Development of C programs for Convolutional Neural Network Accelerators

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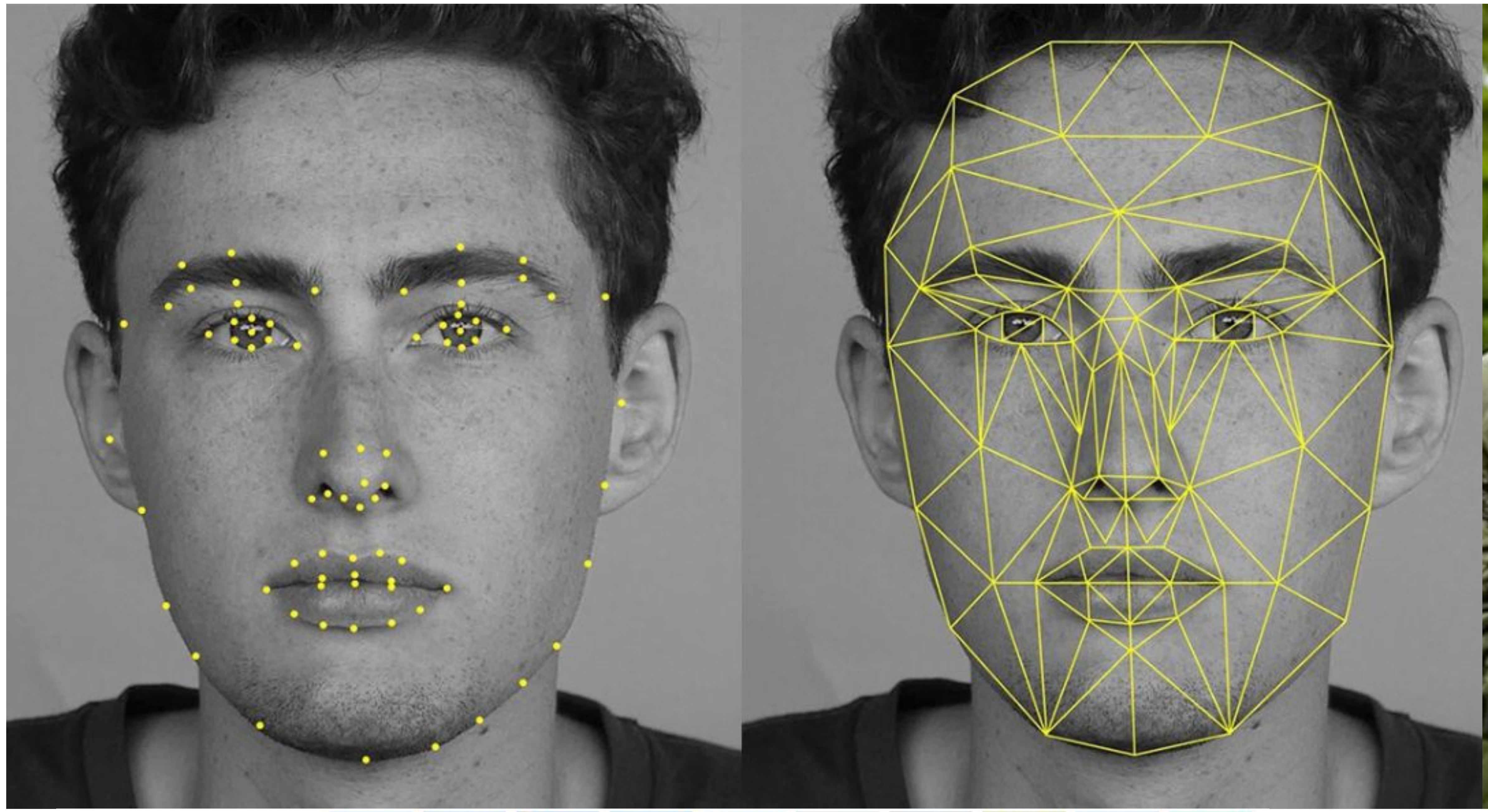
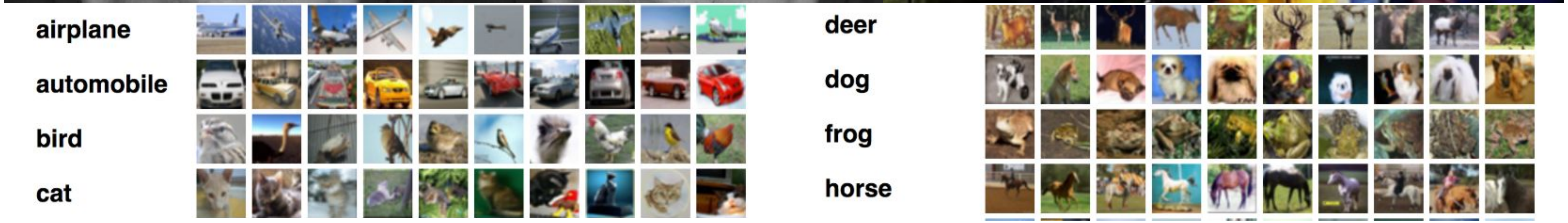
BACKGROUND

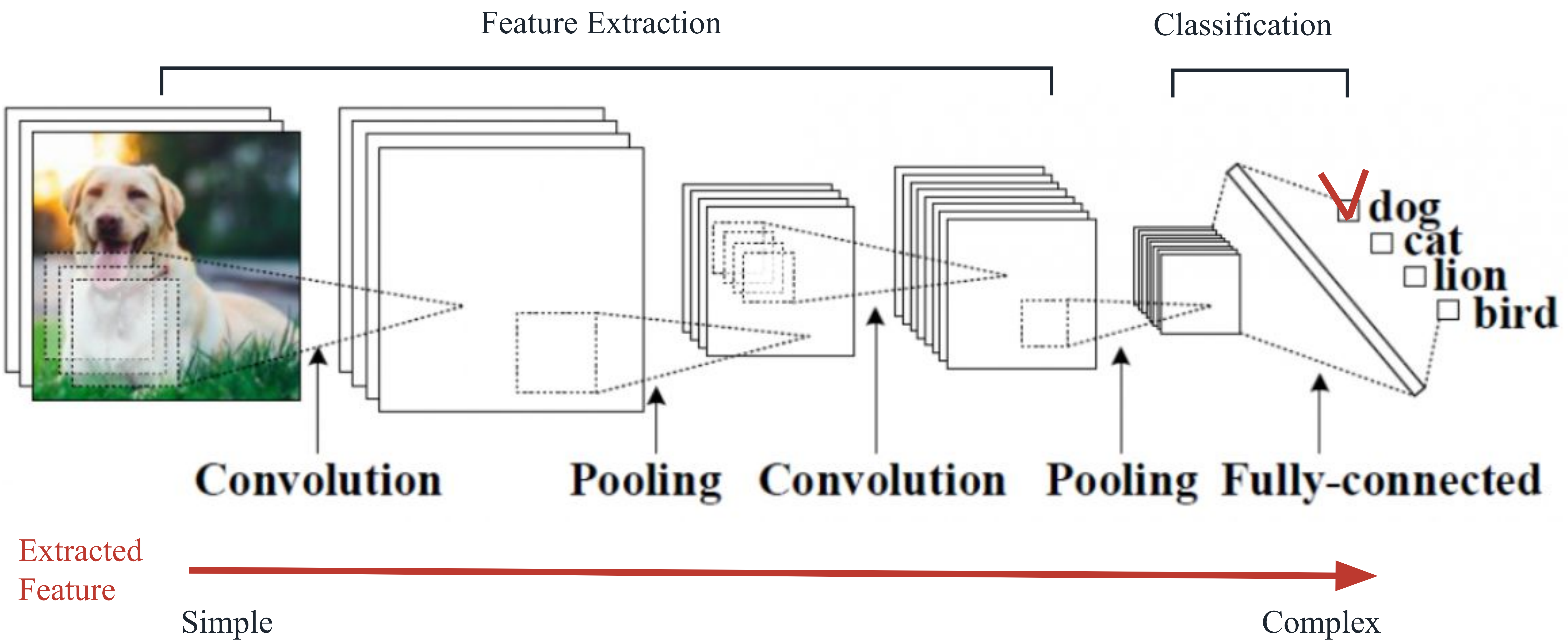
Convolution Neural Network

Keyword : Massive data , Image recognition and classification





1. Convolutional Neural Networks



Feature Extraction

Classification

Extracted Feature

Simple

Complex

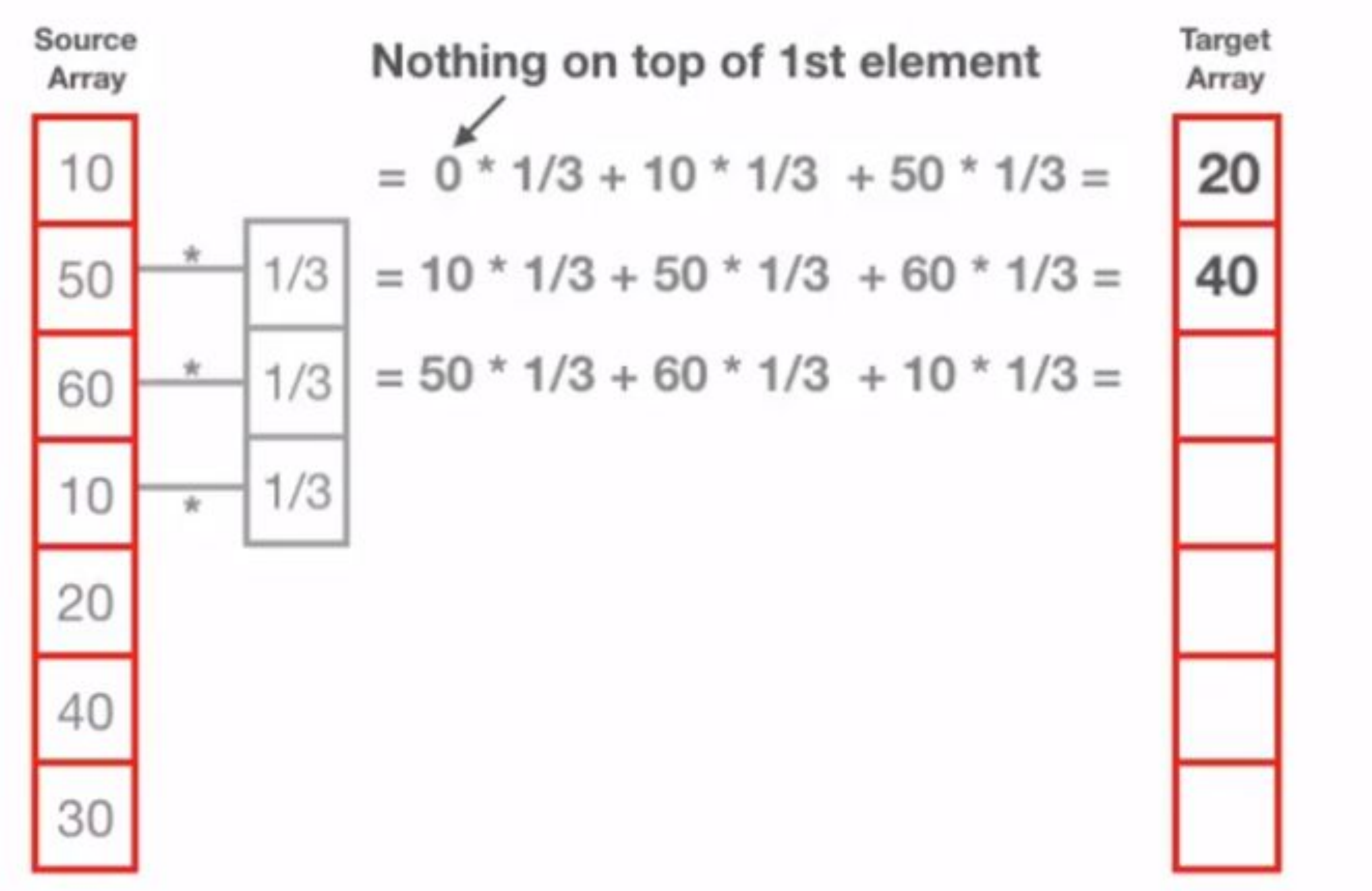
Keep spatial Information of Image

Automatically extract and learn its features

https://www.inflearn.com/course-status-2/

2. Convolution layer

Output = Source * Filter (* Convolution)



