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CMT10 Visual Computing

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Stereo Vision
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School of Computer Science and Informatics
Cardiff University

Overview

- Stereo Vision
 - Multi-view geometry problem
- Triangulation
- Epipolar Geometry
 - The epipolar constraint
 - Essential matrix and fundamental matrix
 - Eight-point algorithm

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Acknowledgement

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Stereo Vision

- Geometric problem formulation: given several images of the same object or scene, compute a representation of its 3D shape.



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Goal: Recovery of 3D Structure

- Geometric problem formulation: given several images of the same object or scene, compute a representation of its 3D shape.
- “Images of the same object”
 - Arbitrary number of images (up to thousands)
 - Arbitrary camera positions (camera network or video sequence)
 - Calibration may be initially unknown
- “Representation of 3D shape”
 - Depth maps
 - Meshes
 - Point clouds
 - Patch clouds
 - Volumetric models
 - Layered models



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Goal: Recovery of 3D Structure

- Recovery of structure from one image is inherently ambiguous



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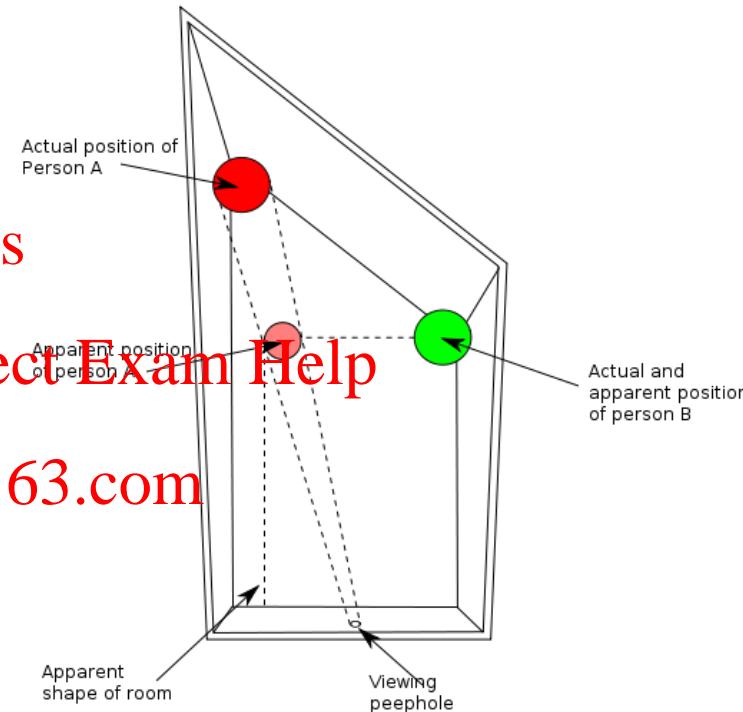
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http://en.wikipedia.org/wiki/Ames_room



Goal: Recovery of 3D Structure

- We will need multi-view geometry



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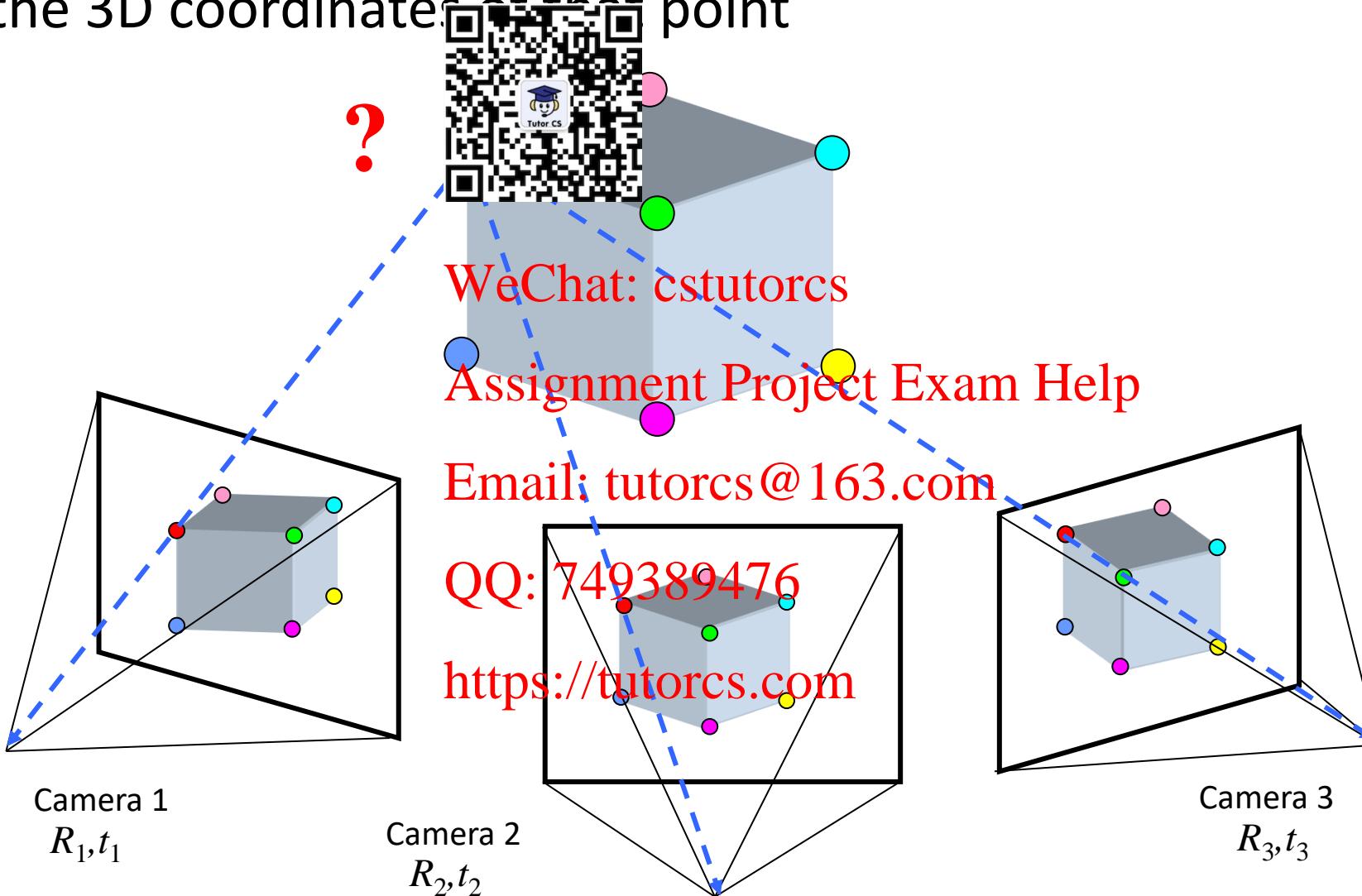
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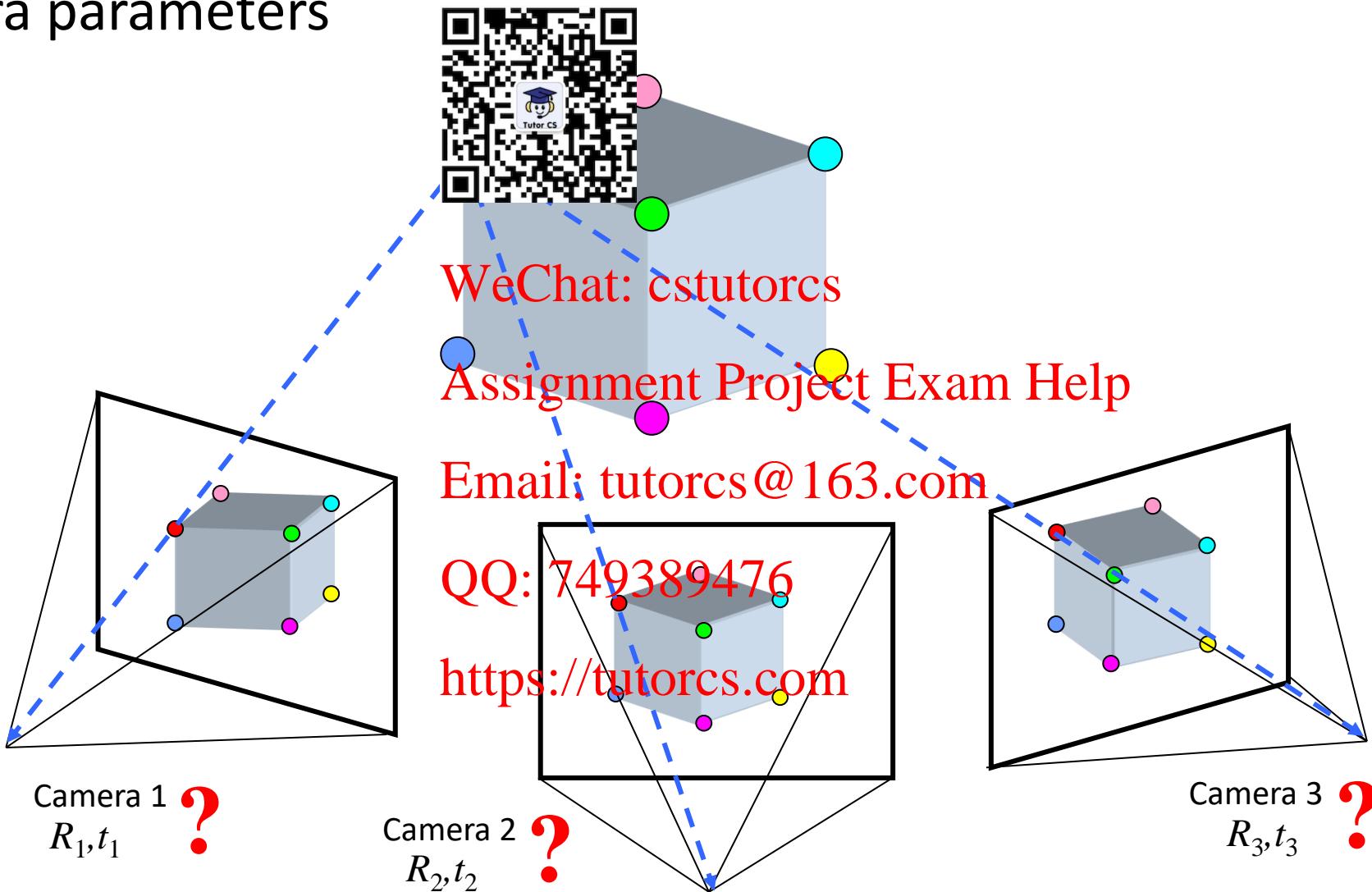
Multiview Geometry Problems

