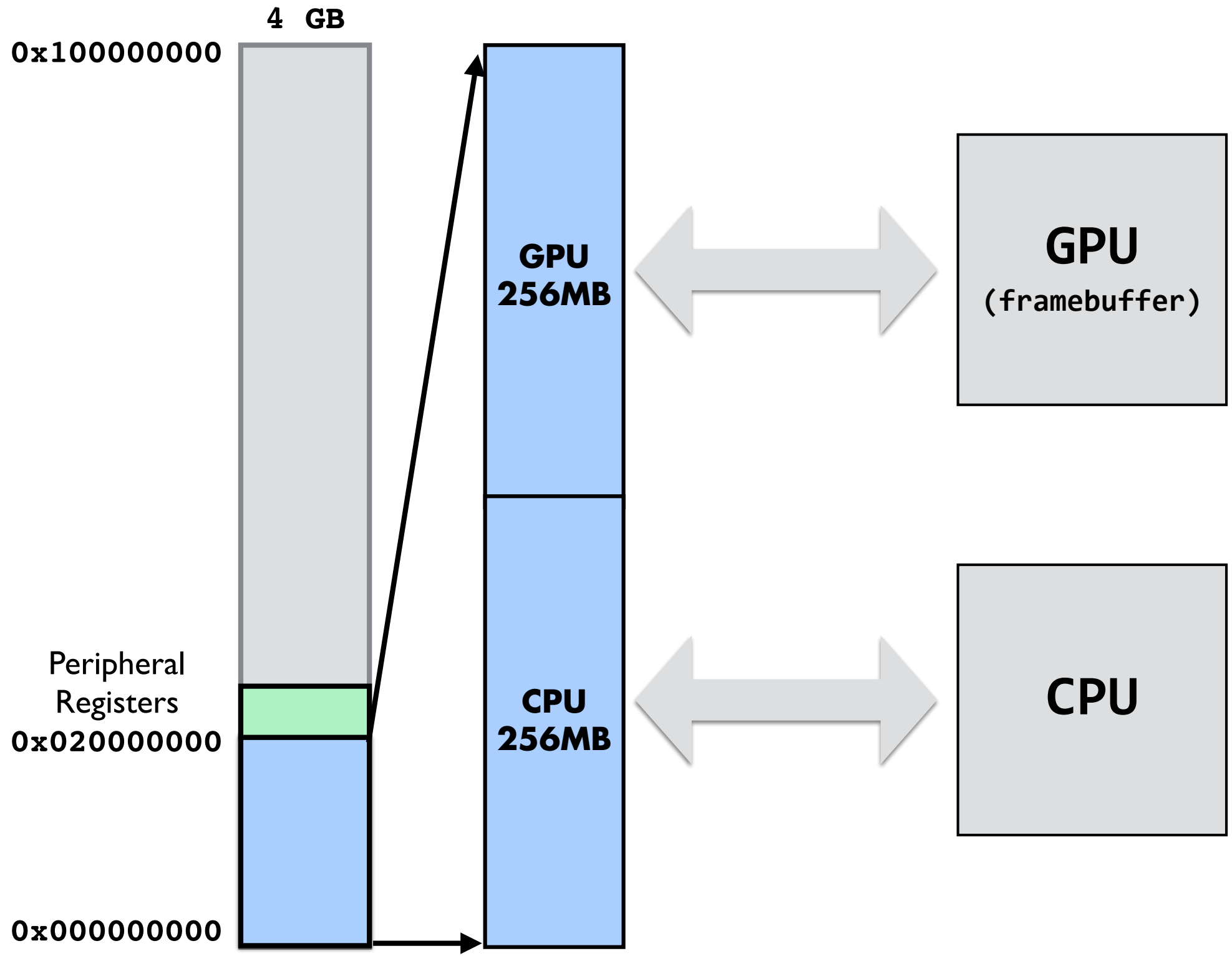
The size of the image sent to the monitor is called the physical size

