计算机视觉-早期视觉：关键点检测

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关键点提取（角点）Keypoint extraction: Corners

为什么提取关键点 Why extract keypoints?

- **Motivation: panorama stitching 全景图拼接**
  - We have two images – how do we combine them?

Why extract keypoints?

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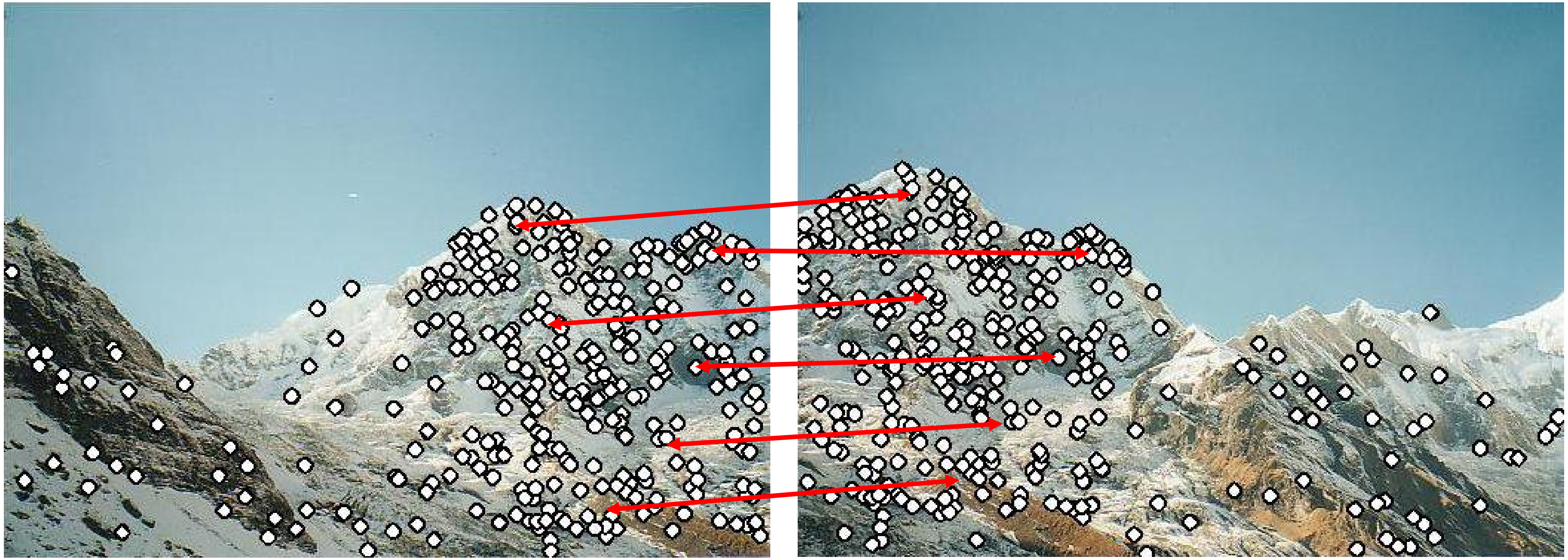


Step 1: extract keypoints 提取关键点

Step 2: match keypoint features 匹配关键点

Why extract keypoints?

- **Motivation: panorama stitching 全景图拼接**
  - We have two images – how do we combine them?

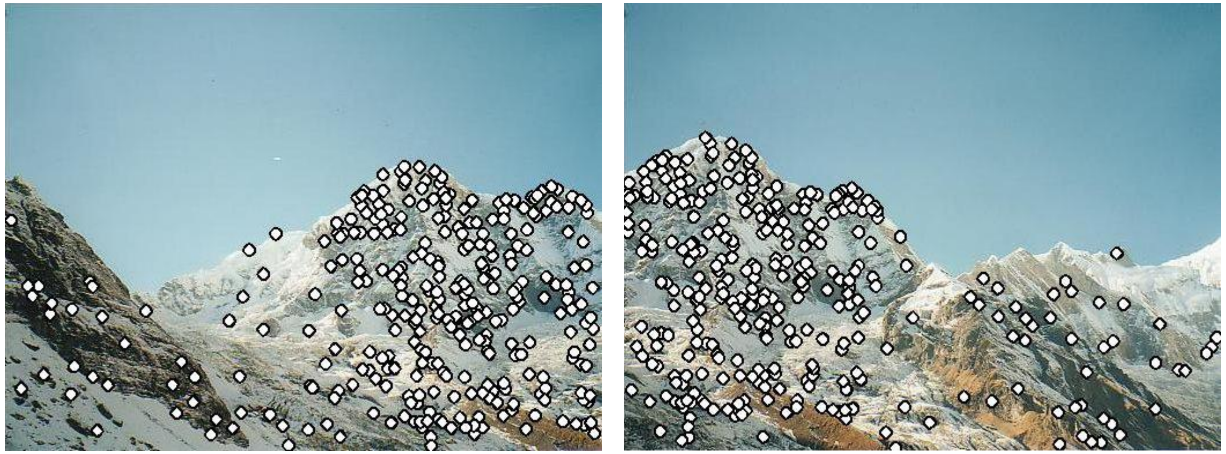
Step 1: extract keypoints

Step 2: match keypoint features

Step 3: align images

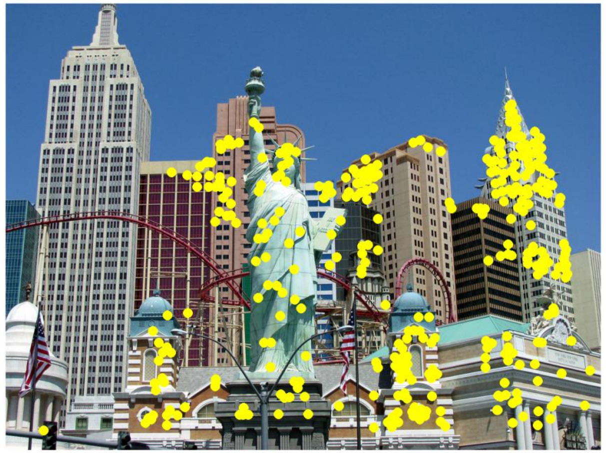
好的关键点 Characteristics of good keypoints

- **紧致 & 高效 Compactness and efficiency**
  - Many fewer keypoints than image pixels 关键点数目比像素少很多
- **显著性 Saliency**
  - Each keypoint is distinctive 关键点是独特的、有特色的
- **局部特性 Locality**
  - A keypoint occupies a relatively small area of the image; robust to clutter and occlusion
- **重复性/再现性 Repeatability**
  - The same keypoint can be found in several images despite geometric and photometric transformations
  - 无论几何或光学变换，
    同一关键点都能被检测到



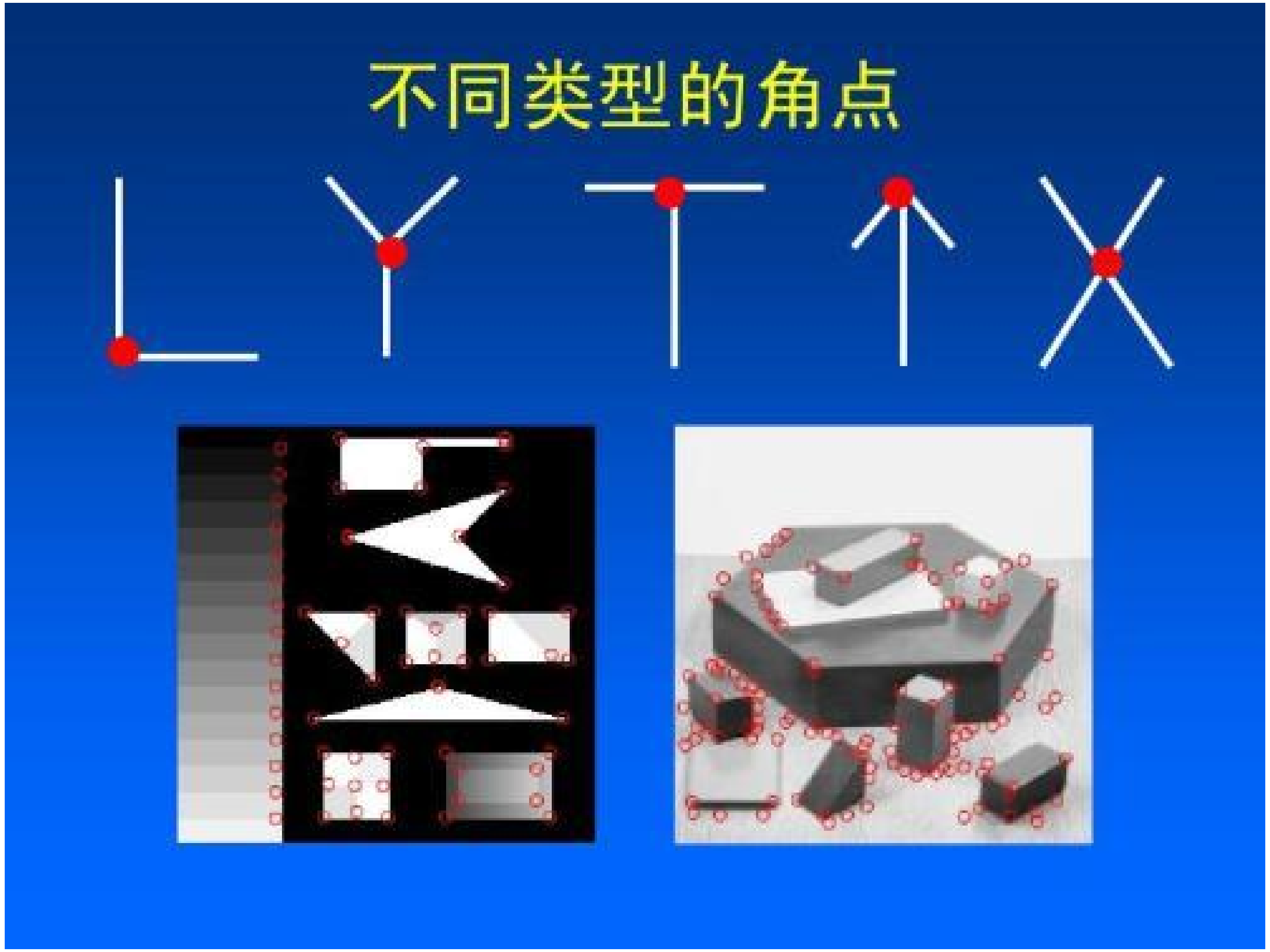
应用 Applications

- **Keypoints are used for:**
  - Image alignment 对齐
  - 3D reconstruction 三维重建
  - Motion tracking 运动跟踪
  - Robot navigation 机器人导航
  - Database indexing and retrieval 数据库检索
  - Object recognition 目标识别



