

lecture 3: matching

deep learning for vision

Yannis Avrithis

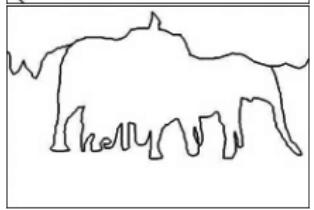
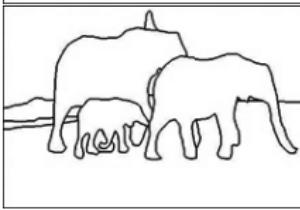
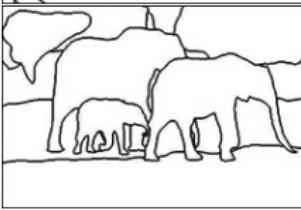
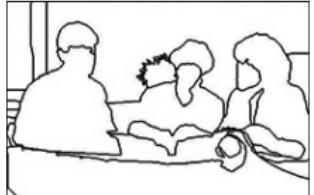
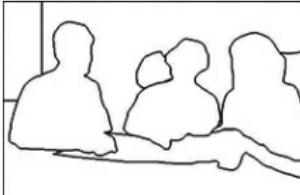
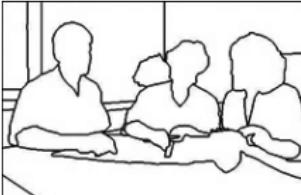
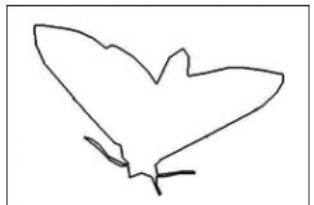
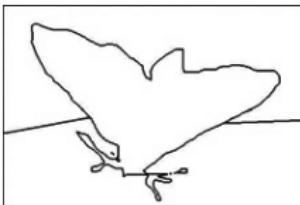
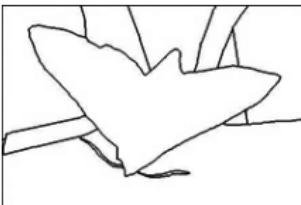
Inria Rennes-Bretagne Atlantique

Rennes, Nov. 2017 – Jan. 2018



derivatives

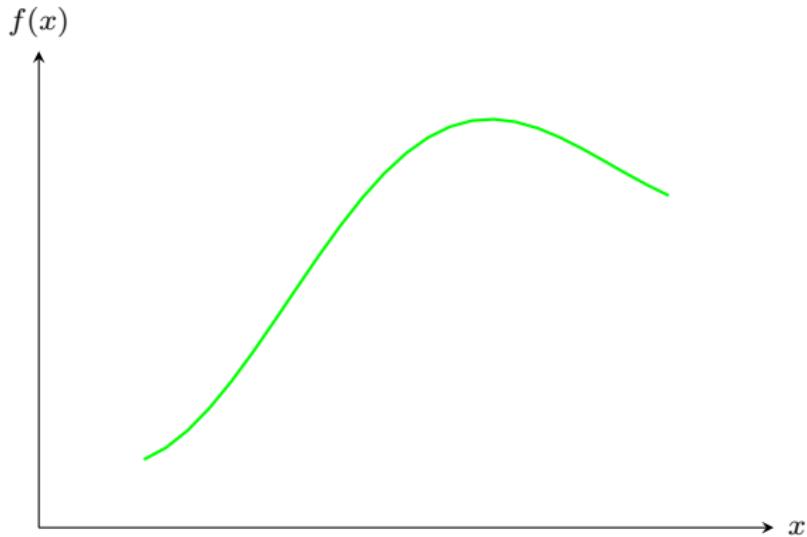
edges



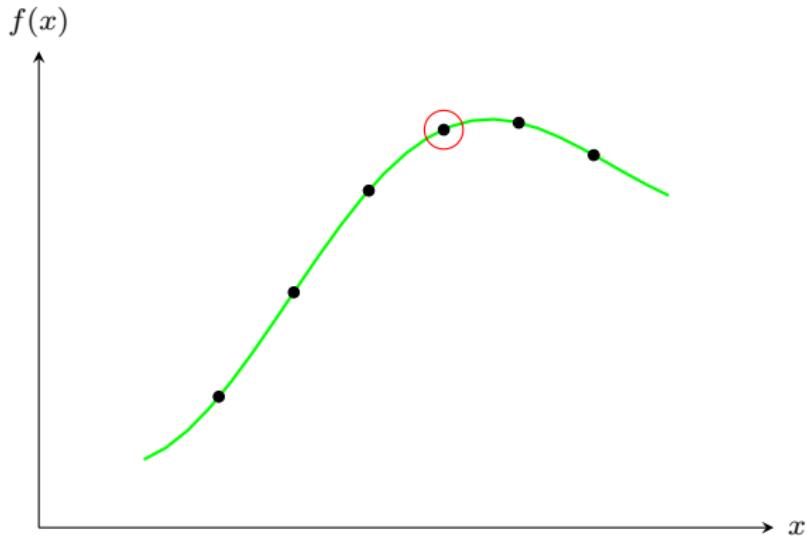
- connection between image recognition and segmentation
- database of human 'ground truth' to evaluate edge detection

Martin, Fowlkes, Tal, Malik. ICCV 2001. A Database of Human Segmented Natural Images and Its Application to Evaluating Segmentation Algorithms and Measuring Ecological Statistics.

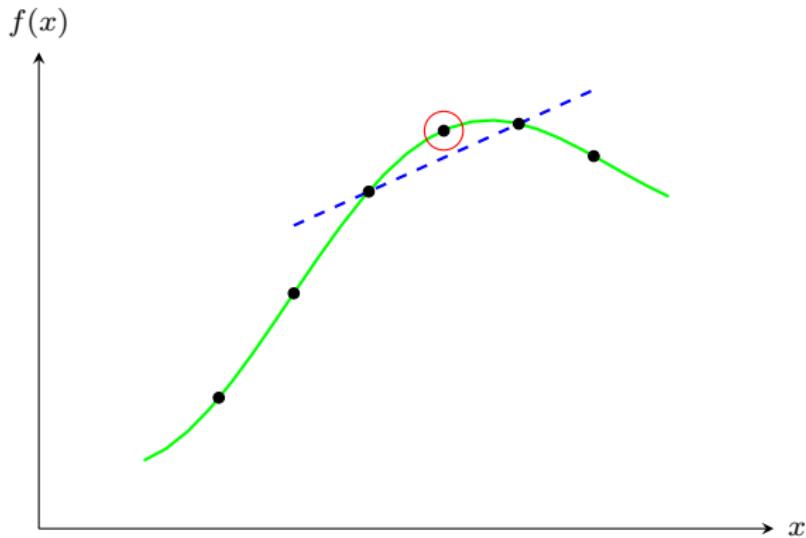
discrete derivative approximation



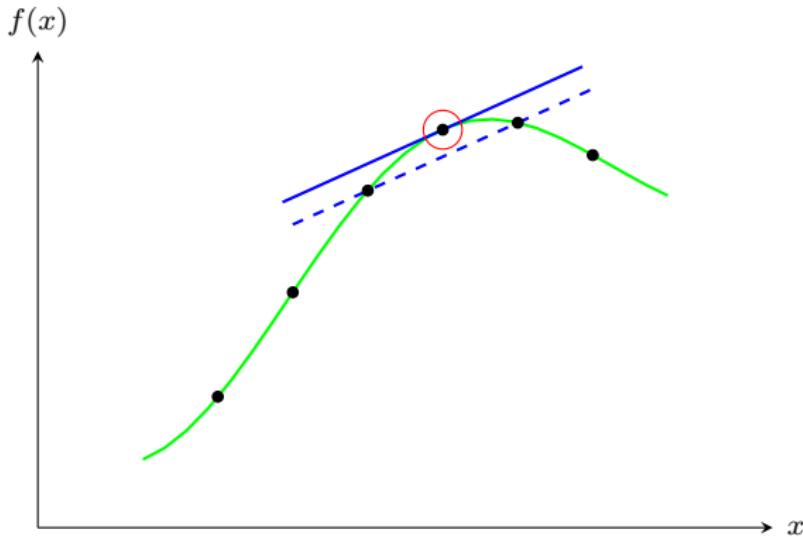
discrete derivative approximation



discrete derivative approximation

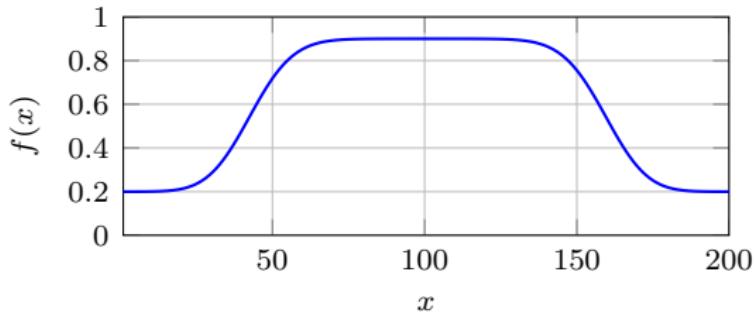
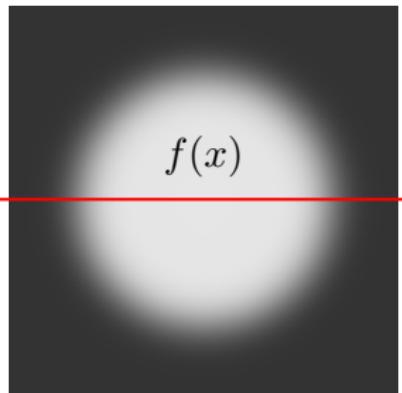


discrete derivative approximation

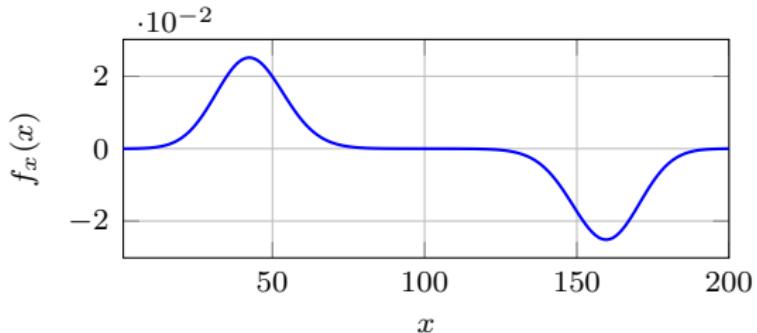
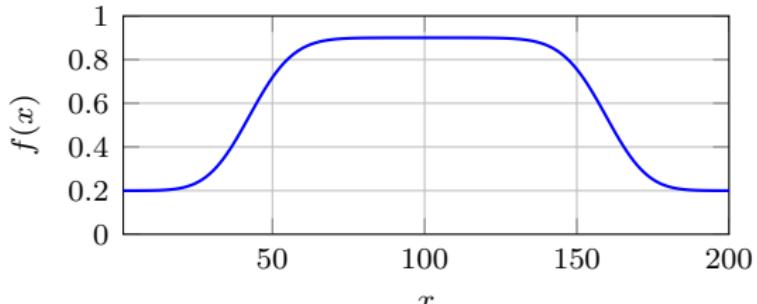
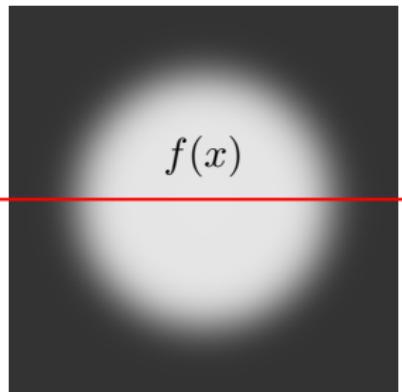


$$\frac{df}{dx}(x) \approx \frac{f(x+1) - f(x-1)}{2}$$

derivative in one dimension

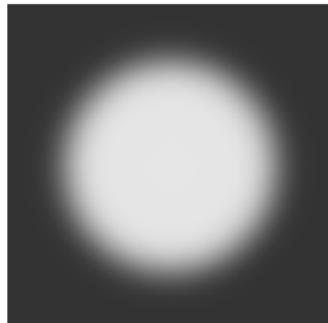


derivative in one dimension

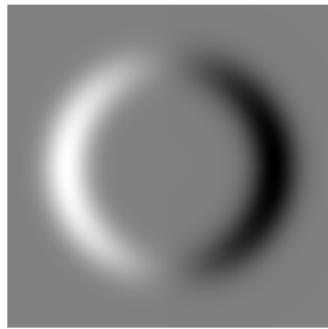


$$f_x(x) := \frac{f(x+1) - f(x-1)}{2} = h * f, \quad h := \frac{1}{2} [1 \ 0 \ -1]$$

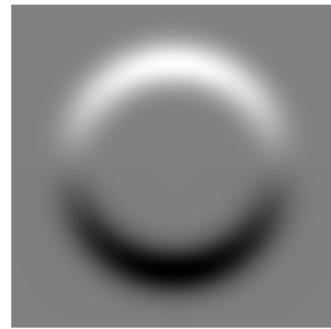
derivative in two dimensions: gradient



f

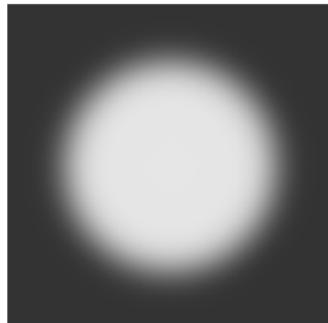


$$f_x := h_x * f$$
$$h_x := \frac{1}{2}[1 \ 0 \ -1]$$

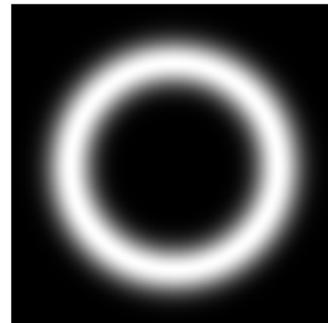


$$f_y := h_y * f$$
$$h_y := \frac{1}{2}[1 \ 0 \ -1]^\top$$

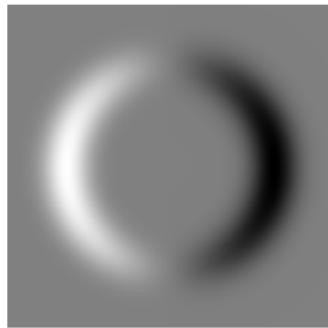
derivative in two dimensions: gradient



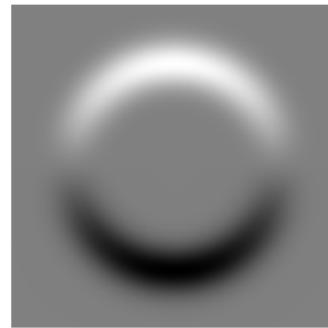
f



$\|(f_x, f_y)\|$

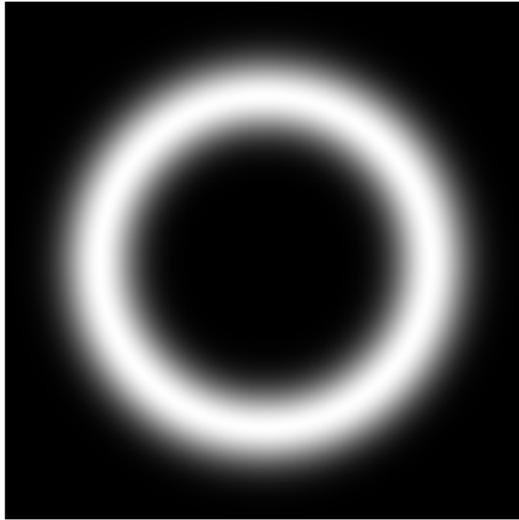


$$f_x := h_x * f$$
$$h_x := \frac{1}{2}[1 \ 0 \ -1]$$

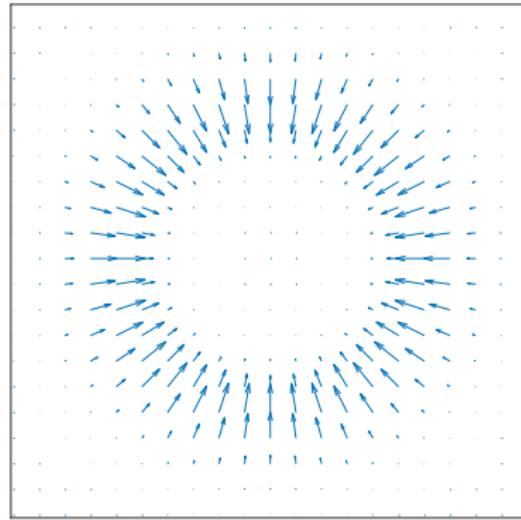


$$f_y := h_y * f$$
$$h_y := \frac{1}{2}[1 \ 0 \ -1]^\top$$

gradient: magnitude and orientation



$$\|(f_x, f_y)\|$$

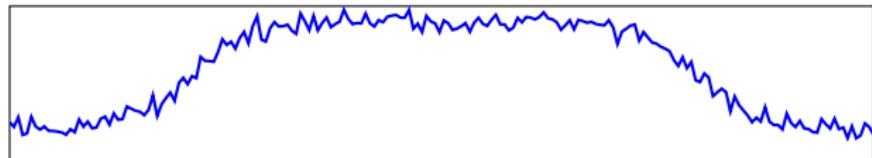


$$(f_x, f_y)$$

$$\nabla f(\mathbf{x}) := \left(\frac{\partial f}{\partial x}, \frac{\partial f}{\partial y} \right) (\mathbf{x}) \approx (h_x * f, h_y * f)(\mathbf{x}) = (f_x, f_y)(\mathbf{x})$$

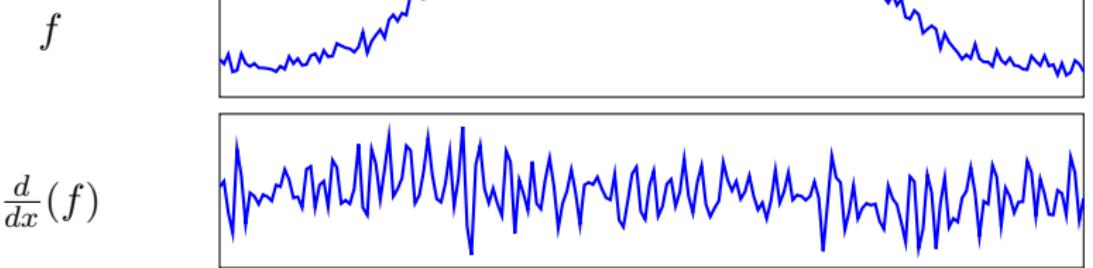
noise

f



- Q: what happened to the edges?
- derivative is a high-pass filter: signal vanishes, noise remains

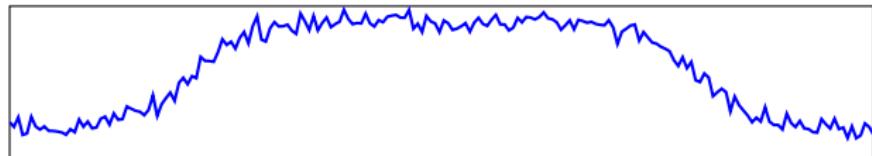
noise



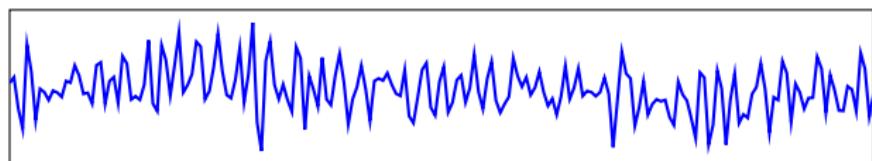
- Q: what happened to the edges?
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noise

f



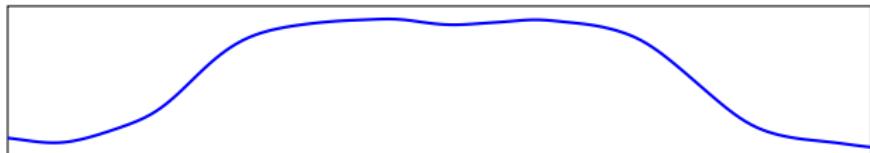
$\frac{d}{dx}(f)$



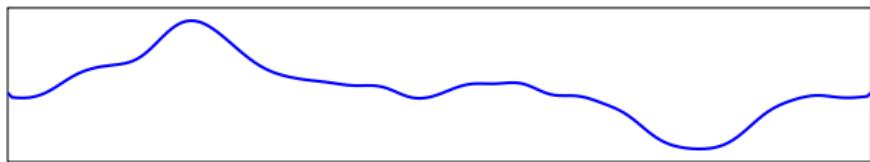
- Q: what happened to the edges?
- derivative is a high-pass filter: signal vanishes, noise remains

smoothing

$g * f$



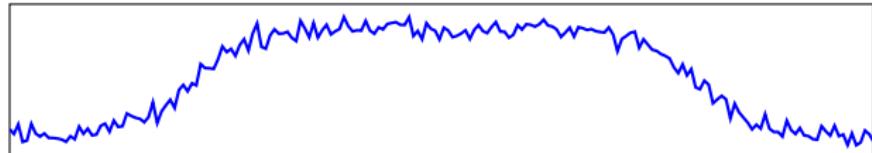
$\frac{d}{dx}(g * f)$



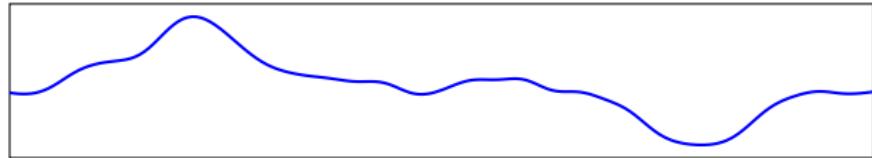
- smooth signal first
- that's better: edges recovered

filter derivative

f

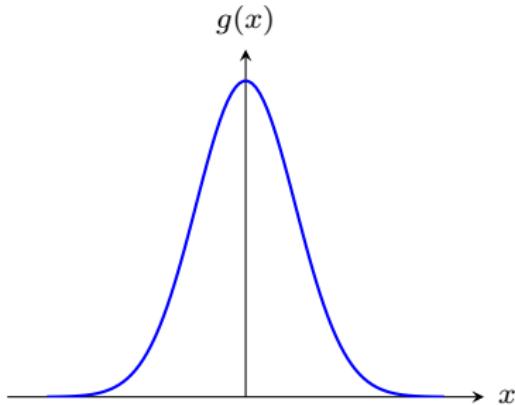


$\frac{d}{dx}(g) * f$

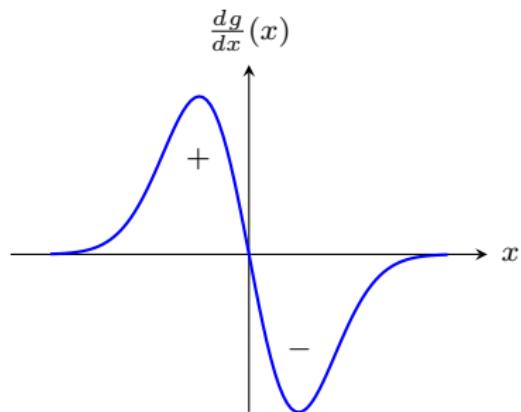


- this is equivalent to convolution with the filter derivative
- that's even better: filter is known in analytic form

1d Gaussian derivative



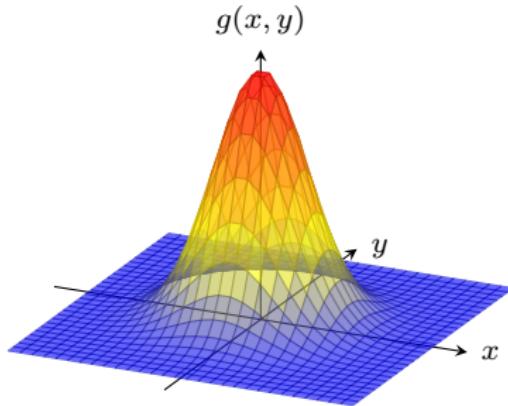
$$g(x) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{x^2}{2\sigma^2}}$$



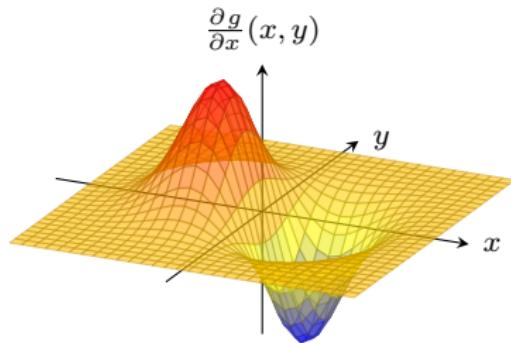
$$\frac{dg}{dx}(x) = -\frac{x}{\sigma^2} g(x)$$

- performs derivation and smoothing at the same time
- σ : “derivation scale”

