CONVOLUTIONAL NEURAL NETWORKS (CNNS)

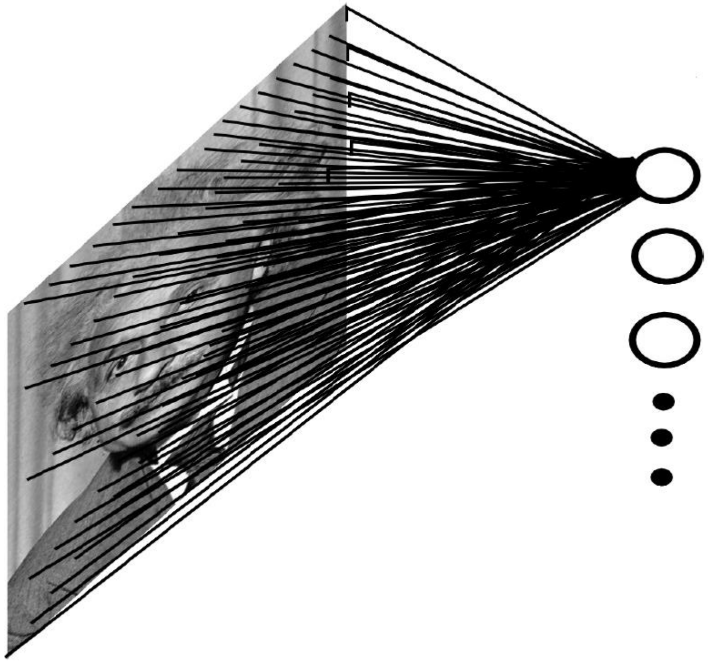
Motivation & basic operations

MOTIVATION

Fully connected neural network

- Example
  - 1000x1000 image
  - 1M hidden units
    $\rightarrow 10^{12} (= 10^6 \times 10^6)$ parameters!
  - Multi-layers?

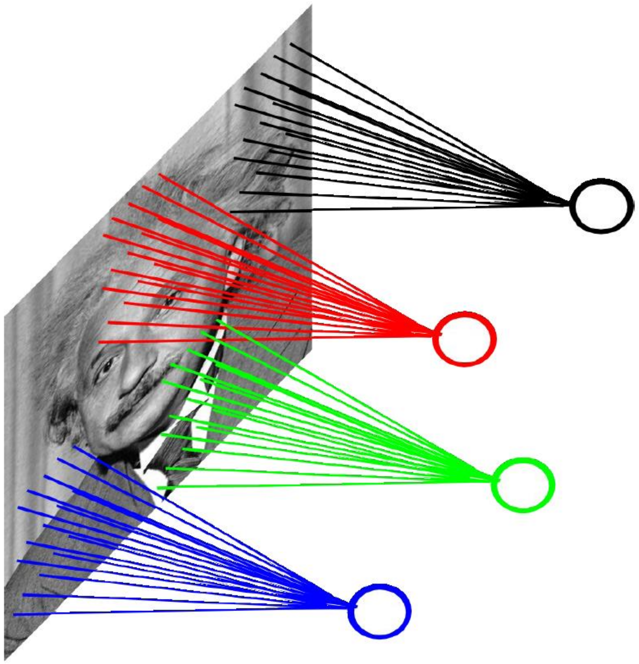
- Let's encode they locality
  - Spatial correlation is local



Locally connected neural net

- Example
  - 1000x1000 image
  - 1M hidden units
  - Filter size: 10x10

$\rightarrow\ 10^8 (= 10^6 \times 10 \times 10)$ parameters!

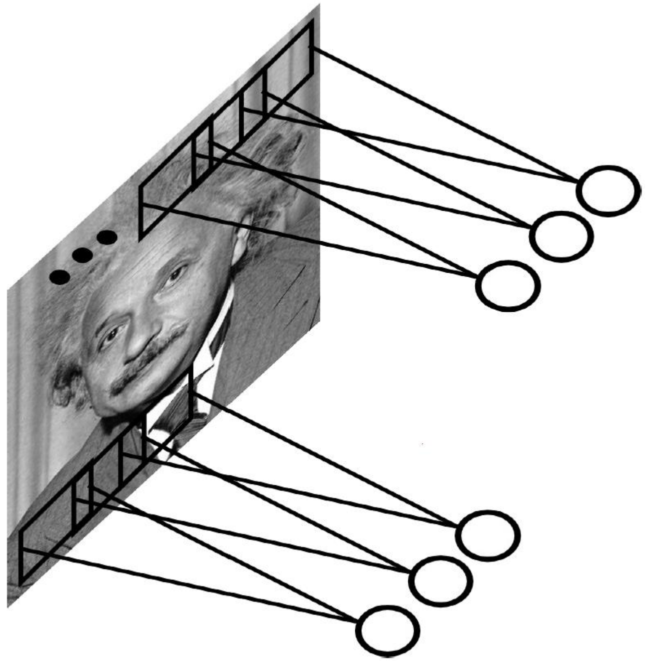


- Let's encode the invariance
  - Statistics is similar at different locations

Convolution neural networks

- Share the same parameters across different locations
  - Convolution with learned kernels
  - Filter size: 10x10

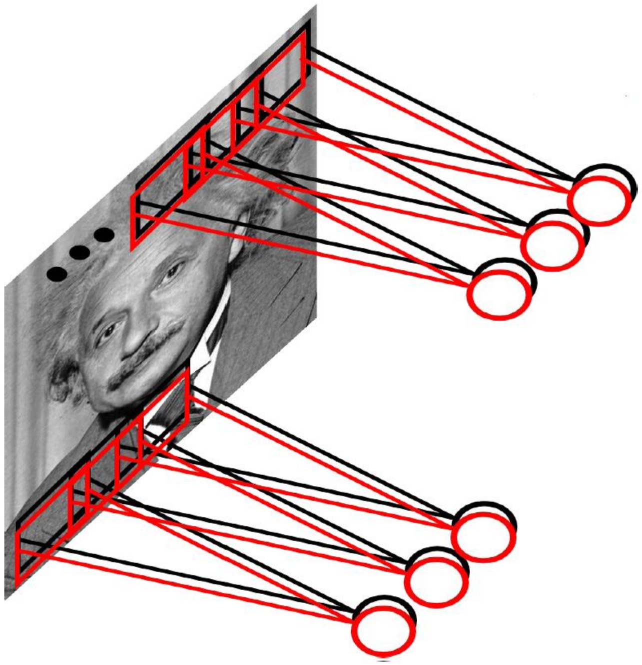
$\rightarrow 10^2$ parameters



Convolution neural networks

- Learn multiple filters
  - 1000x1000 image
  - 100 Filters
  - Filter size: 10x10

➔ 10,000 parameters



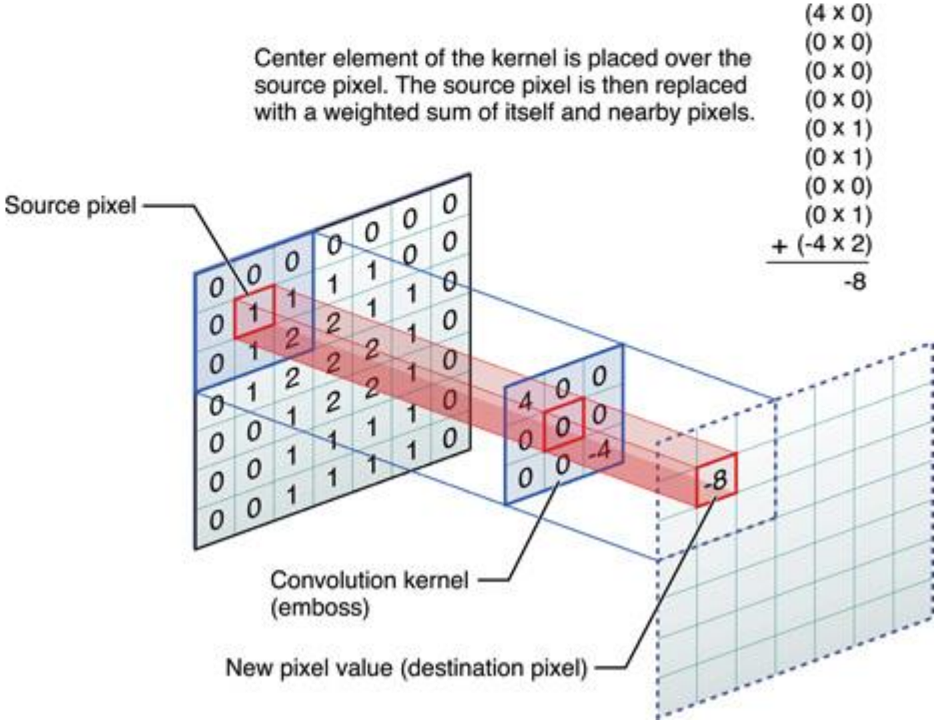
Convolution neural networks

- We can design neural networks that are specifically adapted for image-related problems
  - Must deal with very high-dimensional inputs
  - Can exploit the 2D topology of pixels
  - Can build in invariance to certain variations we can expect
    - Translations, etc

- Ideas
  - Local connectivity
  - Parameter sharing

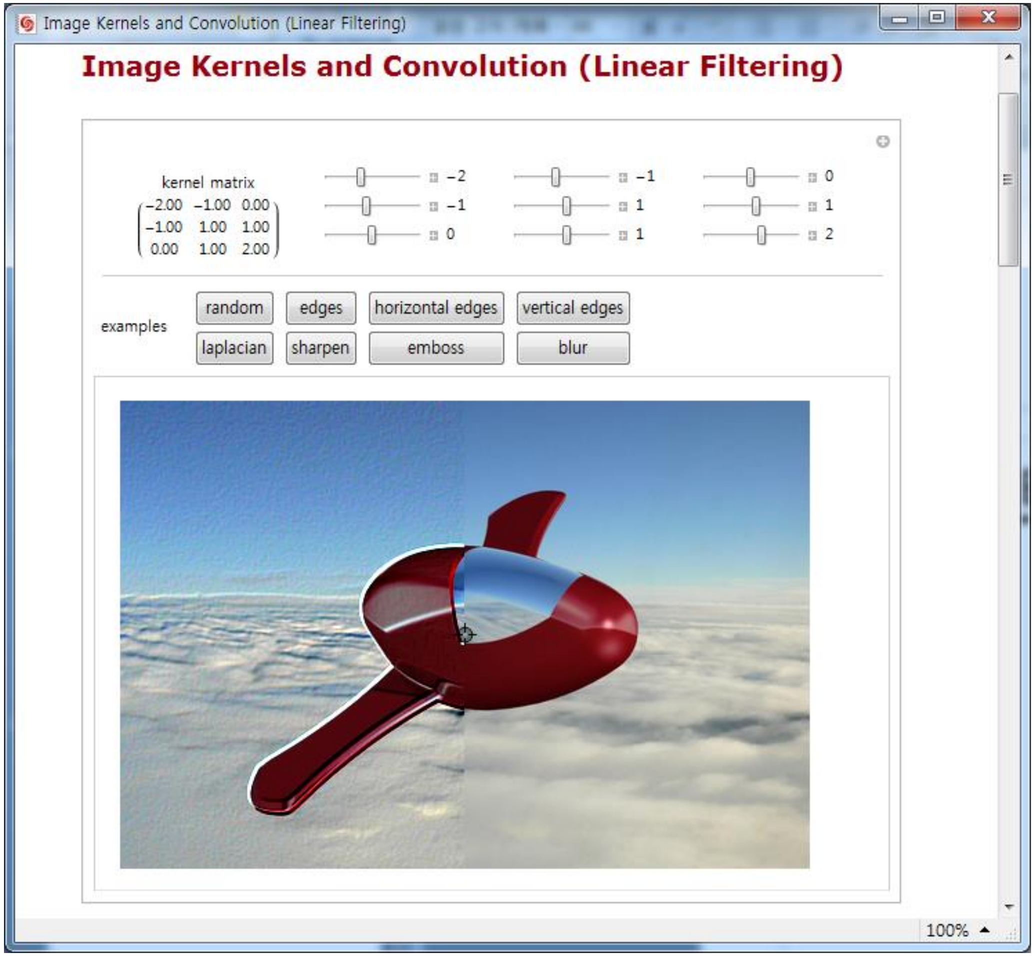
CONVOLUTION (IMAGE PROCESSING)