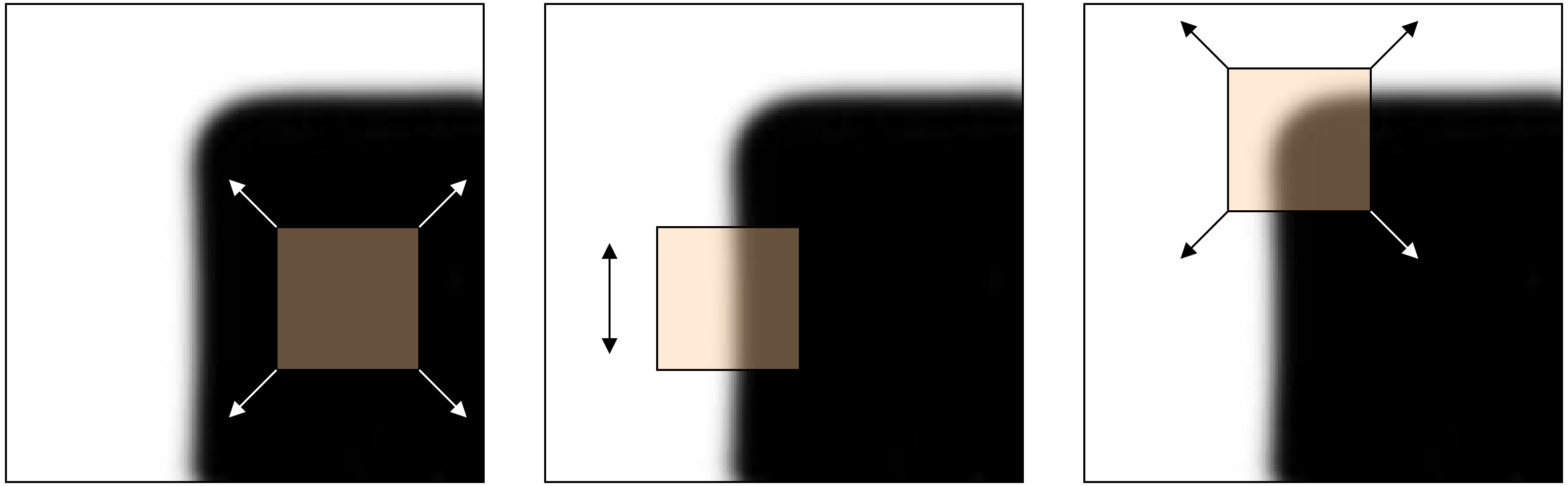
Corner detection: Basic idea
角点检测：基本思想

角点 Corner



角点检测 Corner detection: Basic idea

- **We should easily recognize the point by looking through a small window 在小窗口中就可以很容易识别出**
- **Shifting a window in *any direction* should give *a large change* in intensity 在任意方向移动，强度都应该变化巨大**



"flat" region:
no change in all directions

"edge":
no change along the edge direction

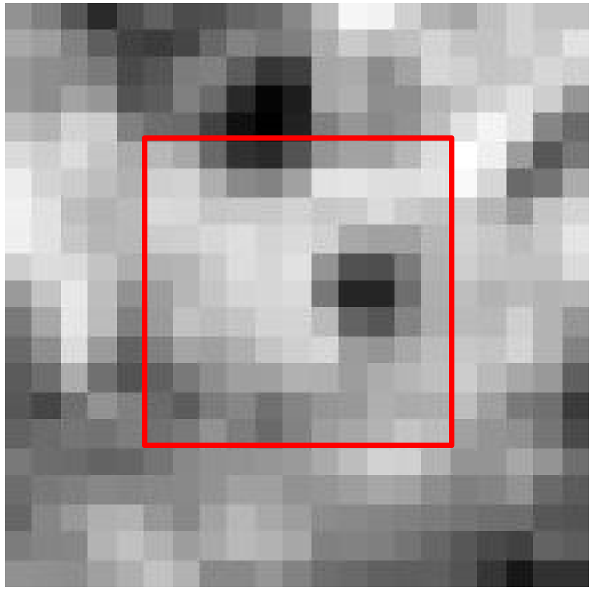
"corner":
significant change in all directions

角点检测 Corner Detection: Derivation

- **Change in appearance of window *W* for the shift [*u*,*v*]:**

$$E(u,v) = \sum_{(x,y)\in W} [I(x+u, y+v) - I(x,y)]^2$$

$I(x, y)$



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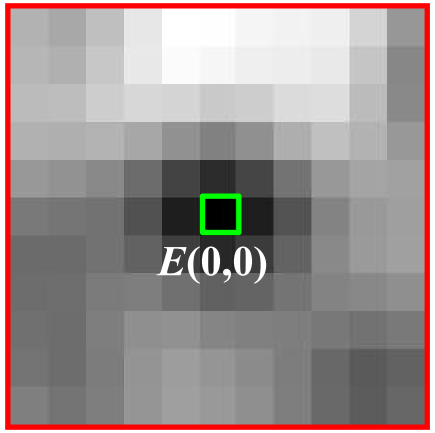

角点检测 Corner Detection: Derivation

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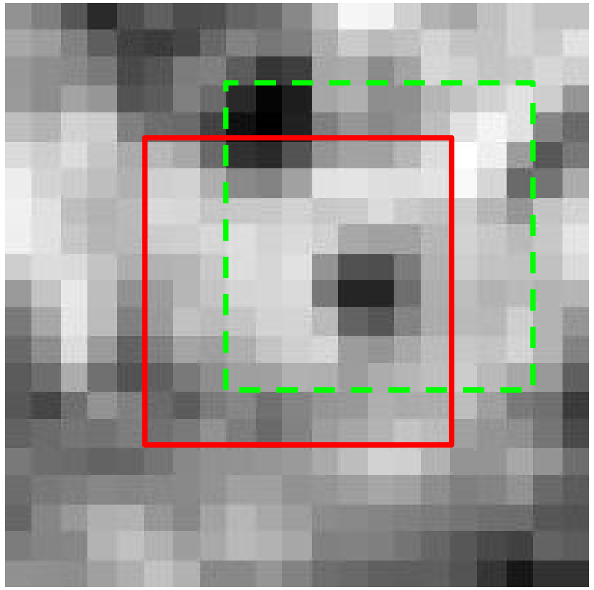

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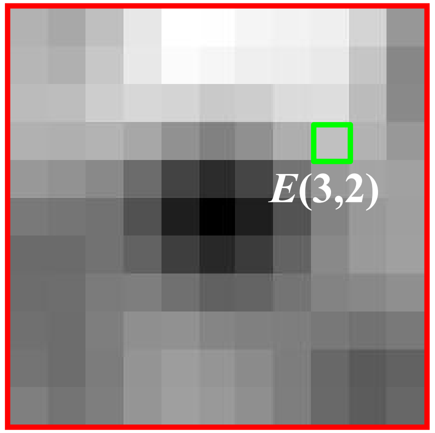


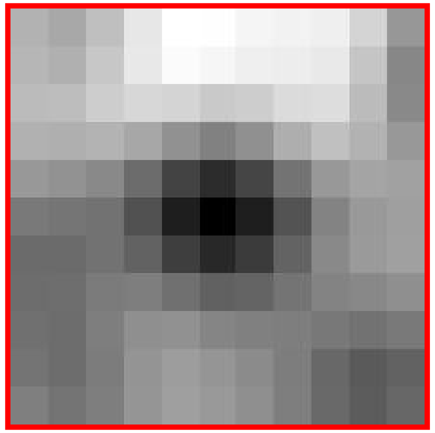
角点检测 Corner Detection: Derivation

- **Change in appearance of window *W* for the shift [*u*,*v*]:**

$$E(u,v) = \sum_{(x,y)\in W} [I(x+u, y+v) - I(x,y)]^2$$

- **We want to find out how this function behaves for small shifts**
  - 小幅移动时该函数的表现

$E(u, v)$



Corner Detection: Derivation

- **First-order Taylor approximation for small motions [u, v]:**

$$I(x+u, y+v) \approx I(x,y) + I_x u + I_y v$$

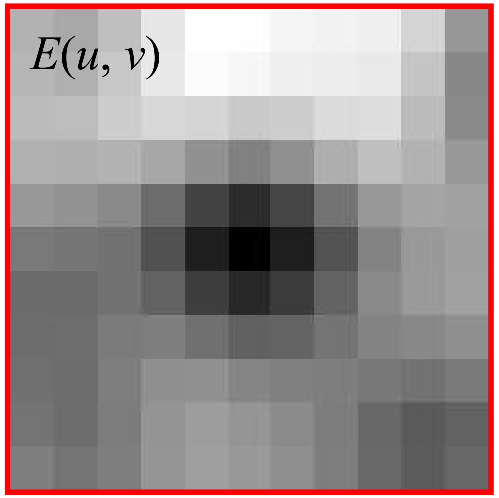
- **Let's plug this into $E(u,v)$:**

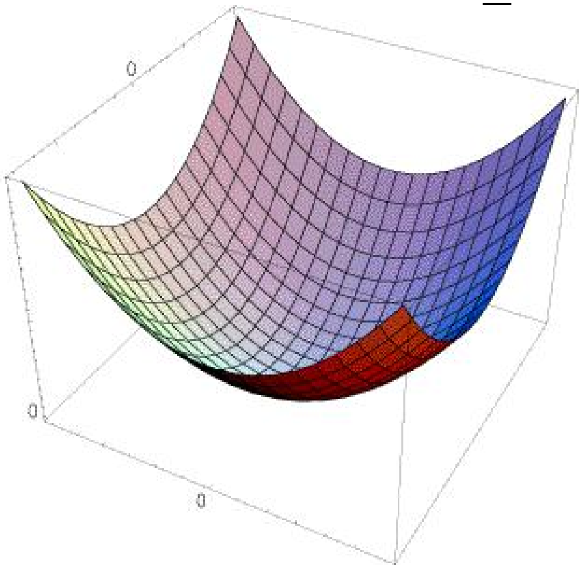
$$E(u,v) = \sum_{(x,y)\in W} [I(x+u, y+v) - I(x,y)]^2$$

Corner Detection: Derivation

•*E*(*u*,*v*) can be locally approximated by a quadratic surface:

$$E(u,v) \approx u^2 \sum_{x,y} I_x^2 + 2uv \sum_{x,y} I_x I_y + v^2 \sum_{x,y} I_y^2$$





In which directions does this surface have the fastest/slowest change?

