CONVOLUTIONAL NEURAL NETWORKS: MOTIVATION & CONVOLUTION OPERATION

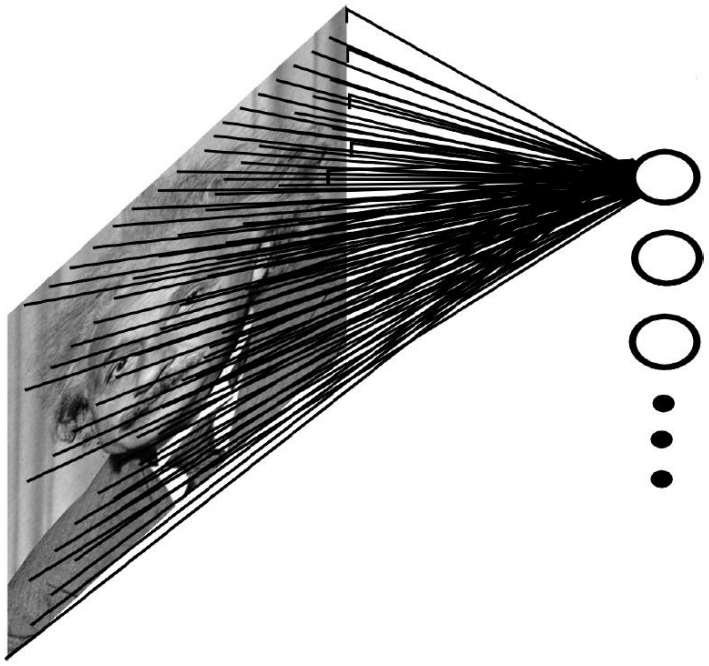
MOTIVATION

Fully connected neural network

- Example
  - 1000x1000 image
  - 1M hidden units

  ➔ $10^{12} (= 10^6 \times 10^6)$ parameters!

- Observation
  - Spatial correlation is local

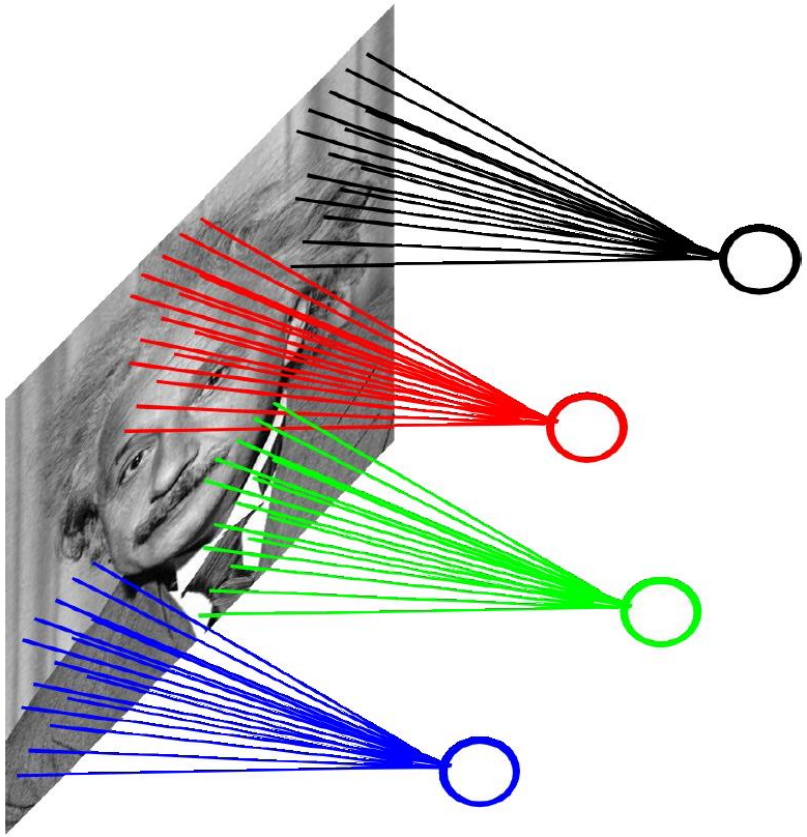


Locally connected neural net

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

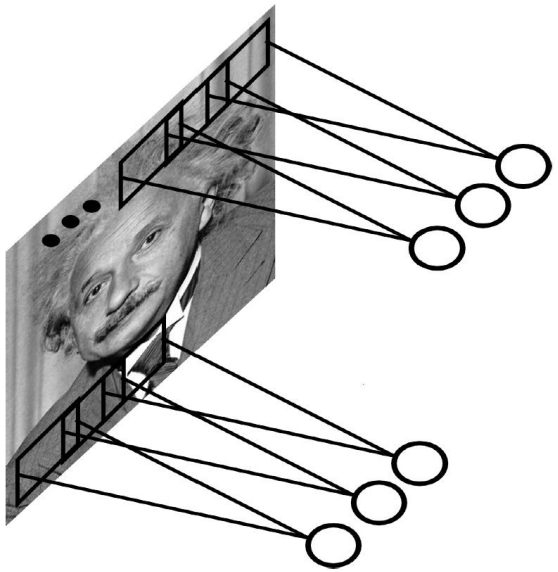
  ➔ $10^8 (= 10^6 \times 10 \times 10)$ parameters!

- Observation
  - Statistics is similar at different locations



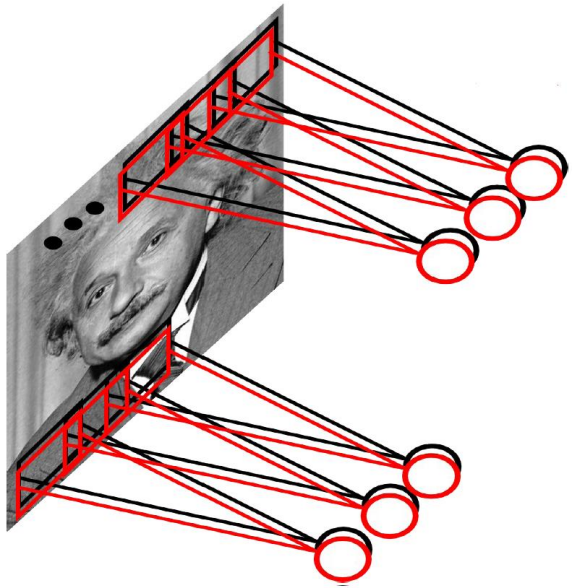
Convolution network

- Share the same parameters across different locations
  - Convolution with learned kernels



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

  10,000 parameters



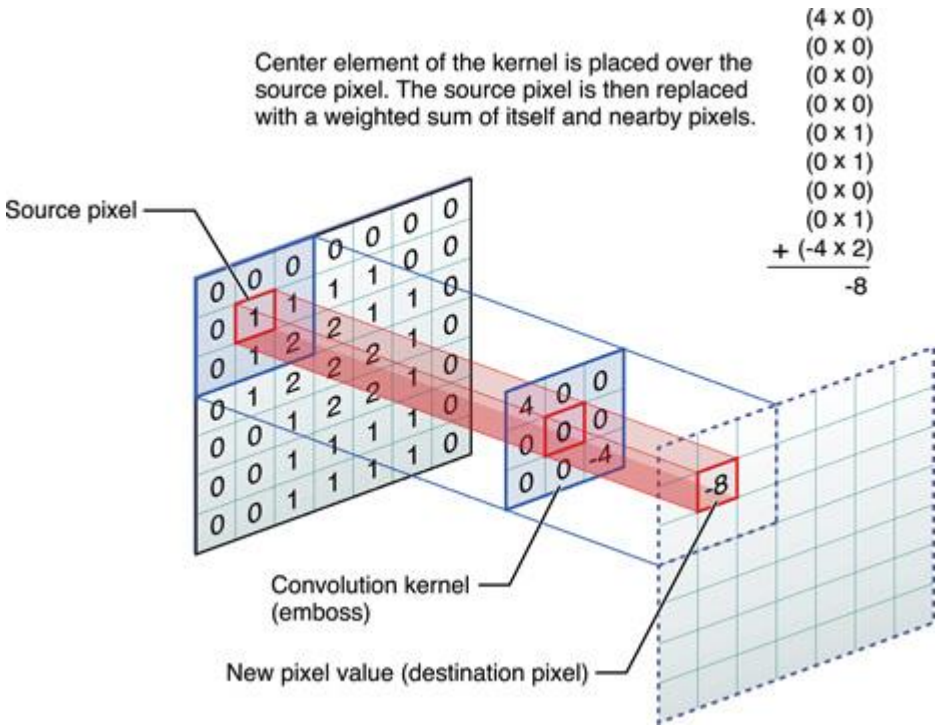
Convolution neural networks

- We can design neural networks that are specifically adapted for these problems
  - Must deal with very high-dimensional inputs
    - 1000x1000 pixels
  - Can exploit the 2D topology of pixels
  - Can build in invariance to certain variations we can expect
    - Translations, etc

- Ideas
  - Local connectivity
  - Parameter sharing

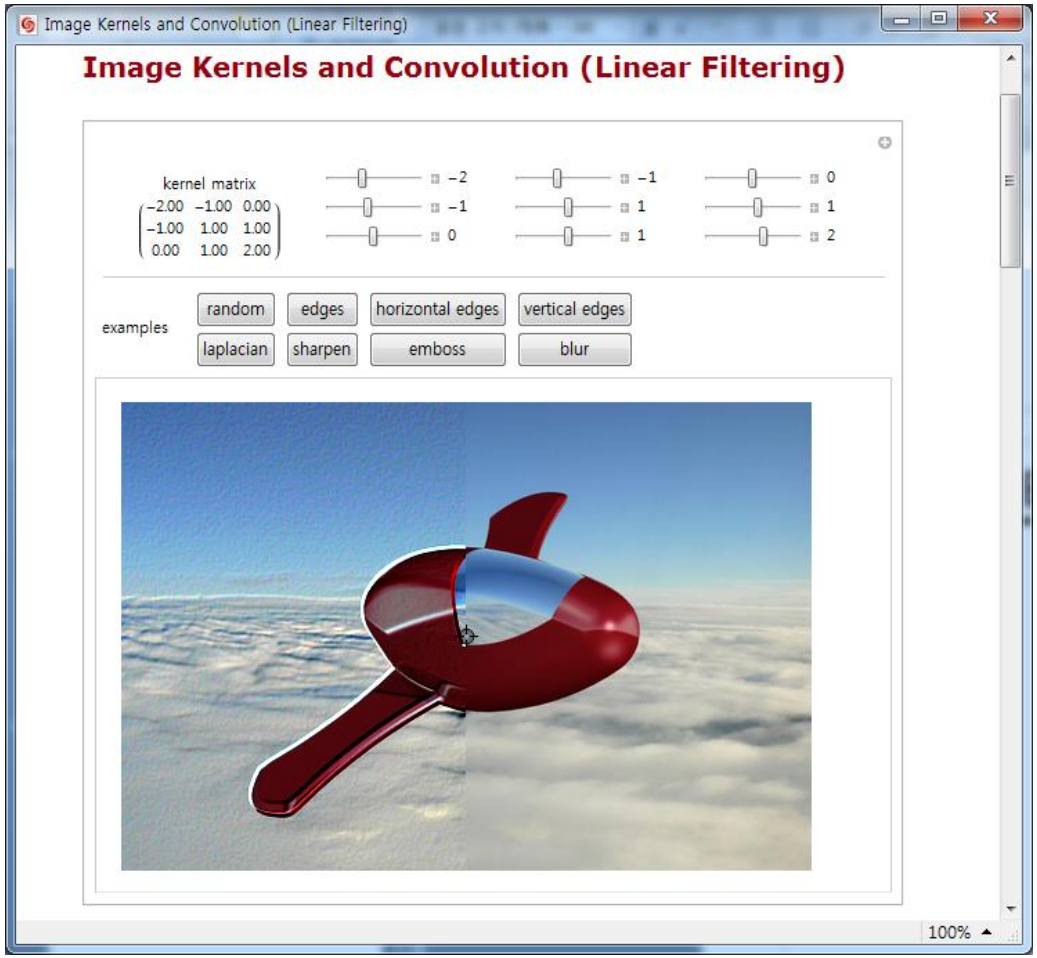
CONVOLUTION (IMAGE PROCESSING)

