Lab 10: VGA Graphic Display

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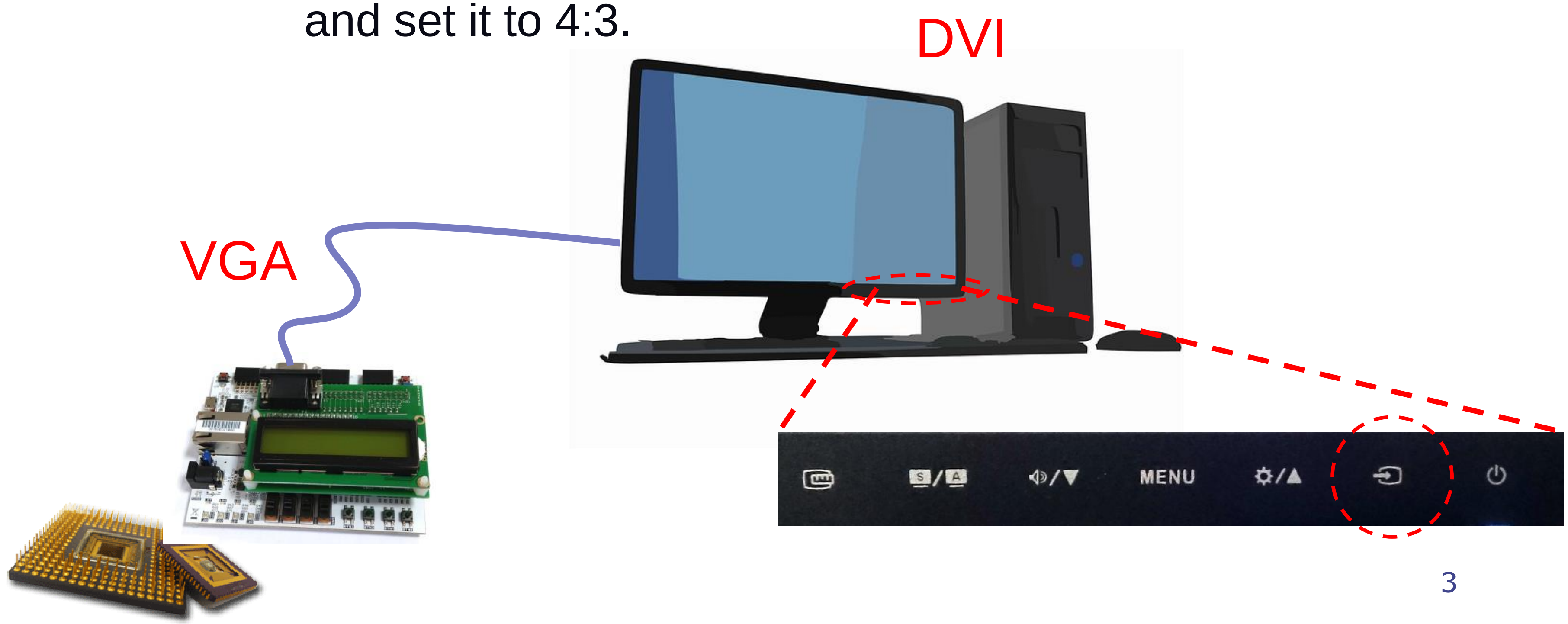
Lab 10: VGA Graphic Display

- In this lab, you will implement a circuit that shows some animations using the VGA video interface:
  - Animate fishes swimming in the seabed picture (not necessarily as complex as the picture below)

- The lab file submission deadline is on 12/13 by 6:00pm.

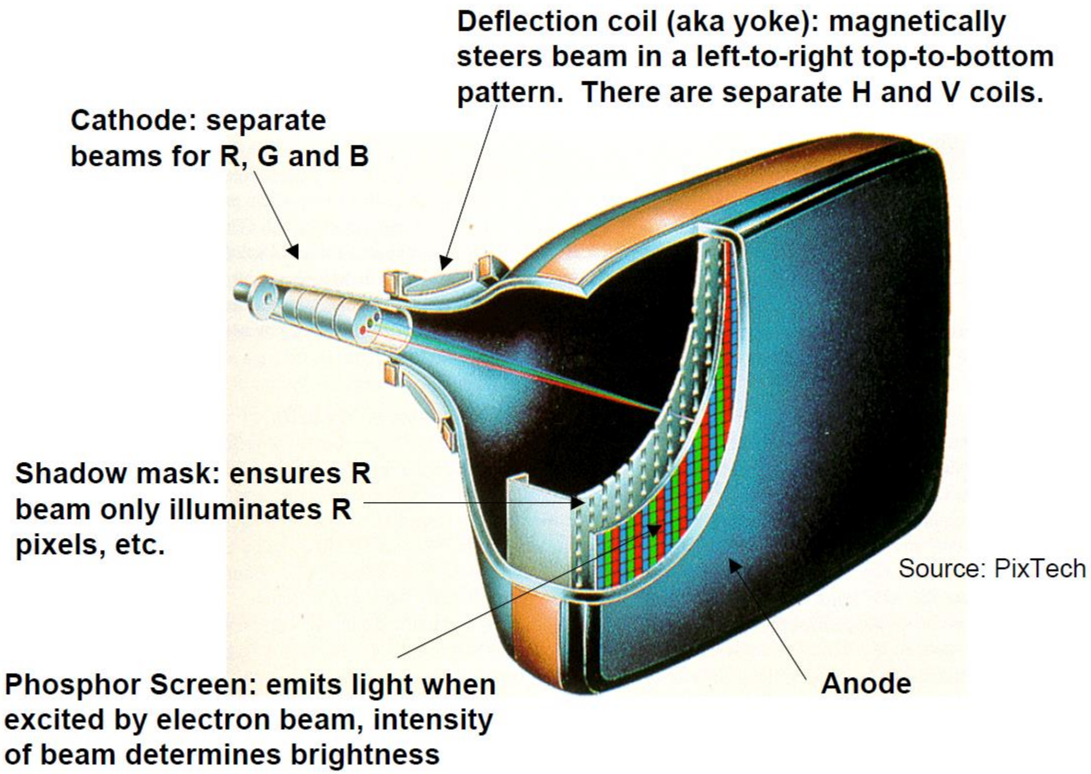
Lab 10 Setup

- In Lab 10, the Arty board will share the LCD monitor with the PC.
  - To see the video output of Arty, you must press the “video source” toggle on the LCD monitor to change the video source from “DVI” (for PC) to “VGA” (for Arty).
  - You should press “MENU”→ “Image” → “Aspect Control” and set it to 4:3.