Corner Detection: Derivation

- *E*(*u*,*v*) can be locally approximated by a quadratic surface:

$$E(u,v) \approx u^2 \sum_{x,y} I_x^2 + 2uv \sum_{x,y} I_x I_y + v^2 \sum_{x,y} I_y^2$$

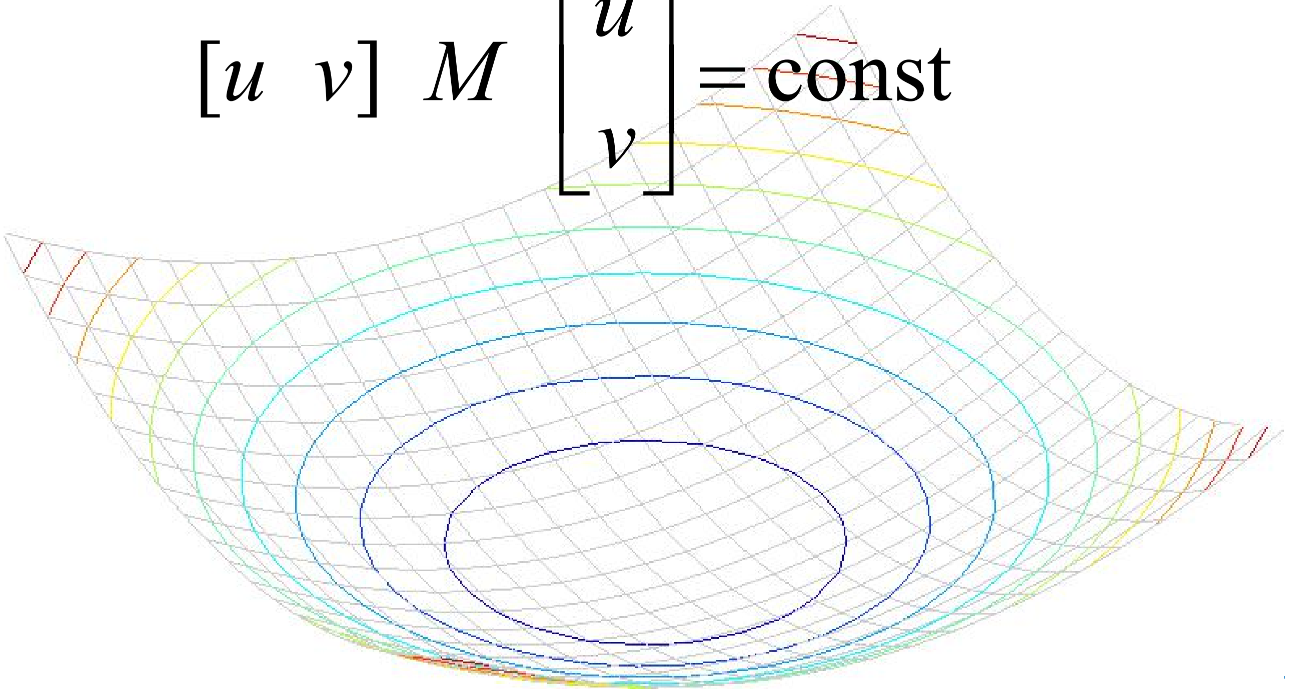
$$= \begin{bmatrix} u & v \end{bmatrix} \begin{bmatrix} \sum_{x,y} I_x^2 & \sum_{x,y} I_x I_y \\ \sum_{x,y} I_x I_y & \sum_{x,y} I_y^2 \end{bmatrix} \begin{bmatrix} u \\ v \end{bmatrix}$$

Second moment matrix M

Interpreting the second moment matrix

A horizontal "slice" of *E*(*u*, *v*) is given by the equation of an ellipse:

$$[u \;\; v] \;\; M \begin{bmatrix} u \\ v \end{bmatrix} = \text{const}$$



Interpreting the second moment matrix

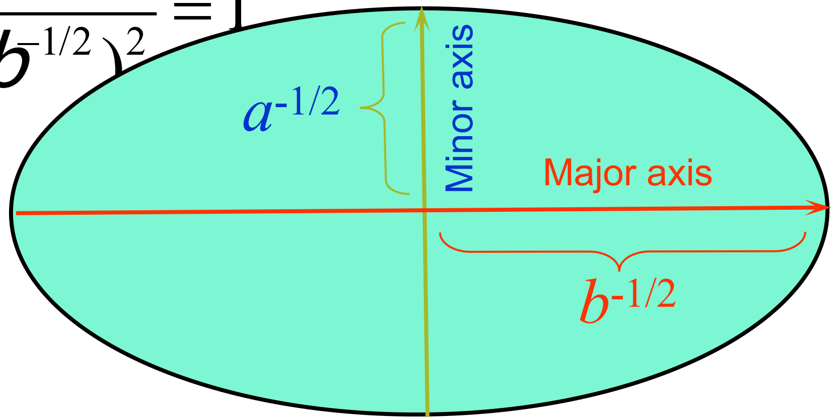
Consider the axis-aligned case (gradients are either horizontal or vertical):

$$M = \begin{bmatrix} \sum_{x,y} I_x^2 & \sum_{x,y} I_x I_y \\ \sum_{x,y} I_x I_y & \sum_{x,y} I_y^2 \end{bmatrix}$$

$$\left[u \; v\right] \begin{bmatrix} a \\ 0 \end{bmatrix} = 1$$

$$au^2 + bv^2 = 1$$

$$\frac{u^2}{(a^{-1/2})^2} + \frac{v^2}{(b^{-1/2})^2} = 1$$



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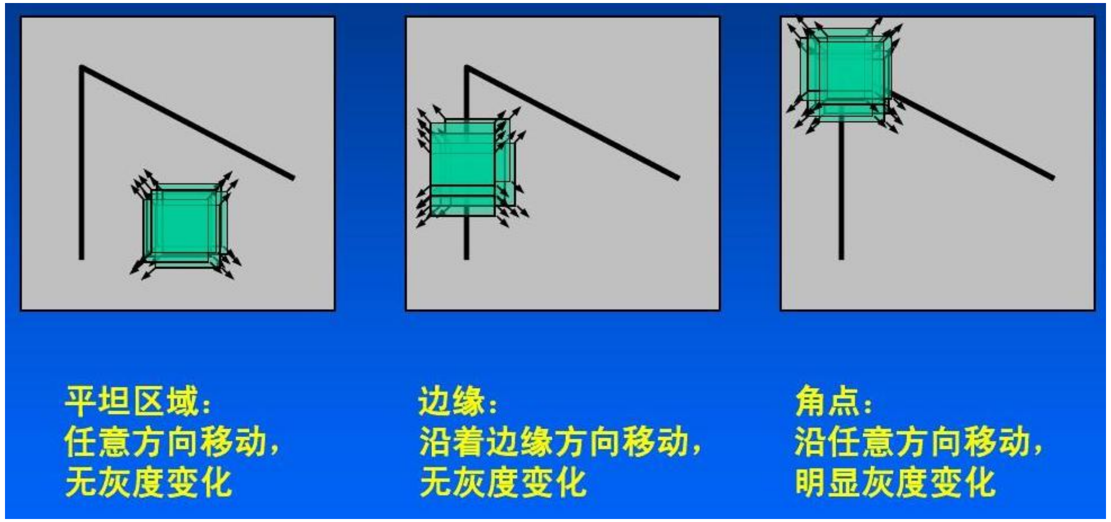


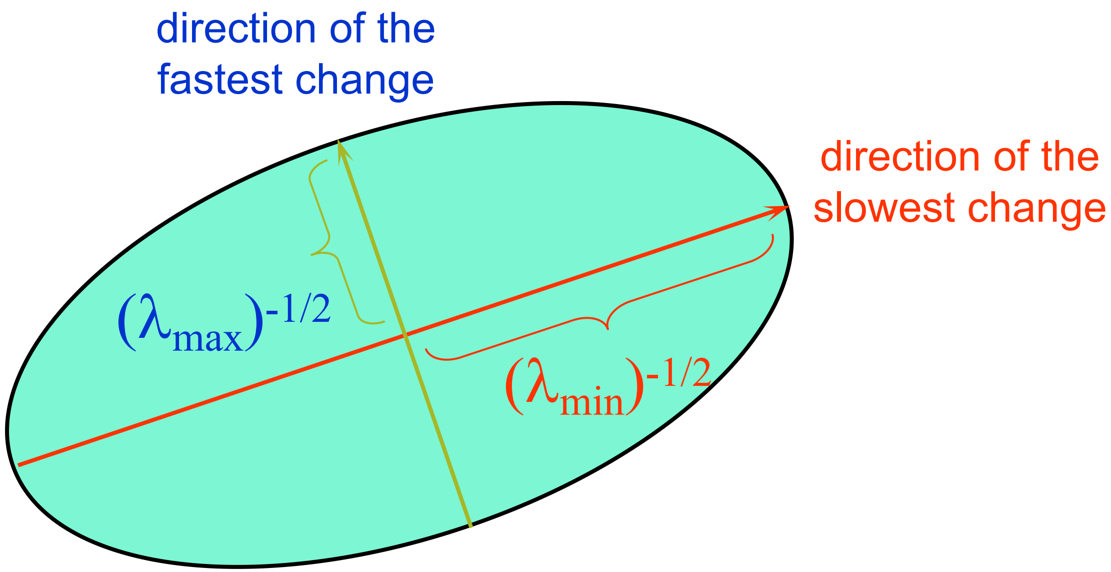
If either *a* or *b* is close to 0, then this is **not** a corner, so we want locations where both are large