2d Gaussian derivative



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



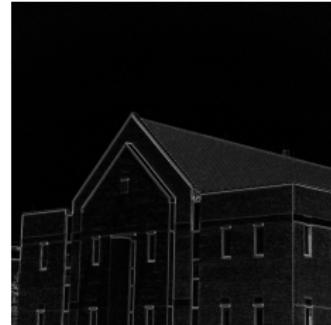
$$g_x(x, y) := \frac{\partial g}{\partial x}(x, y) = -\frac{x}{\sigma^2} g(x, y)$$

- derivation in one direction, smoothing in both
- “derivative = convolution”

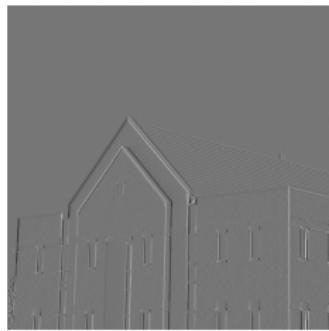
2d gradient



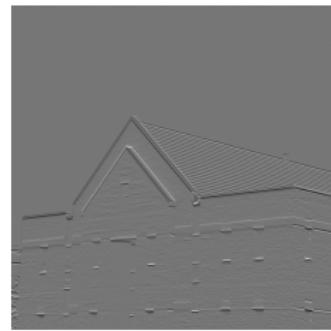
f



$\|(f_x, f_y)\|$

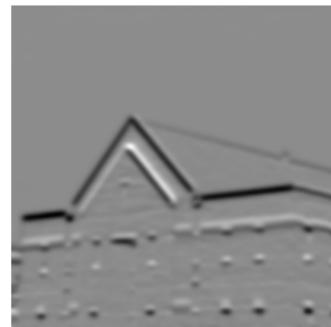


$f_x := h_x * f$

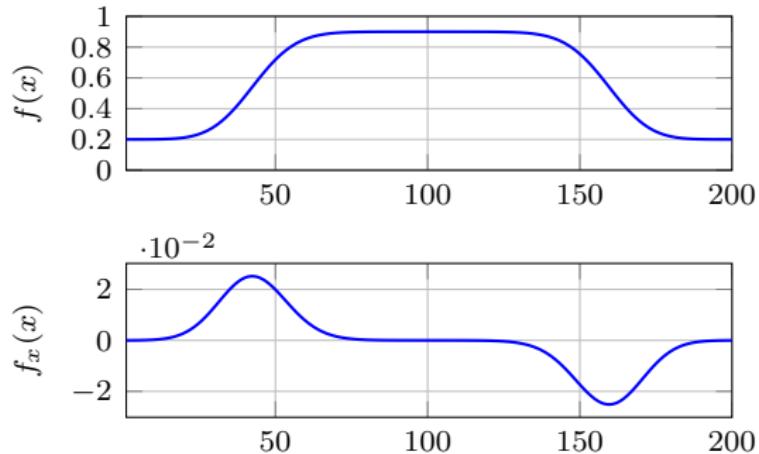
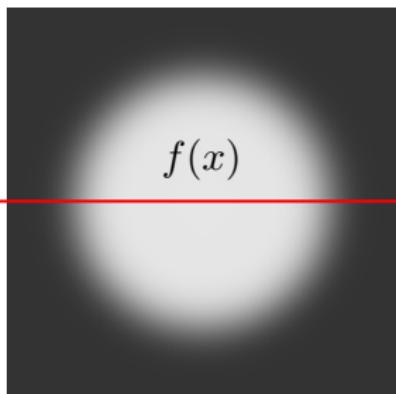


$f_y := h_y * f$

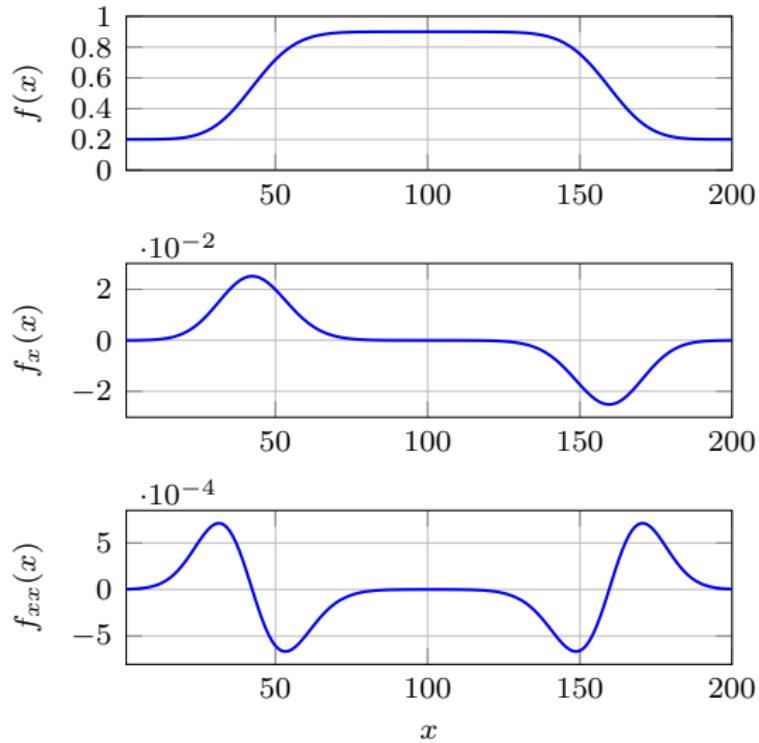
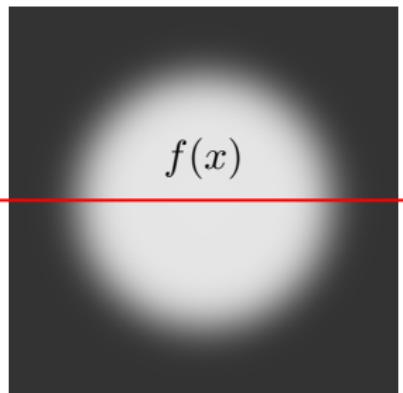
2d gradient by Gaussian derivative

 f  $\|\nabla g * f\|$  $g_x * f$  $g_y * f$

second derivative in one dimension

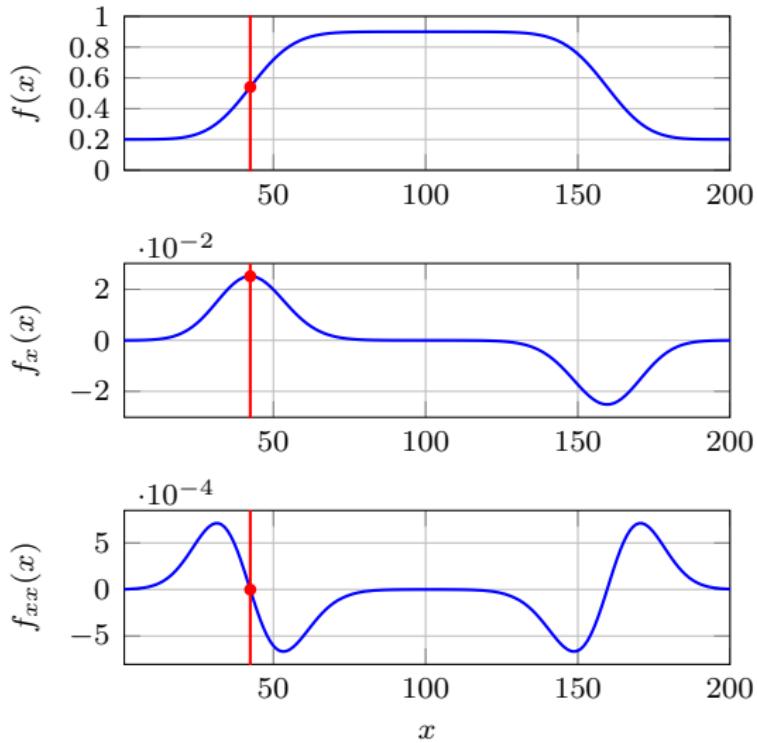
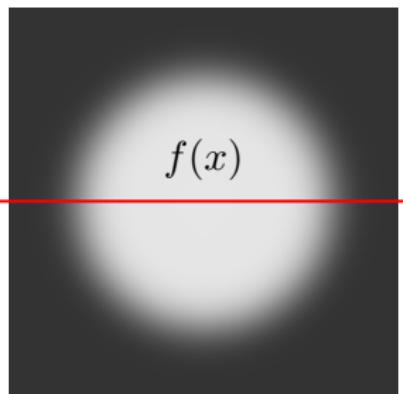


second derivative in one dimension



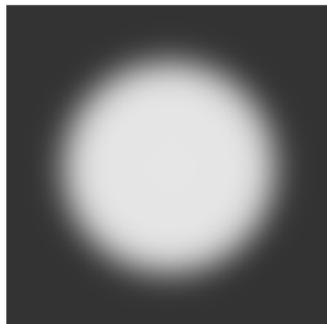
$$f_{xx}(x) := \frac{f(x-1) - 2f(x) + f(x+1)}{4} = h * f, \quad h := \frac{1}{4}[1 \ -2 \ 1]$$

second derivative in one dimension

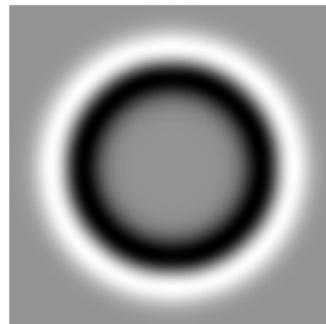


$$f_{xx}(x) := \frac{f(x-1) - 2f(x) + f(x+1)}{4} = h * f, \quad h := \frac{1}{4}[1 \ -2 \ 1]$$

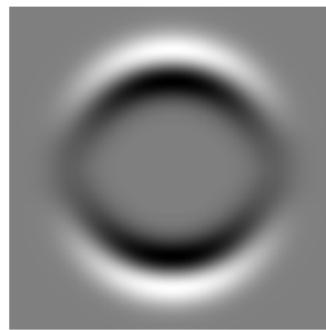
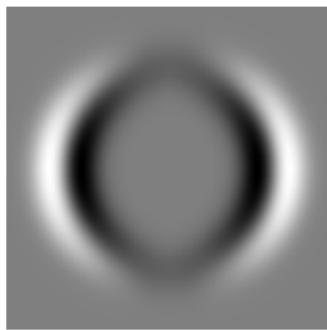
second derivative in two dimensions: Laplacian



f



$f_{xx} + f_{yy}$



$$f_{xx} := h_{xx} * f$$
$$h_{xx} := \frac{1}{4}[1 \ -2 \ 1]$$

$$f_{yy} := h_{yy} * f$$
$$h_y := \frac{1}{4}[1 \ -2 \ 1]^\top$$

Laplacian operator

- discrete approximation

$$h_{xx} := \frac{1}{4}[1 \ -2 \ 1]$$

$$h_{yy} := \frac{1}{4}[1 \ -2 \ 1]^\top$$

$$h_L := h_{xx} + h_{yy} = \begin{pmatrix} 0 & 1 & 0 \\ 1 & -4 & 1 \\ 0 & 1 & 0 \end{pmatrix}$$

- differential operator

$$\nabla^2 f(\mathbf{x}) := \left(\frac{\partial^2 f}{\partial x^2} + \frac{\partial^2 f}{\partial y^2} \right) (\mathbf{x})$$

$$\approx (h_{xx} * f + h_{yy} * f)(\mathbf{x}) = (f_{xx} + f_{yy})(\mathbf{x})$$

Laplacian operator

- discrete approximation

$$h_{xx} := \frac{1}{4}[1 \ -2 \ 1]$$

$$h_{yy} := \frac{1}{4}[1 \ -2 \ 1]^\top$$

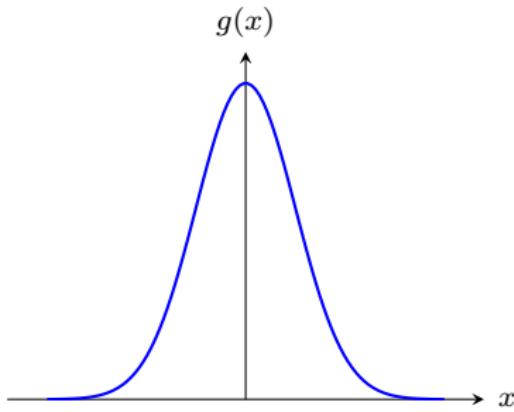
$$h_L := h_{xx} + h_{yy} = \begin{pmatrix} 0 & 1 & 0 \\ 1 & -4 & 1 \\ 0 & 1 & 0 \end{pmatrix}$$

- differential operator

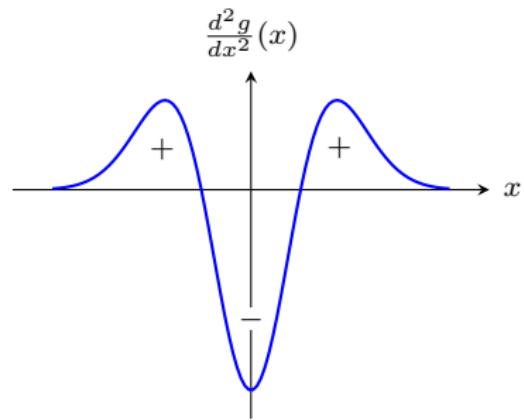
$$\nabla^2 f(\mathbf{x}) := \left(\frac{\partial^2 f}{\partial x^2} + \frac{\partial^2 f}{\partial y^2} \right) (\mathbf{x})$$

$$\approx (h_{xx} * f + h_{yy} * f)(\mathbf{x}) = (f_{xx} + f_{yy})(\mathbf{x})$$

1d Gaussian second derivative



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

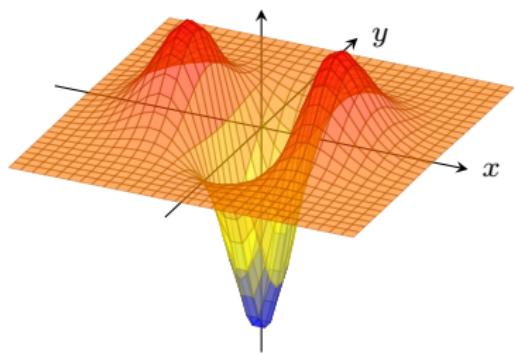


$$\frac{d^2g}{dx^2}(x) = \left(\frac{x^2}{\sigma^4} - \frac{1}{\sigma^2} \right) g(x)$$

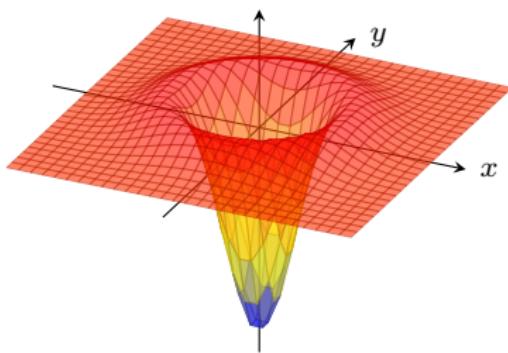
- “center-surround” operator

2d Laplacian of Gaussian (LoG)

$$\frac{\partial^2 g}{\partial x^2}(x, y)$$



$$\nabla^2 g(x, y)$$

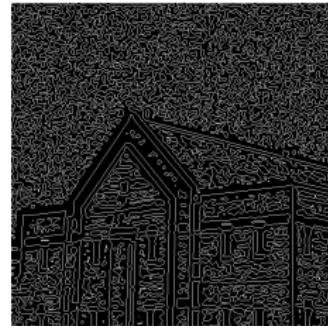


$$\frac{\partial^2 g}{\partial x^2}(x, y) = \left(\frac{x^2}{\sigma^4} - \frac{1}{\sigma^2} \right) g(x, y)$$

$$\nabla^2 g(x, y) := \left(\frac{\partial^2 g}{\partial x^2} + \frac{\partial^2 g}{\partial y^2} \right) (x, y)$$

- rotationally symmetric
- “mexican hat”

edge detection

 f  $L_0(\nabla^2 g * f)$  $\|\nabla g * f\|$  $\nabla^2 g * f$

edge detection



$$L_0(\nabla^2 g * f)$$

edge detection

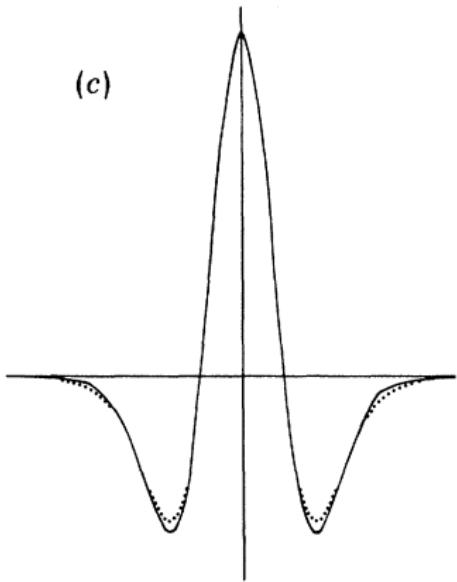


$$L_0(\nabla^2 g * f) \|\nabla g * f\|$$

difference of Gaussians (DoG)

[Marr and Hildreth 1980]

(c)

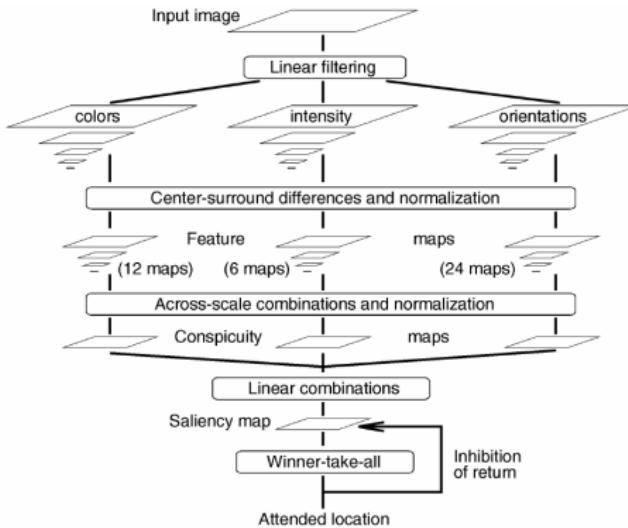


- studied the $\nabla^2 g$ operator as a model of retinal X-cells
- popularized it as a computational theory of edge detection
- hypothesized a biological implementation as a difference of Gaussians with $\sigma_1/\sigma_2 \approx 1.6$

feature detection

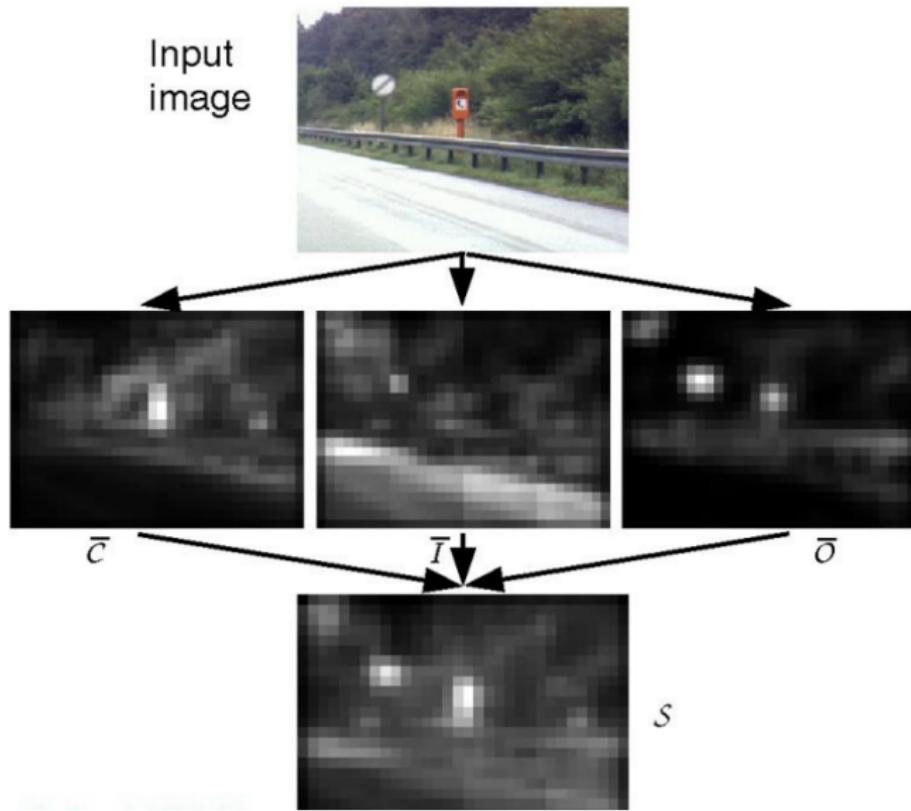
saliency and visual attention

[Itti et al. 1998]

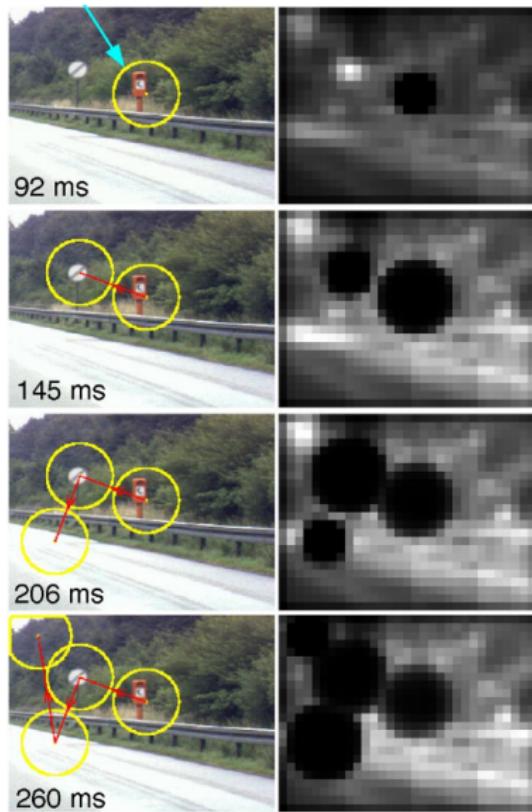


- visual attention system, inspired by the early primate visual system
 - multiple scales, multiple features, center-surround, normalization and winner-take-all operations

saliency and visual attention



saliency and visual attention



scale change



scale change



scale change



scale change



scale change



scale change



scale change

- for every scale factor t , and for every point \mathbf{x} , the scaled image f' at the scaled point $\mathbf{x}' := t\mathbf{x}$ equals the original image f at the original point \mathbf{x}

$$f'(\mathbf{x}') = f'(t\mathbf{x}) = f(\mathbf{x})$$

scale space



scale space



scale space



scale space



scale space



scale space



scale space

[Witkin 1983]

- the scale-space F of f at point \mathbf{x} and scale σ , and its n -th derivative with respect to some variable x , are defined as

$$F(\mathbf{x}; \sigma) := [g(\cdot; \sigma) * f](\mathbf{x})$$

$$F_{x^n}(\mathbf{x}; \sigma) := \frac{\partial^n F}{\partial x^n}(\mathbf{x}; \sigma) = \left[\frac{\partial^n g}{\partial x^n}(\cdot; \sigma) * f \right] (\mathbf{x})$$

- gradient

$$\nabla F = (F_x, F_y)$$

- Laplacian

$$\nabla^2 F = F_{xx} + F_{yy}$$

- we write derivatives but we only compute convolutions

scale space

[Witkin 1983]

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- gradient

$$\nabla F = (F_x, F_y)$$

- Laplacian

$$\nabla^2 F = F_{xx} + F_{yy}$$

- we write derivatives but we only compute convolutions

scale space under scaling

[Witkin 1983]

- for every scale factor t , for every point \mathbf{x} , and for every scale σ , the scale-space F' at the point $\mathbf{x}' := t\mathbf{x}$ and scale $\sigma' := t\sigma$ equals the original scale-space F at the original point \mathbf{x} and scale σ :

$$F'(\mathbf{x}'; \sigma') = F'(t\mathbf{x}, t\sigma) = F(\mathbf{x}; \sigma)$$

and we would like the same for their derivatives

scale-normalized derivatives

[Lindeberg 1998]

- remember, however,

$$\frac{dg}{dx}(x; \sigma) = -\frac{x}{\sigma^2}g(x; \sigma) \quad \frac{d^2g}{dx^2}(x; \sigma) = \left(\frac{x^2}{\sigma^4} - \frac{1}{\sigma^2}\right)g(x; \sigma)$$
$$F'_{x'}(\mathbf{x}'; \sigma') = t^{-1}F_{x^n}(\mathbf{x}; \sigma) \quad F'_{x'x'}(\mathbf{x}'; \sigma') = t^{-2}F_{x^n}(\mathbf{x}; \sigma)$$

- in general, we only have

$$F'_{x'^n}(\mathbf{x}'; \sigma') = t^{-n}F_{x^n}(\mathbf{x}; \sigma)$$

- solution: we normalize the n -th order derivative by σ^n

$$\hat{F}_{x^n}(\mathbf{x}; \sigma) := \sigma^n F_{x^n}(\mathbf{x}; \sigma) = \sigma^n \frac{\partial^n g}{\partial x^n}(\mathbf{x}; \sigma) * f(\mathbf{x})$$