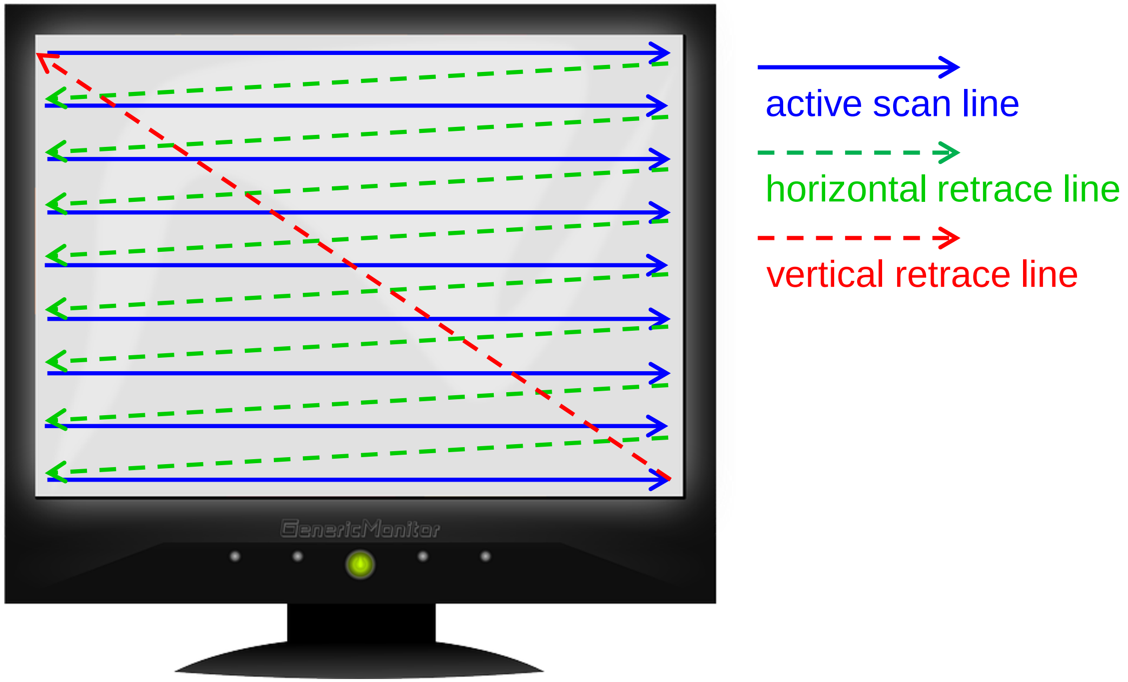
VGA – Old Soldiers Never Die

- VGA stands for Video Graphics Array; it's a video interface originally designed for CRT display.



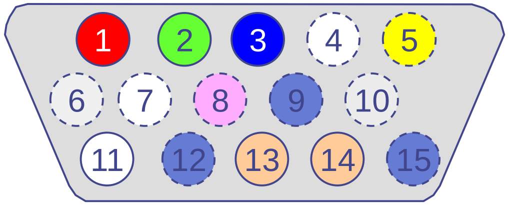
VGA Scanning Pattern

- A VGA screen displays the entire screen pixel-by-pixel:
  - The pixels of the screen are illuminated following a one-dimensional scanning path.
  - When pixel at (x, y) are “scanned,” your circuit must tell the screen what RGB color it should display.



VGA Interface Pin Assignment

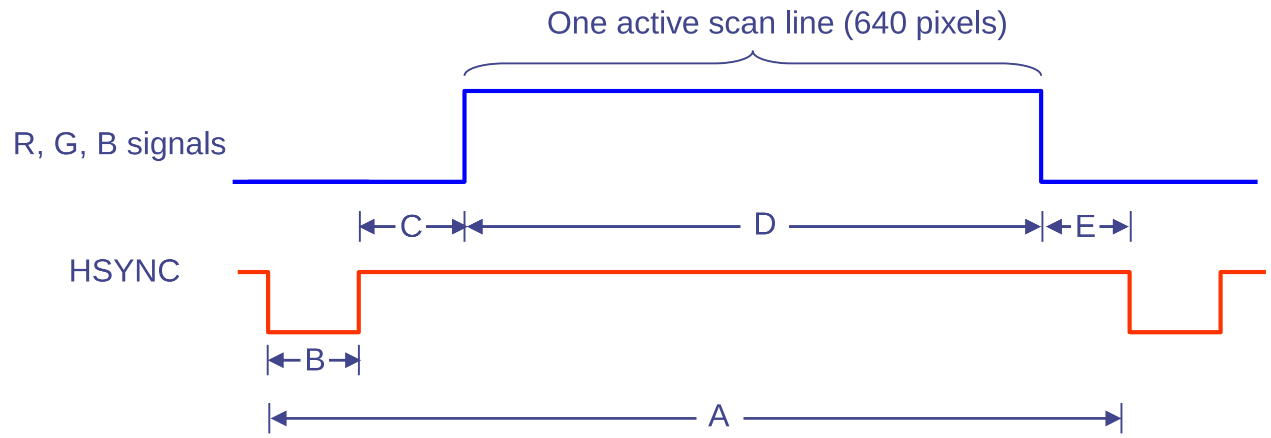
- VGA uses HD15 (a.k.a. D-sub) connectors.
  - Pin #1 Red (0 ~ 0.7V)
  - Pin #2 Green (0 ~ 0.7V)
  - Pin #3 Blue (0 ~ 0.7V)
  - Pin #5, 6, 7, 8 Ground
  - Pin #9 Power (for external I^{2}C device)
  - Pin #10 Sync Return (Sync Ground)
  - Pin #4, 11 No connection
  - Pin #12 I^{2}C SDA
  - Pin #15 I^{2}C SCL
  - Pin #13 Horizontal Sync (2.5V)
  - Pin #14 Vertical Sync (2.5V)



