CS5120
Convolution Engine for Image Processing

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HW03-2

Objective

- Matrix convolution (2D convolution) is a popular computation in digital signal processing
  - Image processing
  - Signal processing
  - Deep learning (convolution neural network, CNN)
  - Etc.

- Design a simple image processing filter (also known as kernel) for edge detection
  - For gray-scale 256x256 images
  - Refer to Wikipedia for more description: https://en.wikipedia.org/wiki/Kernel_(image_processing)

What is Convolution?

- 2D convolution
- Inner product
- Also called *filter* (or kernel) in the image processing

filter

1	2	3
4	5	6
7	8	9

Image

a	b	c
d	e	f
g	h	i

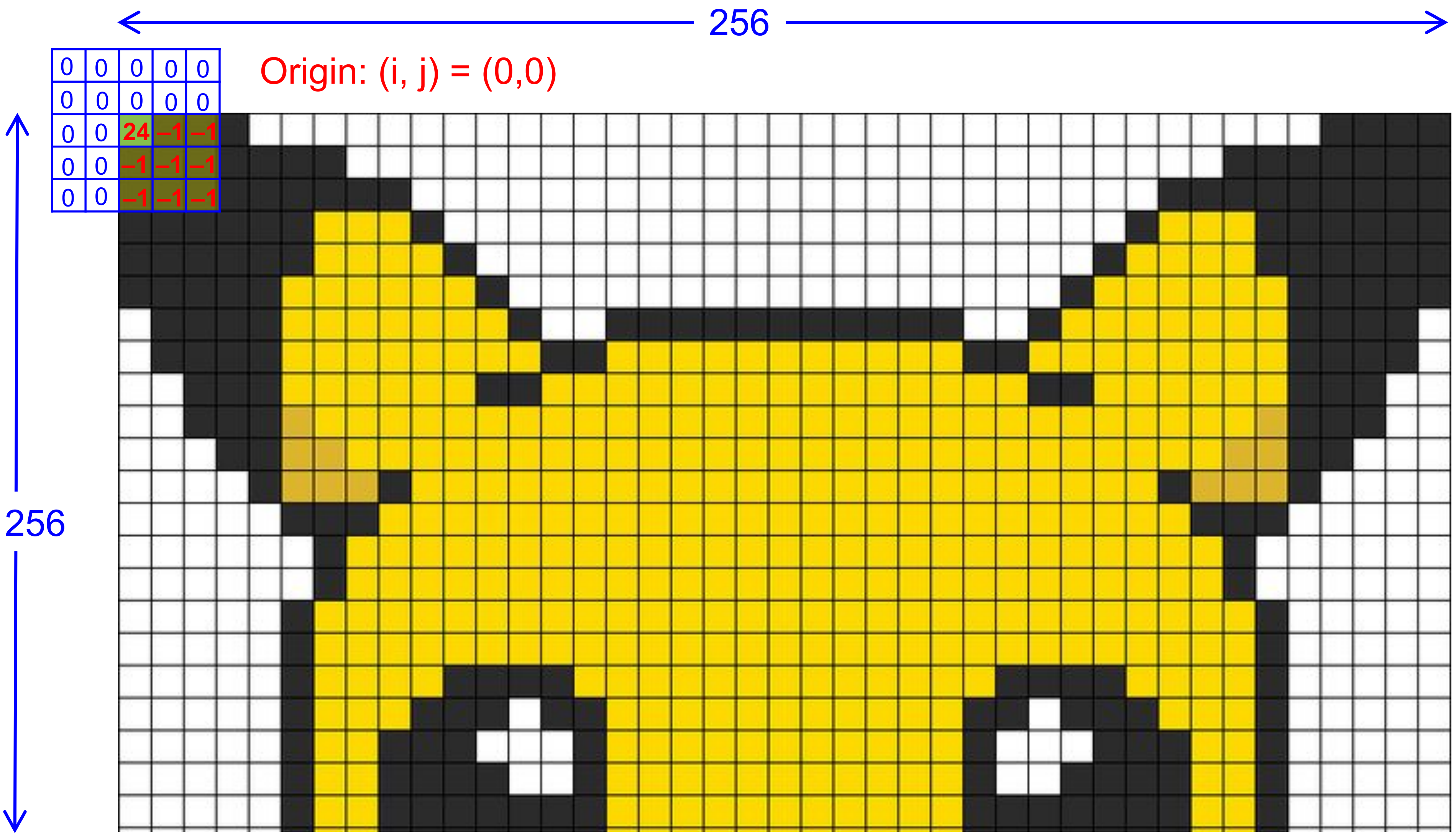
$$y = 1 * a + 2 * b + 3 * c + 4 * d + 5 * e + 6 * f + 7 * g + 8 * h + 9 * i$$