- then, indeed

$$\hat{F}'_{x'^n}(\mathbf{x}'; \sigma') = \hat{F}_{x^n}(\mathbf{x}; \sigma)$$

scale-normalized derivatives

[Lindeberg 1998]

- remember, however,

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normalized Laplacian and scale selection

- normalized Laplacian operator

$$\hat{\nabla}^2 F(\mathbf{x}; \sigma) := \sigma^2 \nabla^2 F(\mathbf{x}; \sigma) = \sigma^2 (F_{xx} + F_{yy})(\mathbf{x}; \sigma)$$

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normalized Laplacian and scale selection

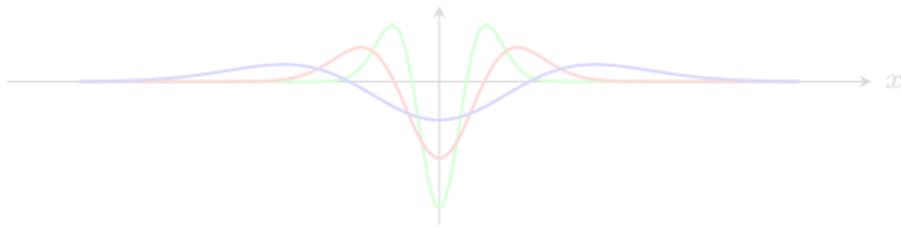
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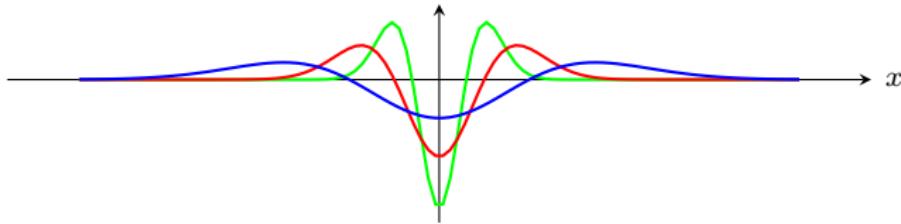
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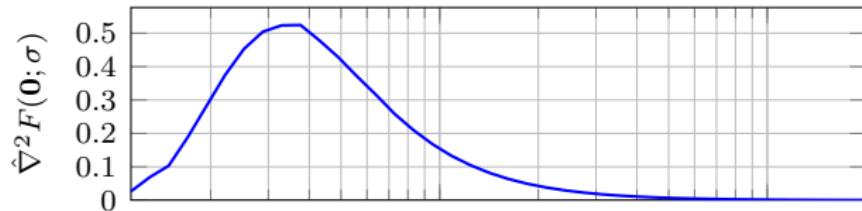
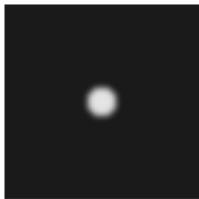
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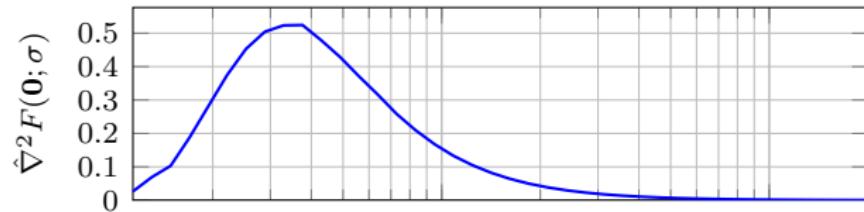
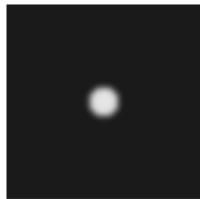


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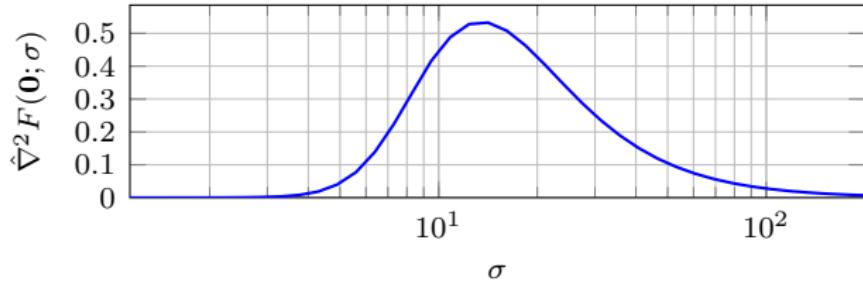
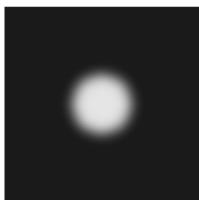
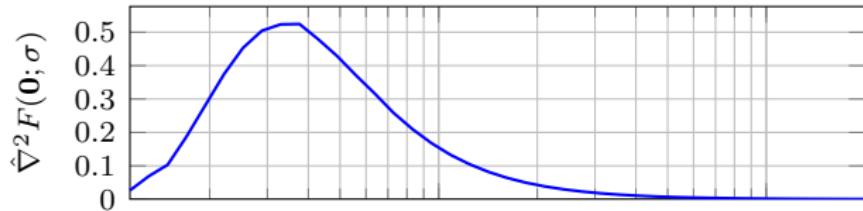
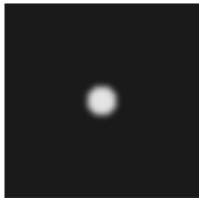
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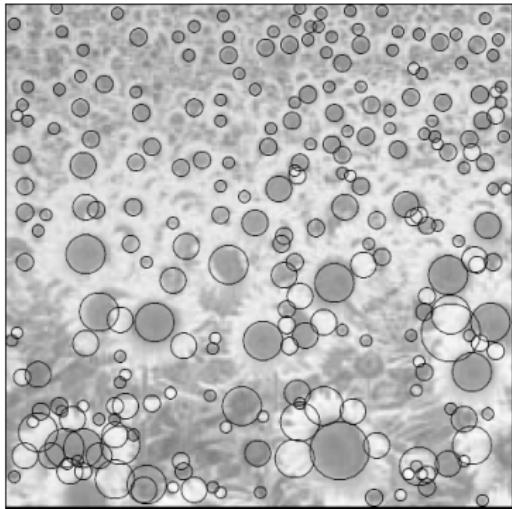
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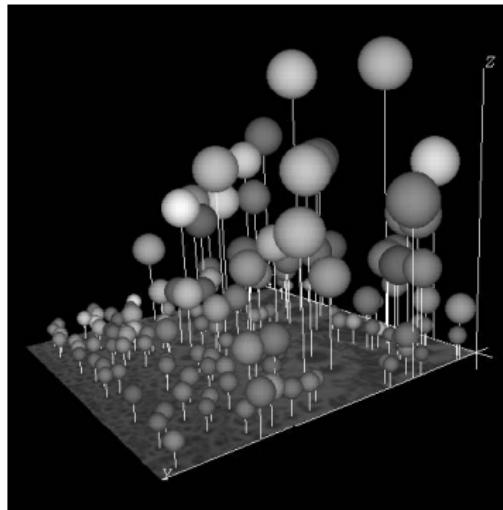


blob detection



- convolution with a circular symmetric center-surround pattern in scale-space
- local maxima in scale-space yield positions and scales of blobs

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difference of Gaussians

- Gaussian satisfies **heat equation** (try it!), hence finite difference approximation to $\frac{\partial g}{\partial \sigma}$ can be used

$$\sigma \nabla^2 g = \frac{\partial g}{\partial \sigma} \approx \frac{g(\mathbf{x}; k\sigma) - g(\mathbf{x}; \sigma)}{k\sigma - \sigma}$$

- then, difference of Gaussians approximates its normalized Laplacian

$$g(\mathbf{x}; k\sigma) - g(\mathbf{x}; \sigma) \approx (k - 1)\sigma^2 \nabla^2 g,$$

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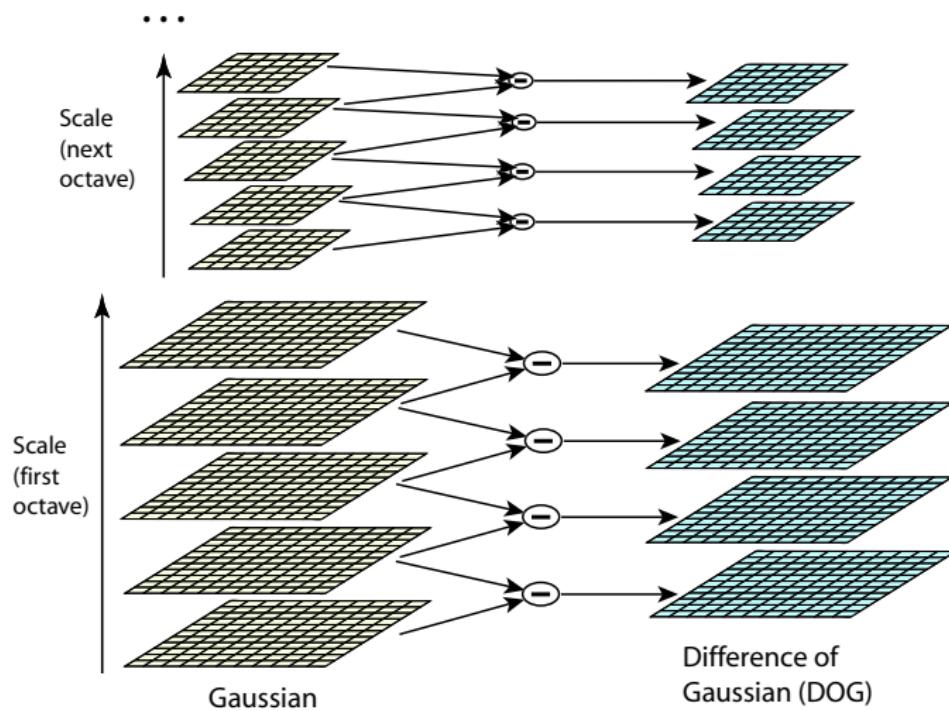
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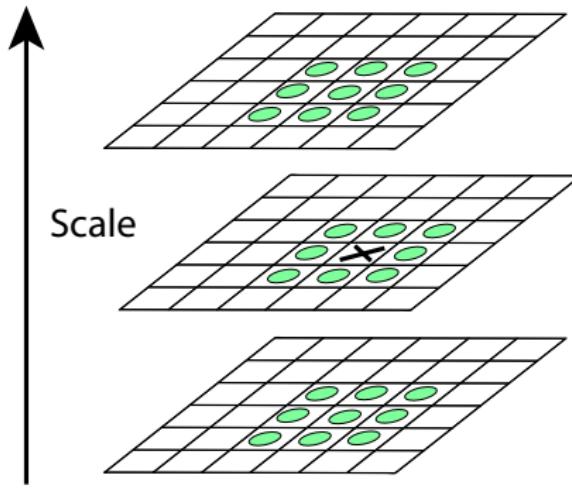
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scale-space computation



- incrementally convolve with Gaussian, subsample at each octave

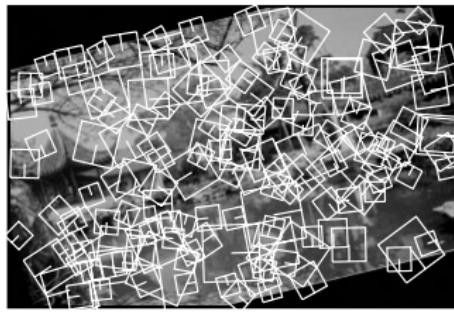
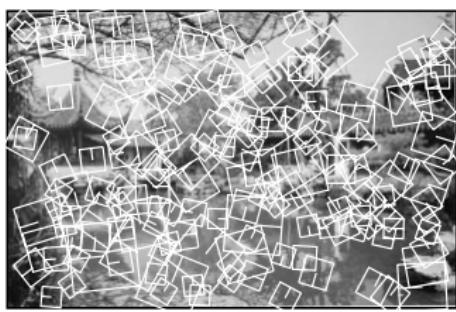
scale-space local extrema



- local maxima among 26 neighbors selected
- accurately localized, edge responses rejected, orientation normalized

scale-invariant feature transform (SIFT)

[Lowe 1999]



- detected patches equivariant to translation, scale and rotation

desired properties of local features

- **repeatable**: in a transformed image, the same feature is detected at a transformed position
- **distinctive**: different image features can be discriminated by their local appearance
- **localized**: relatively small regions, robust to occlusion
 - *elongated*: edges, ridges
 - + *isotropic*: blobs, extremal regions
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the Hessian matrix

- defined as

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the (windowed) second moment matrix

[Förstner 1986]

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$$\begin{aligned}\hat{\mu}F(\mathbf{x}, \sigma) &:= w * \sigma^2 (\nabla F)(\nabla F)^\top(\mathbf{x}, \sigma) \\ &= w * \sigma^2 \begin{pmatrix} F_x^2 & F_x F_y \\ F_x F_y & F_y^2 \end{pmatrix}(\mathbf{x}, \sigma)\end{aligned}$$

where w is another Gaussian at some higher integration scale; σ is called the derivation scale

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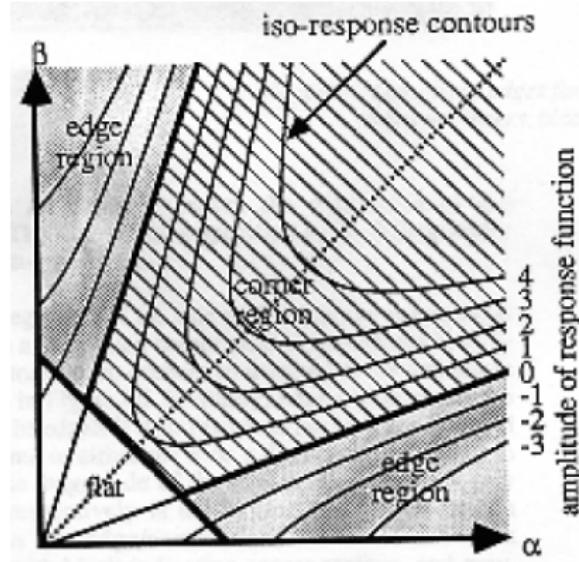
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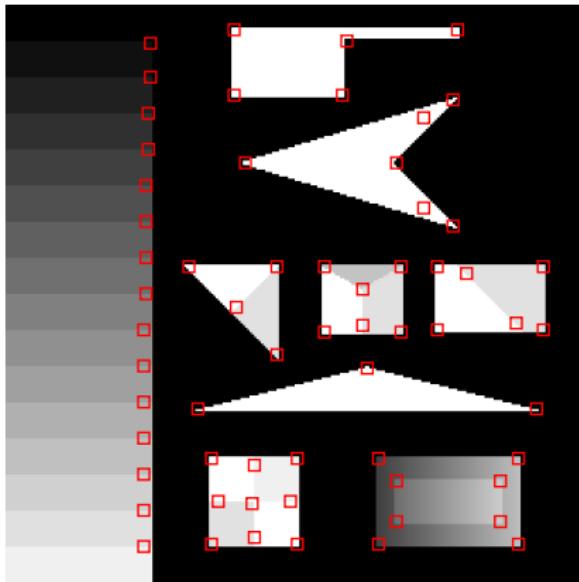
Harris corners

[Harris and Stevens 1988]



- if trace $\lambda_1 + \lambda_2$ is too low \rightarrow flat
 - if condition number λ_1/λ_2 is too high \rightarrow edge
 - response function $r(\mu) = \det \mu - k \operatorname{tr}^2 \mu$

Harris corners (and junctions)



corners



response

- response: positive on corners, negative on edges, zero otherwise
- detection: non-maxima suppression and thresholding

motivation: local autocorrelation

- assume f is differentiable and ignore scale space
- assume an image patch at the origin defined by window w ; how much does it change when we shift by \mathbf{d} ?

$$E(\mathbf{d}) = \sum_{\mathbf{x}} w(\mathbf{x})(f(\mathbf{x} + \mathbf{d}) - f(\mathbf{x}))^2$$

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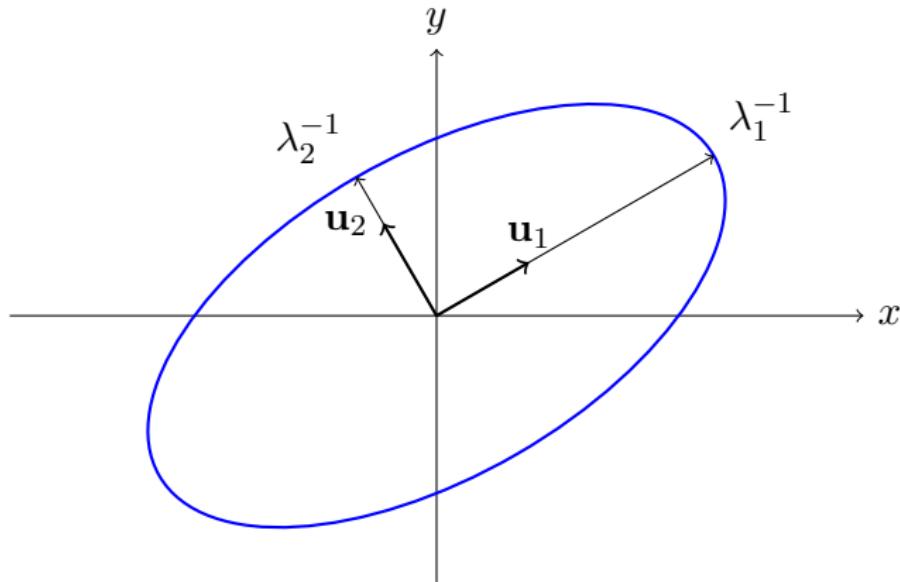
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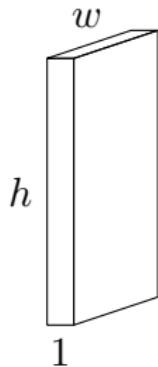
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quadratic form



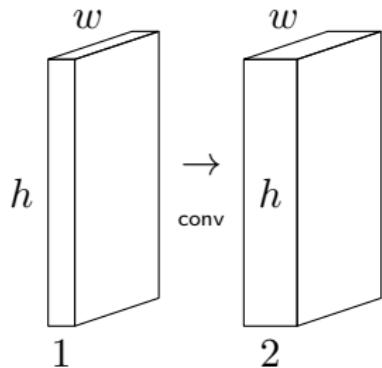
- locus of $(x \ y)A(x \ y)^\top = 1$, where A has eigenvectors $\mathbf{u}_1, \mathbf{u}_2$ and eigenvalues λ_1, λ_2

Harris pipeline



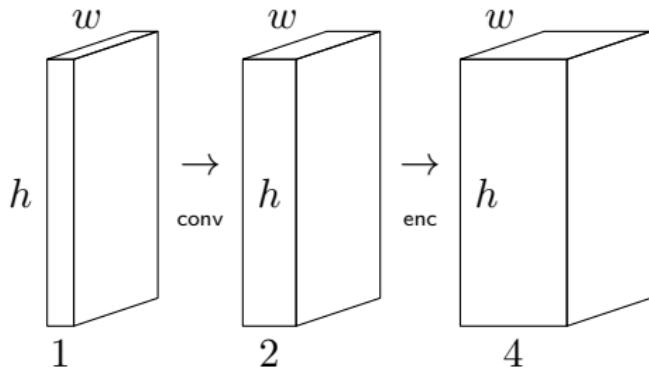
- 3-channel patch (**image**) RGB input → 1-channel gray-scale
- compute gradient $\nabla F = (F_x, F_y)$ at derivation scale
- encode into tensor product $\nabla F \otimes \nabla F = (F_x^2, F_x F_y, F_x F_y, F_y^2)$
- average pooling by window w at integration scale
- compute point-wise nonlinear response function r

Harris pipeline



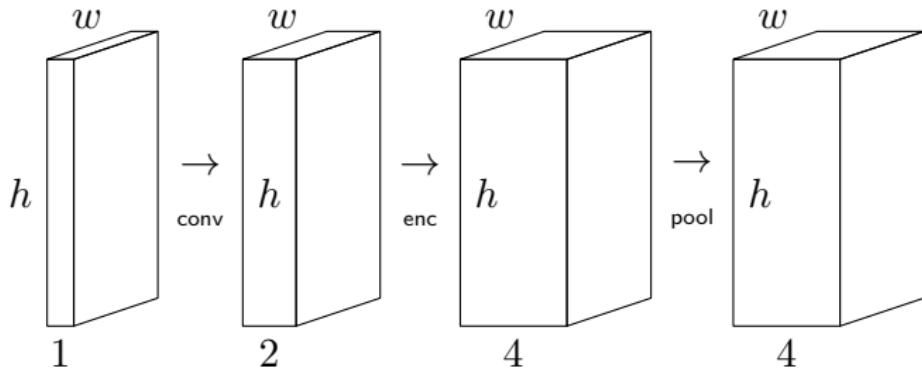
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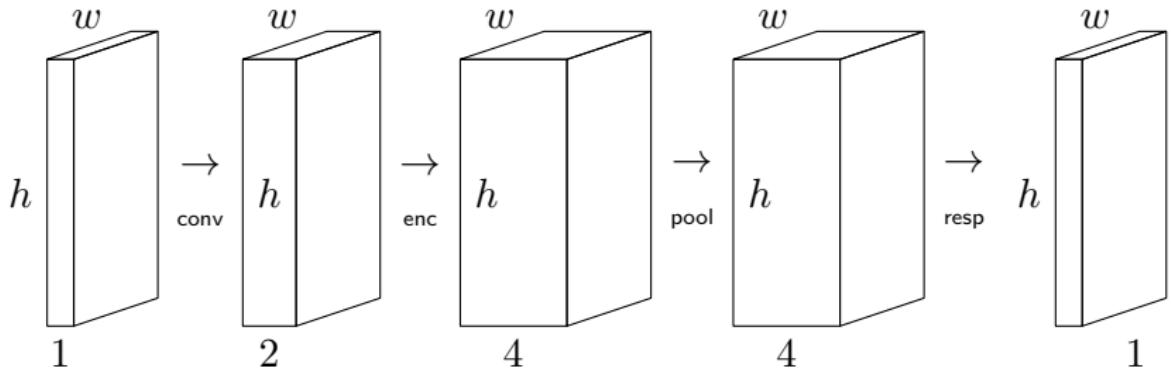
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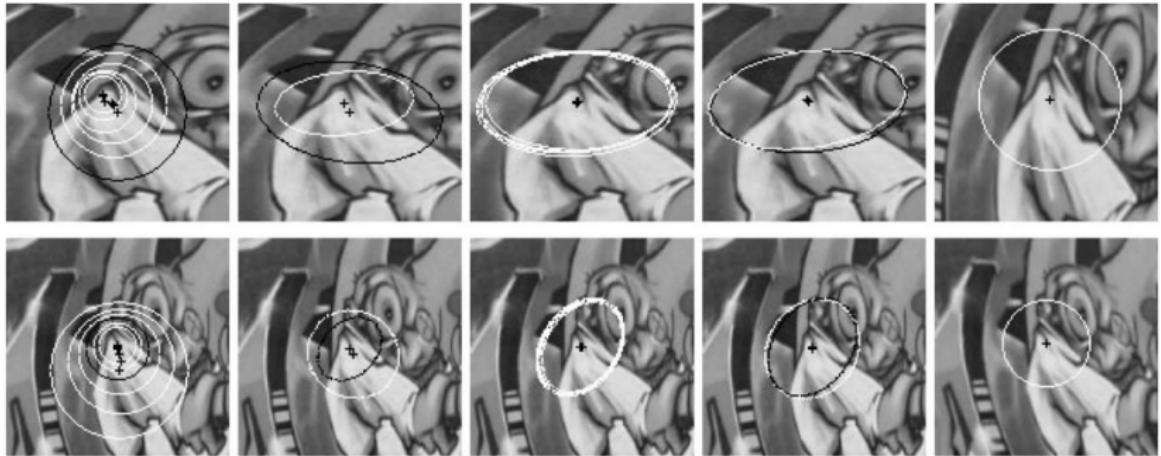
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Harris affine & Hessian affine

[Mikolajczyk and Schmid 2004]



- multi-scale Harris or Hessian detection, Laplacian scale selection
- iterative affine shape adaptation, based on Lindeberg
- Hessian-affine *de facto* standard on image retrieval for several years

spatial matching

dense registration

[Lucas and Kanade 1981]



- for each location in an image, find a displacement with respect to another reference image
- appropriate for small displacements, e.g. stereopsis or optical flow