Nothing on top of 1st element

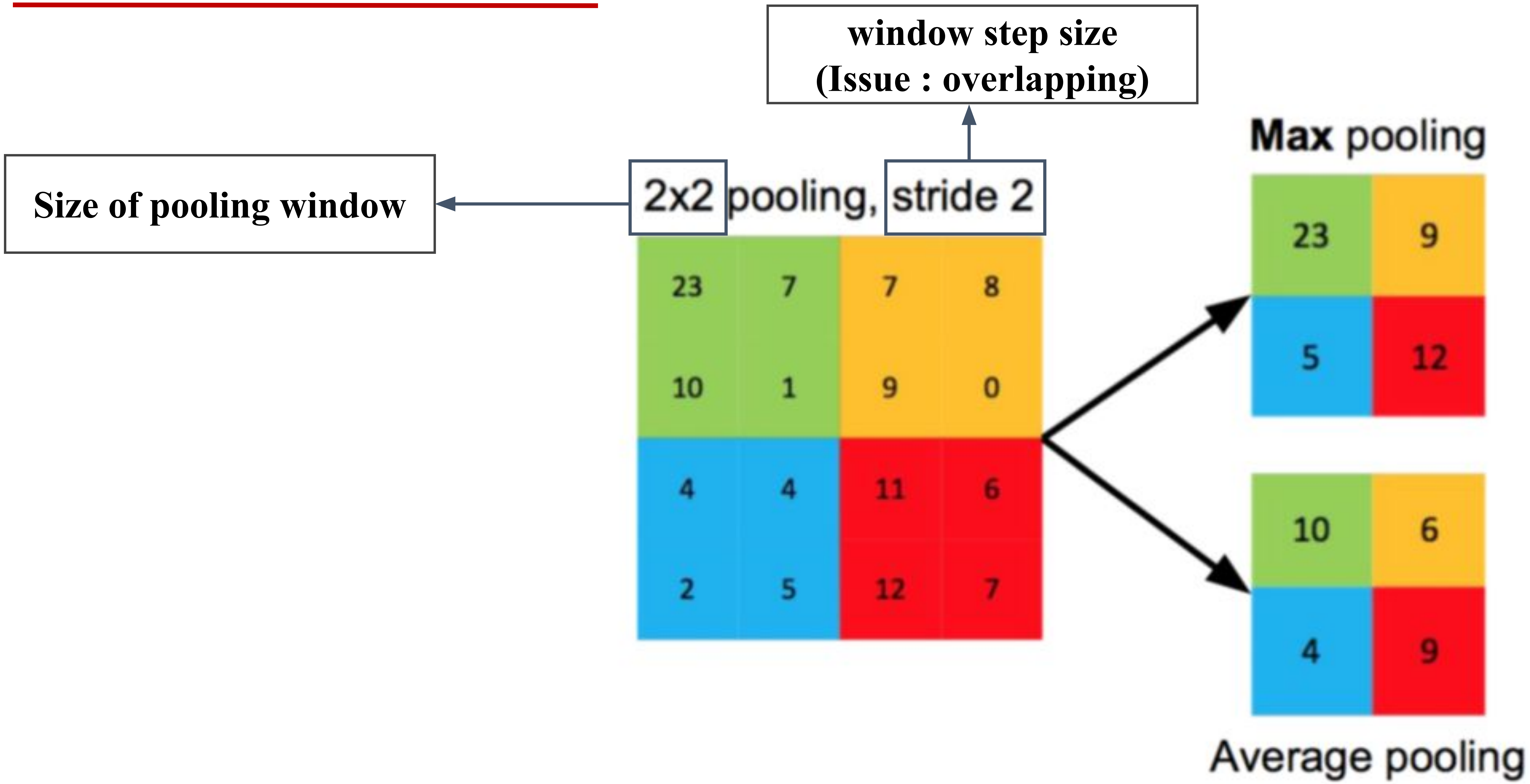
= 0 * 1/3 + 10 * 1/3 + 50 * 1/3 =

= 10 * 1/3 + 50 * 1/3 + 60 * 1/3 =

= 50 * 1/3 + 60 * 1/3 + 10 * 1/3 =

https://www.youtube.com/watch?v=ulKbLD6BRJA

3. Pooling layer

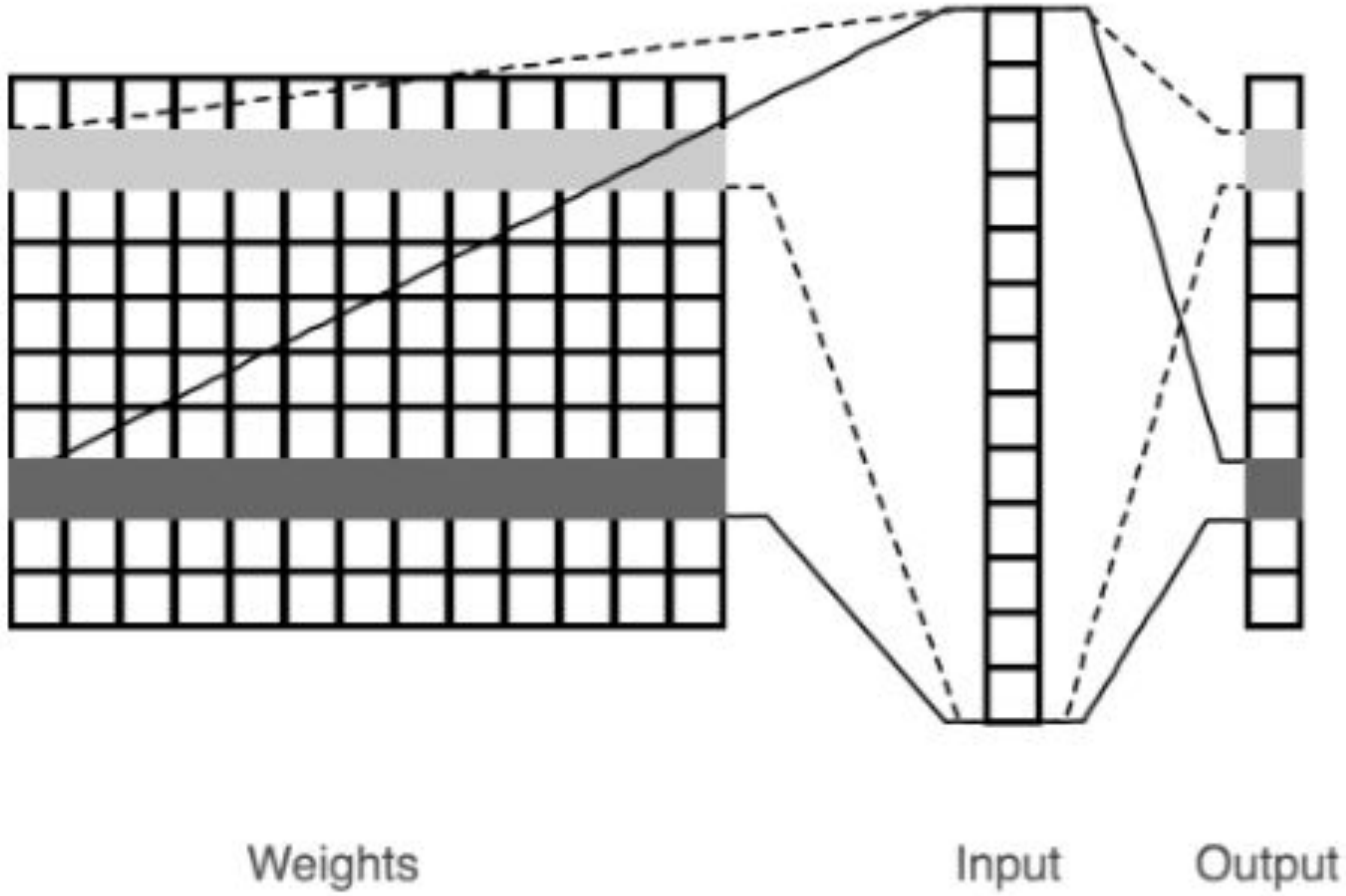


Size of pooling window

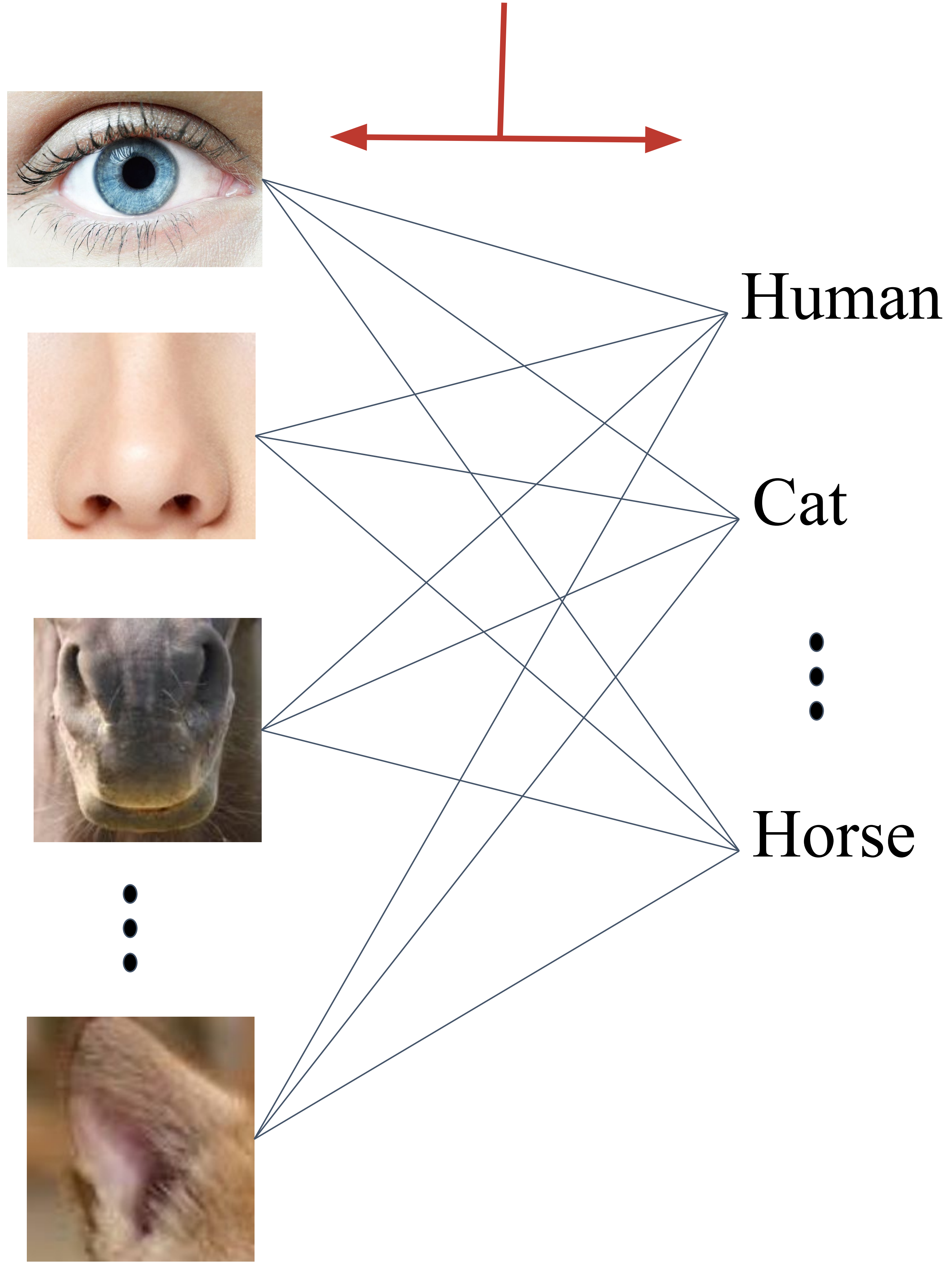
window step size
(Issue : overlapping)

1. Extract strong feature and reduce resolution
2. Increase translation-invariance and noise-resilience

4. Fully connected layer



The more Complex, the deeper it becomes



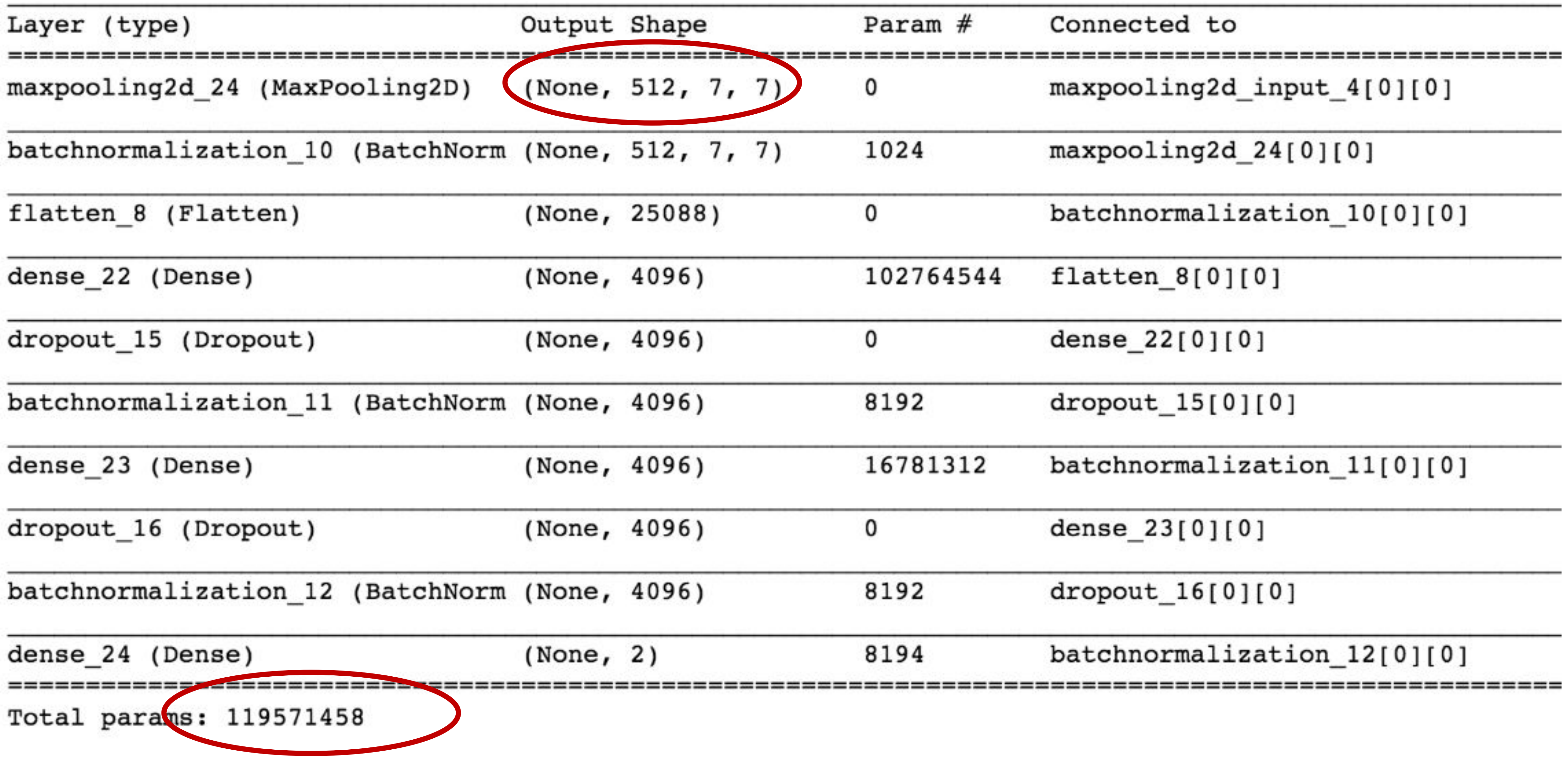
With Extracted Features, do classification

https://www.safaribooksonline.com/library/view/machine-learning-with/9781787121515/79694e8a-e30d-4b30-9b59-abcb2c436182.xhtml