HD-15 male

VGA Signal Timing (1/2)

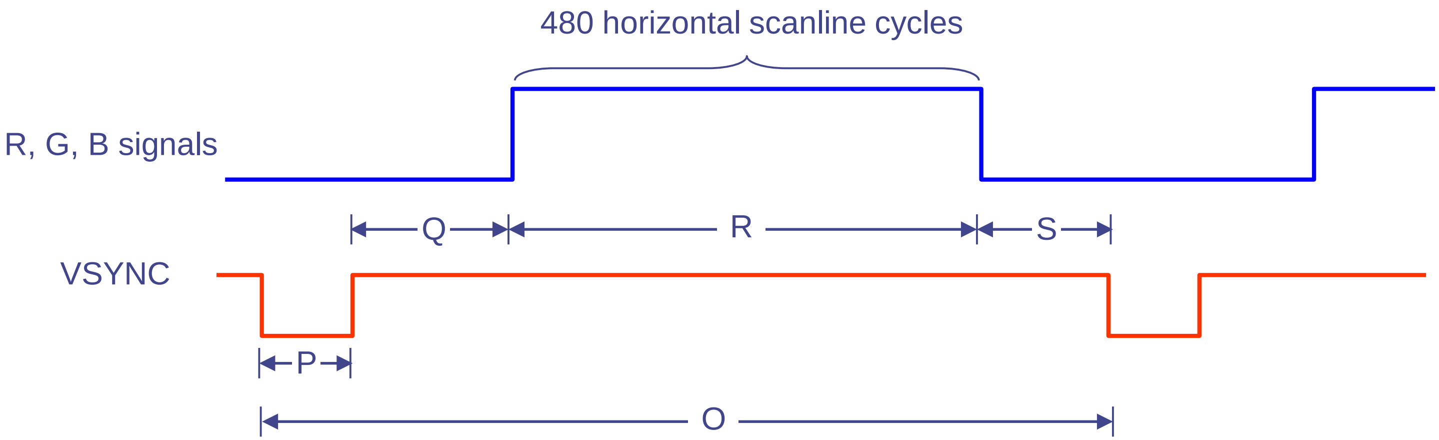
- Horizontal Retrace Cycles (for 640×480@60Hz):
  - 1/31.77μs = 31476 lines
  - 31476/60 = 525 lines/frame



Parameters	A	B	C	D	E
Time	31.77μs	3.813μs	1.907μs	25.42μs	0.6356μs

VGA Signal Timing (2/2)

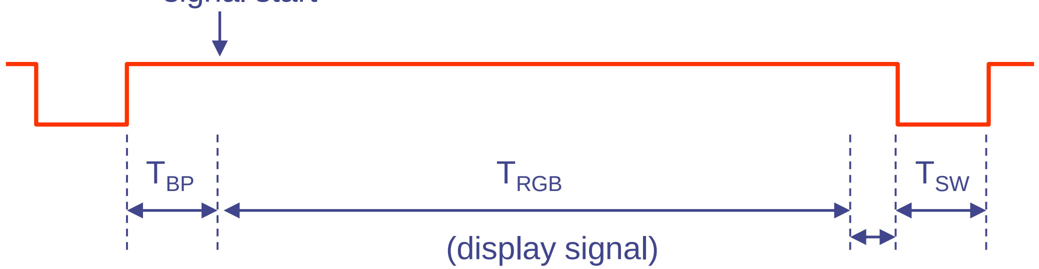
- Vertical Retrace Cycles (for 640x480@60Hz):
  - 1/16.66ms = 60 Hz (frames/second)



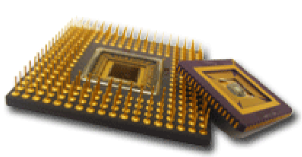
Parameters	O	P	Q	R	S
Time	16.68ms	63.56μs	1.049ms	15.25ms	0.3178ms

Sync Timing in Pixel Clocks

- The Horizontal Sync (HS) and Vertical Sync (VS) signal in pixel clock ticks are as follows:

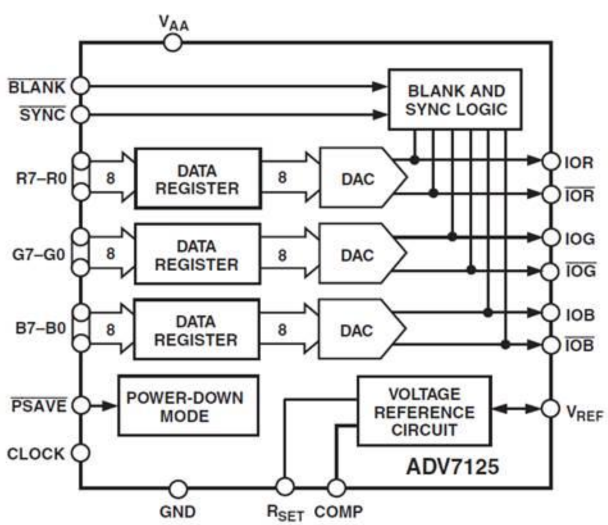


Format	Sync Type	Clock	Total	T_{RGB}	T_{FP}	T_{SW}	T_{BP}
VGA (4:3 Screen) 640x480@60Hz	HS (pixels)	25.175MHz	800	640	48	96	16
	VS (lines)		525	480	10	2	33
VGA (4:3 Screen) 800x600@72Hz	HS (pixels)	50 MHz	1040	800	56	120	64
	VS (lines)		666	600	37	6	23