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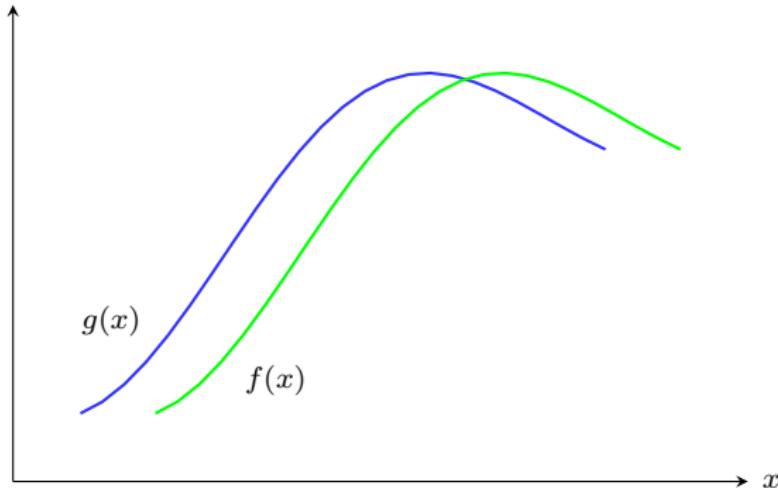
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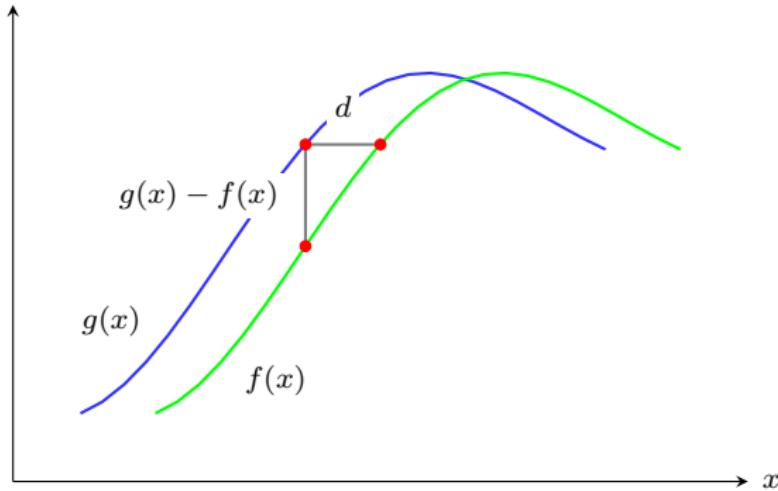
one dimension



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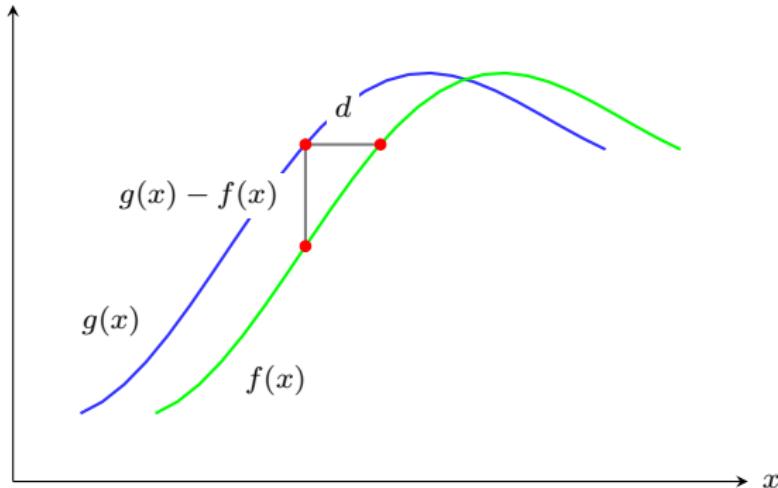
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two dimensions: least squares

- again, assume an image patch defined by window w ; what is the error between the patch shifted by \mathbf{d} in reference image f and a patch at the origin in shifted image g ?

$$E(\mathbf{d}) = \sum_{\mathbf{x}} w(\mathbf{x})(f(\mathbf{x} + \mathbf{d}) - g(\mathbf{x}))^2$$

- error minimized when gradient vanishes

$$\mathbf{0} = \frac{\partial E}{\partial \mathbf{d}} = \sum_{\mathbf{x}} w(\mathbf{x}) 2 \nabla f(\mathbf{x}) (f(\mathbf{x}) + \mathbf{d}^\top \nabla f(\mathbf{x}) - g(\mathbf{x}))$$

- least-squares solution

$$\left(w * (\nabla f)(\nabla f)^\top \right) \mathbf{d} = w * (\nabla f(g - f))$$

two dimensions: least squares

- again, assume an image patch defined by window w ; what is the error between the patch shifted by \mathbf{d} in reference image f and a patch at the origin in shifted image g ?

$$\begin{aligned} E(\mathbf{d}) &= \sum_{\mathbf{x}} w(\mathbf{x})(f(\mathbf{x} + \mathbf{d}) - g(\mathbf{x}))^2 \\ &\approx \sum_{\mathbf{x}} w(\mathbf{x})(f(\mathbf{x}) + \mathbf{d}^\top \nabla f(\mathbf{x}) - g(\mathbf{x}))^2 \end{aligned}$$

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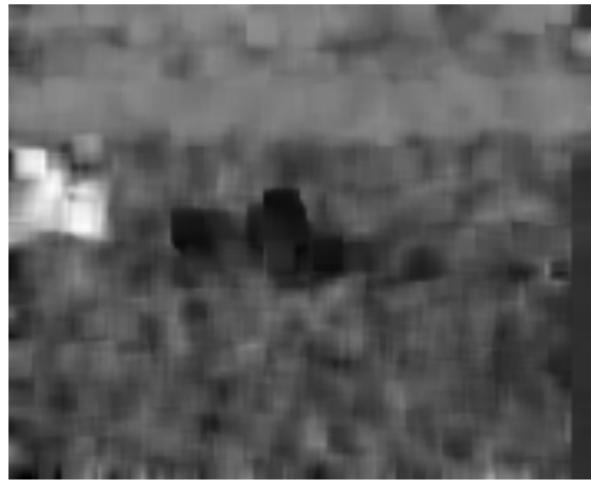
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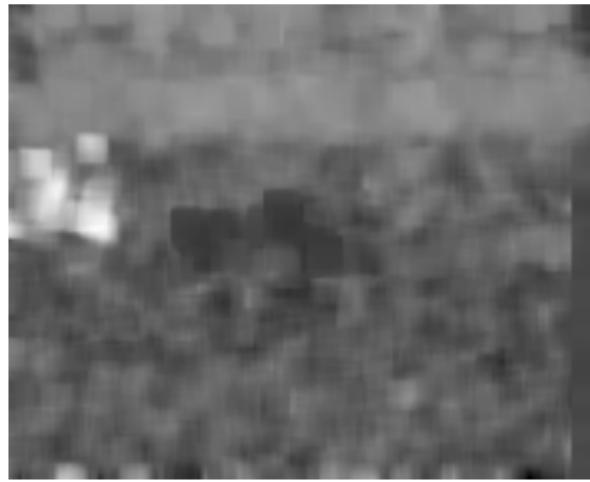
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dense optical flow



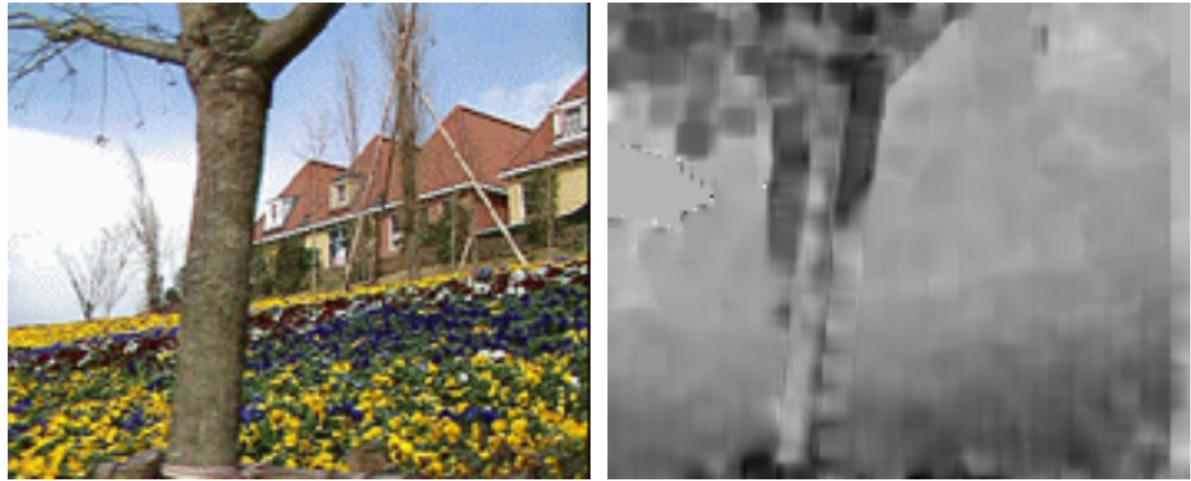
- camera follows background, two objects at opposite horizontal directions
- motion noisy on uniform regions

dense optical flow



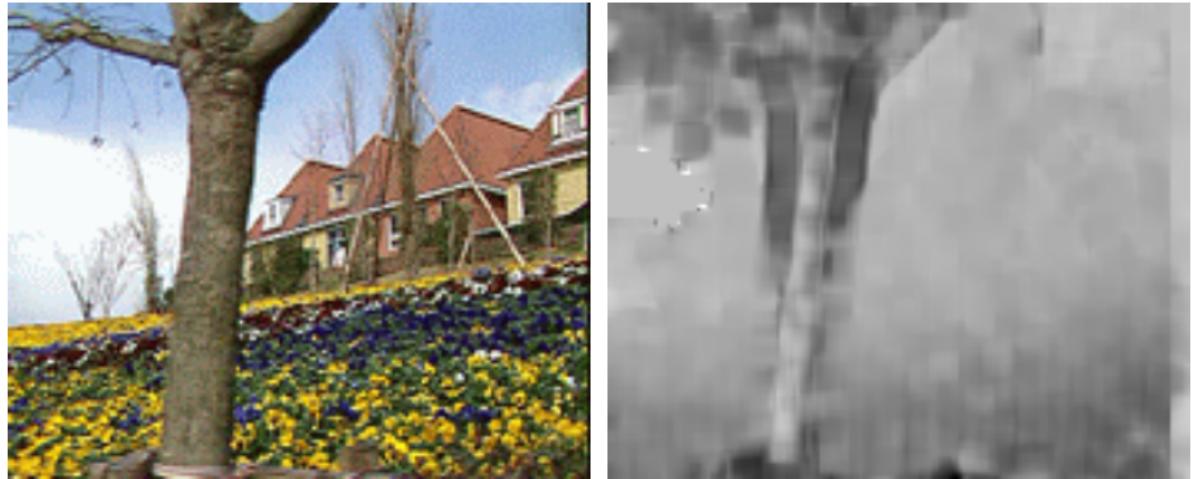
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dense optical flow



- parallax: tree closer to viewer than background
- stable on textured regions
- window size visible on edges

dense optical flow



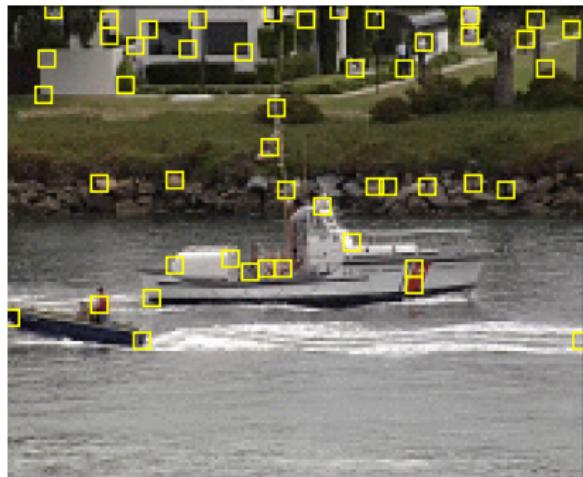
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feature point tracking

[Tomasi and Kanade 1991]

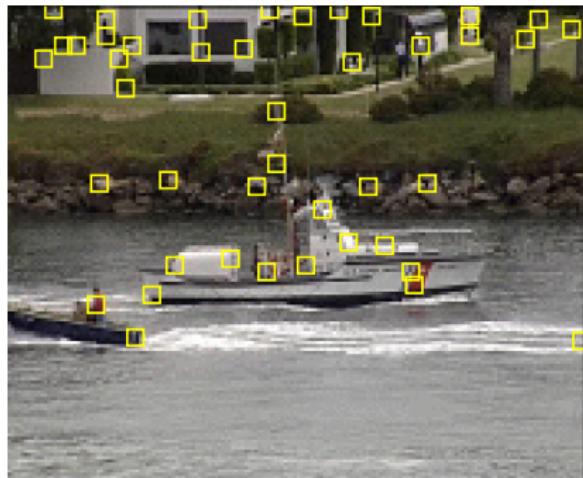
- linear system can be solved reliably if matrix μ is well-conditioned:
 λ_1/λ_2 is not too large
- detect feature points at local maxima of response $\min(\lambda_1, \lambda_2)$

feature point tracking



- uniform regions are not tracked now
- nearly same response as Harris corners
- Q: why do we need the window? what should the size be?

feature point tracking



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wide-baseline matching

- in dense registration, we started from a local “template matching” process and found an efficient solution based on a Taylor approximation
- both make sense for small displacements
- in wide-baseline matching, every part of one image may appear anywhere in the other
- we start by pairwise matching of local descriptors without any order and then attempt to enforce some geometric consistency according to a rigid motion model

wide-baseline matching

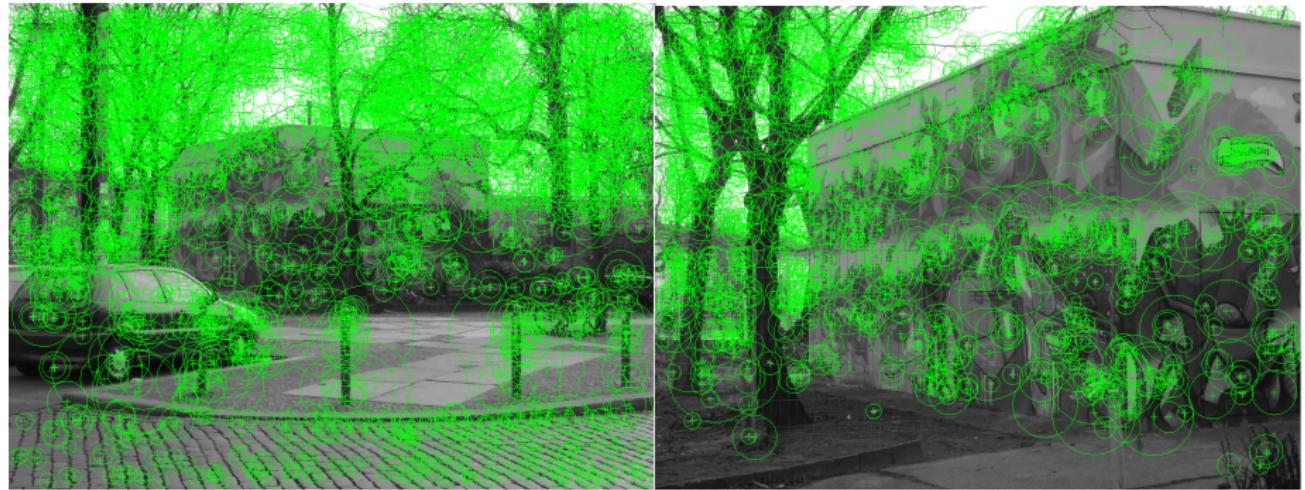
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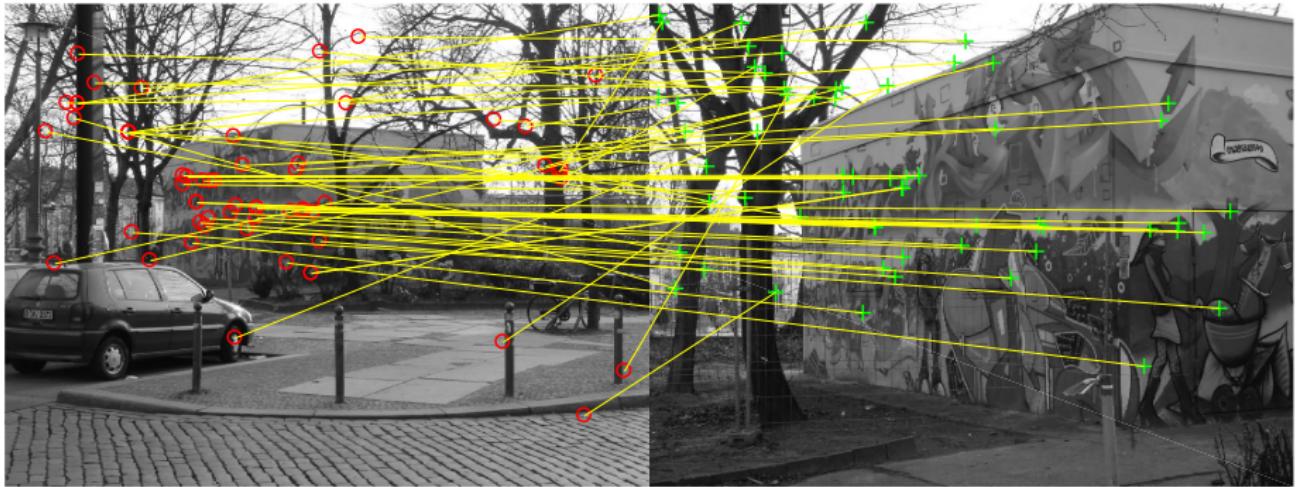
- a region in one image may appear anywhere in the other

wide-baseline matching



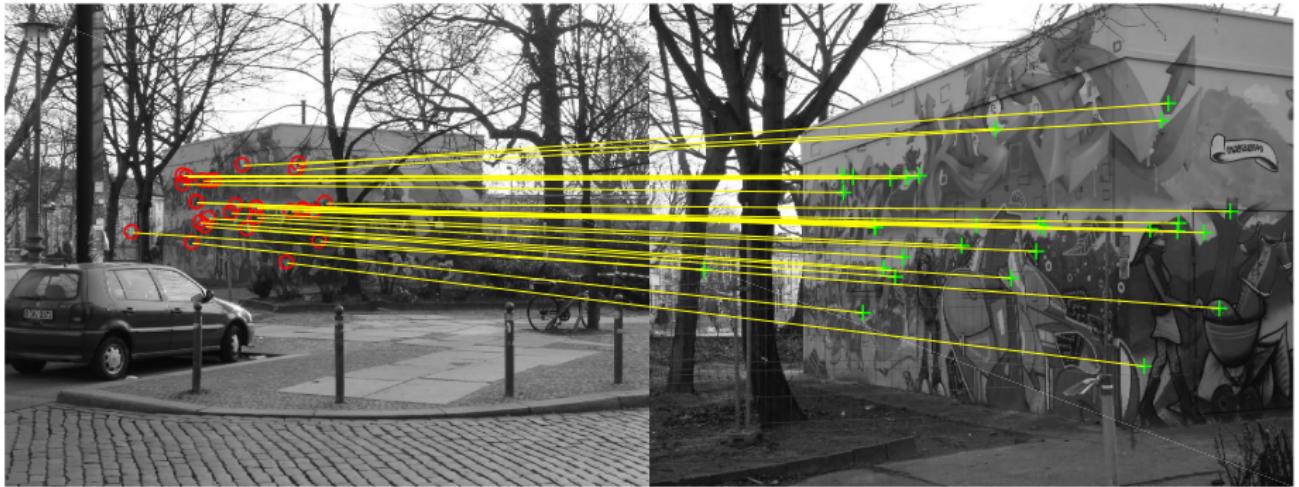
- features detected independently in each image

wide-baseline matching



- tentative correspondences by pairwise descriptor matching

wide-baseline matching



- subset of correspondences that are ‘inlier’ to a rigid transformation

descriptor extraction

for each detected feature in each image

- construct a local histogram of gradient orientations
- find one or more dominant orientations corresponding to peaks in the histogram
- resample local patch at given location, scale, affine shape and orientation
- extract one descriptor for each dominant orientation

descriptor matching



descriptor matching



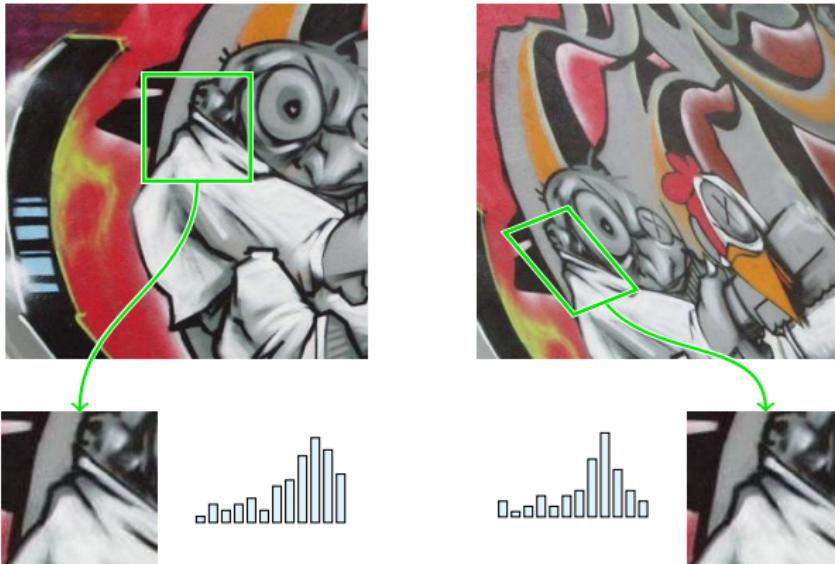
- detect features

descriptor matching



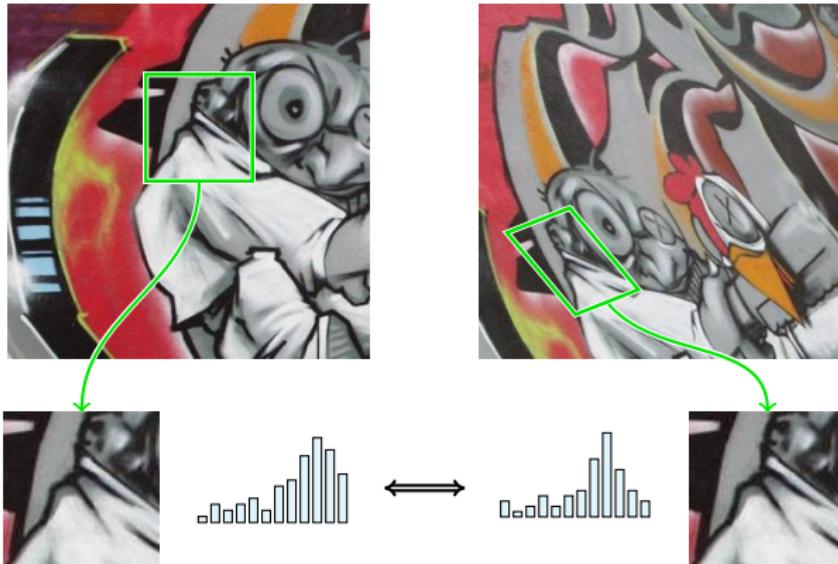
- detect features - find dominant orientation, resample patches

descriptor matching



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descriptor matching

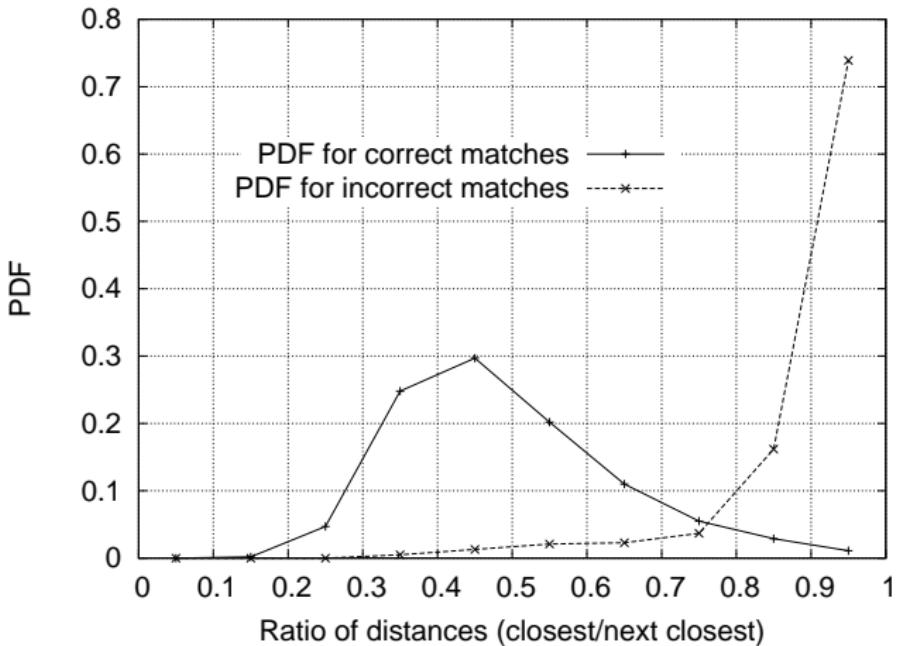


- detect features - find dominant orientation, resample patches - extract descriptors - match pairwise

descriptor matching

- for each descriptor in one image, find its two nearest neighbors in the other
- if ratio of distance of first to distance of second is small, make a correspondence
- this yields a list of **tentative** correspondences

ratio test



- ratio of first to second nearest neighbor distance can determine the probability of a true correspondence

spatial matching

why is it difficult?