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

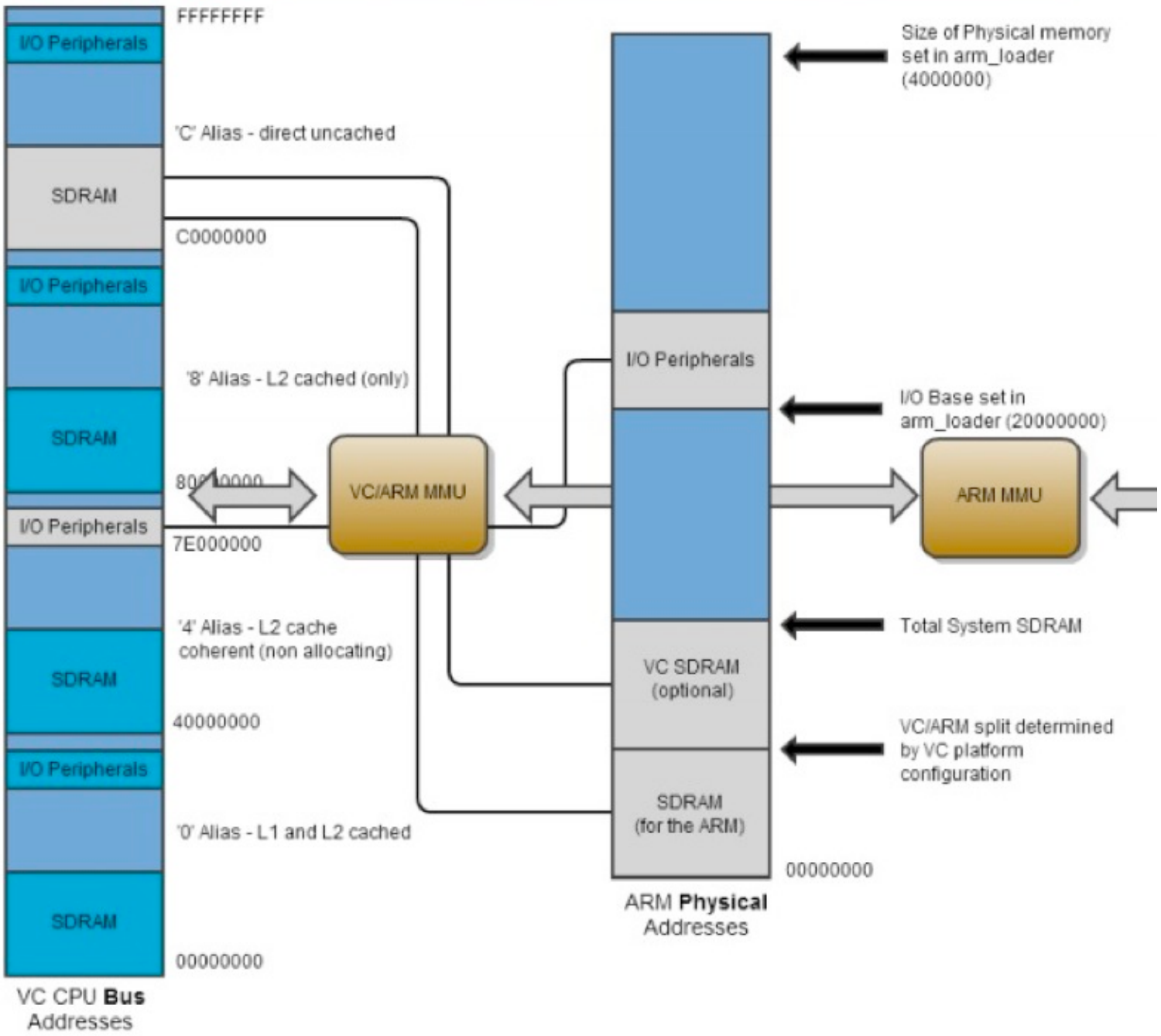
The CPU and GPU share the memory, and hence the framebuffer