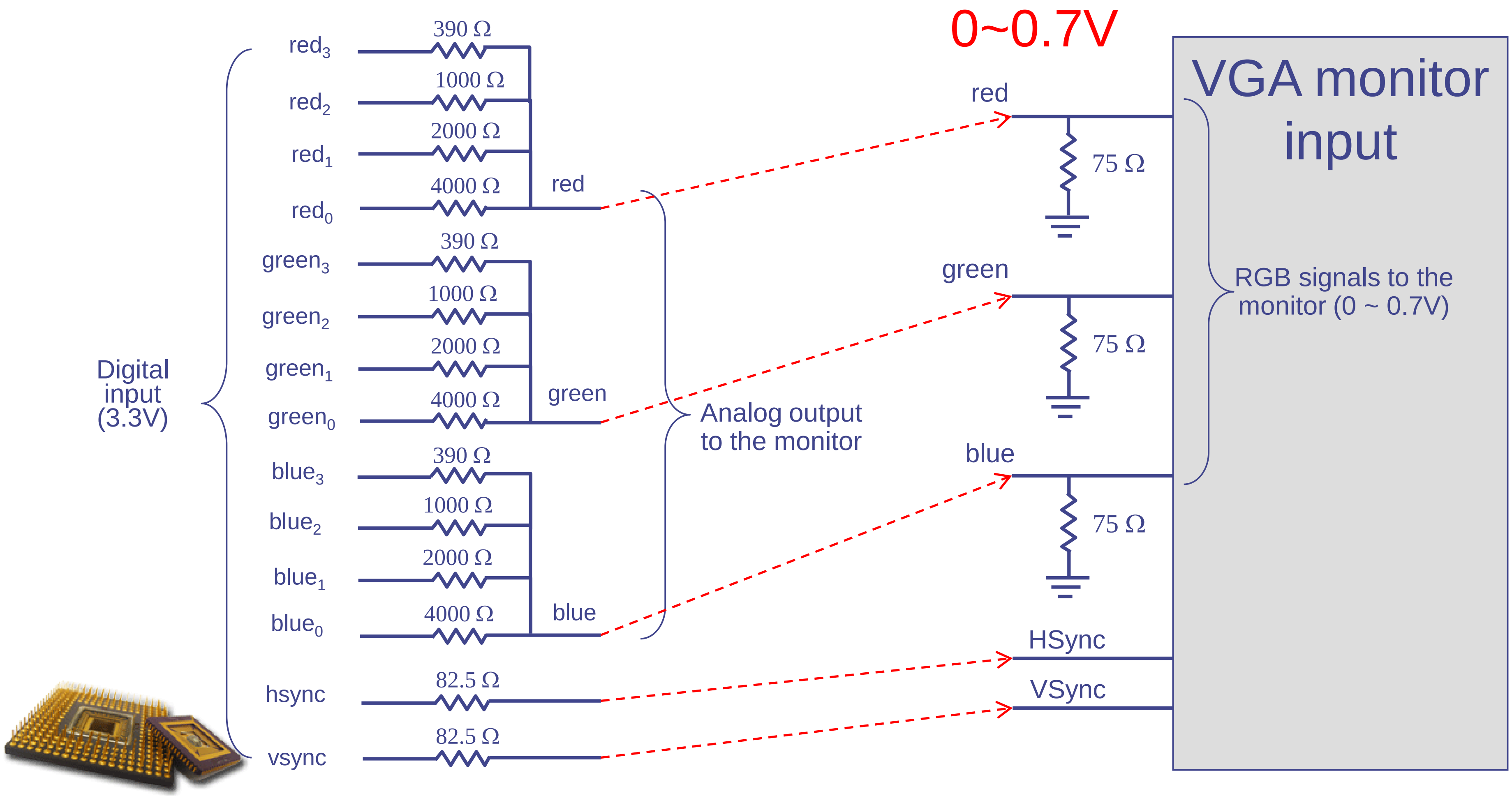
Digital-to-Analog Conversion

- VGA is an analog interface
  - 0v stands for the darkest pixel, 0.7v stands for the brightest.
  - The transition from darkest pixel to brightest pixel is not linear.
- A video digital-to-analog converter (DAC) IC is usually used to convert digital pictures to analog VGA signals.
  - The most popular DAC is the ADV 7125 IC by Analog Devices.



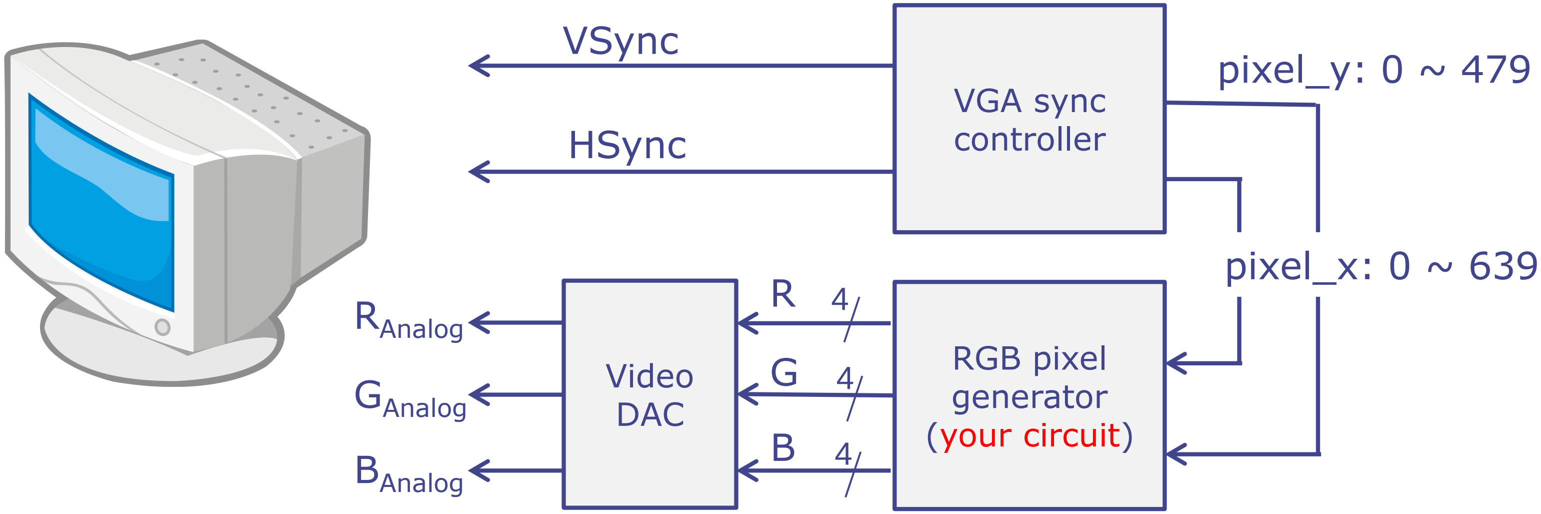
Simple VGA Interface Circuit

- A resister network is used on the I/O board of Arty to provide a 3×4-bit VGA DAC:



VGA Controller for Lab 10

- The Verilog code of a VGA synchronization controller will be provided for this lab:



VGA Sync Controller Interfaces

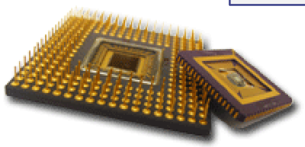
- The I/O port of the VGA controller module:

```
module vga_sync
 (
   input clk,
   input reset,
   output wire oHS,
   output wire oVS,
   output wire visible,
   output wire p_tick,
   output wire [9:0] pixel_x,
   output wire [9:0] pixel_y
 );
```

Ready to get next pixel?