- should allow for a geometric transformation
- fitting the model to data (correspondences) is sensitive to outliers:
should find a subset of *inliers* first
- finding inliers to a transformation requires finding the *transformation* in the first place
- correspondences have gross error
- inliers are typically less than 50%

geometric transformations

- two images f, f' are equal at points x, x'

$$f(\mathbf{x}) = f'(\mathbf{x}')$$

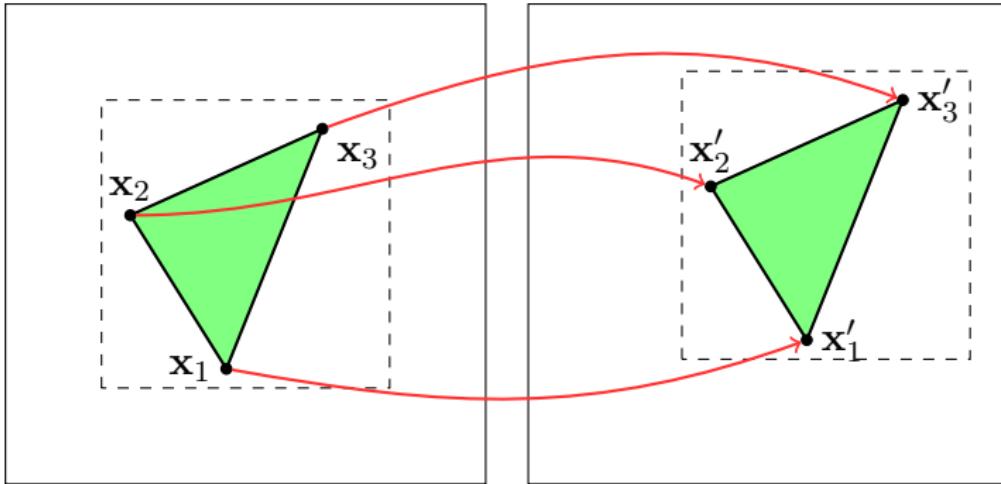
- \mathbf{x} is mapped to \mathbf{x}'

$$\mathbf{x}' = T(\mathbf{x})$$

- T is a bijection of \mathbb{R}^2 to itself:

$$T : \mathbb{R}^2 \rightarrow \mathbb{R}^2$$

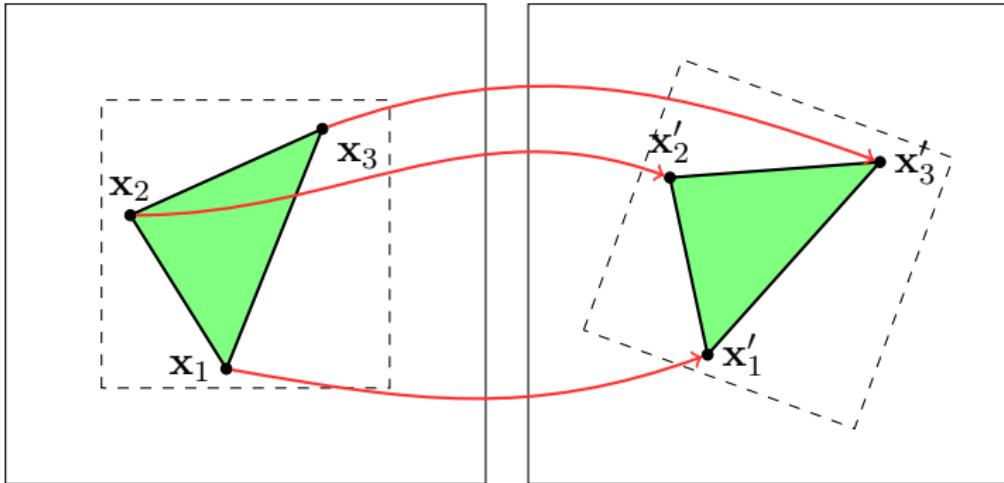
geometric transformations



- translation: 2 degrees of freedom

$$\begin{pmatrix} x' \\ y' \\ 1 \end{pmatrix} = \begin{pmatrix} 1 & 0 & d_x \\ 0 & 1 & d_y \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x \\ y \\ 1 \end{pmatrix}$$

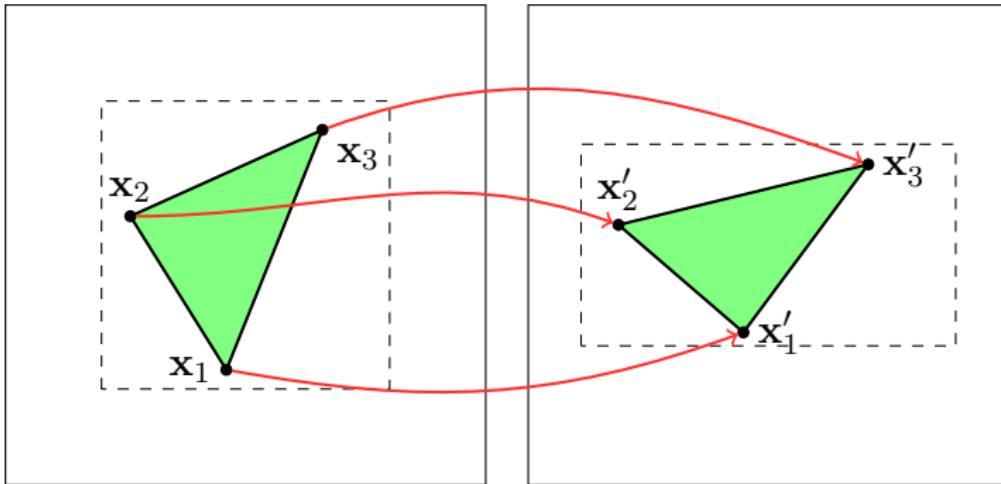
geometric transformations



- rotation: 1 degree of freedom

$$\begin{pmatrix} x' \\ y' \\ 1 \end{pmatrix} = \begin{pmatrix} \cos \theta & -\sin \theta & 0 \\ \sin \theta & \cos \theta & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x \\ y \\ 1 \end{pmatrix}$$

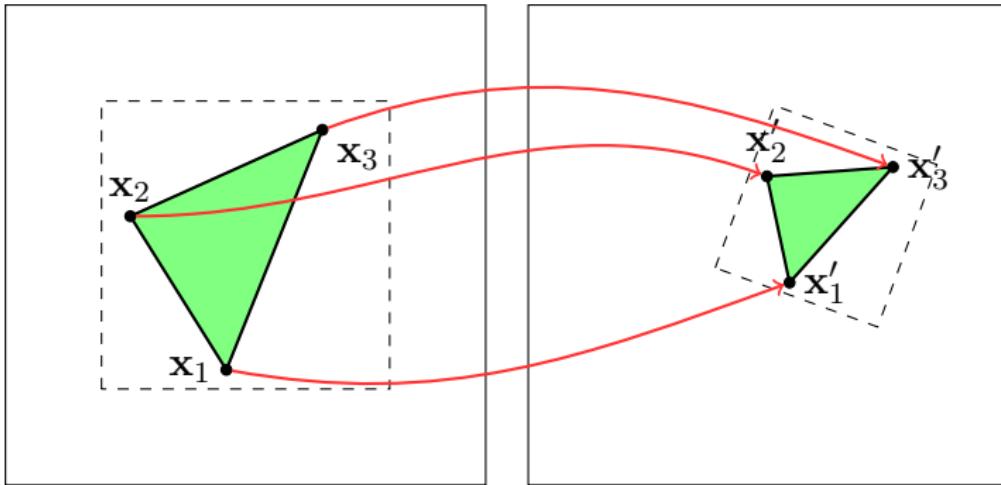
geometric transformations



- scale: 2 degrees of freedom

$$\begin{pmatrix} x' \\ y' \\ 1 \end{pmatrix} = \begin{pmatrix} s_x & 0 & 0 \\ 0 & s_y & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x \\ y \\ 1 \end{pmatrix}$$

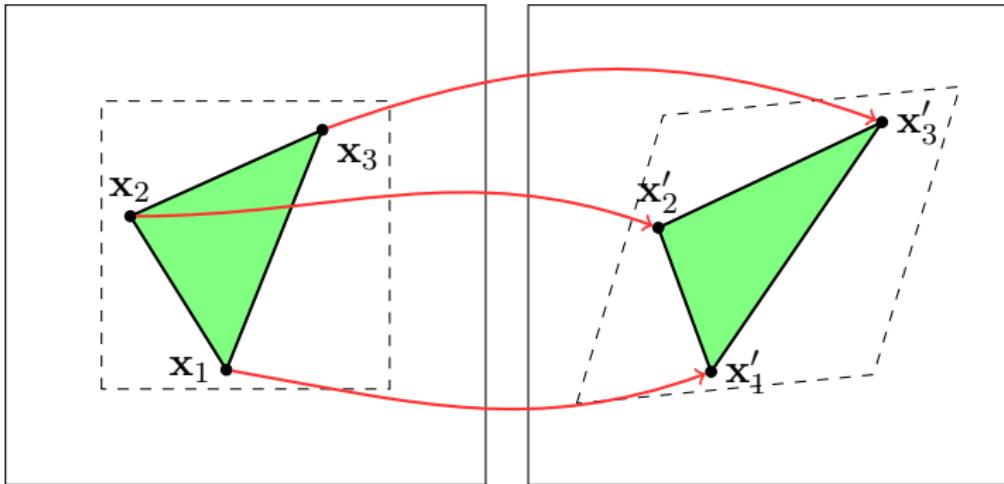
geometric transformations



- similarity: 4 degrees of freedom

$$\begin{pmatrix} x' \\ y' \\ 1 \end{pmatrix} = \begin{pmatrix} r \cos \theta & -r \sin \theta & d_x \\ r \sin \theta & r \cos \theta & d_y \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x \\ y \\ 1 \end{pmatrix}$$

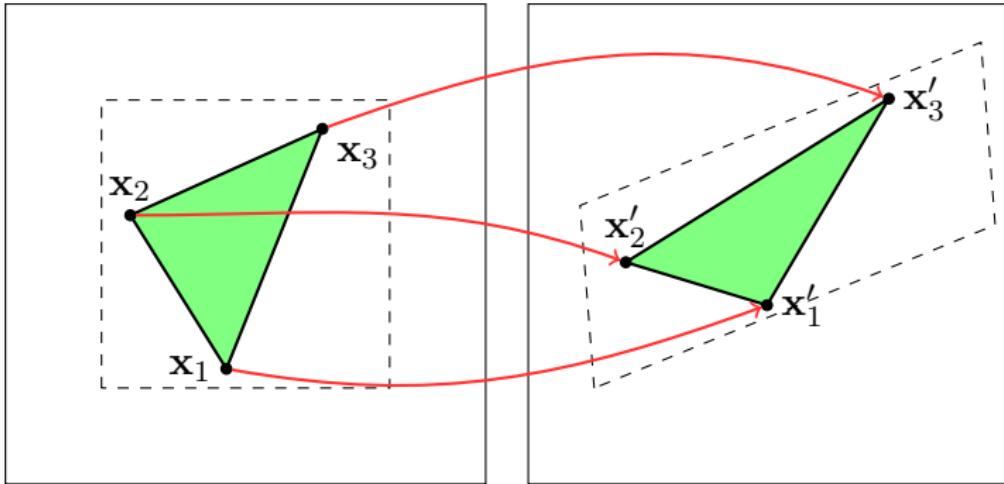
geometric transformations



- shear: 2 degrees of freedom

$$\begin{pmatrix} x' \\ y' \\ 1 \end{pmatrix} = \begin{pmatrix} 1 & b_x & 0 \\ b_y & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x \\ y \\ 1 \end{pmatrix}$$

geometric transformations



- affine: 6 degrees of freedom

$$\begin{pmatrix} x' \\ y' \\ 1 \end{pmatrix} = \begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x \\ y \\ 1 \end{pmatrix}$$

however

- details don't matter; in all cases, the problem is transformed to a linear system (**why?**)

$$\mathbf{A}\mathbf{x} = \mathbf{b}$$

where \mathbf{A}, \mathbf{b} contain coordinates of known point correspondences from images f, f' respectively, and \mathbf{x} contains our model parameters

- we need $n = \lceil d/2 \rceil$ correspondences, where d are the degrees of freedom of our model
- let's take the simplest model as an example: fit a line to two points

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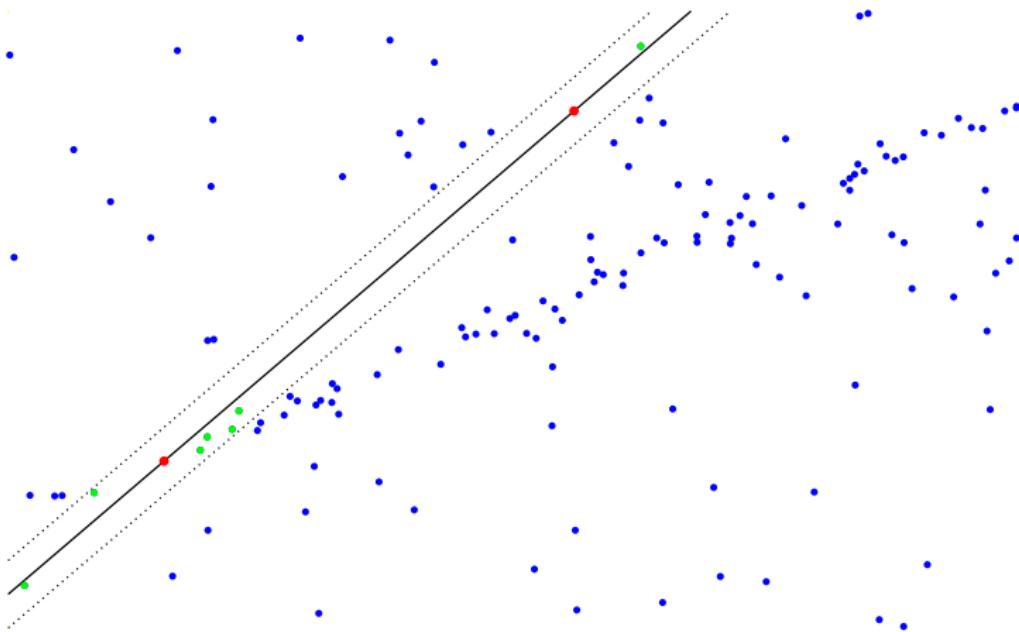
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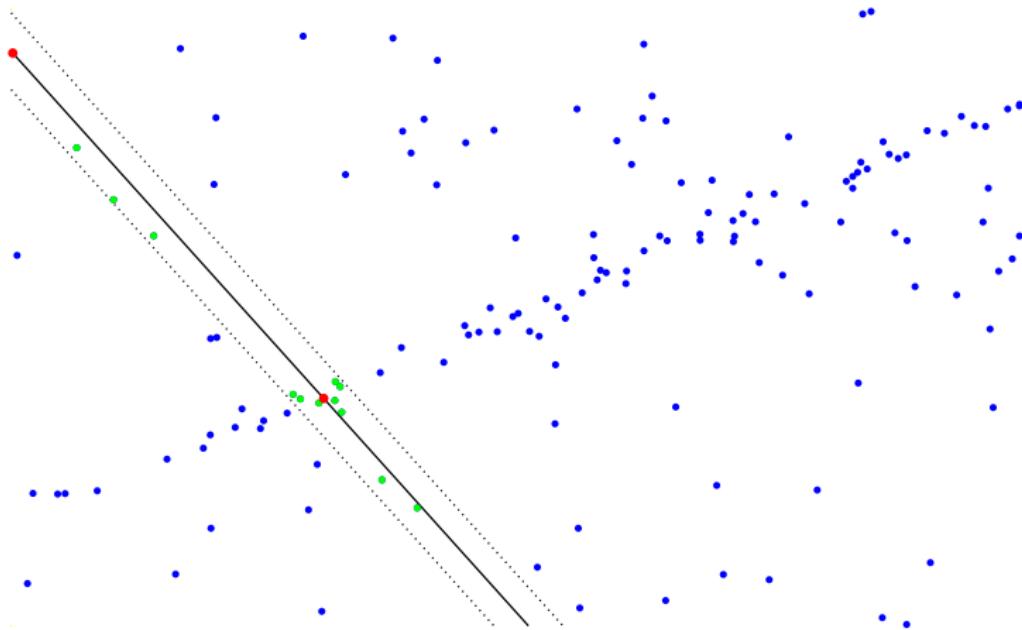
ransac



- pick two points at random, find line through them, count inlier points at fixed distance to line

Fischler and Bolles. CACM 1981. Random Sample Consensus- A Paradigm for Model Fitting With Applications to Image Analysis and Automated Cartography.

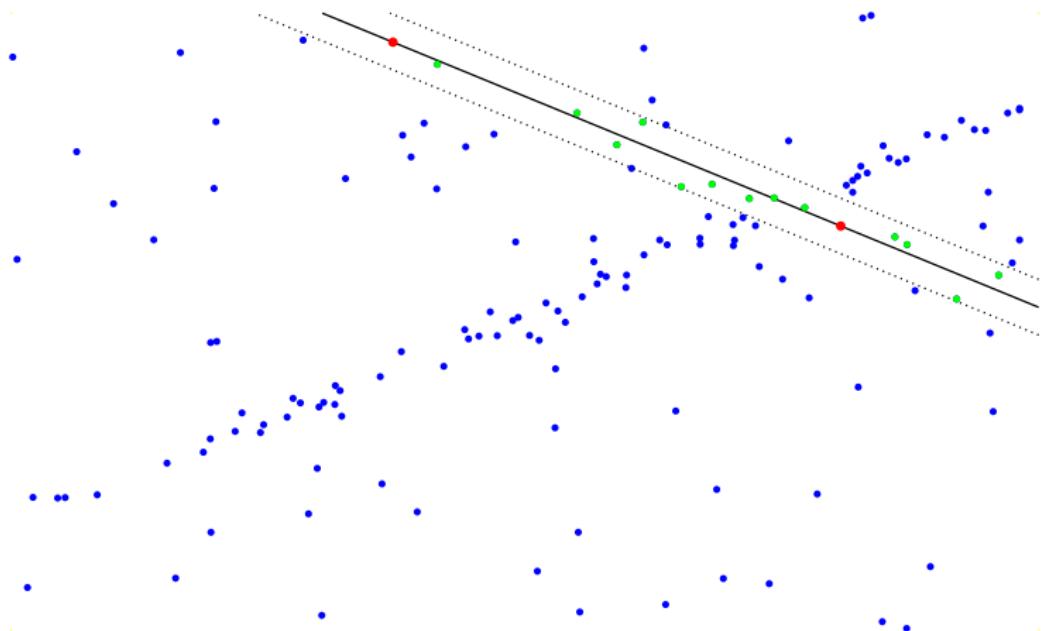
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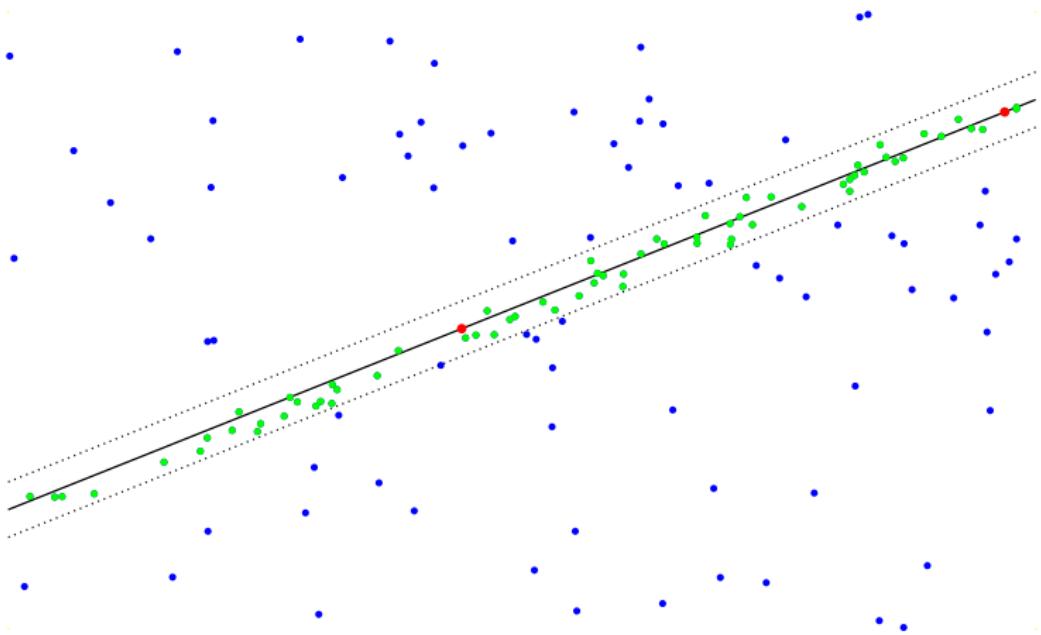
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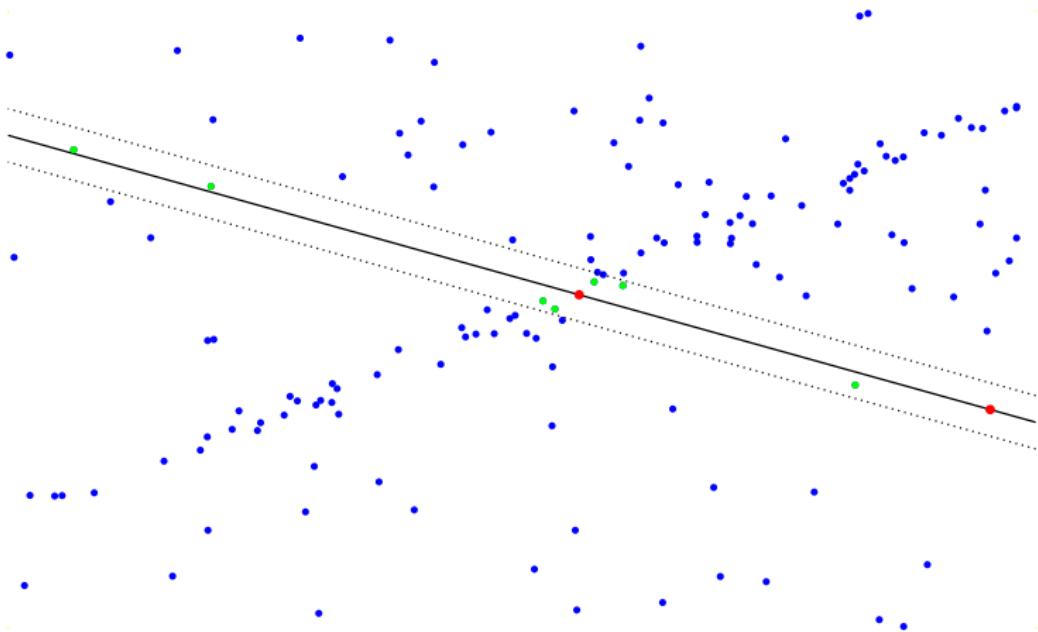
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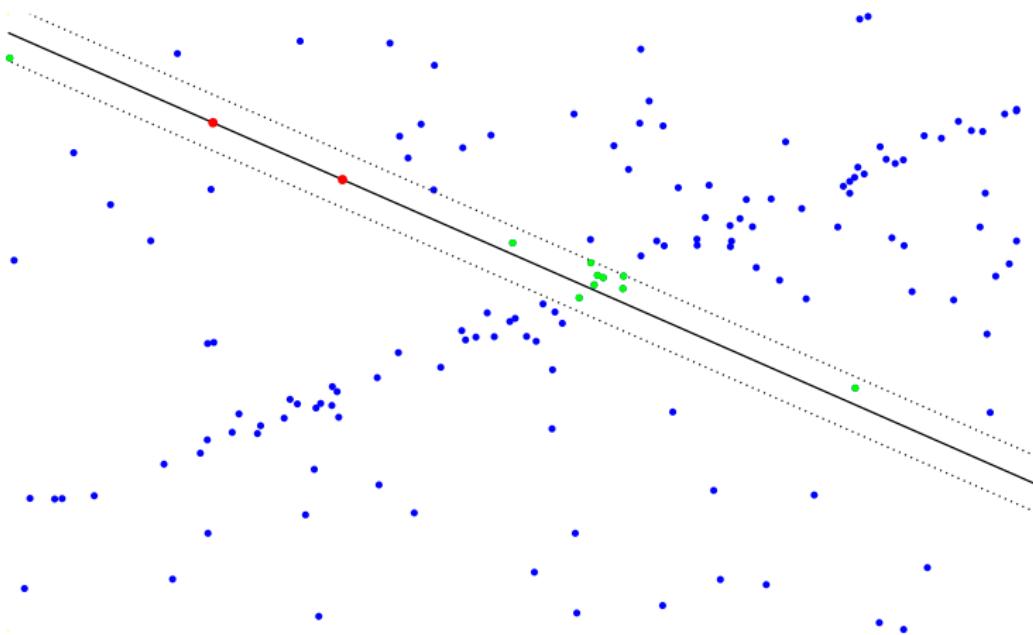
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ransac



