Mathematical Principles in Visual Computing
Projective Geometry – Geometric Relations

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SS 2022

Outline

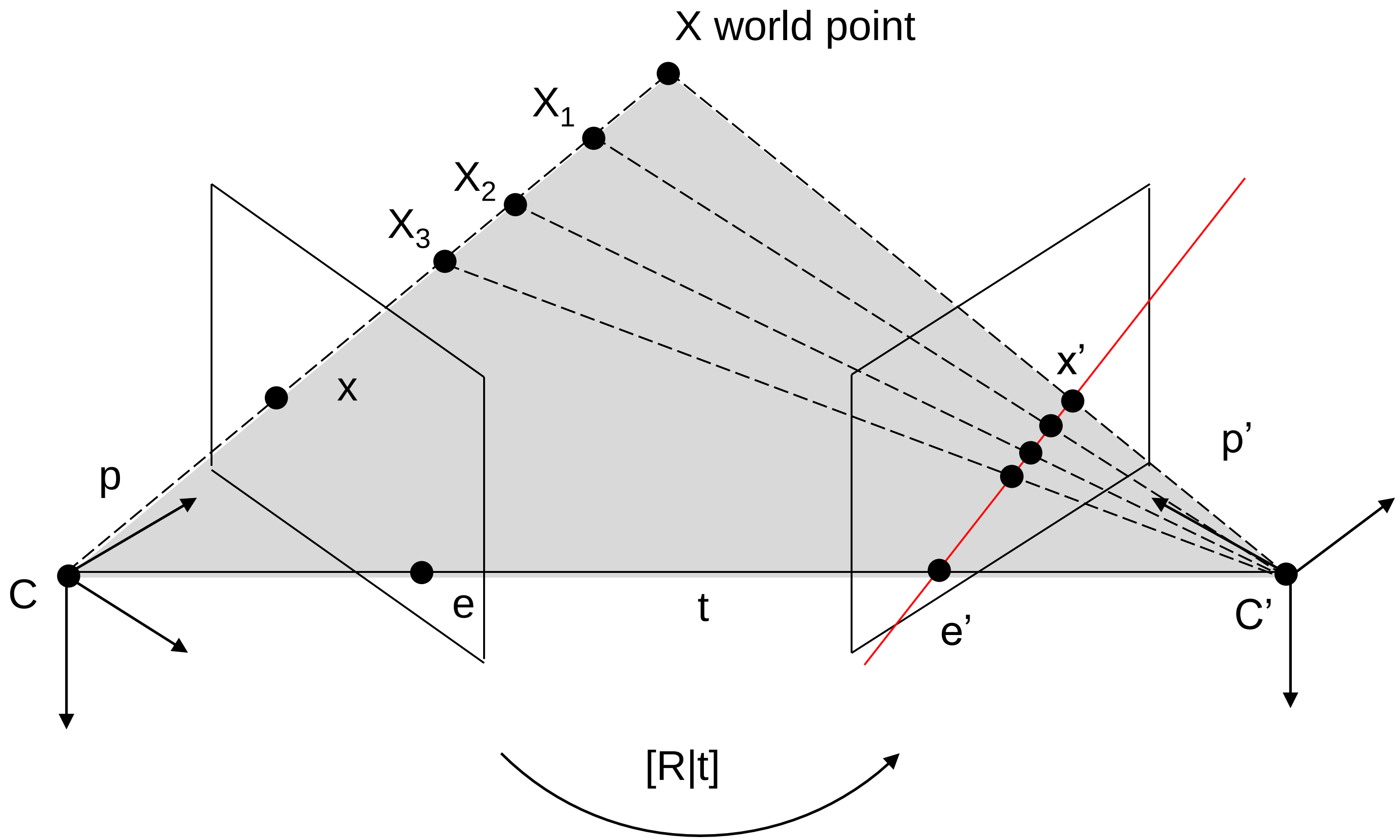
- Epipolar constraint derivation
- Stereo normal case
- Triangulation
- Camera pose estimation

Learning goals

- Understand and derive the epipolar constraint
- Understand the geometric concept of the epipolar plane
- Understand triangulation
- Understand camera pose estimation