Convolution

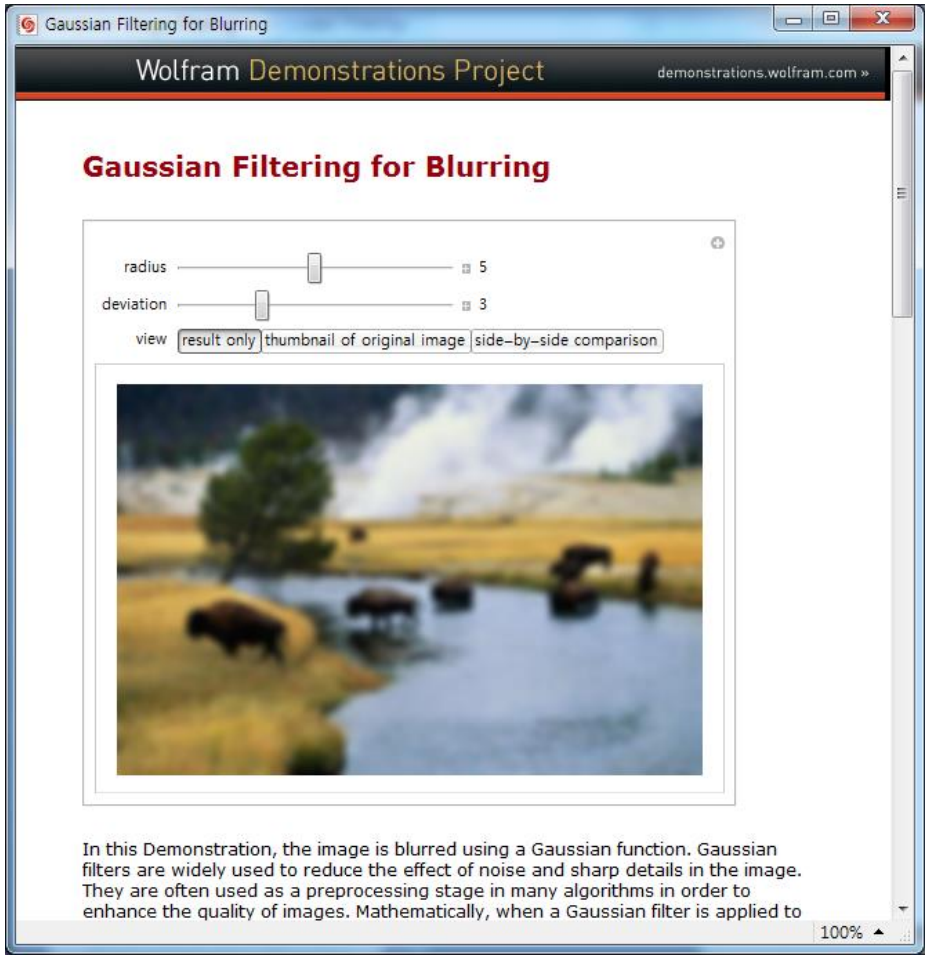


from: https://developer.apple.com/library/ios/documentation/Performance/Conceptual/vImage/ConvolutionOperations/ConvolutionOperations.html

Linear filter



Linear filter (Gaussian)



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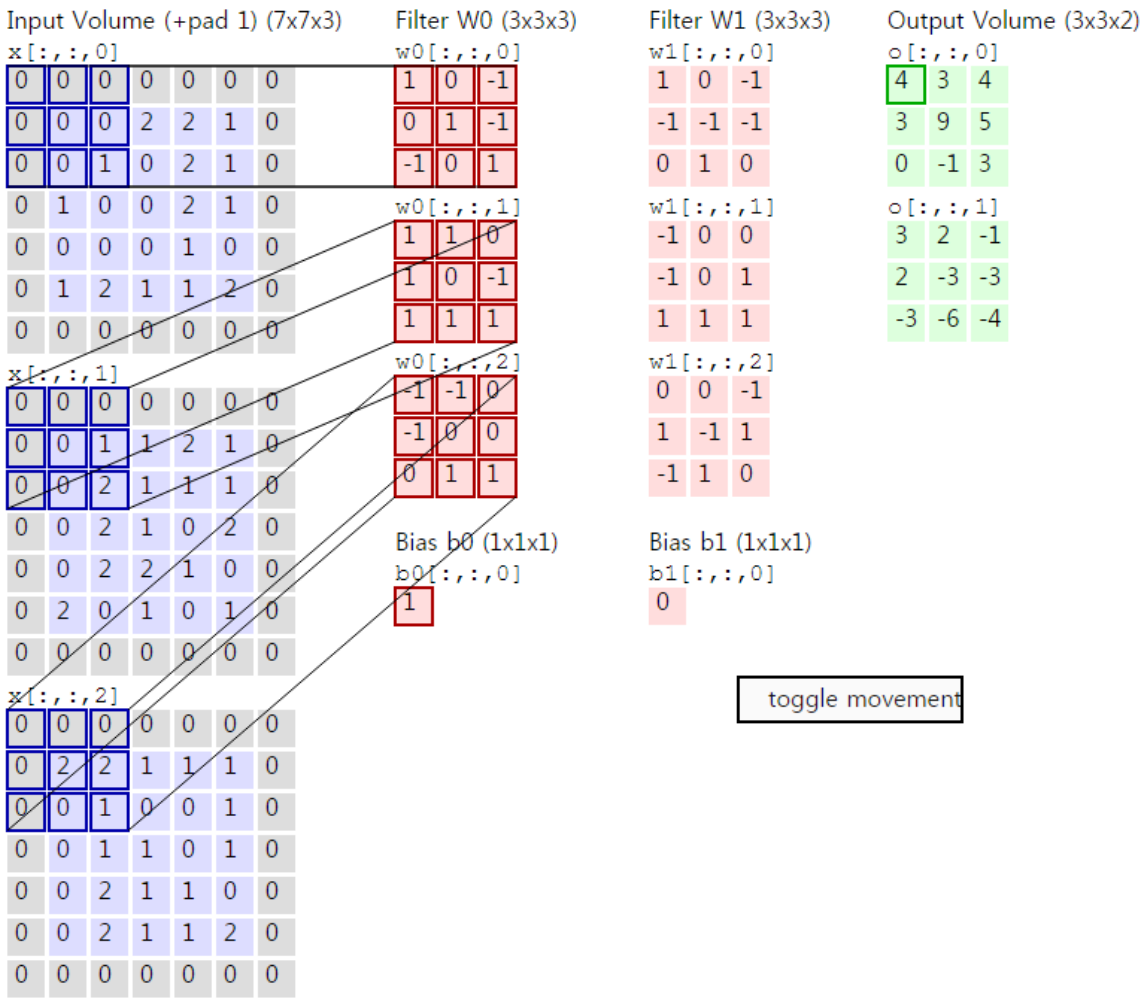
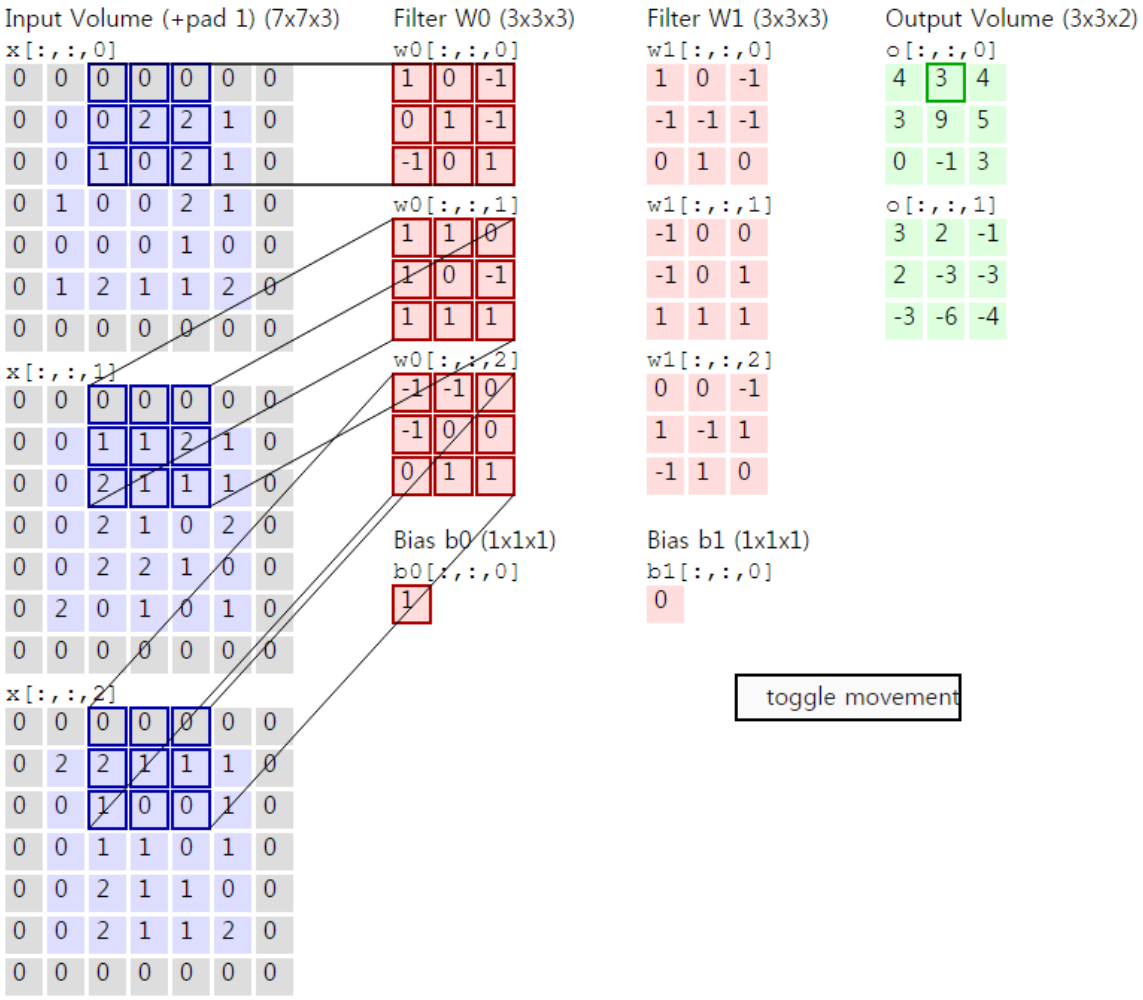
CONVOLUTION (DEEP LEARNING)