Interpreting the second moment matrix

- 对角化 In the general case, need to *diagonalize* M:

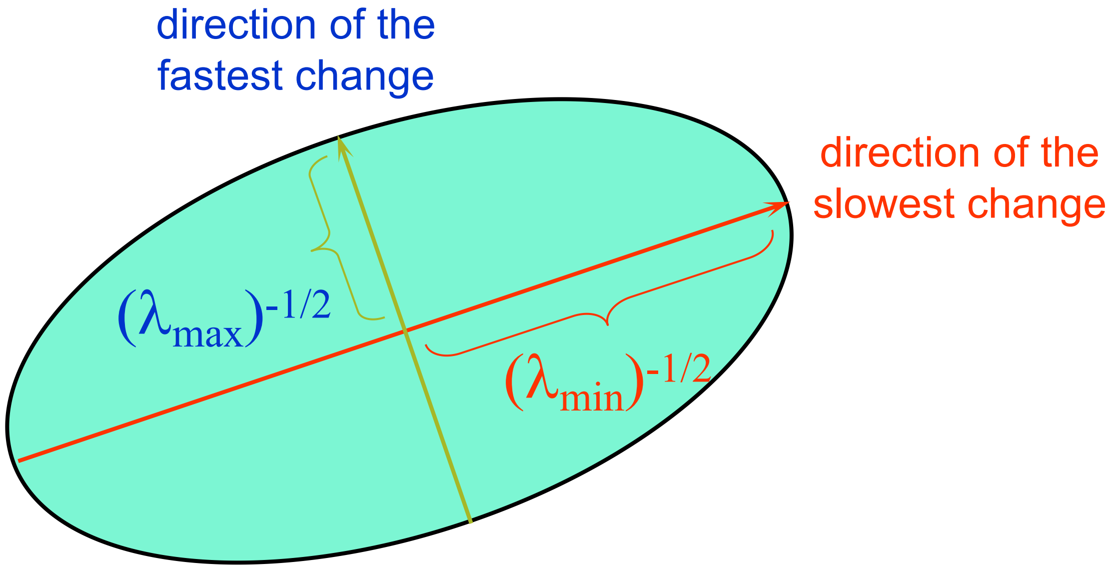
$$M = R^{-1}\begin{bmatrix} \lambda_1 & 0 \\ 0 & \lambda_2 \end{bmatrix} R$$

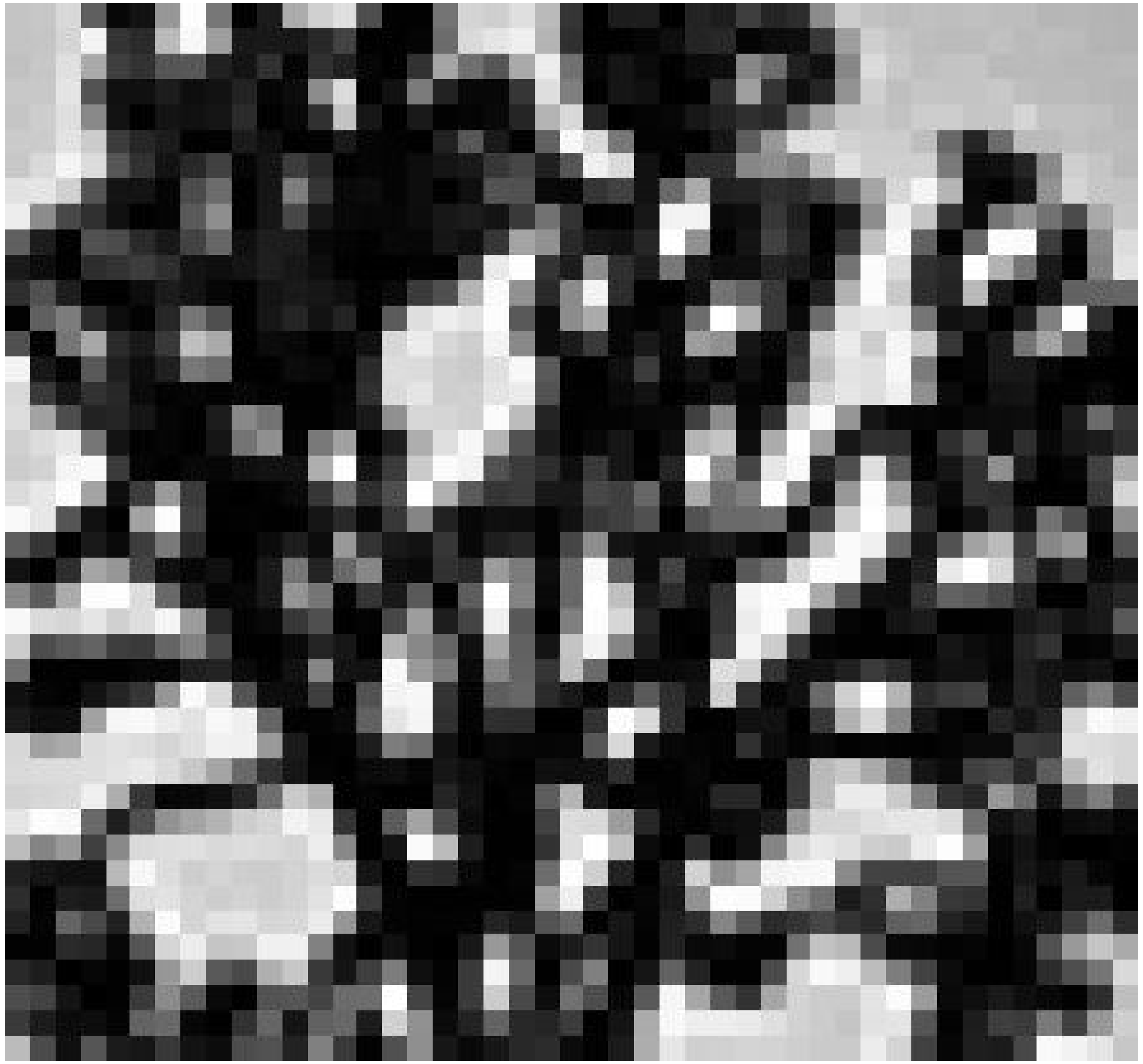
- 特征值决定椭圆轴距，R决定方向The axis lengths of the ellipse are determined by the eigenvalues and the orientation is determined by *R*:



Visualization of second moment matrices

$$M = \begin{bmatrix} \sum_{x,y} I_x^2 & \sum_{x,y} I_x I_y \\ \sum_{x,y} I_x I_y & \sum_{x,y} I_y^2 \end{bmatrix} = \begin{bmatrix} a & 0 \\ 0 & b \end{bmatrix}$$