Convolution Filter (Kernel) of Edge Detection

- Emphasize the edges of the image
- 5x5 convolution filter (kernel)

-1	-1	-1	-1	-1
-1	-1	-1	-1	-1
-1	-1	24	-1	-1
-1	-1	-1	-1	-1
-1	-1	-1	-1	-1

Apply to The Entire Image

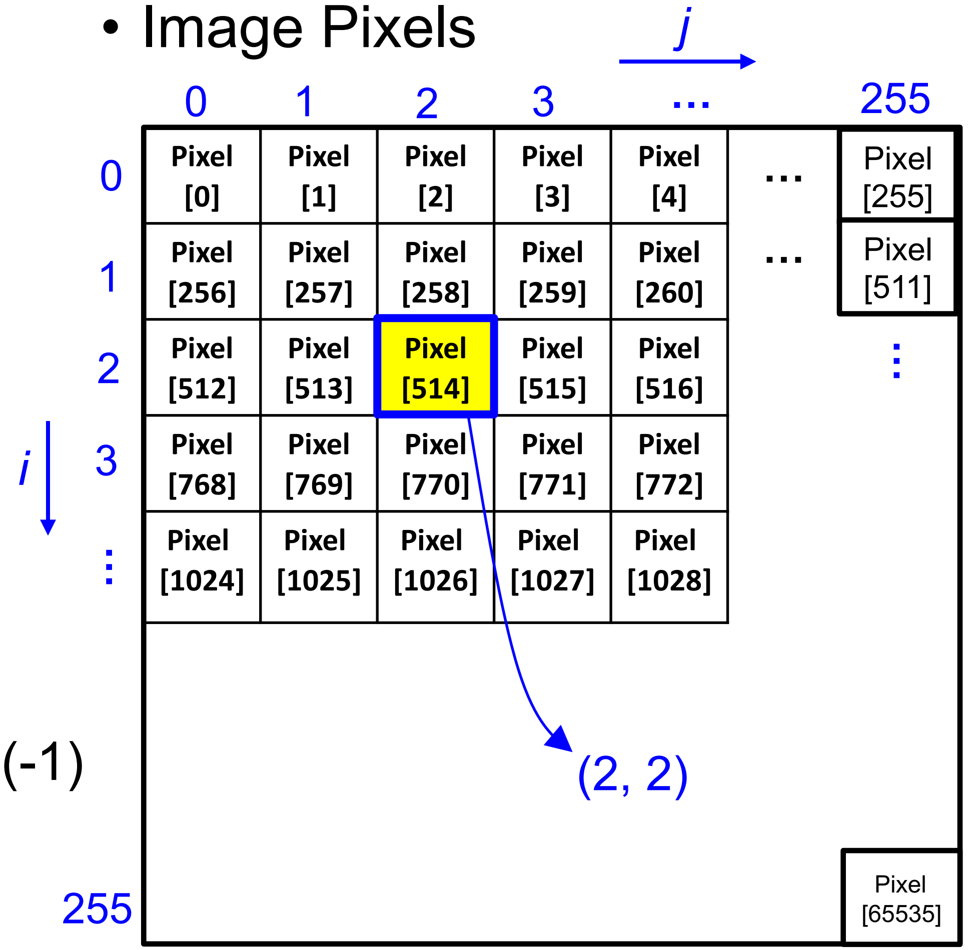


Ex: To Compute The 514th Pixel

- Filter Coefficients

-1	-1	-1	-1	-1
-1	-1	-1	-1	-1
-1	-1	24	-1	-1
-1	-1	-1	-1	-1
-1	-1	-1	-1	-1

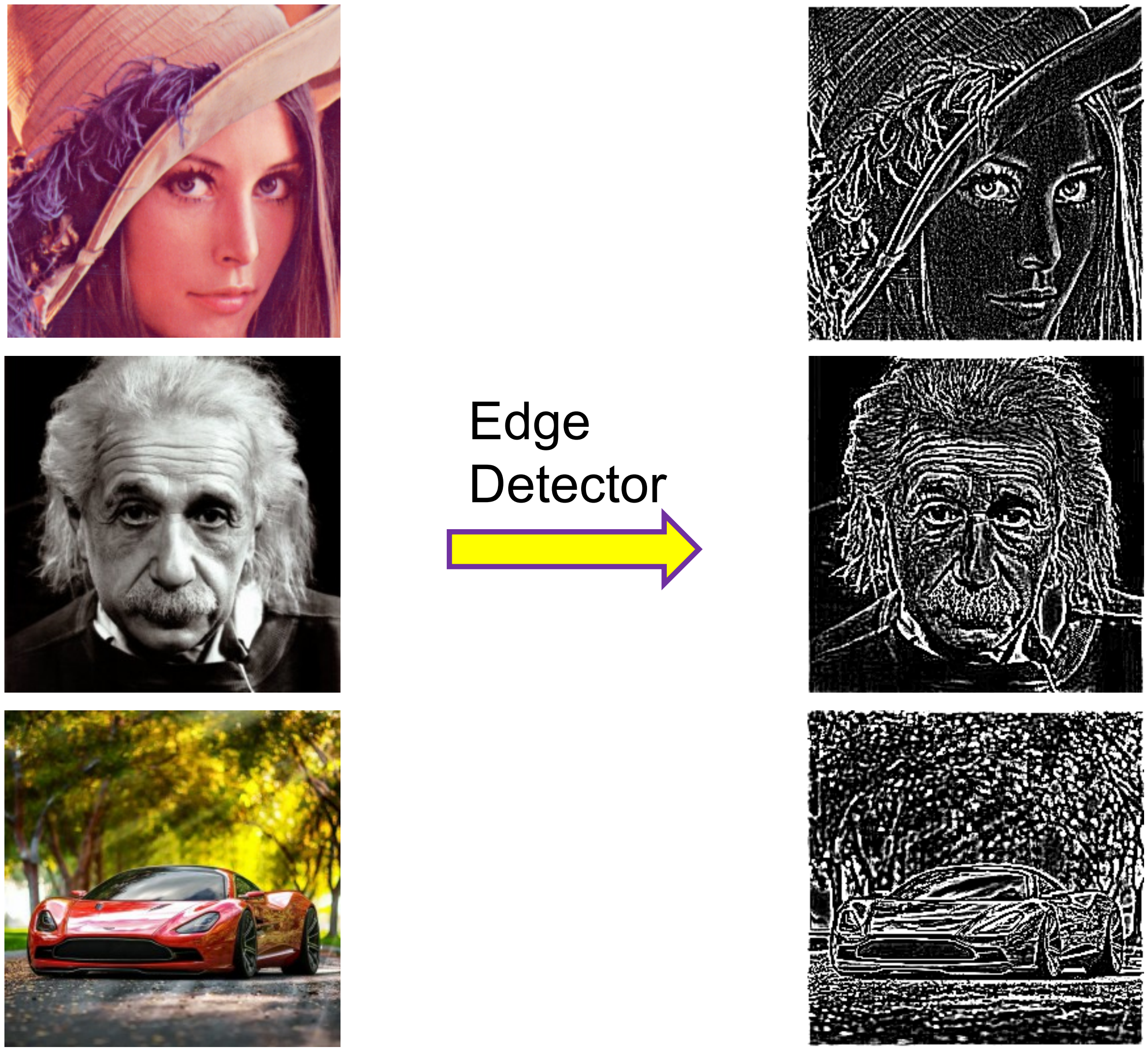
- Image Pixels



(addr = i * 256 + j)