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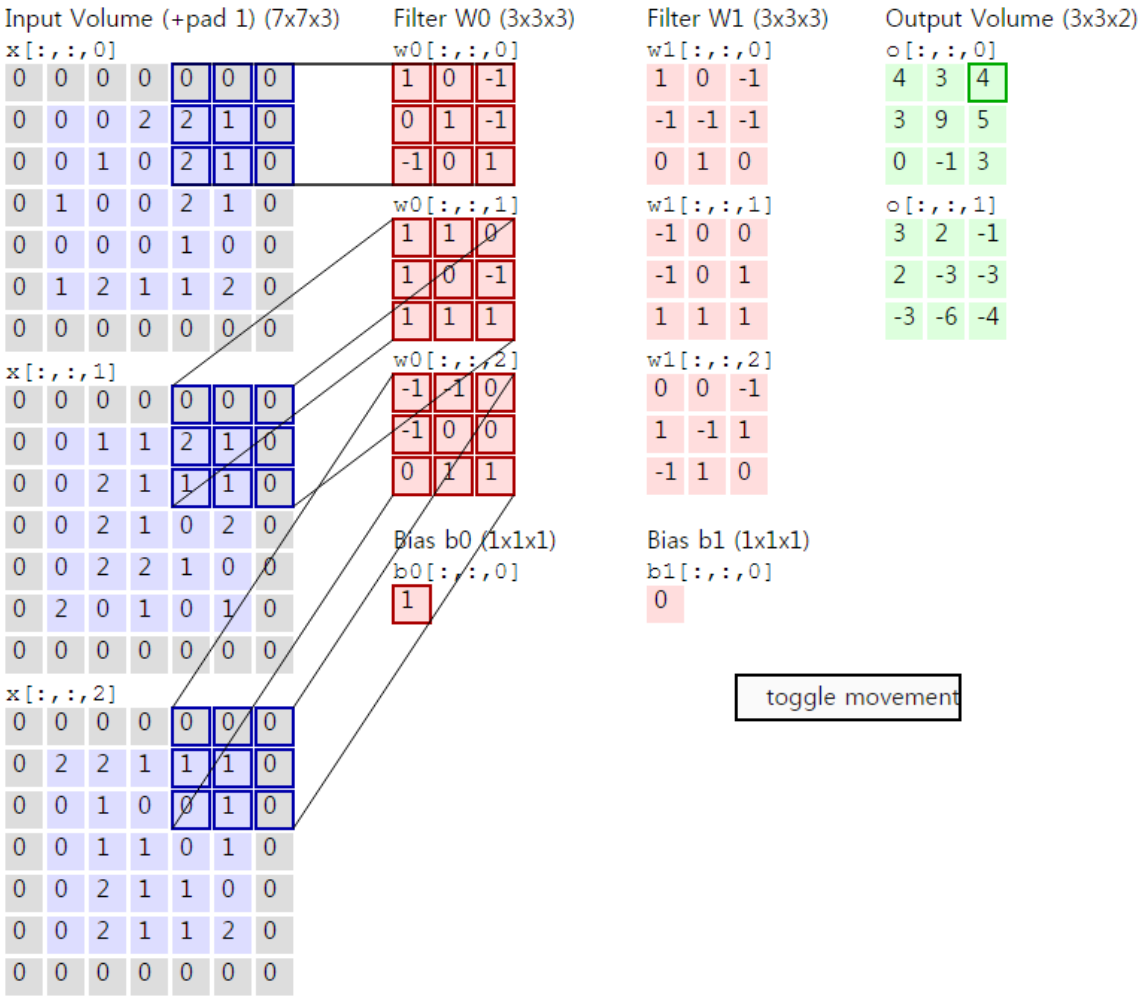
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0 1 2 1 1 2 0
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0 0 1 1 2 1 0
0 0 2 1 1 1 0
0 0 2 1 0 2 0
0 0 2 2 1 0 0
0 2 0 1 0 1 0
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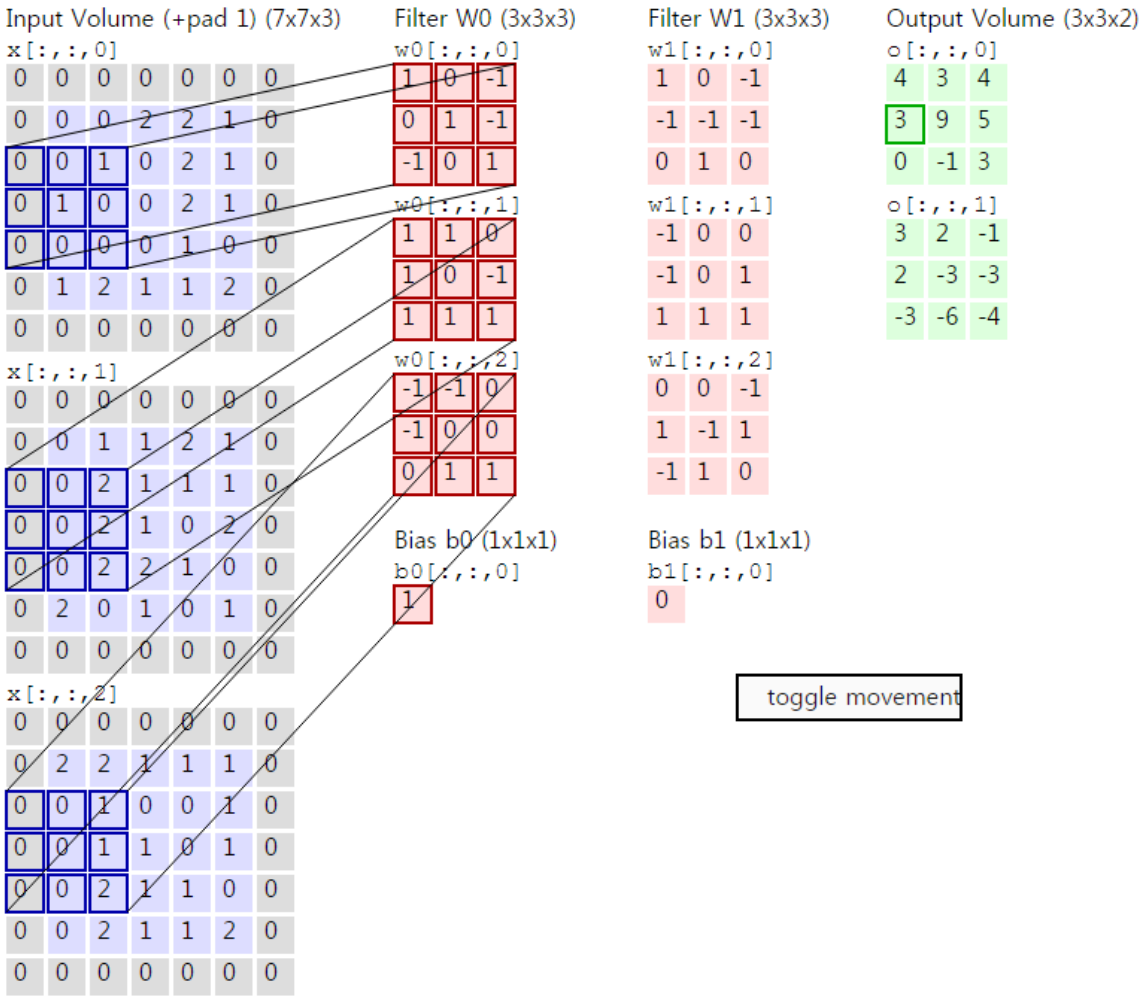
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0 0 0 0 0 0 0
0 0 0 2 2 1 0
0 0 1 0 2 1 0
0 1 0 0 2 1 0
0 0 0 0 1 0 0
0 1 2 1 1 2 0
0 0 0 0 0 0 0
x[:,:,1]
0 0 0 0 0 0 0
0 0 1 1 2 1 0
0 0 2 1 1 1 0
0 0 2 1 0 2 0
0 0 2 2 1 0 0
0 2 0 1 0 1 0
0 0 0 0 0 0 0
x[:,:,2]
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0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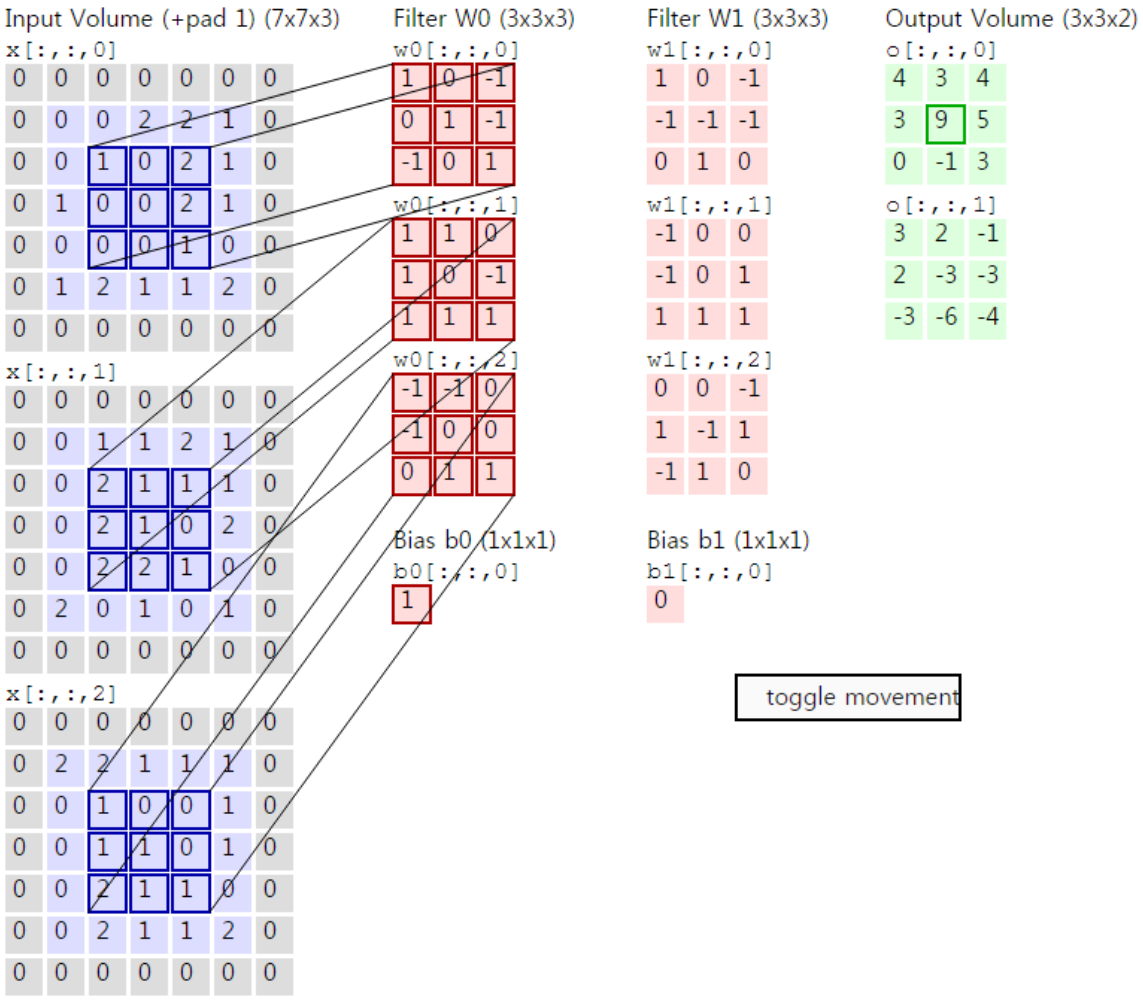