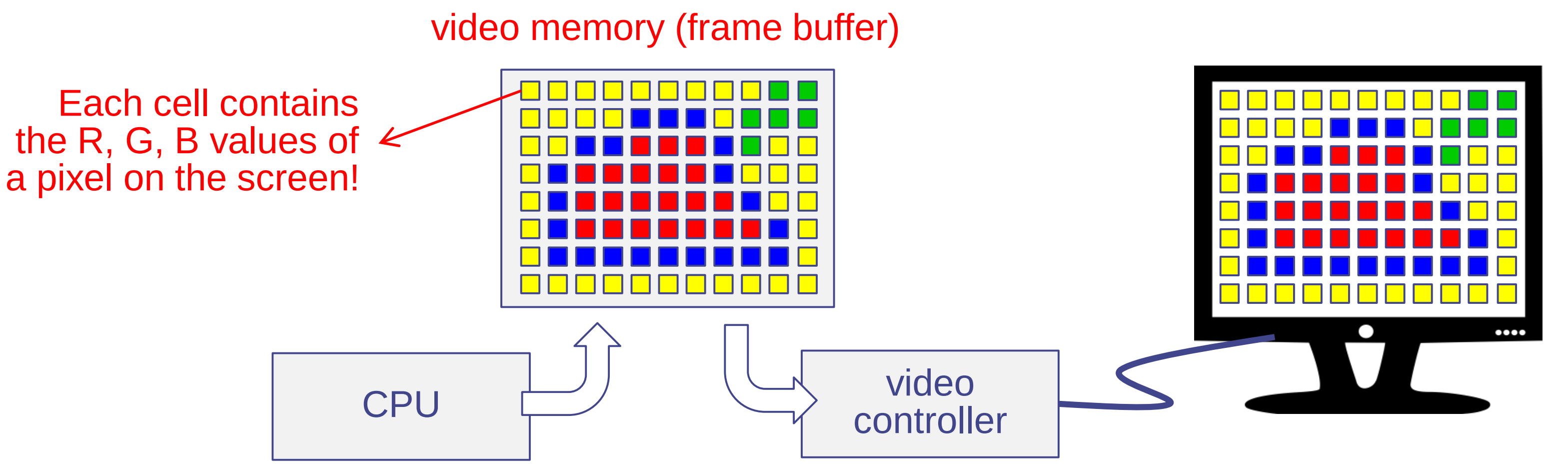
Is it active scan line period or sync period?

* When "`visible`" is false, the RGB output to the monitor MUST be all zeros!



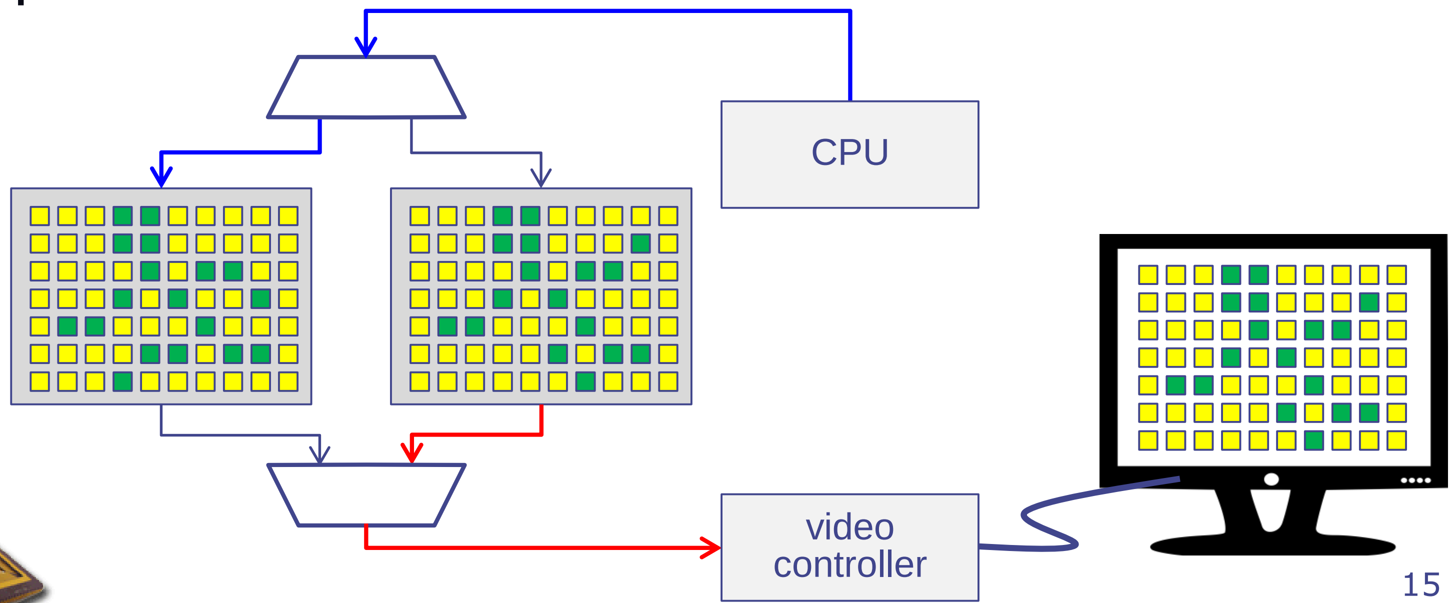
Computer Graphics and Video Buffer

- Processors are too slow to directly generate pixel data for video display.
  - Old arcade games are built using dedicated circuit to produce graphics.
- A break-through idea that enables software-based computer graphics is the concept of frame buffers (FB):



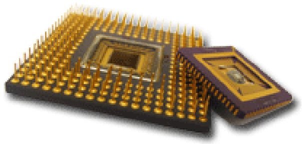
Double-Frame Buffering

- Computer systems usually use a single-port memory for video frame buffer.
  - Most memory bandwidth will be used by the video controller.
  - CPU cannot make significant update to the content of the frame buffer without interrupting the video controller.
- Double frame buffers can be used to solve this problem.