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random sample consensus (ransac)

[Fischler and Bolles 1981]

- X : data (tentative correspondences)
- n : minimum number of samples to fit a model
- $s(x; \theta)$: score of sample x given model parameters θ
- repeat until the probability of a better solution is $> \rho$:
 - hypothesis
 - draw n samples $H \subset X$ at random with $|H| = n$
 - fit model to H , compute parameters θ
 - verification
 - are data consistent with hypothesis? compute score $S = \sum_{x \in X} s(x; \theta)$
 - if $S^* > S$, store solution $\theta^* := \theta$, $S^* := S$

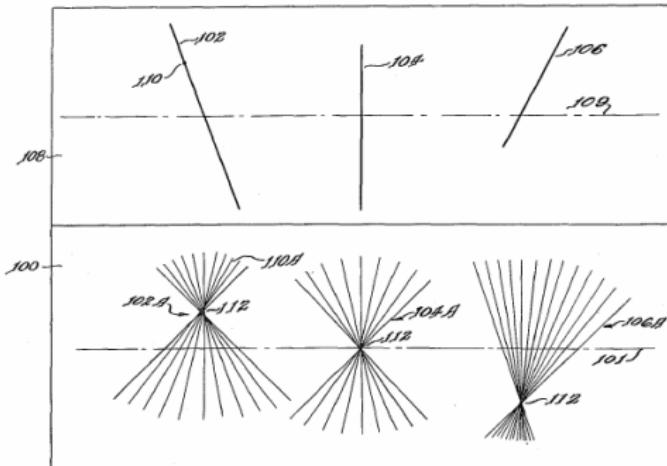
issues

- inlier ratio w unknown
- too expensive when minimum number of samples is large (e.g. $n > 6$) and inlier ratio is small e.g. $w < 10\%$): 10^6 iterations for 1% probability of failure

Hough transform

[Hough 1962]

Fig-1



Dec. 18, 1962

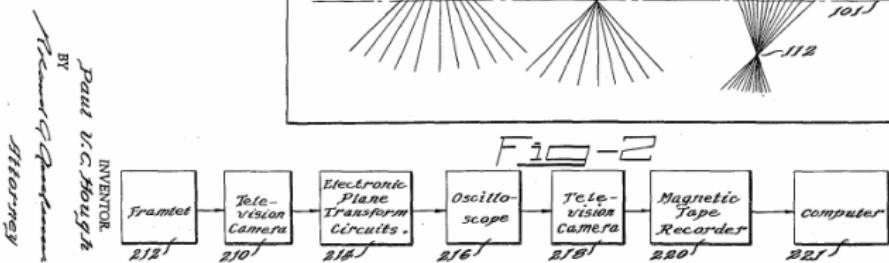
P. V. C. HOUGH

3,069,654

Filed March 25, 1960

METHOD AND MEANS FOR RECOGNIZING COMPLEX PATTERNS

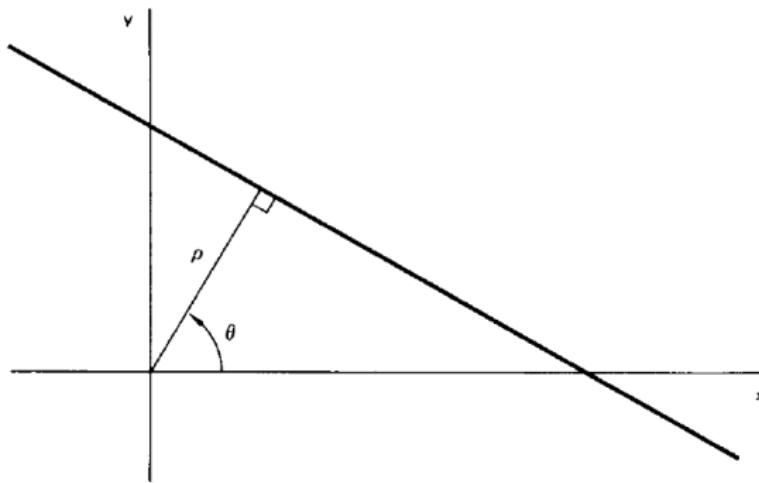
2 Sheets-Sheet 1



- detect lines by a voting process in parameter space
 - slope-intercept parametrization unbounded for vertical lines

Hough transform

[Duda and Hart 1972]



- polar parametrization makes parameter space bounded
- discusses generalization to analytic curves; space exponential in number of parameters
- equivalent to Radon transform, but makes sense for sparse input

Hough transform

idea

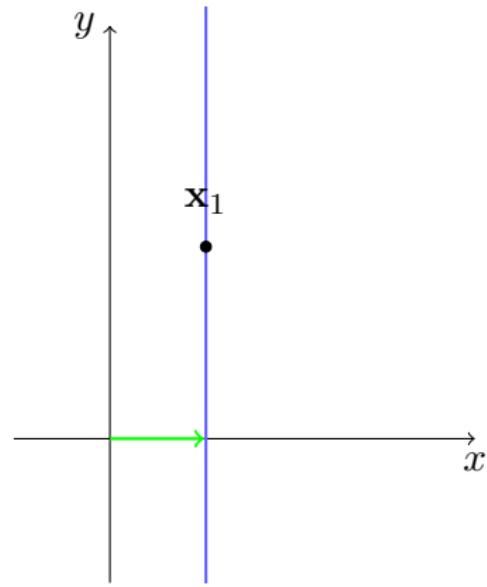
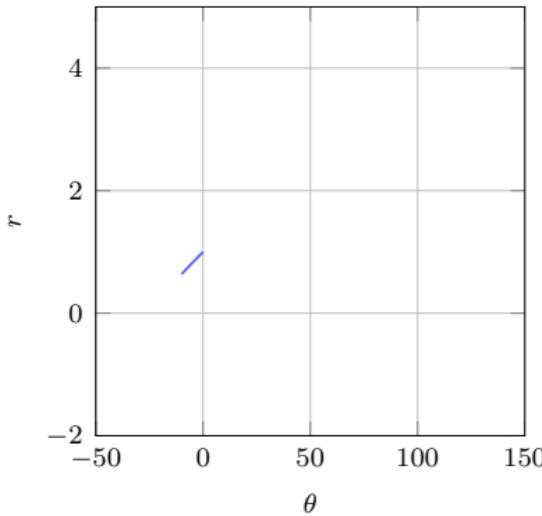
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- but even one sample brings some information
 - in the space of all possible models, vote for the ones that satisfy a given sample
 - collect votes from all samples, and seek for consensus

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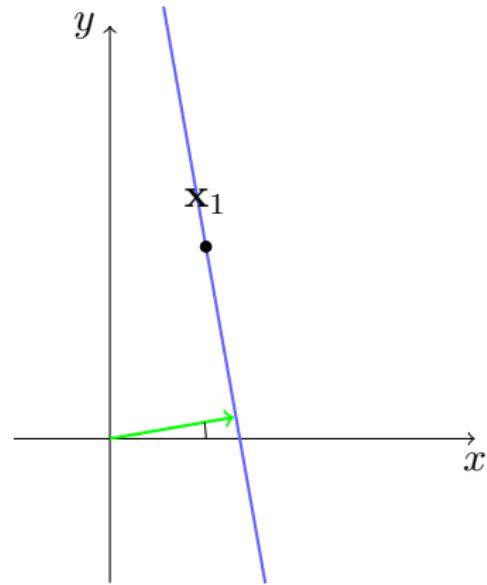
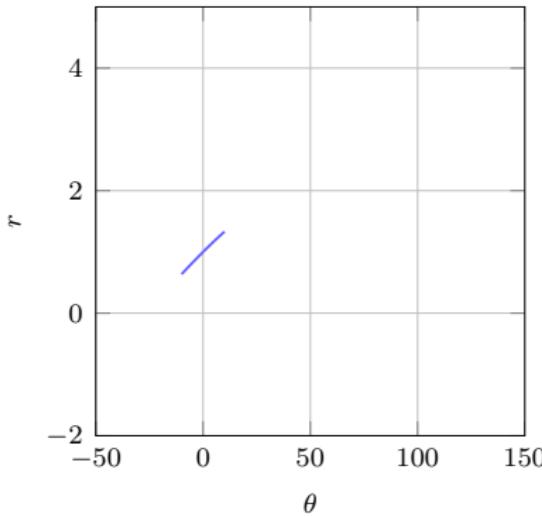
voting in parameter space



- all lines through $x_1 = (x_1, y_1)$ are defined by (r, θ) that satisfy

$$r = x_1 \cos(\theta) + y_1 \sin(\theta)$$

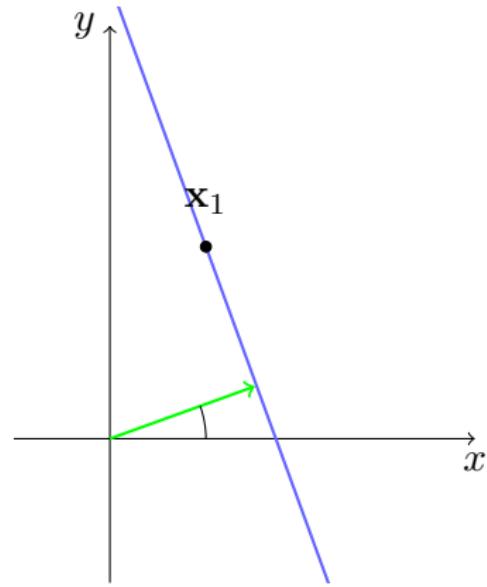
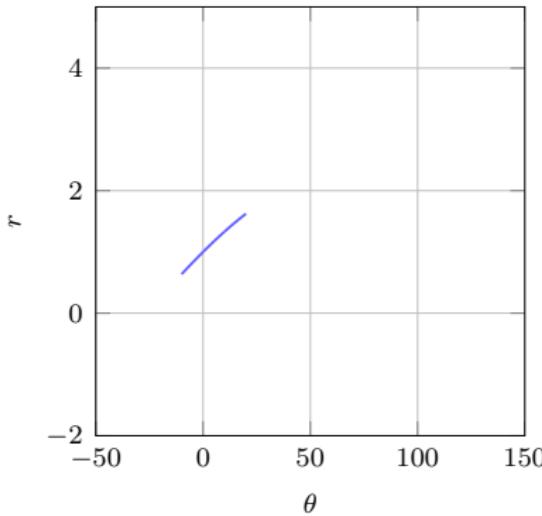
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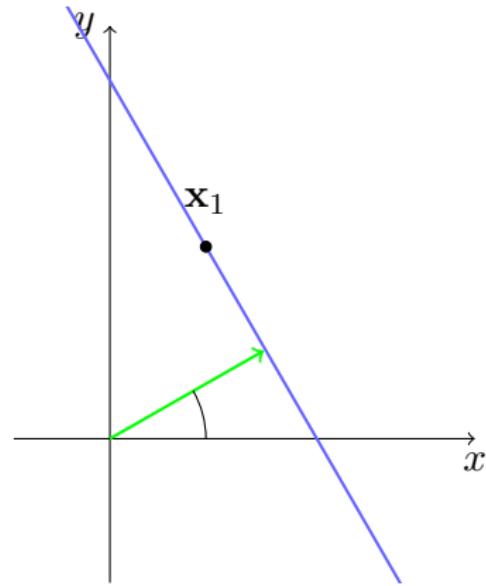
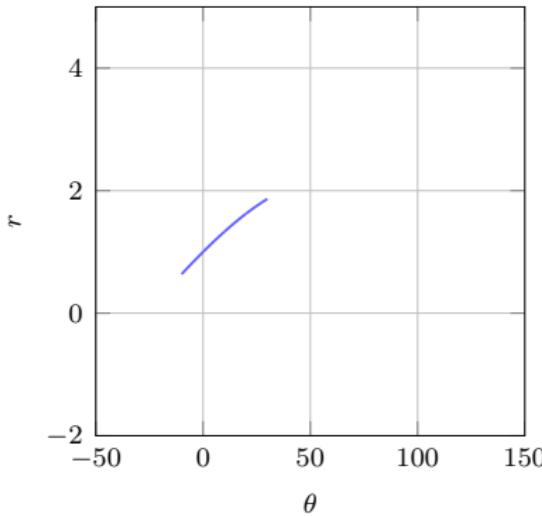
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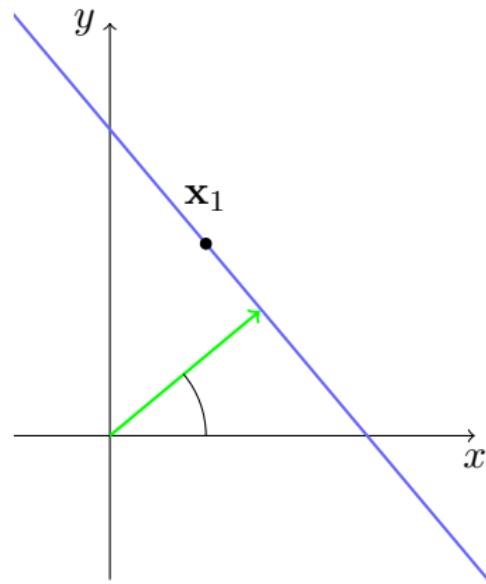
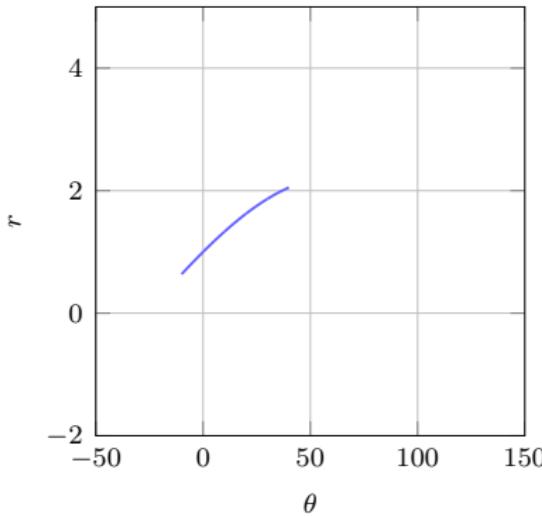
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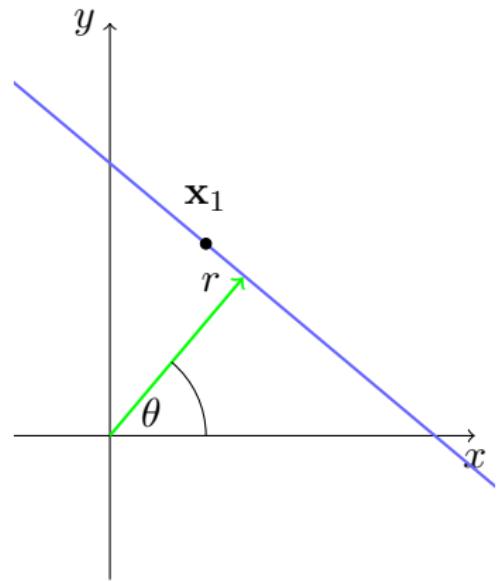
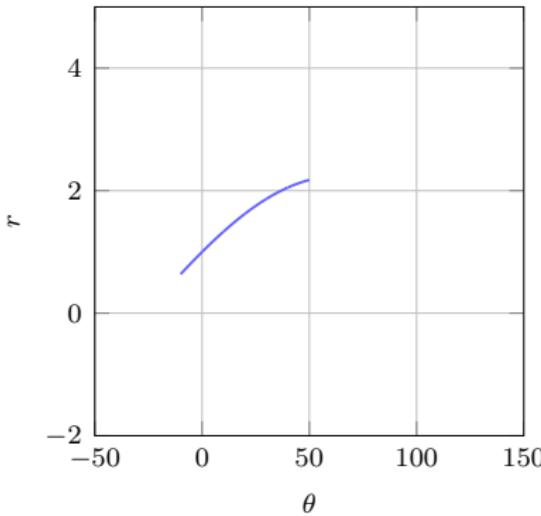
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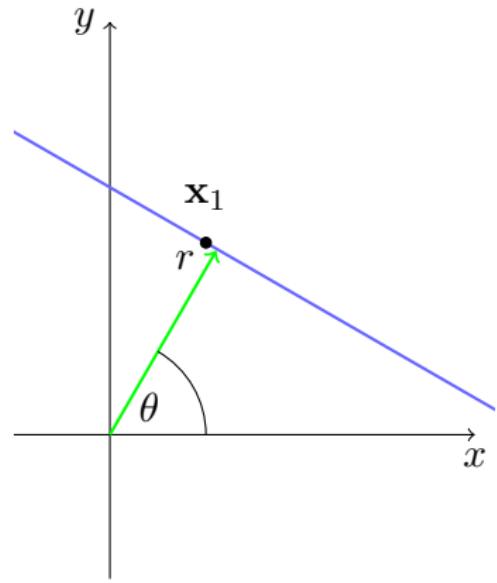
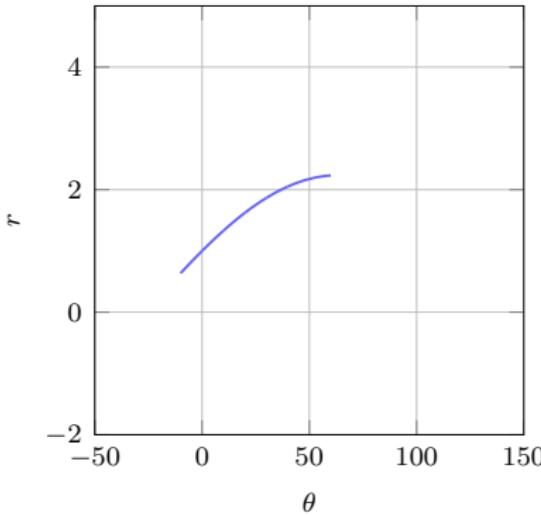
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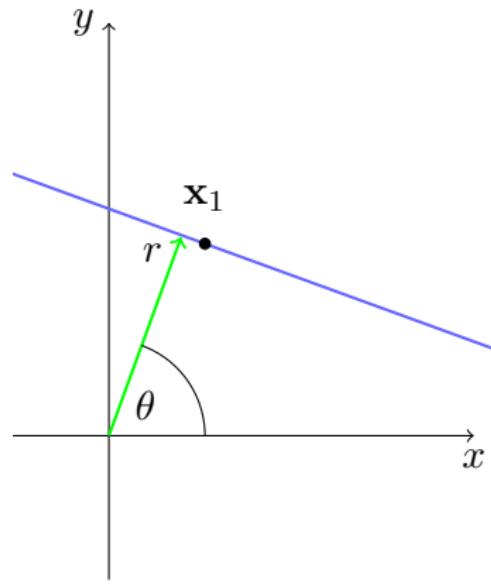
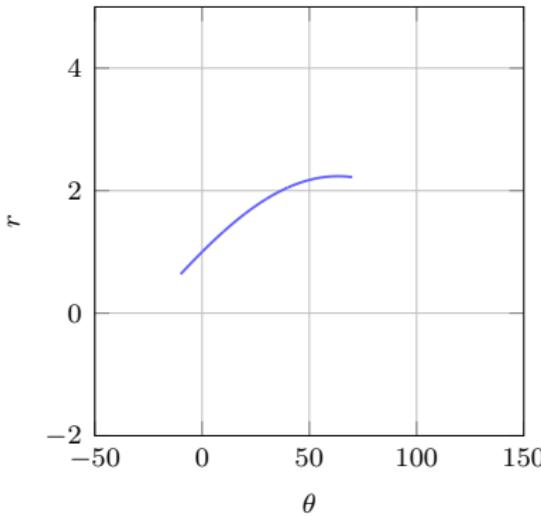
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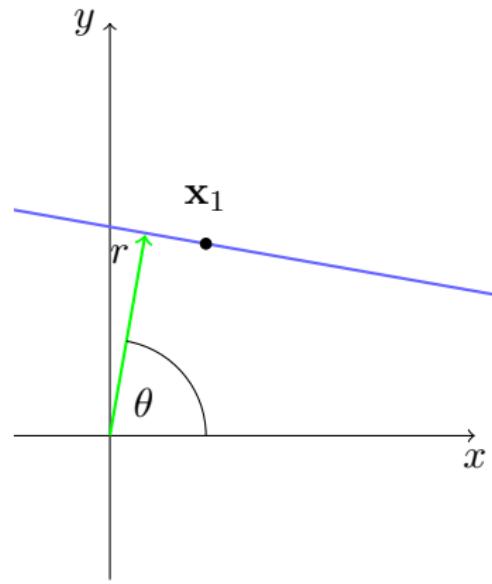
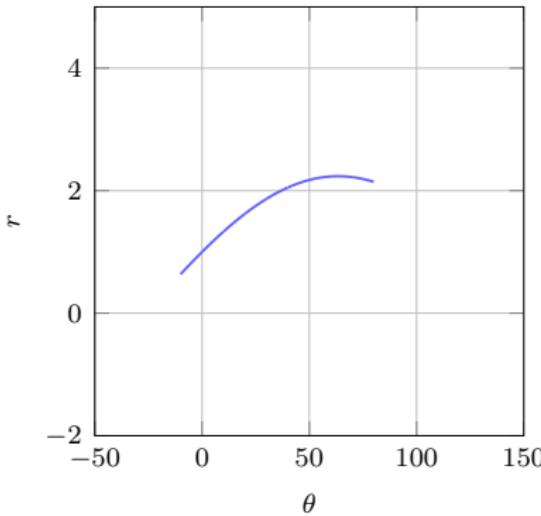
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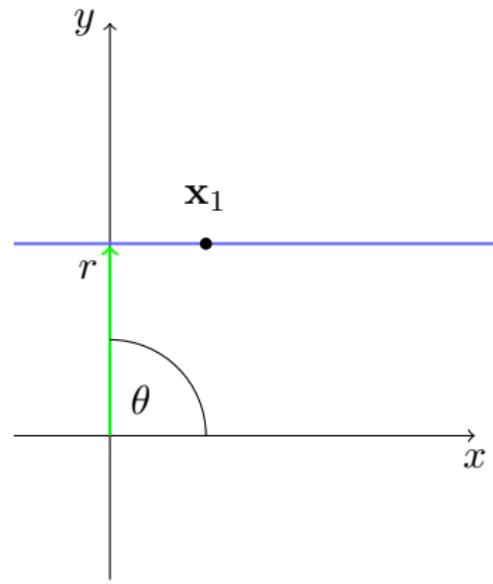
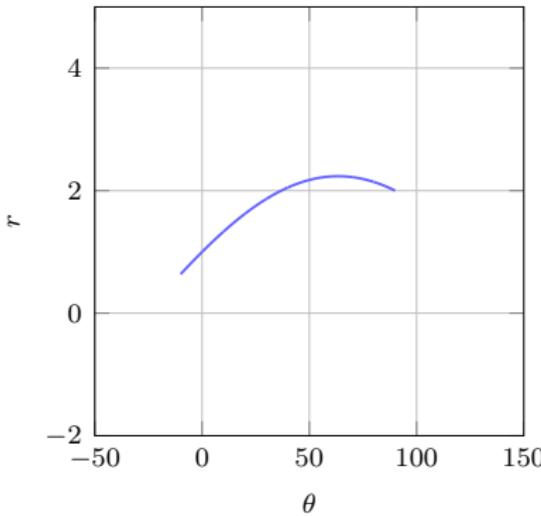
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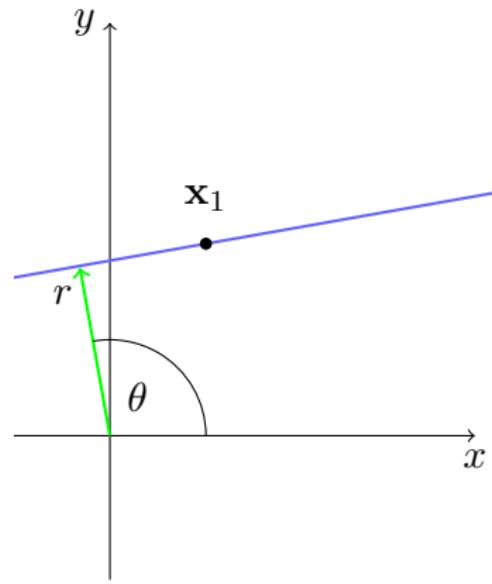
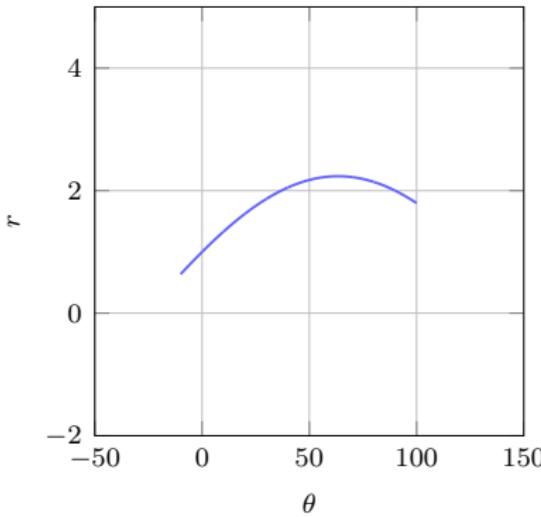
voting in parameter space