Epipolar constraint

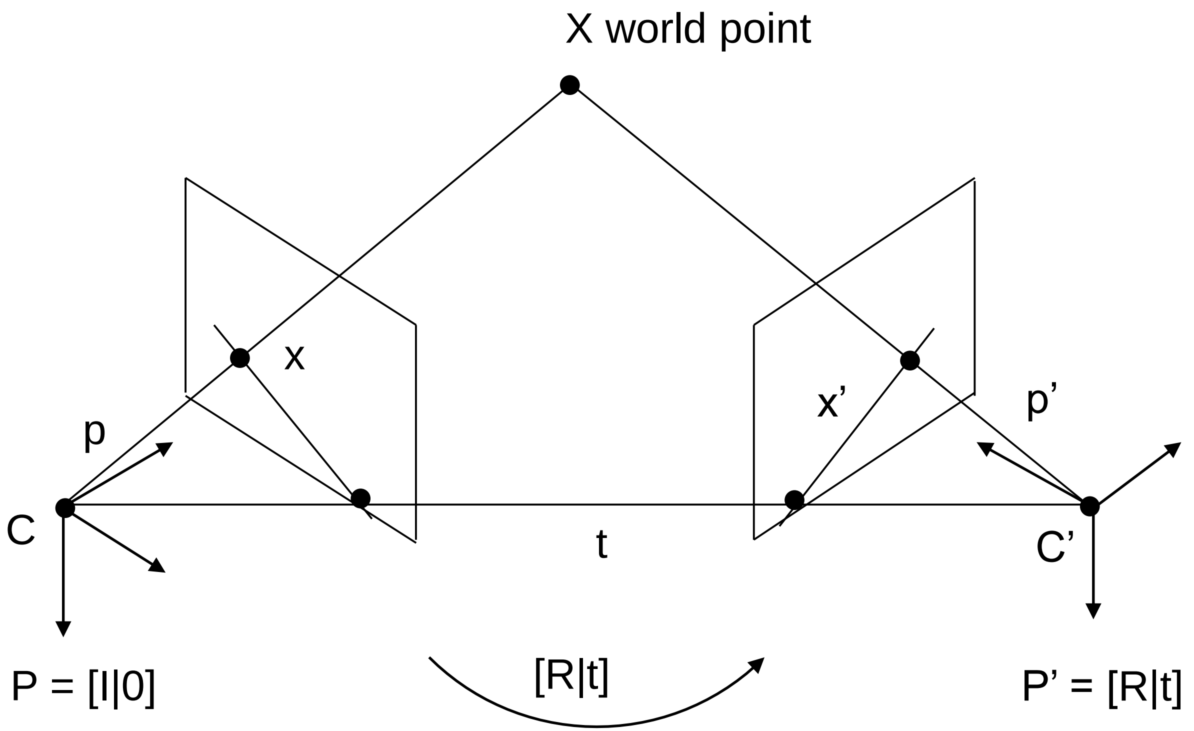
- The epipolar constraint is a mathematical relationship between the point correspondences of two images



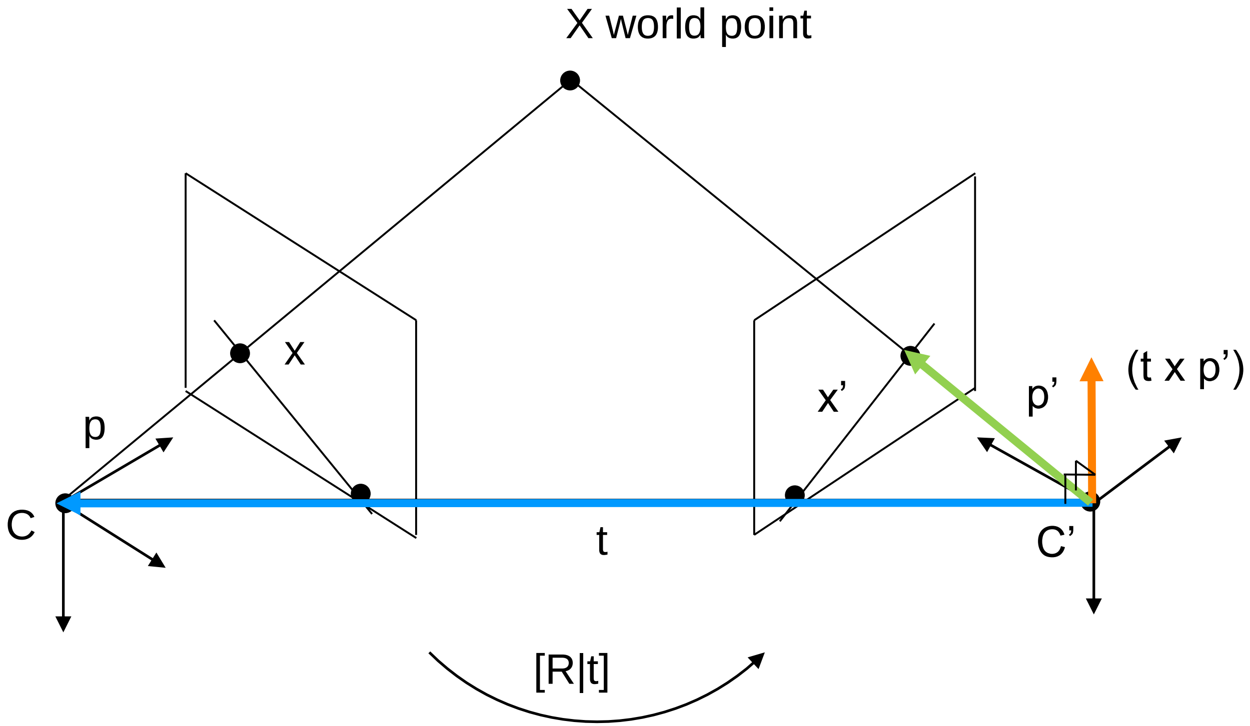
Epipolar constraint – derivation by coplanarity condition