Convolution

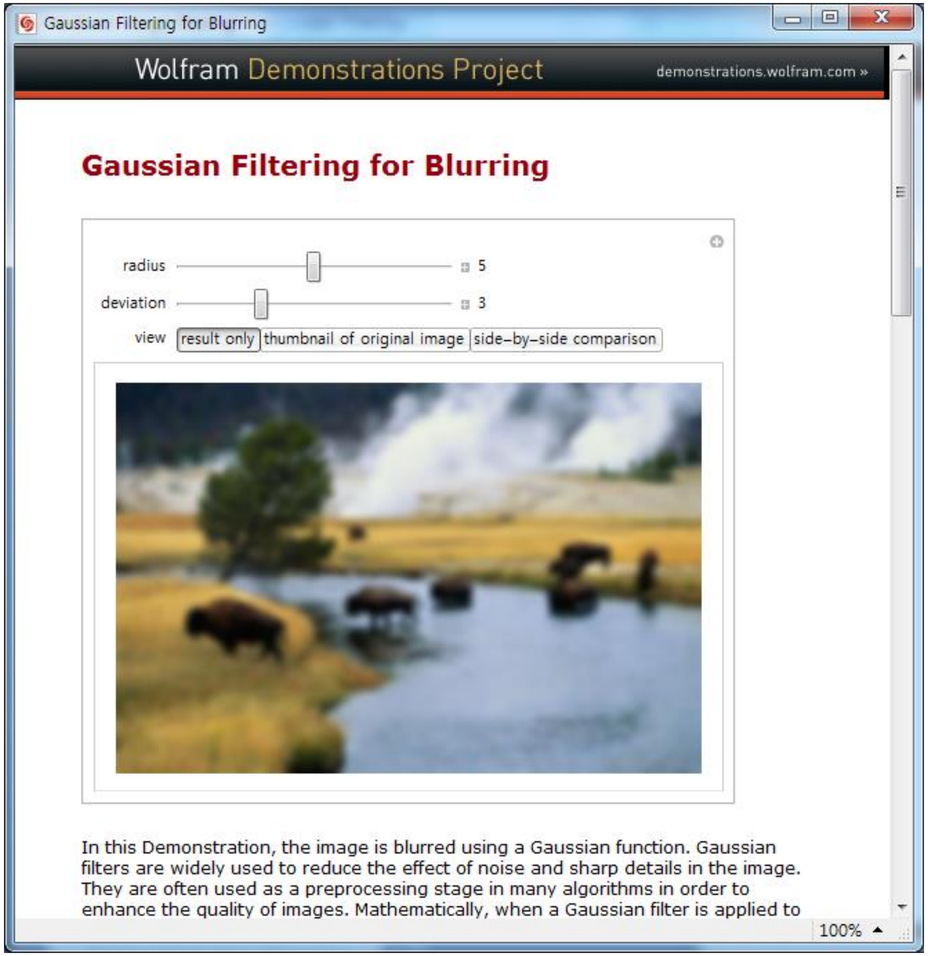


from: https://developer.apple.com/library/ios/documentation/Performance/Conceptual/vImage/ConvolutionOperations/ConvolutionOperations.html

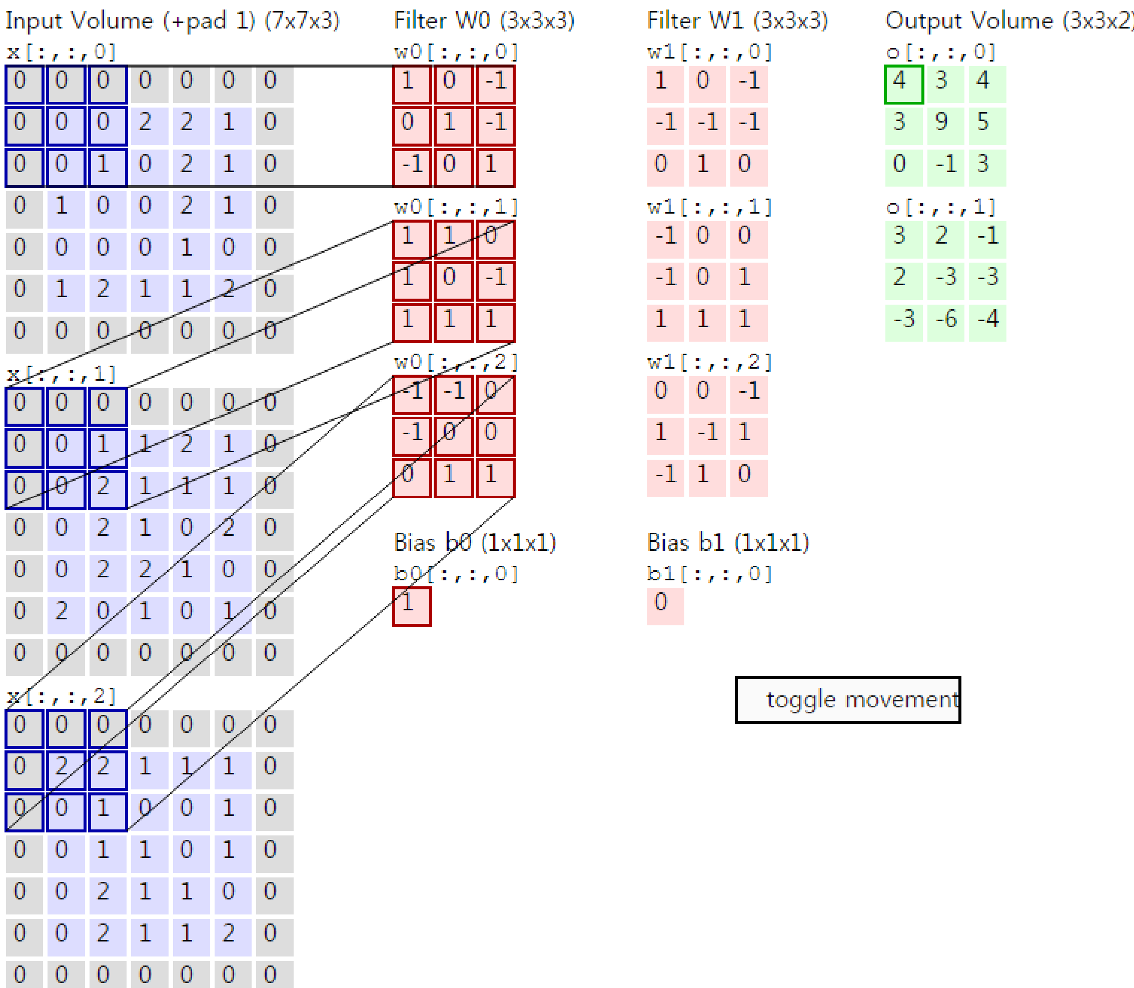
Linear filter



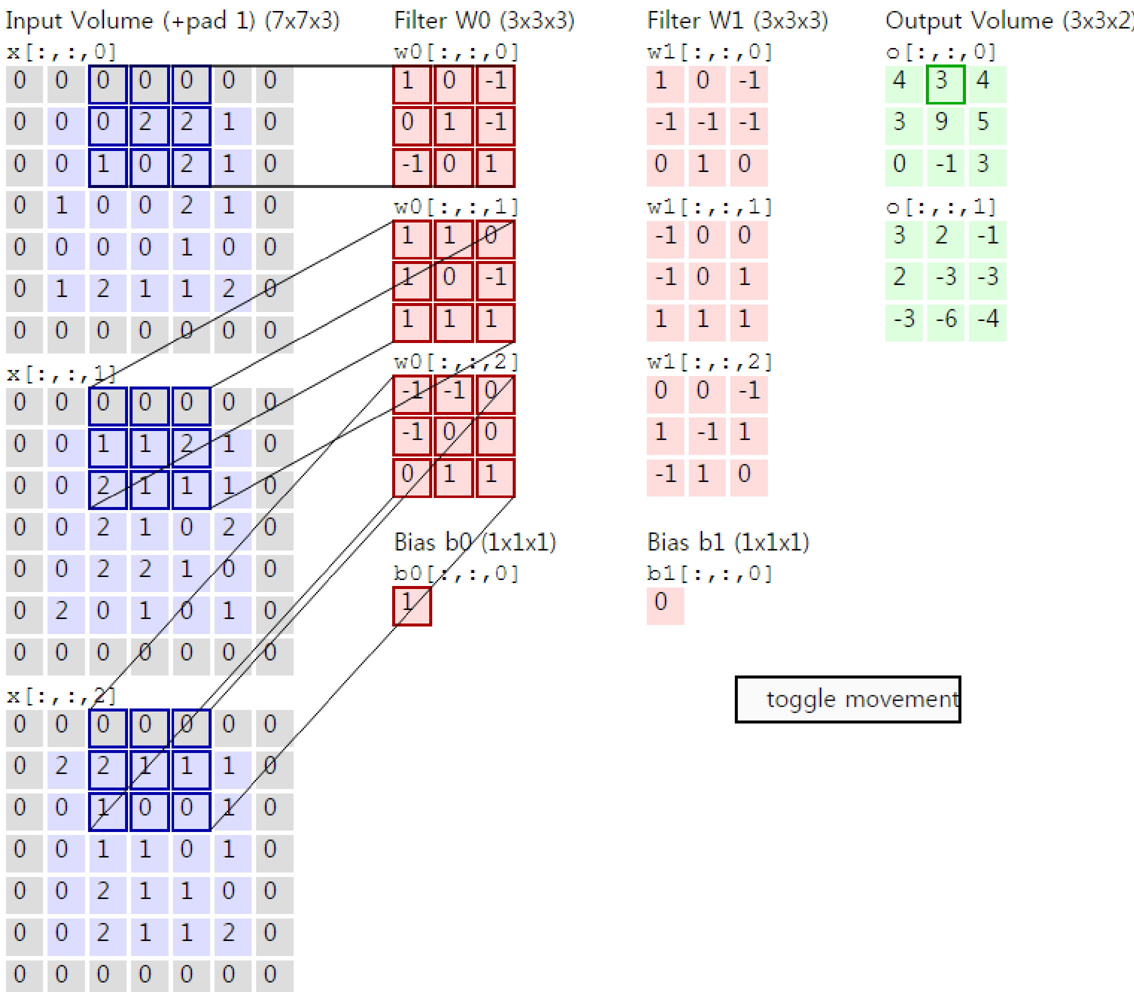
Linear filter (Gaussian)



CONVOLUTION (IN CNN)



Input Volume (+pad 1) (7x7x3)
x[:,:,0]
0 0 0 0 0 0 0
0 0 0 2 2 1 0
0 0 1 0 2 1 0
0 1 0 0 2 1 0
0 0 0 0 1 0 0
0 1 2 1 1 2 0
0 0 0 0 0 0 0
x[:,:,1]
0 0 0 0 0 0 0
0 0 1 1 2 1 0
0 0 2 1 1 1 0
0 0 2 1 0 2 0
0 0 2 2 1 0 0
0 2 0 1 0 1 0
0 0 0 0 0 0 0
x[:,:,2]
0 0 0 0 0 0 0
0 2 2 1 1 1 0
0 0 1 0 0 1 0
0 0 1 1 0 1 0
0 0 2 1 1 0 0
0 0 2 1 1 2 0
0 0 0 0 0 0 0
Filter W0 (3x3x3)
w0[:,:,0]
1 0 -1
0 1 -1
-1 0 1
w0[:,:,1]
1 1 0
1 0 -1
1 1 1
w0[:,:,2]
-1 -1 0
-1 0 0
0 1 1
Bias b0 (1x1x1)
b0[:,:,0]
1
Filter W1 (3x3x3)
w1[:,:,0]
1 0 -1
-1 -1 -1
0 1 0
w1[:,:,1]
-1 0 0
-1 0 1
1 1 1
w1[:,:,2]
0 0 -1
1 -1 1
-1 1 0
Bias b1 (1x1x1)
b1[:,:,0]
0
Output Volume (3x3x2)
o[:,:,0]
4 3 4
3 9 5
0 -1 3
o[:,:,1]
3 2 -1
2 -3 -3
-3 -6 -4
toggle movement