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0 0 1 0 2 1 0
0 1 0 0 2 1 0
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0 1 2 1 1 2 0
0 0 0 0 0 0 0
x[:,:,1]
0 0 0 0 0 0 0
0 0 1 1 2 1 0
0 0 2 1 1 1 0
0 0 2 1 0 2 0
0 0 2 2 1 0 0
0 2 0 1 0 1 0
0 0 0 0 0 0 0
x[:,:,2]
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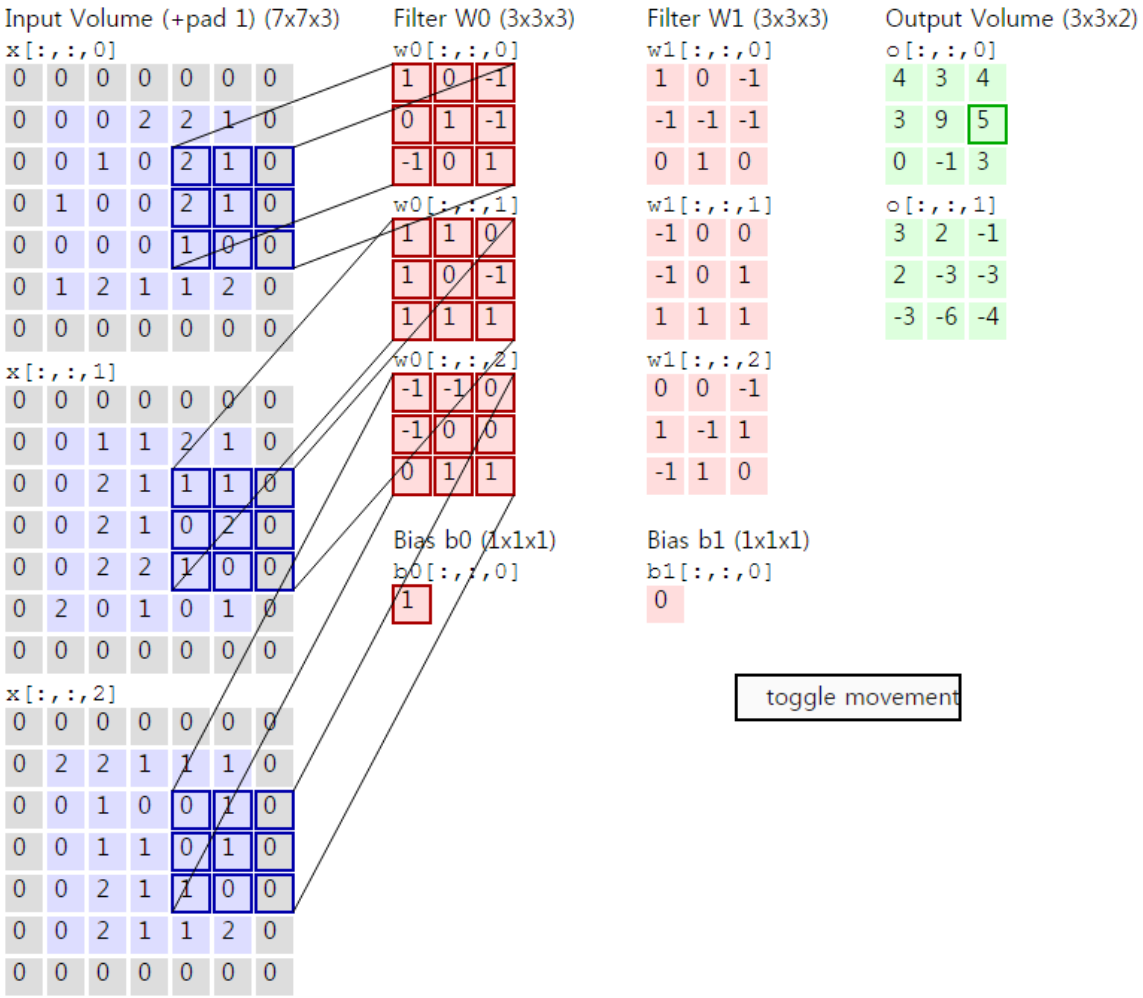
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0 0 1 0 2 1 0
0 1 0 0 2 1 0
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0 1 2 1 1 2 0
0 0 0 0 0 0 0
x[:,:,1]
0 0 0 0 0 0 0
0 0 1 1 2 1 0
0 0 2 1 1 1 0
0 0 2 1 0 2 0
0 0 2 2 1 0 0
0 2 0 1 0 1 0
0 0 0 0 0 0 0
x[:,:,2]