- Vector p and t define a plane
- Vector p’ and t define also a plane
- Both planes must have the same normal
- What we seek is a relation between p and p’

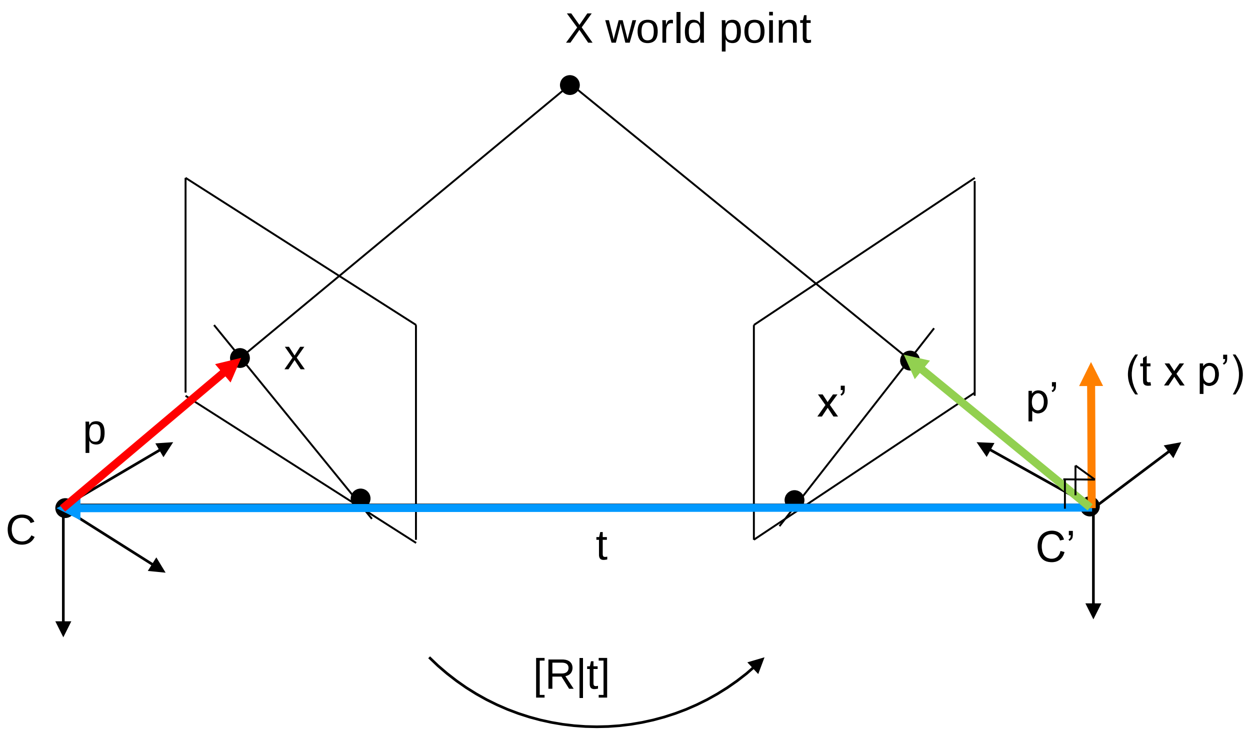
Epipolar constraint – derivation by coplanarity condition