Visualization of second moment matrices

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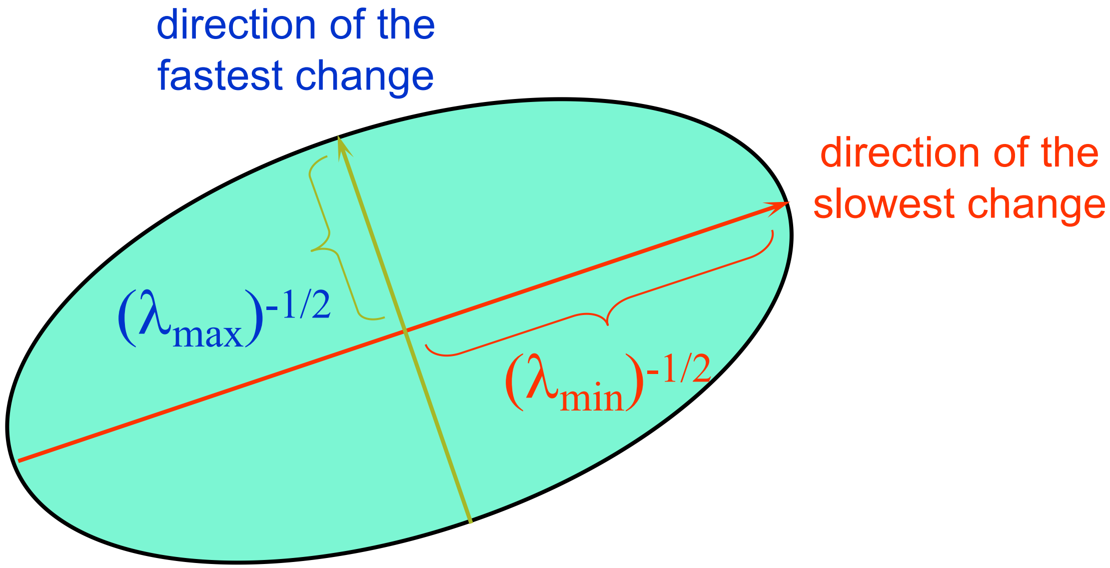
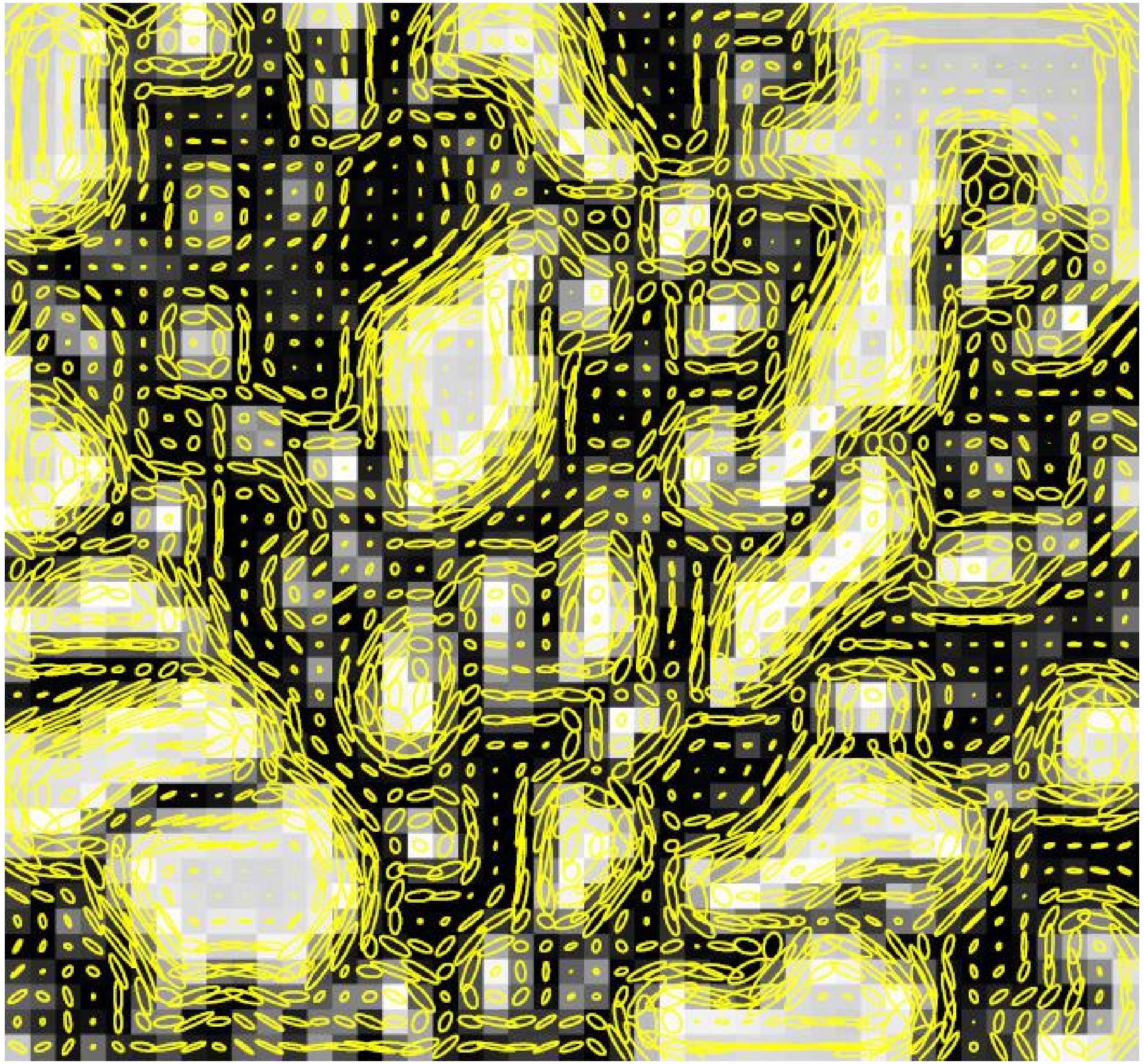
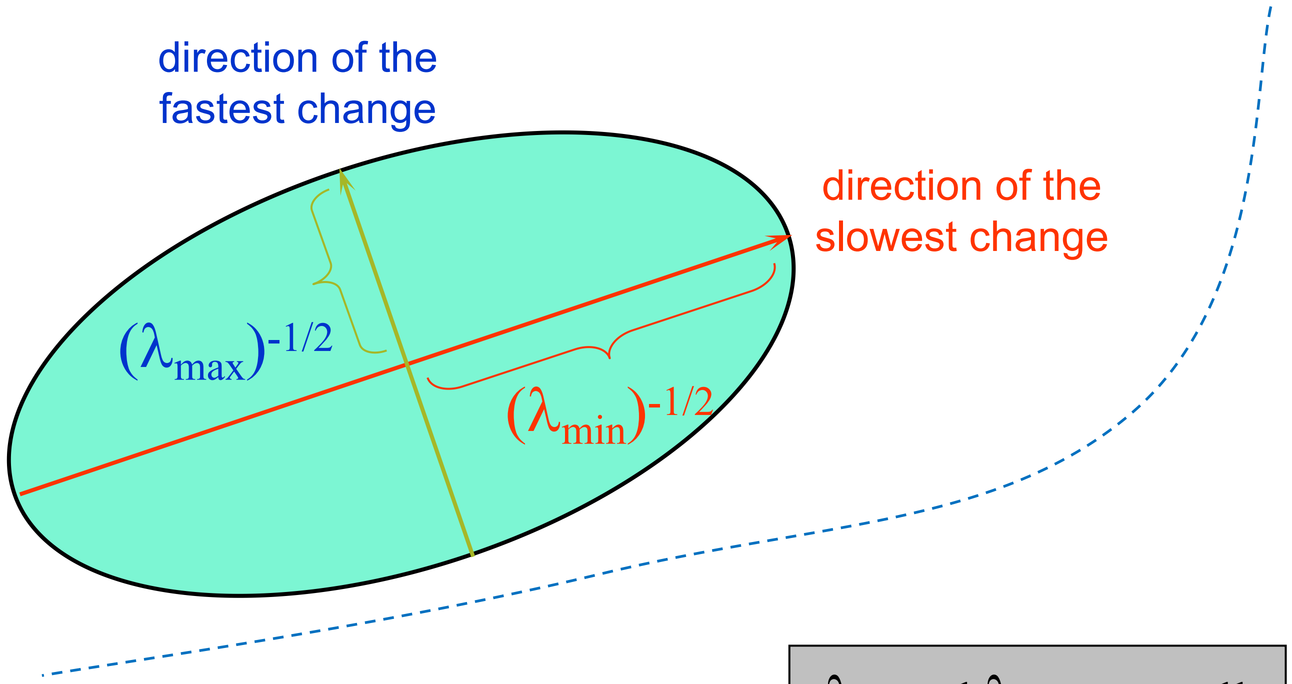


