ECE 464/564 Projects : Fall 2017

Students work on these projects individually. Reminder: Collaboration is encouraged but the sharing of Verilog code is strictly forbidden. Also, group creation of one set of common code is forbidden. We will be running code comparison tools to look for even partial sharing of code.

### **Changes from previous versions:**

- More detail on memory interface for 464/EOL project
- Memory map modified for 564 project

# General information for both projects

A top level module will be provided that instantiates:

- 1. Vector memory.
- 2. Input data memory
- 3. Output memory

A testbench will be provided that instantiates the top level module and:

- 4. Provides a one-cycle wide go signal to start your design.
- 5. Waits for your design to send the finish flag high.
- 6. Counts the number of clock cycles it took to finish.
- 7. It will check your output for correctness

Note, after completing one full calculation, your design should be ready for the go flag to go high again and start another calculation.

Your design is implemented in a separate file MyDesign.v. Please make sure to synthesize only MyDesign.v and NOT the test fixture, nor the SRAM.

#### **ECE 464 and EOL Project**

Your project is to design and implement hardware that conducts the convolution of two vectors. Reminder. The vectors will be 16 digits long, and will consist of 8-bit integers stored in a two's complement format. The result is a 16-bit number. The multipliers are to produce 16 bit outputs. A reminder that a convolution involves multiplying the two vectors A and B to produce a single number C as follows.

$$C = \sum_{i=0}^{i=15} A[i].B[i]$$

Additional specifications:

- The vectors A and B will be stored in two separate SRAMs, each with their own interface to your design.
- C will be produced as an output of your design.

- You are to detect overflow and send an overflow high if overflow is detected. Note this is a signed overflow. You can't just use carry\_out. Overflow is to stay high until go is asserted again.
- You can use Synopsys DesignWare or design your own arithmetic units.
- A test fixture and SRAMs are given to you.
- Please register both the address and data registers to the SRAM. You read the data one clock cycle after the address changes.

# ECE 564-601 Project Convolutional Neural Network

Your project is to design and implement hardware that performs two stages of operations on an input array and generate an output vector.

This is a simplified version of a Convolutional Neural Network, a common algorithm used in machine learning. We will be implementing two layers, the first layer is a feature extraction from an input and the second layer is a fully connected layer to identify classes.

This example is completely contrived and the task is to perform operations on provided data so do not get concerned about the meaning of any values generated.

We are essentially performing a number of dot-products of two vectors. These vectors are extracted from the inputs and from provided vectors.

Remember, the dot-product of two vectors [x] and [y] is:

$$x = [x_0, x_1...x_{n-1}]$$
$$y = [y_0, y_1...y_{n-1}]$$
$$z = \sum_{n=0}^{n-1} x_i \cdot y_i$$

The project input is a 12x12 array of 16-bit twos-complement numbers. The final output will be an 8x1 vector of 16-bit twos-complement numbers stored in memory. Storage details will be described later. The entire operation will be performed with two steps.

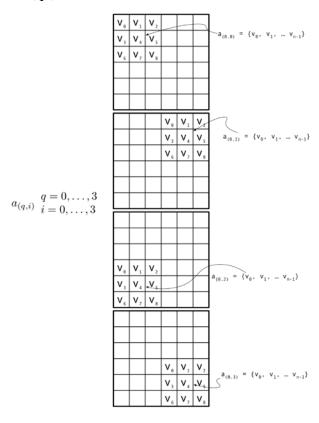
## Step One

The first step is to first perform dot-products on regions of the inputs using four separate stepone vectors. We will refer to these as the [b]<sub>0..3</sub> vectors and they will be supplied in the "Filter Vector memory" as shown in the block diagram and memory map. Each of these [b] vectors are 9x1.

You will consider the 12x12 input as four 6x6 quadrants and operate on each of these quadrants in an identical manner.

Quadrant	Quadrant
0	1
Quadrant	Quadrant
2	3

From each quadrant, you will form four 1x9 vectors, as shown in the figure below. We will refer to these vectors as [a(q,i)].