Cycle-Stealing from the Retrace Time

- Some systems do not have enough memory for double-buffering, other tricks must be used to modify the FB without interfering the video controller.
- During the horizontal or vertical retrace periods, the video controller is NOT reading the FB.
- FB data modifications during the sync periods will not corrupt video.



Good News for Lab 10

- In Lab 10, you do not have to modify the video FB.
  - The video FB is only used to store the background image.
  - All animated foreground objects are generated by your circuit on-the-fly.
- For example, the moving fish in the sea is done by:

A 320x240-pixel background image stored in the 12-bit SRAM.

Several fish images stored in the same SRAM. The green pixels are transparent pixels that shall not be displayed.

You must replace the green pixels by the background pixels.

Sending Frame Buffer Content to VGA

- The frame buffer in the SRAM can be connected to the VGA controller as follows:

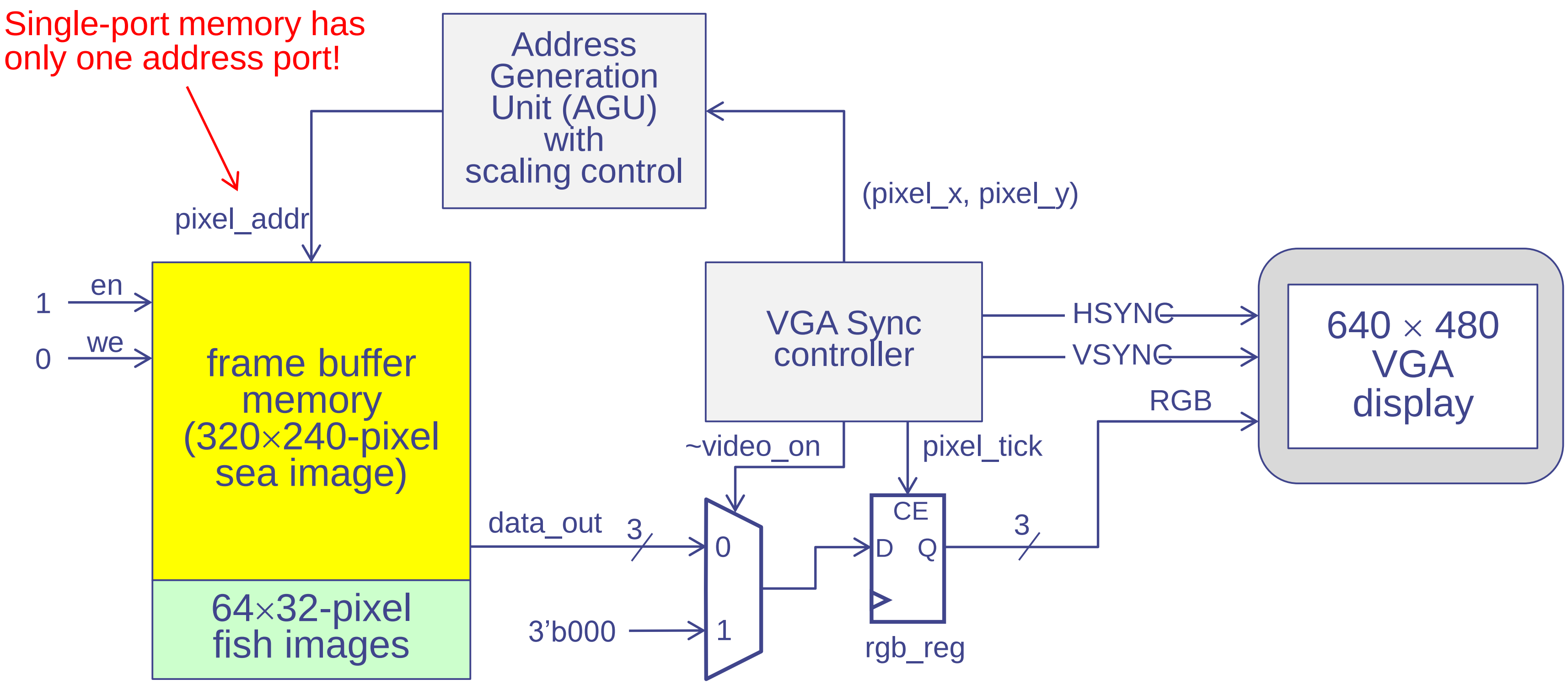
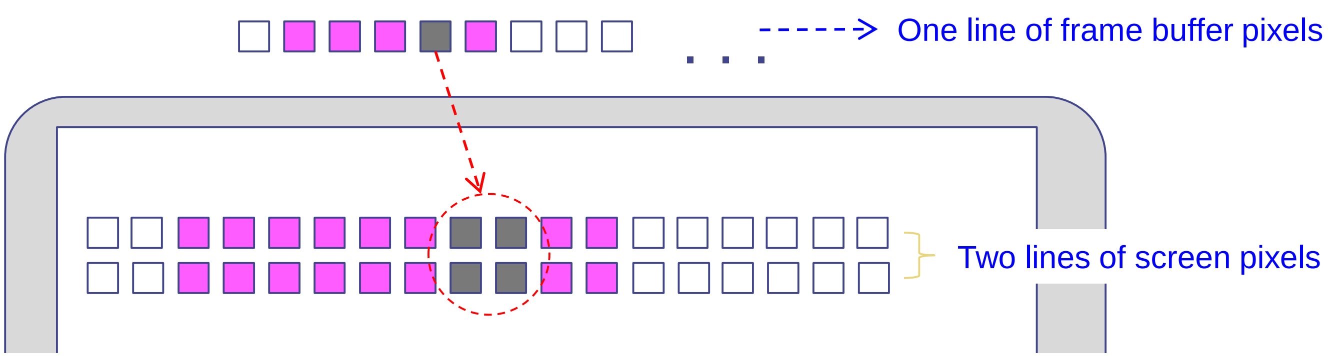


Image Scaling

- The size of our frame buffer has 320×240 pixels, but the VGA resolution is of 640×480 pixels → we must blow up the picture by 2× in each dimension.
- A simple scaling algorithm can be used:
  - Each pixel in the frame buffer is used repeatedly for four pixels on the screen.