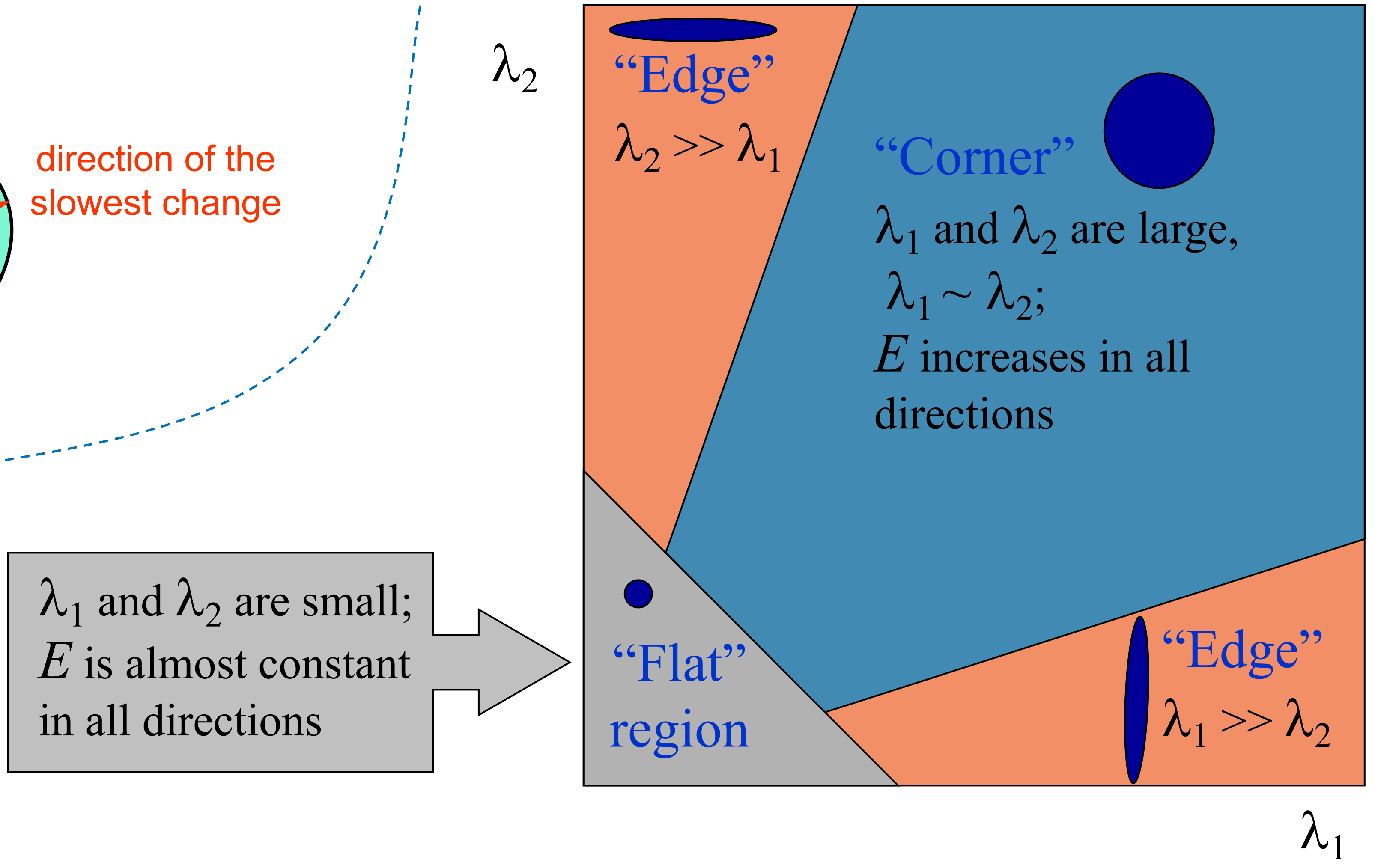


Interpreting the eigenvalues

- **Classification of image points using eigenvalues of *M*:**

$$M = R^{-1}\begin{bmatrix} \lambda_1 & 0 \\ 0 & \lambda_2 \end{bmatrix} R$$





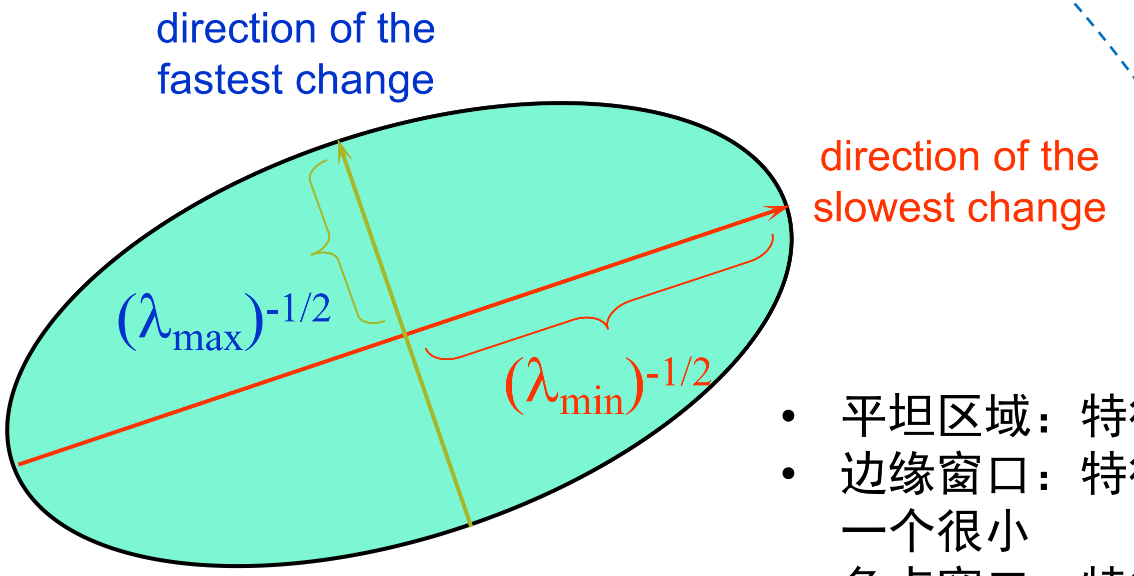
- 平坦区域：特征值都非常小
- 边缘窗口：特征值一个很大，一个很小
- 角点窗口：特征值都很大

Corner response function

$$R = \det(M) - \alpha\,\mathrm{trace}(M)^2 = \lambda_1\lambda_2 - \alpha(\lambda_1 + \lambda_2)^2$$

α: constant (0.04 to 0.06)

$$M = R^{-1}\begin{bmatrix}\lambda_1 & 0 \\ 0 & \lambda_2\end{bmatrix}R$$



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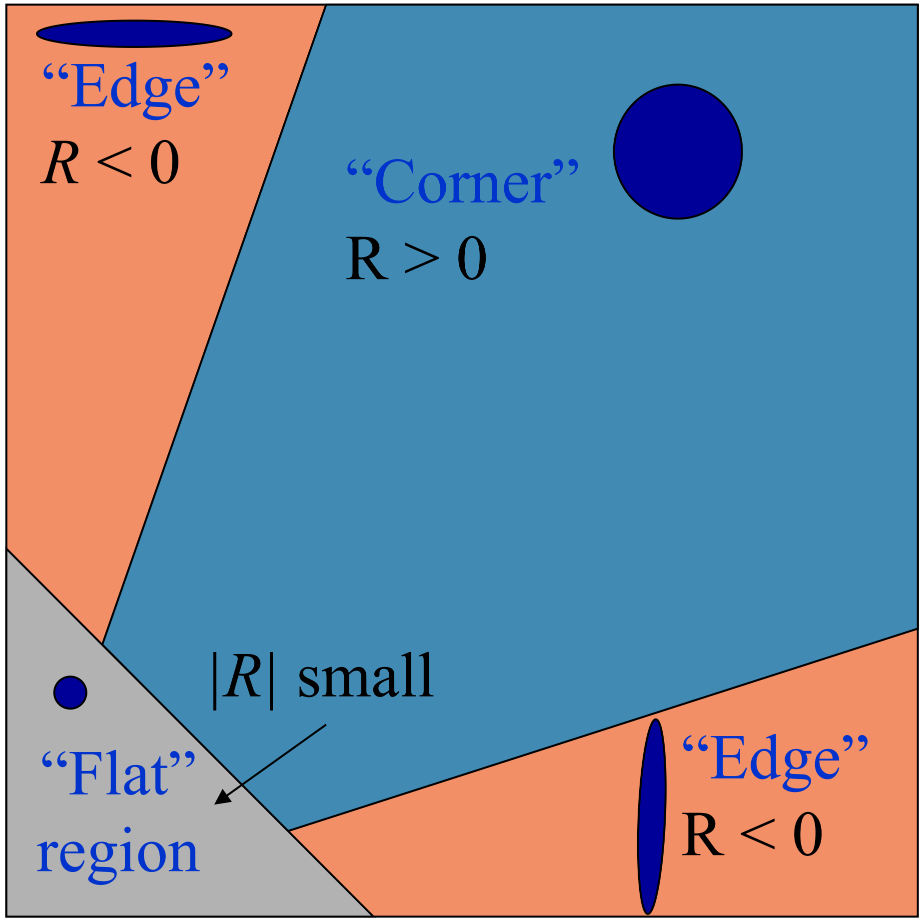

Harris 角点检测算子 The Harris corner detector

1. **计算偏导 Compute partial derivatives at each pixel**
2. **计算局部二阶矩矩阵 Compute second moment matrix *M* in a Gaussian window around each pixel:**

$$M = \begin{bmatrix} \sum_{x,y} w(x,y) I_x^2 & \sum_{x,y} w(x,y) I_x I_y \\ \sum_{x,y} w(x,y) I_x I_y & \sum_{x,y} w(x,y) I_y^2 \end{bmatrix}$$

C.Harris and M.Stephens, A Combined Corner and Edge Detector, *Proceedings of the 4th Alvey Vision Conference*: pages 147—151, 1988.

The Harris corner detector

1. **计算偏导 Compute partial derivatives at each pixel**
2. **计算局部二阶矩矩阵 Compute second moment matrix M in a Gaussian window around each pixel:**
3. **计算角点响应函数 Compute corner response function R**

$$M = \begin{bmatrix} \sum_{x,y} w(x,y) I_x^2 & \sum_{x,y} w(x,y) I_x I_y \\ \sum_{x,y} w(x,y) I_x I_y & \sum_{x,y} w(x,y) I_y^2 \end{bmatrix}$$

$$R = \det(M) - \alpha\, \mathrm{trace}(M)^2 = \lambda_1 \lambda_2 - \alpha(\lambda_1 + \lambda_2)^2$$

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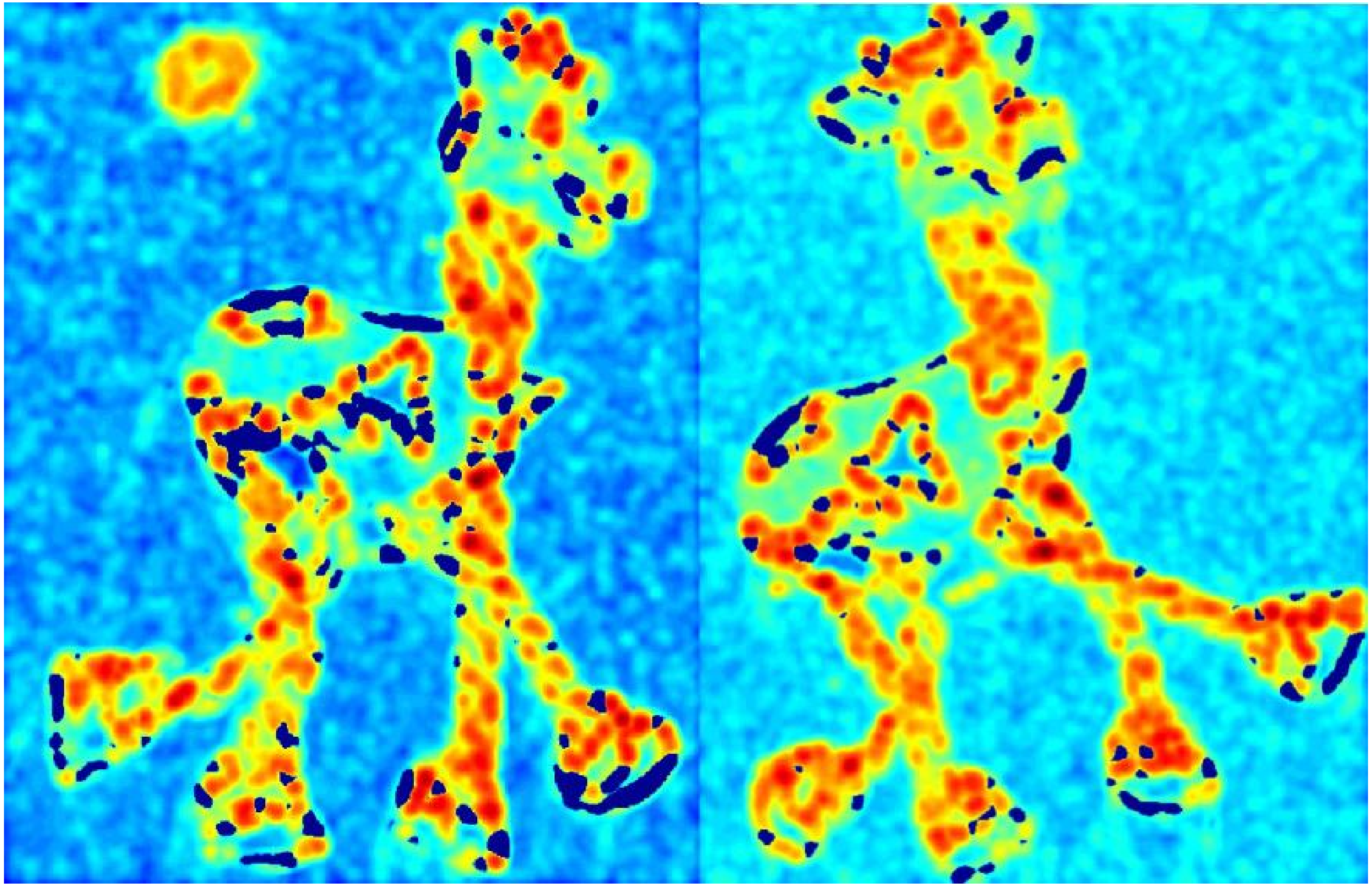
Harris Detector: Steps