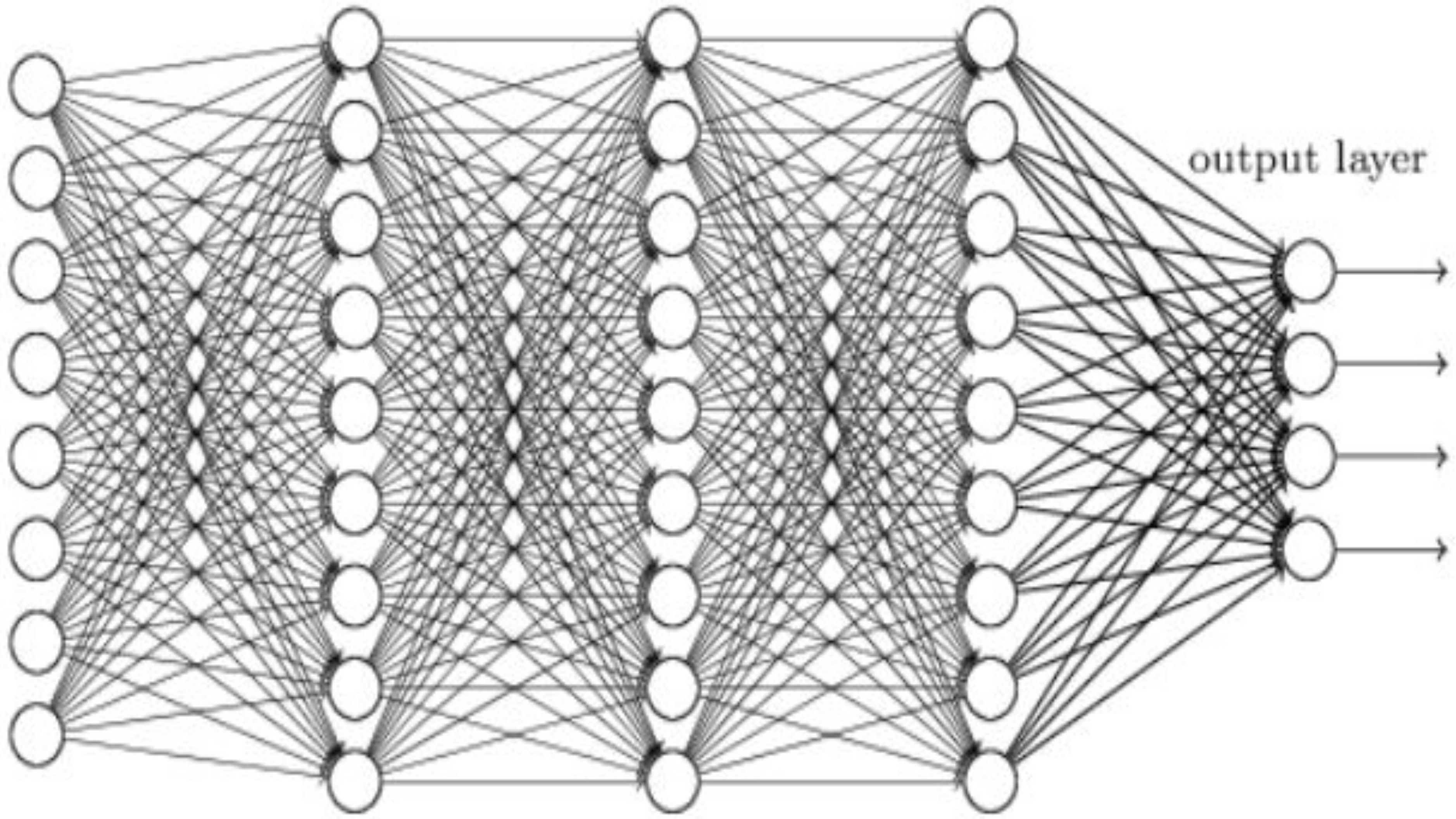
PROJECT

Problem of CNNs

Keyword : Time-consuming, Computing Energy, Calculation



```
____________________________________________________________________________________________________
Layer (type)                     Output Shape          Param #     Connected to
====================================================================================================
maxpooling2d_24 (MaxPooling2D)   (None, 512, 7, 7)     0           maxpooling2d_input_4[0][0]
____________________________________________________________________________________________________
batchnormalization_10 (BatchNorm (None, 512, 7, 7)     1024        maxpooling2d_24[0][0]
____________________________________________________________________________________________________
flatten_8 (Flatten)              (None, 25088)         0           batchnormalization_10[0][0]
____________________________________________________________________________________________________
dense_22 (Dense)                 (None, 4096)          102764544   flatten_8[0][0]
____________________________________________________________________________________________________
dropout_15 (Dropout)             (None, 4096)          0           dense_22[0][0]
____________________________________________________________________________________________________
batchnormalization_11 (BatchNorm (None, 4096)          8192        dropout_15[0][0]
____________________________________________________________________________________________________
dense_23 (Dense)                 (None, 4096)          16781312    batchnormalization_11[0][0]
____________________________________________________________________________________________________
dropout_16 (Dropout)             (None, 4096)          0           dense_23[0][0]
____________________________________________________________________________________________________
batchnormalization_12 (BatchNorm (None, 4096)          8192        dropout_16[0][0]
____________________________________________________________________________________________________
dense_24 (Dense)                 (None, 2)             8194        batchnormalization_12[0][0]
====================================================================================================
Total params: 119571458
```

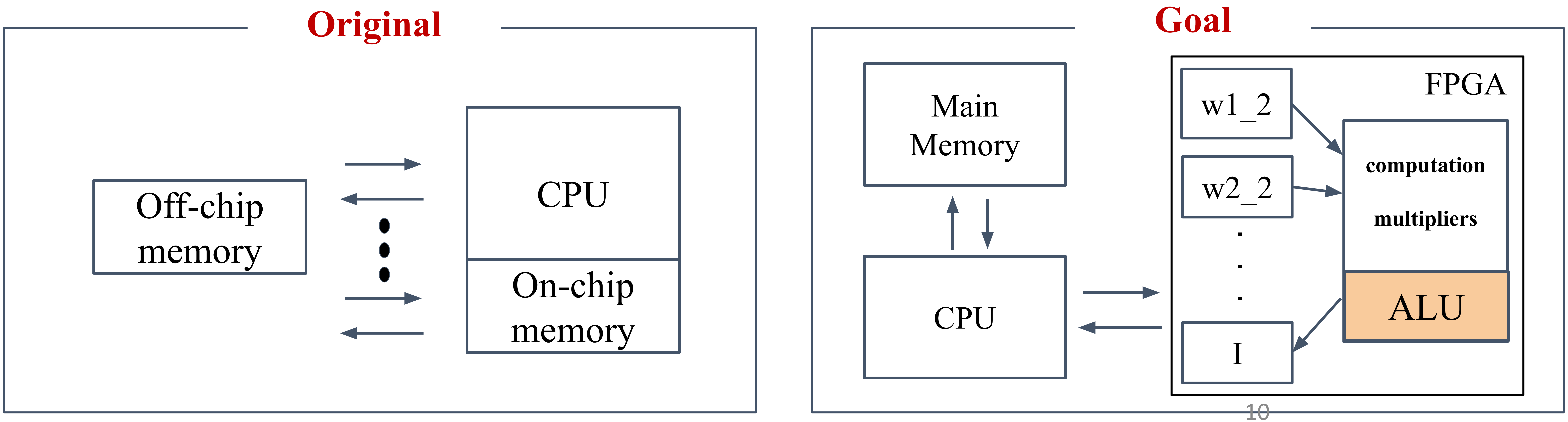


Required a lot of Computing resources and time

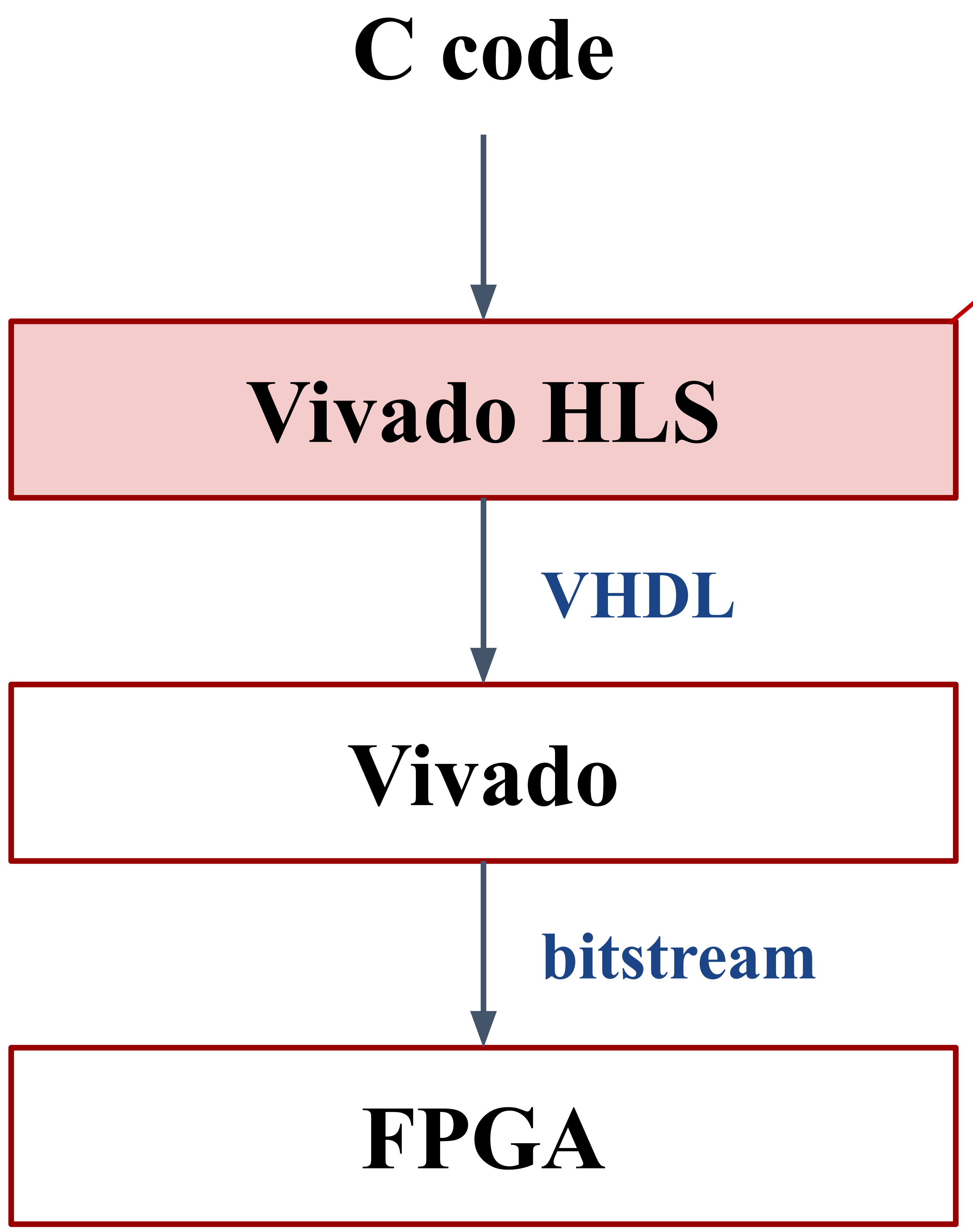
Purpose

Acceleration of Convolution Neural Networks to embed in light machine

Focus on Hardware Acceleration



Approach



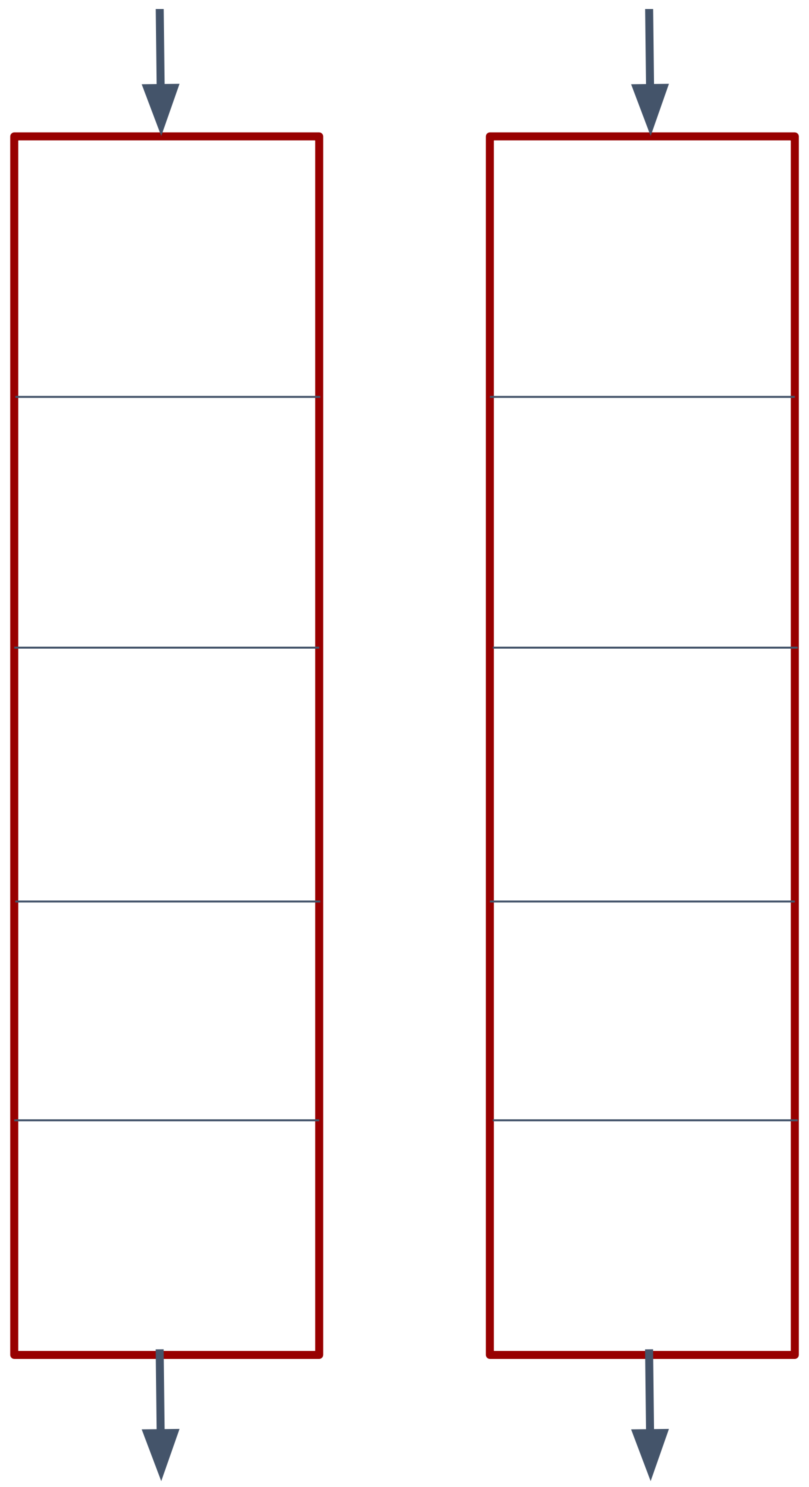
Keypoint

<u>Optimize Hardware</u> so that

- maximize computational efficiency
- minimize computational latency
- minimize memory access

1. Hardware Optimization : Array partition

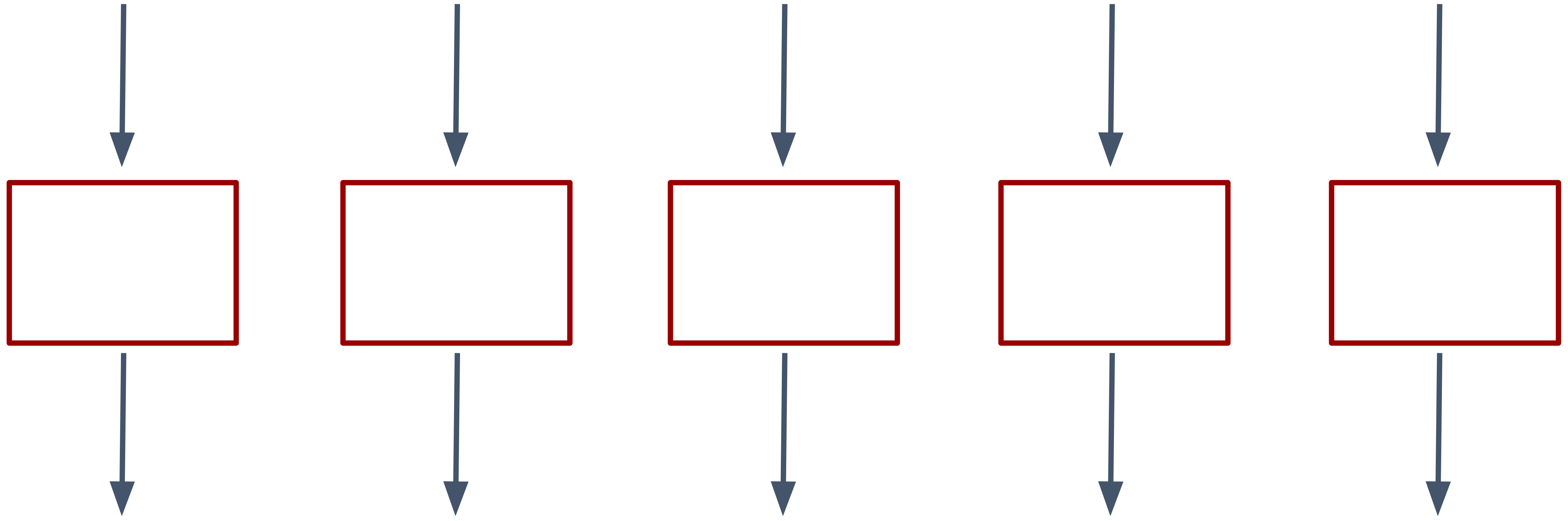
Normal



Array partition : Complete

Command Ex :