The CPU and GPU exchange messages using a mailbox

Mailbox


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

BCM2835 ARM Peripherals



Coordinating CPU+GPU

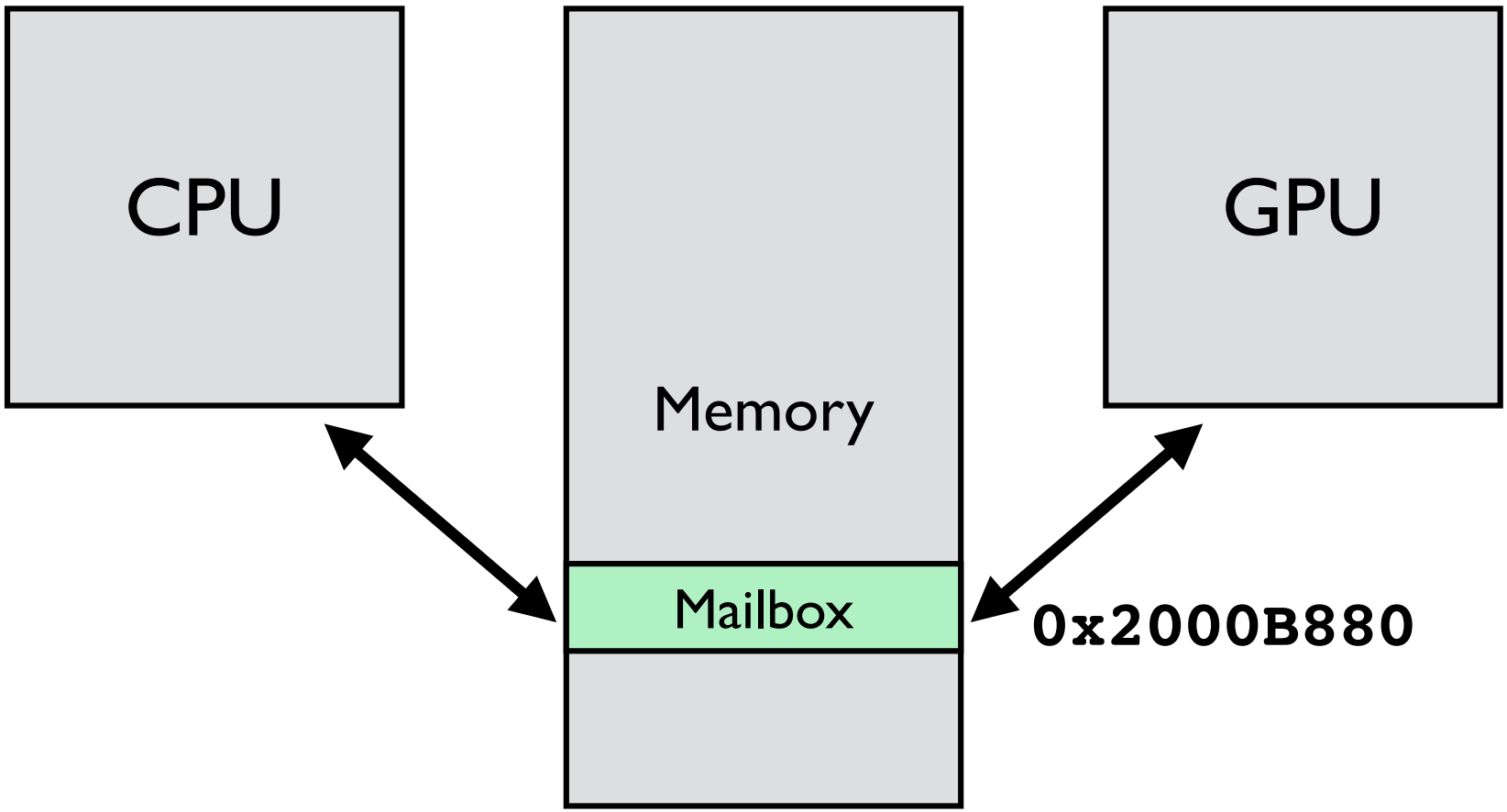
CPU and GPU need to communicate

- **CPU code wants to set/change screen settings**
- **GPU send to the CPU a pointer to the `fb_config_t`**