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0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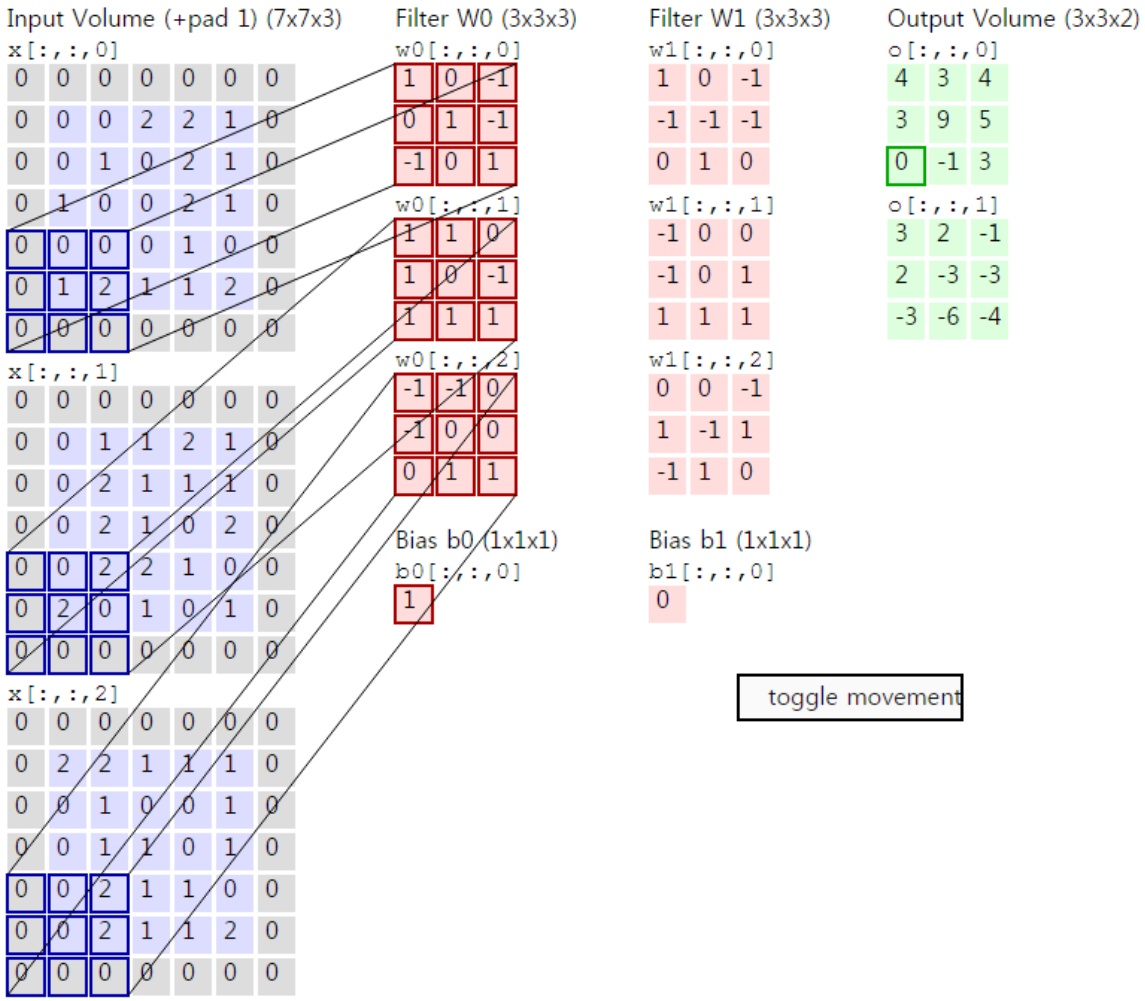
2 -3 -3
-3 -6 -4
toggle movement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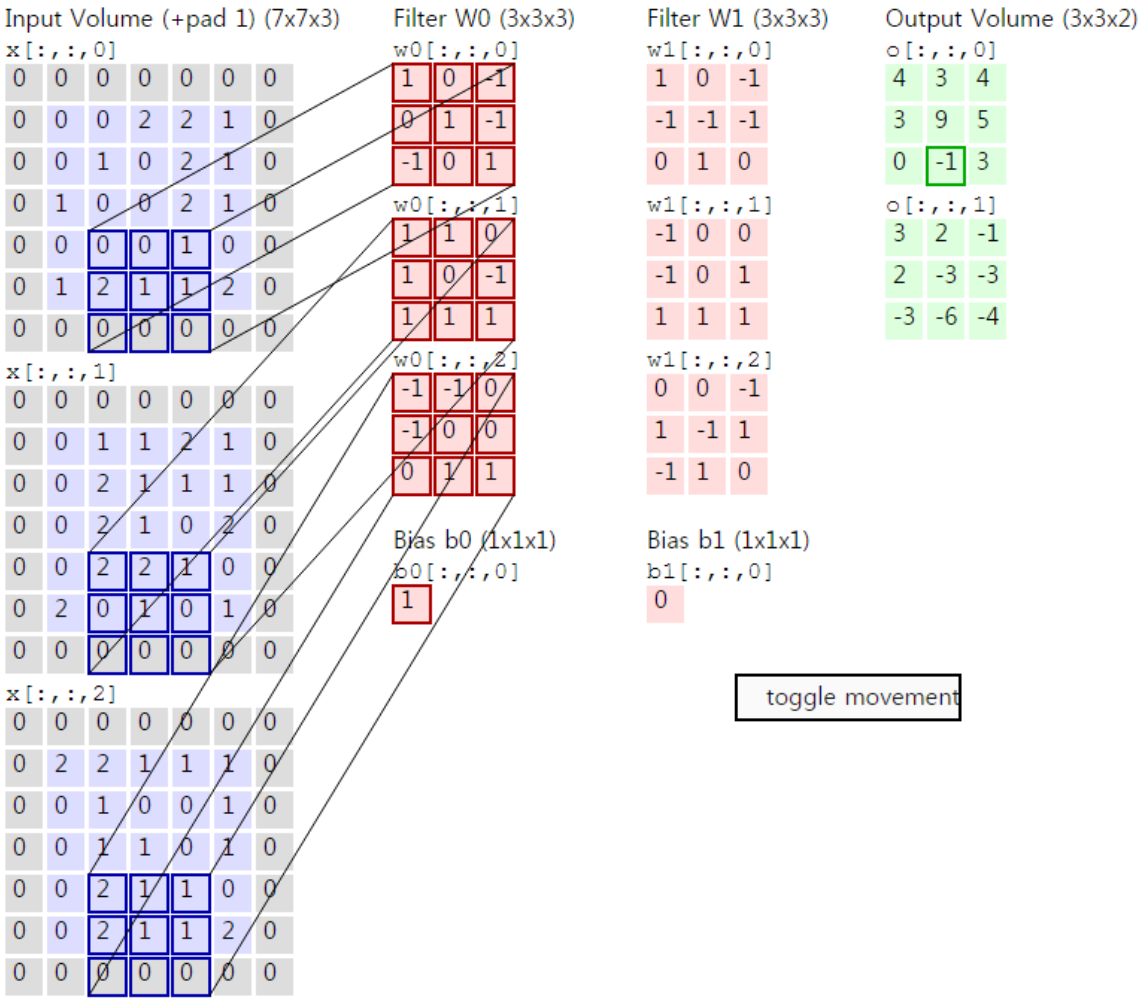
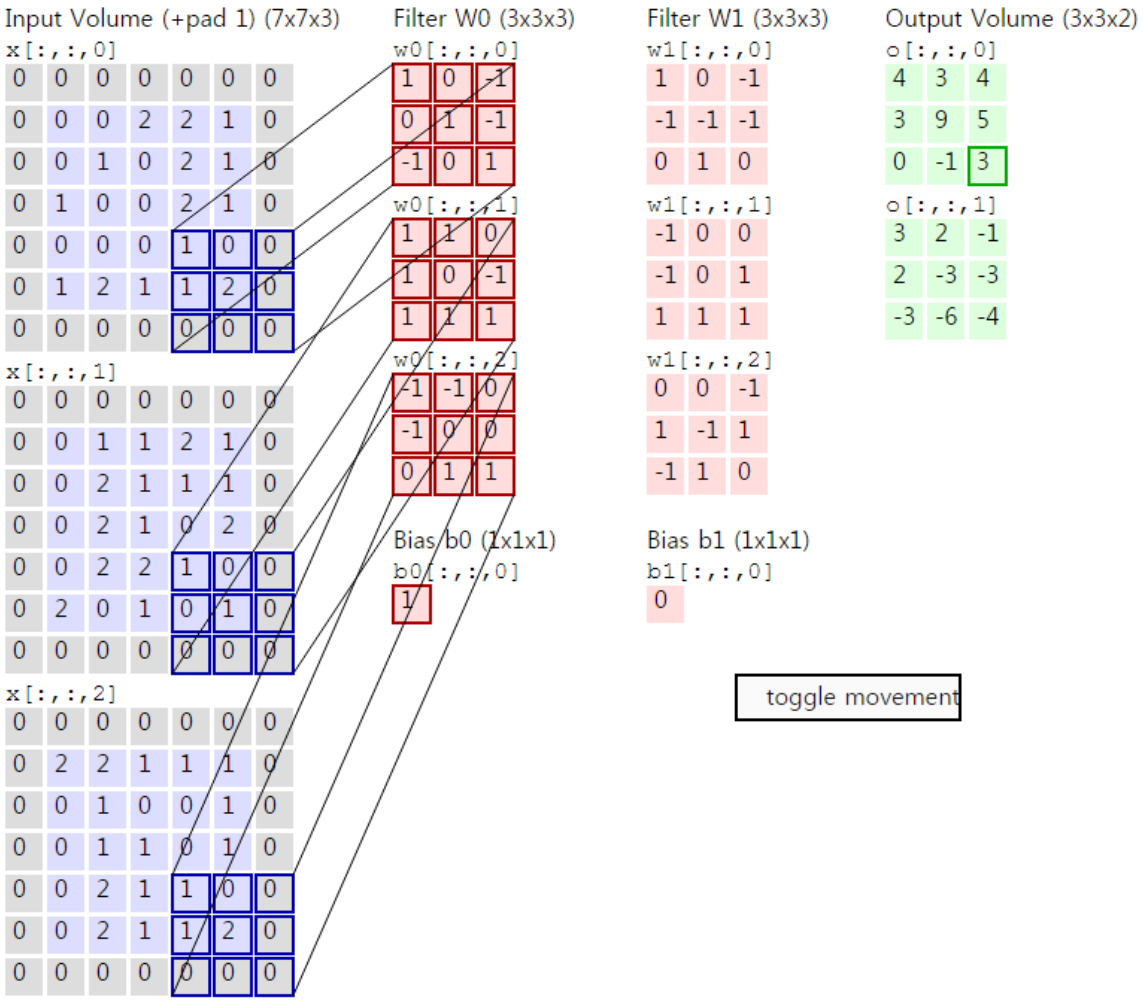
0 0 0 0 0 0 0
0 0 0 2 2 1 0
0 0 1 0 2 1 0
0 1 0 0 2 1 0
0 0 0 0 1 0 0
0 1 2 1 1 2 0
0 0 0 0 0 0 0
x[:,:,1]
0 0 0 0 0 0 0
0 0 1 1 2 1 0
0 0 2 1 1 1 0
0 0 2 1 0 2 0
0 0 2 2 1 0 0
0 2 0 1 0 1 0
0 0 0 0 0 0 0
x[:,:,2]
0 0 0 0 0 0 0
0 2 2 1 1 1 0
0 0 1 0 0 1 0
0 0 1 1 0 1 0
0 0 2 1 1 0 0
0 0 2 1 1 2 0
0 0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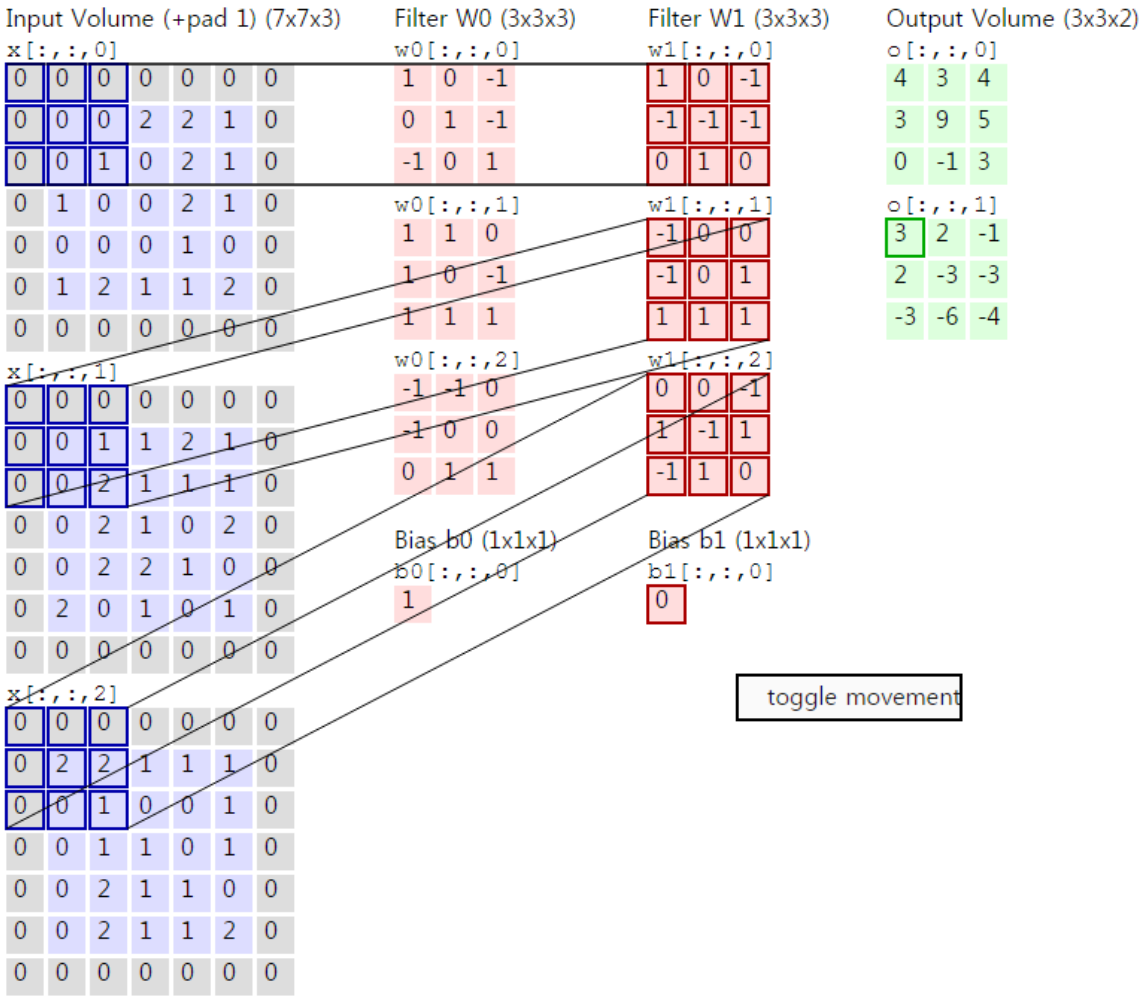
o[:,:,1]
3 2 -1
2 -3 -3
-3 -6 -4
toggle movement