- Structure: Given projections of the same 3D point in two or more images, compute the 3D coordinates of that point



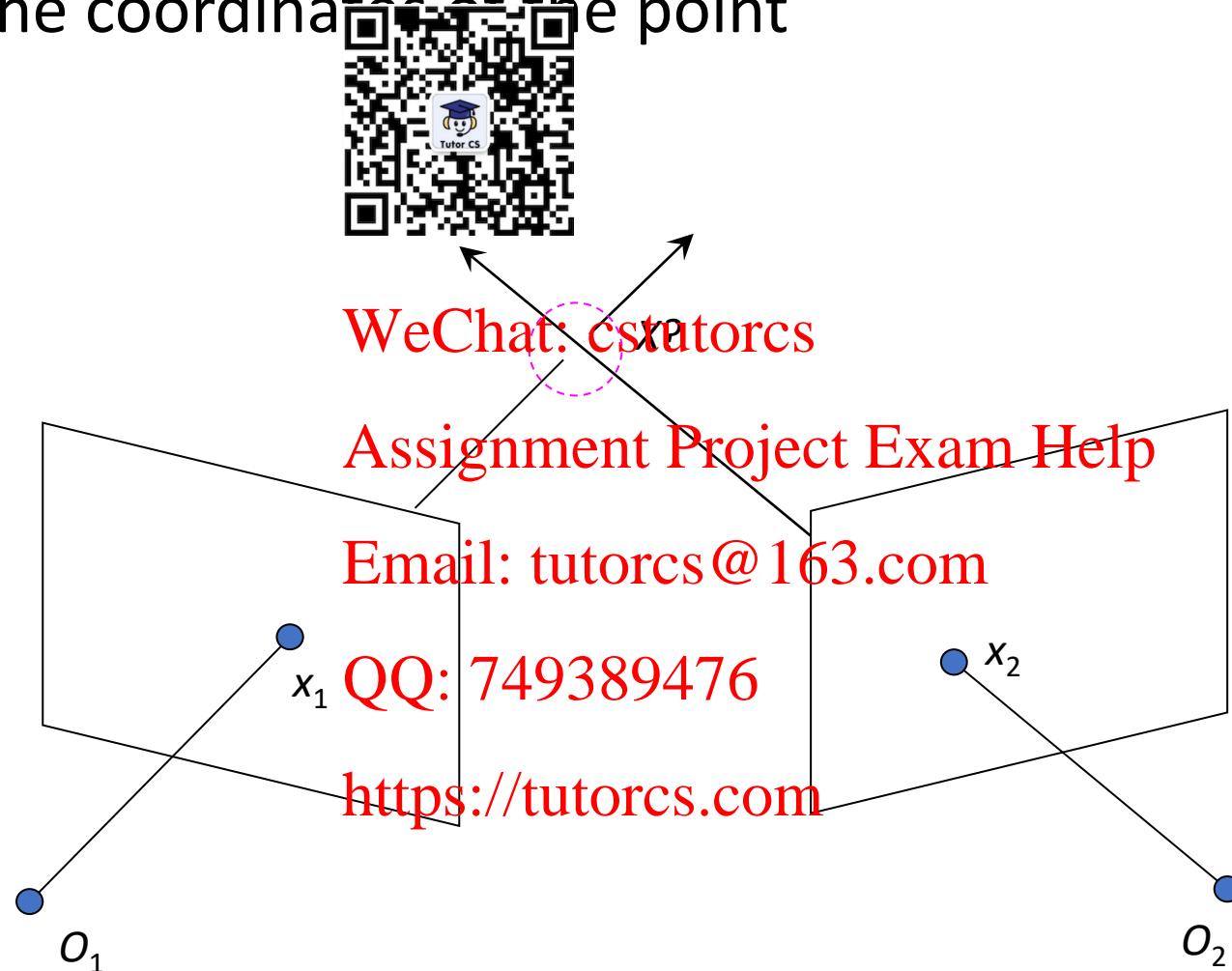
Multiview Geometry Problems

- Motion: Given a set of corresponding points in two or more images, compute the camera parameters