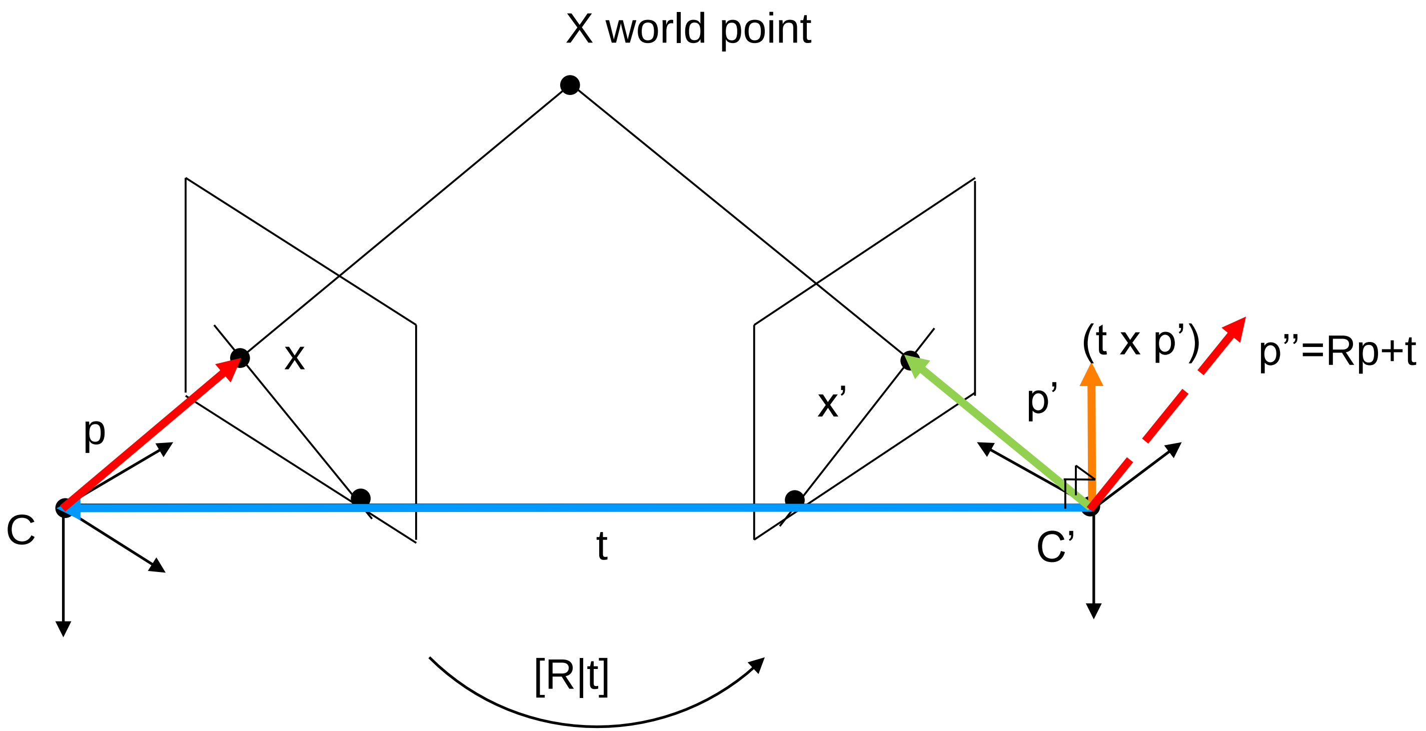
Epipolar constraint – derivation by coplanarity condition