Sample Code of the AGU with Scalar

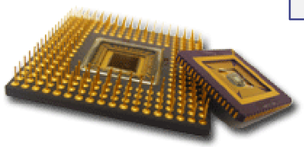
- The address generation unit and the RGB register can be coded as follows:

You can change this to a combinational block, but the critical path will be longer

```
// ---------------------- AGU ----------------------------
always @ (posedge clk) begin
  if (reset)
    pixel_addr <= 0;
  else
    // Scale up a 320x240 image for the 640x480 display.
    // (pixel_x, pixel_y) ranges from (0,0) to (639, 479)
    pixel_addr <= (pixel_y >> 1) * VBUF_W + (pixel_x >> 1);
end

// ------------------ RGB register -----------------------
always @(posedge clk) begin
  if (pixel_tick) rgb_reg <= rgb_next;
end

always @(*) begin
  if (~video_on)
    rgb_next = 3'b000; // Sync period, must set rgb to zeros
  else
    rgb_next = data_out; // RGB value at (pixel_x, pixel_y)
end
```

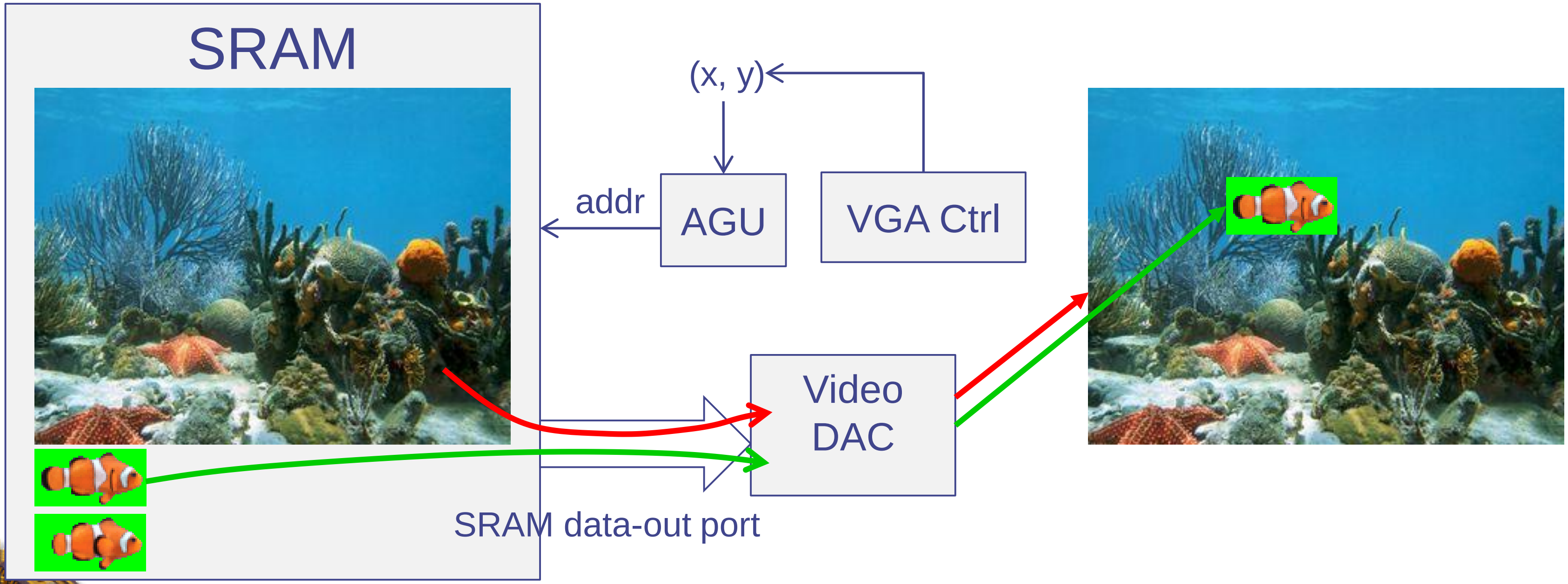


Video Frame Buffer for Lab 10

- In Lab 10, we declare a 12-bit SRAM with 320×240 + $64 \times 32 \times 2$ cells to store the sea image and the fish images.
  - The first 320×240 cells are also used as the video frame buffer.
  - Address 0 is the starting address of the sea image.
  - Address 320×240 is the starting address of the fish images.
- An address generation unit (AGU) will be used to determine whether the pixel data should be read from the sea image or the fish image.
  - Note that the fish is swimming, so the location of the fish image shall be changing all the time.

The Sample Code of Lab 10

- The way to overlay the fish images on the sea image is to read the pixel data from the fish images if (x, y) falls in the fish area; otherwise, read from the sea image.
- The sample code of Lab 10 only uses two images to animate the swimming of the fish → not very smooth!