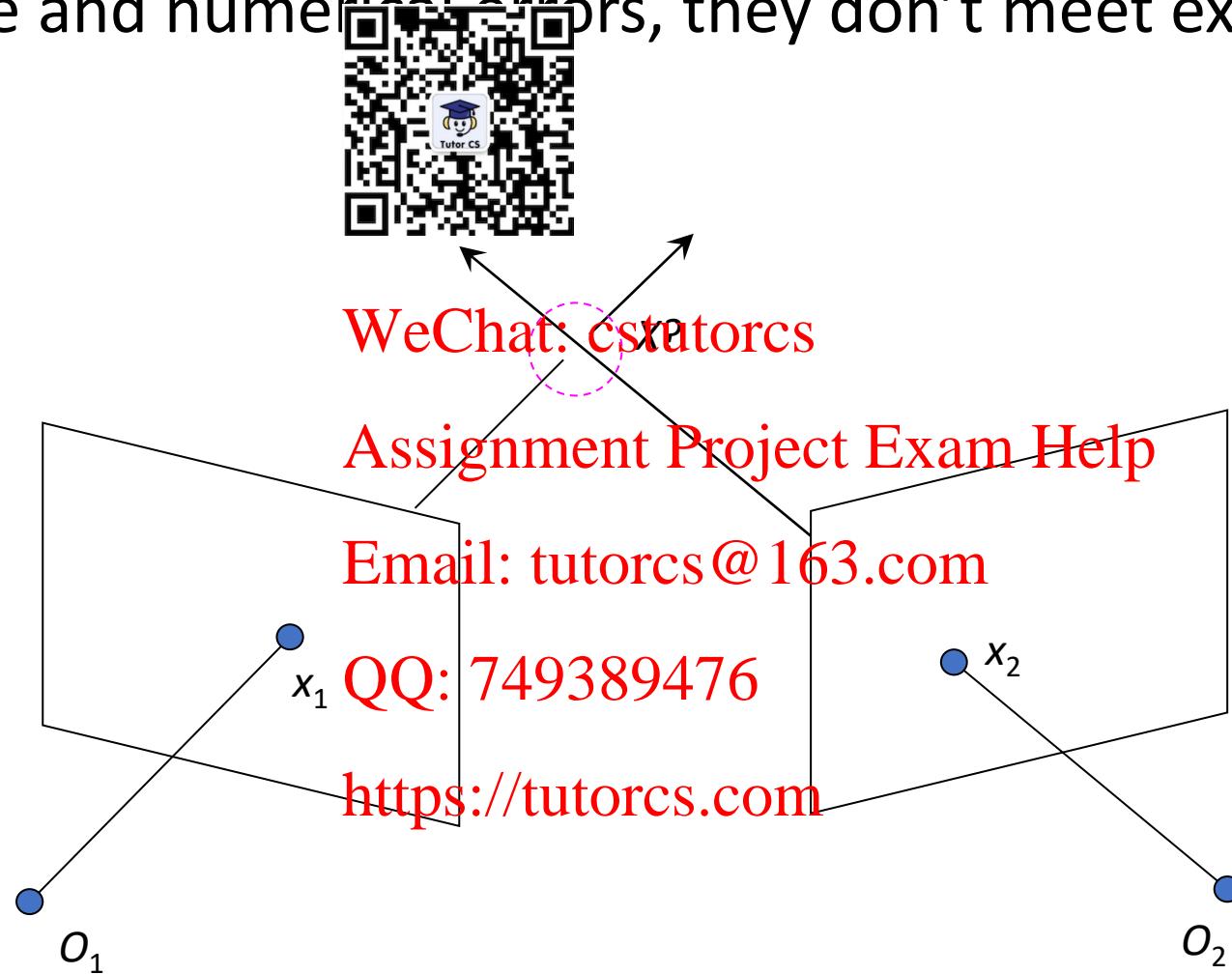
Triangulation

- Given projects of a 3D point ~~程序代写代做CS编程辅导~~ in two or more images (with known camera matrices), find the coordinates of the point