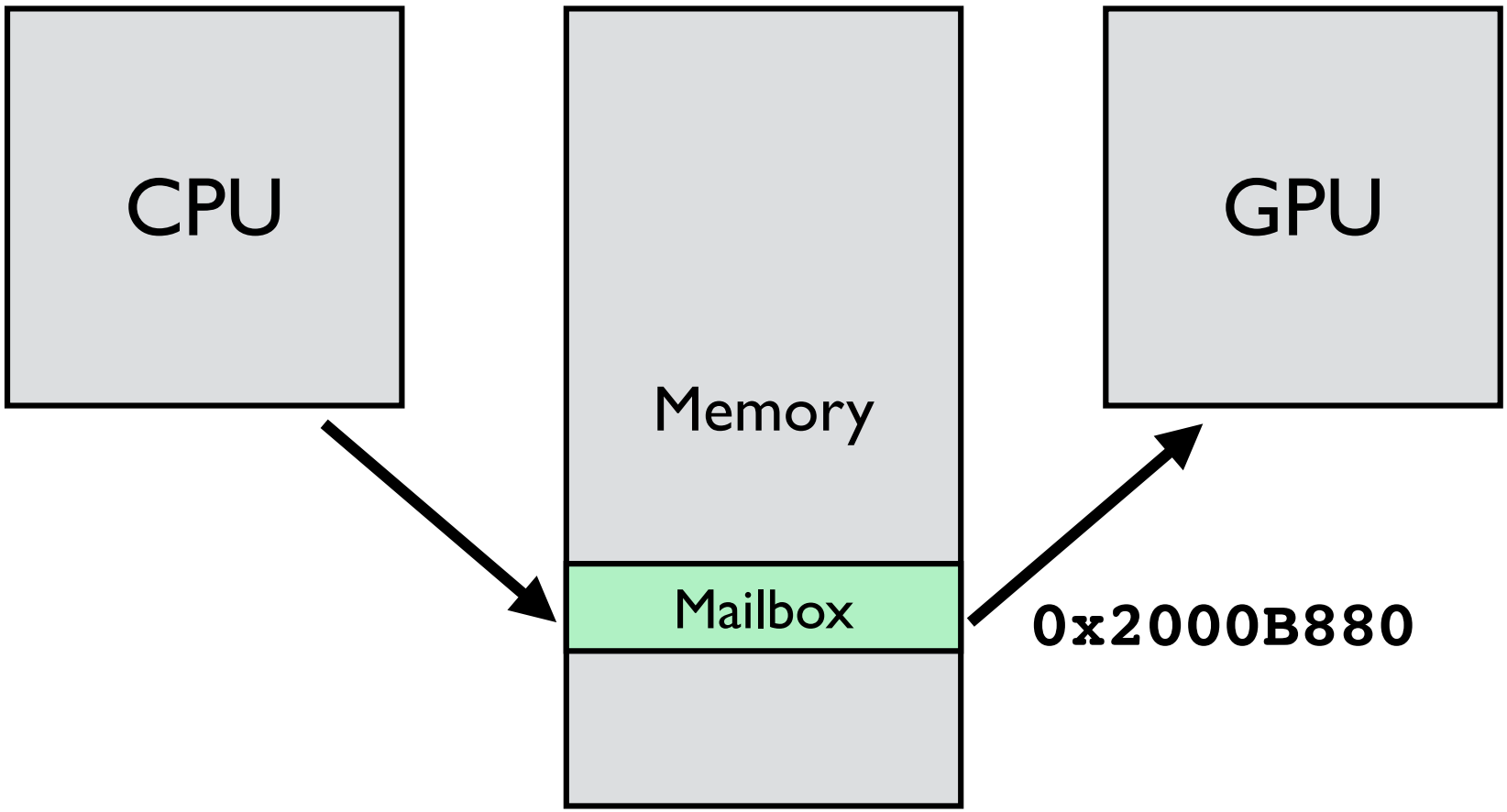
Danger: reading incomplete/partial data

- **They are two processors reading and writing to memory, C compiler has no knowledge that this is happening**
- **Need a simple handshake that depends on a single bit**
  - **"I've set this bit, which means I have sent some data to you. You can write it now."**
  - **"I've cleared the bit, which means I've done writing the data. You can read it now"**