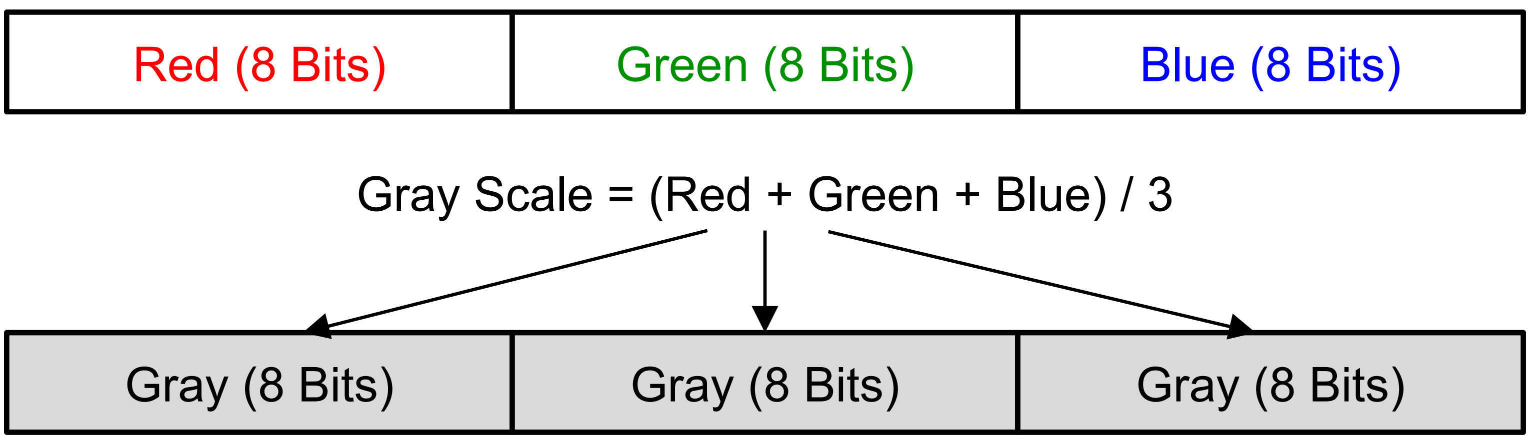
- result =
  Pixel[0]*(-1) + …… + Pixel[4]*(-1)
  + Pixel[256]*(-1) + …… + Pixel[260]*(-1)
  + Pixel[512]*(-1) + Pixel[513]*(-1)
  + Pixel[514]*(24)
  + Pixel[515]*(-1) + Pixel[516]*(-1)
  + Pixel[768]*(-1) + …… + Pixel[772]*(-1)
  + Pixel[1024]*(-1) + …… + Pixel[1028]*(-1)
- If result > 255, result = 255
- If result < 0, result = 0