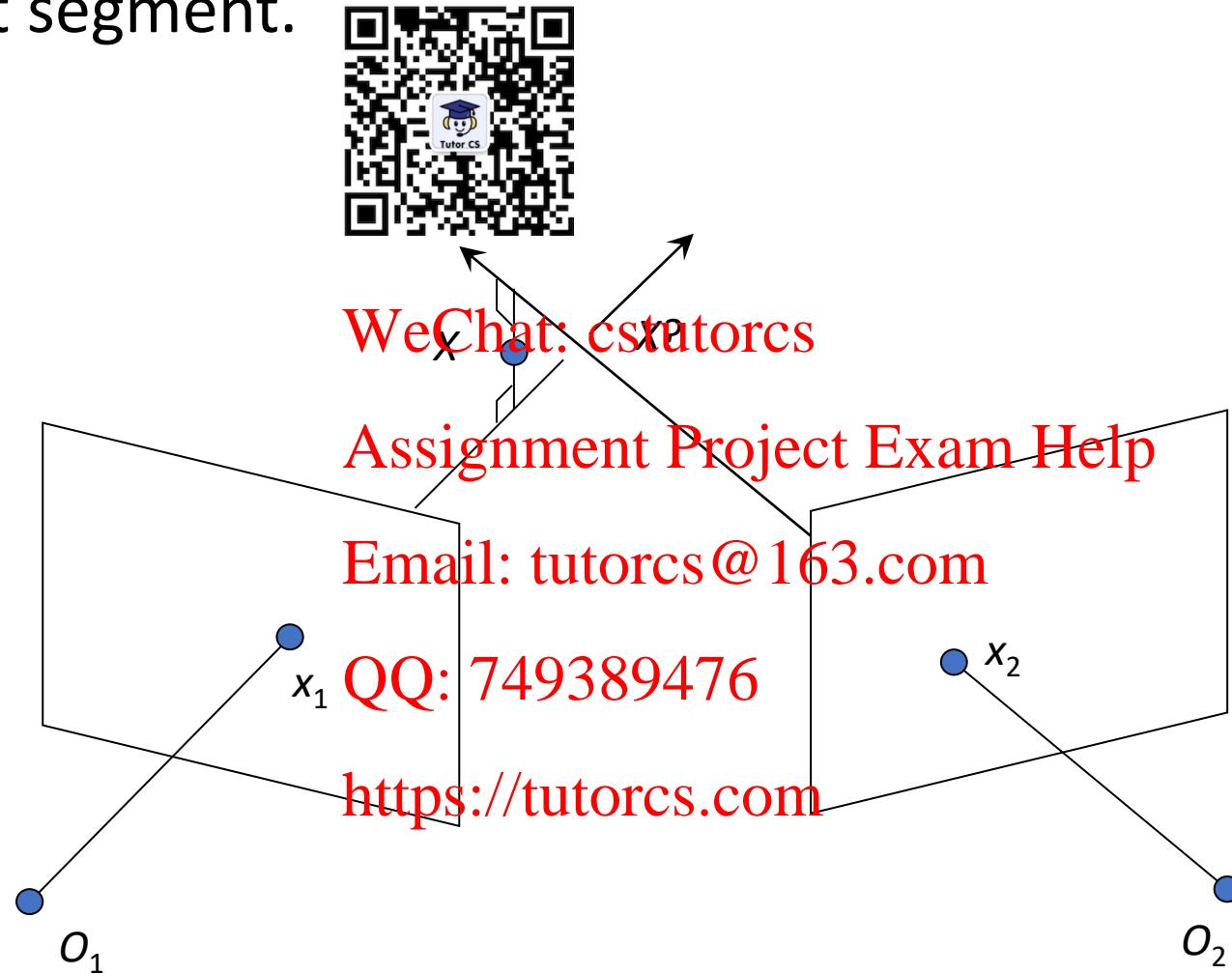
Triangulation

- We want to intersect the two visual rays corresponding to x_1 and x_2 , but because of noise and numerical errors, they don't meet exactly



Triangulation: Geometric Approach

- Find shortest segment connecting the two viewing rays and let X be the midpoint of that segment.



Triangulation: Linear Approach

$$\lambda_1 \mathbf{x}_1 = \mathbf{P}_1 \mathbf{X}$$

$$\lambda_2 \mathbf{x}_2 = \mathbf{P}_2 \mathbf{X}$$

$$\mathbf{x}_1 \times \mathbf{P}_1 \mathbf{X} = 0$$

$$\mathbf{x}_2 \times \mathbf{P}_2 \mathbf{X} = 0$$

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$$[\mathbf{x}_{1\times}] \mathbf{P}_1 \mathbf{X} = 0$$

$$[\mathbf{x}_{2\times}] \mathbf{P}_2 \mathbf{X} = 0$$



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Two independent equations each in terms of
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three unknown entries of X

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Cross product as matrix multiplication:

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$$\mathbf{a} \times \mathbf{b} = \begin{bmatrix} 0 & -a_z & a_y \\ a_z & 0 & -a_x \\ -a_y & a_x & 0 \end{bmatrix} \begin{bmatrix} b_x \\ b_y \\ b_z \end{bmatrix} = [\mathbf{a}_\times] \mathbf{b}$$

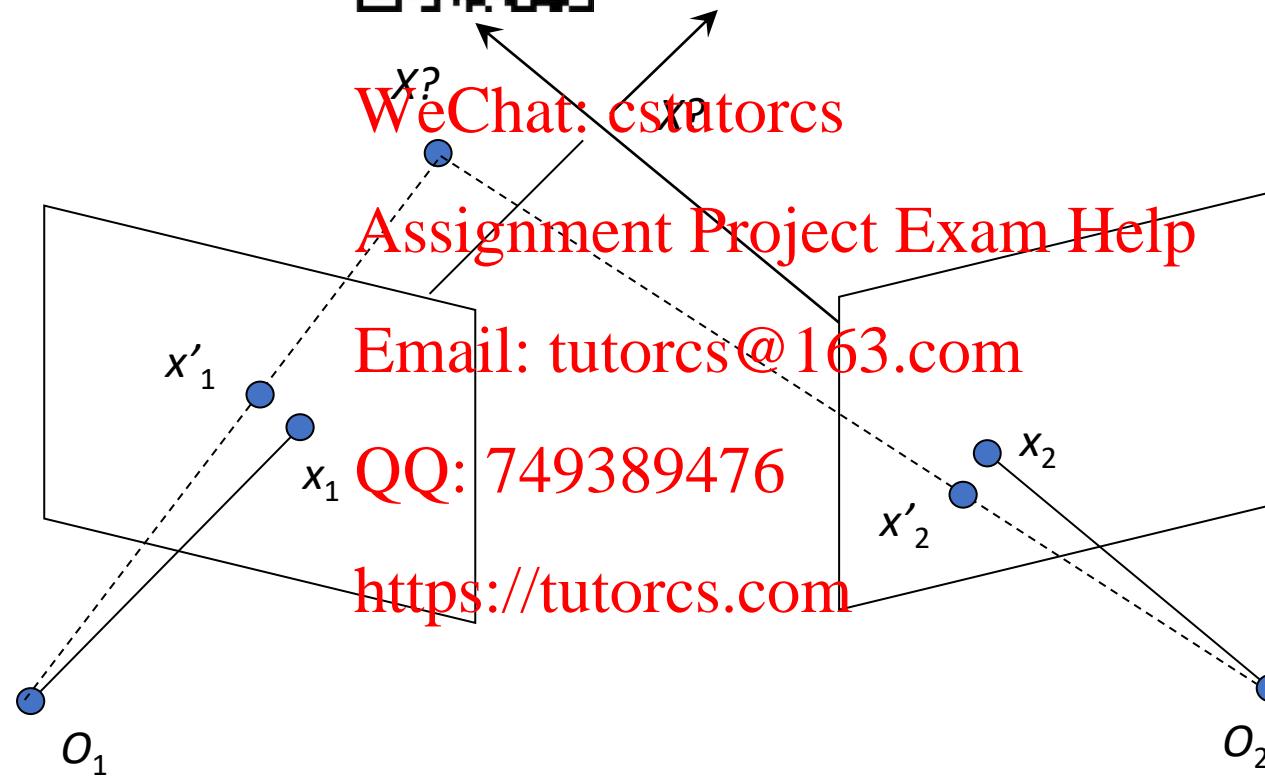
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Triangulation: Non-Linear Approach

- Find X that minimizes

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$$d^2(x_1, P_1 X) + d^2(x_2, P_2 X)$$