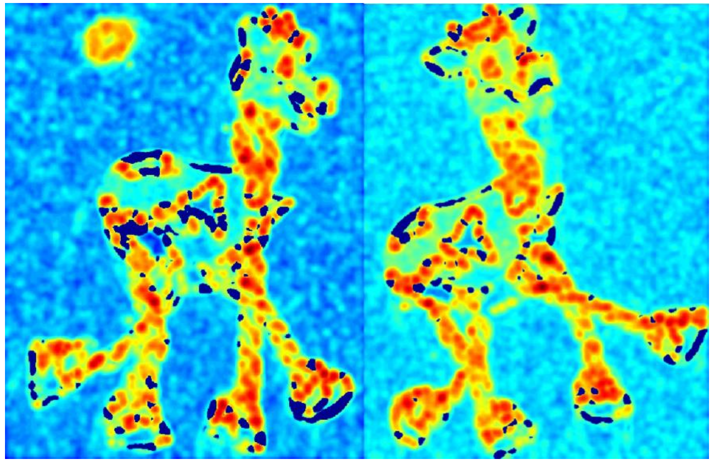
Harris Detector: Steps

Compute corner response R



The Harris corner detector

1. 计算偏导 Compute partial derivatives at each pixel
2. 计算局部二阶矩矩阵 Compute second moment matrix M in a Gaussian window around each pixel:
3. 计算角点响应函数 Compute corner response function R
4. 阈值过滤 Threshold R
5. 局部最大值 Find local maxima of response function (nonmaximum suppression)



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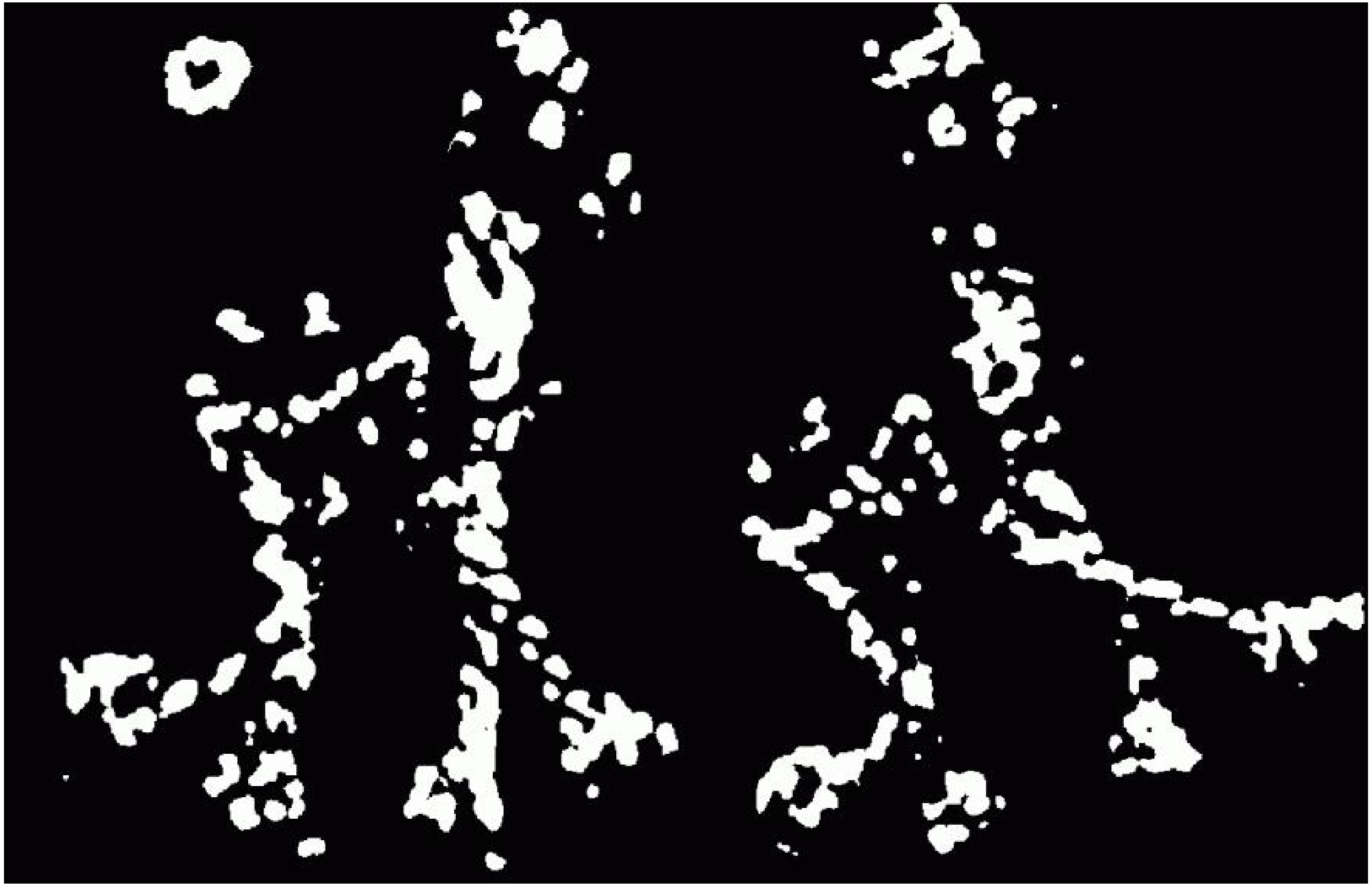
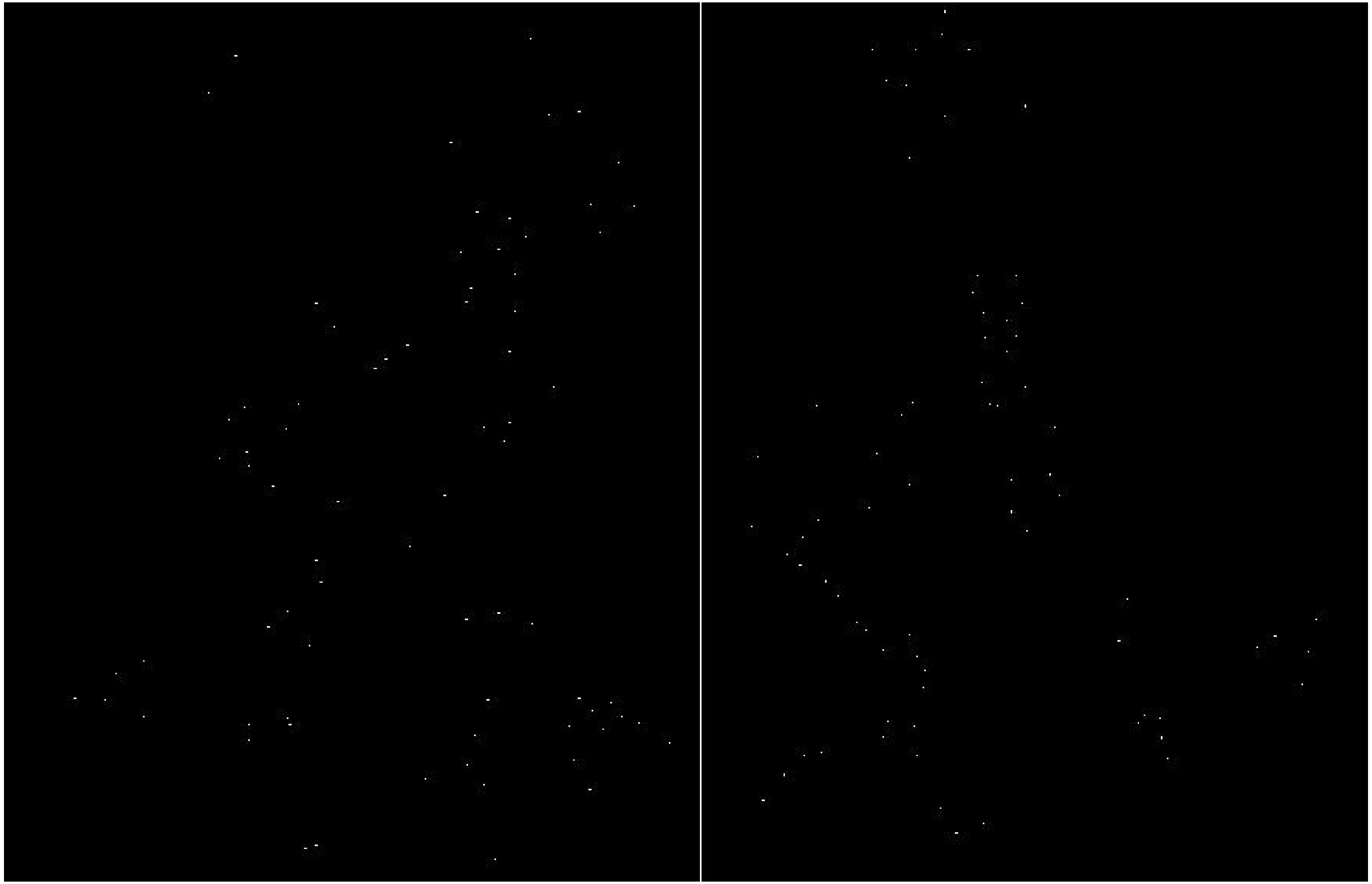
Harris Detector: Steps

