MAI4CAREU Master programmes in Artificial Intelligence 4 Careers in Europe

Visual Computing Group

CYENS CENTRE OF EXCELLENCE

University of Cyprus – MSc Artificial Intelligence

MAI644 – COMPUTER VISION

Lecture 5: Filters – Convolution

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Last time

- Image basics
  - What is an image – addressing pixels
  - Image as a function – image coordinates
- Image interpolation
  - Nearest neighbor
  - Bilinear
  - Bicubic
- Image resizing
  - Enlarge
  - Shrink

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Today's Agenda

- Averaging vs Interpolation
- Systems - filters
- Convolution
  - Box Filter
  - Gaussian
  - Cross correlation vs Convolution
- Examples of filters

[material based on Joseph Redmon's course]

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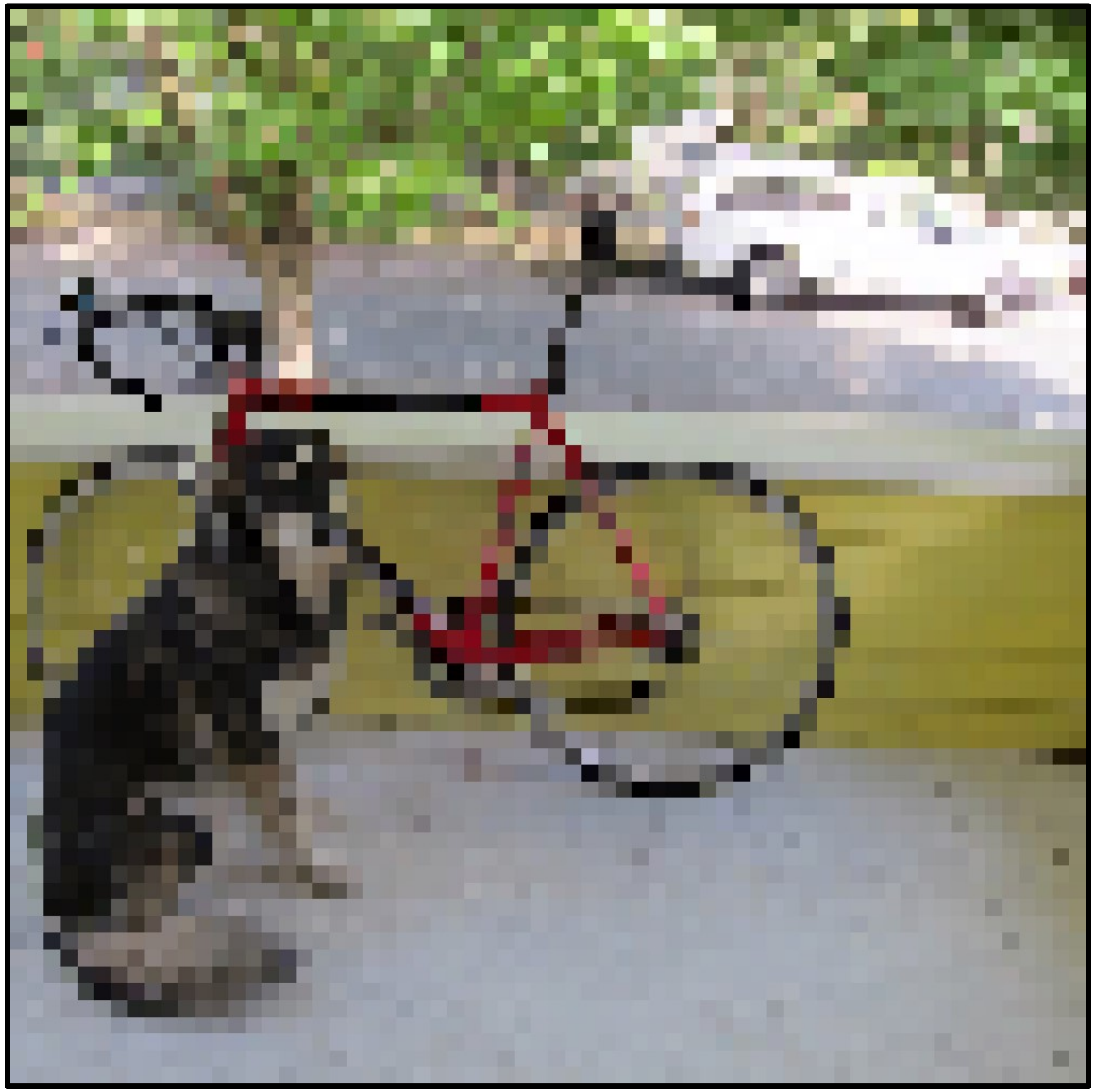
Is this all there is ??



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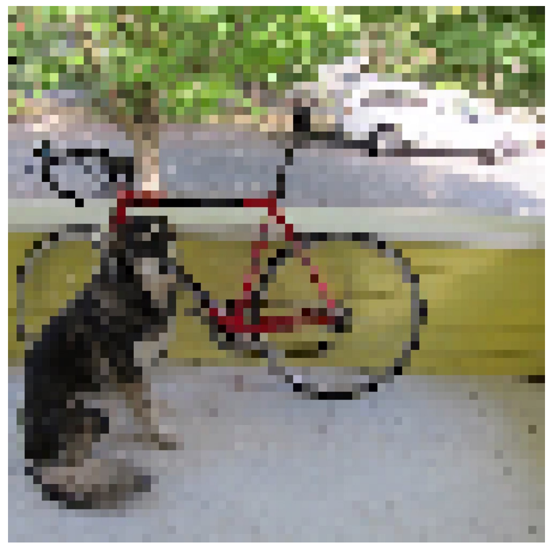
Lots of issues

- NN and Bilinear only look at small area
- Lots of artifacting
- Staircase pattern on diagonal lines
- We'll fix this with filters!

NN



Bilinear

There is a better way!

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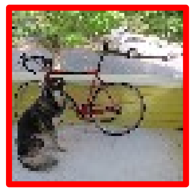
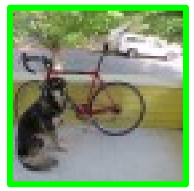
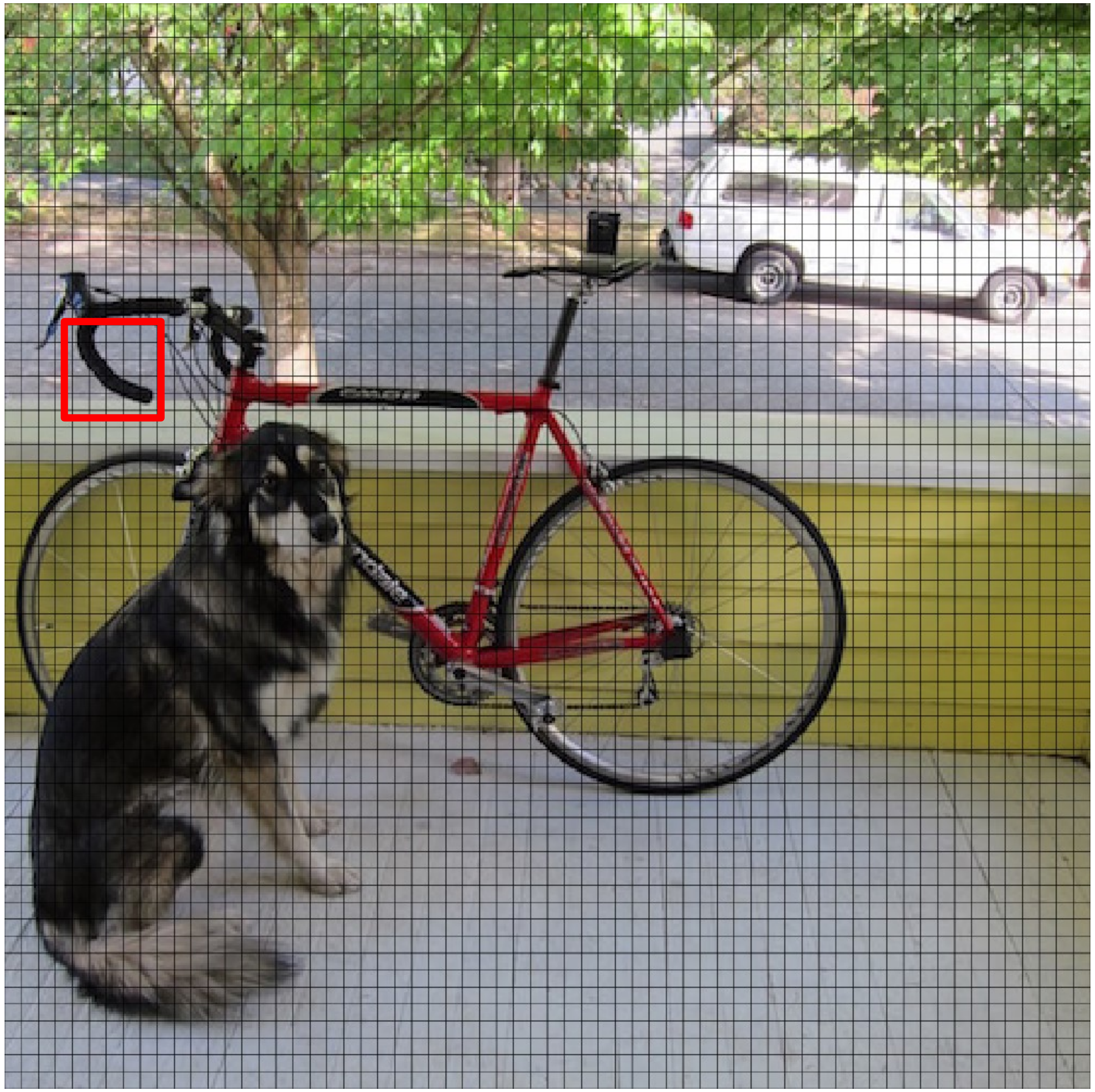
Look at how much better





How?



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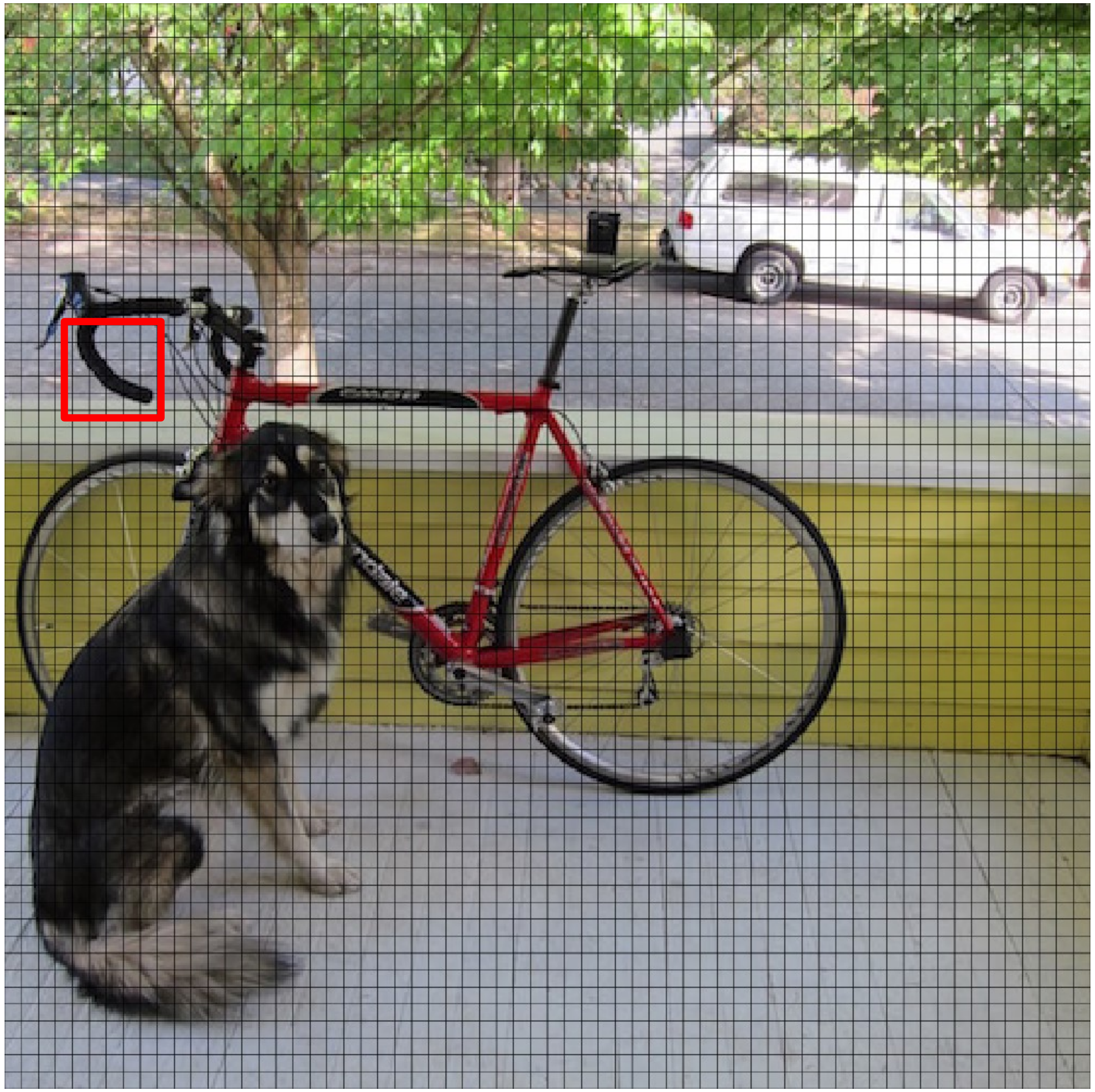
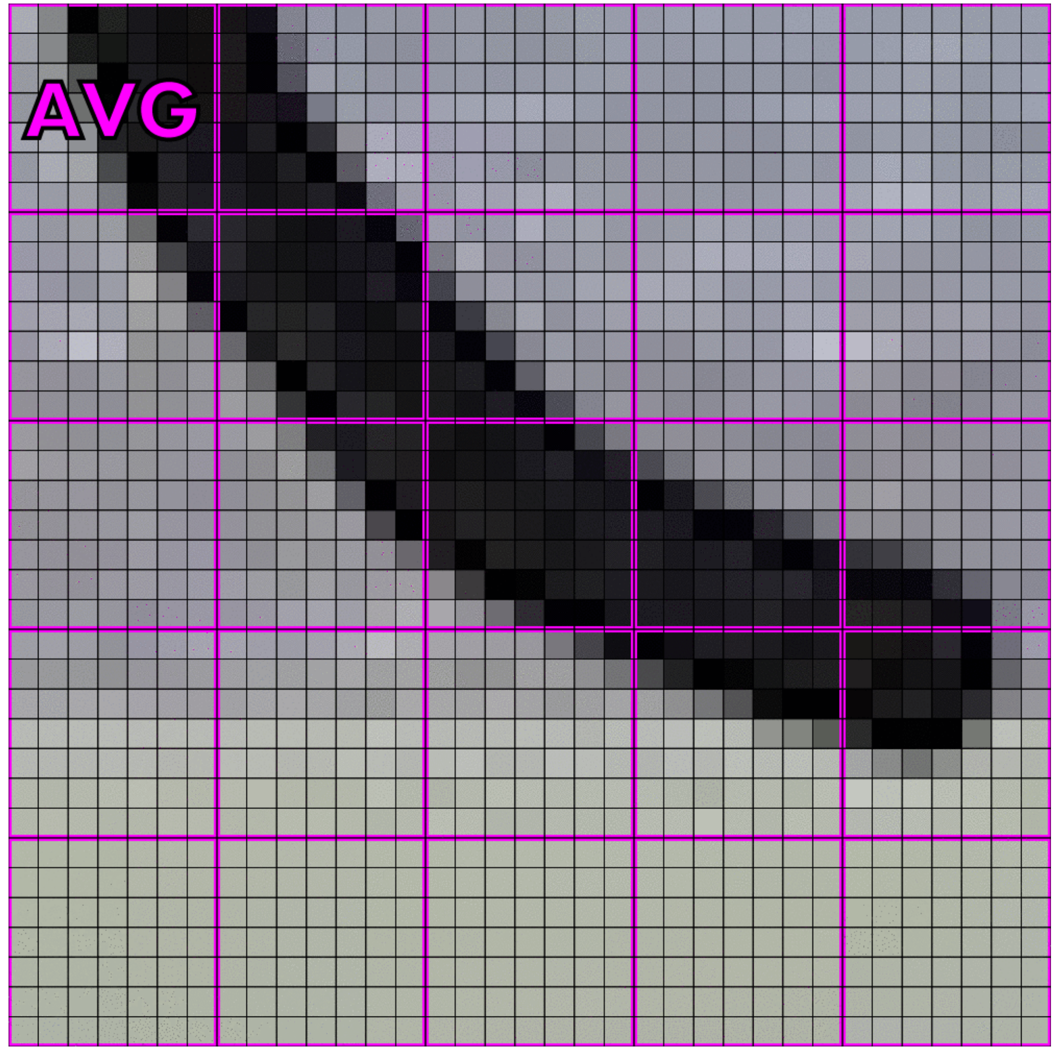
How? Averaging!





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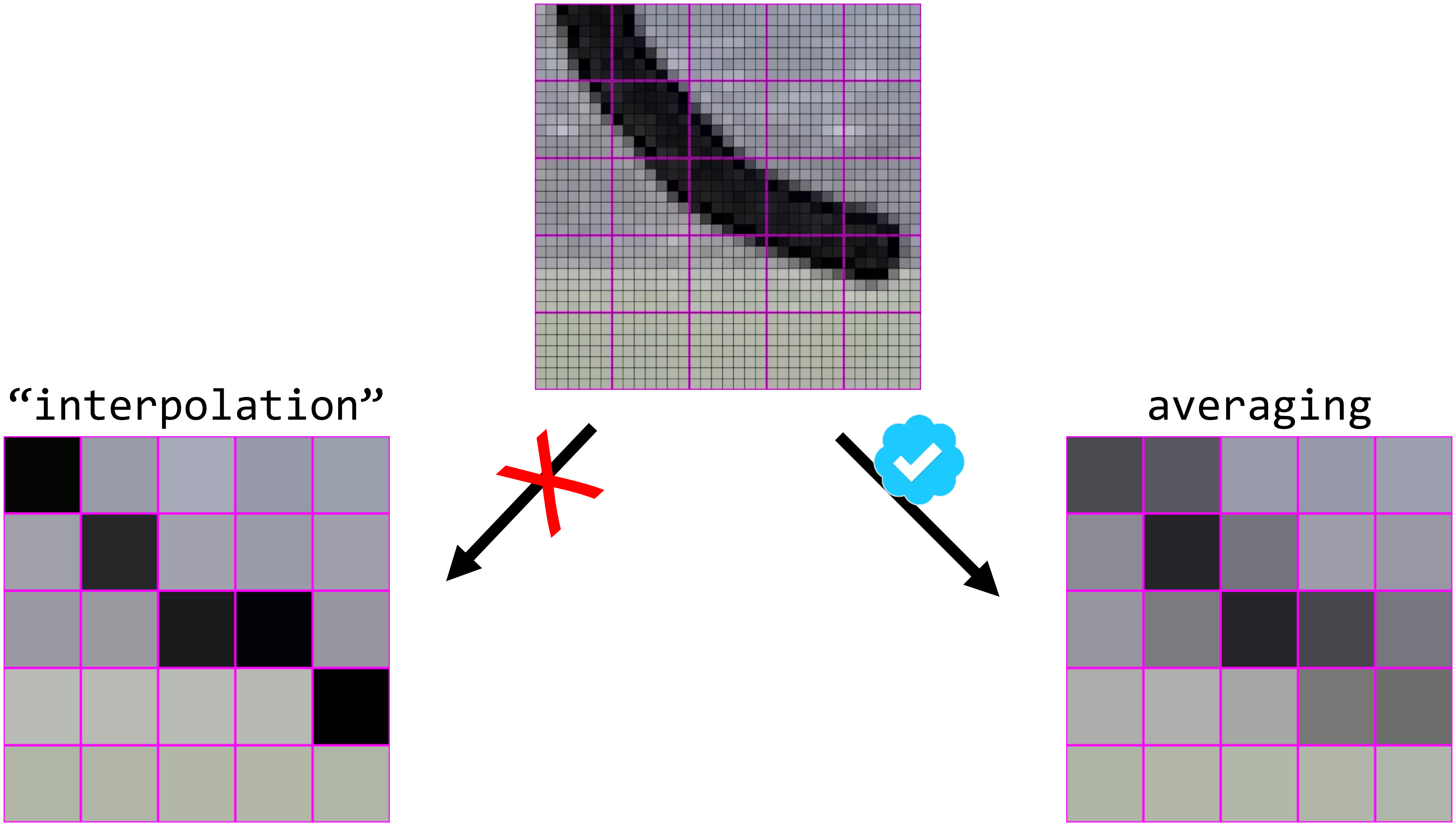
How? Averaging!