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]
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Bias b0 (1x1x1)
b0[:,:,0]
1
Filter W1 (3x3x3)
w1[:,:,0]
1 0 -1
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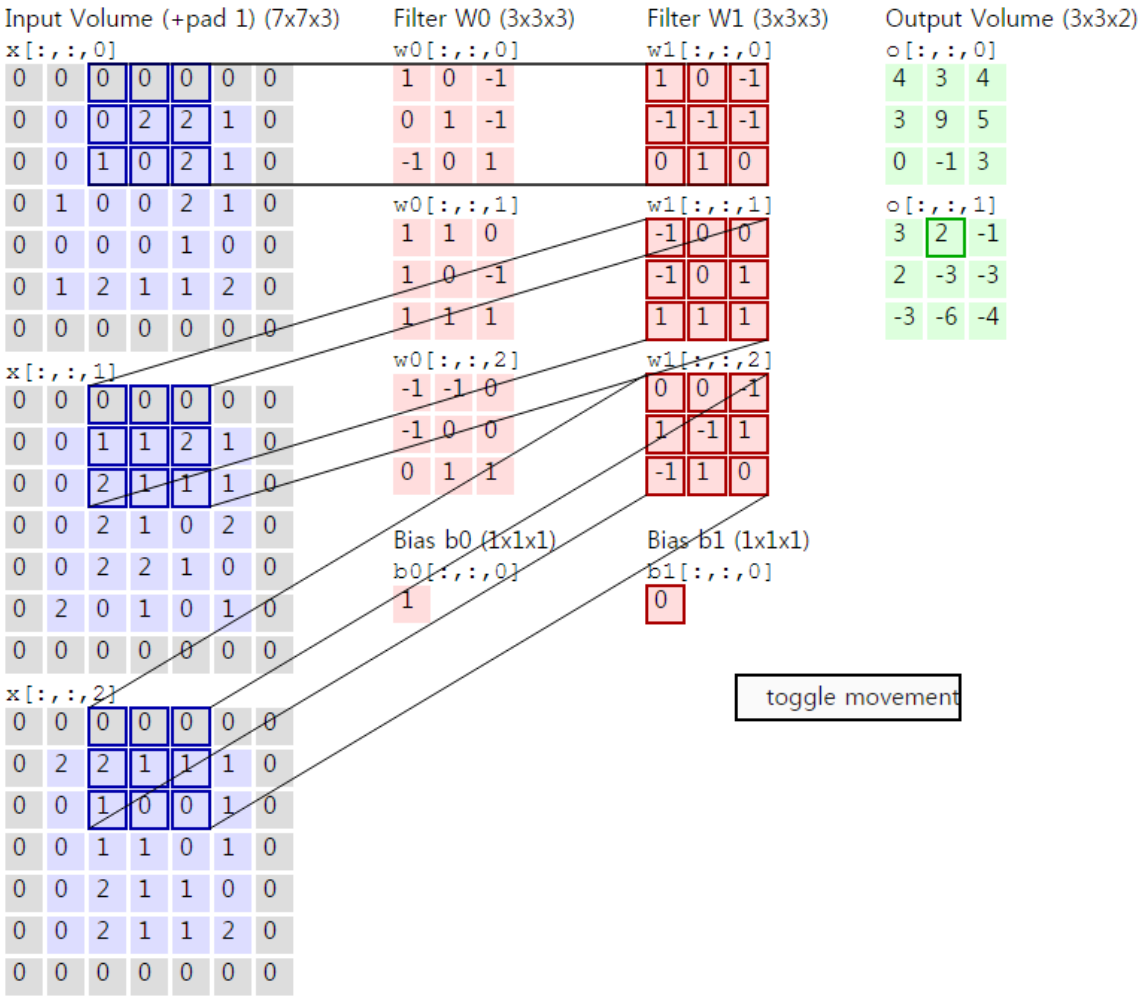
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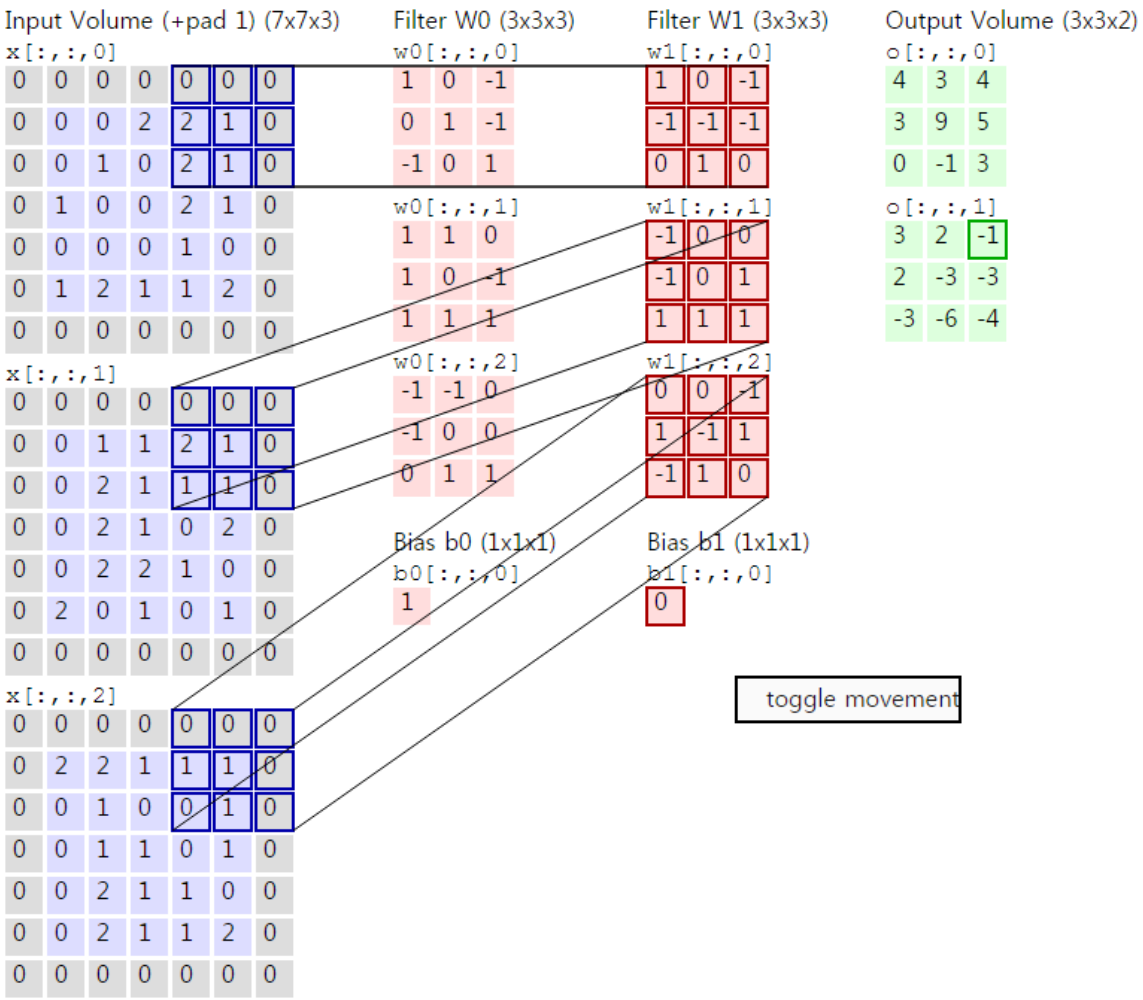
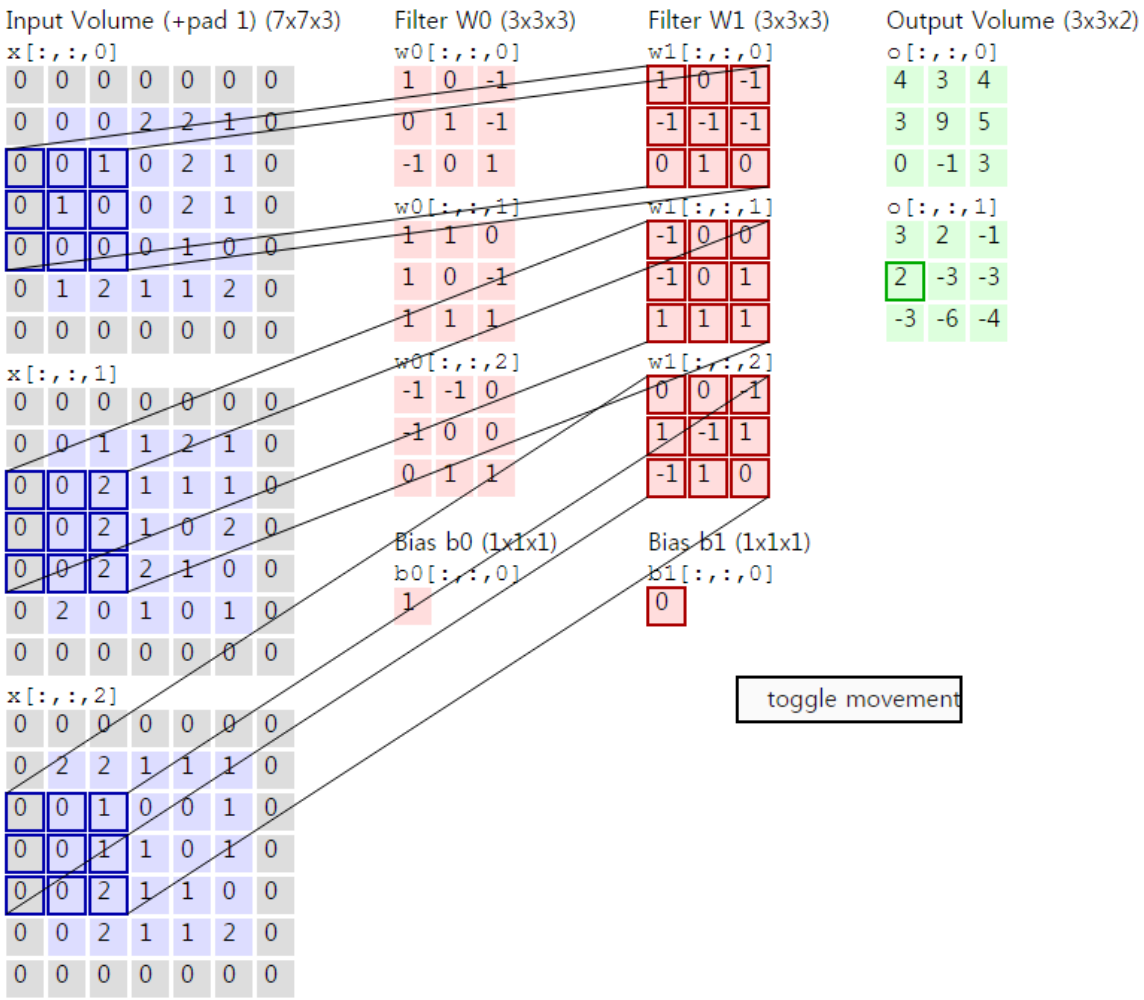
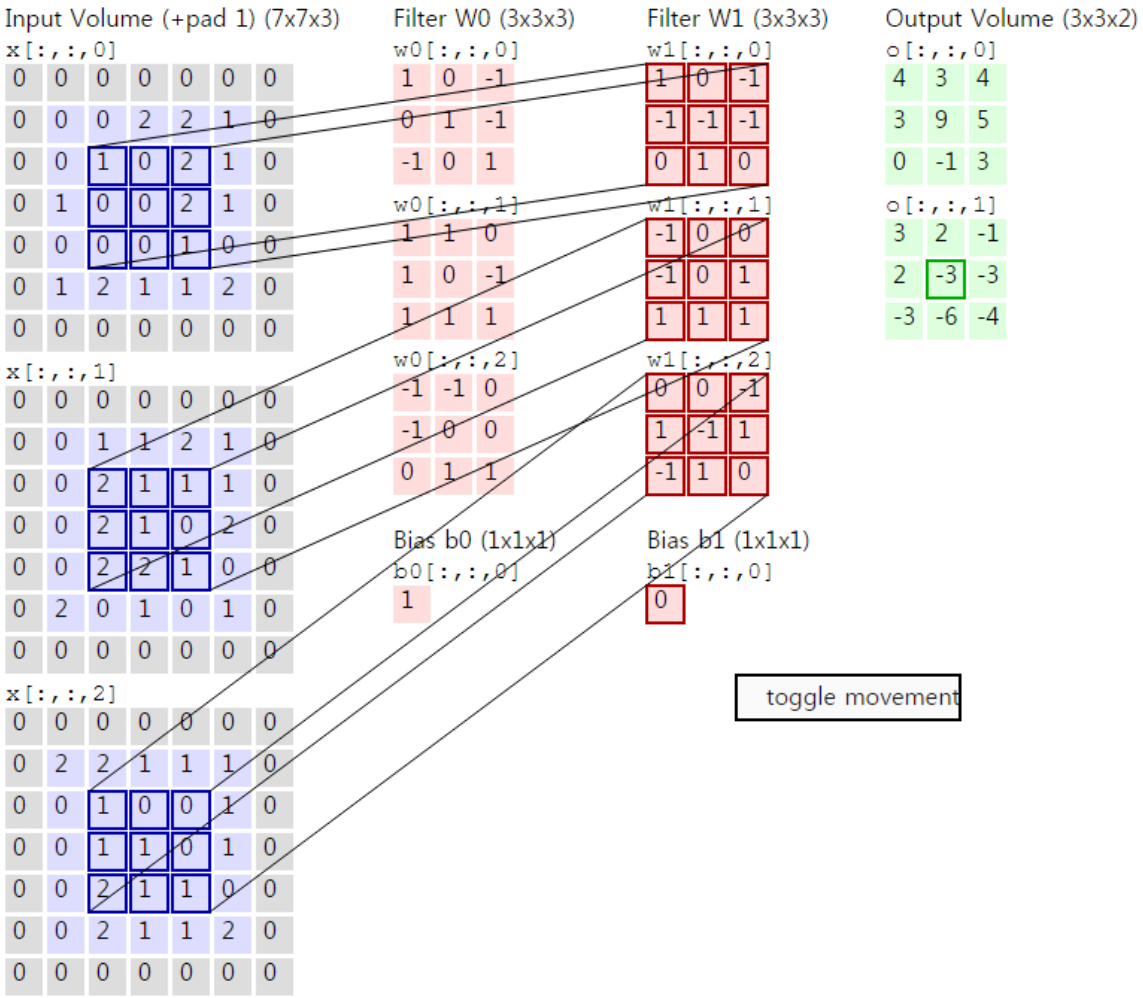