Find points with large corner response: R > threshold



Harris Detector: Steps

Take only the points of local maxima of R

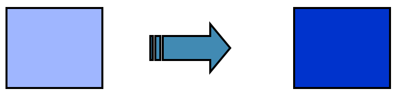


Harris Detector: Steps

角点特征的鲁棒性 Robustness of corner features

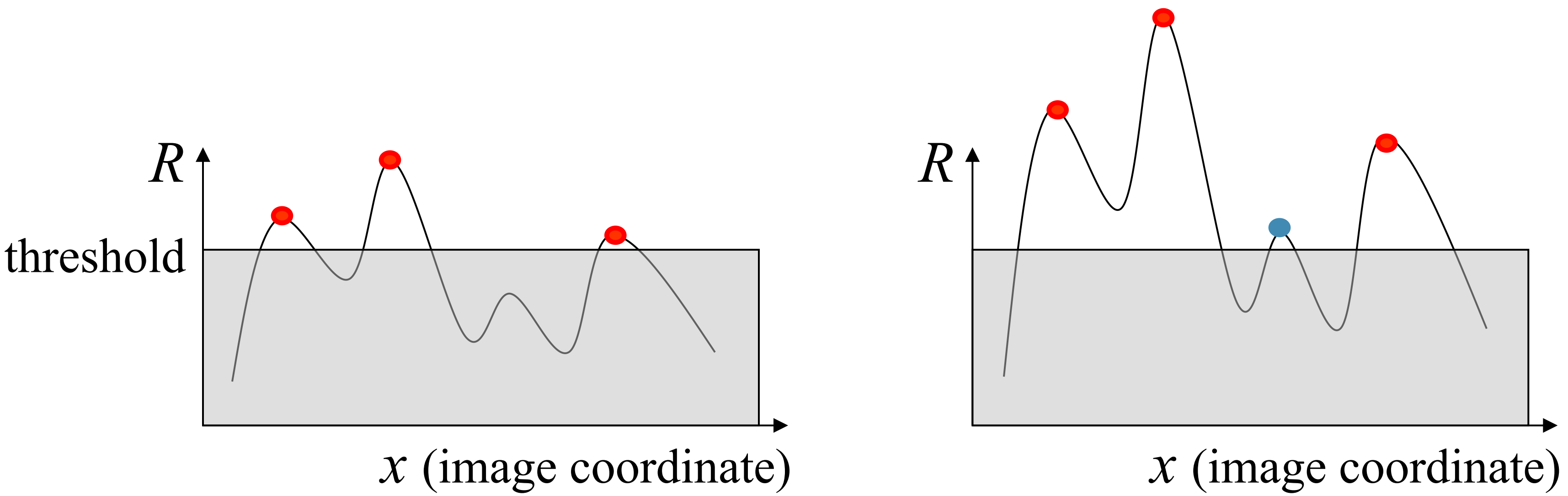
- What happens to corner features when the image undergoes geometric or photometric transformations? **当图像发生几何或光学变换时，角点特征?**

Affine intensity change



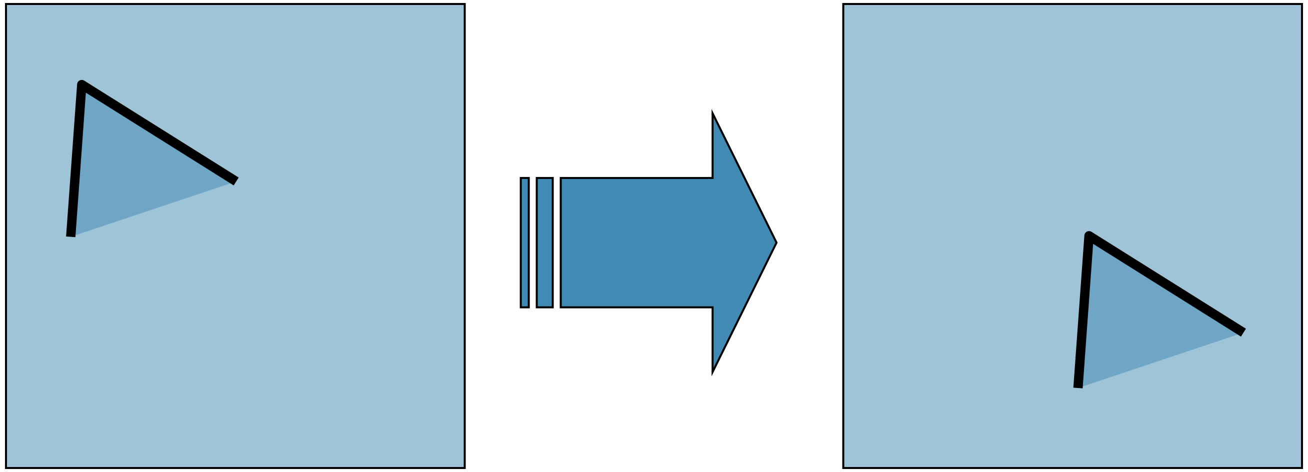
$$I \rightarrow a\,I + b$$

- **Only derivatives are used, so invariant to intensity shift $I \rightarrow I + b$**
  - 只利用了梯度，多一对于亮度偏移具有不变性
- **Intensity scaling: $I \rightarrow a\,I$**



亮度变化部分不变性 *Partially invariant* to affine intensity change

Image translation

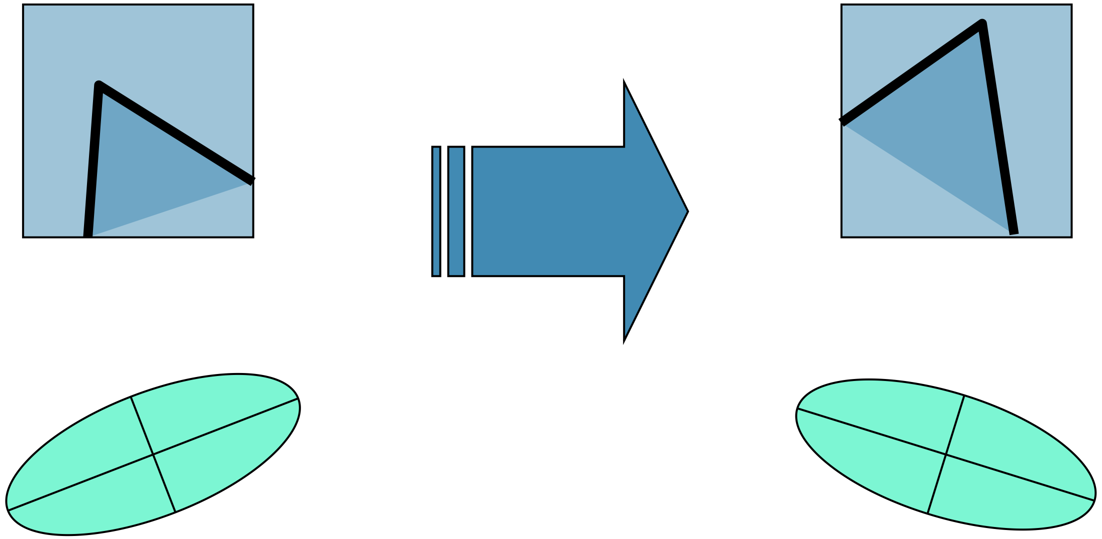


- Derivatives and window function are shift-invariant

Corner location is *covariant* w.r.t. translation

与平移协变

Image rotation

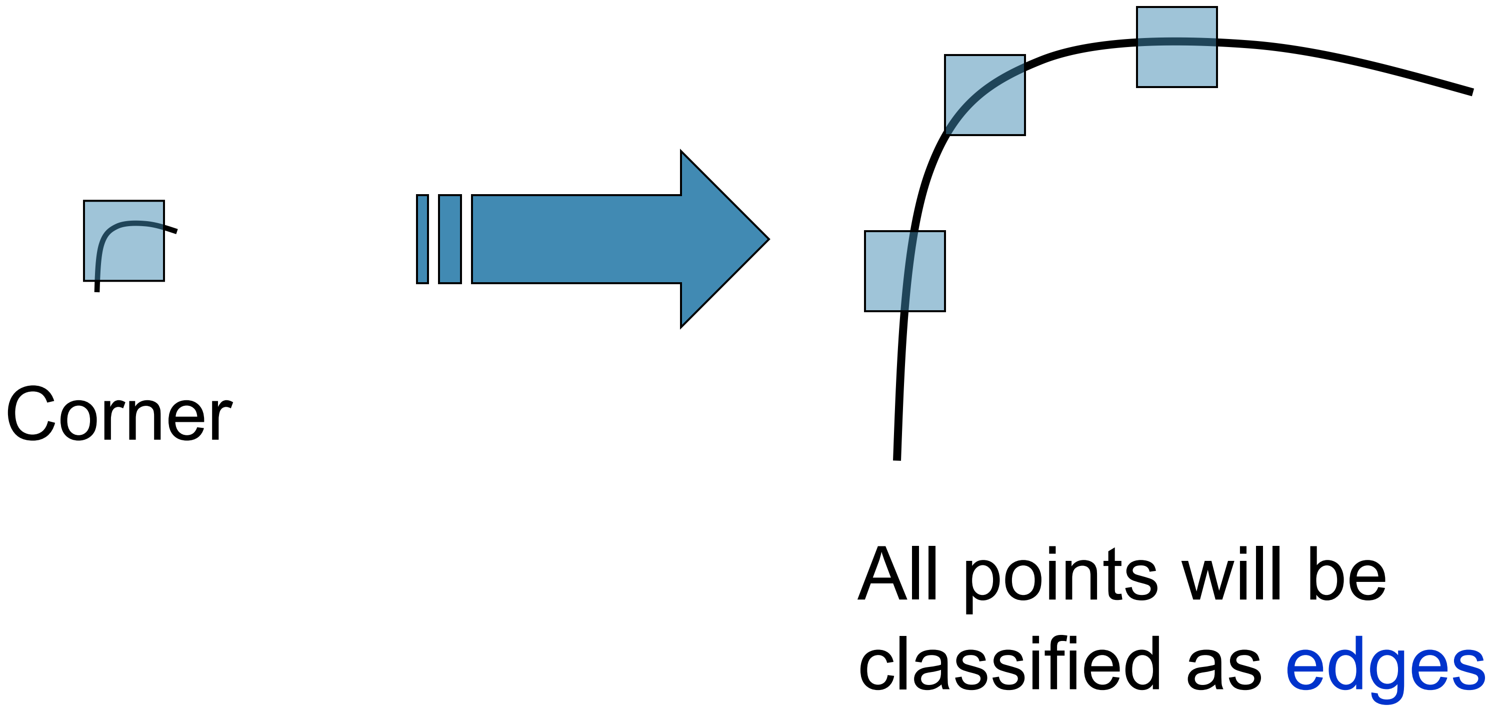


Second moment ellipse rotates but its shape (i.e. eigenvalues) remains the same
二阶矩椭圆旋转但形状（特征值）保持不变

Corner location is covariant w.r.t. rotation

与旋转协变

Scaling



Corner location is not covariant w.r.t. scaling!

与尺度不协变

Summary

- 角点 Corner