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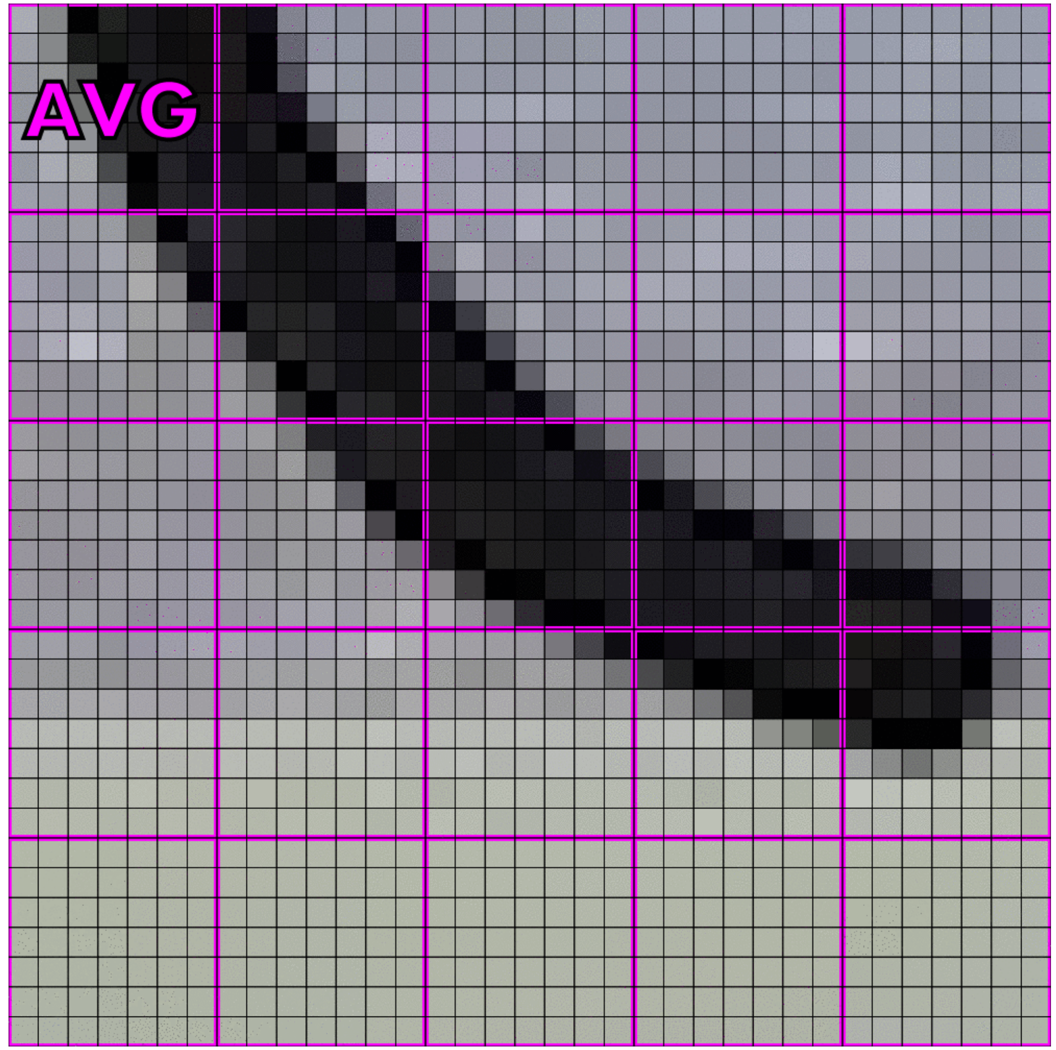
What is averaging?



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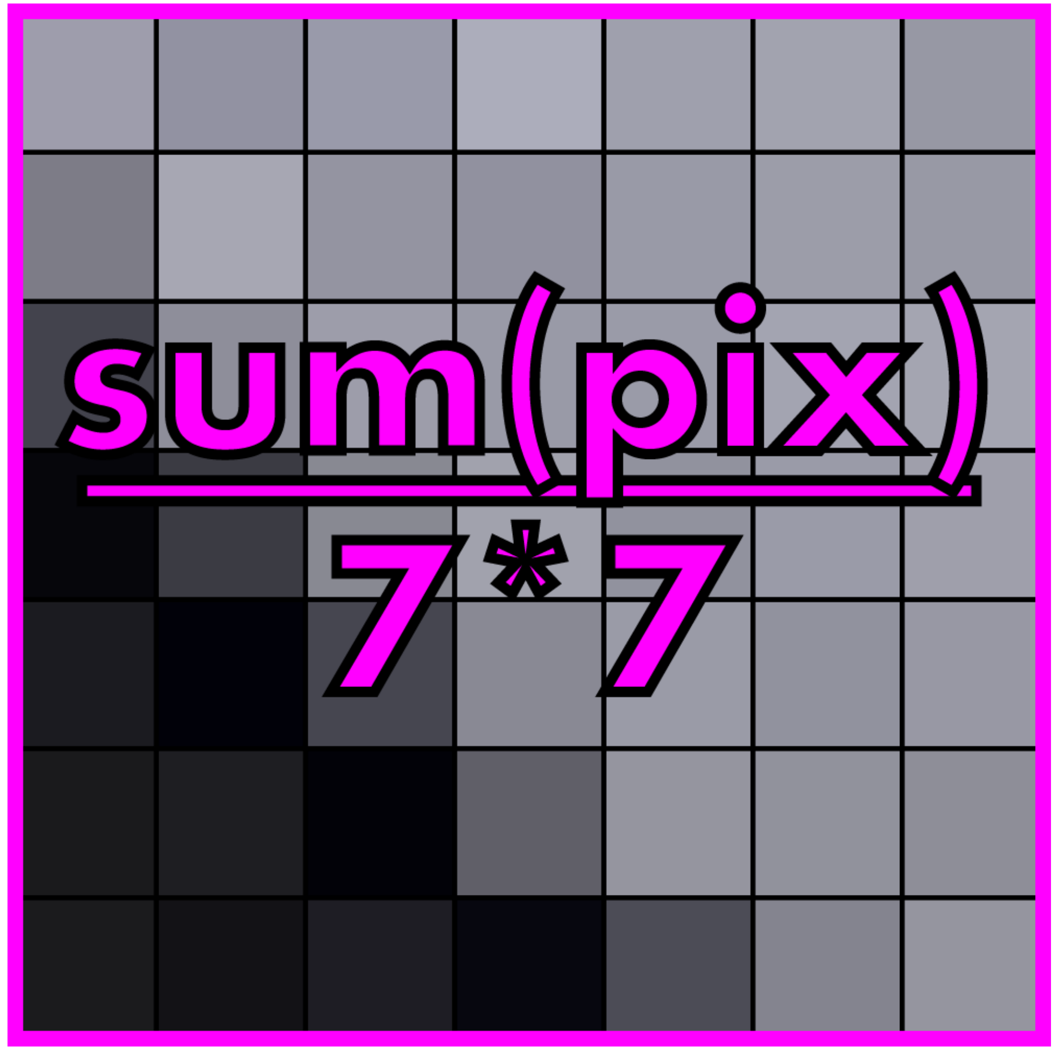
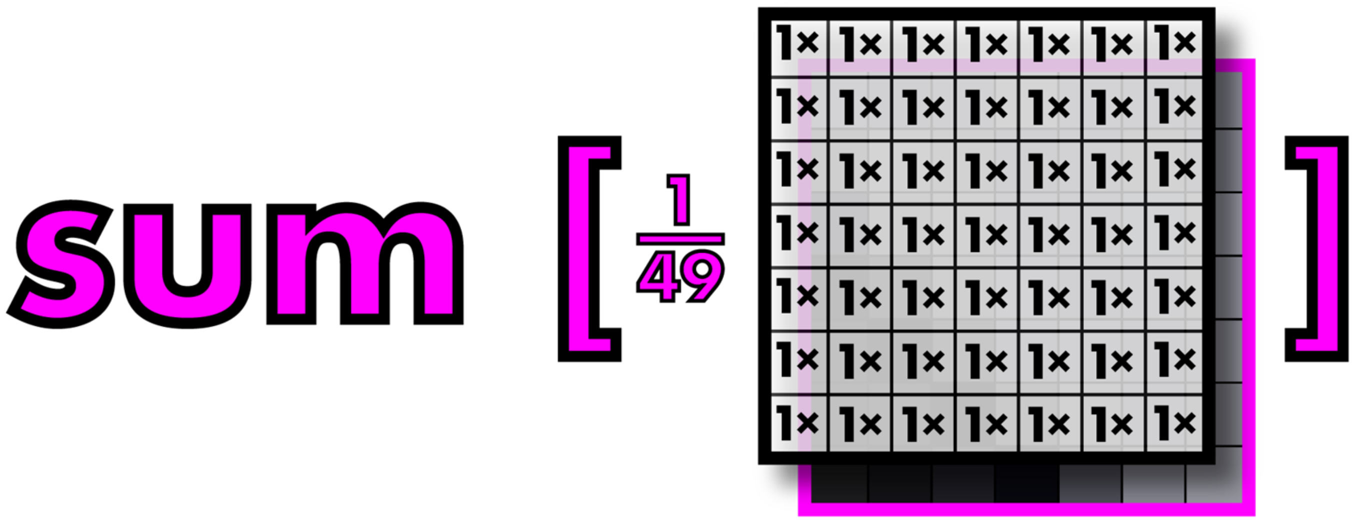
What is averaging? A weighted sum



What is averaging? A weighted sum



What are the weights here ?

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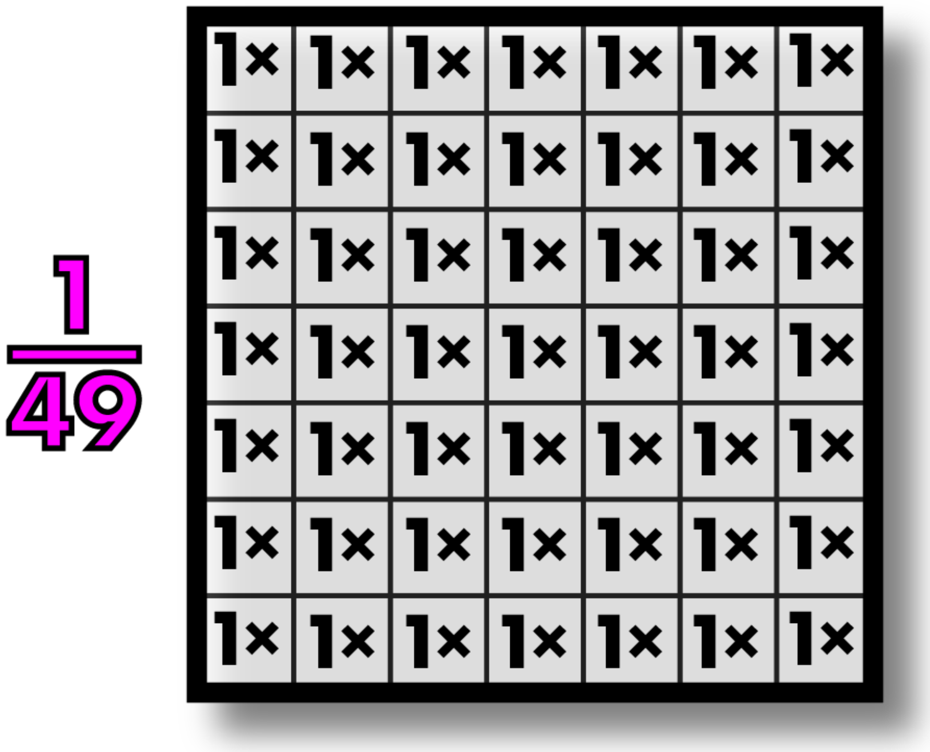
Moving average is a filter

Filter or kernel



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Filtering

- Filtering
  - Forming a new image whose pixel values are transformed from original pixel values
- Goal is to extract useful information from images, or transform images into another domain where we can modify/enhance image properties
  - Features (edges, corners, blobs...)
  - Applications: super-resolution (resizing); in-painting; de-noising;

[Slide by Niebles]

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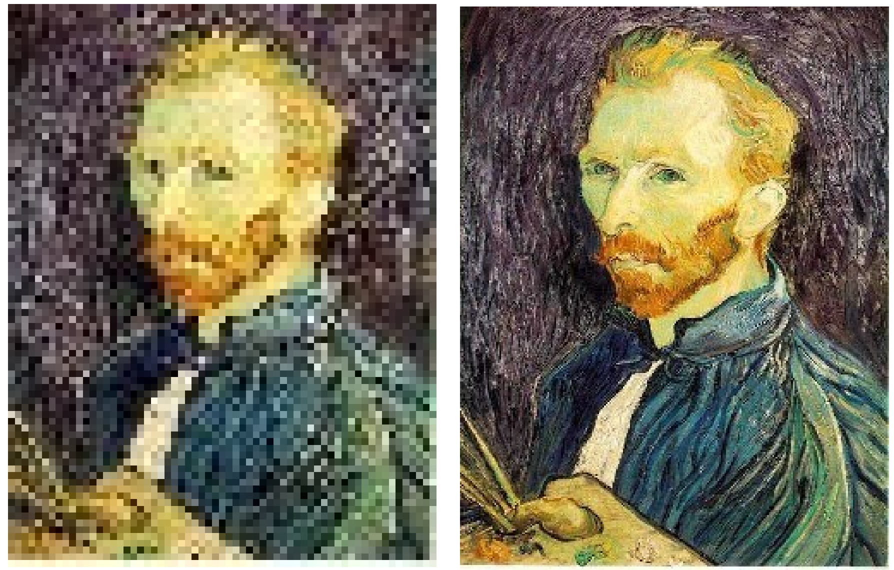
Applications

De-noising

Salt and pepper noise

Super-resolution



In-painting

Bertamio et al

[Slide by Niebles]

Systems

- We define a **system** as a unit that converts an input function f[x,y] into an output (or response) function g[x,y], where (x,y) are the independent variables.
  - In the case of images, (x,y) represents the **spatial position in the image.**

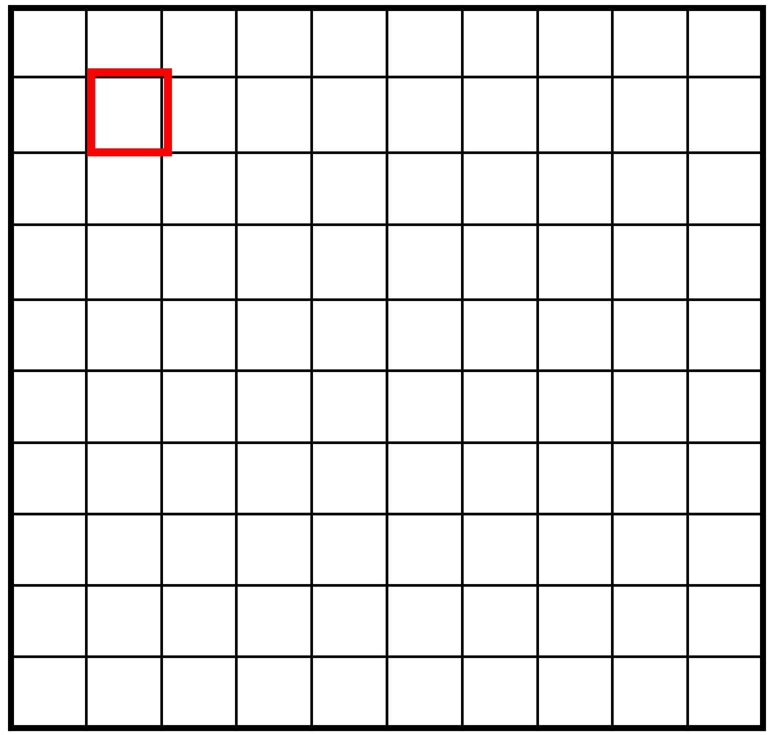
[Slide by Niebles]

Moving average - example

$F[x, y]$

0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	90	90	90	90	90	0	0
0	0	0	90	90	90	90	90	0	0
0	0	0	90	90	90	90	90	0	0
0	0	0	90	0	90	90	90	0	0
0	0	0	90	90	90	90	90	0	0
0	0	0	0	0	0	0	0	0	0
0	0	90	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0

$G[x, y]$



[Slide by Seitz]

Moving average - example

$F[x, y]$

0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	90	90	90	90	90	0	0
0	0	0	90	90	90	90	90	0	0
0	0	0	90	90	90	90	90	0	0
0	0	0	90	0	90	90	90	0	0
0	0	0	90	90	90	90	90	0	0
0	0	0	0	0	0	0	0	0	0
0	0	90	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0

$G[x, y]$

	0	10							

[Slide by Seitz]

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Moving average - example

$F[x, y]$

0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	90	90	90	90	90	0	0
0	0	0	90	90	90	90	90	0	0
0	0	0	90	90	90	90	90	0	0
0	0	0	90	0	90	90	90	0	0
0	0	0	90	90	90	90	90	0	0
0	0	0	0	0	0	0	0	0	0
0	0	90	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0

$G[x, y]$

	0	10	20						

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Moving average - example

$F[x, y]$

0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	90	90	90	90	90	0	0
0	0	0	90	90	90	90	90	0	0
0	0	0	90	90	90	90	90	0	0
0	0	0	90	0	90	90	90	0	0
0	0	0	90	90	90	90	90	0	0
0	0	0	0	0	0	0	0	0	0
0	0	90	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0

$G[x, y]$

	0	10	20	30					

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Moving average - example

$F[x, y]$

0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	90	90	90	90	90	0	0
0	0	0	90	90	90	90	90	0	0
0	0	0	90	90	90	90	90	0	0
0	0	0	90	0	90	90	90	0	0
0	0	0	90	90	90	90	90	0	0
0	0	0	0	0	0	0	0	0	0
0	0	90	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0

$G[x, y]$

	0	10	20	30	30				

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Moving average - example

$F[x, y]$

0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	90	90	90	90	90	0	0
0	0	0	90	90	90	90	90	0	0
0	0	0	90	90	90	90	90	0	0
0	0	0	90	0	90	90	90	0	0
0	0	0	90	90	90	90	90	0	0
0	0	0	0	0	0	0	0	0	0
0	0	90	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0

$G[x, y]$

	0	10	20	30	30	30	20	10	
	0	20	40	60	60	60	40	20	
	0	30	60	90	90	90	60	30	
	0	30	50	80	80	90	60	30	
	0	30	50	80	80	90	60	30	
	0	20	30	50	50	60	40	20	
	10	20	30	30	30	30	20	10	
	10	10	10	0	0	0	0	0	

[Slide by Seitz]

Properties of systems

- Amplitude properties
  - Additivity $S[f_i[n,m] + f_j[n,m]] = S[f_i[n,m]] + S[f_j[n,m]]$
  - Homogeneity $S[\alpha f_i[n,m]] = \alpha S[f_i[n,m]]]$
  - Superposition $S[\alpha f_i[n,m] + \beta f_j[n,m]] = \alpha S[f_i[n,m]] + \beta S[f_j[n,m]]$
  - Stability $|f[n,m]| \leq k \implies |g[n,m]| \leq ck$
  - Invertibility $S^{-1}[S[f_i[n,m]]] = f[n,m]$

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Properties of systems

- Spatial properties
  - Causality $\text{for } n < n_0, m < m_0, \text{ if } f[n,m] = 0 \implies g[n,m] = 0$
  - Shift invariance $f[n - n_0, m - m_0] \xrightarrow{\mathcal{S}} g[n - n_0, m - m_0]$

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Linear Systems - filters

- Linear filtering
  - Form a new image whose pixels are a weighted sum of original pixel values
  - Use the same set of weights at each point
- S is a linear system (function) iff *S satisfies*

$$S[\alpha f_i[n,m] + \beta f_j[h,m]] = \alpha S[f_i[n,m]] + \beta S[f_j[h,m]]$$

superposition property

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Linear Shift Invariant Systems

- We call systems which satisfy the superposition and shift-invariant property *Linear Shift Invariant Systems* (LSI)
- Not all filters are LSI
  - Is thresholding linear?

$$g[n,m] = \begin{cases} 1, & f[n,m] > 100 \\ 0, & \text{otherwise.} \end{cases}$$