- all lines through $\mathbf{x}_1 = (x_1, y_1)$ are defined by (r, θ) that satisfy

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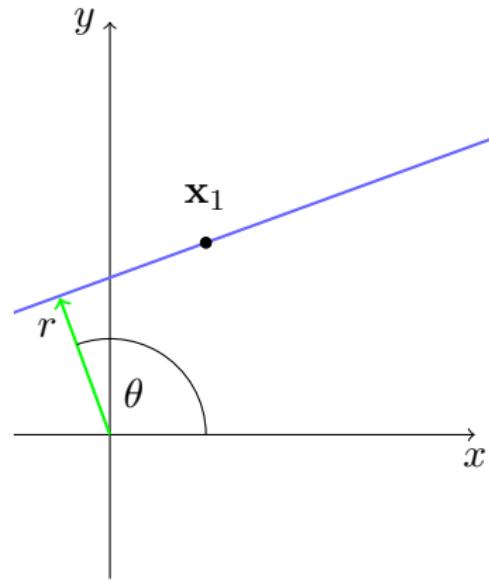
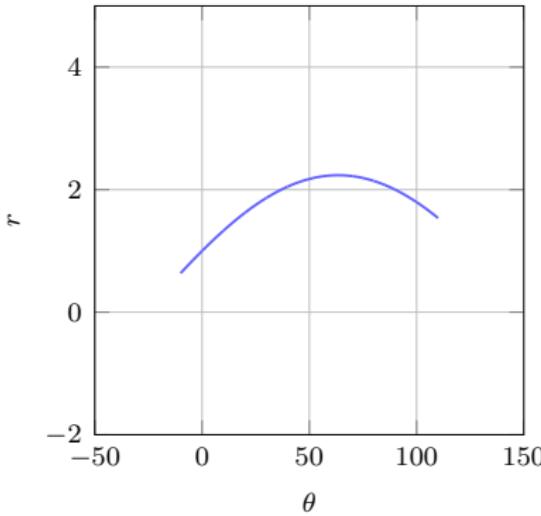
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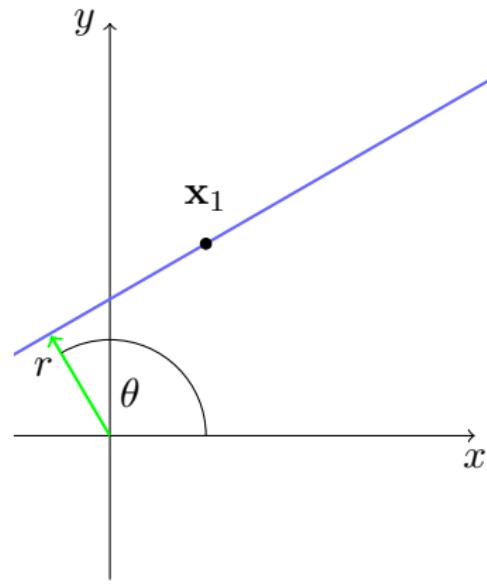
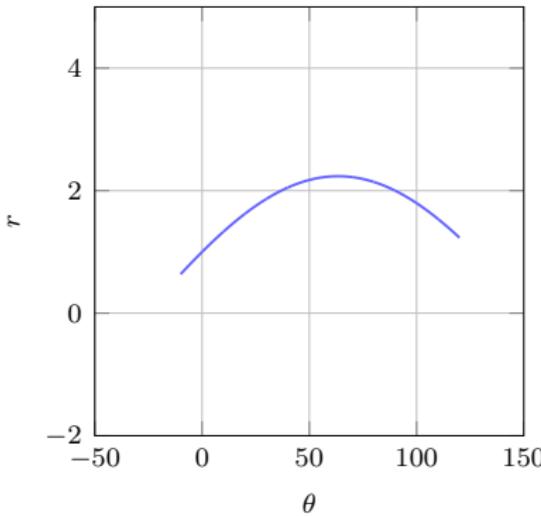
voting in parameter space



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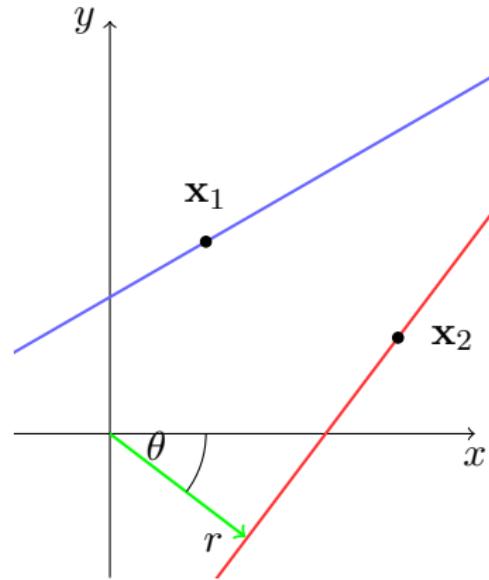
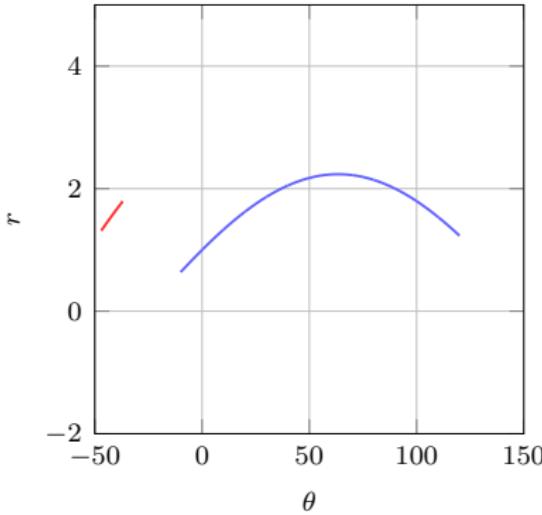
voting in parameter space



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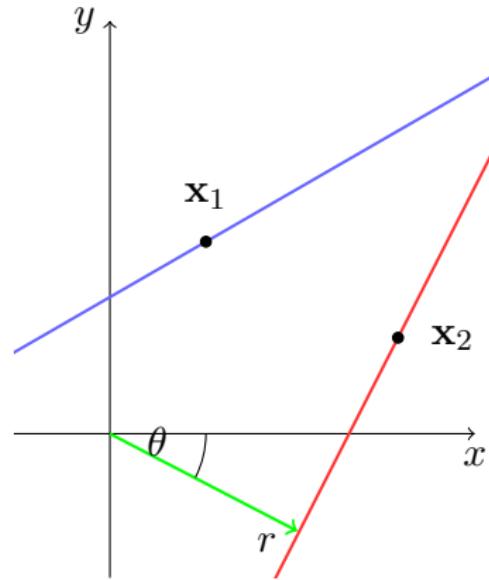
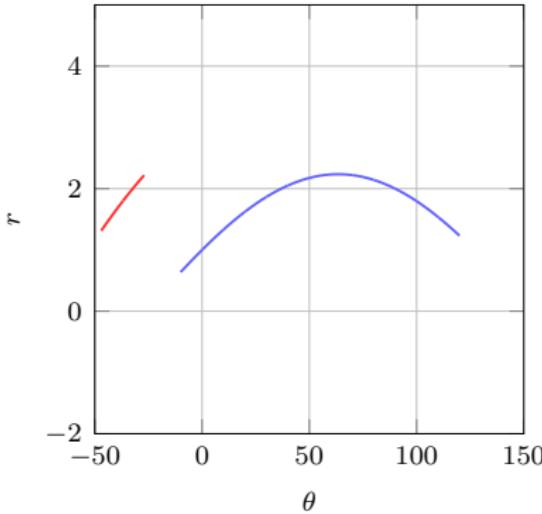
voting in parameter space



- all lines through $x_2 = (x_2, y_2)$ are defined by (r, θ) that satisfy

$$r = x_2 \cos(\theta) + y_2 \sin(\theta)$$

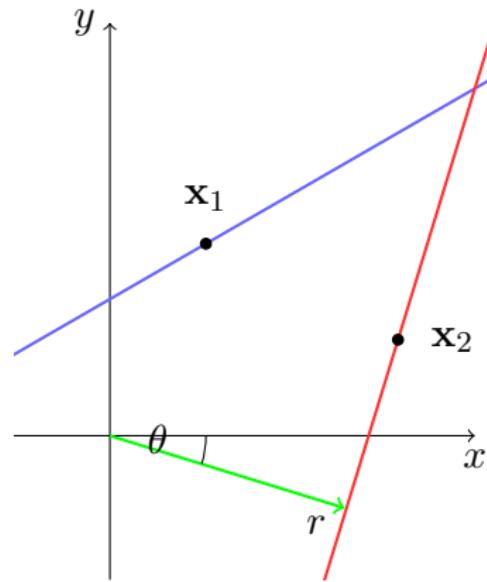
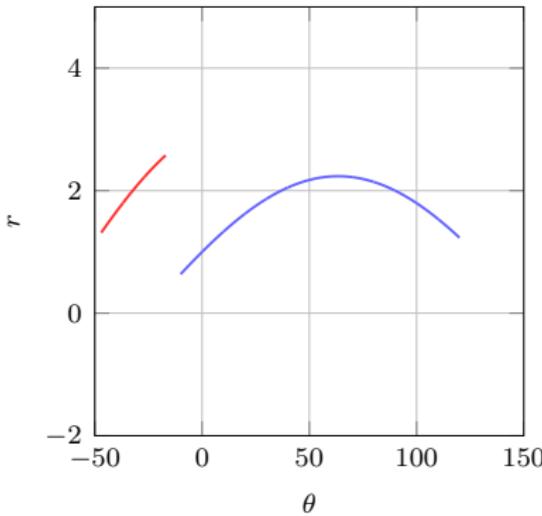
voting in parameter space



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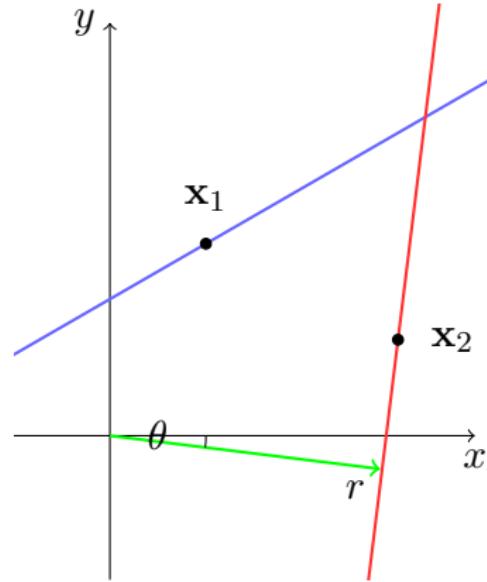
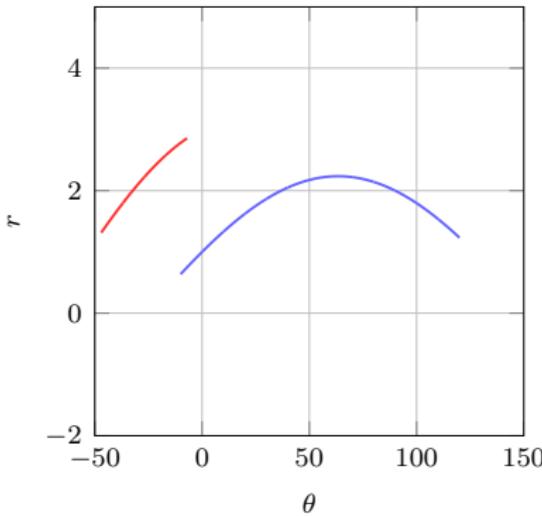
voting in parameter space



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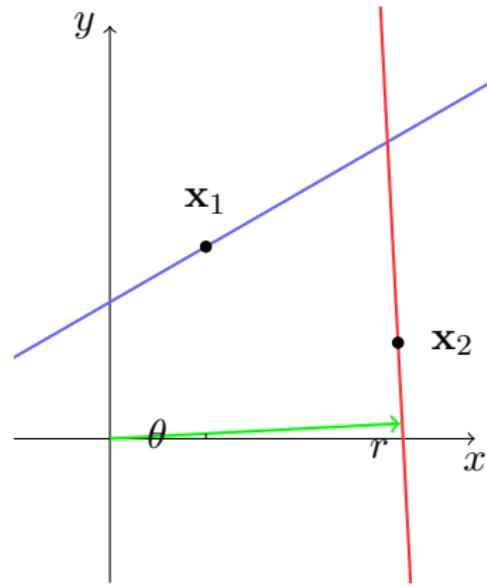
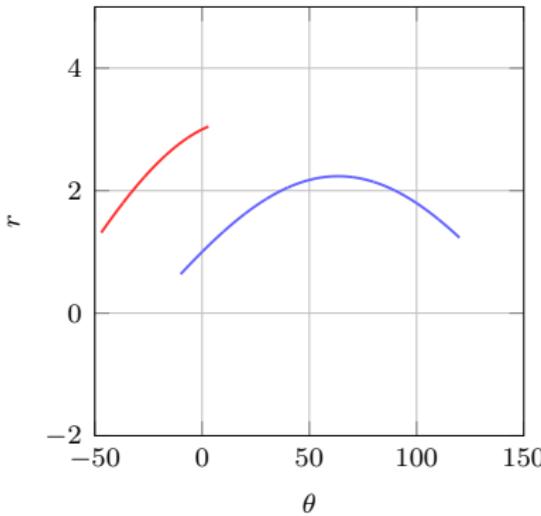
voting in parameter space



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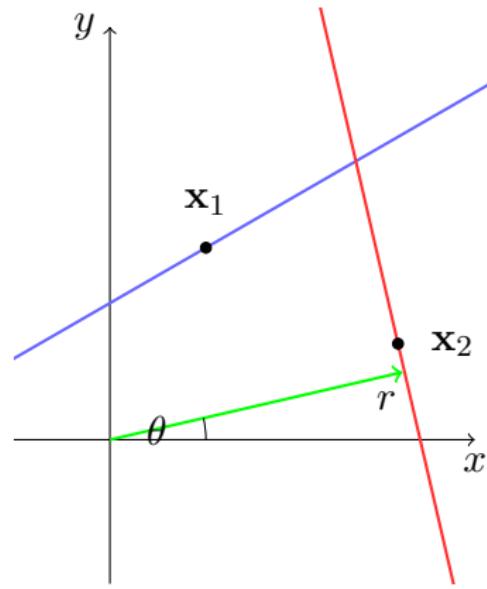
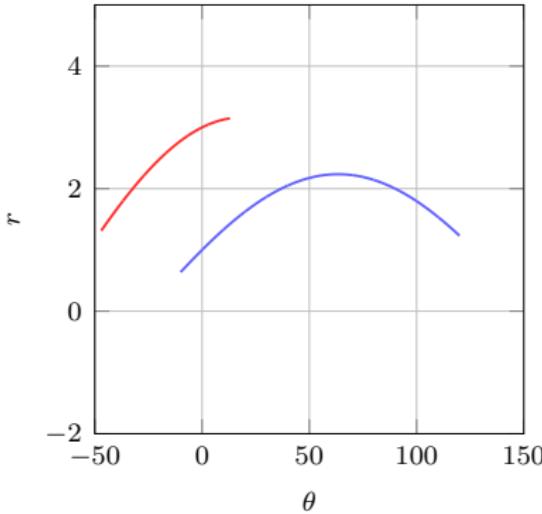
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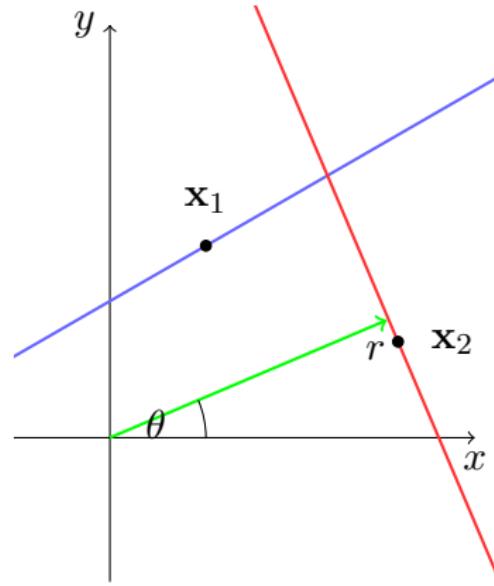
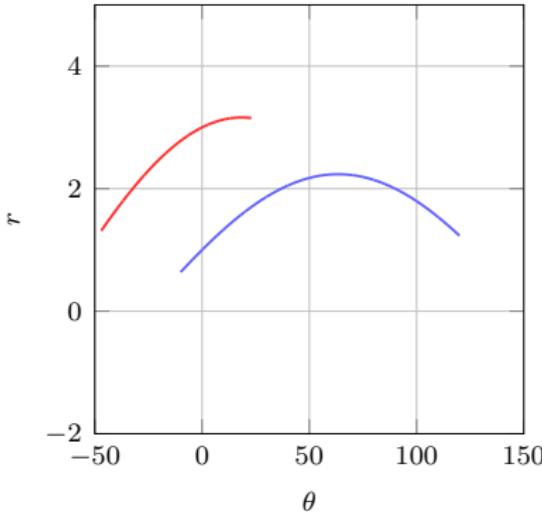
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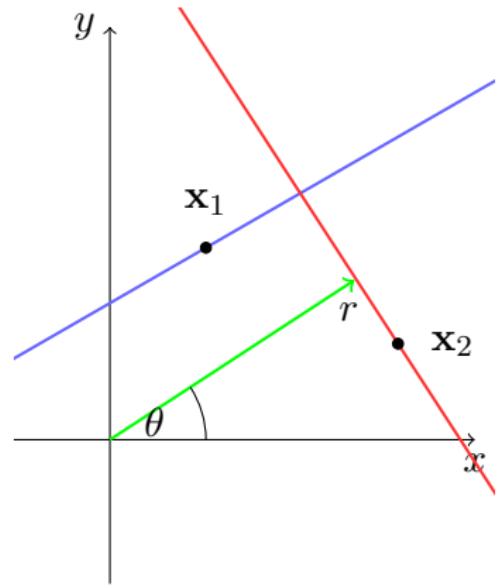
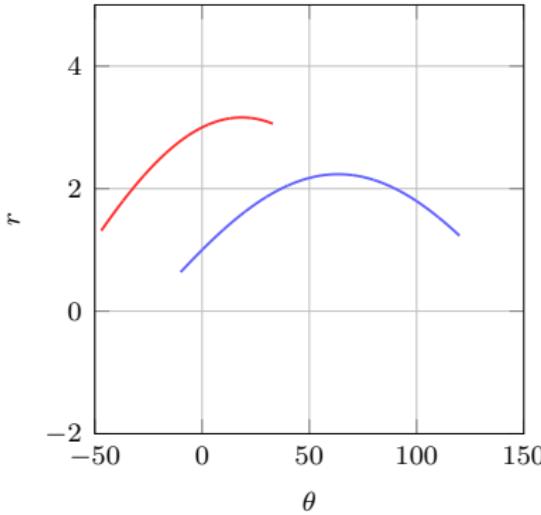
voting in parameter space



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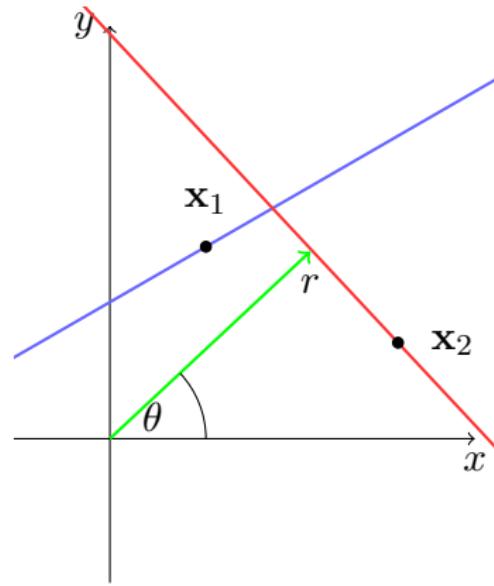
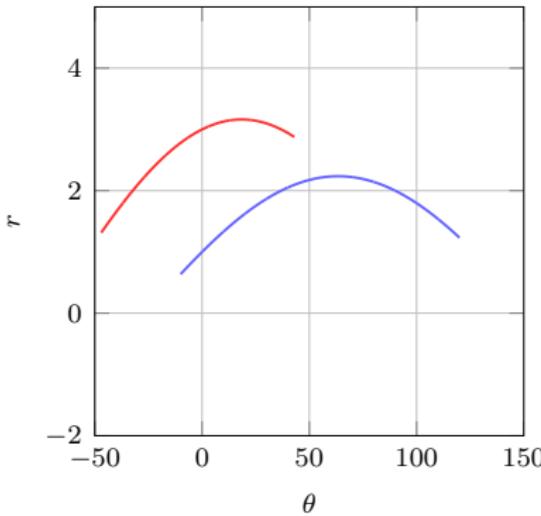
voting in parameter space



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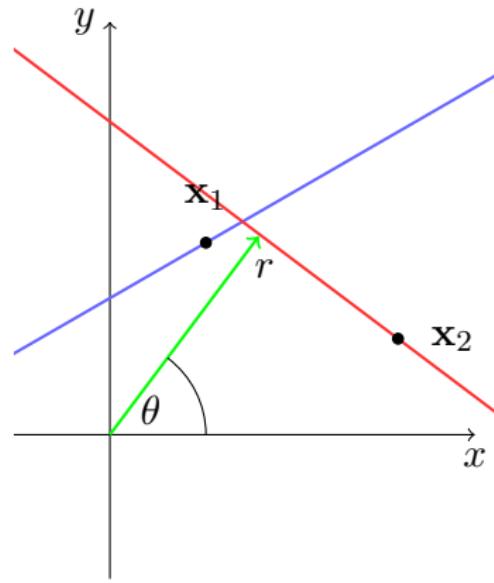
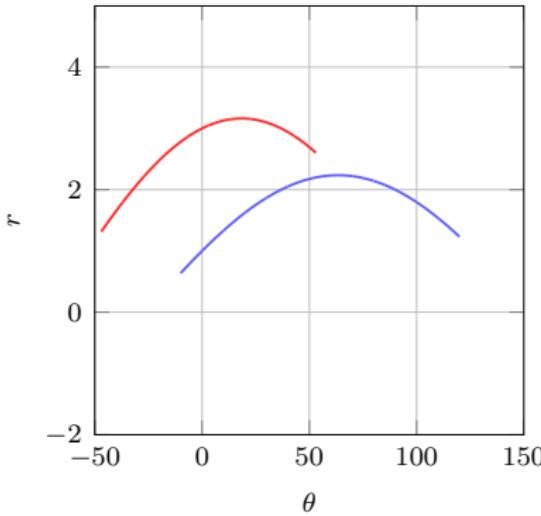
voting in parameter space



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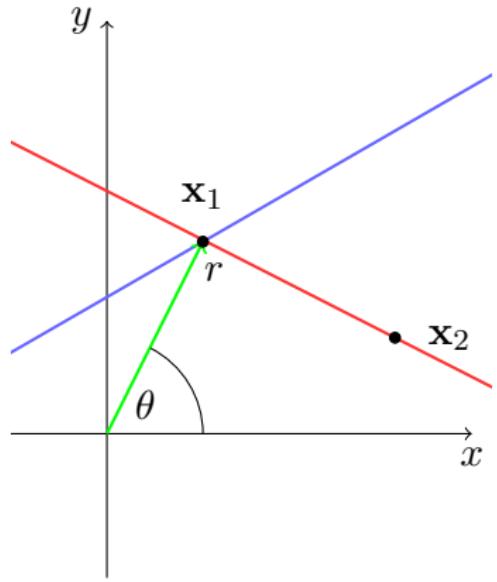
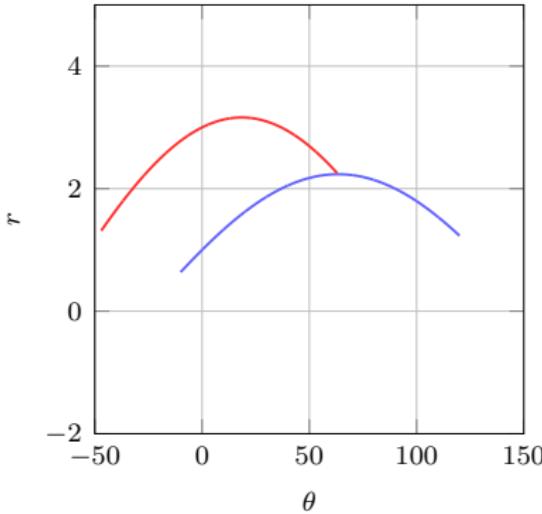
voting in parameter space