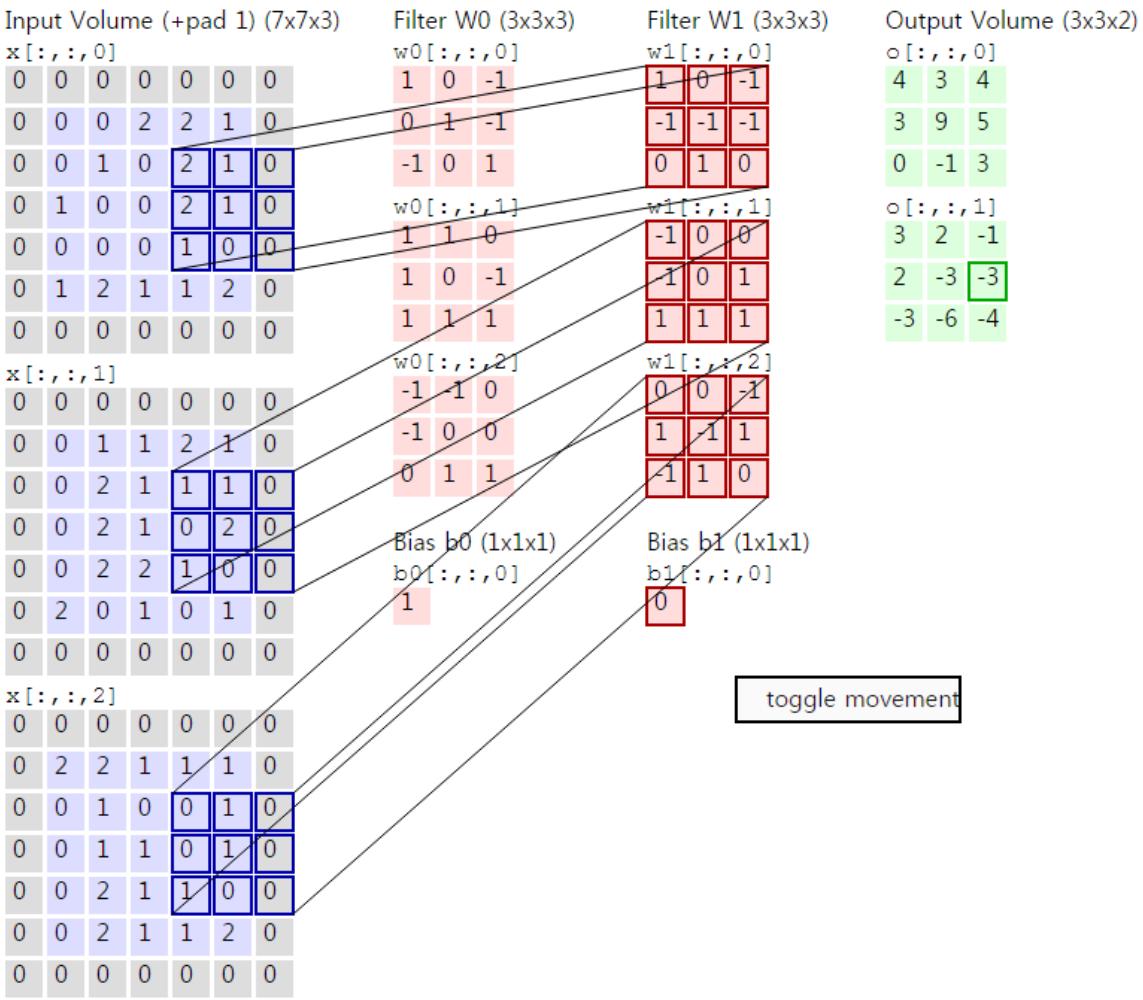
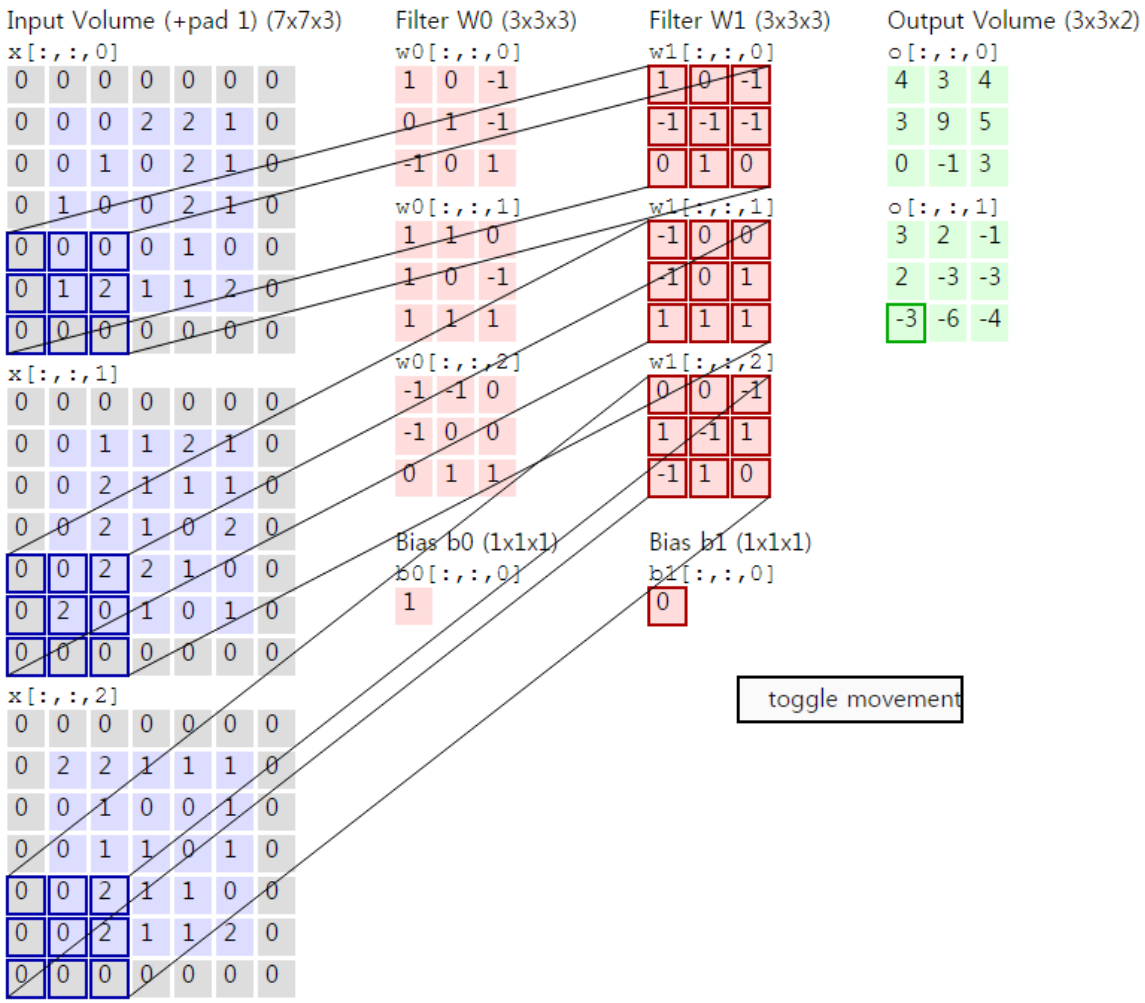
0 0 0 2 2 1 0
0 0 1 0 2 1 0
0 1 0 0 2 1 0
0 0 0 0 1 0 0
0 1 2 1 1 2 0
0 0 0 0 0 0 0
x[:,:,1]
0 0 0 0 0 0 0
0 0 1 1 2 1 0
0 0 2 1 1 1 0
0 0 2 1 0 2 0
0 0 2 2 1 0 0
0 2 0 1 0 1 0
0 0 0 0 0 0 0
x[:,:,2]
0 0 0 0 0 0 0
0 2 2 1 1 1 0
0 0 1 0 0 1 0
0 0 1 1 0 1 0
0 0 2 1 1 0 0
0 0 2 1 1 2 0
0 0 0 0 0 0 0
Filter 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