  - Consider:

    f1[n,m] + f2[n,m] > T
    f1[n,m] < T
    f2[n,m]<T

- LSI systems can be described by the **convolution** operation

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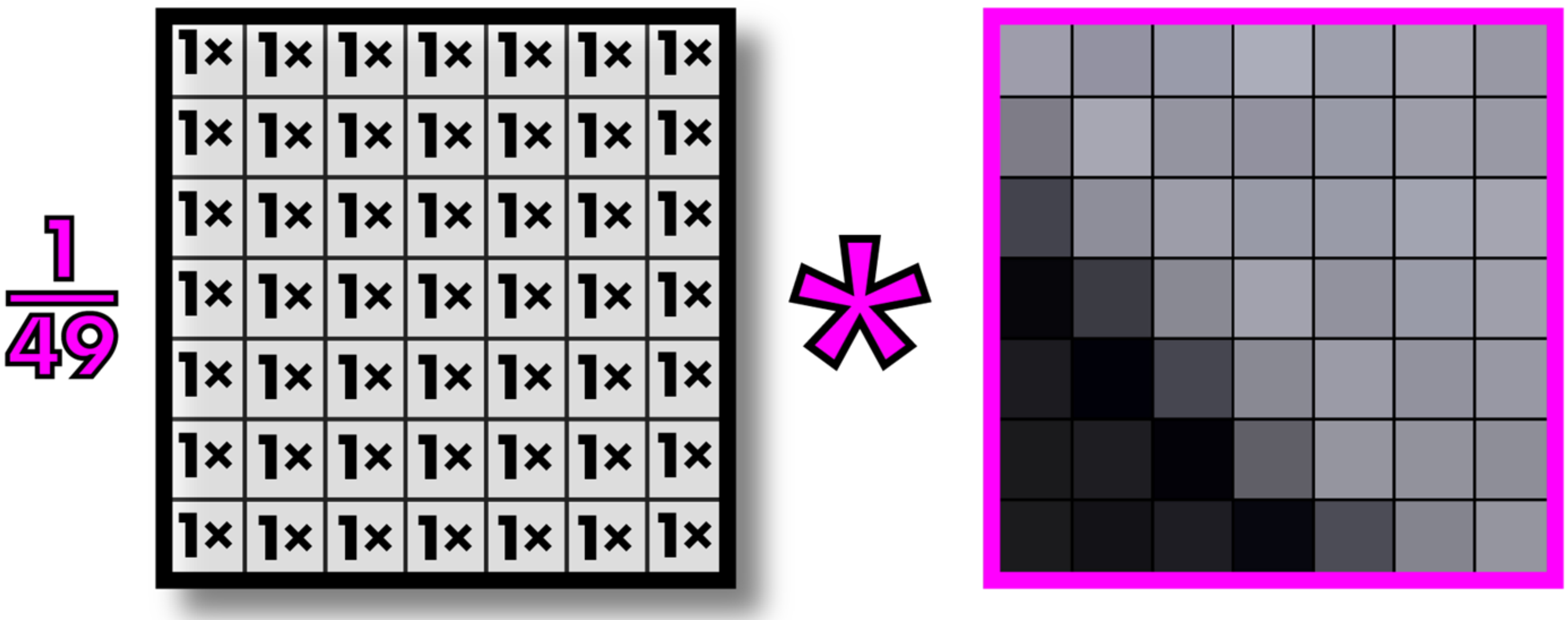
Call this operation *"convolution"*

Filter or kernel



Note: multiplying an image section by a filter is actually called "correlation" and convolution involves inverting the filter first

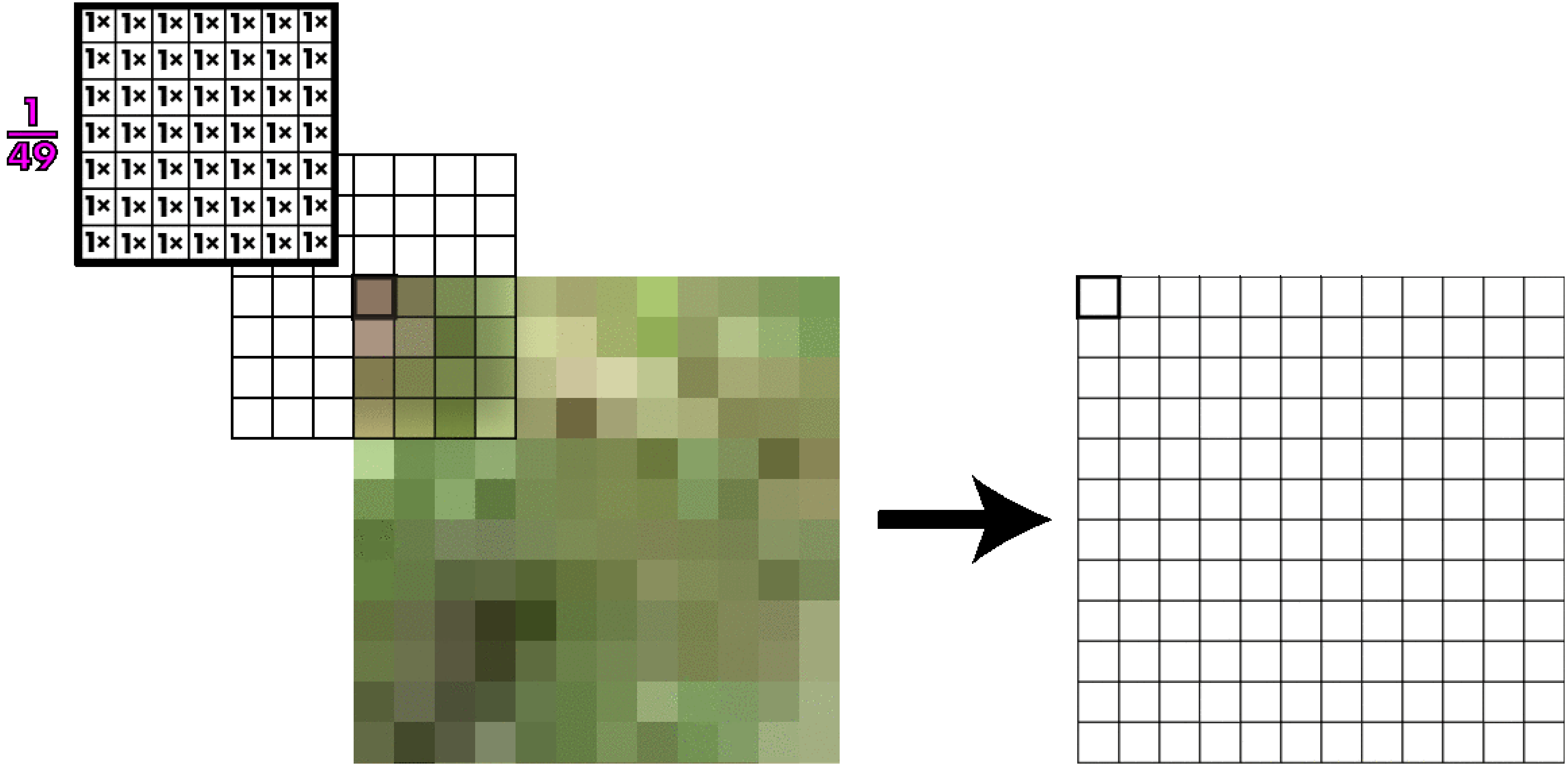
Convolutions on larger images

$\frac{1}{49}$

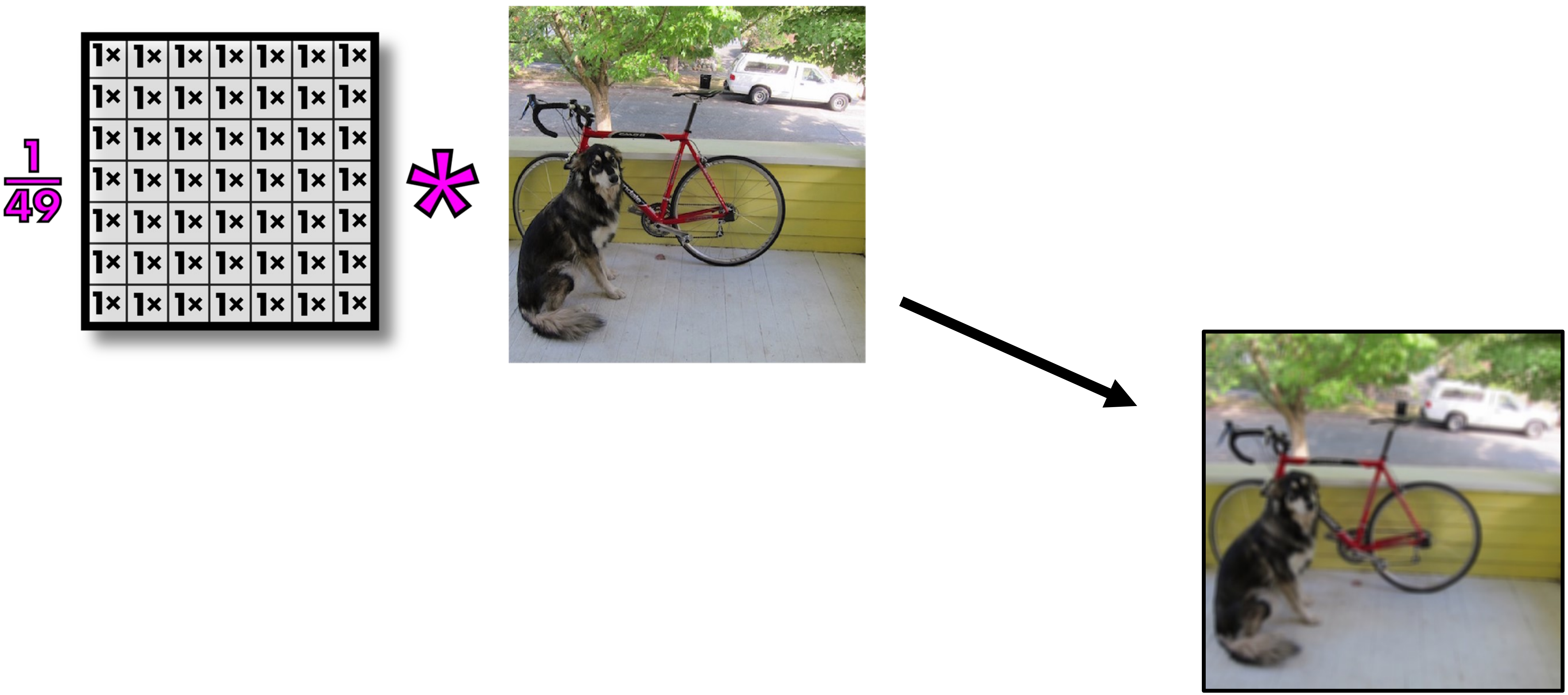
1×	1×	1×	1×	1×	1×	1×
1×	1×	1×	1×	1×	1×	1×
1×	1×	1×	1×	1×	1×	1×
1×	1×	1×	1×	1×	1×	1×
1×	1×	1×	1×	1×	1×	1×
1×	1×	1×	1×	1×	1×	1×
1×	1×	1×	1×	1×	1×	1×

$*$

Kernel slides across image



Convolutions on larger images



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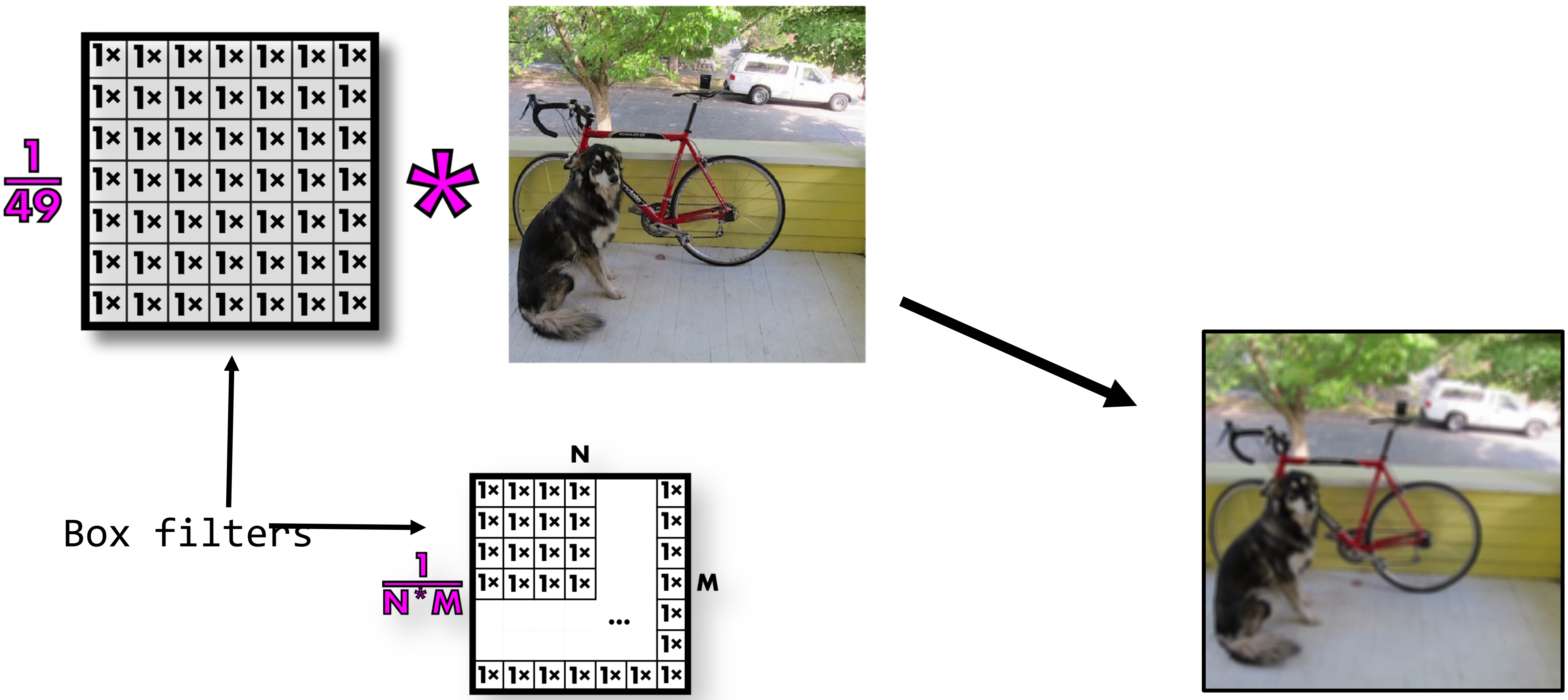
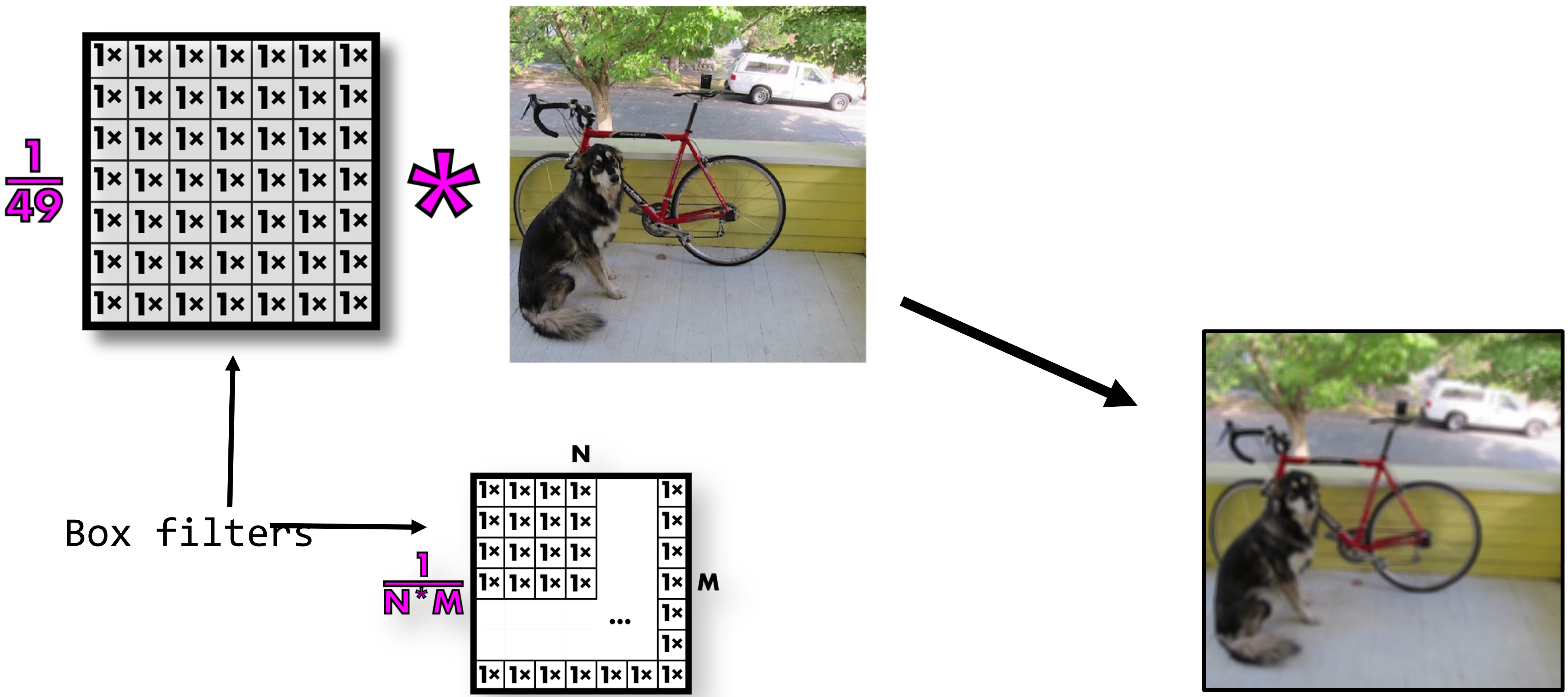
This is called box filter



Box filters smooth image



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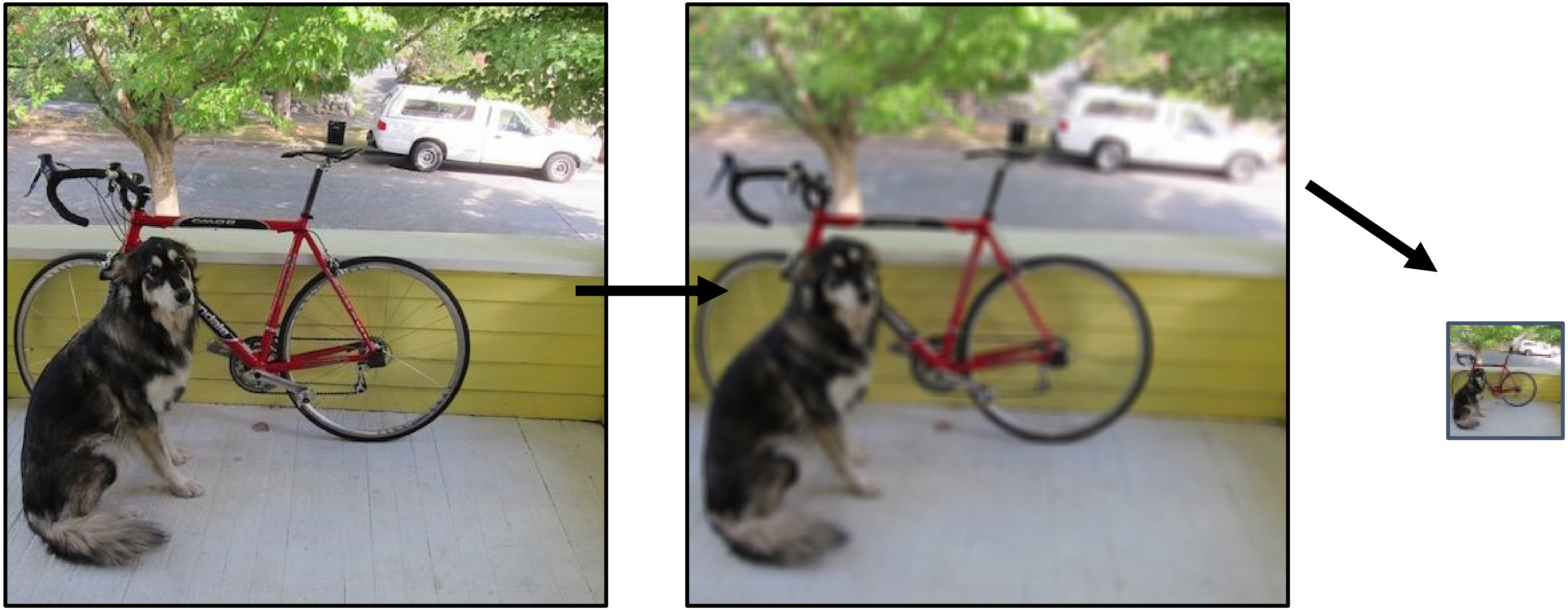
Now we resize our smoothed image