Two-view Geometry

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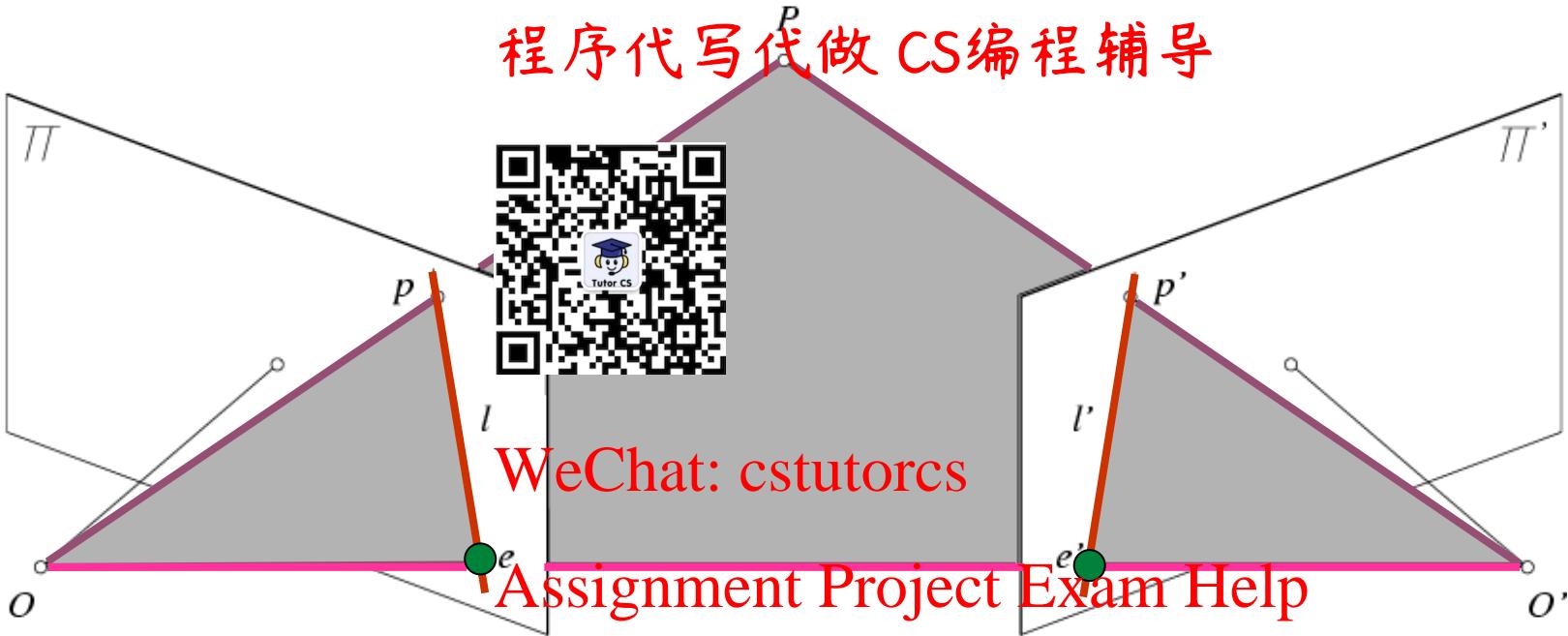
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Epipolar Geometry



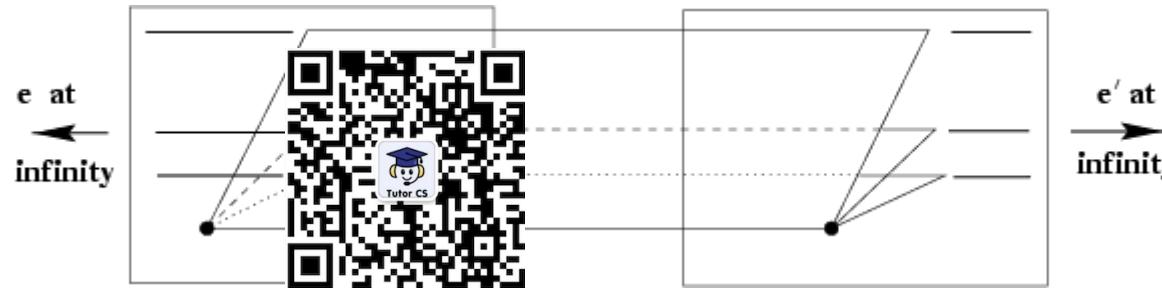
- Baseline – line connecting the two camera centres
- Epipolar Plane – plane containing baseline (1D family)
- Epipoles: intersections of baseline with image planes; projections of the other camera centres
- Epipolar Lines: intersections of epipolar plane with image planes (always come in corresponding pairs)

Example: Converging Cameras



Example: Motion Parallel to Image Plane

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Example: Motion Perpendicular to Image Plane

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Example: Motion Perpendicular to Image Plane

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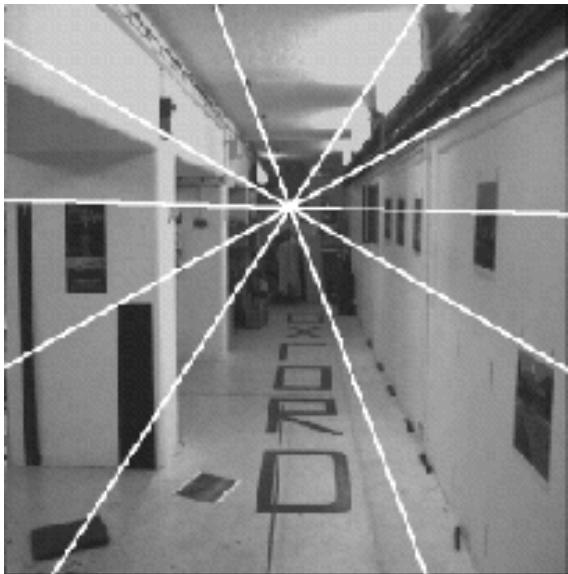
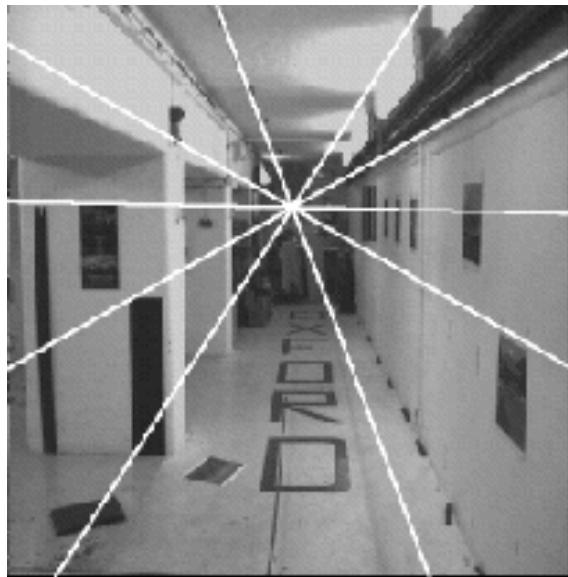
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Example: Motion Perpendicular to Image Plane