Input Volume (+pad 1) (7x7x3)
x[:,:,0]
0 0 0 0 0 0 0
0 0 0 2 2 1 0
0 0 1 0 2 1 0
0 1 0 0 2 1 0
0 0 0 0 1 0 0
0 1 2 1 1 2 0
0 0 0 0 0 0 0
x[:,:,1]
0 0 0 0 0 0 0
0 0 1 1 2 1 0
0 0 2 1 1 1 0
0 0 2 1 0 2 0
0 0 2 2 1 0 0
0 2 0 1 0 1 0
0 0 0 0 0 0 0
x[:,:,2]
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w0[:,:,2]
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Bias b0 (1x1x1)
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w1[:,:,1]
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-1 0 1
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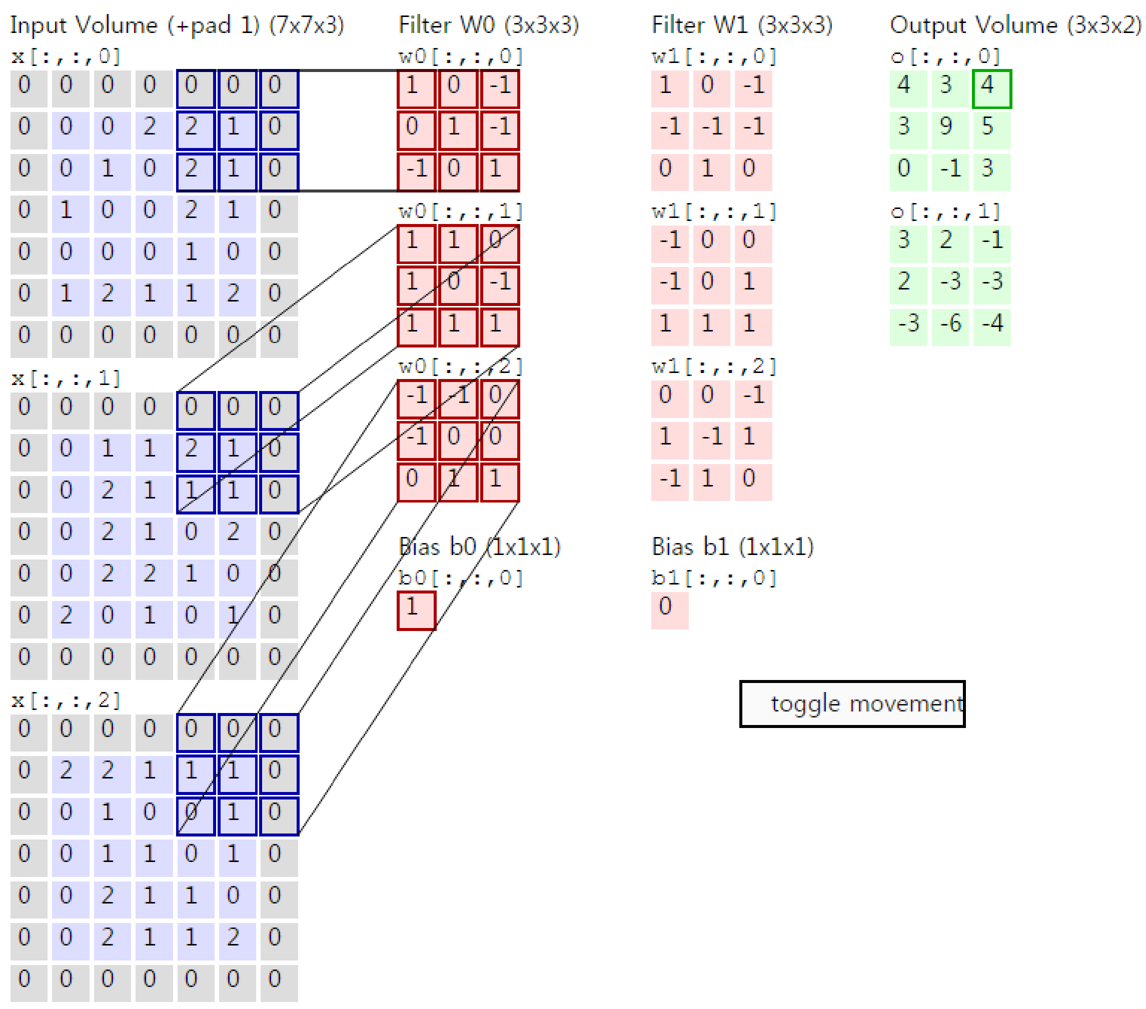
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x[:,:,0]
0 0 0 0 0 0 0
0 0 0 2 2 1 0
0 0 1 0 2 1 0
0 1 0 0 2 1 0
0 0 0 0 1 0 0
0 1 2 1 1 2 0
0 0 0 0 0 0 0
x[:,:,1]
0 0 0 0 0 0 0
0 0 1 1 2 1 0
0 0 2 1 1 1 0
0 0 2 1 0 2 0
0 0 2 2 1 0 0
0 2 0 1 0 1 0
0 0 0 0 0 0 0
x[:,:,2]
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0 0 1 0 0 1 0
0 0 1 1 0 1 0
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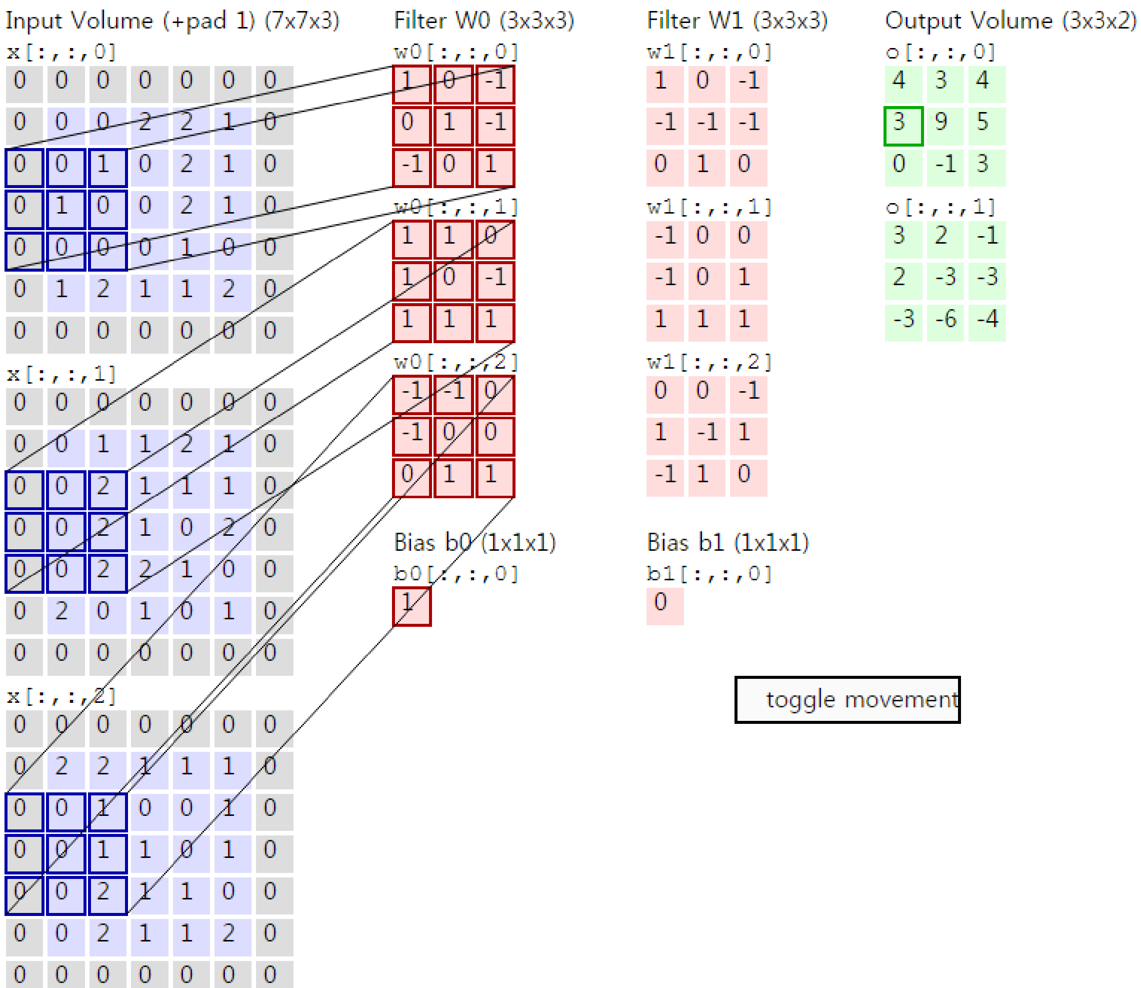
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0 0 0 0 0 0 0
0 0 0 2 2 1 0
0 0 1 0 2 1 0
0 1 0 0 2 1 0
0 0 0 0 1 0 0
0 1 2 1 1 2 0
0 0 0 0 0 0 0
x[:,:,1]
0 0 0 0 0 0 0
0 0 1 1 2 1 0
0 0 2 1 1 1 0
0 0 2 1 0 2 0
0 0 2 2 1 0 0
0 2 0 1 0 1 0
0 0 0 0 0 0 0
x[:,:,2]
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0 2 2 1 1 1 0
0 0 1 0 0 1 0
0 0 1 1 0 1 0
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1 1 0
1 0 -1
1 1 1
w0[:,:,2]
-1 -1 0
-1 0 0
0 1 1
Bias b0 (1x1x1)
b0[:,:,0]
1
Filter W1 (3x3x3)
w1[:,:,0]
1 0 -1
-1 -1 -1
0 1 0
w1[:,:,1]
-1 0 0
-1 0 1
1 1 1
w1[:,:,2]
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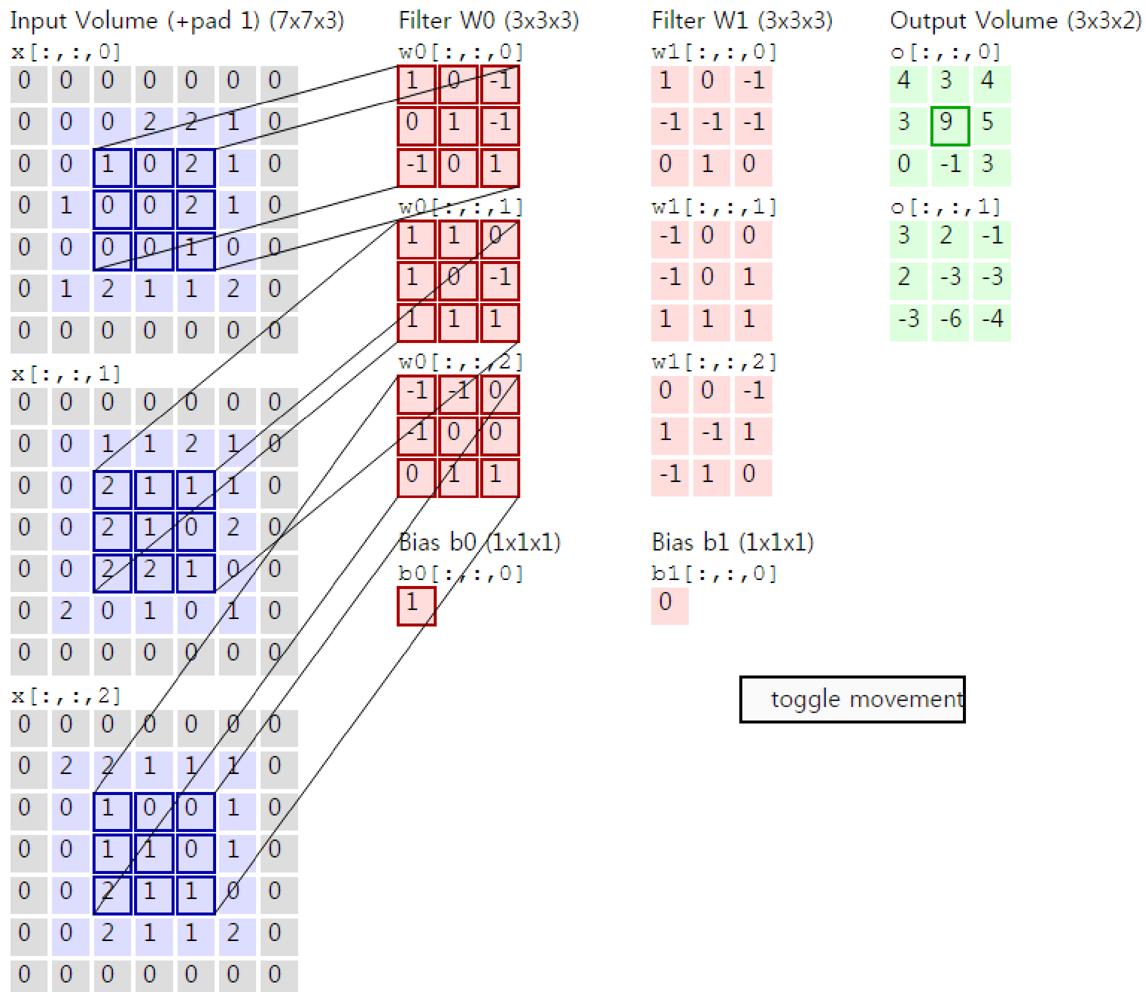
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0 1 0 0 2 1 0
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0 1 2 1 1 2 0
0 0 0 0 0 0 0
x[:,:,1]
0 0 0 0 0 0 0
0 0 1 1 2 1 0
0 0 2 1 1 1 0
0 0 2 1 0 2 0
0 0 2 2 1 0 0
0 2 0 1 0 1 0
0 0 0 0 0 0 0
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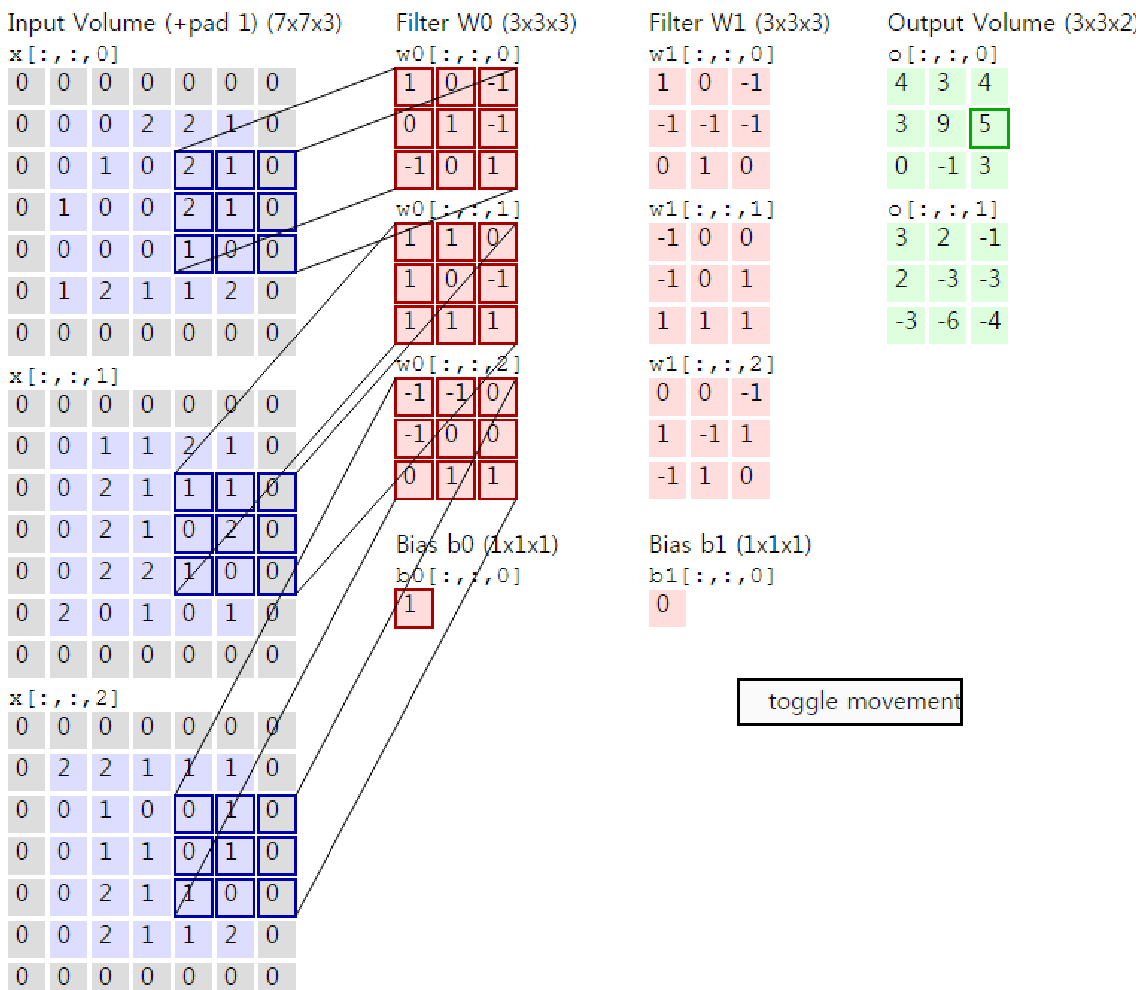
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0 1 2 1 1 2 0
0 0 0 0 0 0 0
x[:,:,1]
0 0 0 0 0 0 0
0 0 1 1 2 1 0
0 0 2 1 1 1 0
0 0 2 1 0 2 0
0 0 2 2 1 0 0
0 2 0 1 0 1 0
0 0 0 0 0 0 0
x[:,:,2]
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-1 -1 0
-1 0 0
0 1 1
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b0[:,:,0]
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w1[:,:,0]
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0 1 0
w1[:,:,1]
-1 0 0
-1 0 1
1 1 1
w1[:,:,2]
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o[:,:,0]
4 3 4
3 9 5
0 -1 3
o[:,:,1]
3 2 -1
2 -3 -3
-3 -6 -4
toggle movement