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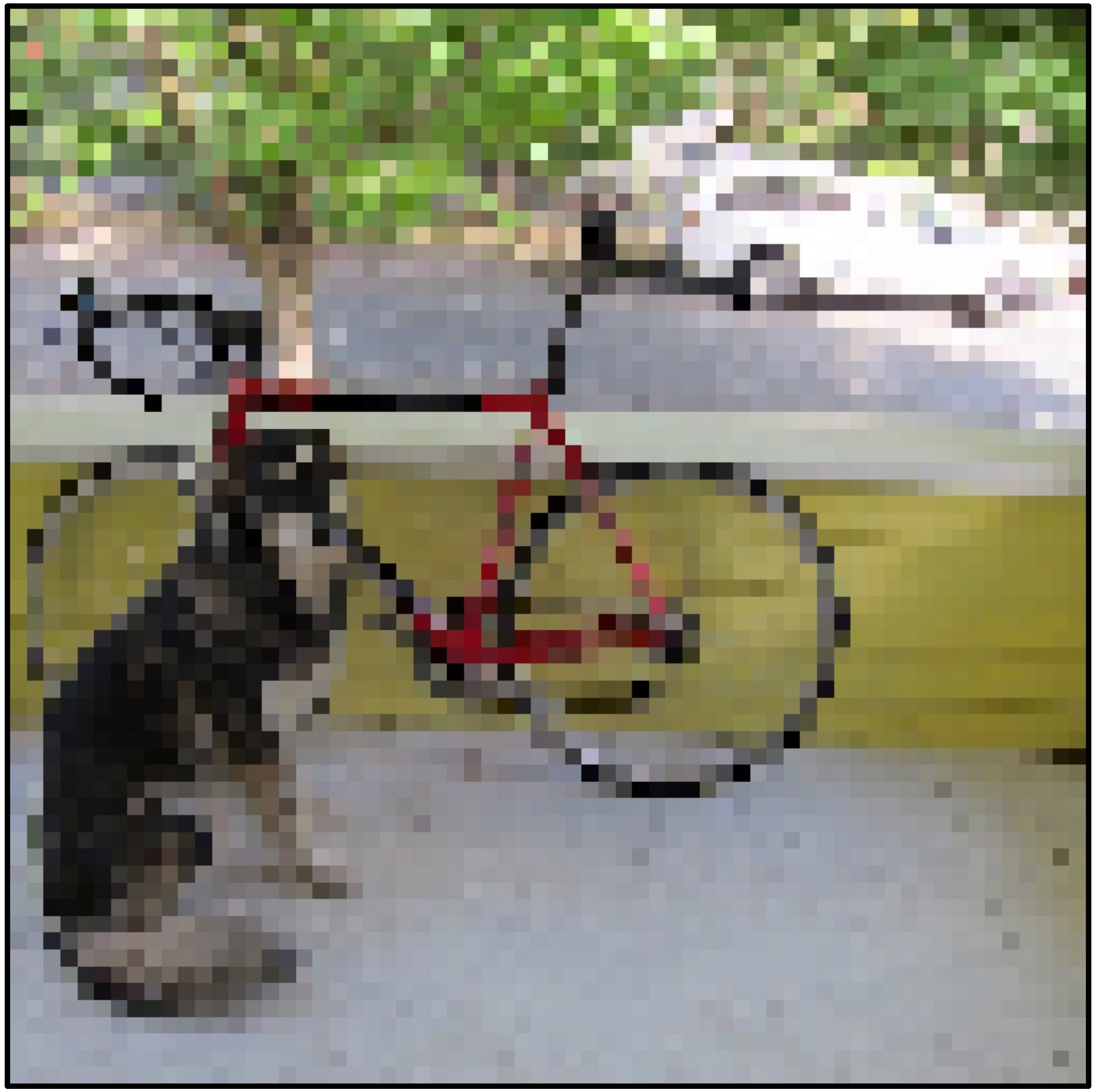
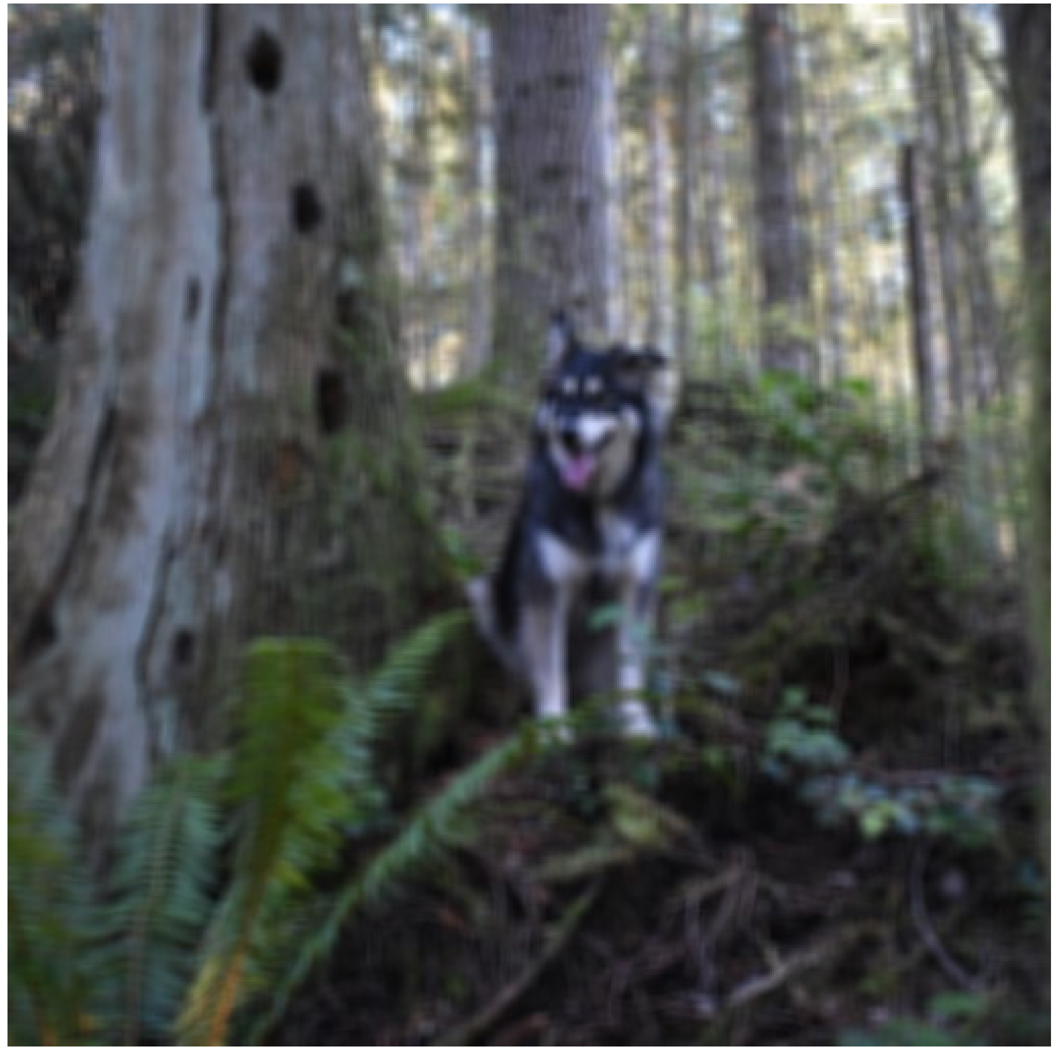
So much better!

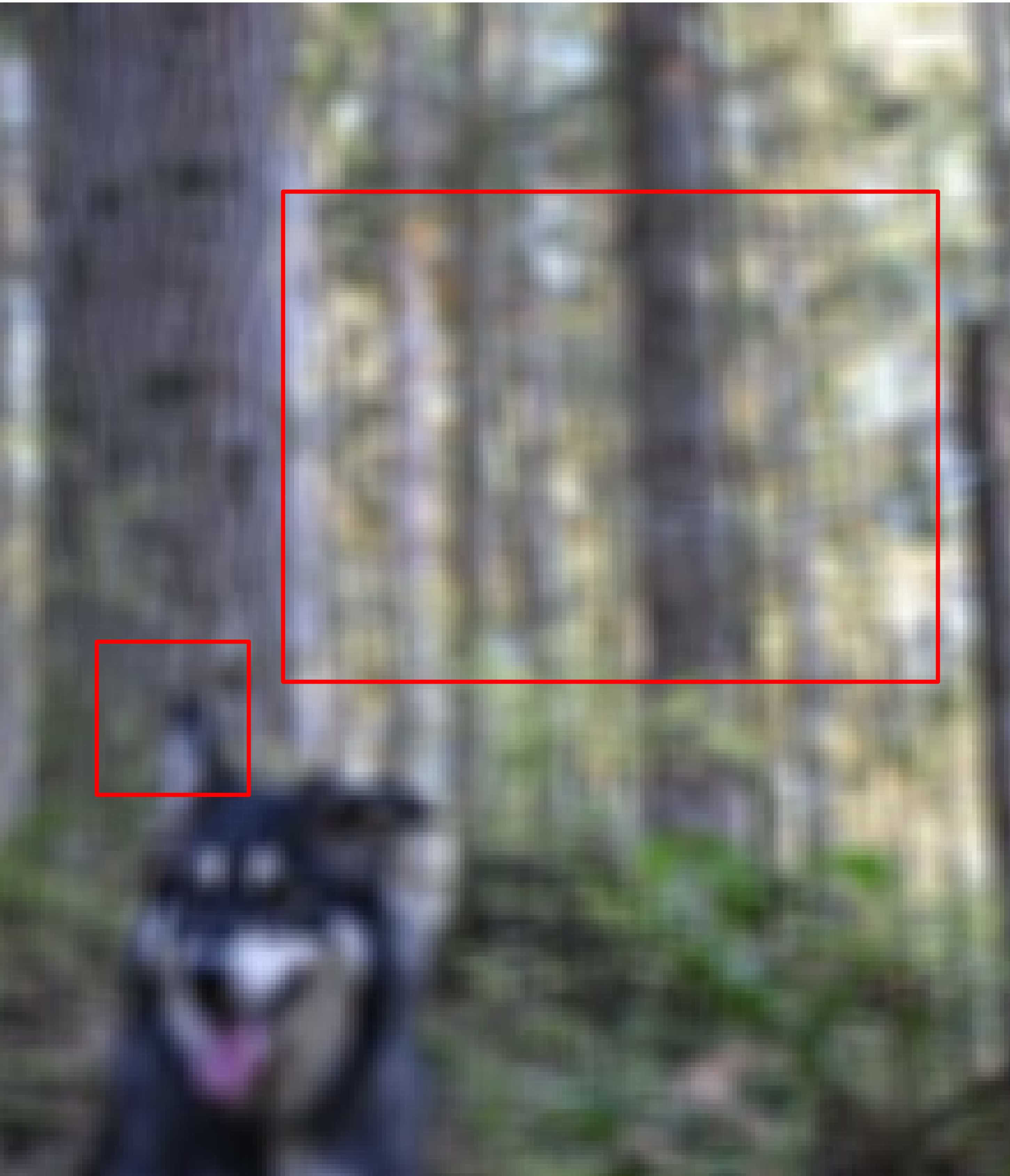
Compare to interpolation



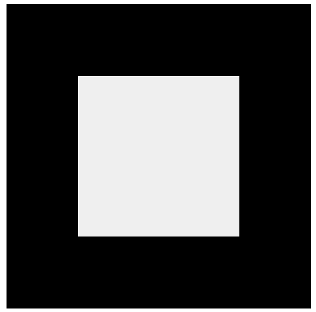
Box filters have artifacts

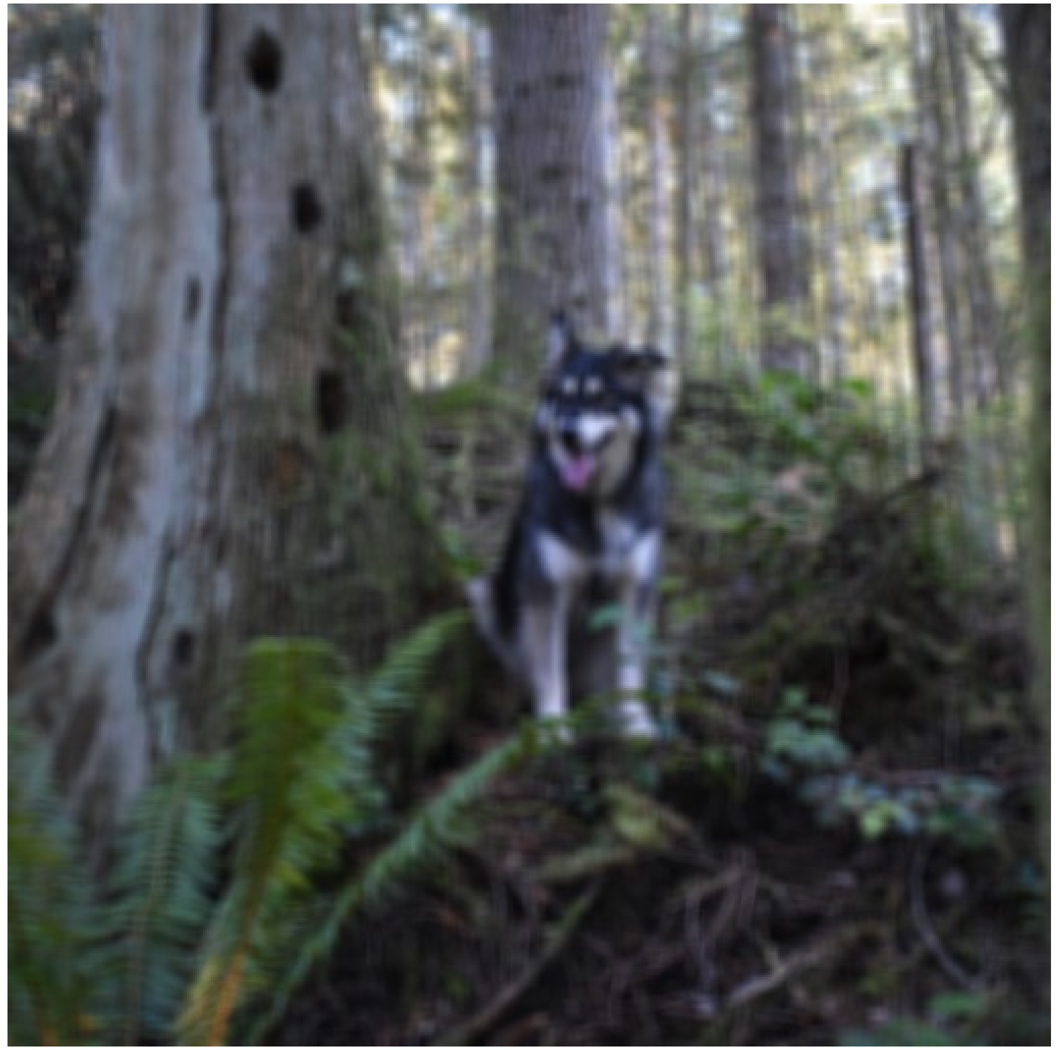


Box filters have artifacts

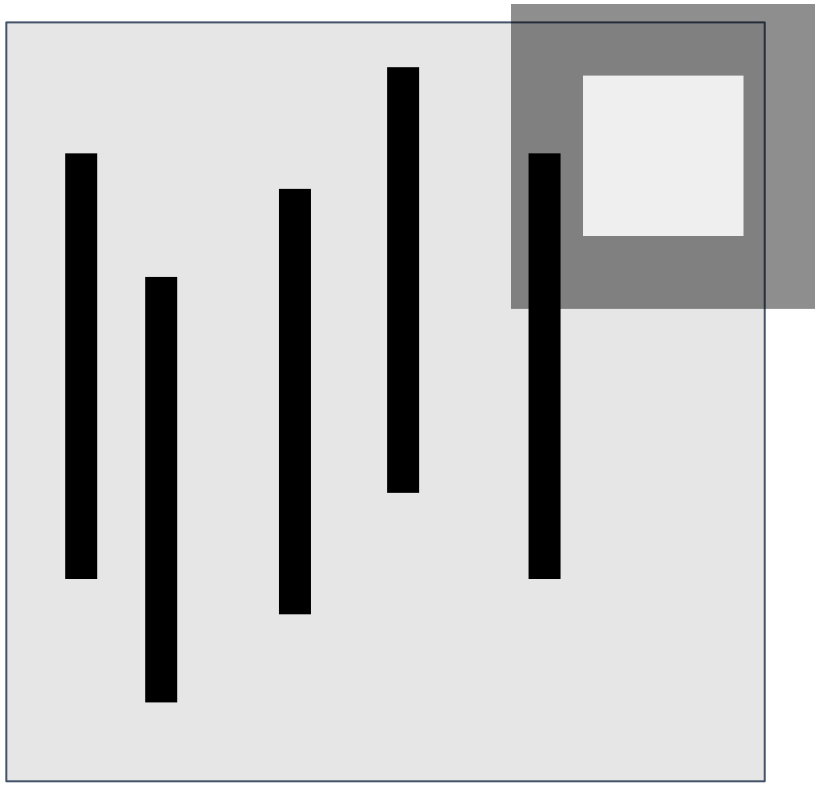


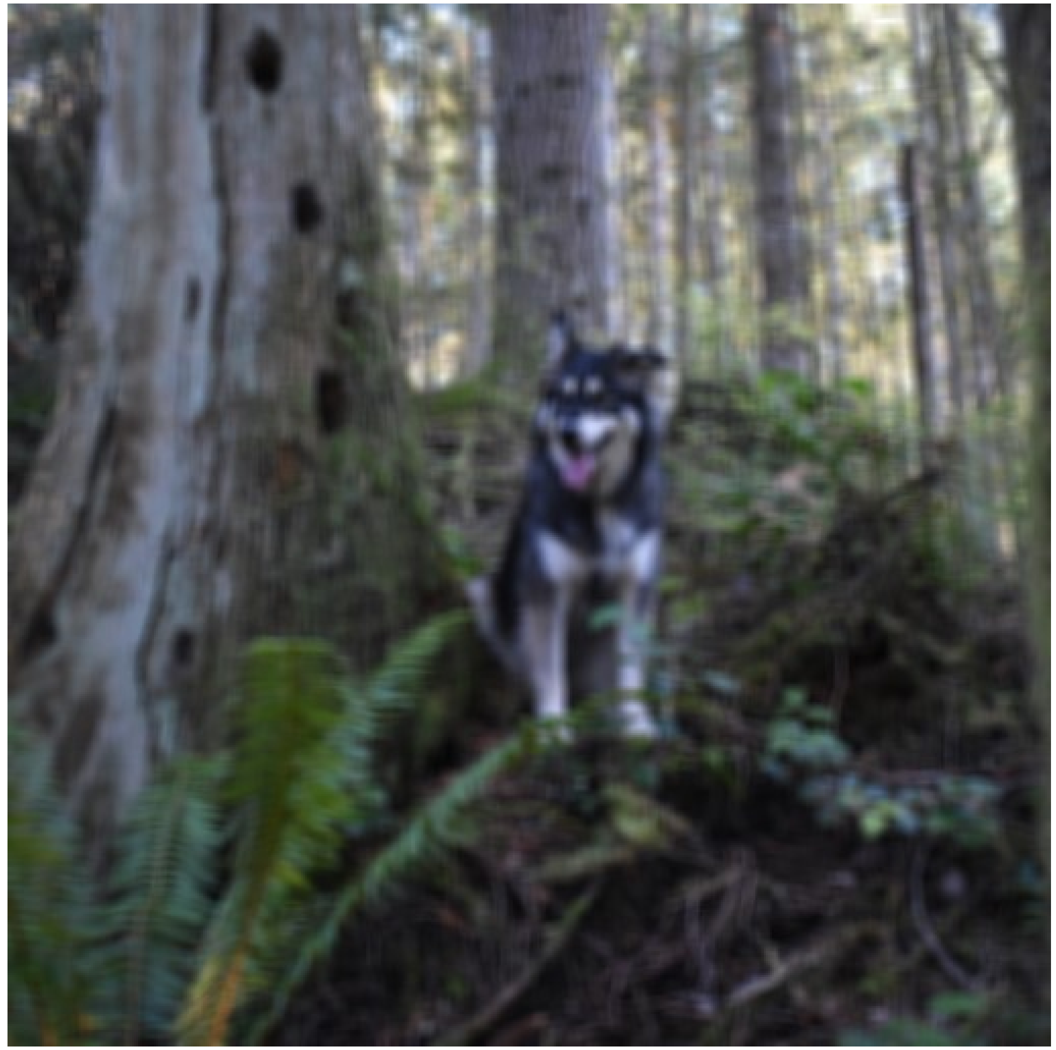
Box filters: vertical + horizontal streaking