#pragma HLS ARRAY_PARTITION variable=B complete



Pros and Cons : Parallel access vs Hardware delay

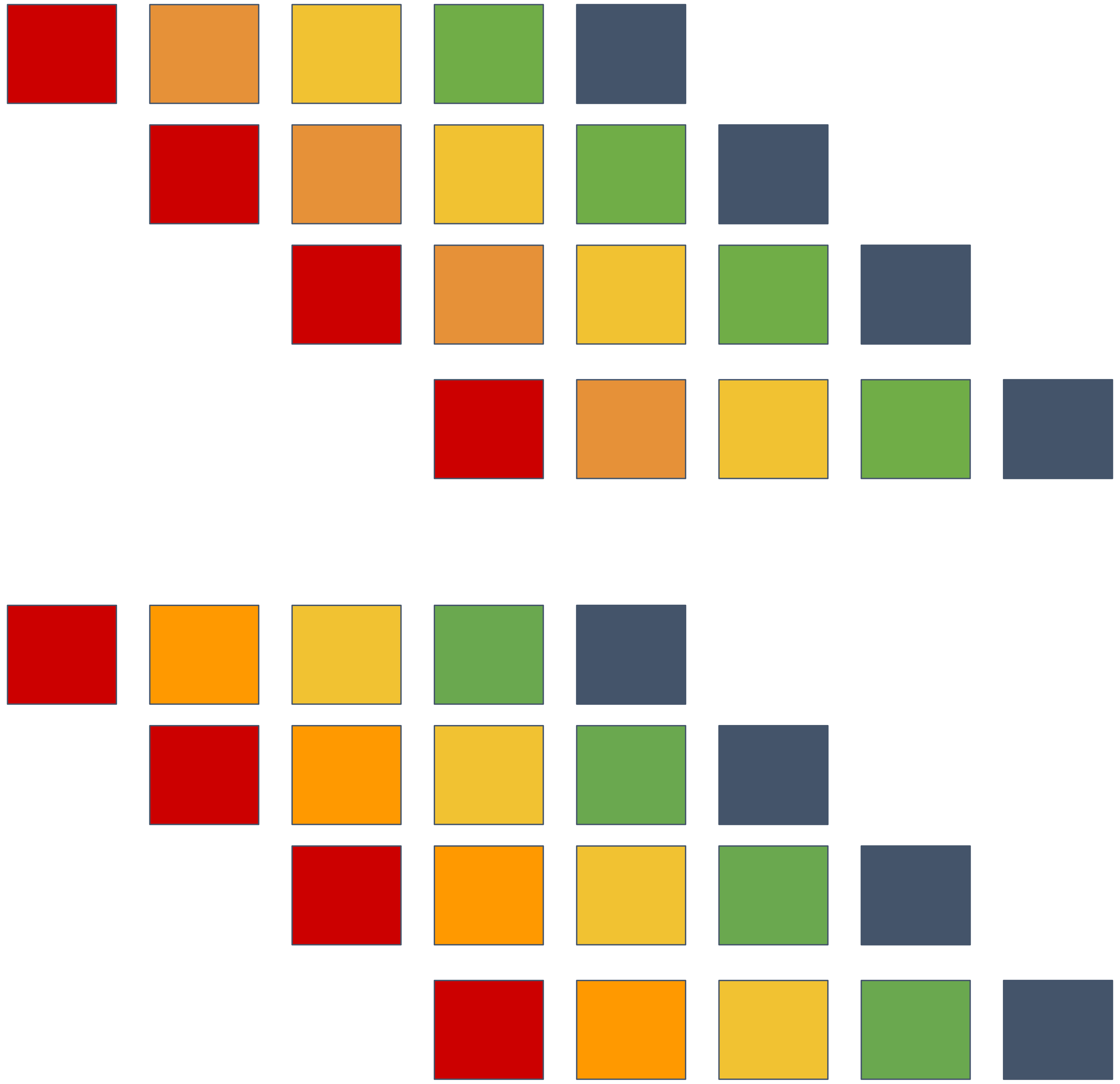
2. Hardware Optimization : Pipeline

In Convolution Code…

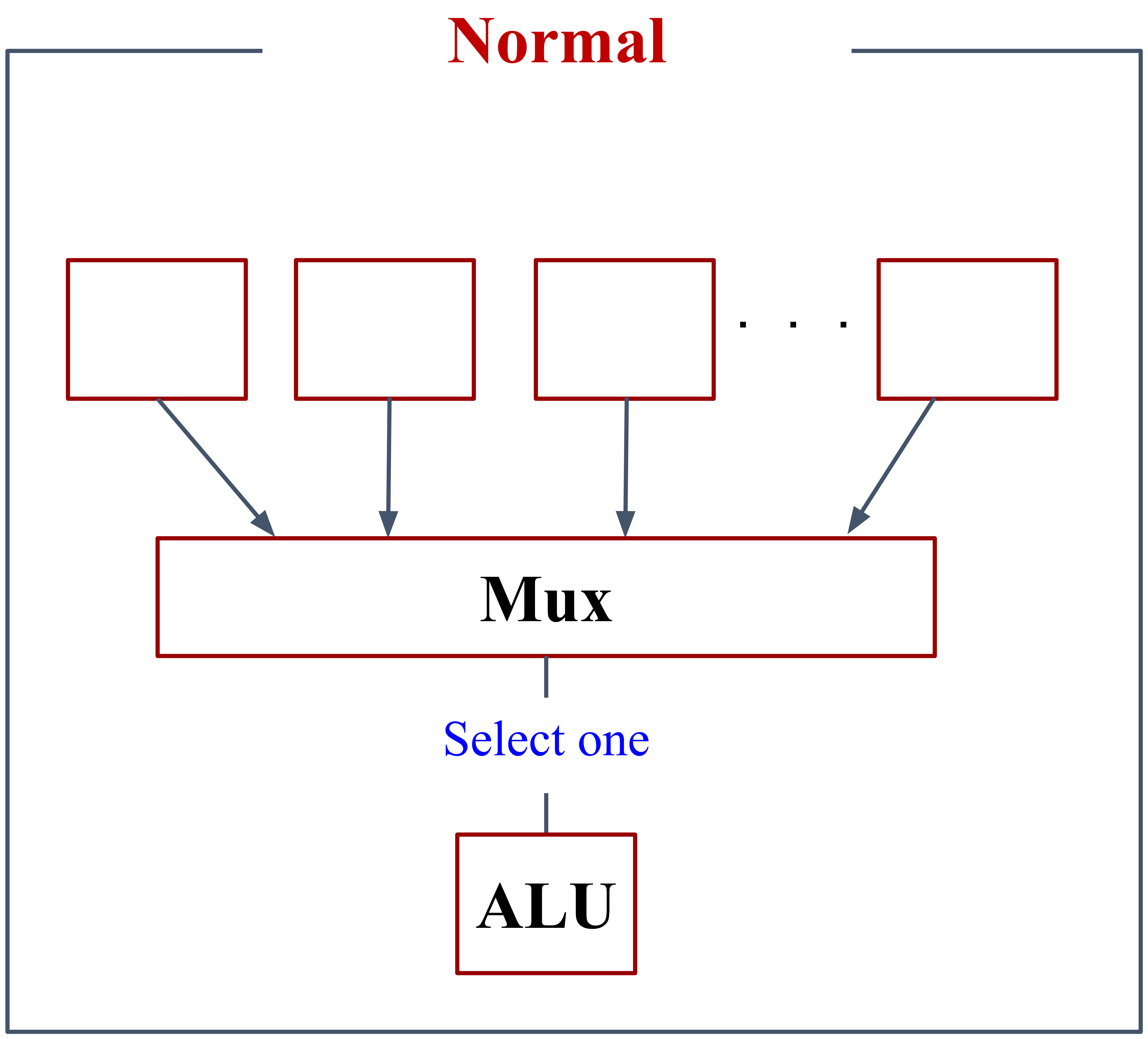
```
for( m = 0 ; m< 4096 ; m ++)
   for( n = 0 ; n < 2048 ; n ++ )
      for( i = 0 ; i < 256 ; i ++ )
         for( j = 0 ; j < 256 ; j ++ ){
            for(x =0 ; x <3 ; x ++){
               for(y = 0 ; y <3 ; y ++ ){
                  O[i][j]  += I[i][j] * W[m][n][x][y]
               }
            }
         }
```

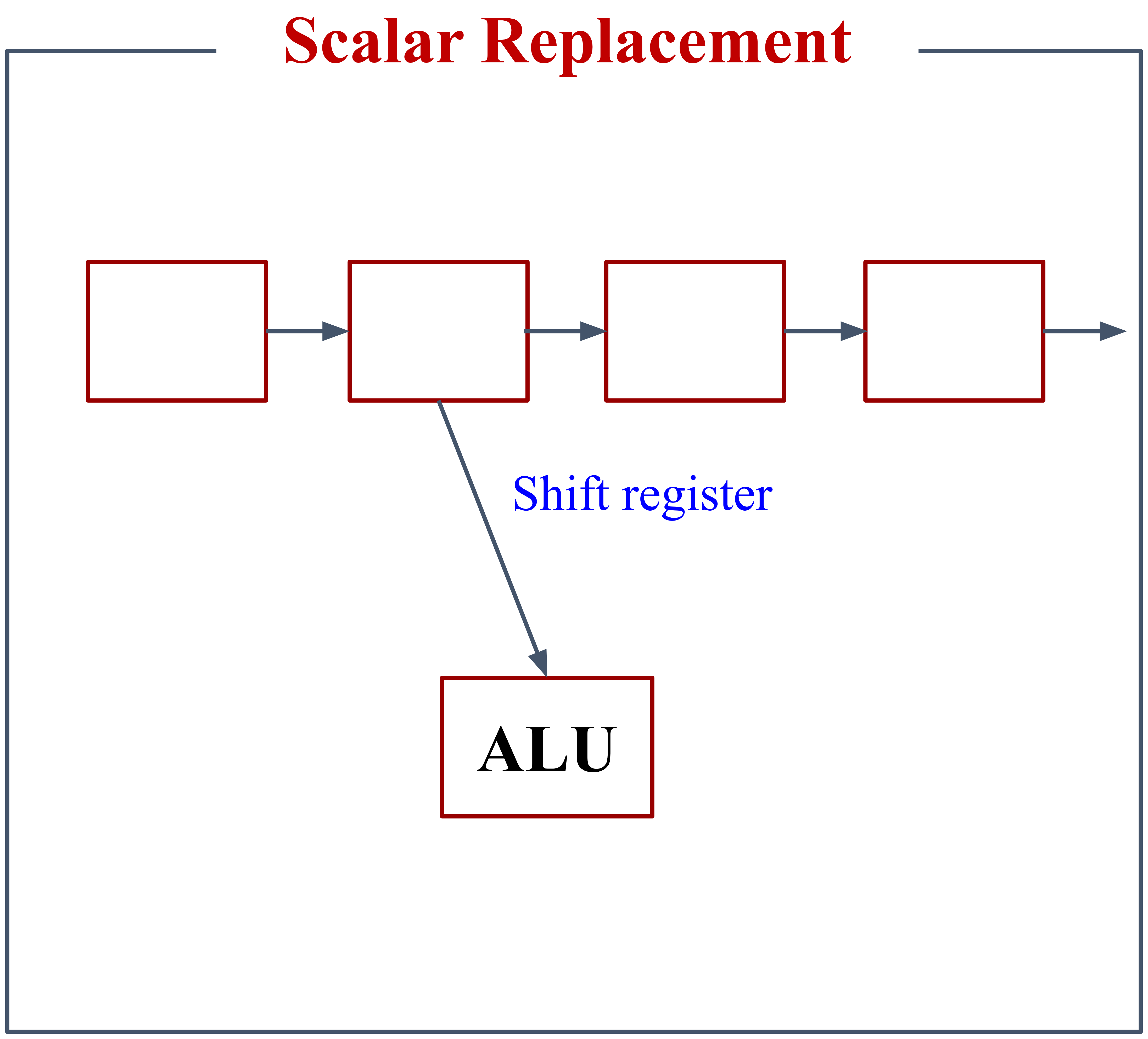
Apply Pipeline →

Command Ex : #pragma HLS PIPELINE



3. (Future)Hardware Optimization: Scalar Replacement





Our Role

1. Template library

Implement function
in CNN model
without model dependency

2. Verifier

SW version
vs
Python(keras)