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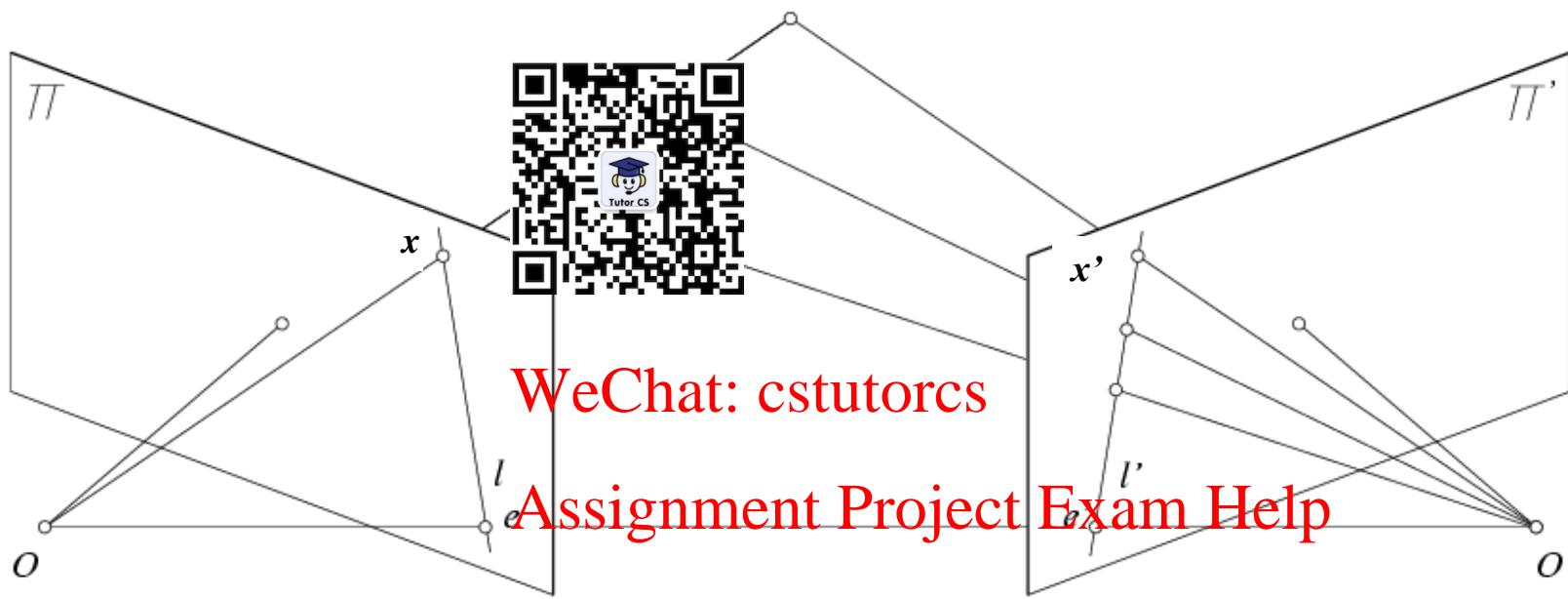


Epipoles have same coordinates in both images.

- Points move along lines radiating from e : “focus of expansion”

Epipolar Constraint

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- If we observe a point x in one image, where can the corresponding point x' be in the other image?

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Epipolar Constraint

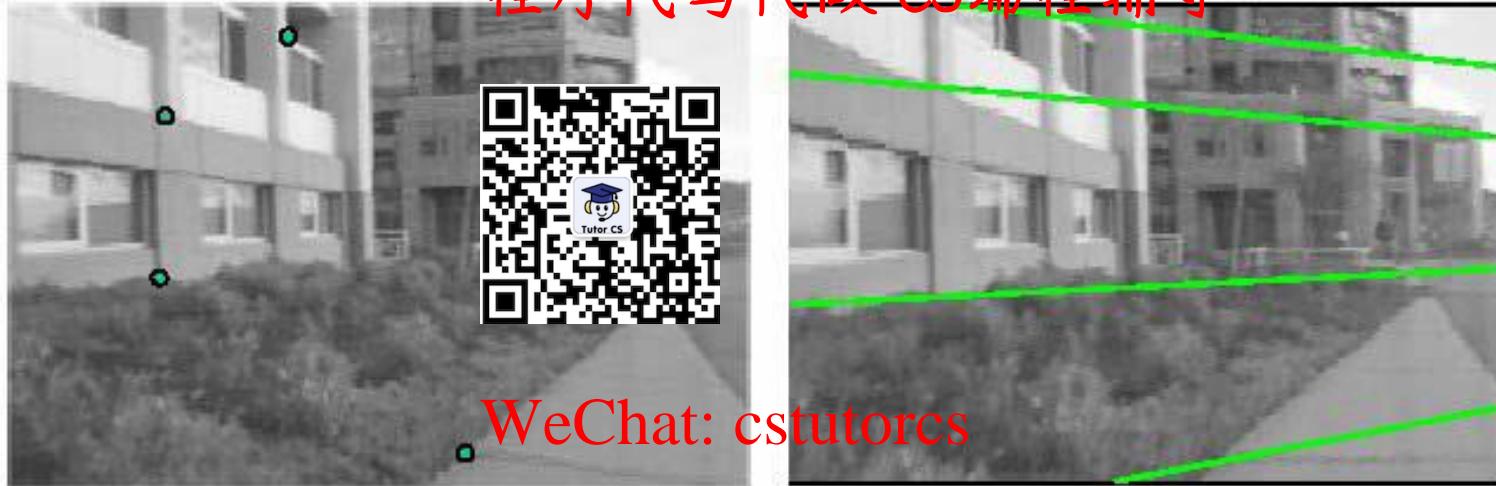
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- Potential matches for x have to lie on the corresponding epipolar line l'
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- Potential matches for x' have to lie on the corresponding epipolar line l
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Epipolar Constraint Example

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Epipolar Constraint: Calibrated Case

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- Assume that the intrinsic and extrinsic parameters of the cameras are known
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- We can multiply the projection matrix of each camera (and the image points) by the inverse of the calibration matrix to get *normalised* image coordinates.
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- We can also set the global coordinate system to the coordinate system of the first camera. Then the projection matrix of the first camera is $[I | 0]$.