You will then perform a dot-product of each of these  $[a_{(q,i)}]$  vectors against each of the four supplied step one  $[b]_{0..3}$  vectors.

$$b = [b_0, b_1...b_8]$$

$$a = [a_0, a_1...a_8]$$

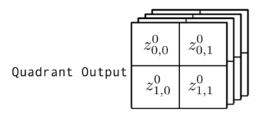
$$c = \sum_{n=0}^{8} a_i \cdot b_i$$

This will create four int32's c values which we will form into consider to be a 2x2 array. For each [c], perform the following min function and truncate the result z to 16-bits.

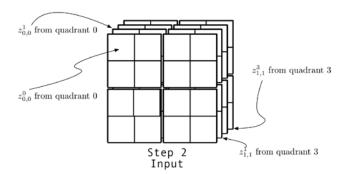
$$z_{i,j}^{b} = f(c_{i,j}^{b}) = \begin{cases} c_{i} & , c_{i} \ge 0 \\ 0 & , otherwise \end{cases} \text{ where } b = 0 \dots 3, i = 0, 1, j = 0, 1$$

Each quadrant will require 16 dot products.

This operation on each quadrant will form a 2x2x4 output array.



We will now take combine the four 2x2 quadrant outputs and form a 4x4x4 array as shown in the figure below which will be the input to step two.



#### Step Two

In step two, we again will be to perform dot products on this step one output but we will use eight supplied [m] vectors. These [m] vectors are supplied in the "Filter Vector memory" as shown in the block diagram and memory map.

These eight [m] vectors have 64 elements and you will perform a dot product of each [m<sub>i</sub>], i=0..7 vector(s) against a 64-element vector formed from the 4x4x4 output of step one. To reshape the 4x4x4 output of step 1 to create a 1x64 [u] vector, you will extract the elements in row-major fashion starting at the first layer.

Again each dot-product will be followed by the function f(x) as shown below.

$$m_{i} = [m_{i,0}, m_{i,1}...m_{i,63}]$$

$$u = [u_{0}, u_{1}...u_{6}3]$$

$$w_{i} = \sum_{n=0}^{63} m_{i} \cdot u, i = 0, ..., 7$$

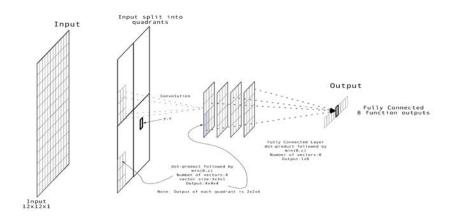
$$O_{i} = f(w_{i}) = \begin{cases} w_{i} & , w_{i} \geq 0 \\ 0 & , otherwise \end{cases}$$
 where  $i = 0 ... 7$ 

This will result in eight outputs, O and this will be the output of our system.

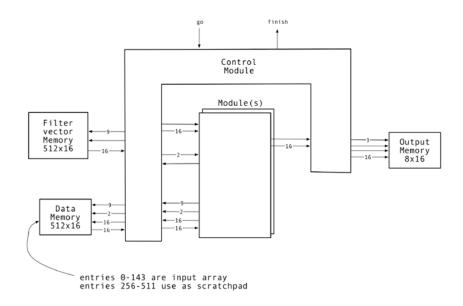
You will be provided with matlab code that demonstrates all the steps. That code is attached to the end of this document.

# Summary

Below is an overall flow diagram of our system. If you do a search for neural networks, you will see similar images but likely much more complicated with many more layers.



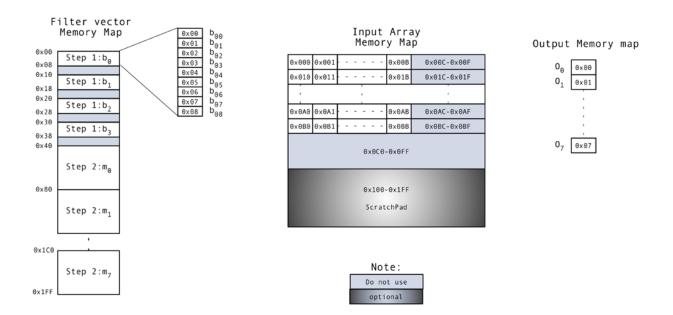
Below is a block diagram.



You are required to use a common module for the step-one quadrant operations.

You can implement step-two as you wish.