Box filters: vertical + horizontal streaking





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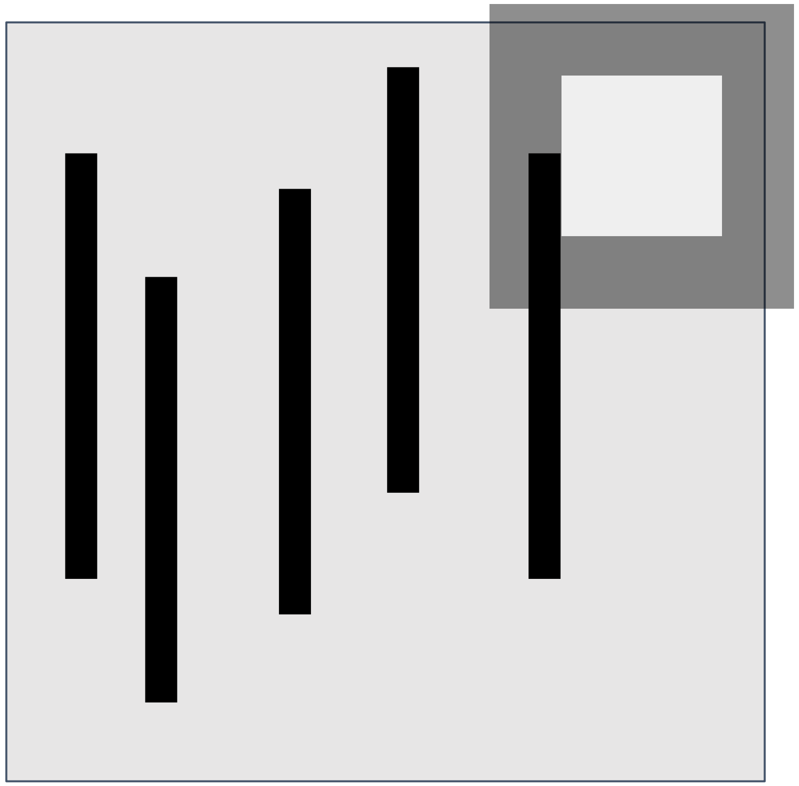
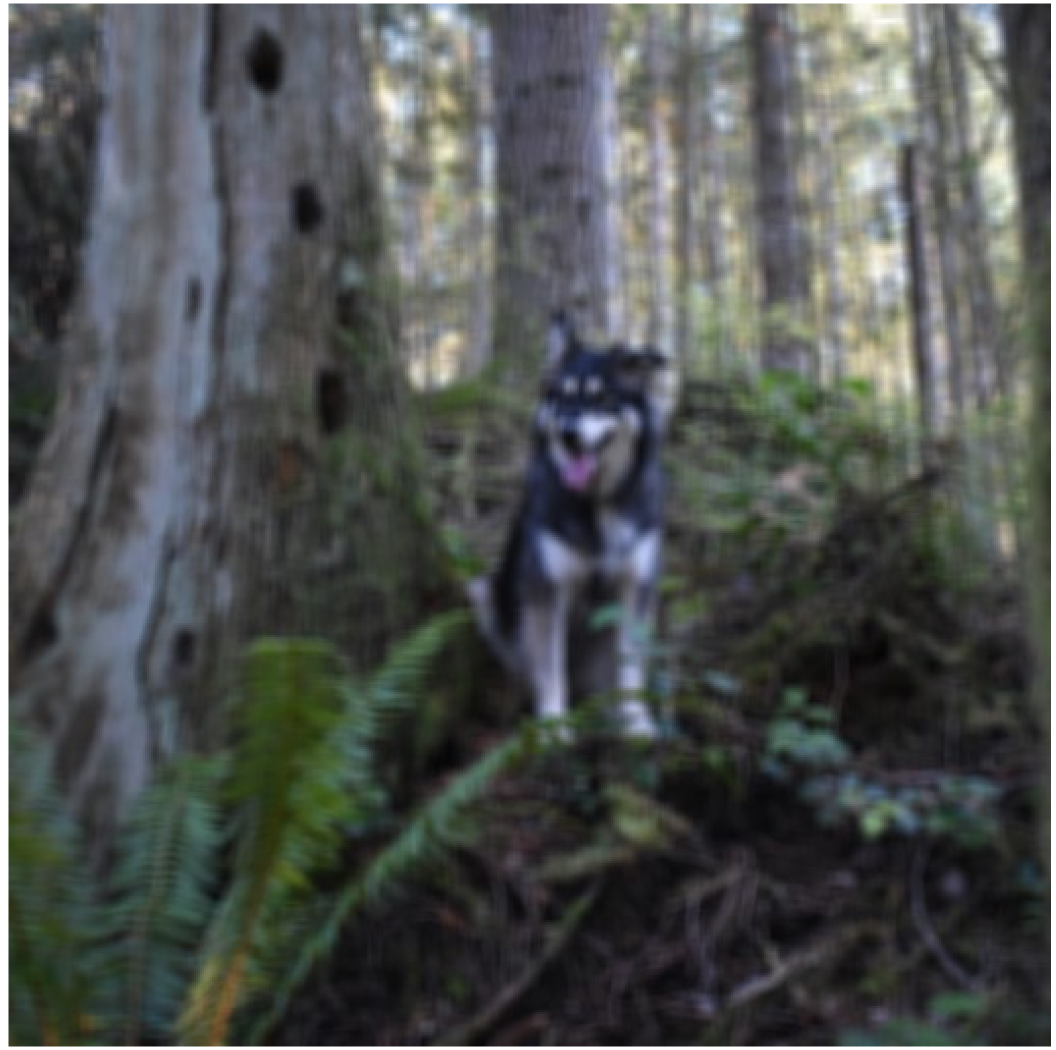
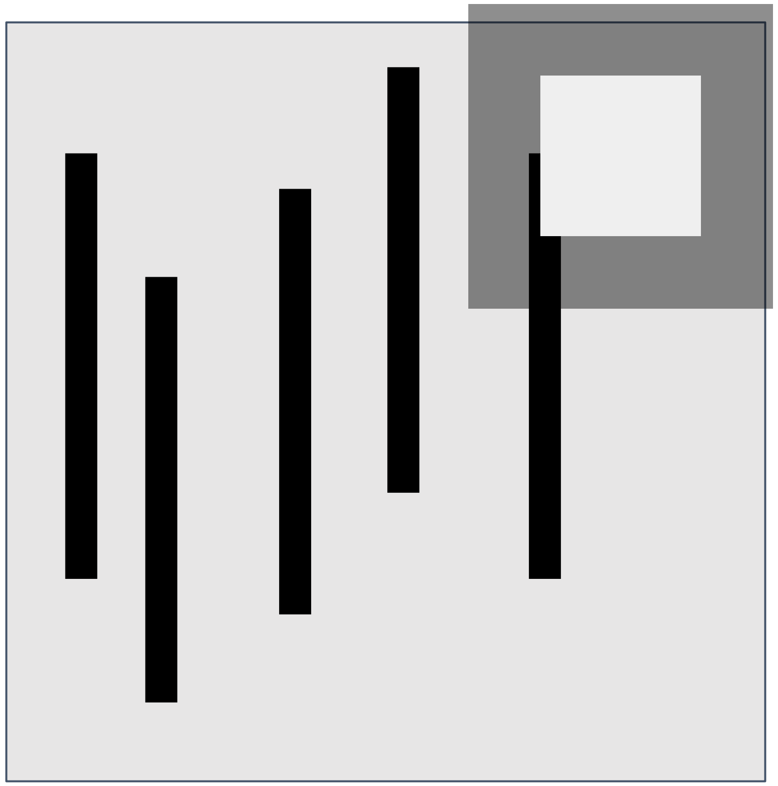
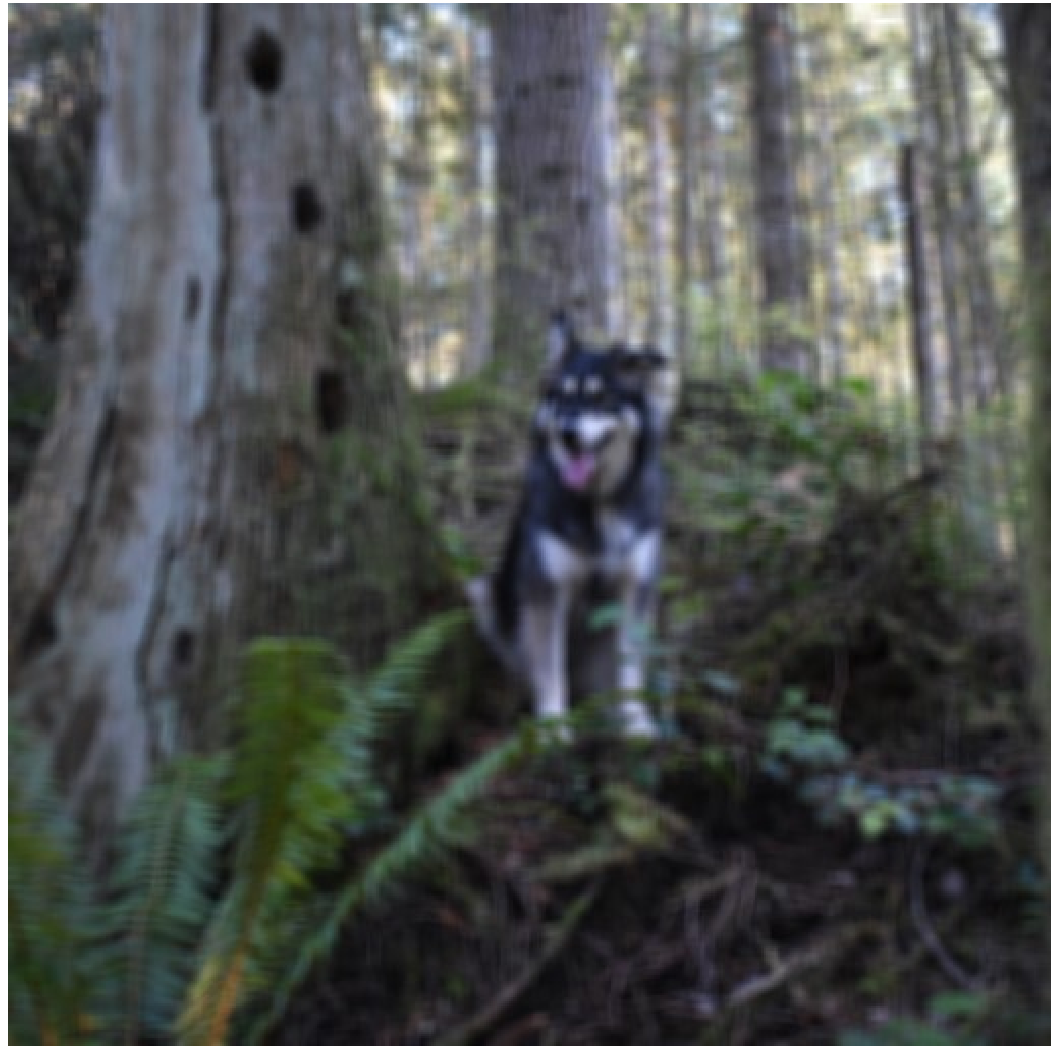
Box filters: vertical + horizontal streaking



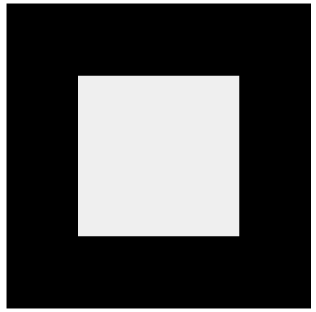


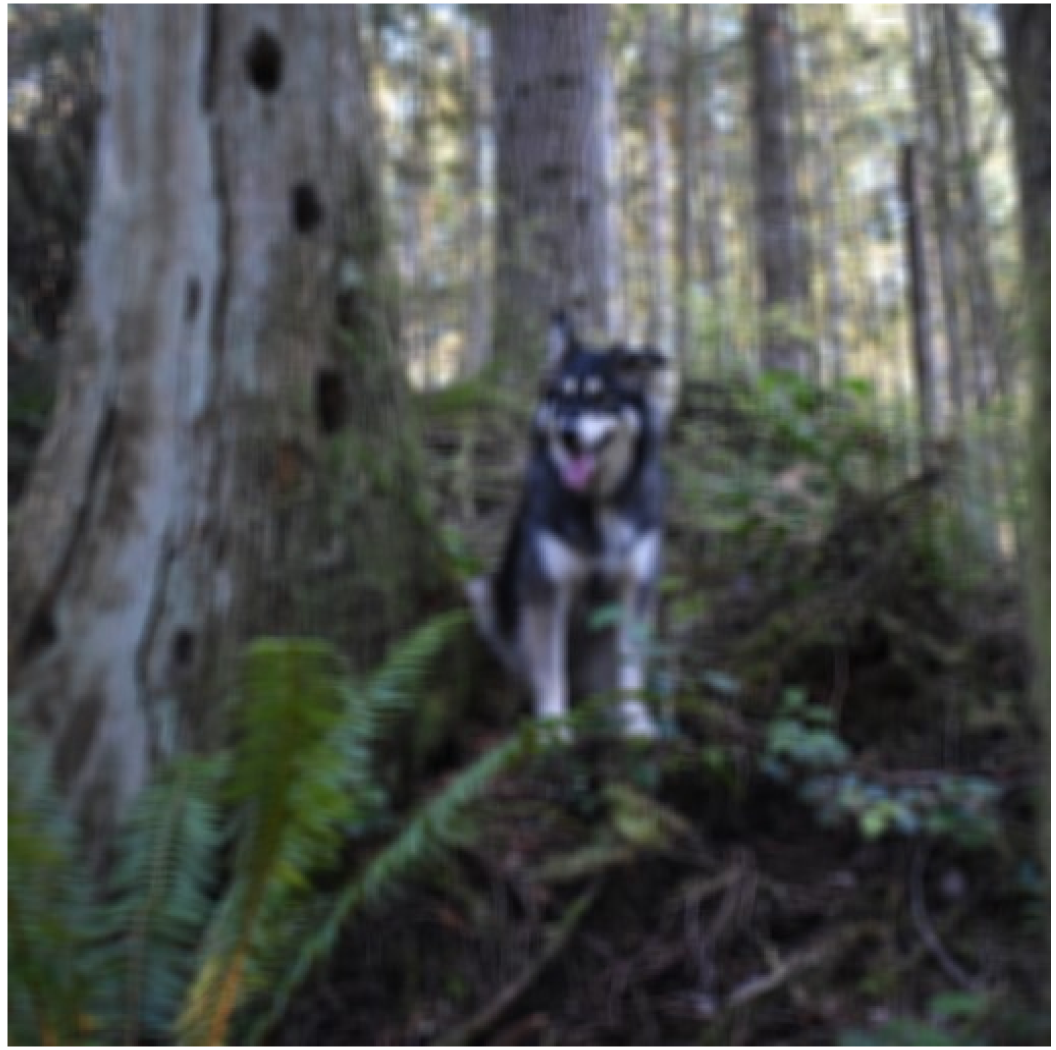
Box filters: vertical + horizontal streaking





We want a smoothly weighted kernel





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Today's Agenda

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- Convolution
  - Box Filter
  - Gaussian
  - Cross correlation vs Convolution
- Examples of filters

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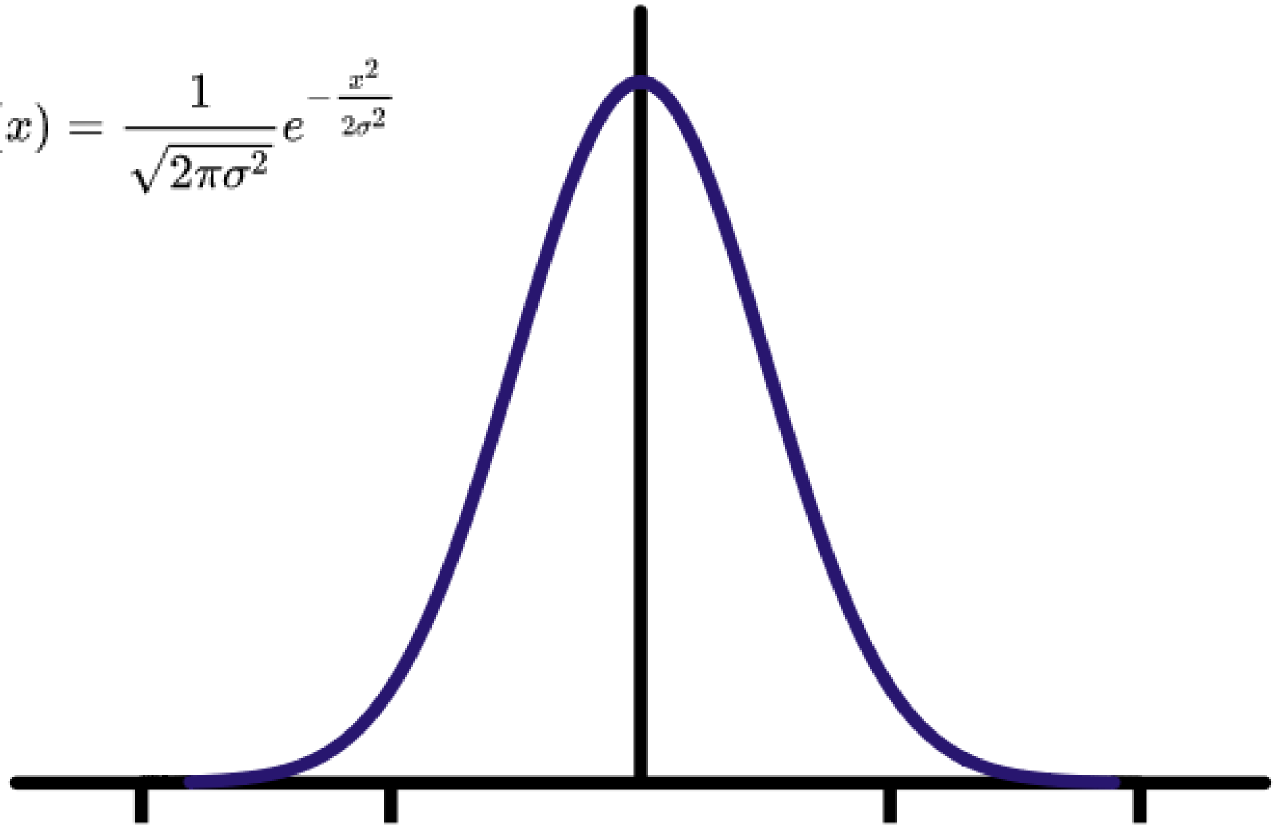
Gaussians