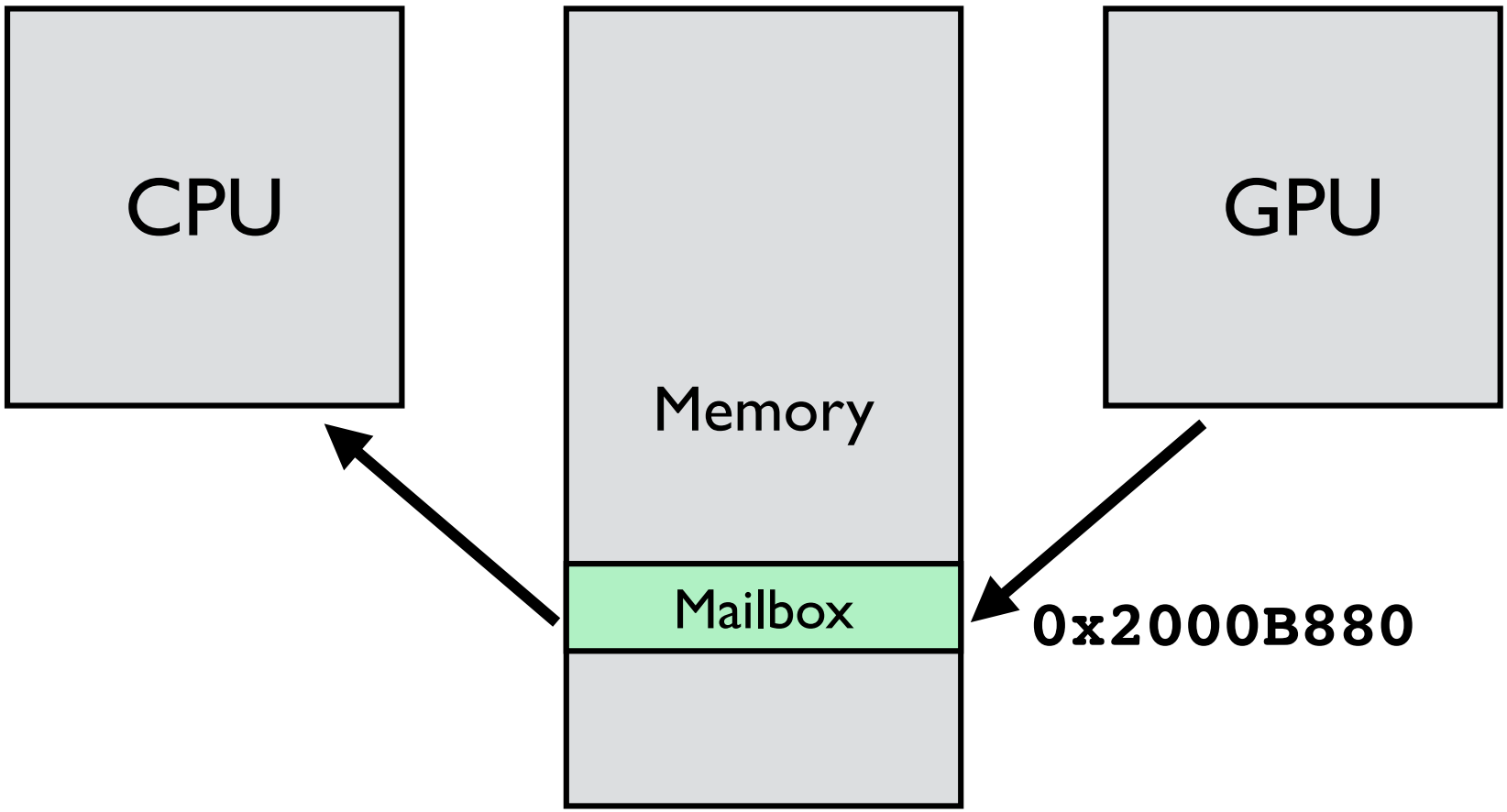
Mailbox



CPU "Mails" Message to GPU

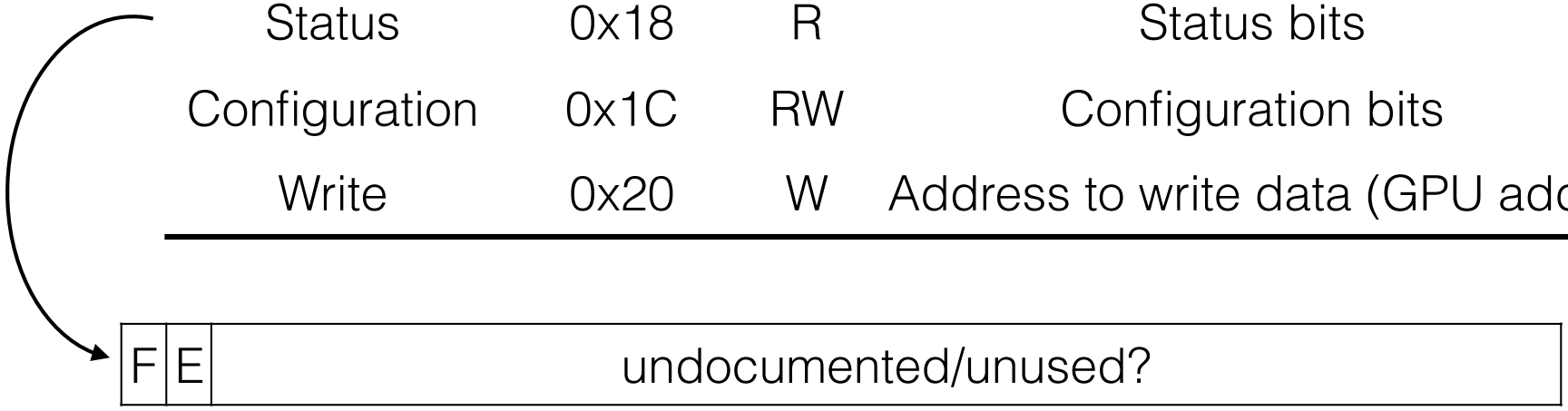


GPU Mails Reply to CPU



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 = Full
E = Empty

```
#define MAILBOX_BASE   0x2000B880
#define MAILBOX_FULL   (1<<31)
#define MAILBOX_EMPTY  (1<<30)
#define GPU_NOCACHE 0x40000000

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;
static volatile mailbox_t *mailbox = (volatile mailbox_t *)MAILBOX_BASE;

void mailbox_write(unsigned int channel, unsigned int addr) {
    // mailbox has a maximum of 16 channels
    if (channel >= MAILBOX_MAXCHANNEL)
        return;
    // addr must be a multiple of 16
    if (addr & 0xF)
        return;
    // wait until mailbox is not full ...
    while (mailbox->status & MAILBOX_FULL) ;
    // set GPU_NOCACHE bit so that the GPU does not cache the memory
    addr |= GPU_NOCACHE;
    // addr is a multiple of 16, so the low 4 bits are zeros
    // 4-bit channel number is stuffed into those low bits
    mailbox->write = addr + channel;
}
```

cs107e.github.io/cs107e/src/mailbox.c