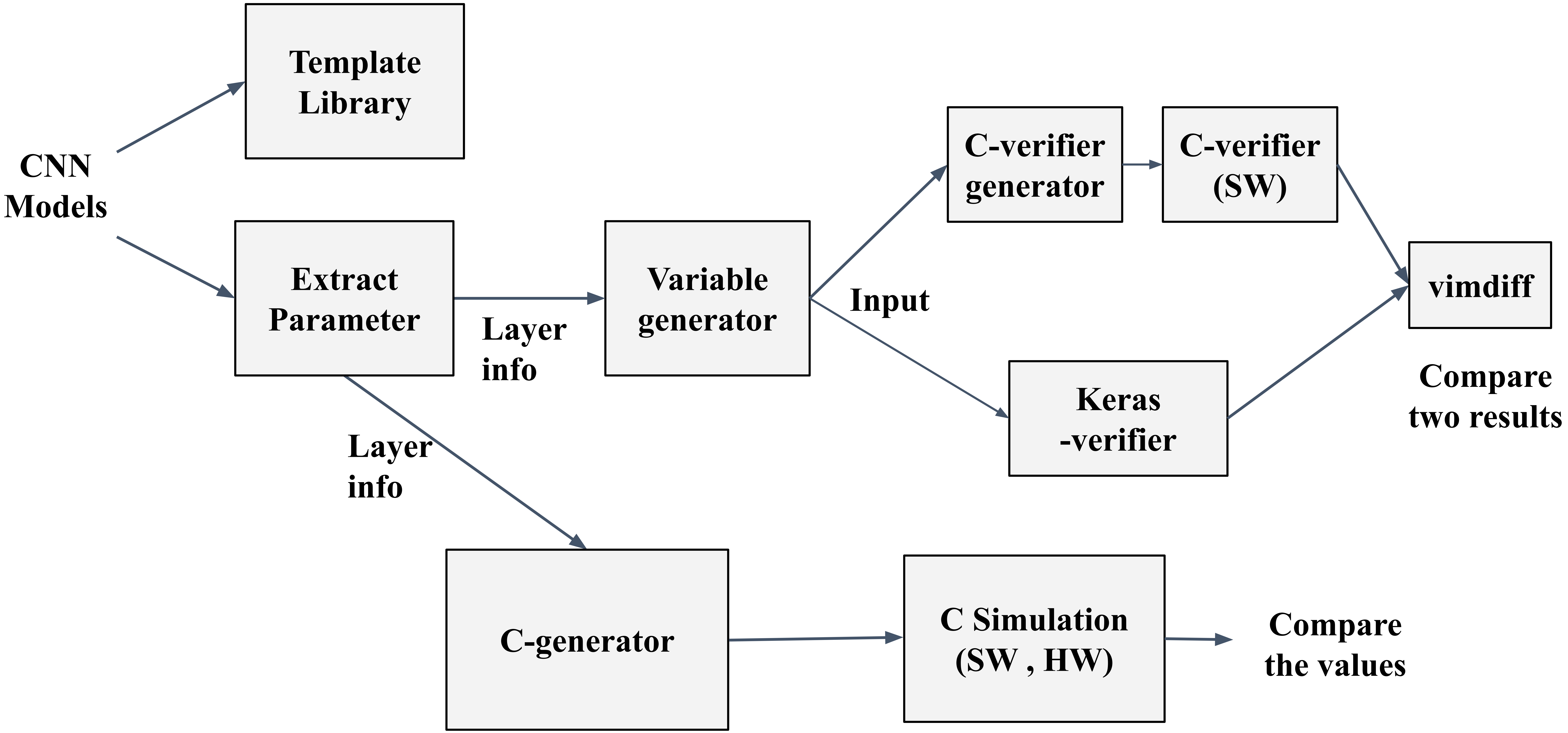
3. Generator

Generate C code for Vivado

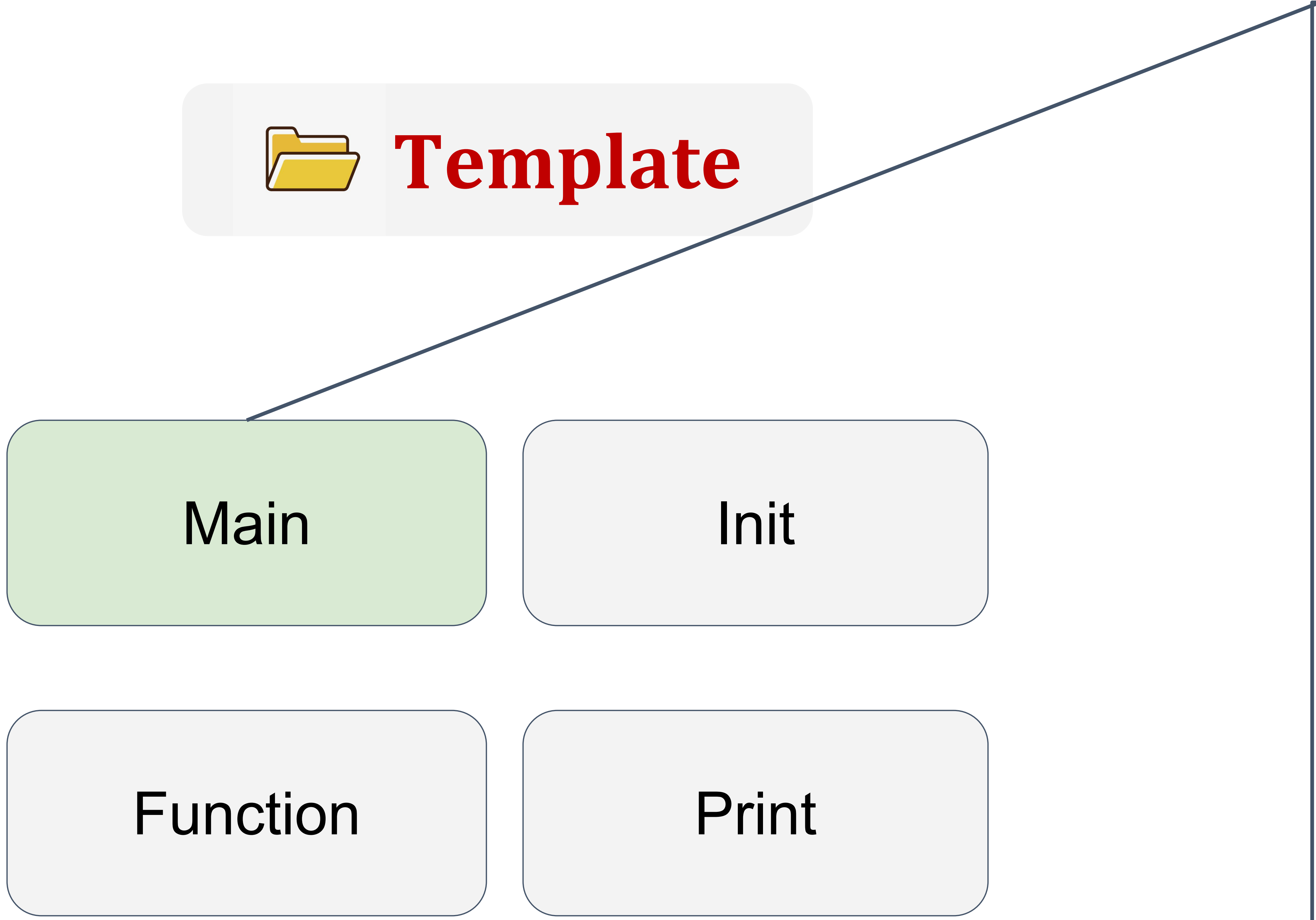
4. C simulation

SW version
vs
HW version

Work Process



1. Template Library

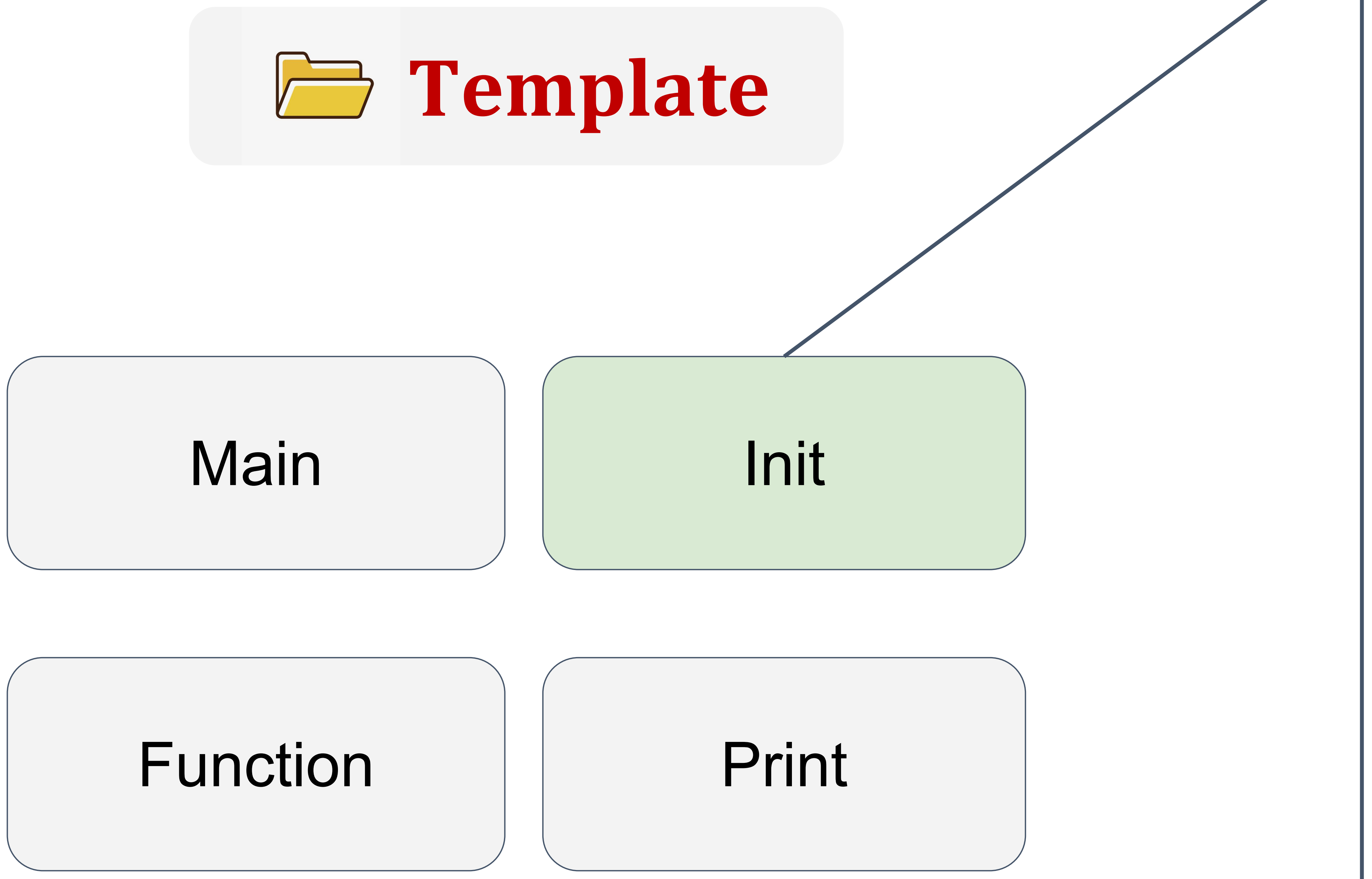


Main

Skeleton code for each program

- C_Verification.txt : For Verifier
- Cpp.txt : For Generator
- Test_cpp.txt : For Generator

1. Template Library

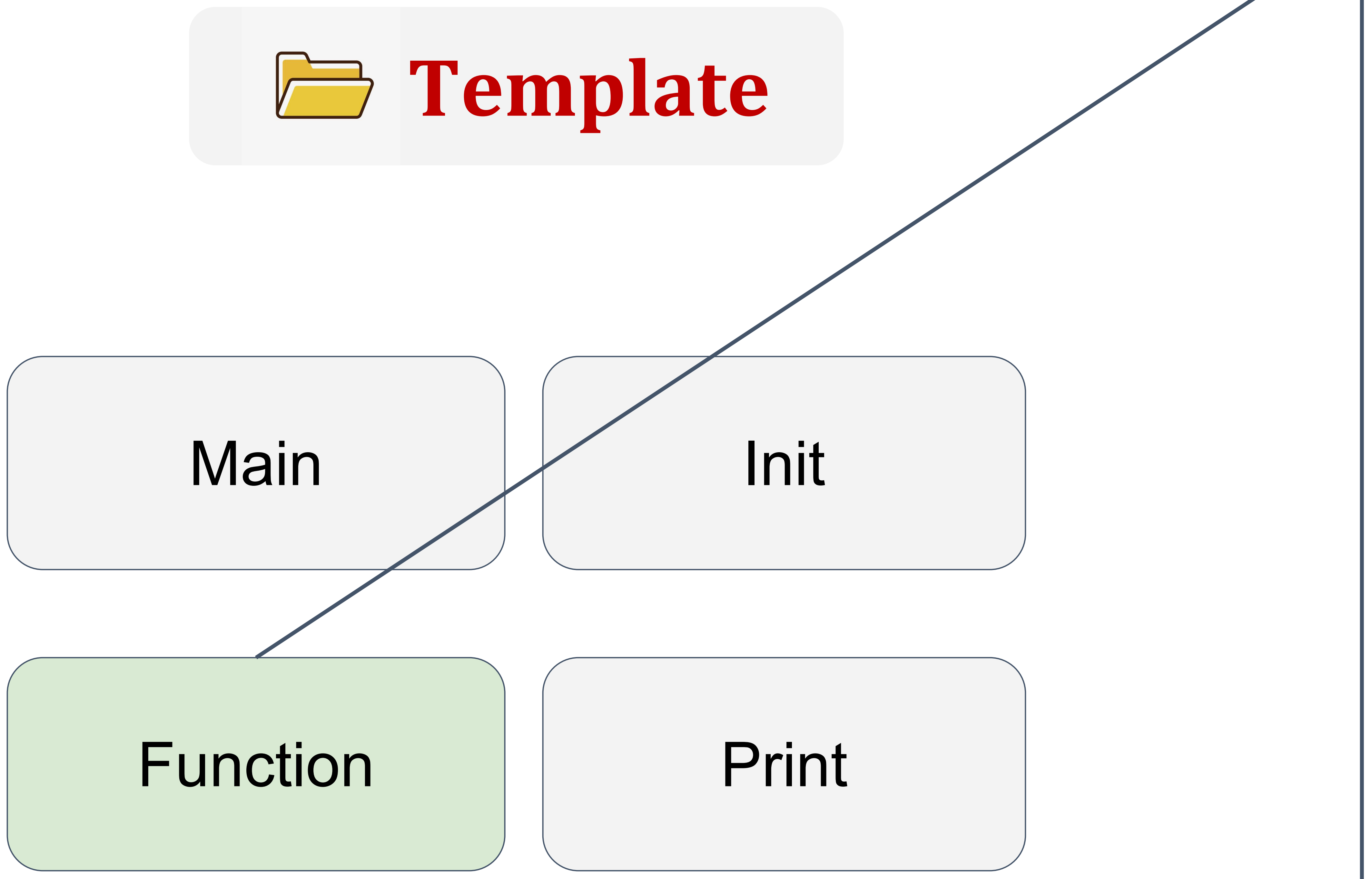


Init

Variable Initialization code

- Init_input.txt : Initialize input
- Init_weight.txt : Initialize weight
- Init_Bias.txt : Initialize bias

1. Template Library



Function

Implemented C functions for CNNs model
Currently applied Model : VGG16, VGG19, Resnet 50

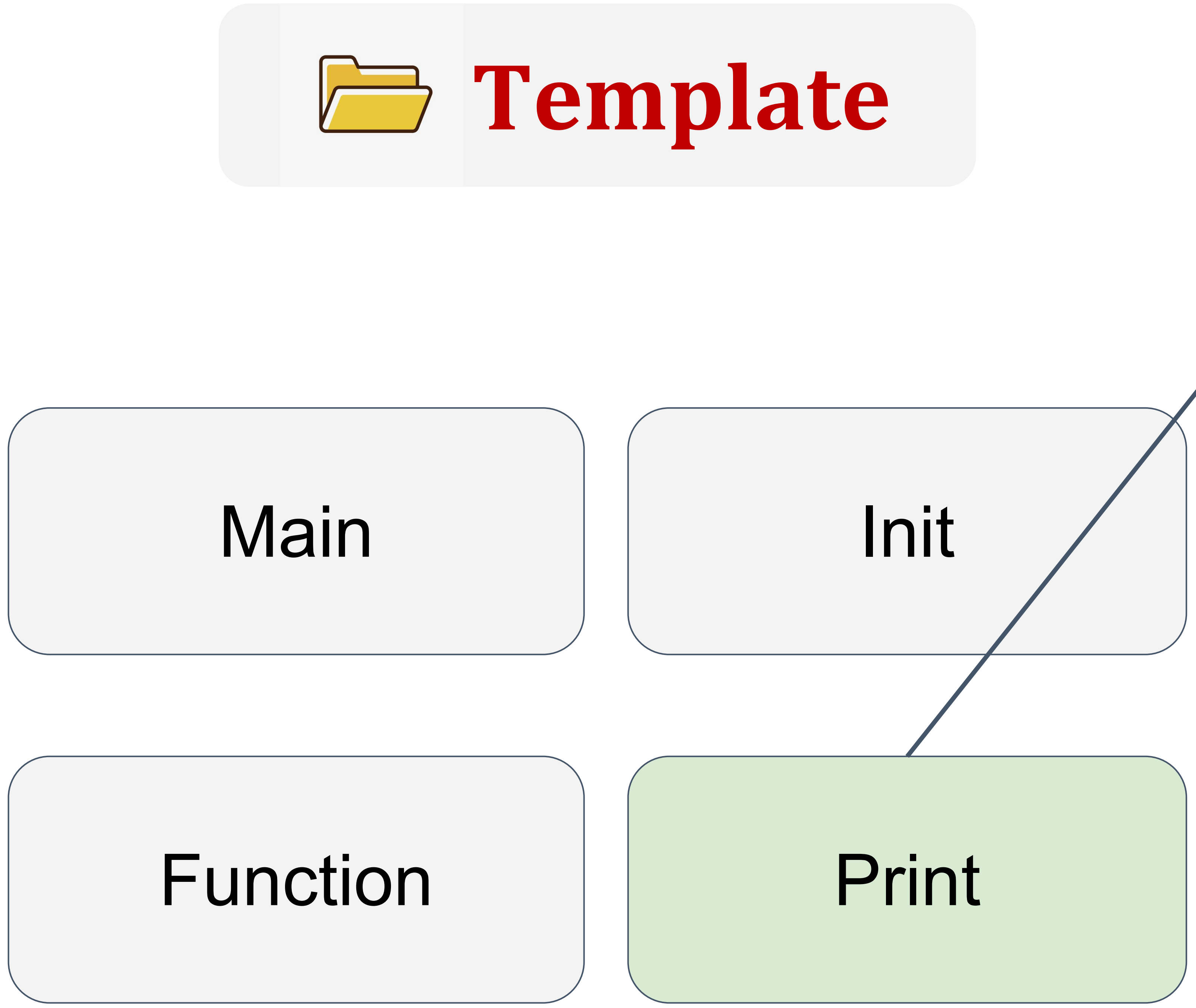
1) Optimized HW function
2) SW function

- MaxPooling2D.txt
- AveragePooling2D.txt
- Convolution2D_Same.txt
- Convolution2D_Valid.txt

……..