$$G(x) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{x^2}{2\sigma^2}}$$



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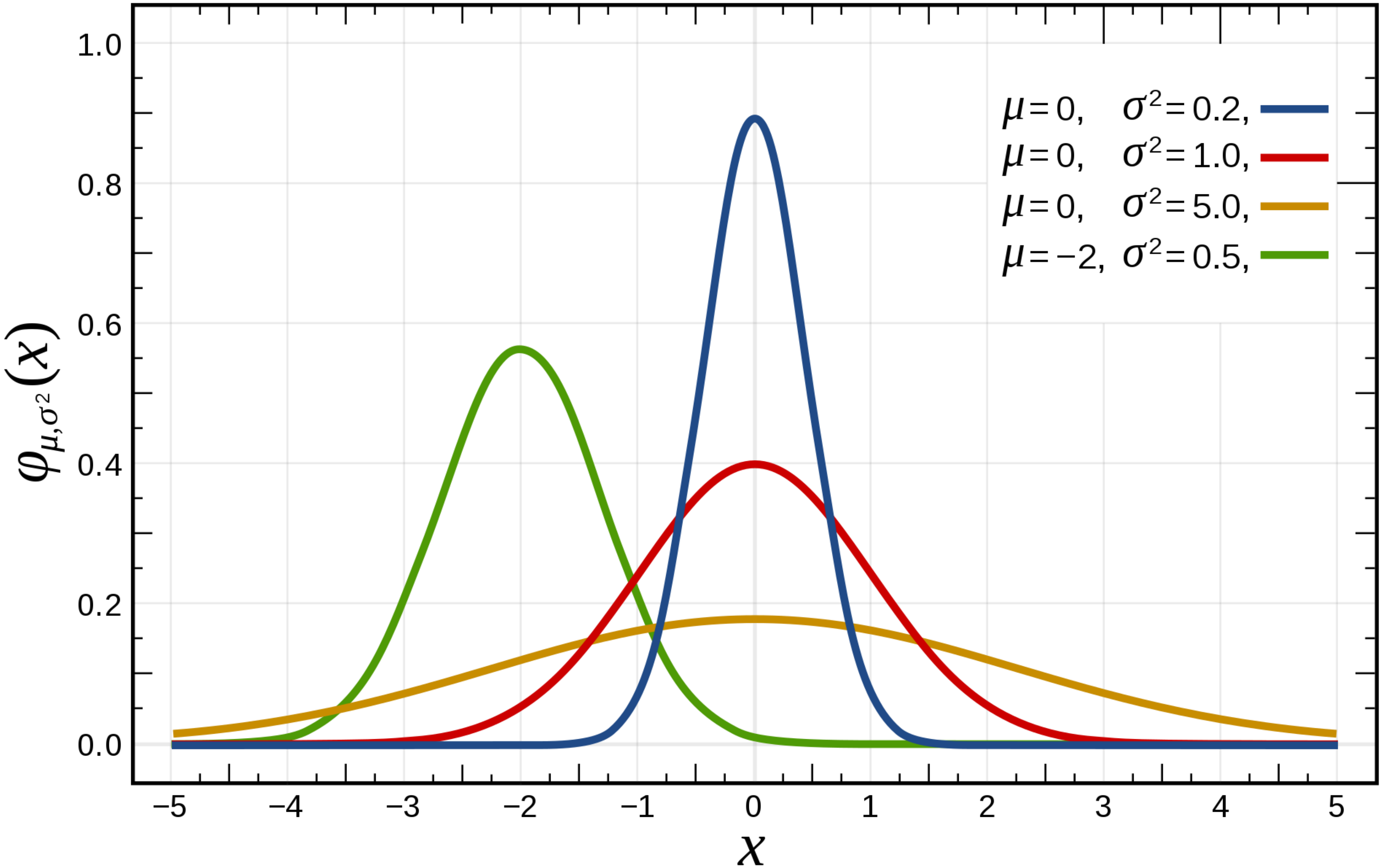
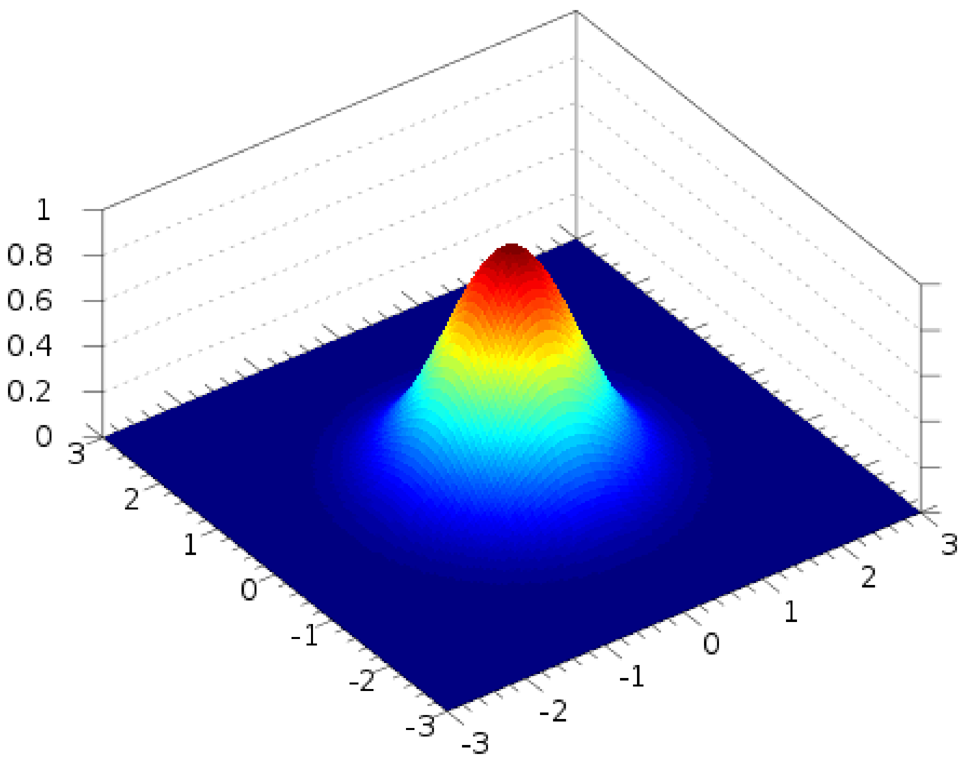
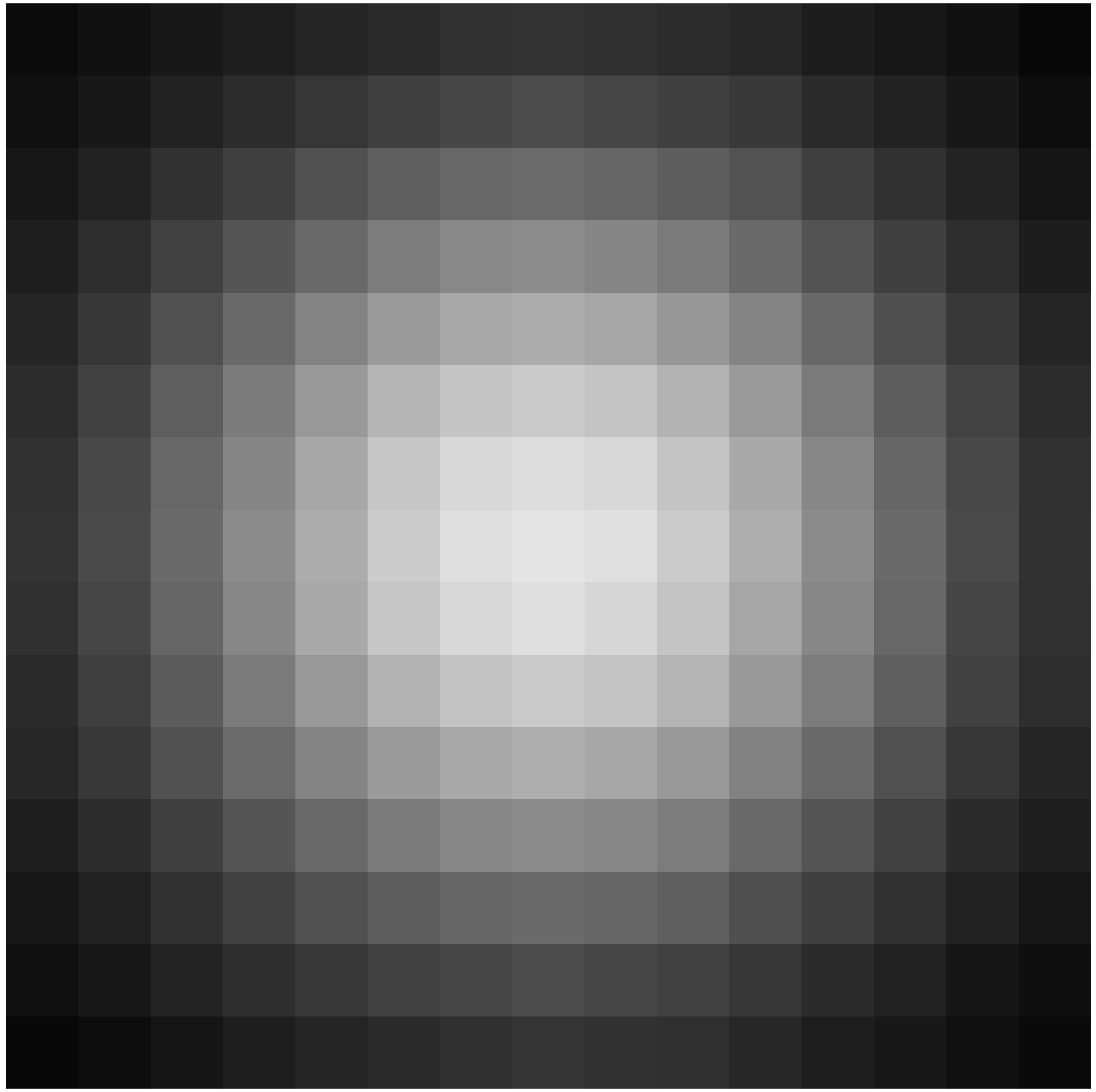
Gaussians – how σ affects the shape



2D Gaussian

$$g(x, y) = \frac{1}{2\pi\sigma^2} \cdot e^{-\frac{x^2+y^2}{2\sigma^2}}$$





Example 7x7 Gaussian

0.000	0.000	0.001	0.001	0.001	0.000	0.000
0.000	0.002	0.012	0.020	0.012	0.002	0.000
0.001	0.012	0.068	0.109	0.068	0.012	0.001
0.001	0.020	0.109	0.172	0.109	0.020	0.001
0.001	0.012	0.068	0.109	0.068	0.012	0.001
0.000	0.002	0.012	0.020	0.012	0.002	0.000
0.000	0.000	0.001	0.001	0.001	0.000	0.000

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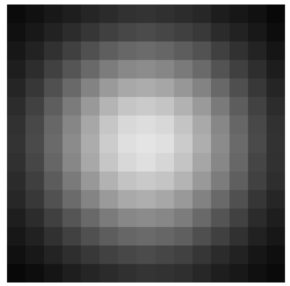
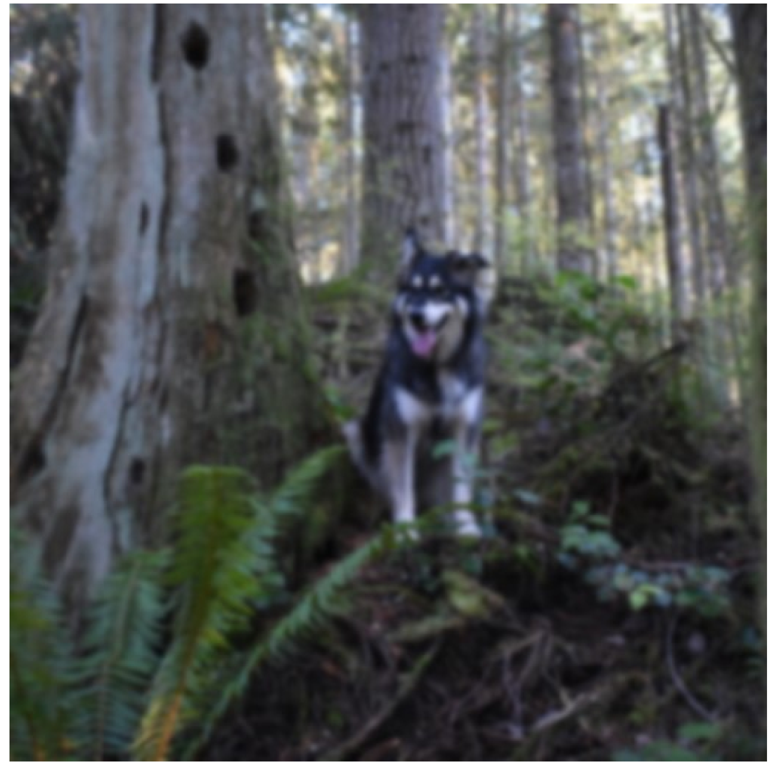
Better smoothing with Gaussians

*



=



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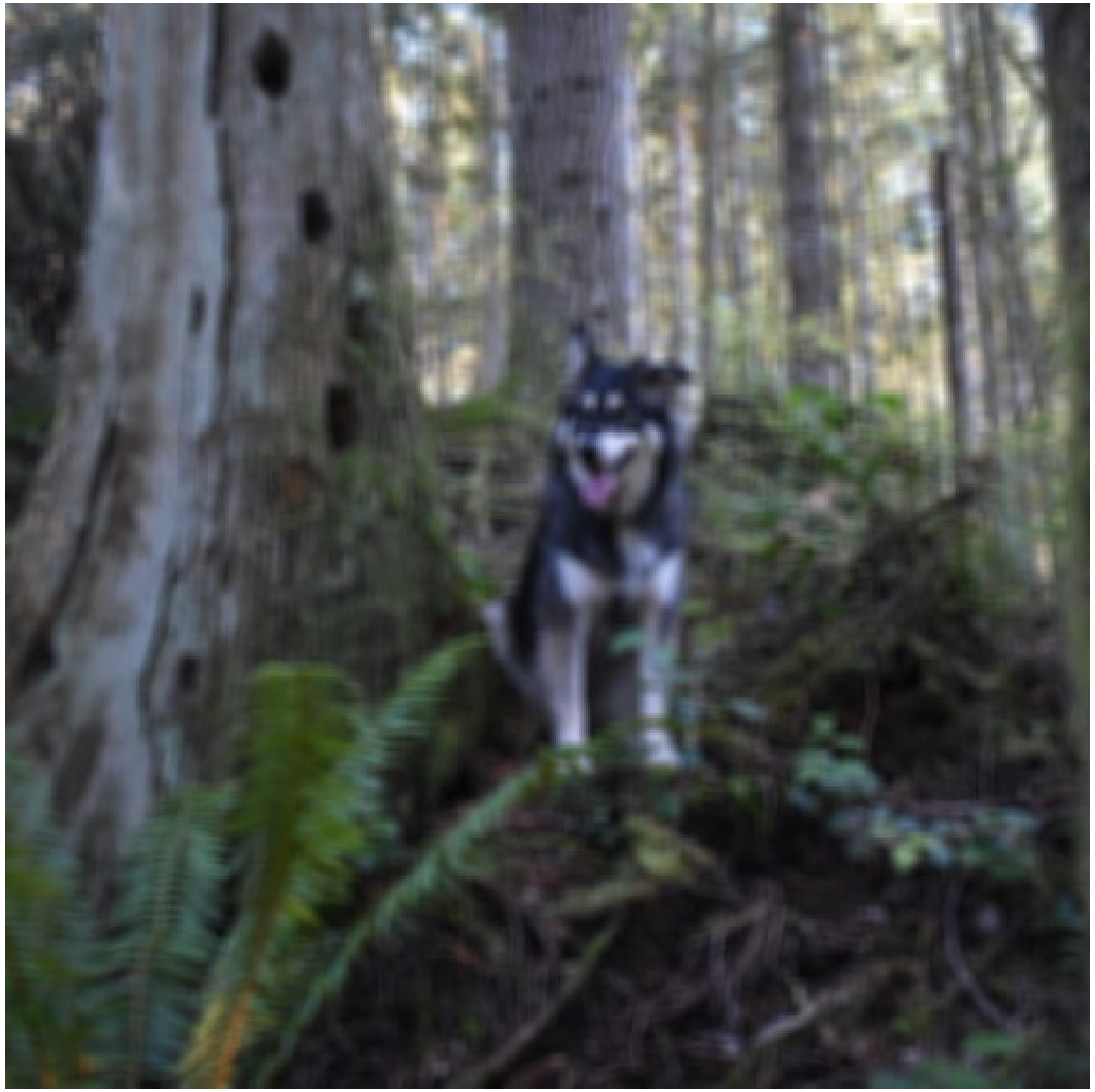
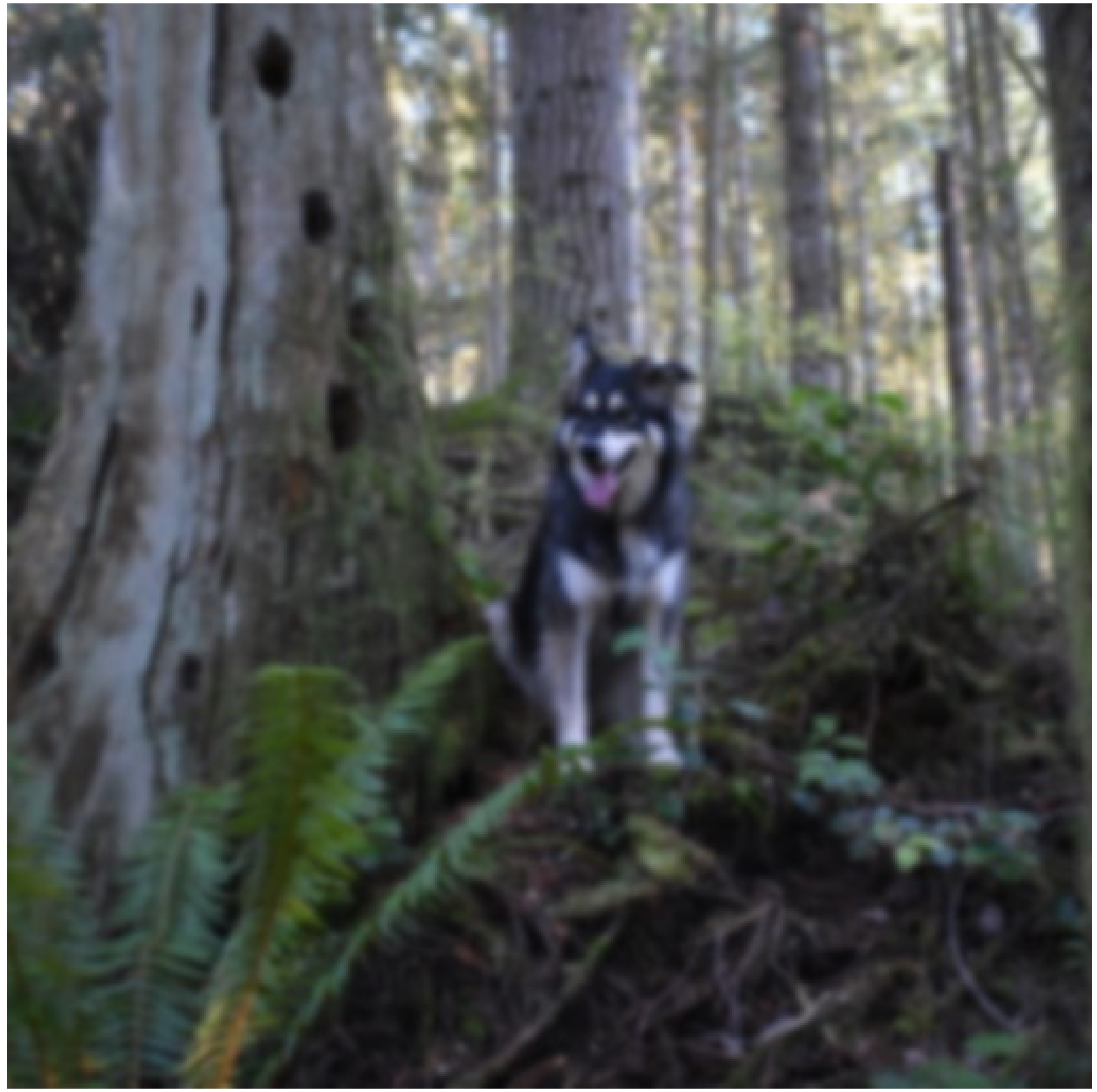
Better smoothing with Gaussians





Better smoothing with Gaussians

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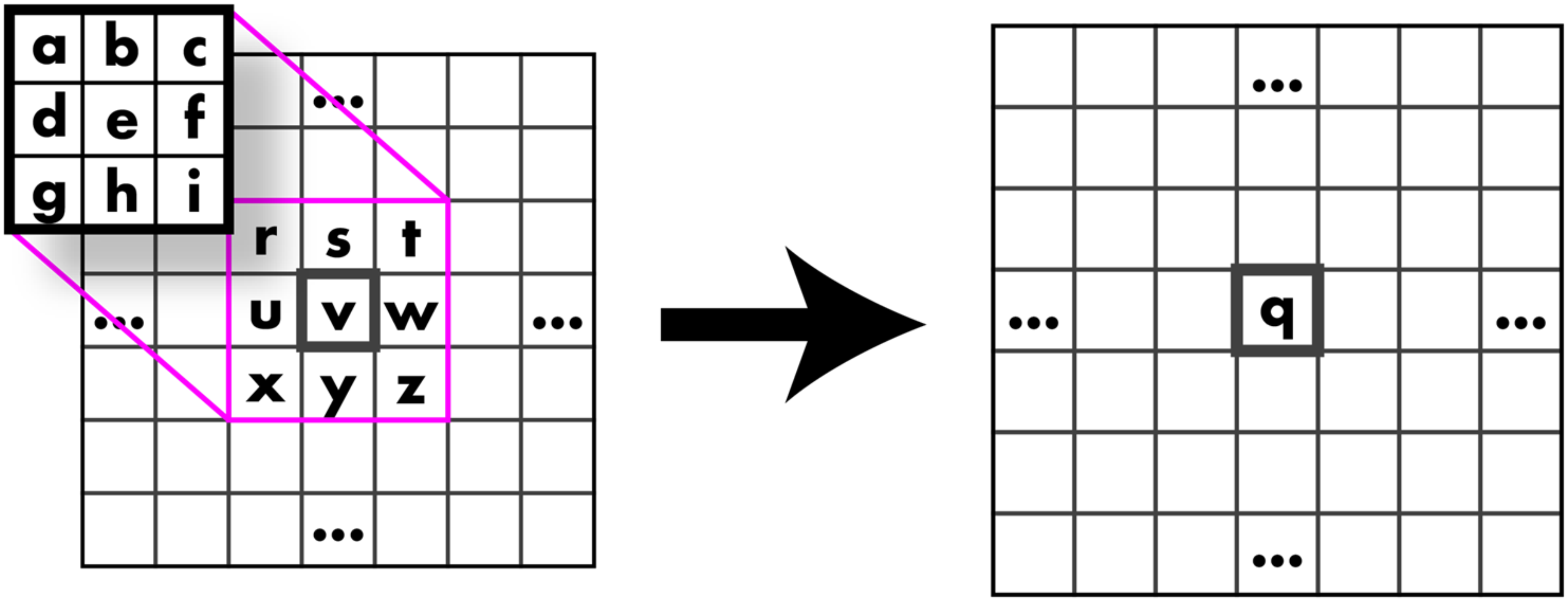
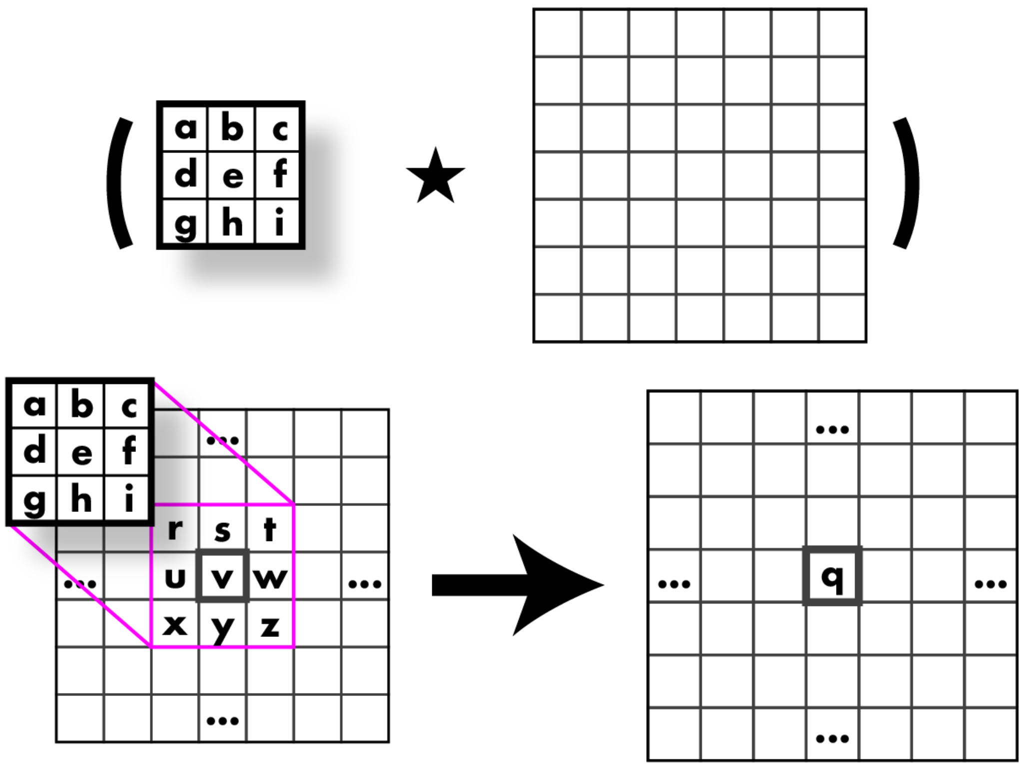
So what is convolution??