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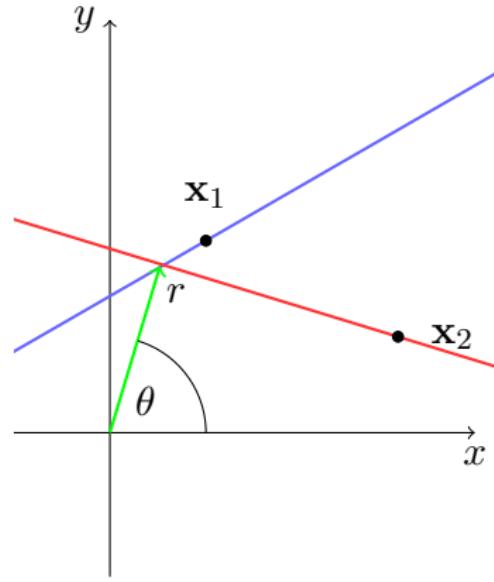
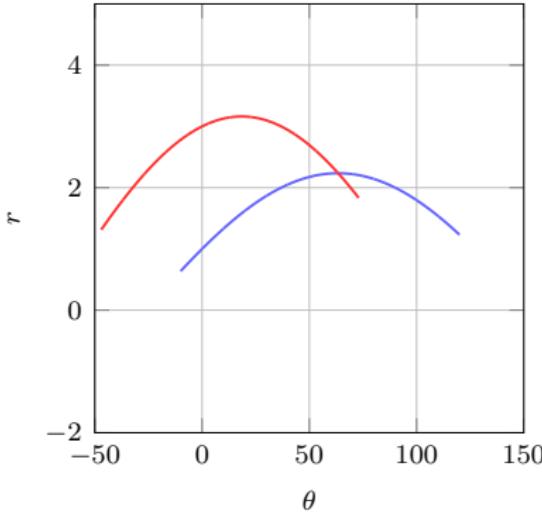
voting in parameter space



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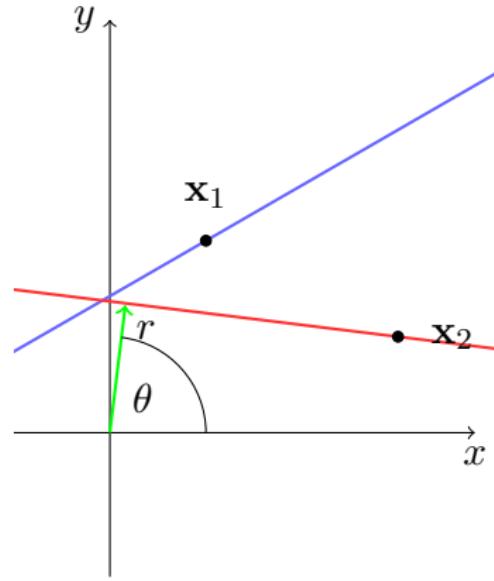
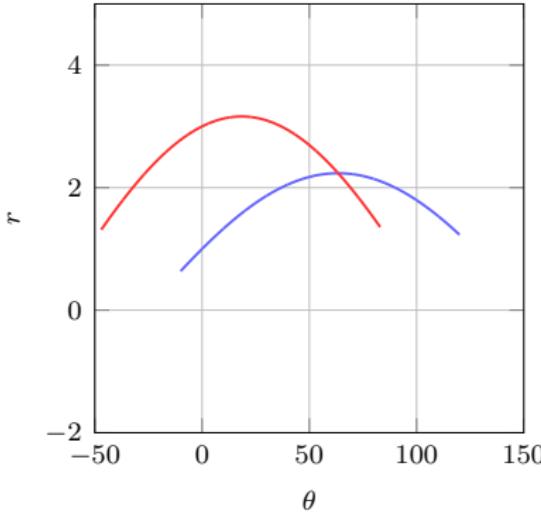
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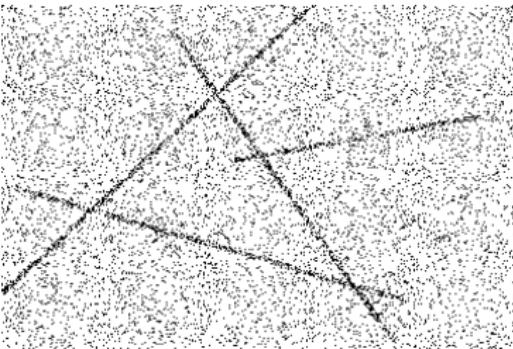
voting in parameter space



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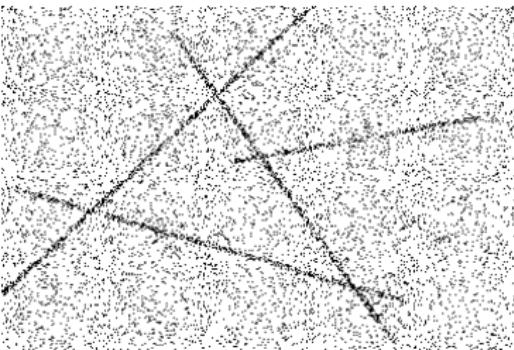
$$r = x_2 \cos(\theta) + y_2 \sin(\theta)$$

line detection

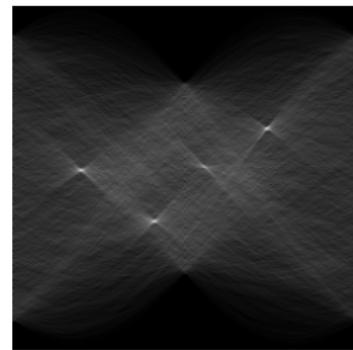


points

line detection

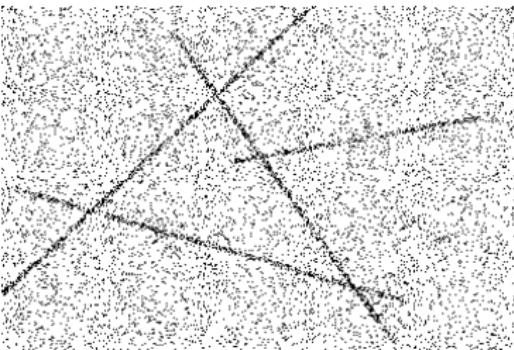


points

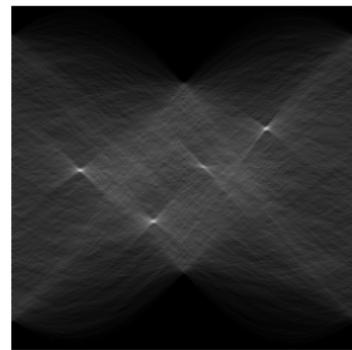


accumulator

line detection



points



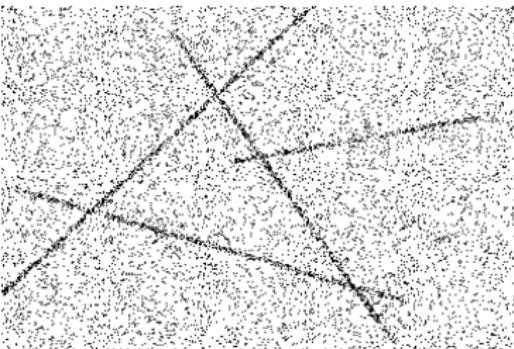
accumulator



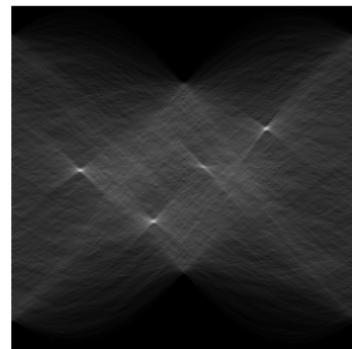
thresholding

Duda and Hart. CACM 1972 Use of the Hough Transformation to Detect Lines and Curves in pictures.

line detection



points

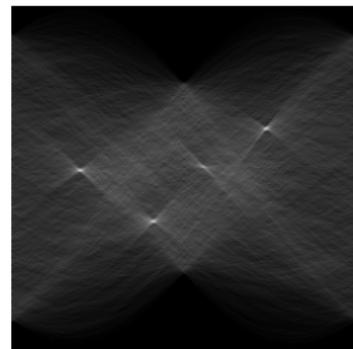
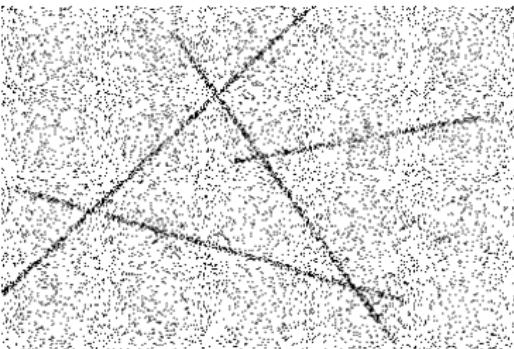


accumulator

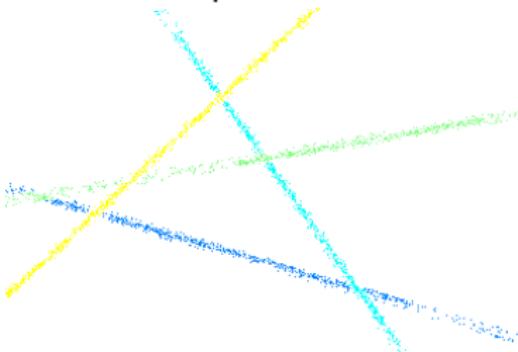


local maxima

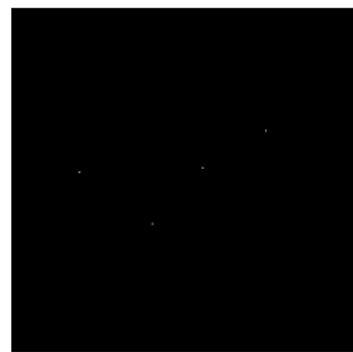
line detection



points



labels



local maxima

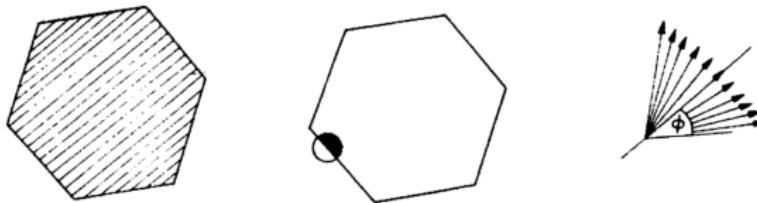
Duda and Hart. CACM 1972 Use of the Hough Transformation to Detect Lines and Curves in pictures.

Hough voting

- X : data
- n : number of model parameters
- A : n -dimensional accumulator array, initially zero
- **hypotheses**: for each sample $x \in X$
 - for each set of model parameters θ consistent with x
 - **voting**: increment $A[\theta]$
- “**verification**”:
 - threshold A , relative to maximum
 - **non-maxima suppression**: detect local maxima

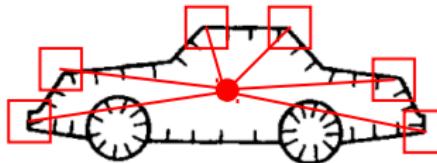
generalized Hough transform

[Ballard 1981]



- generalize to arbitrary shapes
- similarity transformation, 4d parameter space: translation \mathbf{d} , scaling s , rotation θ
- use gradient orientation to reduce number of votes per sample

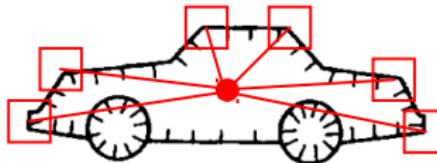
translation space



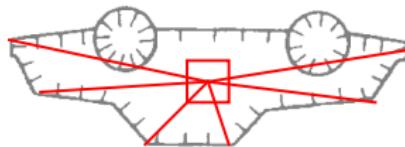
model image

- **model:** record coordinates relative to reference point
- **test:** each point votes for all possible coordinates of reference point, which are reversed

translation space



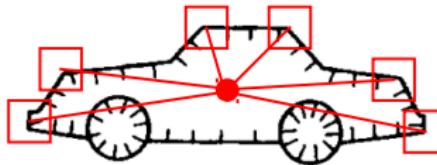
model image



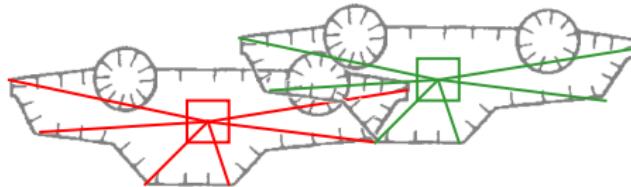
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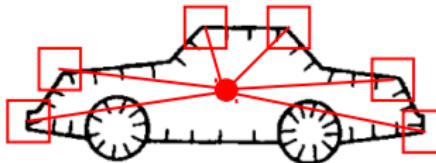
model image



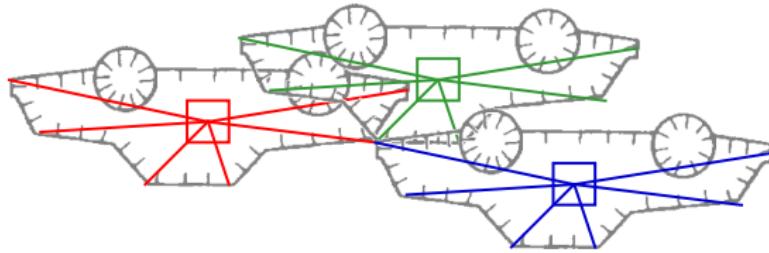
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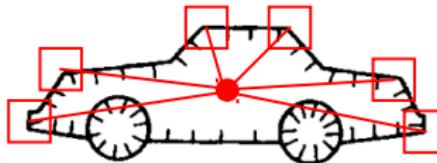
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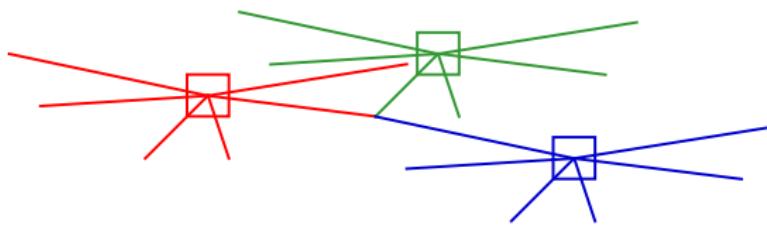
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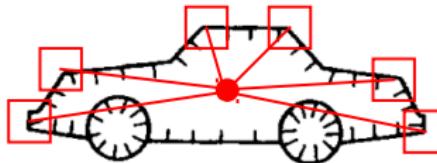
model image



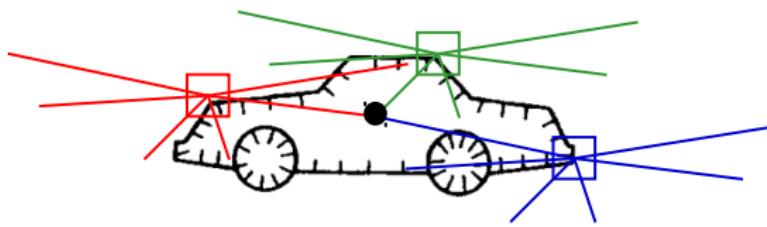
test image

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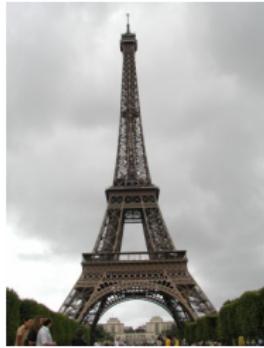
model image



test image

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Eiffel tower detection



model image



test image

Ballard. PR 1981. Generalizing the Hough Transform to Detect Arbitrary shapes.

Eiffel tower detection



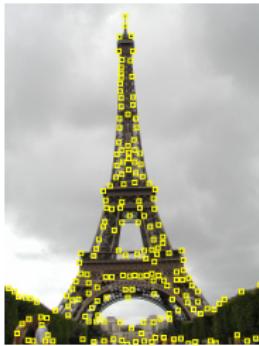
model image points



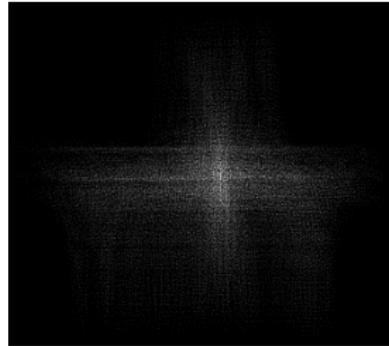
test image points

Ballard. PR 1981. Generalizing the Hough Transform to Detect Arbitrary shapes.

Eiffel tower detection



model image points



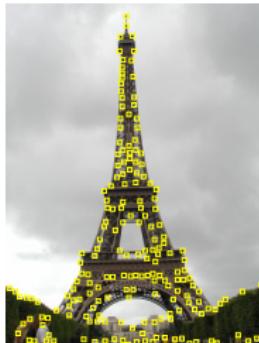
accumulator



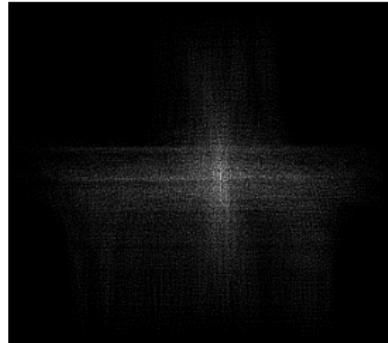
test image points

Ballard. PR 1981. Generalizing the Hough Transform to Detect Arbitrary shapes.

Eiffel tower detection



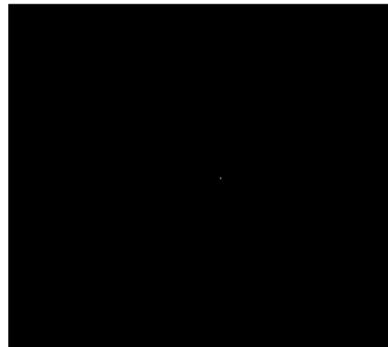
model image points



accumulator



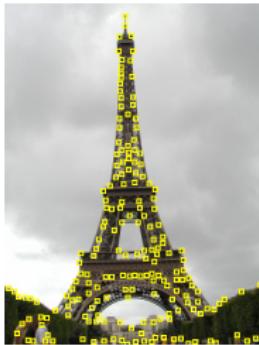
test image points



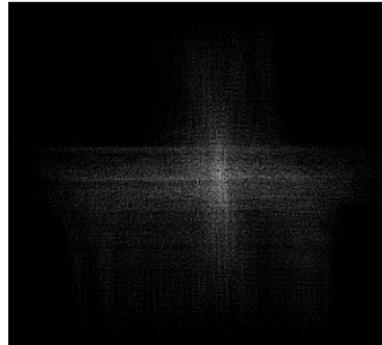
local maxima

Ballard. PR 1981. Generalizing the Hough Transform to Detect Arbitrary shapes.

Eiffel tower detection



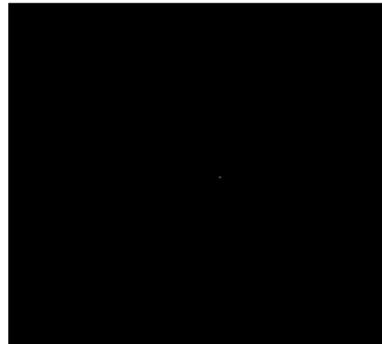
model image points



accumulator



detected location



local maxima

Ballard. PR 1981. Generalizing the Hough Transform to Detect Arbitrary shapes.

Hough is (sparse) cross-correlation

- model points H , test points X as signals

$$h[\mathbf{n}] = \sum_{\mathbf{h} \in H} \delta[\mathbf{n} - \mathbf{h}]$$

$$x[\mathbf{n}] = \sum_{\mathbf{x} \in X} \delta[\mathbf{n} - \mathbf{x}]$$

- for each test point $\mathbf{x} \in X$
 - for each translation $\mathbf{x} - \mathbf{h}$ consistent with \mathbf{x} (for $\mathbf{h} \in H$)
 - increment the count of $\mathbf{x} - \mathbf{h}$ in the accumulator
- in symbols

$$A = \sum_{\mathbf{x} \in X} \sum_{\mathbf{h} \in H} \delta[\mathbf{n} - (\mathbf{x} - \mathbf{h})]$$

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 - voting: increment accumulator A at $\mathbf{x} - \mathbf{h}$
- in symbols

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- for each test point $\mathbf{x} \in X$
 - for each translation $\mathbf{x} - \mathbf{h}$ consistent with \mathbf{x} (for $\mathbf{h} \in H$)
 - **voting**: increment accumulator A at $\mathbf{x} - \mathbf{h}$
- in symbols - try it!

$$A = \sum_{\mathbf{x} \in X} \sum_{\mathbf{h} \in H} \delta[\mathbf{n} - (\mathbf{x} - \mathbf{h})] = \sum_{\mathbf{k}} x[\mathbf{k}] h[\mathbf{k} - \mathbf{n}]$$

local shape

[Lowe 2004]

- a SIFT feature is determined by location, scale and orientation; a single feature correspondence can yield a 4-dof similarity transformation
- **hypotheses**: sparse Hough voting in 4-dimensional space; each correspondence casts a single vote in a hash table
- **verification**: on each bin with at least 3 votes, find inliers, form linear system $\mathbf{Ax} = \mathbf{b}$ and fit a 6-dof affine transformation by least-squares

$$\mathbf{x} = (\mathbf{A}^\top \mathbf{A})^{-1} \mathbf{A}^\top \mathbf{b}$$

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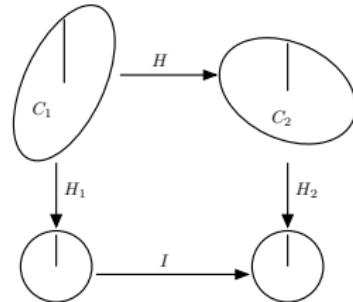
object recognition



local shape

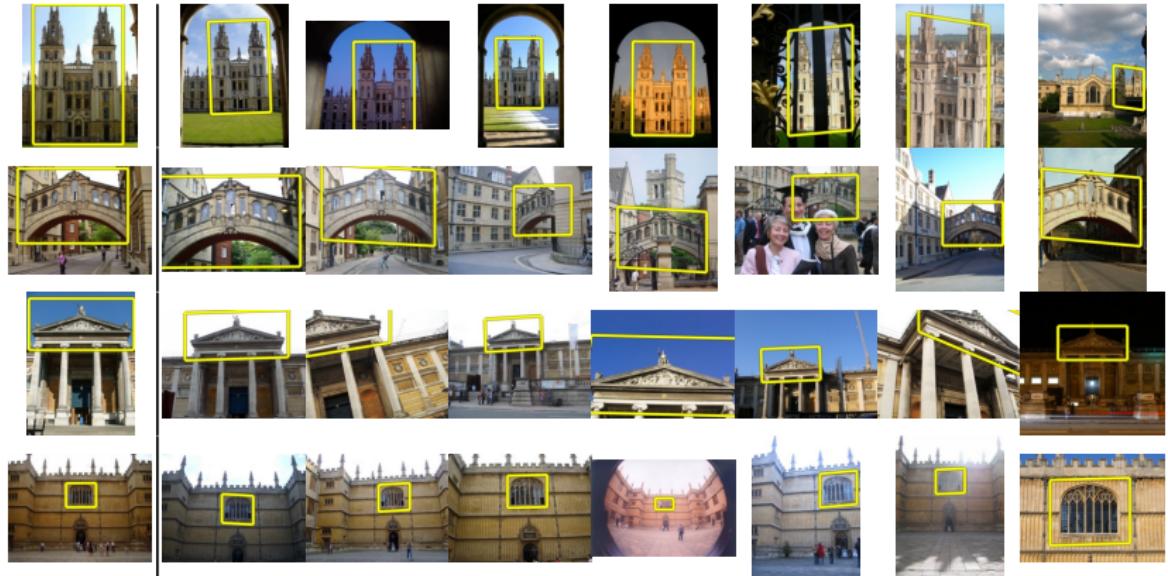
[Philbin et al. 2007]

Transformation	dof	Matrix
translation + isotropic scale	3	$\begin{bmatrix} a & 0 & t_x \\ 0 & a & t_y \end{bmatrix}$
translation + anisotropic scale	4	$\begin{bmatrix} a & 0 & t_x \\ 0 & b & t_y \end{bmatrix}$
translation + vertical shear	5	$\begin{bmatrix} a & 0 & t_x \\ b & c & t_y \end{bmatrix}$



- same idea, a single feature correspondence can yield a transformation that can be 3,4,5-dof
- but now use ransac where there is only one hypothesis per correspondence; all hypotheses can be enumerated and verified
- again, 6-dof fitting on inliers in the end
- so Hough can be seen as filtering of hypotheses by agreement

object retrieval



- image retrieval based on a bag-of-words representation
- fast spatial verification performed on top-ranking images

summary

- derivatives as convolution
- edges: gradient magnitude and Laplacian
- scale-space and scale selection
- blobs: normalized Laplacian
- corners/junctions: windowed second moment matrix
- dense registration / sparse feature tracking
- wide-baseline matching by local features
- robust fitting: ransac, Hough
- Hough as cross-correlation
- local shape for global transformation hypotheses