Green Screen Technique

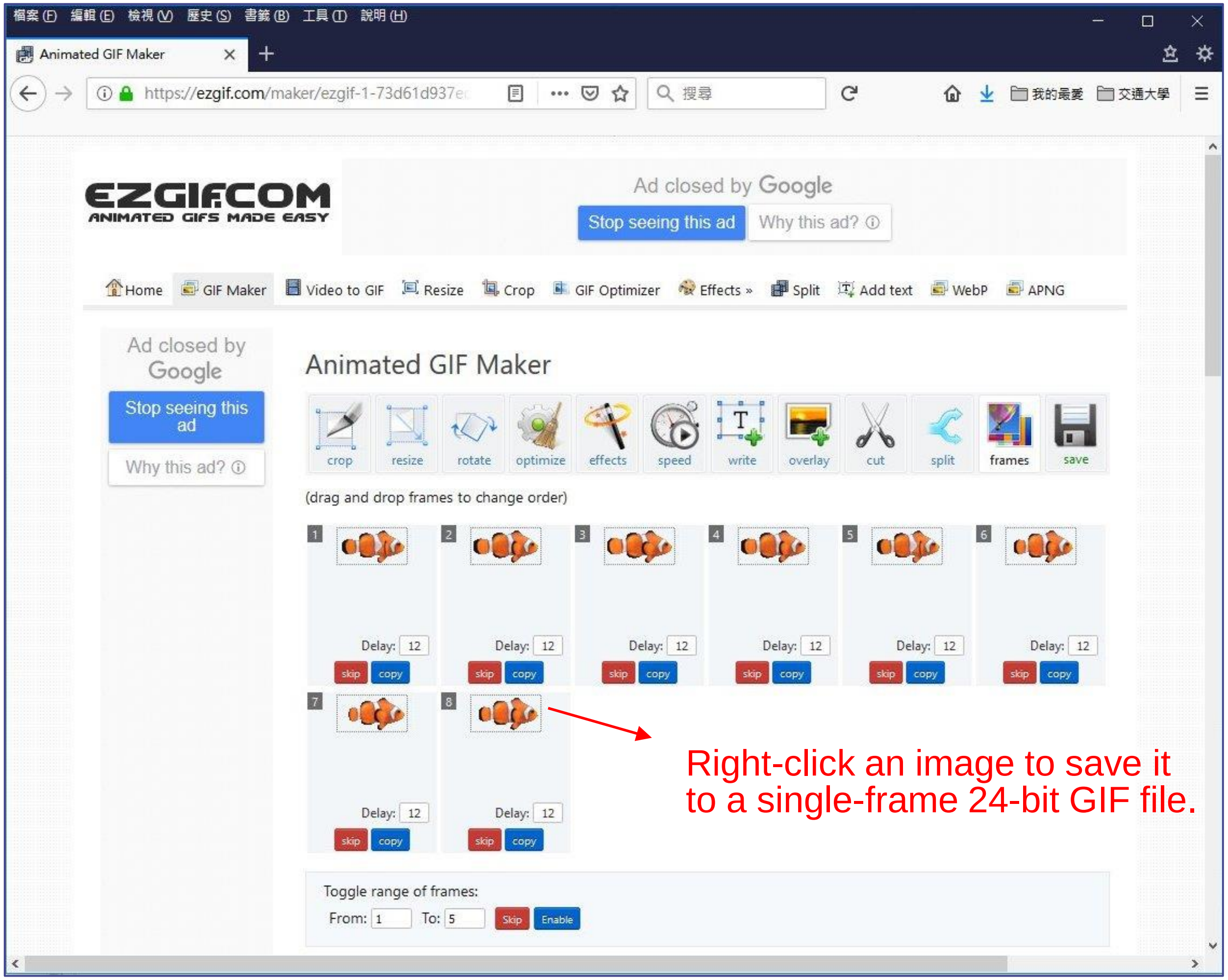
- Green screens are often used in video production to overlay foreground objects on a background shot at a different location.
  - Green pixels of the foreground images will be replaced by the background image pixels at the same coordinates.

How to Create Animation Images

- For fish animation, you must create several images of a fish swimming.
- Steps:
  - Download an animated GIF image from the Internet (or E3)
  - Use image editing tools to extract animated GIF frames, paint their background green, and save them as 24-bit PPM images.
    Two good tools for animated GIF editing:
    - Ezgif on-line GIF editor (https://ezgif.com/)
    - Xnview image viewer & converter
  - Convert the sequence of PPM files to a memory file for Verilog
    - Download and compile `ppm2mem.c` from the E3 website

Extracting Animated GIF Frames

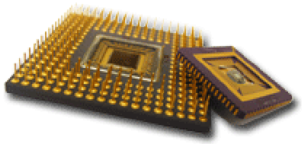
- Upload an animated GIF image to ezgif.com for editing:



Right-click an image to save it to a single-frame 24-bit GIF file.

Converting GIF to PPM Images

- Now, you should have a sequence of color GIF images of the animated swimming fish.
- Use another free image tool, e.g. Xnview, to convert each GIF image to a PPM image
  - Note that the "transparent" background pixels in the GIF image will become RGB = 0x000000 in the PPM image.
  - You should make sure that the fish image itself has no pixel value of 0x000000.



Convert *.PPM to *.MEM

- We can now convert the background image and the sequence of fish images to a Vivado 12-bit memory file using a C program `ppm2mem.c` available on E3:

  ```
  C:\> ppm2mem seabed.ppm 1.ppm 2.ppm …
  ```

  The output is a Vivado memory file, `images.mem`.

- Note that the program `ppm2mem` also changes all black pixels to green pixels, from 24-bit `RGB=0x000000` to 12-bit `RGB=0x0f0`.

What You Need to Do for Lab 10?

- Basic grade (50%):
  - Replace the green pixels around the fish by the co-located background pixels
  - Use at least eight images to draw the fish
- Advanced grade (50%): you must add more advanced fish animations in the sea

Lab 10 sample code

Green-screen blending

Pretty seabed scene

Your task for Lab 10!

What's on E3 for Lab 10?

- For Lab 10, you can find the following files on E3:
  - `lab10.zip` – the sample workspace of Lab 10
  - `ppm2mem.c` – a command-line C program that converts multiple 24-bit PPM image files to a Vivado memory file
  - `seabed.ppm` – the background image of Lab 10
  - `fish1~3.gif` – the animated GIF of three different fishes
  - `crown_fishes.gif` – the GIF shown on page 2 of this PPT

Final Comments

- You have about 98KB left in the on-chip memory of the FPGA for your animation images.
  - A 64×32 fish image takes $64 \times 32 \times 1.5 = 3072$ bytes.
- Your Verilog MEM file size must be the same as the SRAM declared in your circuit $\rightarrow$ don't forget to change the SRAM size in the circuit code!
- For advanced grade, we will check:
  - How many fishes do you have in the ocean?
  - How smooth your animated fishes move?
  - What are the trajectories of the swimming fishes?
  - Do you handle the case when multiple fishes overlap?
  - Other details of your implementation.