Input Volume (+pad 1) (7x7x3)

x[:,:,0]

0	0	0	0	0	0	0
0	0	0	2	2	1	0
0	0	1	0	2	1	0
0	1	0	0	2	1	0
0	0	0	0	1	0	0
0	1	2	1	1	2	0
0	0	0	0	0	0	0

x[:,:,1]

0	0	0	0	0	0	0
0	0	1	1	2	1	0
0	0	2	1	1	1	0
0	0	2	1	0	2	0
0	0	2	2	1	0	0
0	2	0	1	0	1	0
0	0	0	0	0	0	0

x[:,:,2]

0	0	0	0	0	0	0
0	2	2	1	1	1	0
0	0	1	0	0	1	0
0	0	1	1	0	1	0
0	0	2	1	1	0	0
0	0	2	1	1	2	0
0	0	0	0	0	0	0

Filter W0 (3x3x3)

w0[:,:,0]

1	0	-1
0	1	-1
-1	0	1

w0[:,:,1]

1	1	0
1	0	-1
1	1	1

w0[:,:,2]

-1	-1	0
-1	0	0
0	1	1

Bias b0 (1x1x1)

b0[:,:,0]

1

Filter W1 (3x3x3)

w1[:,:,0]

1	0	-1
-1	-1	-1
0	1	0

w1[:,:,1]

-1	0	0
-1	0	1
1	1	1

w1[:,:,2]

0	0	-1
1	-1	1
-1	1	0

Bias b1 (1x1x1)

b1[:,:,0]

0

Output Volume (3x3x2)

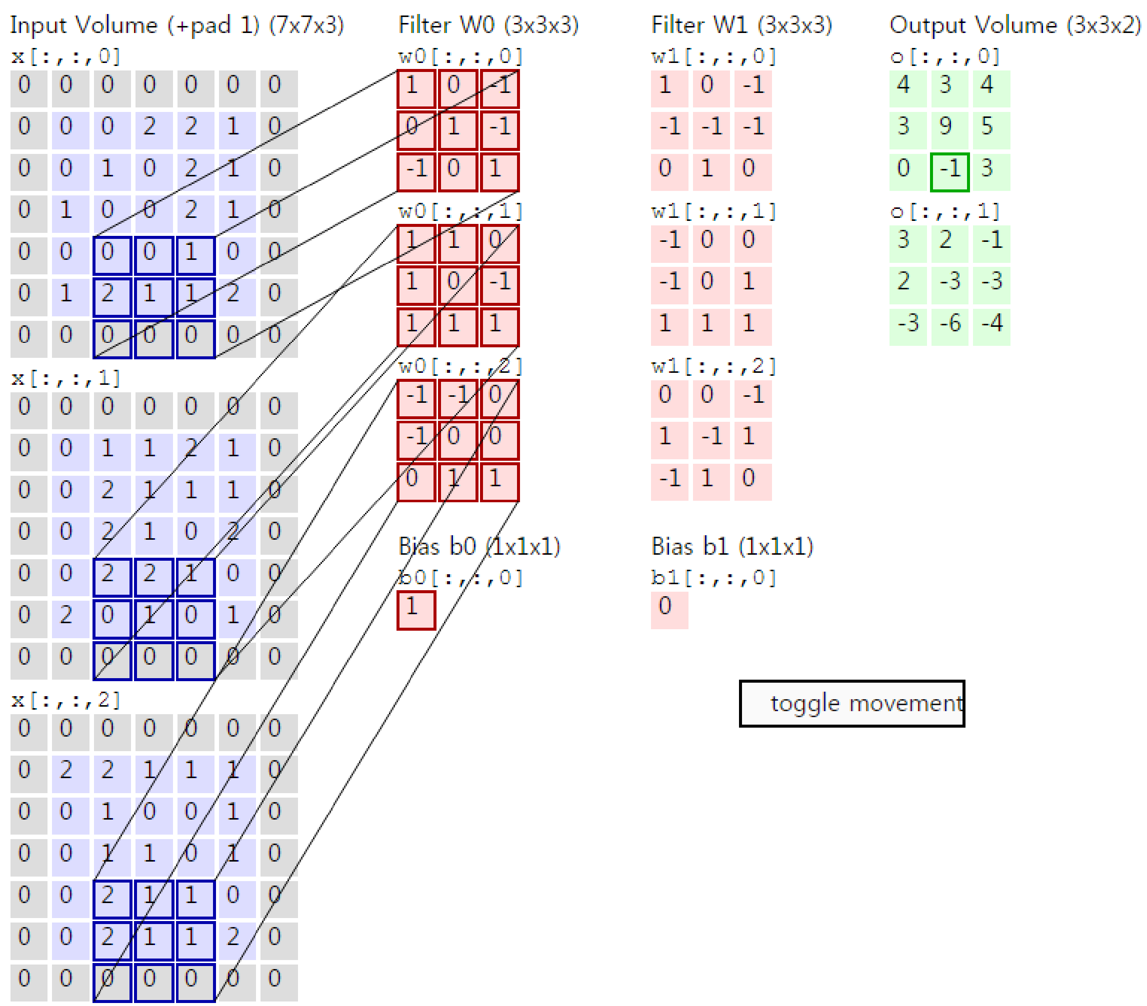
o[:,:,0]

4	3	4
3	9	5
0	-1	3

o[:,:,1]