Epipolar Constraint: Calibrated Case



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- The vectors x , t , and Rx' are coplanar

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Epipolar Constraint: Calibrated Case



$$x \cdot [t \times (Rx')] = 0 \quad \text{Email: tutorcs@163.com} \quad \text{with} \quad E = [t_x]R$$

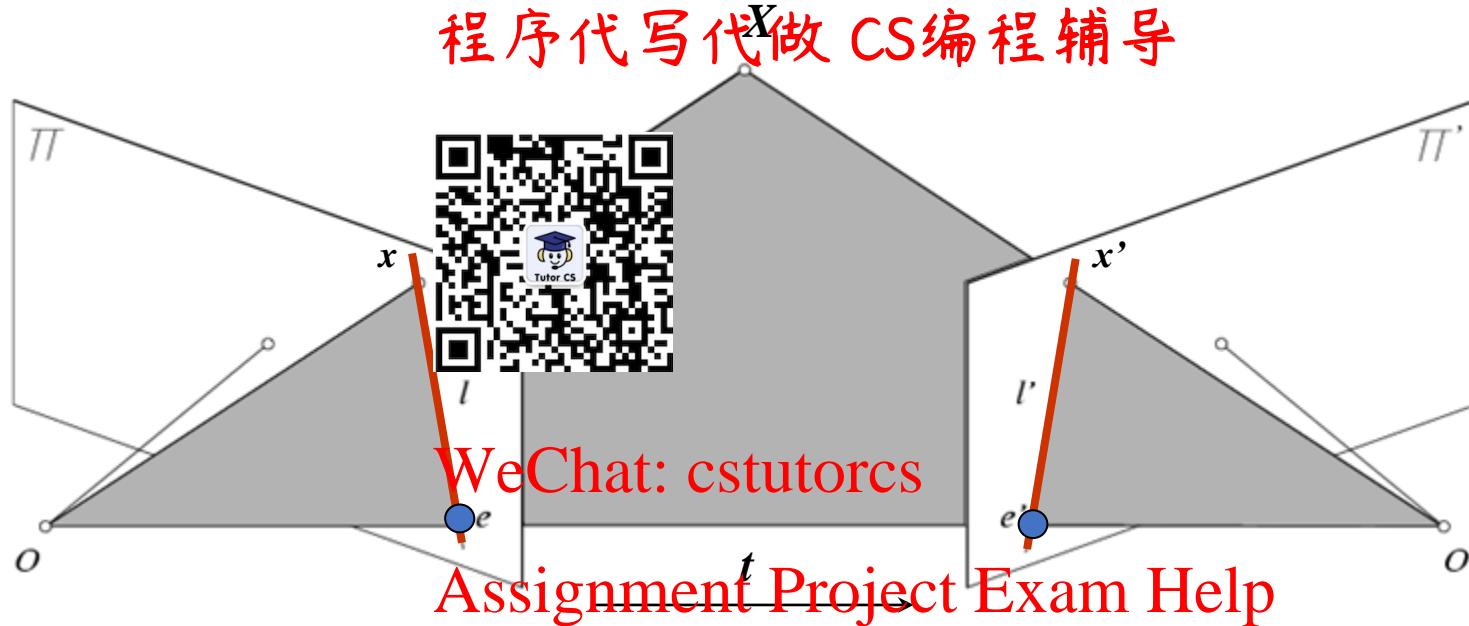
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- The vectors x , t , and Rx' are coplanar

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Essential Matrix
(Longuet-Higgins, 1981)

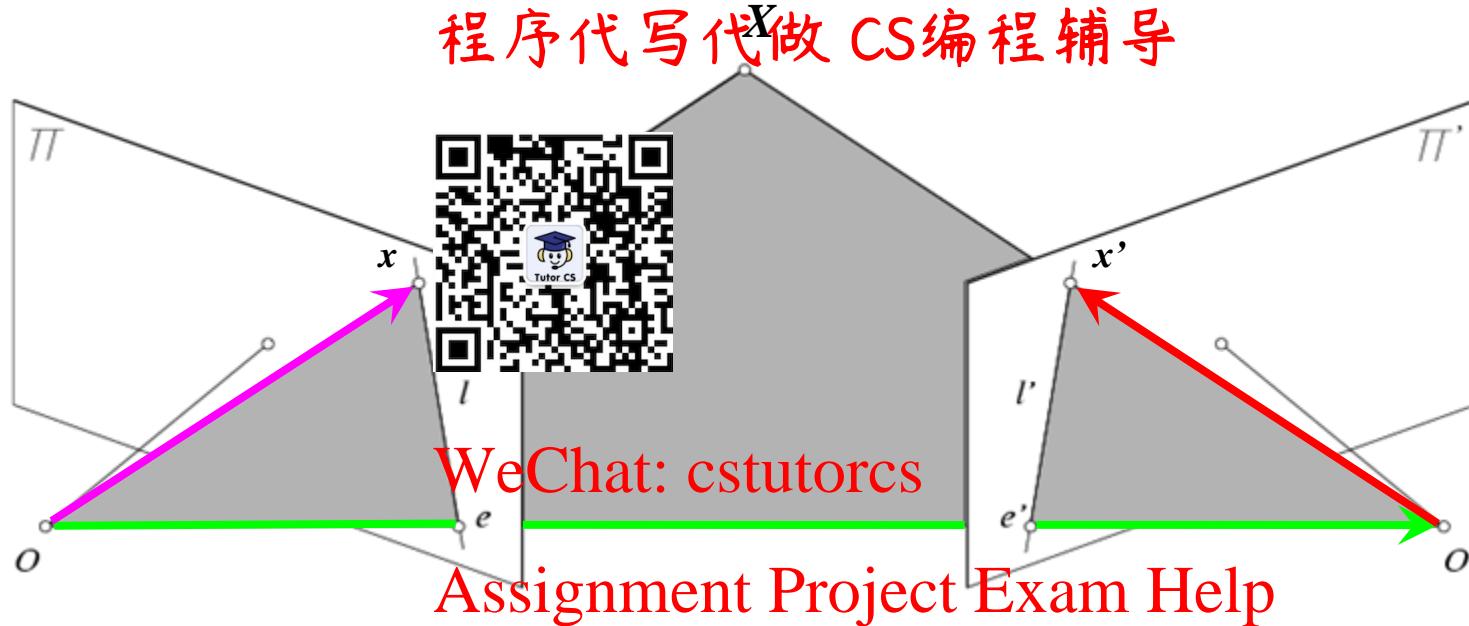
Epipolar Constraint: Calibrated Case



$$x \cdot [t \times (Rx')] = 0 \quad \text{Email: tutores@163.com} \quad E^T x = 0 \quad \text{with} \quad E = [t_x] R$$

- Ee' is the epipolar line associated with x' ($l = Ex'$)
- $E^T x$ is the epipolar line associated with x ($l' = E^T x$)
- $Ee' = 0$ and $E^T e = 0$
- E is singular (rank two), and E has five degrees of freedom

Epipolar Constraint: Uncalibrated Case



- The calibration matrices K and K' of the two cameras are unknown
- We can write the epipolar constraint in terms of *unknown* normalized coordinates

$$\hat{x}^T E \hat{x}' = 0$$

$$x = K \hat{x}, \quad x' = K' \hat{x}'$$

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Epipolar Constraint: Uncalibrated Case

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$$\hat{x}^T E \hat{x}' = 0 \quad \xrightarrow{\text{Email: tutorcs@163.com}} \quad x^T F x' = 0 \quad \text{with} \quad F = K^{-T} E K'^{-1}$$