# Here are the storage memory maps



# Additional specifications:

- You can use Synopsys DesignWare or design your own arithmetic units.
- A test fixture and SRAMs will be provided.
- If you choose to store some of your temporary data in local memory, use the scratchpad area on the Input memory

Note: Again, when multiplying int16s you can truncate the resulting int32 to int16

# Compile and Simulation

```
vlog -sv ece564_project_tb_top.v
vsim -c -do "run 2us; quit" tb_top
```

You can display the expected intermediate and output results by adding defines to vlog vlog -sv +define+TB\_DISPLAY\_INTERMEDIATE+TB\_DISPLAY\_EXPECTED tb\_top.v

#### Example Matlab Code

```
clear all
% IA is the Input Array, 12x12 of int16's
1 = AT
 12579
                                           -2942
                                                   11576
                                                          -10913
                                                                    -17007
                                                                              5883
                                                                                    -16281
 17282
         -2288
                  13897
                         -15256
                                   14622
                                           -8114
                                                     4530
                                                              354
                                                                    10408
                                                                             -2975
                                                                                      -9824
                                                                                              -4870
                                                             7785
                                          -13830
                                                   -19651
-15713
         -1399
                   5228
                          -7920
                                   16784
                                                                    -11515
                                                                             -14584
                                                                                      9978
                                                                                              -18716
  7204
         10017
                   2416
                           6906
                                   11613
                                            5368
                                                   -14010
                                                             1150
                                                                    -14404
                                                                            -11842
                                                                                       -988
                                                                                              -3131
 -1294
        -16093
                  14075
                            674
                                   17598
                                          -10939
                                                    12993
                                                           -10468
                                                                      2774
                                                                             14857
                                                                                     -10516
                                                                                               8477
        -16696
                   7316
                          -8374
                                   17078
                                                                     16833
                                                                                     -17074
  1046
                                            2488
                                                    -6603
                                                             -3255
                                                                              -5312
                                                                                              -14117
 -7497
         10285
                  15998
                          17310
                                   -6240
                                          -10261
                                                    11635
                                                            -8166
                                                                     -1298
                                                                             -9664
                                                                                      19437
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                                                                             -14690
                   3043
                                    -8204
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  1803
          -7383
                          11441
                                          -15498
                                                             6197
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  4652
         15106
                   9792
                           6845
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-12763
                  -2607
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                           4153
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                                                     -539
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% B contains the 1x9 step 1 filters
B = [
-13435
         18765
                  -5643 -17177
                                   -6822
                                          -10447
                                                     9571
                                                            14312
                                                                     -1344
                                                    12477
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% M contains the 1x64 step 2 filters
M = [
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6163
       -7099
               -5274 -12097
                                                          16502
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                                  6492
                                          7659
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                                                                            11542
                                                                                   -18679
% Extract the four 6x6 regions of the input array, we will calls these Quadrants
Quadrant0 = IA(1:6,1:6)
Ouadrant = Ouadrant0
Quadrant(:,:,2) = IA(1:6,7:12)
Quadrant(:,:,3) = IA(7:12,1:6)
Quadrant(:,:,4) = IA(7:12,7:12)
% Perform a dot-product of the b-vector with each corner of the ROI
C = zeros(2,2);
for layer = 1:4
    for QuadrantN = 1:4
               = [Ouadrant(1,1:3,OuadrantN) Ouadrant(2,1:3,OuadrantN) Ouadrant(3,1:3,OuadrantN)];
        A_1_2
               = [Quadrant(1,4:6,QuadrantN) Quadrant(2,4:6,QuadrantN)];
        A_2_1 = [Quadrant(4,1:3,QuadrantN) Quadrant(5,1:3,QuadrantN) Quadrant(6,1:3,QuadrantN)];
A_2_2 = [Quadrant(4,4:6,QuadrantN) Quadrant(5,4:6,QuadrantN) Quadrant(6,4:6,QuadrantN)];
        C(1,1) = A_1_1*B(layer,:)';
        C(1,2) = A_1_2*B(layer,:)'
        C(2,1) = A_2_1*B(layer,:)';
        C(2,2) = A_2_2*B(layer,:)';
        % apply f(x) and truncate
        Z = \max(0,C)/(2^16)
        Zq(:,:,layer,QuadrantN) = Z;
    end
end
```