3	2	-1
2	-3	-3
-3	-6	-4

toggle movement



Input Volume (+pad 1) (7x7x3)
x[:,:,0]
0 0 0 0 0 0 0
0 0 0 2 2 1 0
0 0 1 0 2 1 0
0 1 0 0 2 1 0
0 0 0 0 1 0 0
0 1 2 1 1 2 0
0 0 0 0 0 0 0
x[:,:,1]
0 0 0 0 0 0 0
0 0 1 1 2 1 0
0 0 2 1 1 1 0
0 0 2 1 0 2 0
0 0 2 2 1 0 0
0 2 0 1 0 1 0
0 0 0 0 0 0 0
x[:,:,2]
0 0 0 0 0 0 0
0 2 2 1 1 1 0
0 0 1 0 0 1 0
0 0 1 1 0 1 0
0 0 2 1 1 0 0
0 0 2 1 1 2 0
0 0 0 0 0 0 0
Filter W0 (3x3x3)
w0[:,:,0]
1 0 -1
0 1 -1
-1 0 1
w0[:,:,1]
1 1 0
1 0 -1
1 1 1
w0[:,:,2]
-1 -1 0
-1 0 0
0 1 1
Bias b0 (1x1x1)
b0[:,:,0]
1
Filter W1 (3x3x3)
w1[:,:,0]
1 0 -1
-1 -1 -1
0 1 0
w1[:,:,1]
-1 0 0
-1 0 1
1 1 1
w1[:,:,2]
0 0 -1
1 -1 1
-1 1 0
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Output Volume (3x3x2)
o[:,:,0]
4 3 4
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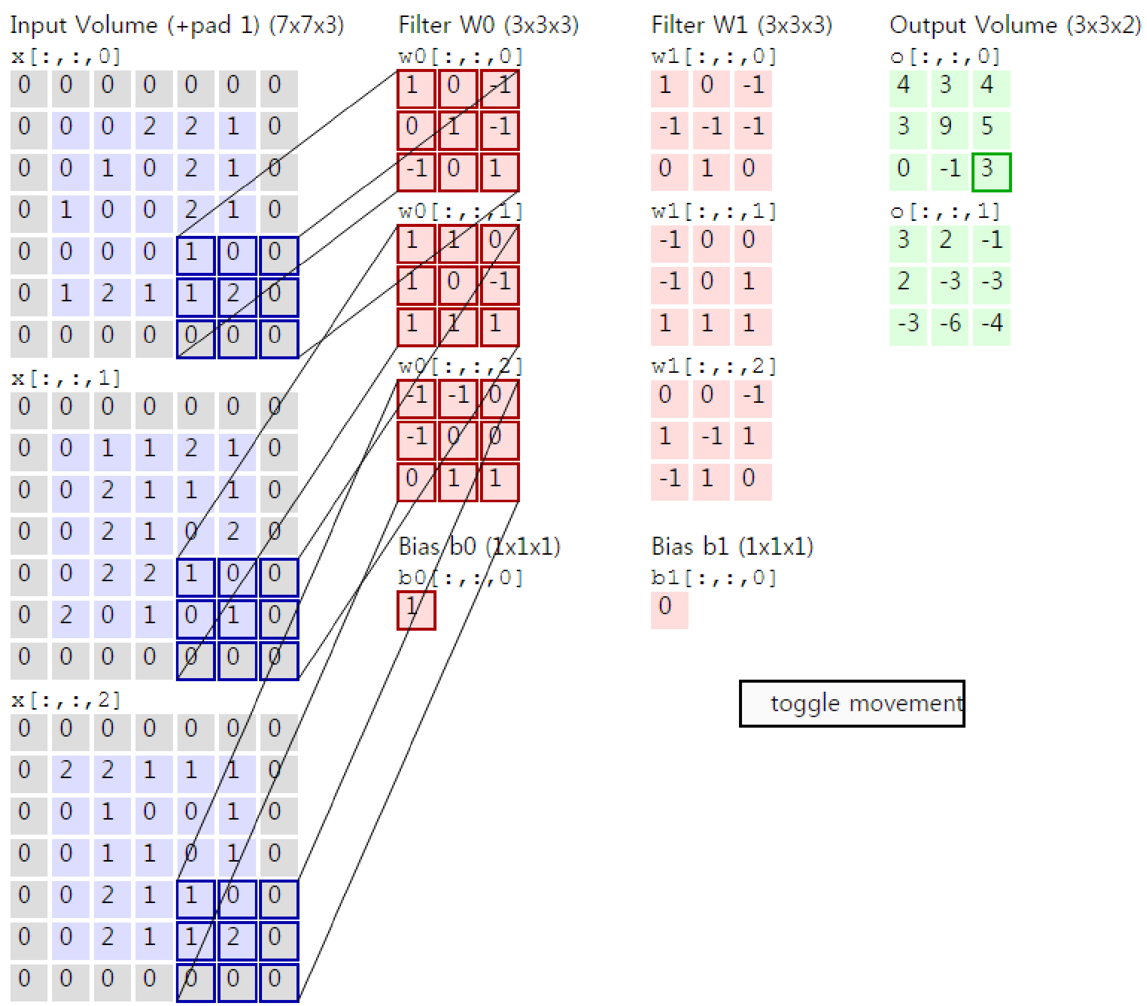