Image Examples with Edge Detection



Input Image Format

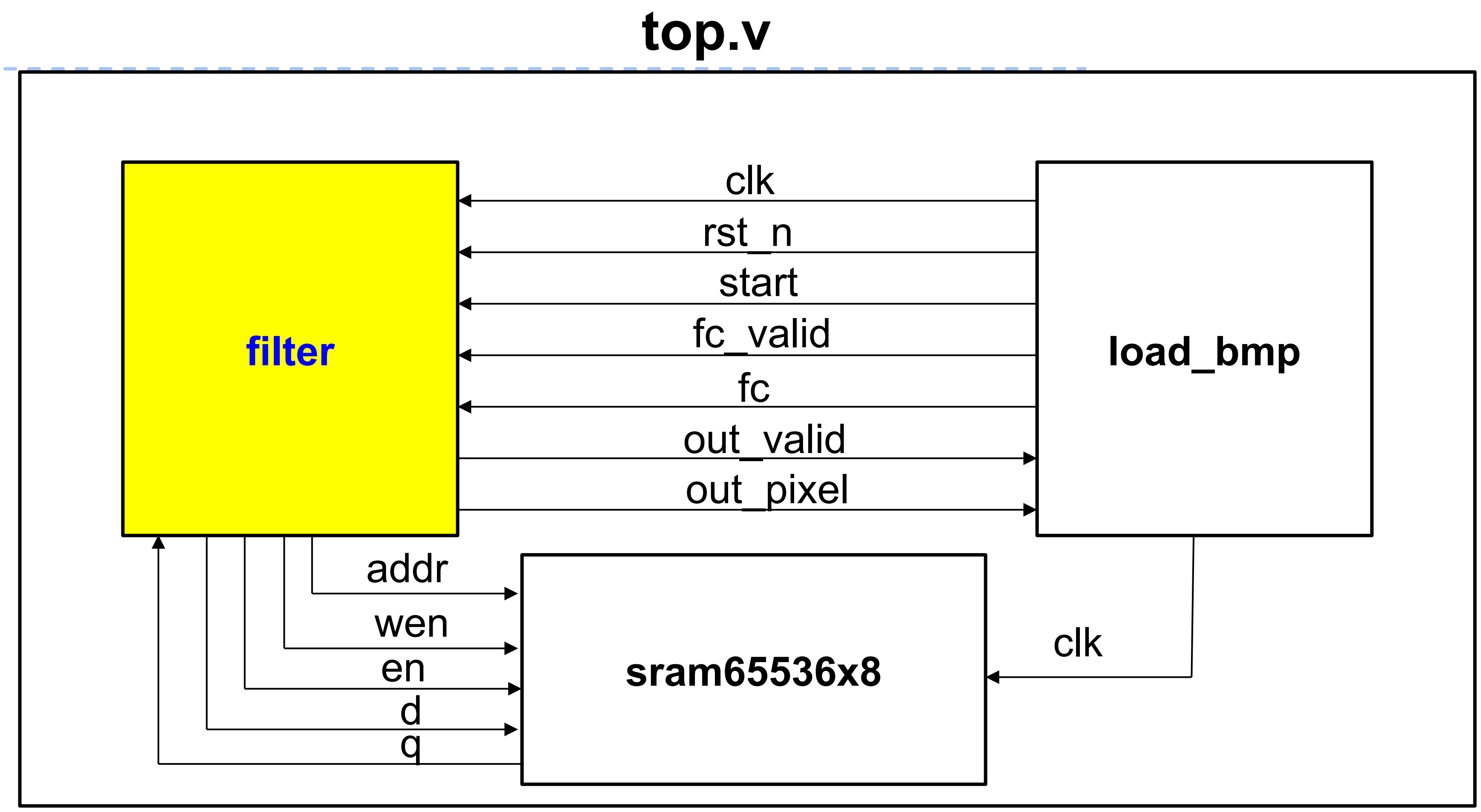
- In a color image, each pixel can be represented as a 24-bit data
  - Three 8-bit unsigned integers (ranging from 0 to 255)
  - RGB encoding



Testbench (load_bmp.v)

- Our testbench will load a color BMP image file, and convert to its gray-scale representation for you
- In addition, the testbench will load the gray-scale pixels into an SRAM block
  - The pixels will be stored in a linear order (row by row)
  - From address 0 to address 65535
  - Signal: start
- Then, it will output the filter coefficients to the filter
  - Signals: fc_valid and fc
- It will accept the processed (65,536) pixels one by one in order, and convert them into the output image
  - Signals: out_valid and out_pixel
- Source code is the best document