- Dense.txt

1. Template Library



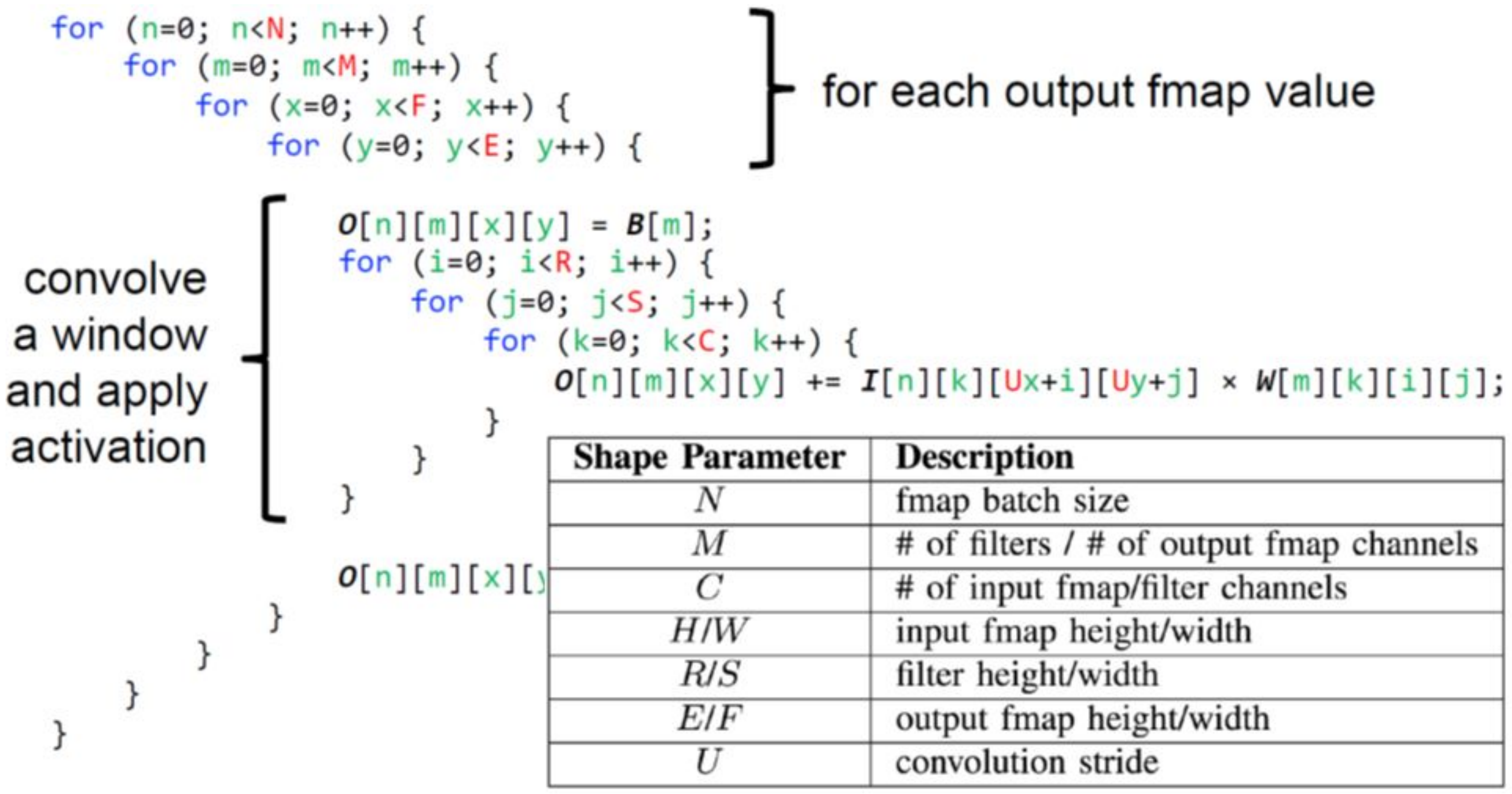
Print

Print function
to compare the results of each layer

- Print4D.txt
- Print3D.txt
- Print2D.txt
- Print1D.txt

How to match keras and C

C


for each output fmap value
convolve a window and apply activation

```
for (n=0; n<N; n++) {
    for (m=0; m<M; m++) {
        for (x=0; x<F; x++) {
            for (y=0; y<E; y++) {
                O[n][m][x][y] = B[m];
                for (i=0; i<R; i++) {
                    for (j=0; j<S; j++) {
                        for (k=0; k<C; k++) {
                            O[n][m][x][y] += I[n][k][Ux+i][Uy+j] × W[m][k][i][j];
                        }
                    }
                }
                O[n][m][x][
            }
        }
    }
}
```

Shape Parameter	Description
N	fmap batch size
M	# of filters / # of output fmap channels
C	# of input fmap/filter channels
H/W	input fmap height/width
R/S	filter height/width
E/F	output fmap height/width
U	convolution stride

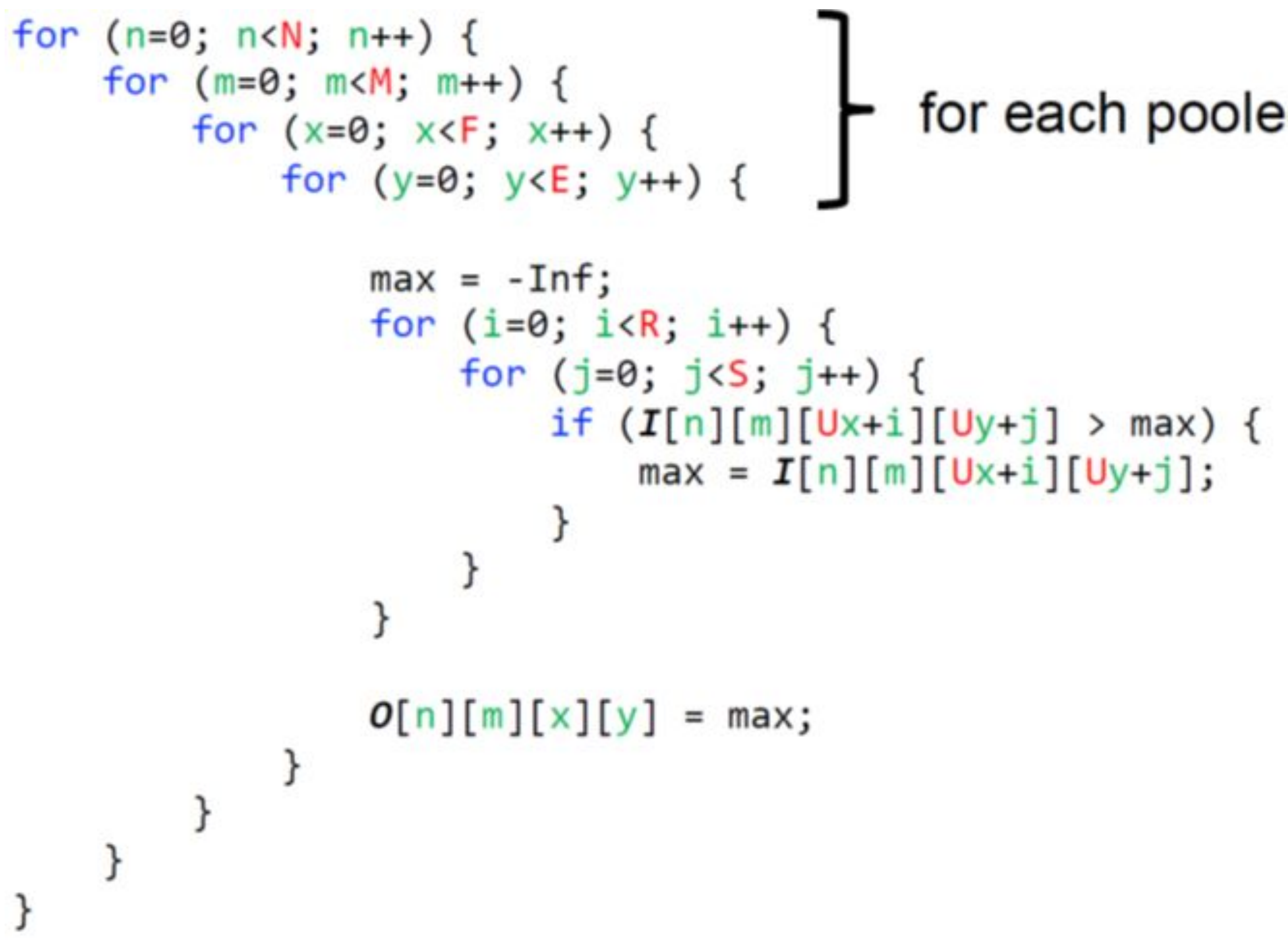
Keras

Conv2D(filters, kernel_size, strides, padding, data_format, dilation_rate, activation, use_bias , kernel_initializer, bias_initializer, kernel_regularizer, bias_regularizer, activity_regularizer, kernel_constraint, bias_constraint)

- filters : number of output filter
- kernel_size : filter size
- padding : ‘same’ , ‘valid’
- data_format : ‘channels_last’ , ‘channel_first’
- dilation_rate : k = 1, 2, 4 ..
- activation : activation function
- use bias : W*x + bias (True/ False)
- kernel_initializer : weight initializer
- ...

How to match keras and C

C



```
for (n=0; n<N; n++) {
    for (m=0; m<M; m++) {
        for (x=0; x<F; x++) {
            for (y=0; y<E; y++) {

                max = -Inf;
                for (i=0; i<R; i++) {
                    for (j=0; j<S; j++) {
                        if (I[n][m][Ux+i][Uy+j] > max) {
                            max = I[n][m][Ux+i][Uy+j];
                        }
                    }
                }

                O[n][m][x][y] = max;
            }
        }
    }
}
```

for each pooled value

find the max
with in a window

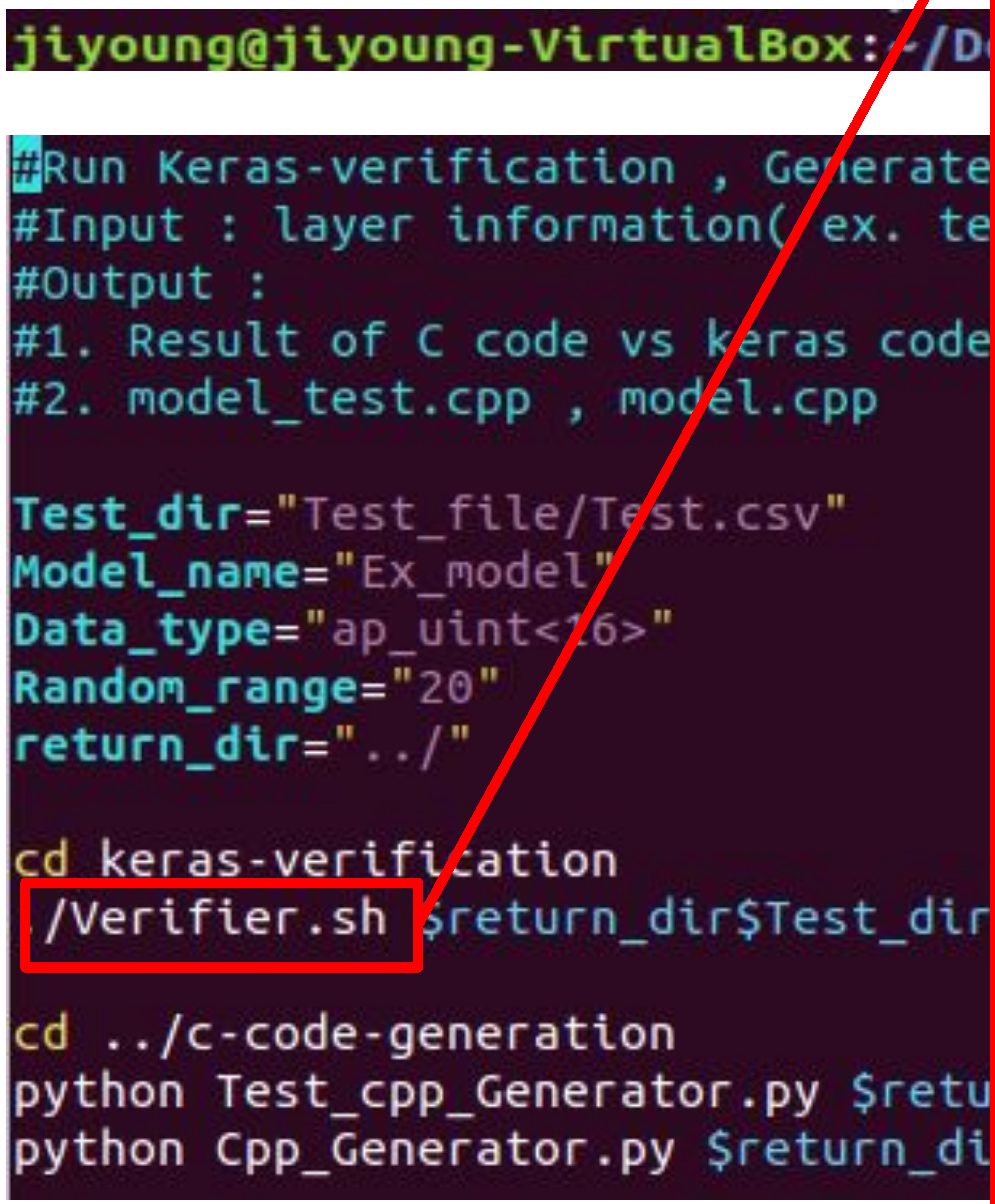
Keras

MaxPooling2D(pool-size , strides , padding, data_format)

- pool-size : pooling window
- strides : step
- padding : ‘same’ (Add zero-padding)
  ‘valid’ (Traverse only with in the image)
- data_format : ‘channels_last’ (batch, channel, width, height)
  ‘channels_first’ (batch, width, height, channel)