- Fx' is the epipolar line associated with x' ($l = Fx'$)
- $F^T x$ is the epipolar line associated with x ($l' = F^T x$)
- $Fe' = 0$ and $F^T e = 0$
- F is singular (rank two), and F has seven degrees of freedom

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The Eight-point Algorithm

$$\mathbf{x} = (u, v, 1)^T, \quad \mathbf{x}' = (u', v', 1)^T$$

$$(u, v, 1) \begin{pmatrix} F_{11} & F_{12} & F_{13} \\ F_{21} & F_{22} & F_{23} \\ F_{31} & F_{32} & F_{33} \end{pmatrix} \begin{pmatrix} u' \\ v' \\ 1 \end{pmatrix} = 0$$

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$$(uu', uv', u, vu', vv', v, u', v', 1)$$

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$$\begin{pmatrix} u_1u'_1 & u_1v'_1 & u_1 & v_1u'_1 & v_1v'_1 & v_1 & u'_1 & v'_1 & F_{11} \\ u_2u'_2 & u_2v'_2 & u_2 & v_2u'_2 & v_2v'_2 & v_2 & u'_2 & v'_2 & F_{12} \\ u_3u'_3 & u_3v'_3 & u_3 & v_3u'_3 & v_3v'_3 & v_3 & u'_3 & v'_3 & F_{13} \\ u_4u'_4 & u_4v'_4 & u_4 & v_4u'_4 & v_4v'_4 & v_4 & u'_4 & v'_4 & F_{21} \\ u_5u'_5 & u_5v'_5 & u_5 & v_5u'_5 & v_5v'_5 & v_5 & u'_5 & v'_5 & F_{22} \\ u_6u'_6 & u_6v'_6 & u_6 & v_6u'_6 & v_6v'_6 & v_6 & u'_6 & v'_6 & F_{23} \\ u_7u'_7 & u_7v'_7 & u_7 & v_7u'_7 & v_7v'_7 & v_7 & u'_7 & v'_7 & F_{31} \\ u_8u'_8 & u_8v'_8 & u_8 & v_8u'_8 & v_8v'_8 & v_8 & u'_8 & v'_8 & F_{32} \end{pmatrix} \begin{pmatrix} 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \end{pmatrix}$$

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$$\begin{pmatrix} F_{11} \\ F_{12} \\ F_{13} \\ F_{21} \\ F_{22} \\ F_{23} \\ F_{31} \\ F_{32} \\ F_{33} \end{pmatrix} = 0$$

Minimize:

$$\sum_{i=1}^N (\mathbf{x}_i^T \mathbf{F} \mathbf{x}_i')^2$$

under the constraint

$$F_{33} = 1$$

The Eight-point Algorithm

- Meaning of error

$$\sum_{i=1}^N (x_i^T F x_i')^2$$

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Sum of Euclidean distances between points x_i and epipolar line Fx_i' (or points x_i' and epipolar line $F^T x_i$) multiplied by a scale factor

- Non-linear approach: minimize

$$\sum_{i=1}^N [d^2(x_i, Fx_i') + d^2(x_i', F^T x_i)]$$

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Problem with Eight-point Algorithm

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$$\begin{matrix} u_1v'_1 & u_1 & v_1u'_1 & v_1v'_1 & v_1 & u'_1 & v'_1 \\ u_2v'_2 & u_2 & v_2u'_2 & v_2v'_2 & v_2 & u'_2 & v'_2 \\ u_3u'_3 & u_3v'_3 & u_3 & v_3u'_3 & v_3v'_3 & v_3 & u'_3 & v'_3 \\ u_4u'_4 & u_4v'_4 & u_4 & v_4u'_4 & v_4v'_4 & v_4 & u'_4 & v'_4 \\ u_5u'_5 & u_5v'_5 & u_5 & v_5u'_5 & v_5v'_5 & v_5 & u'_5 & v'_5 \\ u_6u'_6 & u_6v'_6 & u_6 & v_6u'_6 & v_6v'_6 & v_6 & u'_6 & v'_6 \\ u_7u'_7 & u_7v'_7 & u_7 & v_7u'_7 & v_7v'_7 & v_7 & u'_7 & v'_7 \\ u_8u'_8 & u_8v'_8 & u_8 & v_8u'_8 & v_8v'_8 & v_8 & u'_8 & v'_8 \end{matrix} \begin{pmatrix} F_{11} \\ F_{12} \\ F_{13} \\ F_{21} \\ F_{22} \\ F_{23} \\ F_{31} \\ F_{32} \end{pmatrix} = - \begin{pmatrix} 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \end{pmatrix}$$

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Problem with Eight-point Algorithm

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250906.36	183269.57	921.81	20093	66.13	738.21	272.19	198.81
2692.28	131633.03	176.27	6196.73	382975.59	405.71	15.27	746.79
416374.23	871684.30	935.47	408110.89	854384.92	916.90	445.10	931.81
191183.60	171759.40	410.27	416435.62	374125.90	893.65	465.99	418.65
48988.86	30401.76	57.89	298604.57	185309.58	352.87	846.32	525.15
164786.04	546559.67	813.17	1998.37	6628.15	9.86	202.65	672.14
116407.01	2727.75	138.89	169941.17	3982.21	202.77	838.12	19.64
135384.58	75411.13	198.72	411350.03	229127.78	603.79	681.28	379.48

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$$\begin{pmatrix} F_{11} \\ F_{12} \\ F_{13} \\ F_{21} \\ F_{22} \\ F_{23} \\ F_{31} \\ F_{32} \end{pmatrix} = - \begin{pmatrix} 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \end{pmatrix}$$

- Poor numerical conditioning <https://tutorcs.com>
- Can be fixed by rescaling the data

The Normalized Eight-point Algorithm

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(Hartley, 1995)

- Centre the image data at the origin and scale it so that the mean squared distance between the origin and the data points is 2 pixels
- Use the eight-point algorithm to compute F from the normalized points
- Enforce the rank 2 constraint (for example, take SVD of F and throw out the smallest singular value)
- Transform fundamental matrix back to the original units: if T and T' are the normalized transformations in the two images, then the fundamental matrix in the original coordinates is T^TFT'

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Comparison of Estimation Algorithms

	Av. Dist. 1	Av. Dist. 2
8-point	2.33 pixels	2.33 pixels
Normalized 8-point	0.92 pixel	0.92 pixel
Nonlinear least squares	0.86 pixel	0.80 pixel

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From Epipolar Geometry to Camera Calibration

- Estimating the fundamental matrix is known as “weak” calibration
- If we know the calibration ~~程序代写代做CS编程辅导~~ of the two cameras, we can estimate the essential matrix: $E = K^T F K'$
- The essential matrix gives us relative rotation and translation between the cameras, or their extrinsic parameters



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Summary

- What is the problem of stereo vision? 程序代写代做 CS 编程辅导
- What is baseline? What are epipolar line, and epipolar plane? How to determine epipolar lines?
- What is essential matrix? What is fundamental matrix?
- Describe eight-point algorithm



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