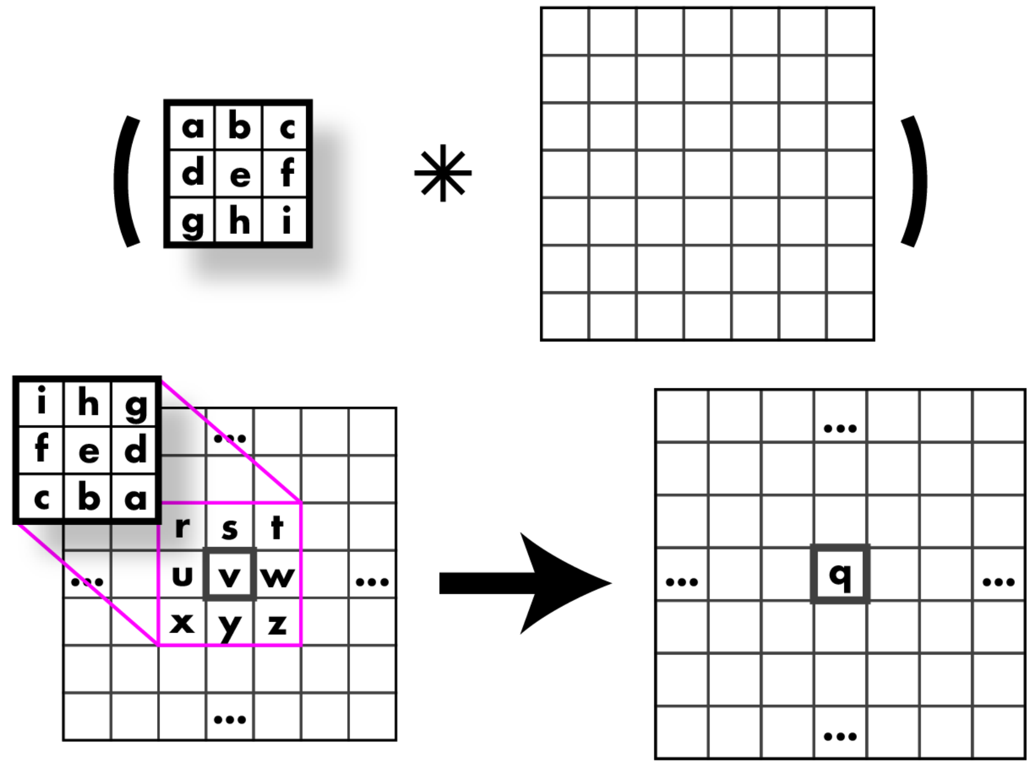
Cross-Correlation vs Convolution

Cross-Correlation



q = a×r + b×s + c×t + d×u + e×v + f×w + g×x + h×y + i×z

Convolution

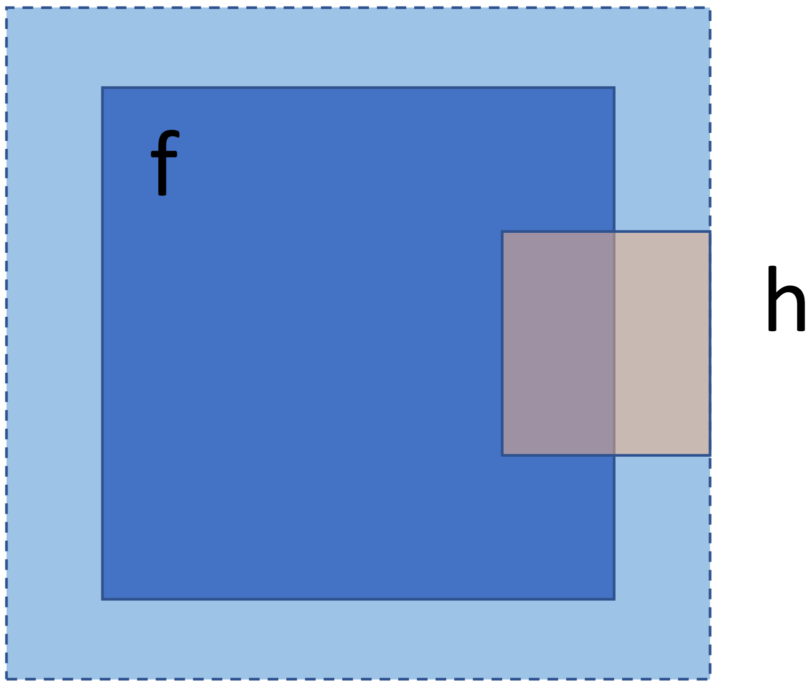


q = i×r + h×s + g×t + f×u + e×v + d×w + c×x + b×y + a×z

Image support and edge effect

- A computer will only convolve **finite support signals**

- What happens at the edge?



- zero "padding"
- edge value replication
- mirror extension
- ...

[Slide by Niebles]

2D convolution example

Input

1	2	3
4	5	6
7	8	9

Kernel

n \ m	-1	0	1
-1	-1	-2	-1
0	0	0	0
1	1	2	1

Output

-13	-20	-17
-18	-24	-18
13	20	17

[Slide by Song Ho Ahn]

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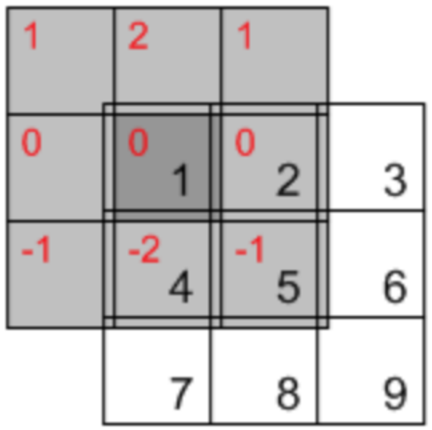
2D convolution example



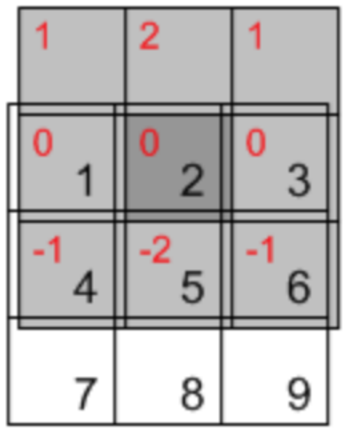
$$
\begin{aligned}
&= x[-1,-1]\cdot h[1,1] + x[0,-1]\cdot h[0,1] + x[1,-1]\cdot h[-1,1] \\
&\quad + x[-1,0]\cdot h[1,0] + x[0,0]\cdot h[0,0] + x[1,0]\cdot h[-1,0] \\
&\quad + x[-1,1]\cdot h[1,-1] + x[0,1]\cdot h[0,-1] + x[1,1]\cdot h[-1,-1] \\
&= 0\cdot 1 + 0\cdot 2 + 0\cdot 1 + 0\cdot 0 + 1\cdot 0 + 2\cdot 0 + 0\cdot(-1) + 4\cdot(-2) + 5\cdot(-1) = -13
\end{aligned}
$$

-13	-20	-17
-18	-24	-18
13	20	17

Output

[Slide by Song Ho Ahn]

2D convolution example



$$
\begin{aligned}
&= x[0,-1]\cdot h[1,1] + x[1,-1]\cdot h[0,1] + x[2,-1]\cdot h[-1,1] \\
&\quad + x[0,0]\cdot h[1,0] + x[1,0]\cdot h[0,0] + x[2,0]\cdot h[-1,0] \\
&\quad + x[0,1]\cdot h[1,-1] + x[1,1]\cdot h[0,-1] + x[2,1]\cdot h[-1,-1] \\
&= 0\cdot 1 + 0\cdot 2 + 0\cdot 1 + 1\cdot 0 + 2\cdot 0 + 3\cdot 0 + 4\cdot(-1) + 5\cdot(-2) + 6\cdot(-1) = -20
\end{aligned}
$$

-13	-20	-17
-18	-24	-18
13	20	17

Output

[Slide by Song Ho Ahn]

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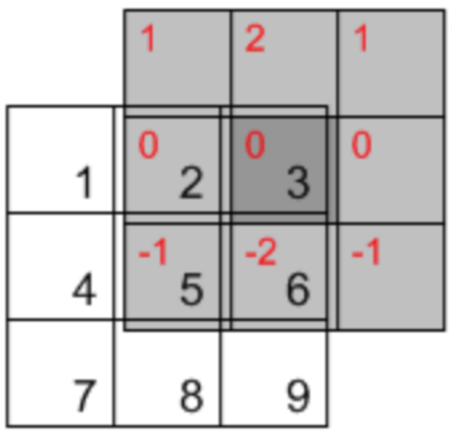
2D convolution example



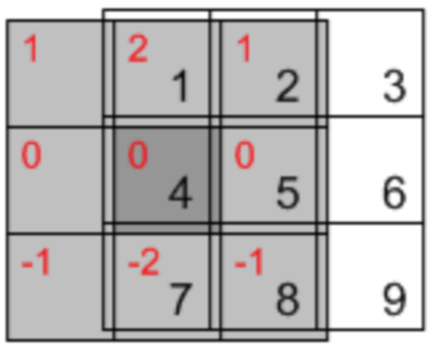
$$\begin{aligned} &= x[1,-1]\cdot h[1,1] + x[2,-1]\cdot h[0,1] + x[3,-1]\cdot h[-1,1] \\ &\quad + x[1,0]\cdot h[1,0] + x[2,0]\cdot h[0,0] + x[3,0]\cdot h[-1,0] \\ &\quad + x[1,1]\cdot h[1,-1] + x[2,1]\cdot h[0,-1] + x[3,1]\cdot h[-1,-1] \\ &= 0\cdot 1 + 0\cdot 2 + 0\cdot 1 + 2\cdot 0 + 3\cdot 0 + 0\cdot 0 + 5\cdot(-1) + 6\cdot(-2) + 0\cdot(-1) = -17 \end{aligned}$$

-13	-20	-17
-18	-24	-18
13	20	17

Output

[Slide by Song Ho Ahn]

2D convolution example



$$
\begin{aligned}
&= x[-1,0]\cdot h[1,1] + x[0,0]\cdot h[0,1] + x[1,0]\cdot h[-1,1] \\
&\quad + x[-1,1]\cdot h[1,0] + x[0,1]\cdot h[0,0] + x[1,1]\cdot h[-1,0] \\
&\quad + x[-1,2]\cdot h[1,-1] + x[0,2]\cdot h[0,-1] + x[1,2]\cdot h[-1,-1] \\
&= 0\cdot 1 + 1\cdot 2 + 2\cdot 1 + 0\cdot 0 + 4\cdot 0 + 5\cdot 0 + 0\cdot(-1) + 7\cdot(-2) + 8\cdot(-1) = -18
\end{aligned}
$$

-13	-20	-17
-18	-24	-18
13	20	17

Output

[Slide by Song Ho Ahn]

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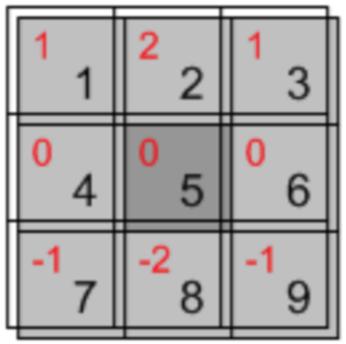
2D convolution example



$$
\begin{aligned}
&= x[0,0]\cdot h[1,1] + x[1,0]\cdot h[0,1] + x[2,0]\cdot h[-1,1] \\
&\quad + x[0,1]\cdot h[1,0] + x[1,1]\cdot h[0,0] + x[2,1]\cdot h[-1,0] \\
&\quad + x[0,2]\cdot h[1,-1] + x[1,2]\cdot h[0,-1] + x[2,2]\cdot h[-1,-1] \\
&= 1\cdot 1 + 2\cdot 2 + 3\cdot 1 + 4\cdot 0 + 5\cdot 0 + 6\cdot 0 + 7\cdot(-1) + 8\cdot(-2) + 9\cdot(-1) = -24
\end{aligned}
$$

-13	-20	-17
-18	-24	-18
13	20	17

Output

[Slide by Song Ho Ahn]

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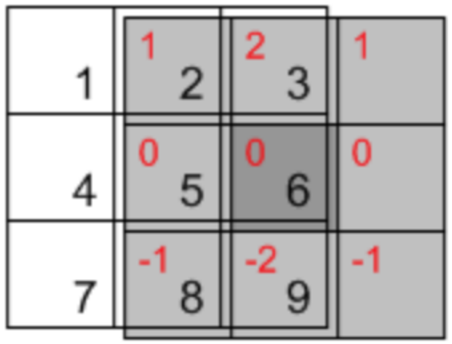
2D convolution example



$$
\begin{aligned}
&= x[1,0]\cdot h[1,1] + x[2,0]\cdot h[0,1] + x[3,0]\cdot h[-1,1] \\
&\quad + x[1,1]\cdot h[1,0] + x[2,1]\cdot h[0,0] + x[3,1]\cdot h[-1,0] \\
&\quad + x[1,2]\cdot h[1,-1] + x[2,2]\cdot h[0,-1] + x[3,2]\cdot h[-1,-1] \\
&= 2\cdot 1 + 3\cdot 2 + 0\cdot 1 + 5\cdot 0 + 6\cdot 0 + 0\cdot 0 + 8\cdot(-1) + 9\cdot(-2) + 0\cdot(-1) = -18
\end{aligned}
$$

-13	-20	-17
-18	-24	-18
13	20	17

Output

[Slide by Song Ho Ahn]

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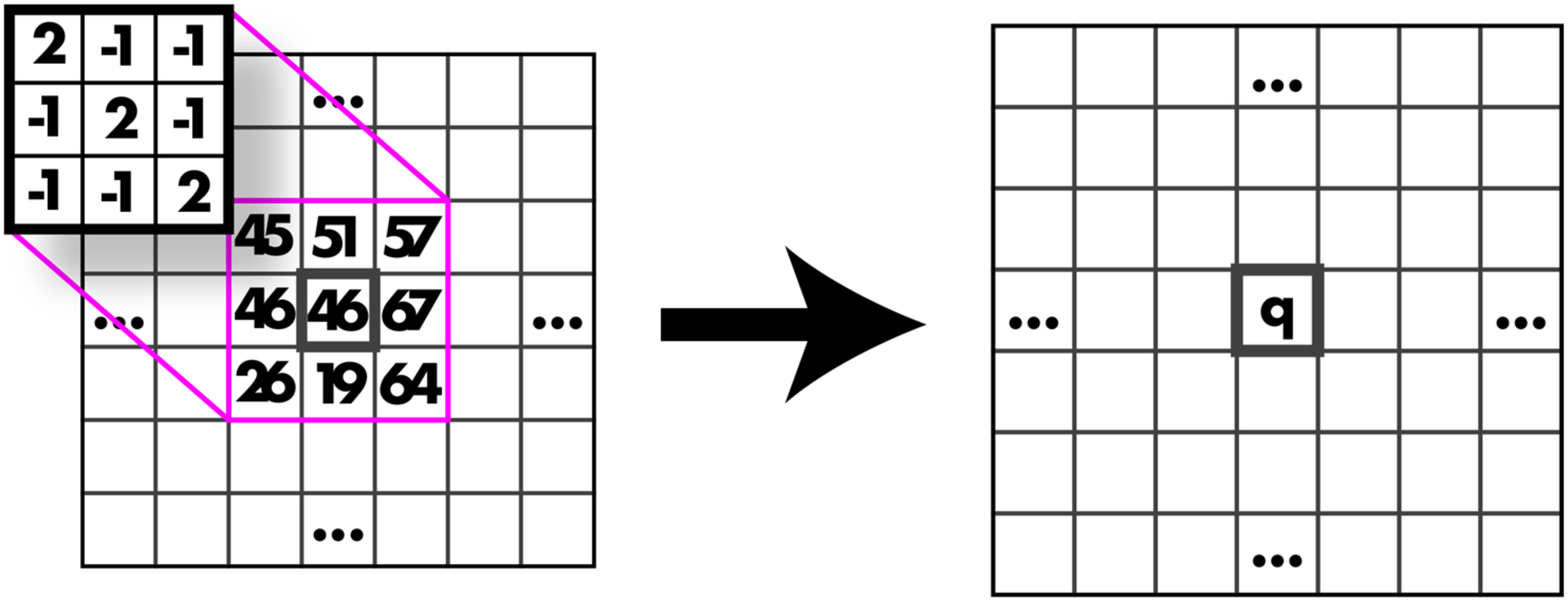
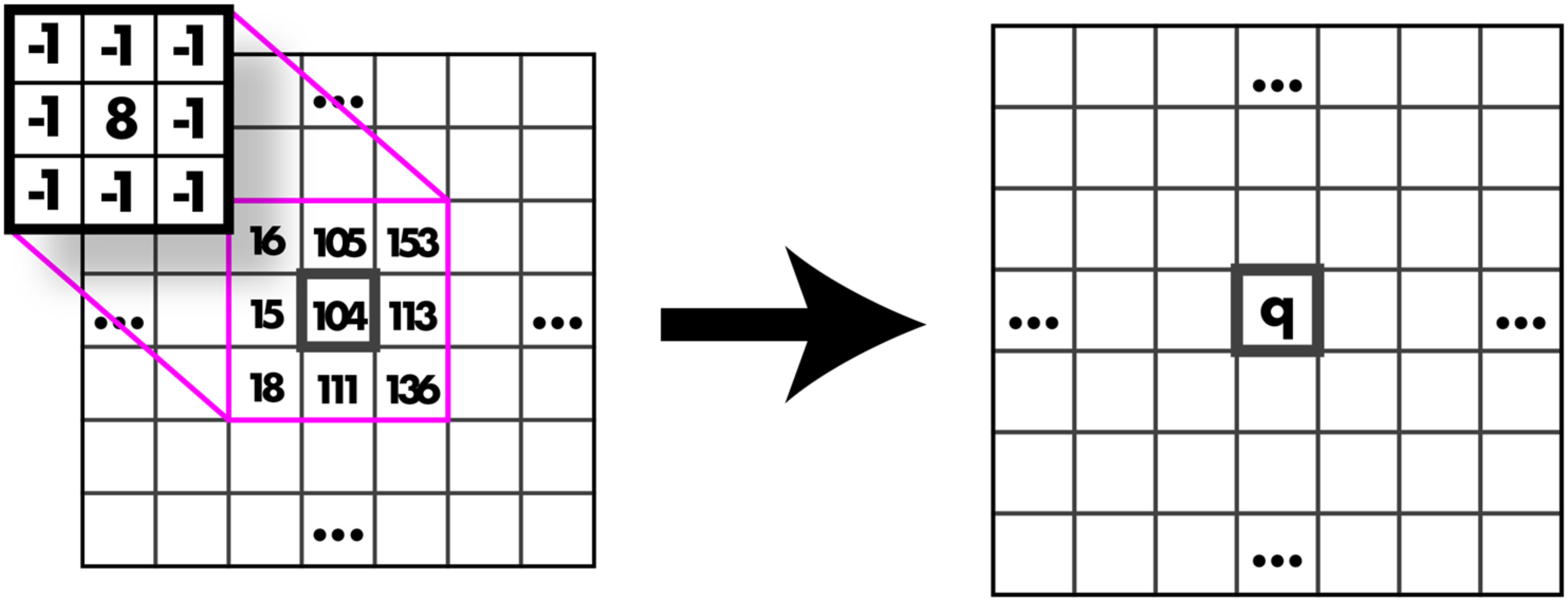
Calculate it!