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0 0 0 0 0 0 0
0 0 0 2 2 1 0
0 0 1 0 2 1 0
0 1 0 0 2 1 0
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0 1 2 1 1 2 0
0 0 0 0 0 0 0
x[:,:,1]
0 0 0 0 0 0 0
0 0 1 1 2 1 0
0 0 2 1 1 1 0
0 0 2 1 0 2 0
0 0 2 2 1 0 0
0 2 0 1 0 1 0
0 0 0 0 0 0 0
x[:,:,2]
0 0 0 0 0 0 0
0 2 2 1 1 1 0
0 0 1 0 0 1 0
0 0 1 1 0 1 0
0 0 2 1 1 0 0
0 0 2 1 1 2 0
0 0 0 0 0 0 0
Filter W0 (3x3x3)
w0[:,:,0]
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0 1 -1
-1 0 1
w0[:,:,1]
1 1 0
1 0 -1
1 1 1
w0[:,:,2]
-1 -1 0
-1 0 0
0 1 1
Bias b0 (1x1x1)
b0[:,:,0]
1
Filter W1 (3x3x3)
w1[:,:,0]
1 0 -1
-1 -1 -1
0 1 0
w1[:,:,1]
-1 0 0
-1 0 1
1 1 1
w1[:,:,2]
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Bias b1 (1x1x1)
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0
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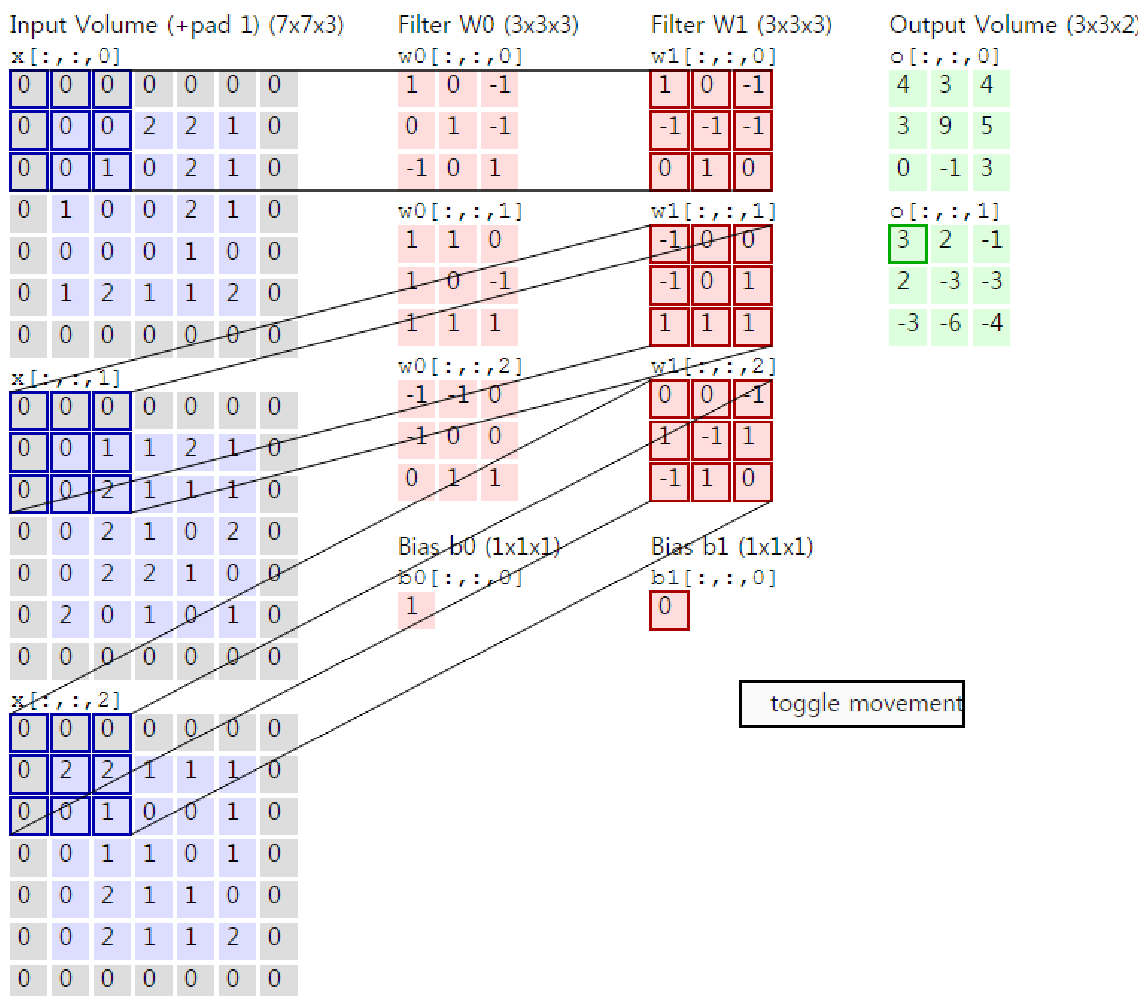
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0 0 0 0 0 0 0
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0 0 1 0 2 1 0
0 1 0 0 2 1 0
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0 1 2 1 1 2 0
0 0 0 0 0 0 0
x[:,:,1]
0 0 0 0 0 0 0
0 0 1 1 2 1 0
0 0 2 1 1 1 0
0 0 2 1 0 2 0
0 0 2 2 1 0 0
0 2 0 1 0 1 0
0 0 0 0 0 0 0
x[:,:,2]
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Bias b0 (1x1x1)
b0[:,:,0]
1
Filter W1 (3x3x3)
w1[:,:,0]
1 0 -1
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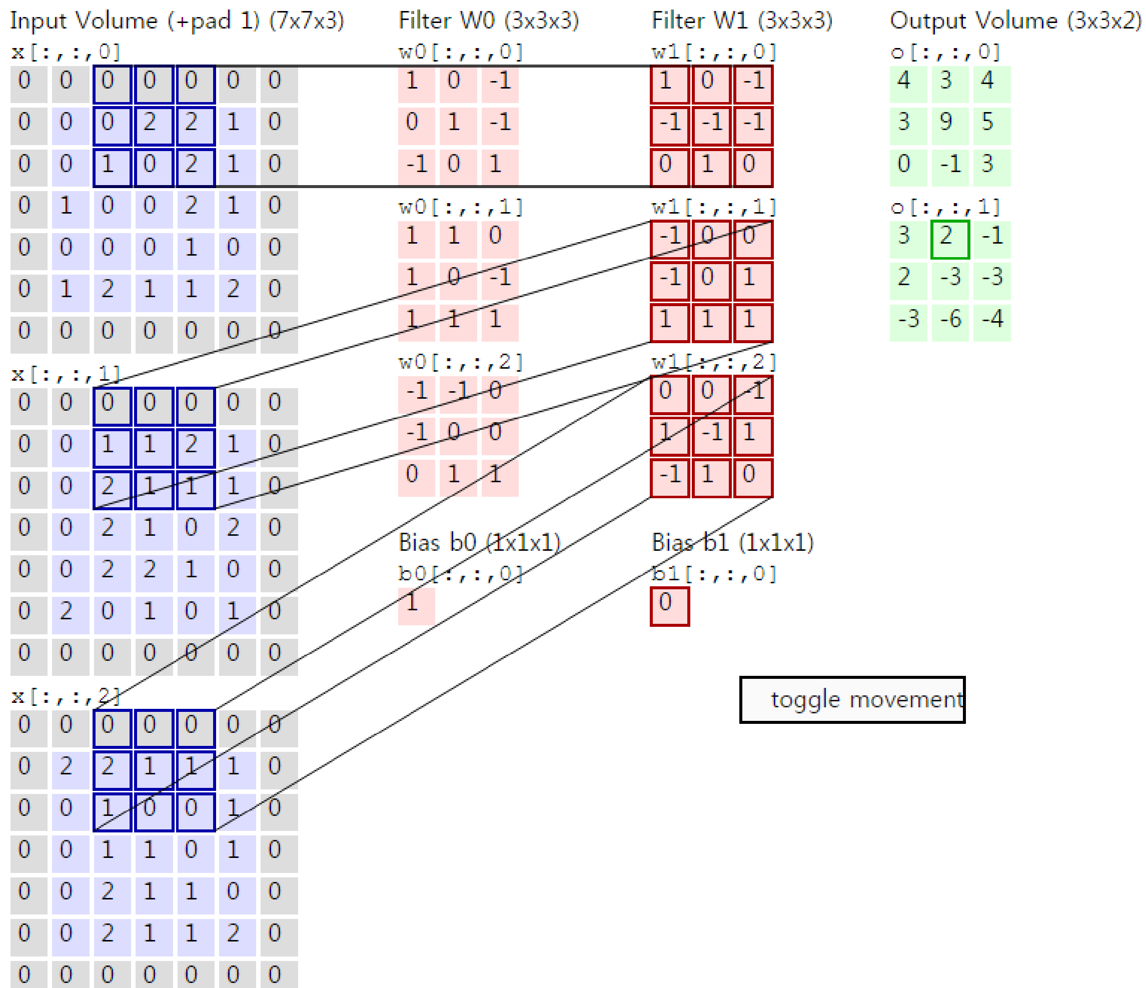
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0 0 0 2 2 1 0
0 0 1 0 2 1 0
0 1 0 0 2 1 0
0 0 0 0 1 0 0
0 1 2 1 1 2 0
0 0 0 0 0 0 0
x[:,:,1]
0 0 0 0 0 0 0
0 0 1 1 2 1 0
0 0 2 1 1 1 0
0 0 2 1 0 2 0
0 0 2 2 1 0 0
0 2 0 1 0 1 0
0 0 0 0 0 0 0
x[:,:,2]
0 0 0 0 0 0 0
0 2 2 1 1 1 0
0 0 1 0 0 1 0
0 0 1 1 0 1 0
0 0 2 1 1 0 0
0 0 2 1 1 2 0
0 0 0 0 0 0 0
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0 1 -1
-1 0 1
w0[:,:,1]
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1 0 -1
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w0[:,:,2]
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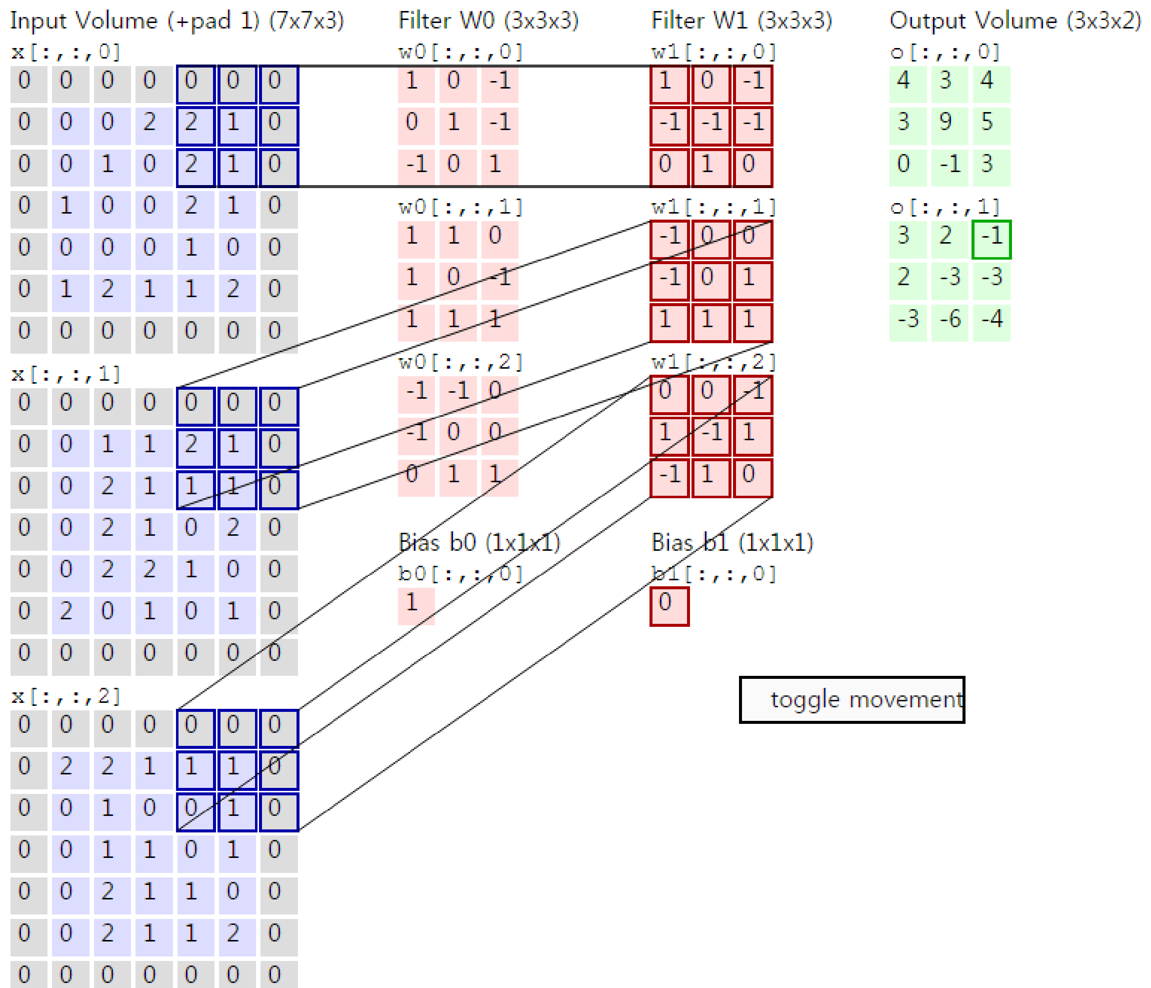
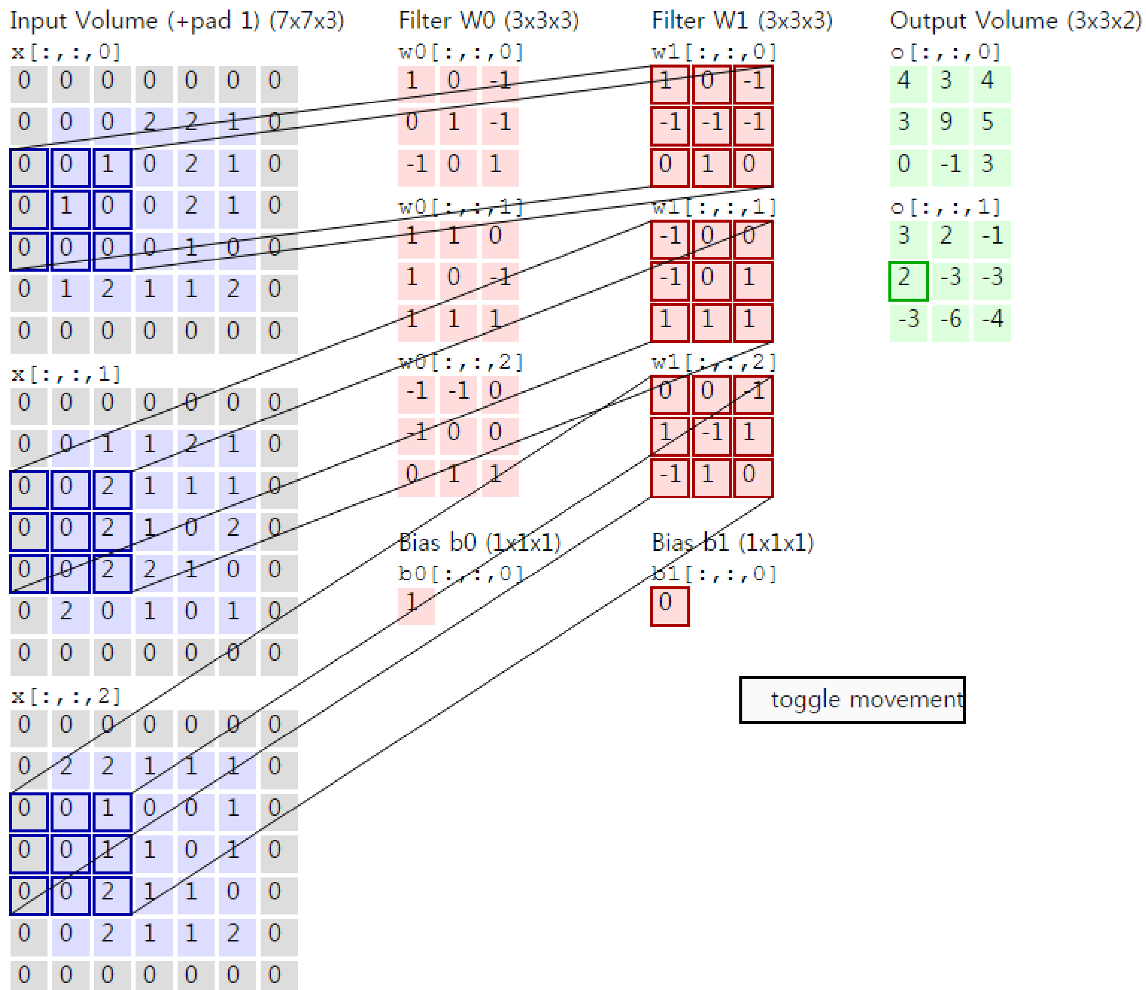
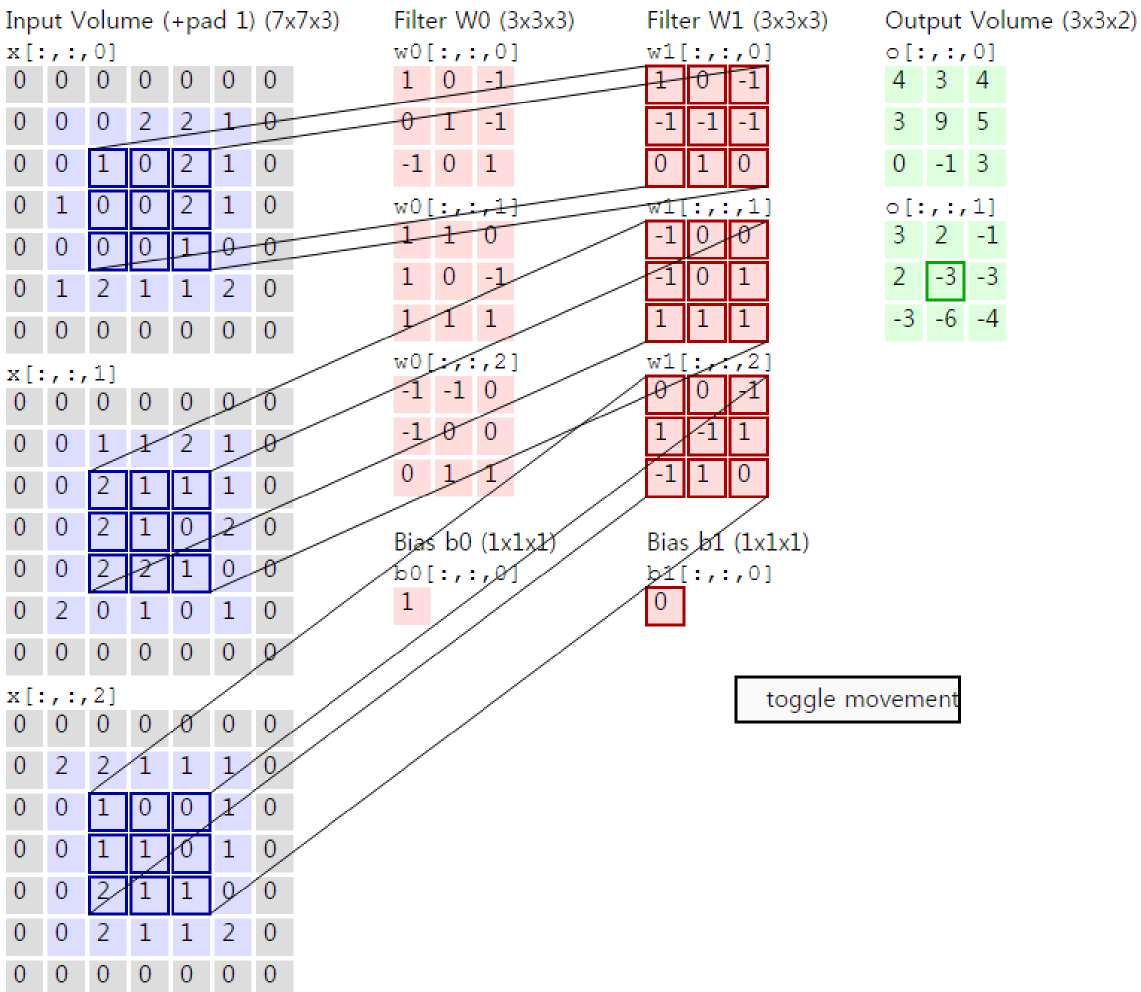
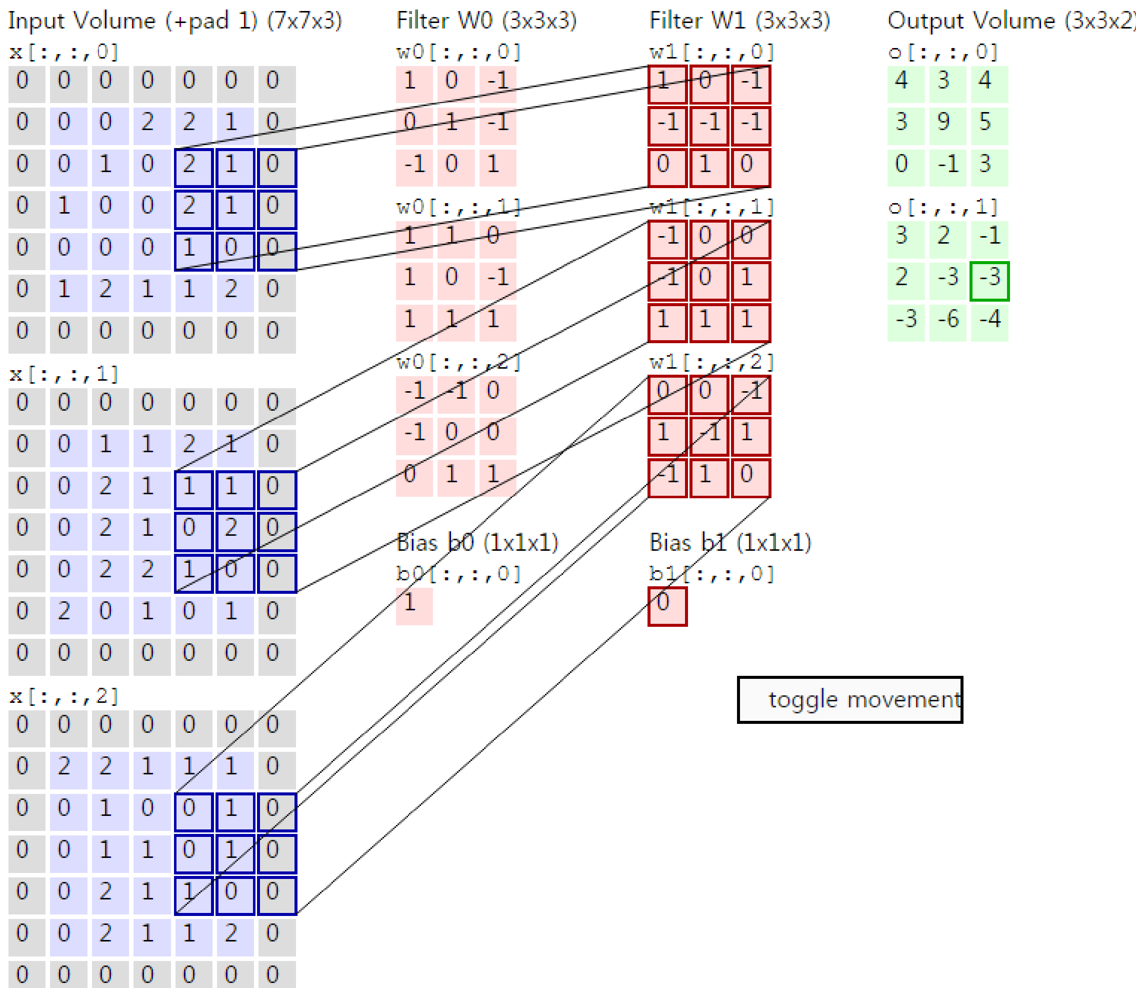
-1 -1 -1
0 1 0
w1[:,:,1]
-1 0 0
-1 0 1
1 1 1
w1[:,:,2]
0 0 -1
1 -1 1
-1 1 0
Bias b1 (1x1x1)
b1[:,:,0]
0
Output Volume (3x3x2)
o[:,:,0]
4 3 4
3 9 5
0 -1 3
o[:,:,1]
3 2 -1
2 -3 -3
-3 -6 -4
toggle movement