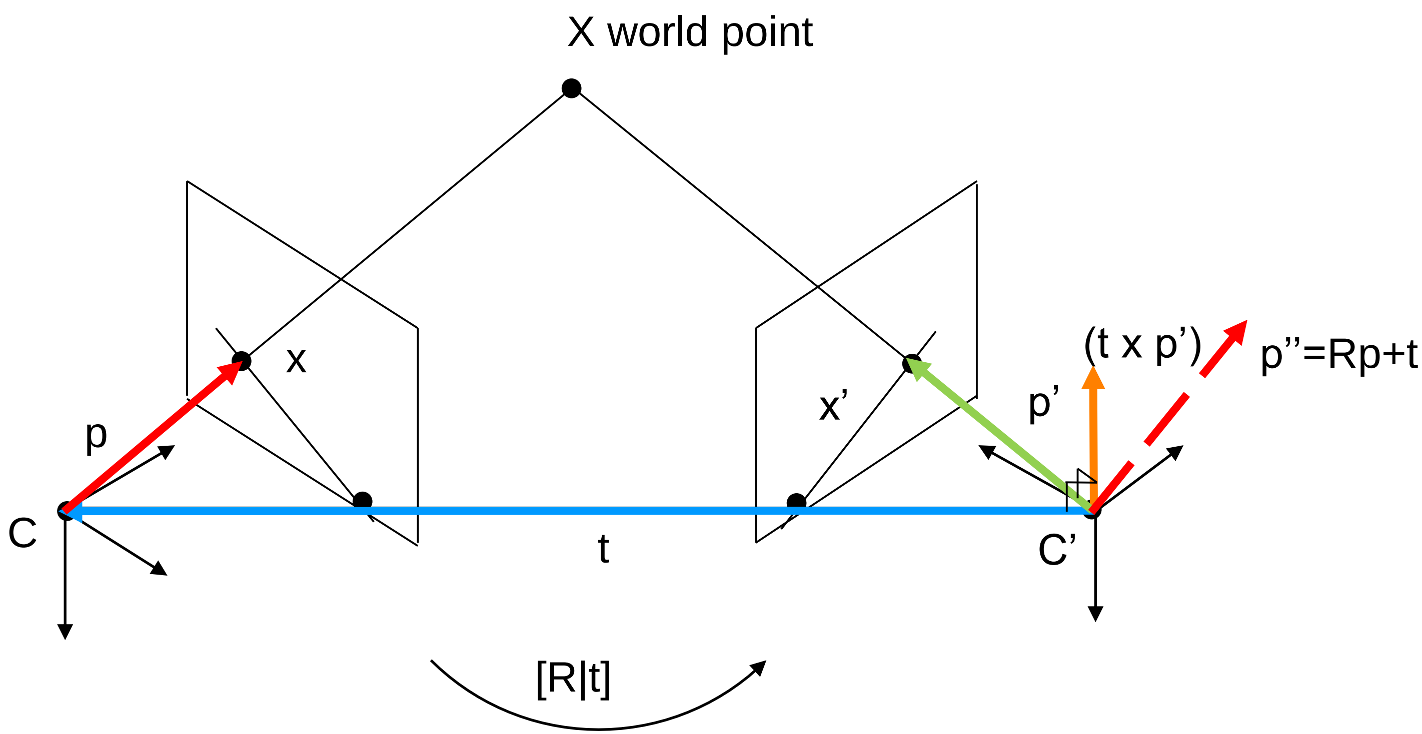
Epipolar constraint – derivation by coplanarity condition



Epipolar constraint – derivation by coplanarity condition



Epipolar constraint – derivation by coplanarity condition



$$t \times p' = t \times p''$$
$$t \times p' = t \times (Rp + t)$$
$$with\, p'' = Rp + t$$
$$t \times p' = t \times Rp + t \times t$$
$$p'^T (t \times p') = 0$$
$$p'^T (t \times Rp) = 0$$

$$p'^T \underbrace{[t]_x R}_{E} p = 0$$

$$\boxed{p'^T E p = 0}$$

E is called the Essential matrix

Fundamental matrix

- p,p' from the Essential matrix derivation are in normalized coordinates
- x,x' are image coordinates, x=Kp, x'=Kp'
- By replacing p,p' with x,x' one gets the Fundamental matrix