Overall Architecture

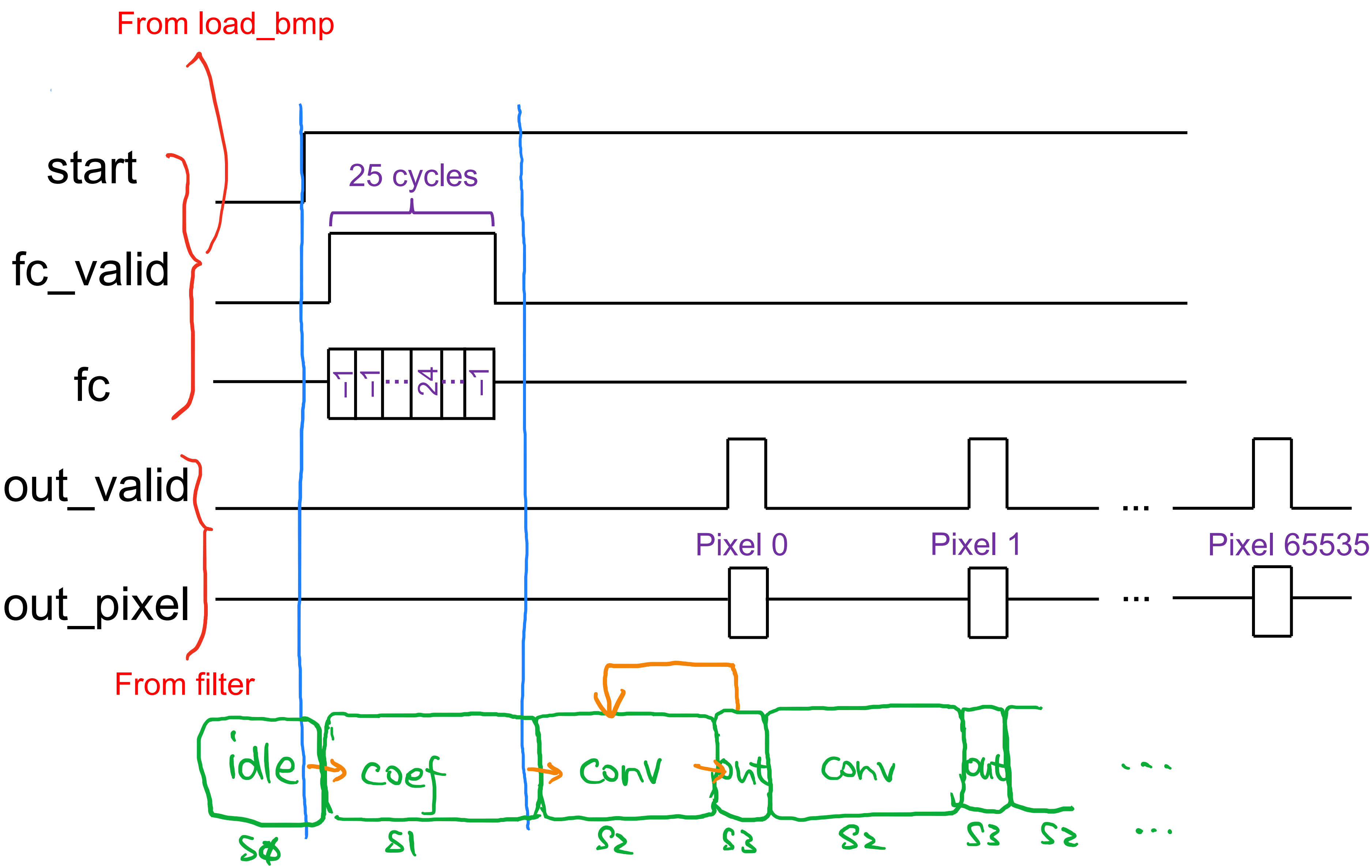


Note:
wen can be constant 1; **d** can be constant 0, if we don't write into SRAM at all!

IO Signals

Signal	Explanation
start	When load_bmp.v finishes loading all the pixel value into SRAM, start = 1. Otherwise, start = 0
fc_valid	When load_bmp.v is feeding filter coefficients to filter.v, fc_valid = 1. Otherwise, fc_valid = 0
fc	Filter coefficients (passed from load_bmp.v to filter.v)
out_valid	When the out_pixel is ready, out_valid = 1. Otherwise, out_valid = 0
out_pixel	The pixel value which will be written to output file.
addr	The memory address to read or write
wen	Write enable signal for SRAM (low active)
en	Enable signal of SRAM for both read/write (high active)
d	Data written to SRAM
q	Data read from SRAM

Timing


From load_bmp
start
fc_valid
fc
out_valid
out_pixel
From filter
25 cycles
-1
-1
...
24
...
-1
Pixel 0
Pixel 1
...
Pixel 65535
idle
coef
conv
out
conv
out
...
S0
S1
S2
S3
S2
S3
S2
...