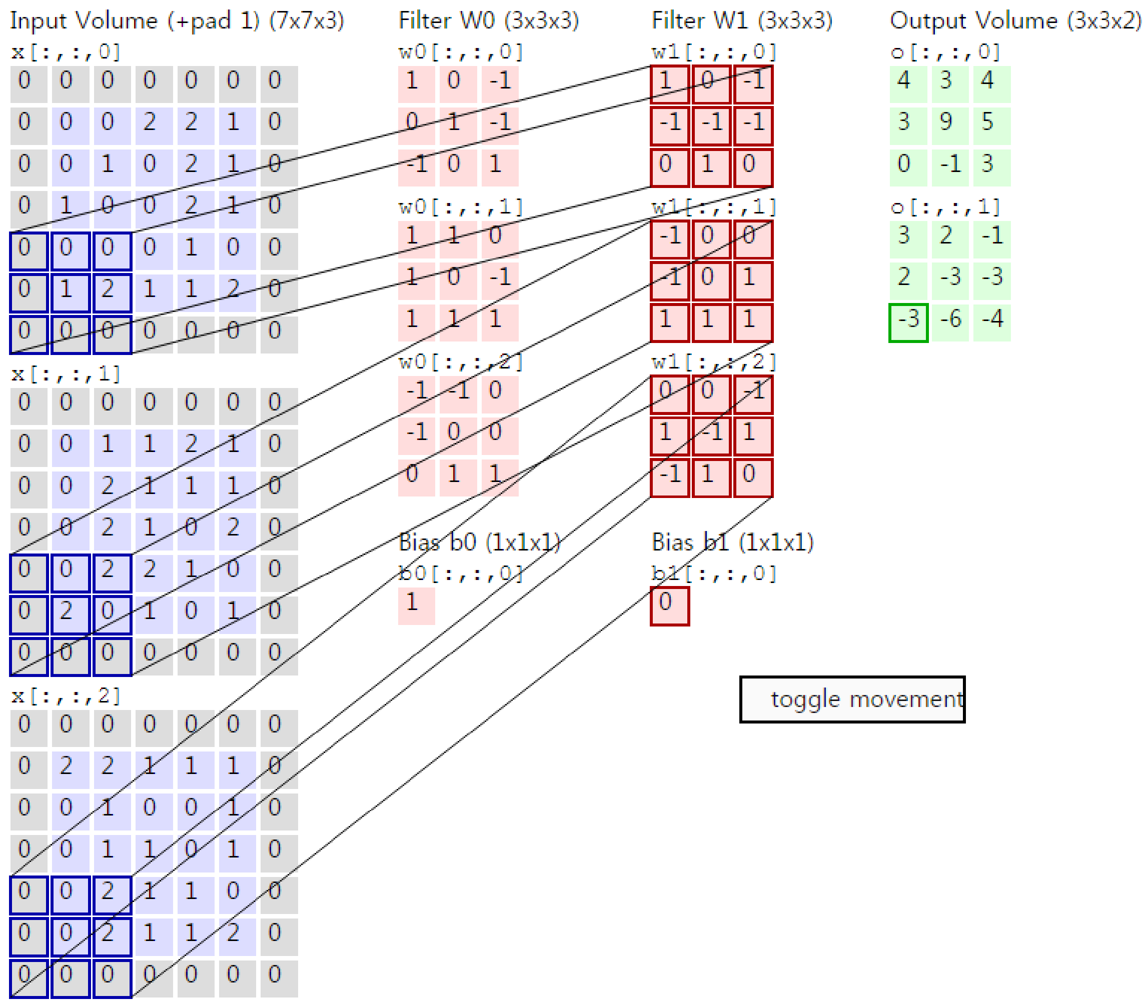


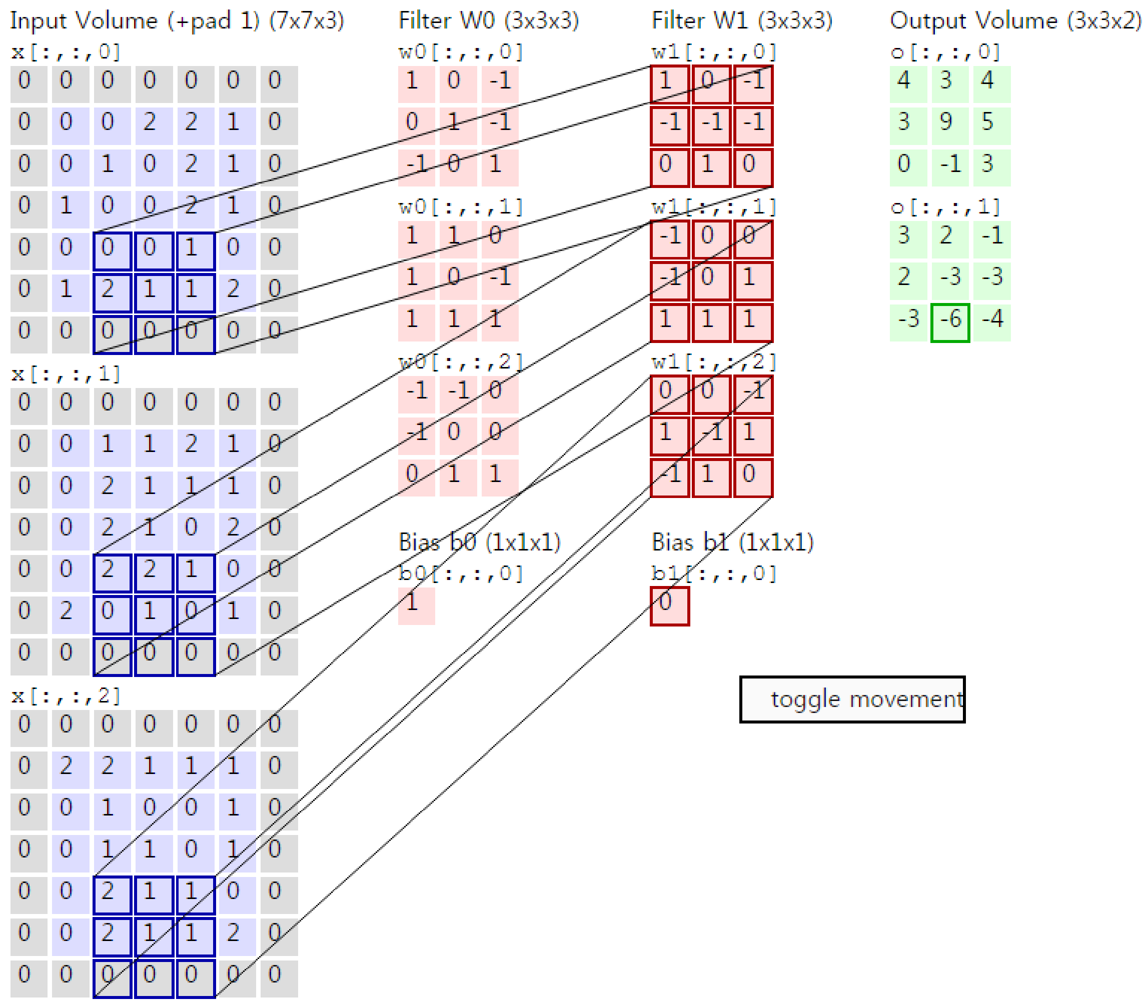
Input Volume (+pad 1) (7x7x3)
x[:,:,0]
0 0 0 0 0 0 0
0 0 0 2 2 1 0
0 0 1 0 2 1 0
0 1 0 0 2 1 0
0 0 0 0 1 0 0
0 1 2 1 1 2 0
0 0 0 0 0 0 0
x[:,:,1]
0 0 0 0 0 0 0
0 0 1 1 2 1 0
0 0 2 1 1 1 0
0 0 2 1 0 2 0
0 0 2 2 1 0 0
0 2 0 1 0 1 0
0 0 0 0 0 0 0
x[:,:,2]
0 0 0 0 0 0 0
0 2 2 1 1 1 0
0 0 1 0 0 1 0
0 0 1 1 0 1 0
0 0 2 1 1 0 0
0 0 2 1 1 2 0
0 0 0 0 0 0 0
Filter W0 (3x3x3)
w0[:,:,0]
1 0 -1
0 1 -1
-1 0 1
w0[:,:,1]
1 1 0
1 0 -1
1 1 1
w0[:,:,2]
-1 -1 0
-1 0 0
0 1 1
Bias b0 (1x1x1)
b0[:,:,0]
1
Filter W1 (3x3x3)
w1[:,:,0]
1 0 -1
-1 -1 -1
0 1 0
w1[:,:,1]
-1 0 0
-1 0 1
1 1 1
w1[:,:,2]
0 0 -1
1 -1 1
-1 1 0
Bias b1 (1x1x1)
b1[:,:,0]
0
Output Volume (3x3x2)
o[:,:,0]
4 3 4
3 9 5
0 -1 3
o[:,:,1]
3 2 -1
2 -3 -3
-3 -6 -4
toggle movement