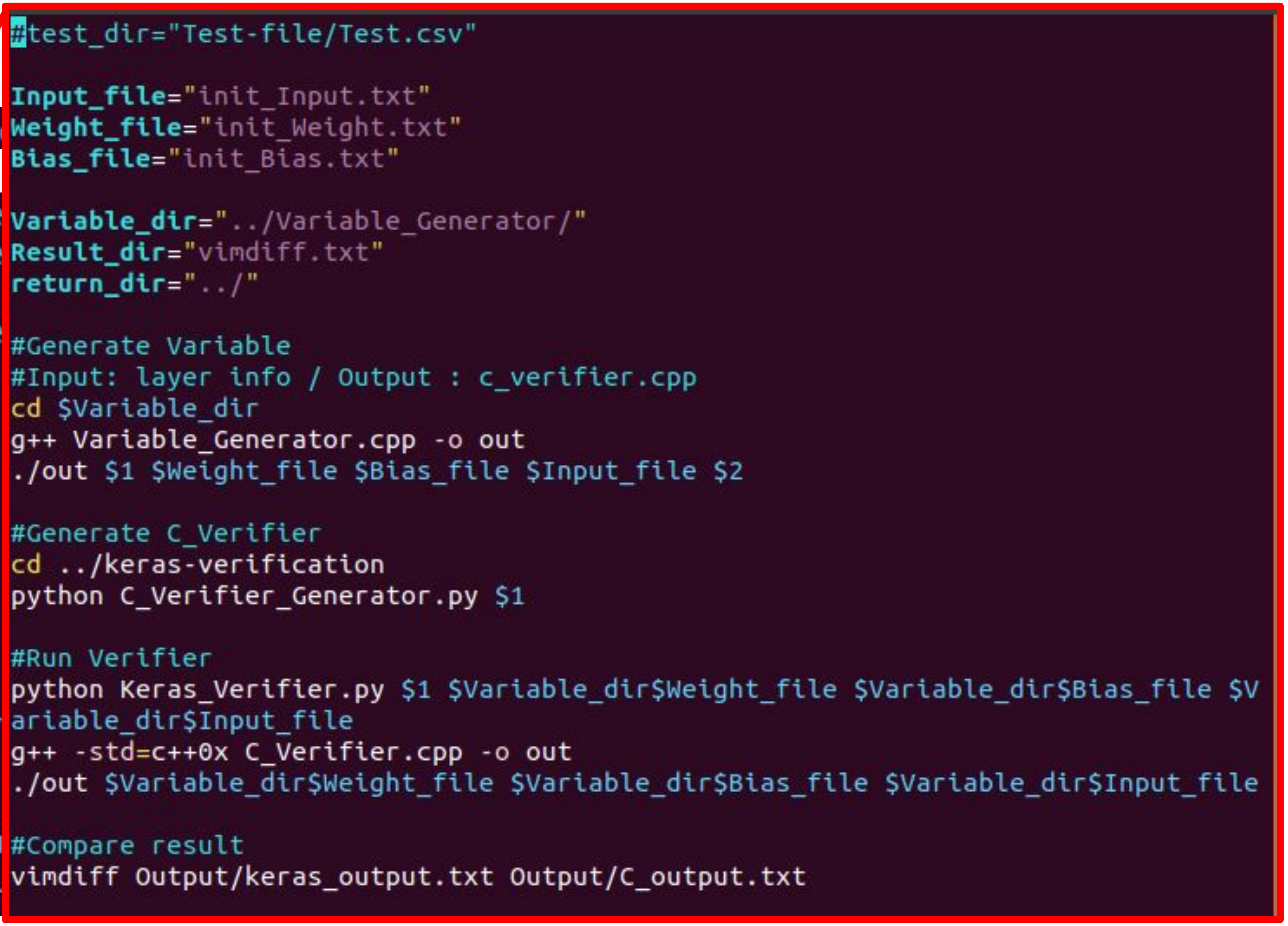
2) Result

1. Run



```
jiyoung@jiyoung-VirtualBox:~/D
```

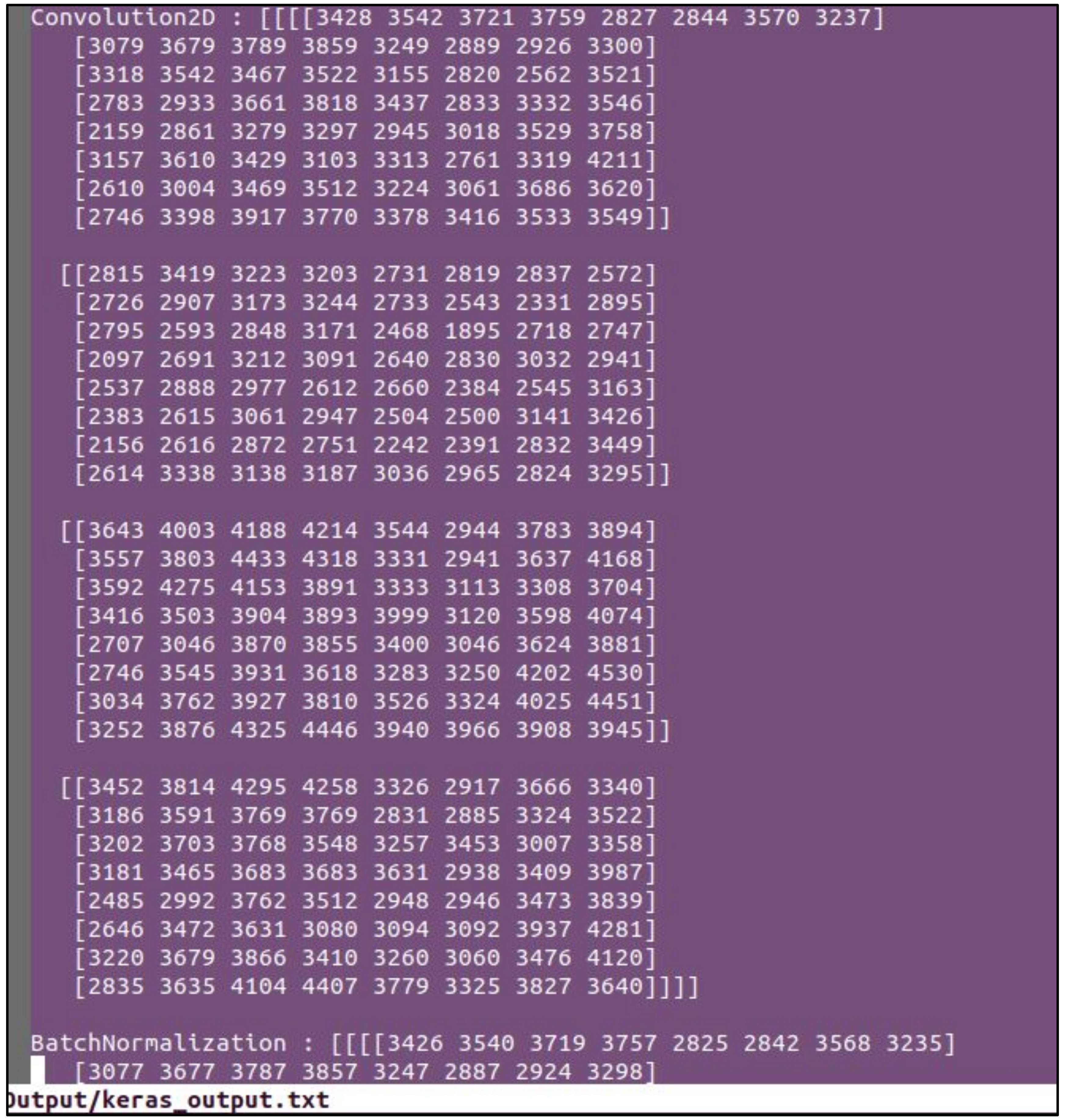
```
#Run Keras-verification , Generate
#Input : layer information( ex. te
#Output :
#1. Result of C code vs keras code
#2. model_test.cpp , model.cpp

Test_dir="Test_file/Test.csv"
Model_name="Ex_model"
Data_type="ap_uint<16>"
Random_range="20"
return_dir="../"

cd keras-verification
./Verifier.sh $return_dir$Test_dir

cd ../c-code-generation
python Test_cpp_Generator.py $retu
python Cpp_Generator.py $return_di
```



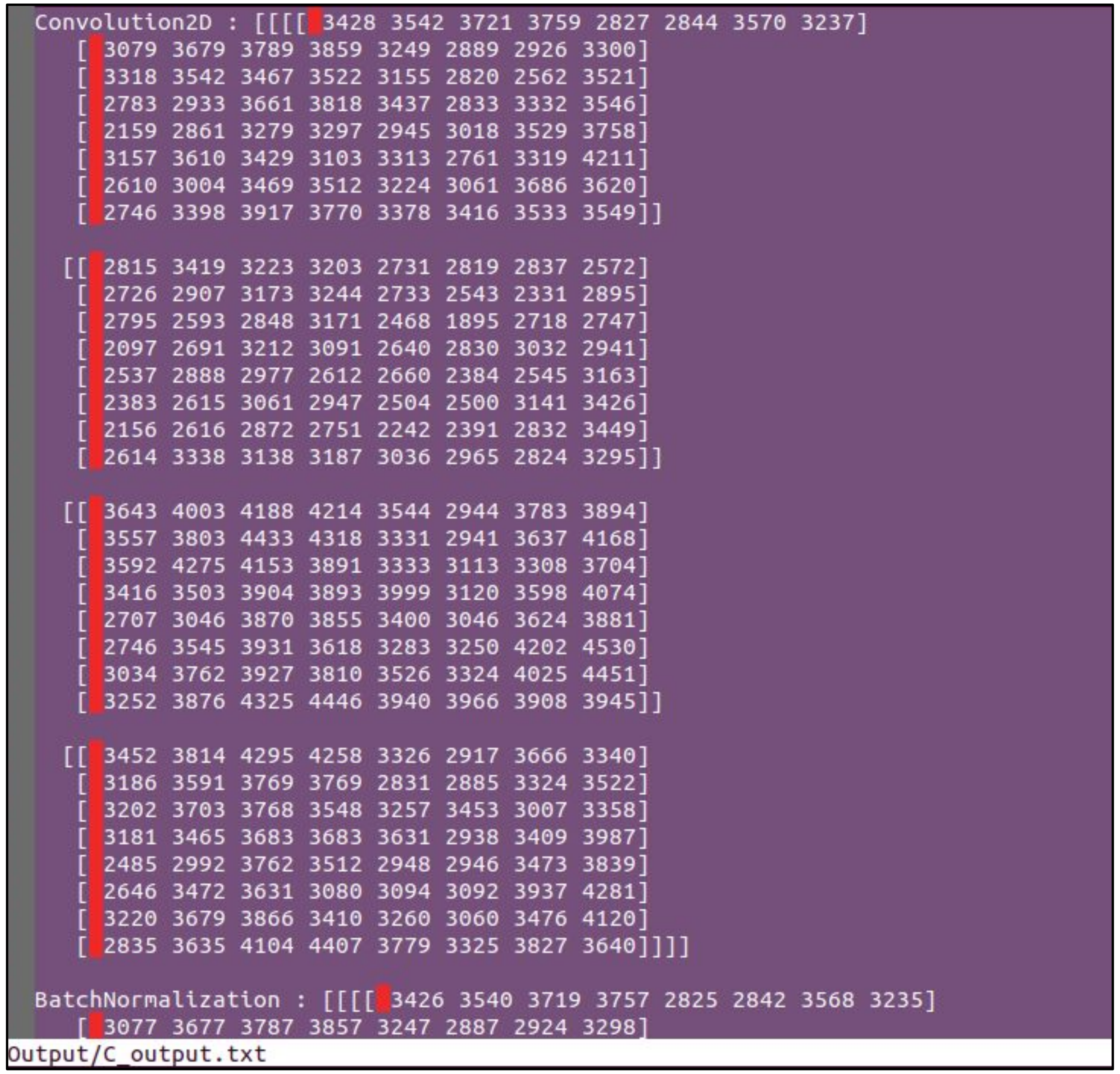
```
#test_dir="Test-file/Test.csv"

Input_file="init_Input.txt"
Weight_file="init_Weight.txt"
Bias_file="init_Bias.txt"

Variable_dir="../Variable_Generator/"
Result_dir="vimdiff.txt"
return_dir="../"

#Generate Variable
#Input: layer info / Output : c_verifier.cpp
cd $Variable_dir
g++ Variable_Generator.cpp -o out
./out $1 $Weight_file $Bias_file $Input_file $2

#Generate C_Verifier
cd ../keras-verification
python C_Verifier_Generator.py $1

#Run Verifier
python Keras_Verifier.py $1 $Variable_dir$Weight_file $Variable_dir$Bias_file $V
ariable_dir$Input_file
g++ -std=c++0x C_Verifier.cpp -o out
./out $Variable_dir$Weight_file $Variable_dir$Bias_file $Variable_dir$Input_file

#Compare result
vimdiff Output/keras_output.txt Output/C_output.txt
```