Design Files

- **Makefile**
  - Running the simulation easier by typing `make`
  - Also `make clean` for your reference (use it carefully!)
- **top.v**
  - Top module which connects load_bmp.v, sram.v, and filter.v
- **load_bmp.v**
  - Testbench
  - Parsing the input BMP image
  - Feeding the filter coefficients to filter.v
  - Writing out the output BMP image
- **hw03a.v or hw03b.v or hw03c.v**
  - The design you are going to implement
- **sram.v**
  - 65536x8 SRAM model
  - Loading the gray-scale pixels into SRAM initially
    - The 2D image is stored in a linear (1D) order
    - Ex: to address the pixel (i, j), you can access the address (i * 256 + j)

Data Files

- **Input image**
  - lena_256x256.bmp
  - einstein_256x256.bmp
  - car_256x256.bmp
- **Golden files (for the output validation)**
  - lena_golden.txt
  - einstein_golden.txt
  - car_golden.txt
- **Gray scale log**
  - img_gray_dec.txt: gray-scale input pixels (decimal)
  - img_gray_hex.txt: gray-scale input pixels (hex)
- **Your output log**
  - out_log.txt (containing all the computed pixel values)
  - Can be compared with golden files for output validation

    ```
    $ diff out_log.txt lena_golden.txt
    ```

Makefile

```
DEBUG = 3
SRC = top.v load_bmp.v sram.v hw03a.v
BAK = *.bak
LOG = *.log *.key *.fsdb img_gray*.txt out_log.txt *_output.bmp
INCA_libs = INCA_libs
all:
	ncverilog +debug=${DEBUG} ${SRC} +access+r
clean:
	-rm -f ${BAK} ${LOG}
	-rm -rf ${INCA_libs}
```

- A different way from shell script (*.sh) to help the simulation
- Type make to run the simulation
  $ make
  $ make clean
- You may refer to online resources
  - E.g., 鳥哥的Linux私房菜
    http://linux.vbird.org/linux_basic/1010index.php

Discussion

- How many cycles do you need to process the entire image?
- Any chance to improve the performance further?
  - E.g., reducing the number of memory accesses…
- Is it possible to utilize pipeline technique to improve the performance?
- You may also create a second SRAM to store the gray-scale output image if it helps

Hint: Signed Numbers

- Using signed integers may help

9 bits

```
reg signed [8:0] value;
…
   value = $signed({1'b0, gray_scale});
```

8-bit unsigned int!

- Make sure you have enough data width to store the inner product

Hint: Possible Concept of Counters

- Filter Coefficients

(y,x)=(i-2,j-2)

two counters for 2D image

- Image Pixels

(y,x)=(i+0, j+0)

0~255 0~255

(-2,-2)

	-2	-1	0	1	2
-2	-1	-1	-1	-1	-1
-1	-1	-1	-1	-1	-1
0	-1	-1	24	-1	-1
1	-1	-1	-1	-1	-1
2	-1	-1	-1	-1	-1

(0,0)

→ j

i	0	1	2	3	4	. . . 255
0	Pixel [0]	Pixel [1]	Pixel [2]	Pixel [3]	Pixel [4]	
1	Pixel [256]	Pixel [257]	Pixel [258]	Pixel [259]	Pixel [260]	
2	Pixel [512]	Pixel [513]	Pixel [514]	Pixel [515]	Pixel [516]	
3	Pixel [768]	Pixel [769]	Pixel [770]	Pixel [771]	Pixel [772]	
4	Pixel [1024]	Pixel [1025]	Pixel [1026]	Pixel [1027]	Pixel [1028]	
⋮ 255						

(+2,-2)

(i+2, j-2)

(y,x)=(i+2,j+2)

(+2,+2)

two counters for 2D filter

(m,n)

-2~2 -2~2

(i+m, j+n)

convert (y,x) to memory address

addr = y*256+x

Hint: Some More Suggestions

- You may compute the first few output pixels for the verification before applying for the entire image
- Once again, a detailed planning before Verilog coding is always a good design strategy

And most importantly, enjoy the design!!