Calculate it!



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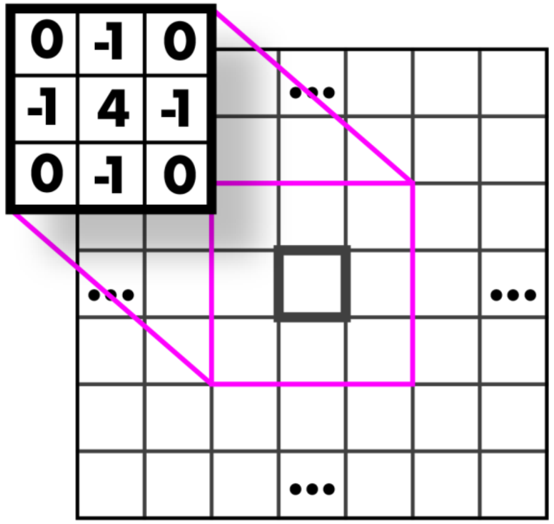
Guess that kernel!



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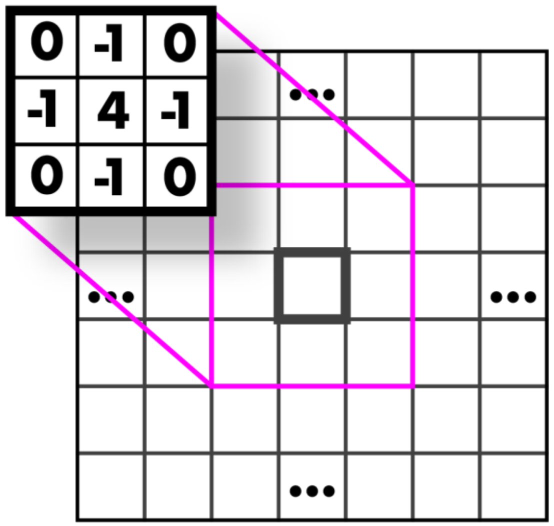
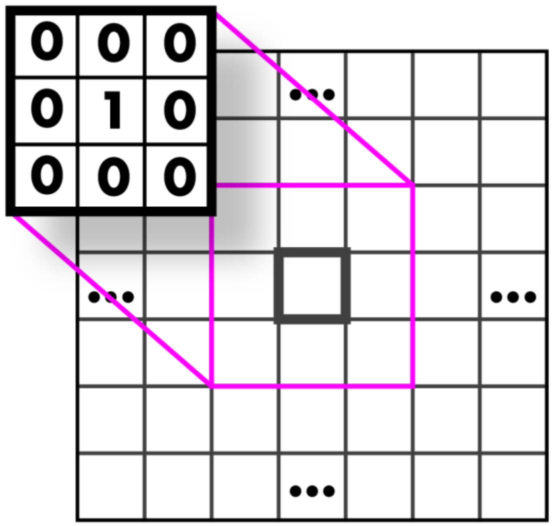
Highpass Kernel: finds edges



applied to grayscale

Guess that kernel!



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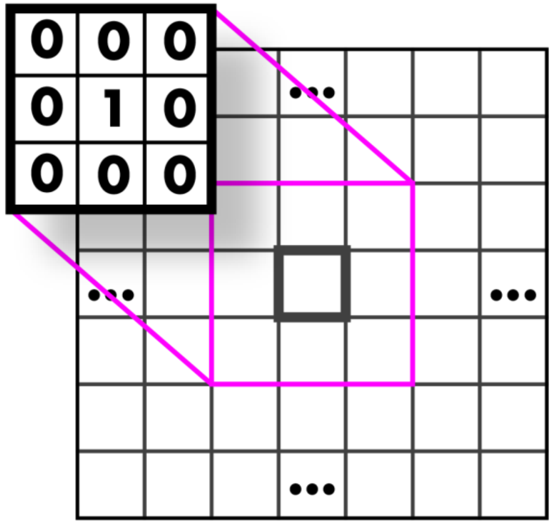
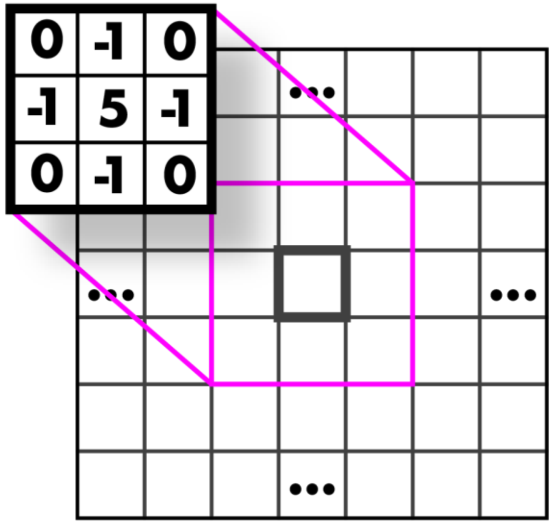
Identity Kernel: Does nothing!

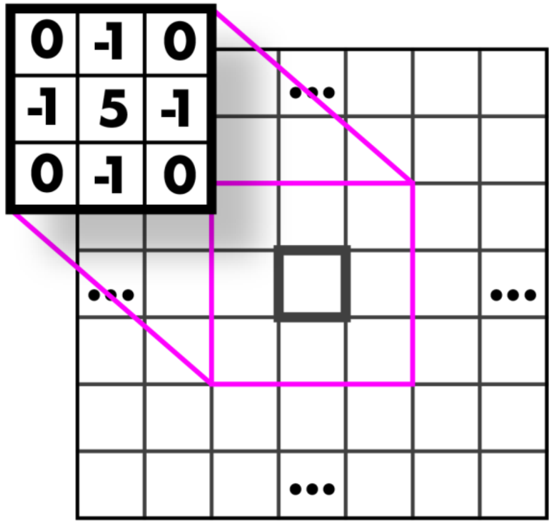


Guess that kernel!



Sharpen Kernel: sharpens!

applied to all three channels



Note: sharpen = highpass + identity! Why ?

Sharpen Kernel: sharpens!

What does blurring take away?

Highpass

–

=

Let’s add it back:

Identity + Highpass

+

=

[Slide by D. Lowe]

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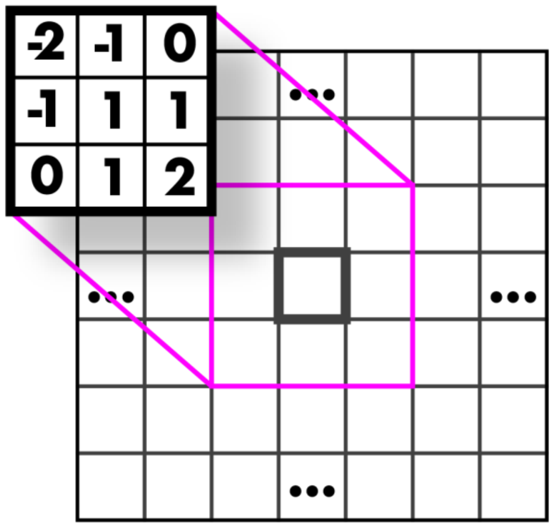
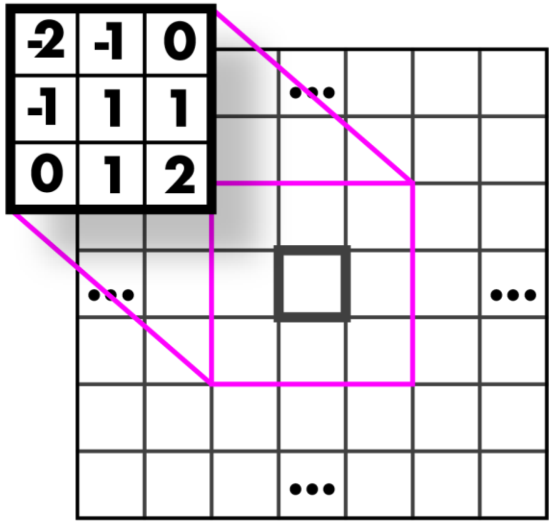
Guess that kernel!



Emboss Kernel: styling

applied to all three channels



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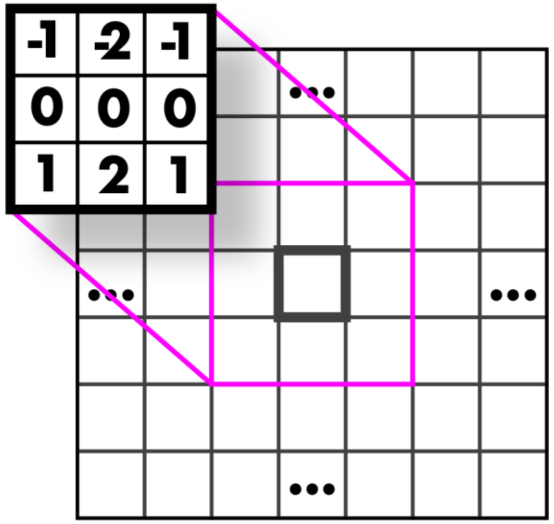
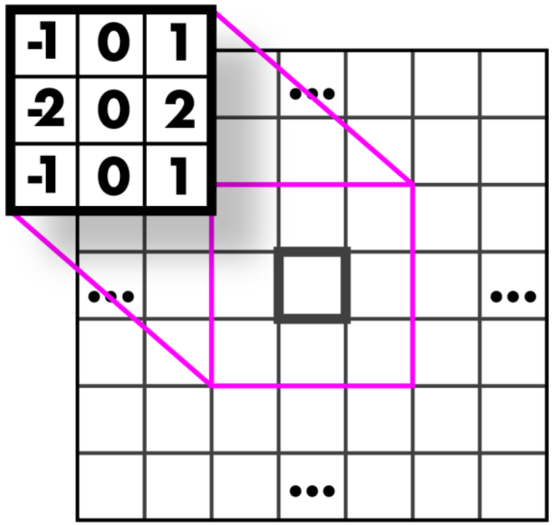
Guess those kernels!





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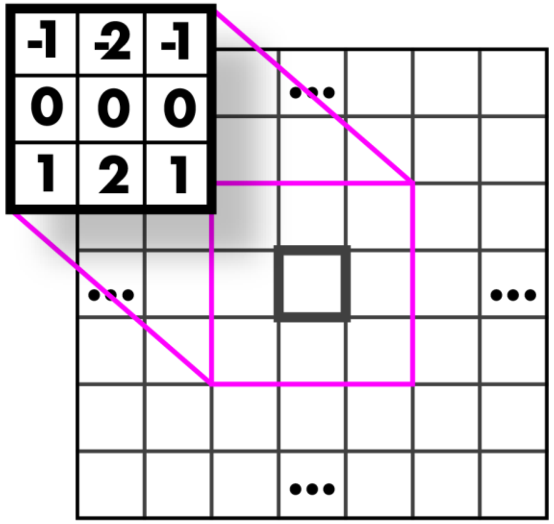
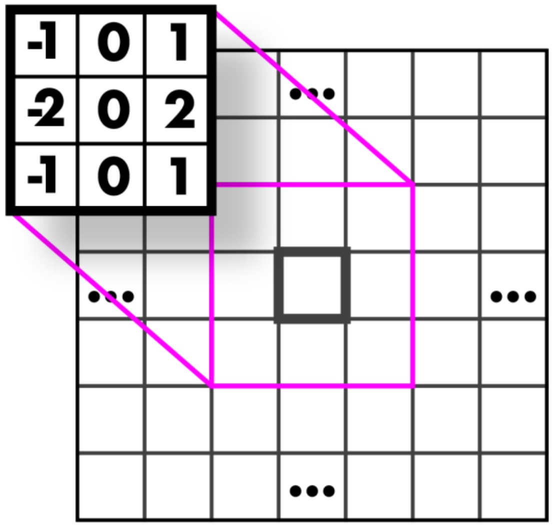
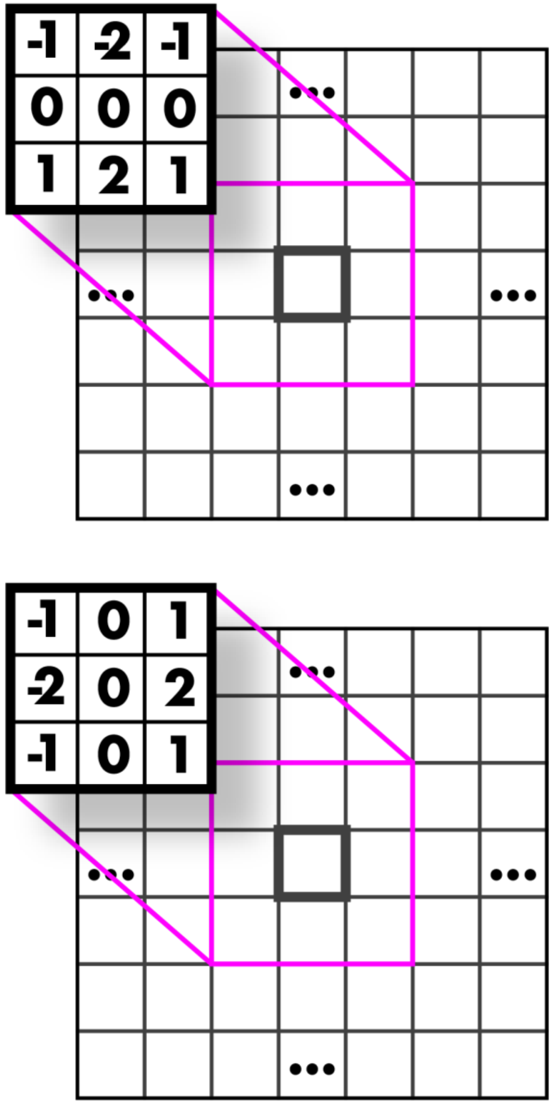
Sobel Kernels: edges and...

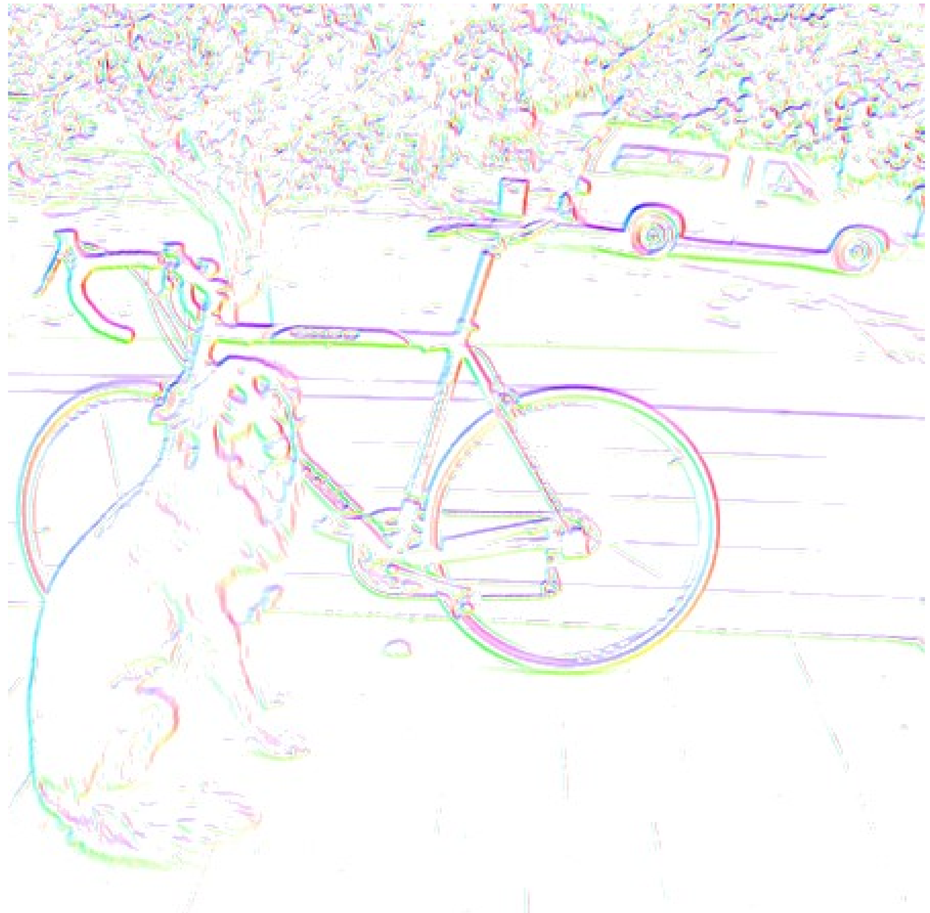
applied to grayscale and thresholded





Sobel Kernels: edges and gradient!





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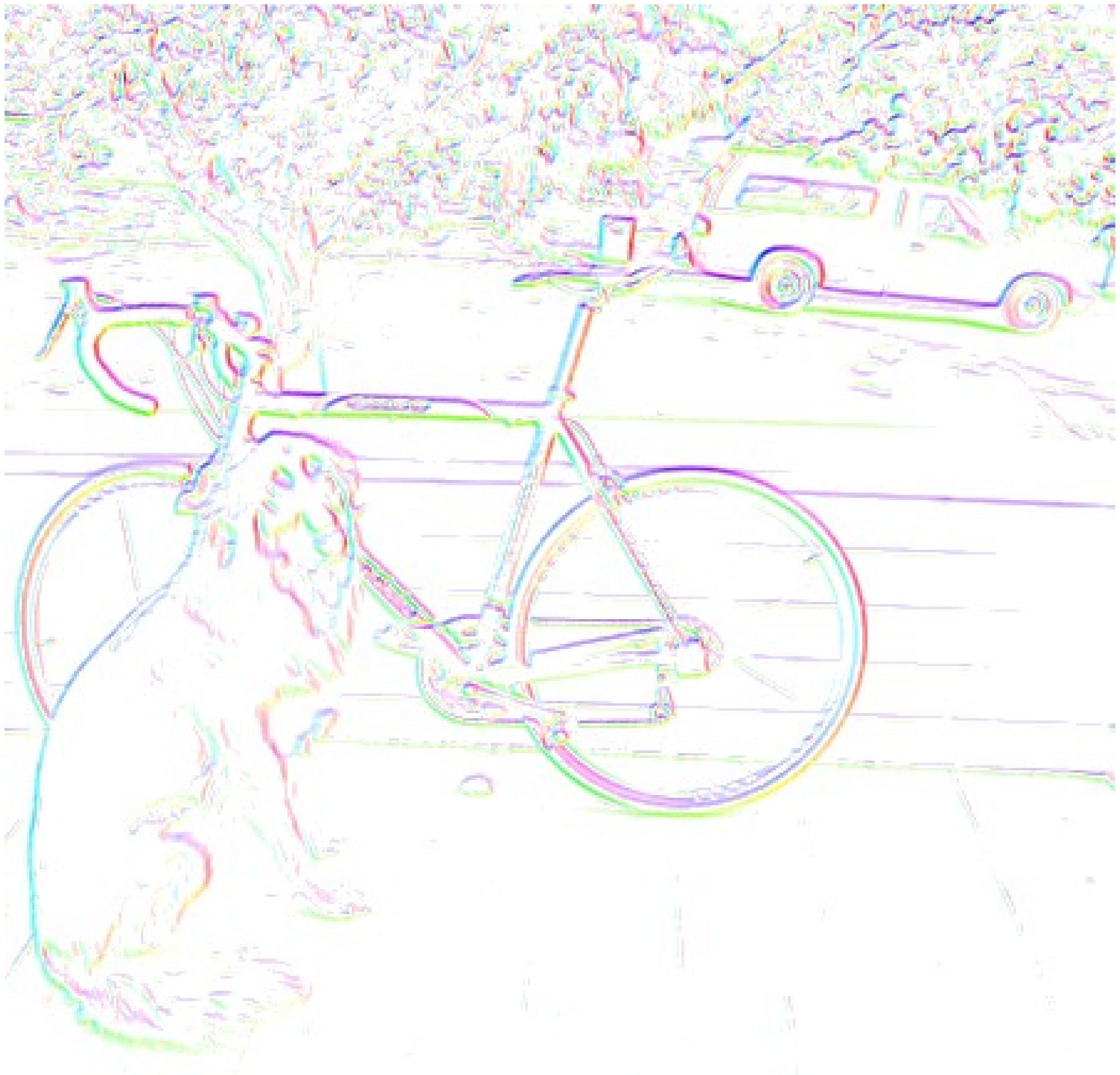
Sobel Kernels: edges and gradient!



This visualization is showing the magnitude and direction of the gradient

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And so much more!!

- Next time
  - Edges
  - Features

Thank you.

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