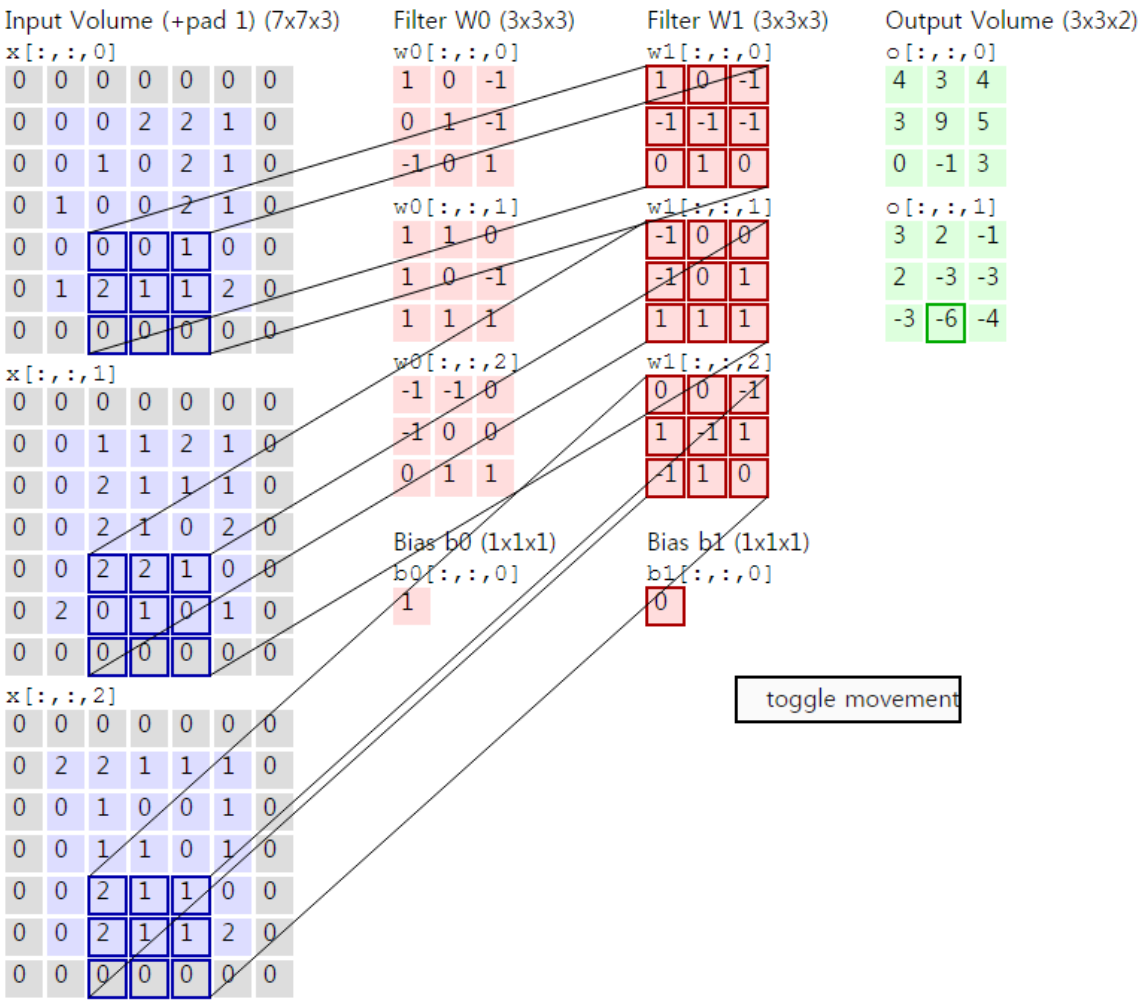

Input Volume (+pad 1) (7x7x3)
x[:,:,0]
0 0 0 0 0 0 0
0 0 0 2 2 1 0
0 0 1 0 2 1 0
0 1 0 0 2 1 0
0 0 0 0 1 0 0
0 1 2 1 1 2 0
0 0 0 0 0 0 0
x[:,:,1]
0 0 0 0 0 0 0
0 0 1 1 2 1 0
0 0 2 1 1 1 0
0 0 2 1 0 2 0
0 0 2 2 1 0 0
0 2 0 1 0 1 0
0 0 0 0 0 0 0
x[:,:,2]
0 0 0 0 0 0 0
0 2 2 1 1 1 0
0 0 1 0 0 1 0
0 0 1 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

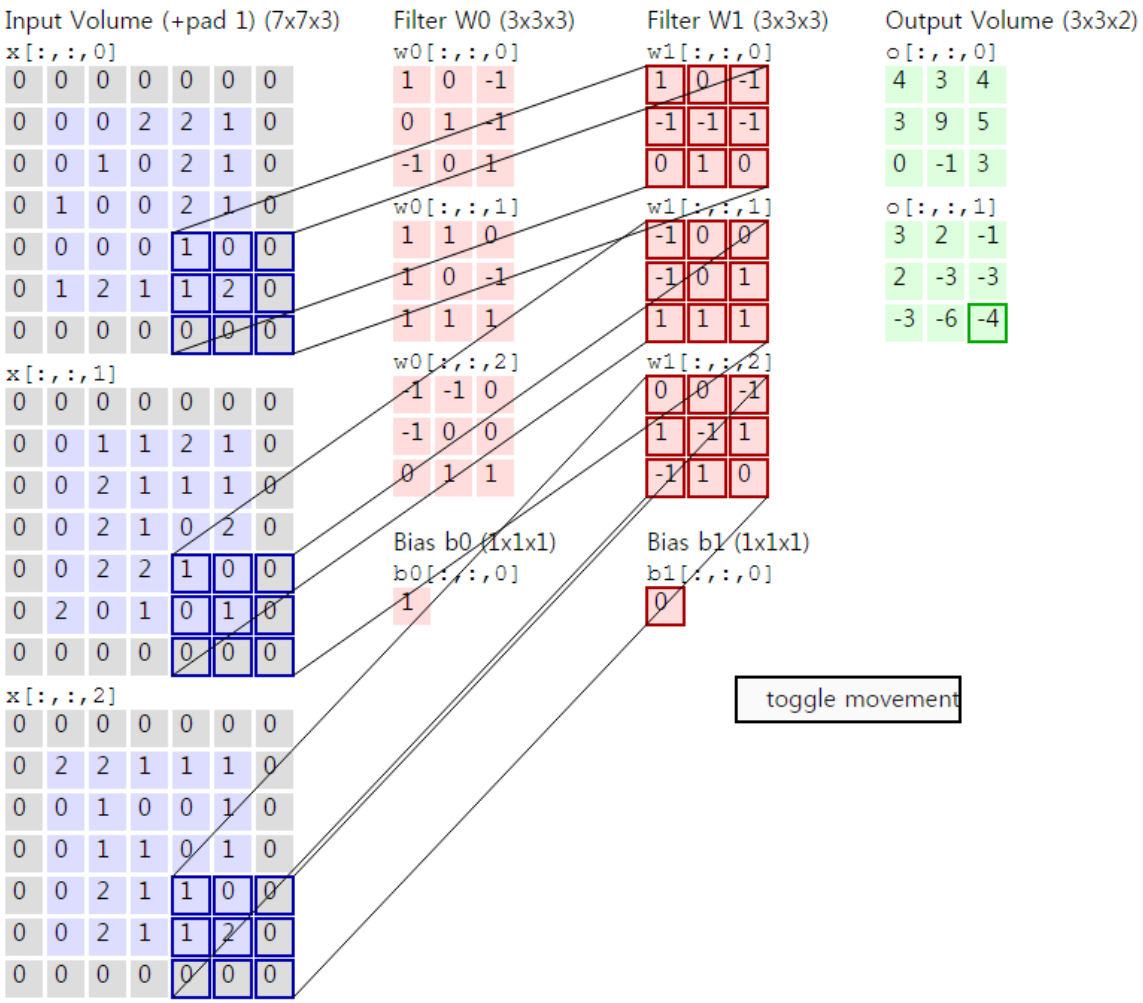

Input Volume (+pad 1) (7x7x3)
x[:,:,0]
0 0 0 0 0 0 0
0 0 0 2 2 1 0
0 0 1 0 2 1 0
0 1 0 0 2 1 0
0 0 0 0 1 0 0
0 1 2 1 1 2 0
0 0 0 0 0 0 0
x[:,:,1]
0 0 0 0 0 0 0
0 0 1 1 2 1 0
0 0 2 1 1 1 0
0 0 2 1 0 2 0
0 0 2 2 1 0 0
0 2 0 1 0 1 0
0 0 0 0 0 0 0
x[:,:,2]
0 0 0 0 0 0 0
0 2 2 1 1 1 0
0 0 1 0 0 1 0
0 0 1 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
toggle movement
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


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
toggle movement
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