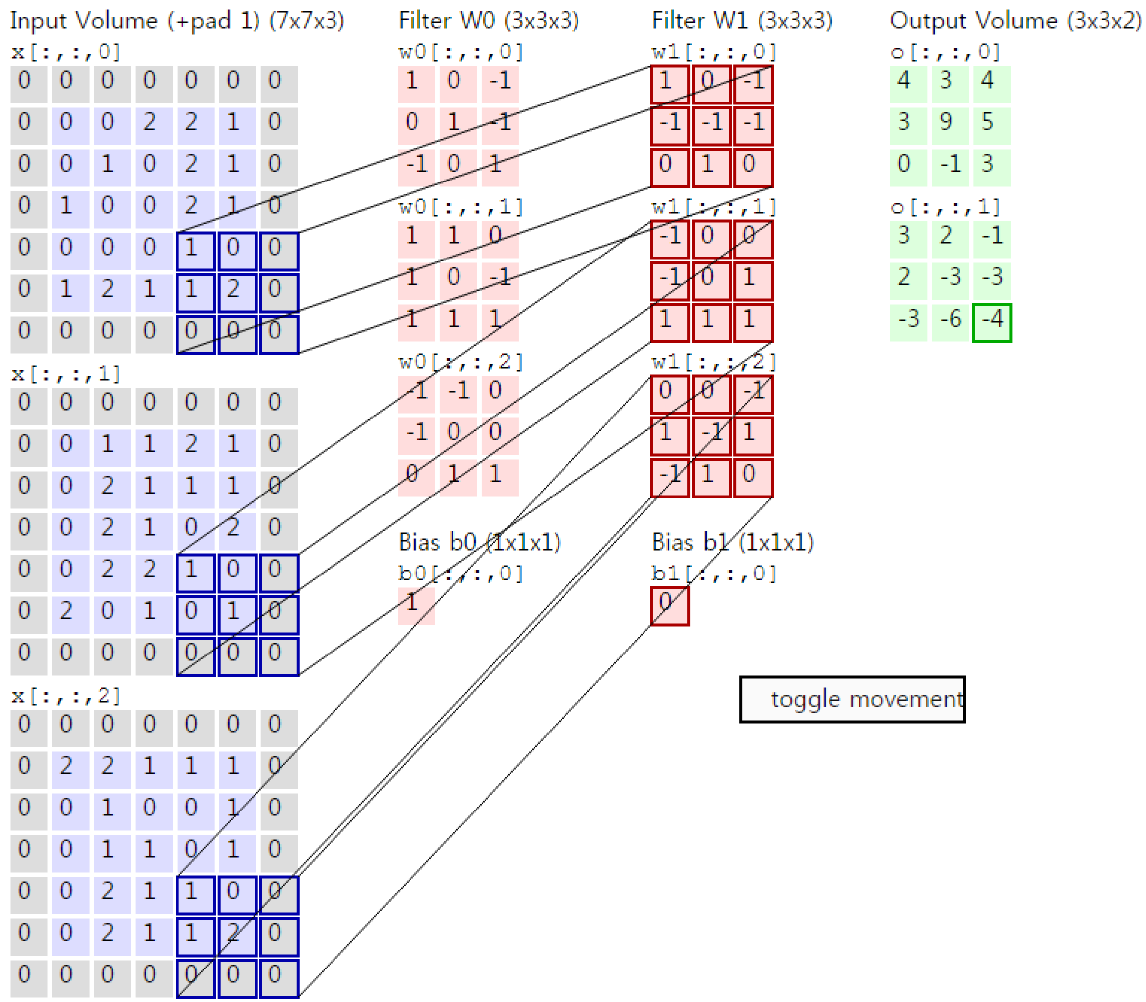

Input Volume (+pad 1) (7x7x3)
x[:,:,0]
0 0 0 0 0 0 0
0 0 0 2 2 1 0
0 0 1 0 2 1 0
0 1 0 0 2 1 0
0 0 0 0 1 0 0
0 1 2 1 1 2 0
0 0 0 0 0 0 0
x[:,:,1]
0 0 0 0 0 0 0
0 0 1 1 2 1 0
0 0 2 1 1 1 0
0 0 2 1 0 2 0
0 0 2 2 1 0 0
0 2 0 1 0 1 0
0 0 0 0 0 0 0
x[:,:,2]
0 0 0 0 0 0 0
0 2 2 1 1 1 0
0 0 1 0 0 1 0
0 0 1 1 0 1 0
0 0 2 1 1 0 0
0 0 2 1 1 2 0
0 0 0 0 0 0 0
Filter W0 (3x3x3)
w0[:,:,0]
1 0 -1
0 1 -1
-1 0 1
w0[:,:,1]
1 1 0
1 0 -1
1 1 1
w0[:,:,2]
-1 -1 0
-1 0 0
0 1 1
Bias b0 (1x1x1)
b0[:,:,0]
1
Filter W1 (3x3x3)
w1[:,:,0]
1 0 -1
-1 -1 -1
0 1 0
w1[:,:,1]
-1 0 0
-1 0 1
1 1 1
w1[:,:,2]
0 0 -1
1 -1 1
-1 1 0
Bias b1 (1x1x1)
b1[:,:,0]
0
Output Volume (3x3x2)
o[:,:,0]
4 3 4
3 9 5
0 -1 3
o[:,:,1]
3 2 -1
2 -3 -3
-3 -6 -4
toggle movement


Input Volume (+pad 1) (7x7x3)
x[:,:,0]
0 0 0 0 0 0 0
0 0 0 2 2 1 0
0 0 1 0 2 1 0
0 1 0 0 2 1 0
0 0 0 0 1 0 0
0 1 2 1 1 2 0
0 0 0 0 0 0 0
x[:,:,1]
0 0 0 0 0 0 0
0 0 1 1 2 1 0
0 0 2 1 1 1 0
0 0 2 1 0 2 0
0 0 2 2 1 0 0
0 2 0 1 0 1 0
0 0 0 0 0 0 0
x[:,:,2]
0 0 0 0 0 0 0
0 2 2 1 1 1 0
0 0 1 0 0 1 0
0 0 1 1 0 1 0
0 0 2 1 1 0 0
0 0 2 1 1 2 0
0 0 0 0 0 0 0
Filter W0 (3x3x3)
w0[:,:,0]
1 0 -1
0 1 -1
-1 0 1
w0[:,:,1]
1 1 0
1 0 -1
1 1 1
w0[:,:,2]
-1 -1 0
-1 0 0
0 1 1
Bias b0 (1x1x1)
b0[:,:,0]
1
Filter W1 (3x3x3)
w1[:,:,0]
1 0 -1
-1 -1 -1
0 1 0
w1[:,:,1]
-1 0 0
-1 0 1
1 1 1
w1[:,:,2]
0 0 -1
1 -1 1
-1 1 0
Bias b1 (1x1x1)
b1[:,:,0]
0
Output Volume (3x3x2)
o[:,:,0]
4 3 4
3 9 5
0 -1 3
o[:,:,1]
3 2 -1
2 -3 -3
-3 -6 -4
toggle movement


Input Volume (+pad 1) (7x7x3)
x[:,:,0]
0 0 0 0 0 0 0
0 0 0 2 2 1 0
0 0 1 0 2 1 0
0 1 0 0 2 1 0
0 0 0 0 1 0 0
0 1 2 1 1 2 0
0 0 0 0 0 0 0
x[:,:,1]
0 0 0 0 0 0 0
0 0 1 1 2 1 0
0 0 2 1 1 1 0
0 0 2 1 0 2 0
0 0 2 2 1 0 0
0 2 0 1 0 1 0
0 0 0 0 0 0 0
x[:,:,2]
0 0 0 0 0 0 0
0 2 2 1 1 1 0
0 0 1 0 0 1 0
0 0 1 1 0 1 0
0 0 2 1 1 0 0
0 0 2 1 1 2 0
0 0 0 0 0 0 0
Filter W0 (3x3x3)
w0[:,:,0]
1 0 -1
0 1 -1
-1 0 1
w0[:,:,1]
1 1 0
1 0 -1
1 1 1
w0[:,:,2]
-1 -1 0
-1 0 0
0 1 1
Bias b0 (1x1x1)
b0[:,:,0]
1
Filter W1 (3x3x3)
w1[:,:,0]
1 0 -1
-1 -1 -1
0 1 0
w1[:,:,1]
-1 0 0
-1 0 1
1 1 1
w1[:,:,2]
0 0 -1
1 -1 1
-1 1 0
Bias b1 (1x1x1)
b1[:,:,0]
0
Output Volume (3x3x2)
o[:,:,0]
4 3 4
3 9 5
0 -1 3
o[:,:,1]
3 2 -1
2 -3 -3
-3 -6 -4
toggle movement


Input Volume (+pad 1) (7x7x3)
x[:,:,0]
0 0 0 0 0 0 0
0 0 0 2 2 1 0
0 0 1 0 2 1 0
0 1 0 0 2 1 0
0 0 0 0 1 0 0
0 1 2 1 1 2 0
0 0 0 0 0 0 0
x[:,:,1]
0 0 0 0 0 0 0
0 0 1 1 2 1 0
0 0 2 1 1 1 0
0 0 2 1 0 2 0
0 0 2 2 1 0 0
0 2 0 1 0 1 0
0 0 0 0 0 0 0
x[:,:,2]
0 0 0 0 0 0 0
0 2 2 1 1 1 0
0 0 1 0 0 1 0
0 0 1 1 0 1 0
0 0 2 1 1 0 0
0 0 2 1 1 2 0
0 0 0 0 0 0 0
Filter W0 (3x3x3)
w0[:,:,0]
1 0 -1
0 1 -1
-1 0 1
w0[:,:,1]
1 1 0
1 0 -1
1 1 1
w0[:,:,2]
-1 -1 0
-1 0 0
0 1 1
Bias b0 (1x1x1)
b0[:,:,0]
1
Filter W1 (3x3x3)
w1[:,:,0]
1 0 -1
-1 -1 -1
0 1 0
w1[:,:,1]
-1 0 0
-1 0 1
1 1 1
w1[:,:,2]
0 0 -1
1 -1 1
-1 1 0
Bias b1 (1x1x1)
b1[:,:,0]
0
Output Volume (3x3x2)
o[:,:,0]
4 3 4
3 9 5
0 -1 3
o[:,:,1]
3 2 -1
2 -3 -3
-3 -6 -4
toggle movement


Input Volume (+pad 1) (7x7x3)
x[:,:,0]
0 0 0 0 0 0 0
0 0 0 2 2 1 0
0 0 1 0 2 1 0
0 1 0 0 2 1 0
0 0 0 0 1 0 0
0 1 2 1 1 2 0
0 0 0 0 0 0 0
x[:,:,1]
0 0 0 0 0 0 0
0 0 1 1 2 1 0
0 0 2 1 1 1 0
0 0 2 1 0 2 0
0 0 2 2 1 0 0
0 2 0 1 0 1 0
0 0 0 0 0 0 0
x[:,:,2]
0 0 0 0 0 0 0
0 2 2 1 1 1 0
0 0 1 0 0 1 0
0 0 1 1 0 1 0
0 0 2 1 1 0 0
0 0 2 1 1 2 0
0 0 0 0 0 0 0
Filter W0 (3x3x3)
w0[:,:,0]
1 0 -1
0 1 -1
-1 0 1
w0[:,:,1]
1 1 0
1 0 -1
1 1 1
w0[:,:,2]
-1 -1 0
-1 0 0
0 1 1
Bias b0 (1x1x1)
b0[:,:,0]
1
Filter W1 (3x3x3)
w1[:,:,0]
1 0 -1
-1 -1 -1
0 1 0
w1[:,:,1]
-1 0 0
-1 0 1
1 1 1
w1[:,:,2]
0 0 -1
1 -1 1
-1 1 0
Bias b1 (1x1x1)
b1[:,:,0]
0
Output Volume (3x3x2)
o[:,:,0]
4 3 4
3 9 5
0 -1 3
o[:,:,1]
3 2 -1
2 -3 -3
-3 -6 -4
toggle movement



Input Volume (+pad 1) (7x7x3)
x[:,:,0]
0 0 0 0 0 0 0
0 0 0 2 2 1 0
0 0 1 0 2 1 0
0 1 0 0 2 1 0
0 0 0 0 1 0 0
0 1 2 1 1 2 0
0 0 0 0 0 0 0
x[:,:,1]
0 0 0 0 0 0 0
0 0 1 1 2 1 0
0 0 2 1 1 1 0
0 0 2 1 0 2 0
0 0 2 2 1 0 0
0 2 0 1 0 1 0
0 0 0 0 0 0 0
x[:,:,2]
0 0 0 0 0 0 0
0 2 2 1 1 1 0
0 0 1 0 0 1 0
0 0 1 1 0 1 0
0 0 2 1 1 0 0
0 0 2 1 1 2 0
0 0 0 0 0 0 0
Filter W0 (3x3x3)
w0[:,:,0]
1 0 -1
0 1 -1
-1 0 1
w0[:,:,1]
1 1 0
1 0 -1
1 1 1
w0[:,:,2]
-1 -1 0
-1 0 0
0 1 1
Bias b0 (1x1x1)
b0[:,:,0]
1
Filter W1 (3x3x3)
w1[:,:,0]
1 0 -1
-1 -1 -1
0 1 0
w1[:,:,1]
-1 0 0
-1 0 1
1 1 1
w1[:,:,2]
0 0 -1
1 -1 1
-1 1 0
Bias b1 (1x1x1)
b1[:,:,0]
0
Output Volume (3x3x2)
o[:,:,0]
4 3 4
3 9 5
0 -1 3
o[:,:,1]
3 2 -1
2 -3 -3
-3 -6 -4
toggle movement