2) Result

2. Print Diff



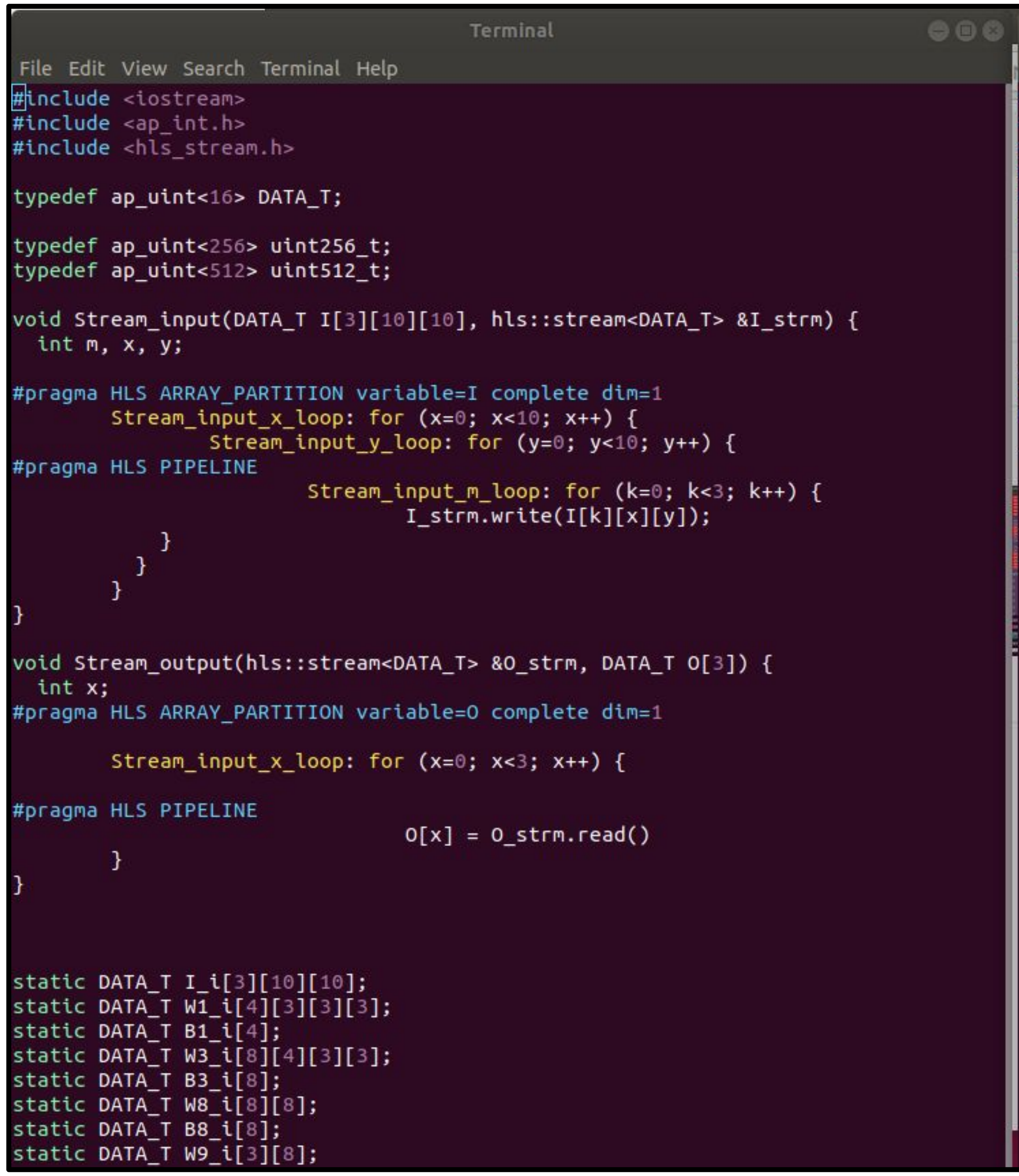
```
Convolution2D : [[[[3428 3542 3721 3759 2827 2844 3570 3237]
   [3079 3679 3789 3859 3249 2889 2926 3300]
   [3318 3542 3467 3522 3155 2820 2562 3521]
   [2783 2933 3661 3818 3437 2833 3332 3546]
   [2159 2861 3279 3297 2945 3018 3529 3758]
   [3157 3610 3429 3103 3313 2761 3319 4211]
   [2610 3004 3469 3512 3224 3061 3686 3620]
   [2746 3398 3917 3770 3378 3416 3533 3549]]

  [[2815 3419 3223 3203 2731 2819 2837 2572]
   [2726 2907 3173 3244 2733 2543 2331 2895]
   [2795 2593 2848 3171 2468 1895 2718 2747]
   [2097 2691 3212 3091 2640 2830 3032 2941]
   [2537 2888 2977 2612 2660 2384 2545 3163]
   [2383 2615 3061 2947 2504 2500 3141 3426]
   [2156 2616 2872 2751 2242 2391 2832 3449]
   [2614 3338 3138 3187 3036 2965 2824 3295]]

  [[3643 4003 4188 4214 3544 2944 3783 3894]
   [3557 3803 4433 4318 3331 2941 3637 4168]
   [3592 4275 4153 3891 3333 3113 3308 3704]
   [3416 3503 3904 3893 3999 3120 3598 4074]
   [2707 3046 3870 3855 3400 3046 3624 3881]
   [2746 3545 3931 3618 3283 3250 4202 4530]
   [3034 3762 3927 3810 3526 3324 4025 4451]
   [3252 3876 4325 4446 3940 3966 3908 3945]]

  [[3452 3814 4295 4258 3326 2917 3666 3340]
   [3186 3591 3769 3769 2831 2885 3324 3522]
   [3202 3703 3768 3548 3257 3453 3007 3358]
   [3181 3465 3683 3683 3631 2938 3409 3987]
   [2485 2992 3762 3512 2948 2946 3473 3839]
   [2646 3472 3631 3080 3094 3092 3937 4281]
   [3220 3679 3866 3410 3260 3060 3476 4120]
   [2835 3635 4104 4407 3779 3325 3827 3640]]]]

BatchNormalization : [[[[3426 3540 3719 3757 2825 2842 3568 3235]
   [3077 3677 3787 3857 3247 2887 2924 3298]
Output/keras_output.txt
```



```
Convolution2D : [[[[ 3428 3542 3721 3759 2827 2844 3570 3237]
   [ 3079 3679 3789 3859 3249 2889 2926 3300]
   [ 3318 3542 3467 3522 3155 2820 2562 3521]
   [ 2783 2933 3661 3818 3437 2833 3332 3546]
   [ 2159 2861 3279 3297 2945 3018 3529 3758]
   [ 3157 3610 3429 3103 3313 2761 3319 4211]
   [ 2610 3004 3469 3512 3224 3061 3686 3620]
   [ 2746 3398 3917 3770 3378 3416 3533 3549]]

  [[ 2815 3419 3223 3203 2731 2819 2837 2572]
   [ 2726 2907 3173 3244 2733 2543 2331 2895]
   [ 2795 2593 2848 3171 2468 1895 2718 2747]
   [ 2097 2691 3212 3091 2640 2830 3032 2941]
   [ 2537 2888 2977 2612 2660 2384 2545 3163]
   [ 2383 2615 3061 2947 2504 2500 3141 3426]
   [ 2156 2616 2872 2751 2242 2391 2832 3449]
   [ 2614 3338 3138 3187 3036 2965 2824 3295]]

  [[ 3643 4003 4188 4214 3544 2944 3783 3894]
   [ 3557 3803 4433 4318 3331 2941 3637 4168]
   [ 3592 4275 4153 3891 3333 3113 3308 3704]
   [ 3416 3503 3904 3893 3999 3120 3598 4074]
   [ 2707 3046 3870 3855 3400 3046 3624 3881]
   [ 2746 3545 3931 3618 3283 3250 4202 4530]
   [ 3034 3762 3927 3810 3526 3324 4025 4451]
   [ 3252 3876 4325 4446 3940 3966 3908 3945]]

  [[ 3452 3814 4295 4258 3326 2917 3666 3340]
   [ 3186 3591 3769 3769 2831 2885 3324 3522]
   [ 3202 3703 3768 3548 3257 3453 3007 3358]
   [ 3181 3465 3683 3683 3631 2938 3409 3987]
   [ 2485 2992 3762 3512 2948 2946 3473 3839]
   [ 2646 3472 3631 3080 3094 3092 3937 4281]
   [ 3220 3679 3866 3410 3260 3060 3476 4120]
   [ 2835 3635 4104 4407 3779 3325 3827 3640]]]]

BatchNormalization : [[[[ 3426 3540 3719 3757 2825 2842 3568 3235]
   [ 3077 3677 3787 3857 3247 2887 2924 3298]
Output/C_output.txt
```

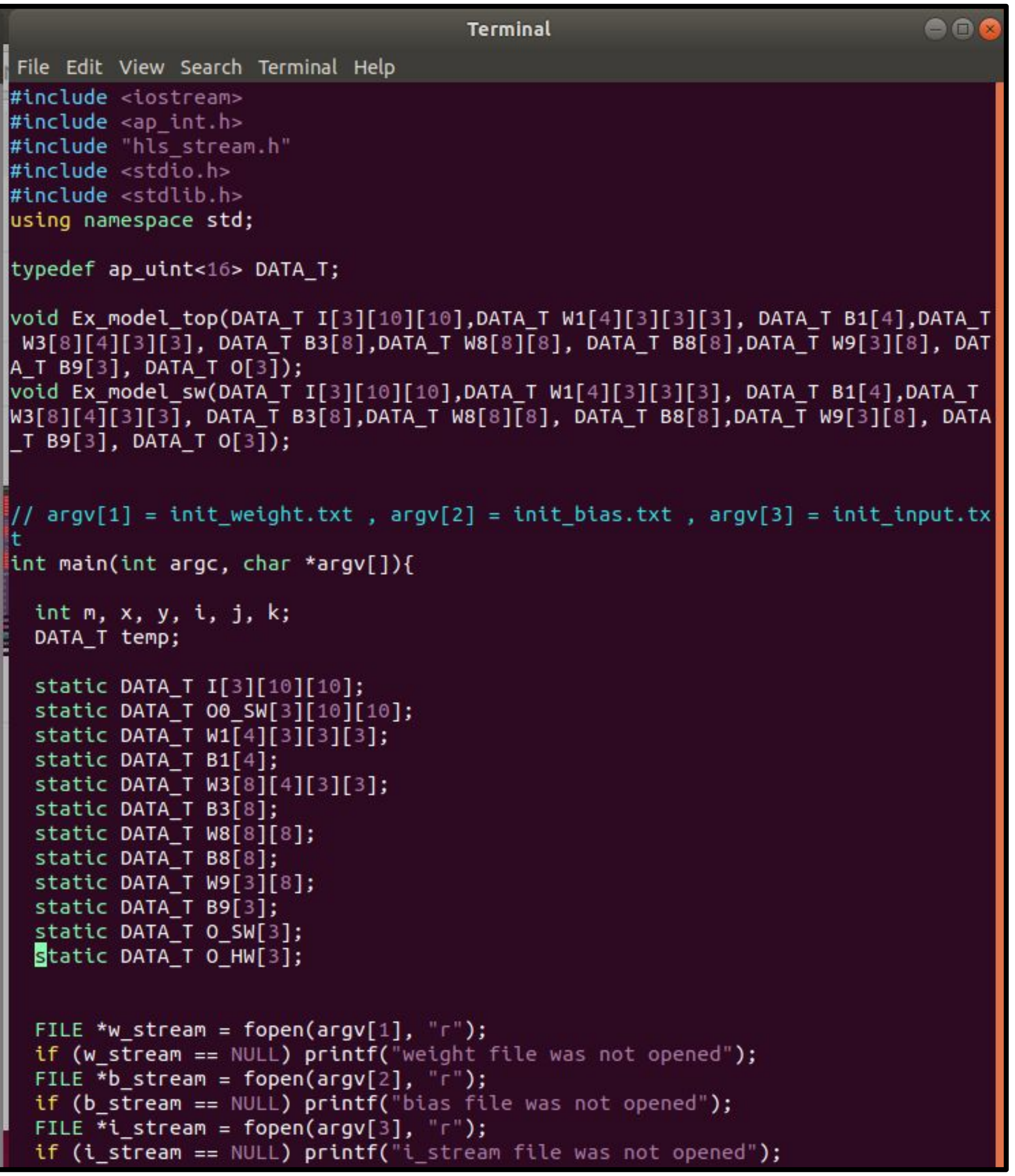
2) Result

3. Generate File



```
#include <iostream>
#include <ap_int.h>
#include <hls_stream.h>

typedef ap_uint<16> DATA_T;

typedef ap_uint<256> uint256_t;
typedef ap_uint<512> uint512_t;

void Stream_input(DATA_T I[3][10][10], hls::stream<DATA_T> &I_strm) {
  int m, x, y;

#pragma HLS ARRAY_PARTITION variable=I complete dim=1
        Stream_input_x_loop: for (x=0; x<10; x++) {
                Stream_input_y_loop: for (y=0; y<10; y++) {
#pragma HLS PIPELINE
                        Stream_input_m_loop: for (k=0; k<3; k++) {
                                I_strm.write(I[k][x][y]);
                }
            }
        }
}

void Stream_output(hls::stream<DATA_T> &O_strm, DATA_T O[3]) {
  int x;
#pragma HLS ARRAY_PARTITION variable=O complete dim=1

        Stream_input_x_loop: for (x=0; x<3; x++) {

#pragma HLS PIPELINE
                                O[x] = O_strm.read()
        }
}



static DATA_T I_i[3][10][10];
static DATA_T W1_i[4][3][3][3];
static DATA_T B1_i[4];
static DATA_T W3_i[8][4][3][3];
static DATA_T B3_i[8];
static DATA_T W8_i[8][8];
static DATA_T B8_i[8];
static DATA_T W9_i[3][8];
```

< Model.cpp >



```
#include <iostream>
#include <ap_int.h>
#include "hls_stream.h"
#include <stdio.h>
#include <stdlib.h>
using namespace std;

typedef ap_uint<16> DATA_T;

void Ex_model_top(DATA_T I[3][10][10],DATA_T W1[4][3][3][3], DATA_T B1[4],DATA_T
 W3[8][4][3][3], DATA_T B3[8],DATA_T W8[8][8], DATA_T B8[8],DATA_T W9[3][8], DAT
A_T B9[3], DATA_T O[3]);
void Ex_model_sw(DATA_T I[3][10][10],DATA_T W1[4][3][3][3], DATA_T B1[4],DATA_T
W3[8][4][3][3], DATA_T B3[8],DATA_T W8[8][8], DATA_T B8[8],DATA_T W9[3][8], DATA
_T B9[3], DATA_T O[3]);


// argv[1] = init_weight.txt , argv[2] = init_bias.txt , argv[3] = init_input.tx
t
int main(int argc, char *argv[]){

  int m, x, y, i, j, k;
  DATA_T temp;

  static DATA_T I[3][10][10];
  static DATA_T O0_SW[3][10][10];
  static DATA_T W1[4][3][3][3];
  static DATA_T B1[4];
  static DATA_T W3[8][4][3][3];
  static DATA_T B3[8];
  static DATA_T W8[8][8];
  static DATA_T B8[8];
  static DATA_T W9[3][8];
  static DATA_T B9[3];
  static DATA_T O_SW[3];
  static DATA_T O_HW[3];


  FILE *w_stream = fopen(argv[1], "r");
  if (w_stream == NULL) printf("weight file was not opened");
  FILE *b_stream = fopen(argv[2], "r");
  if (b_stream == NULL) printf("bias file was not opened");
  FILE *i_stream = fopen(argv[3], "r");
  if (i_stream == NULL) printf("i_stream file was not opened");
```

< Testbench.cpp >

Conclusion

Current State

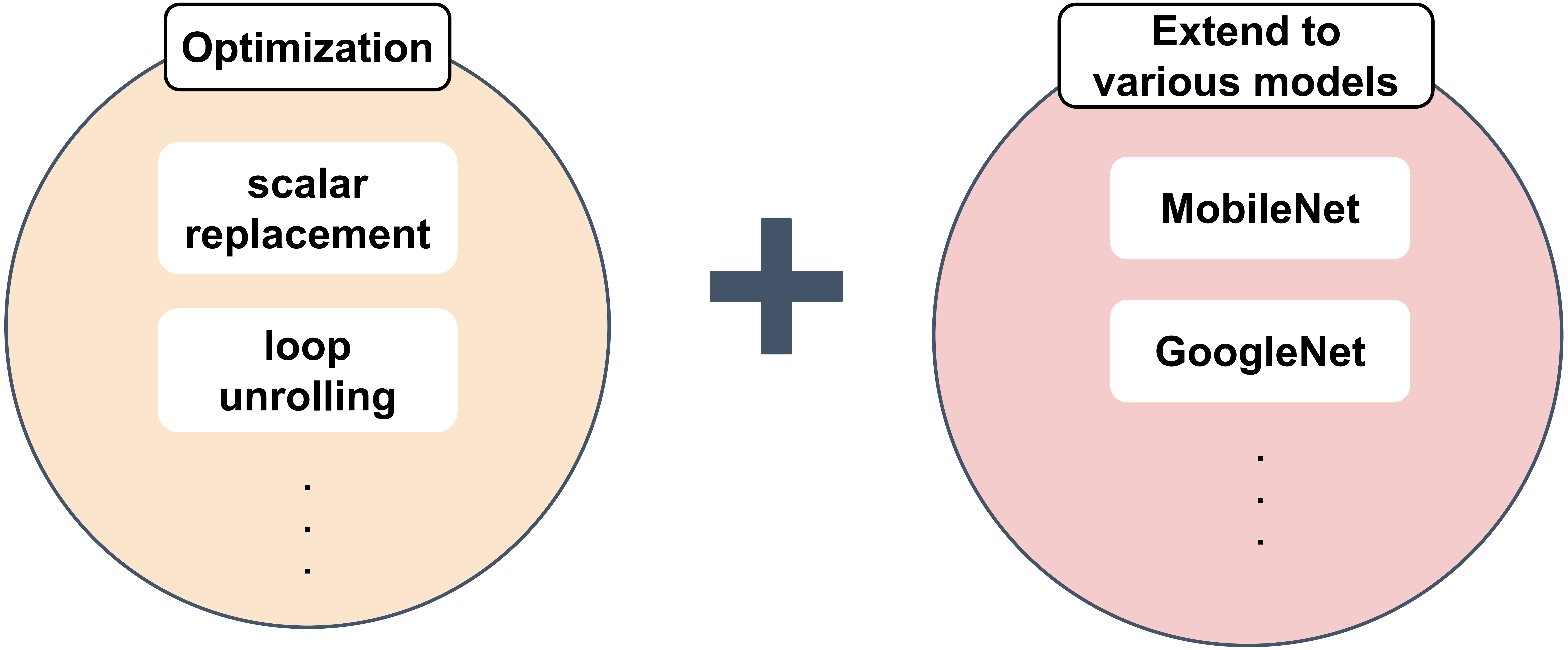
Xiao, Qingcheng, et al. "Exploring heterogeneous algorithms for accelerating deep convolutional neural networks on FPGAs." *Proceedings of the 54th Annual Design Automation Conference 2017*. ACM, 2017.

Reduce memory size

Use new optimizing ways

Minimize computational latency

Future Plan


Optimization
scalar replacement
loop unrolling
.
.
.
Extend to various models
MobileNet
GoogleNet
.
.
.

THANK YOU