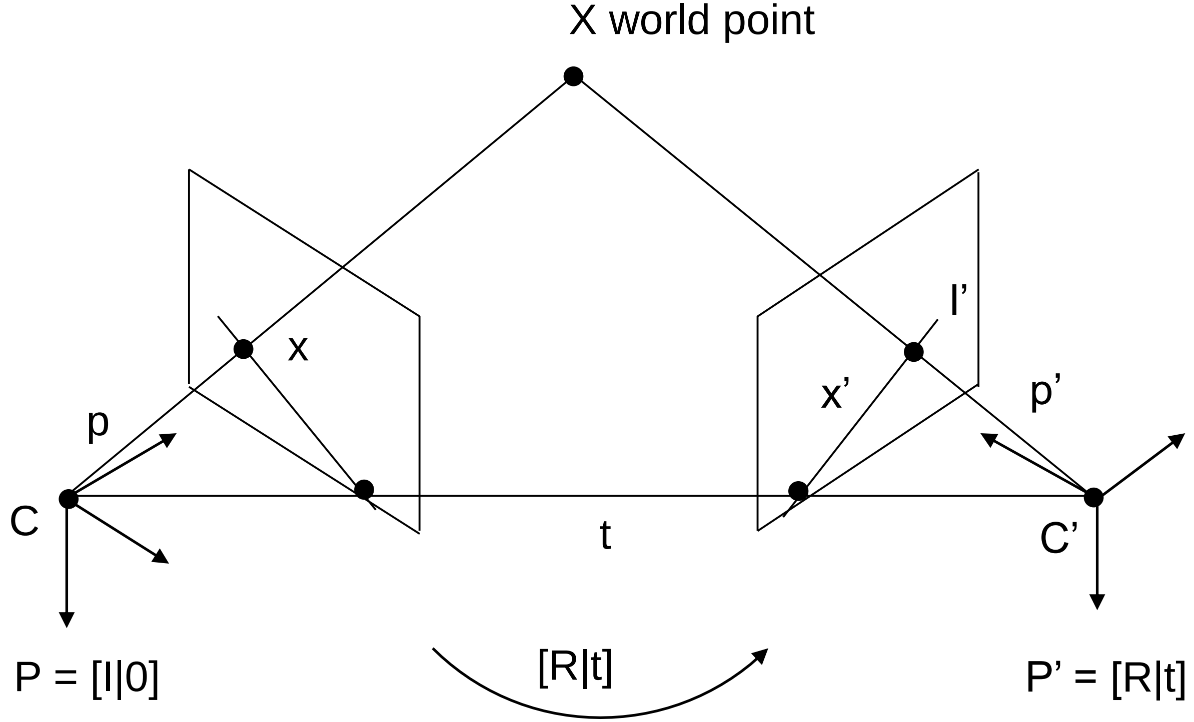
$$p \quad = K^{-1}x$$

$$p' \quad = K^{-1}x'$$

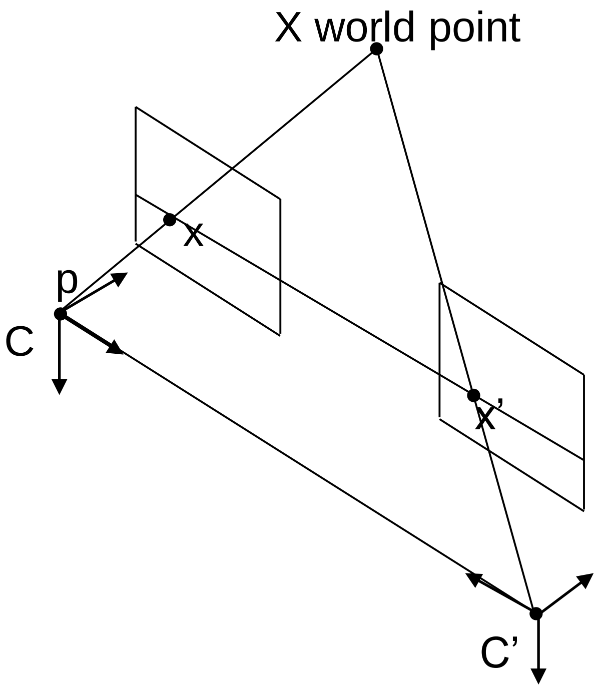
$$\begin{aligned}
&{p'}^{T}Ep = 0 \\
&{x'}^{T}K^{-T}EK^{-1}x = 0 \\
&{x'}^{T}Fx = 0 \\
&\mathrm{F} = K^{-T}EK^{-1}
\end{aligned}$$

Epipolar lines

- The corresponding line l' to image coordinate x
- l' is the line connecting the epipole e' and the image coordinate x'
- Hypothesis: $l' = Fx$
- Point x' must lie on l', thus $x'^T l' = 0$
- Now $x'^T F x = 0$

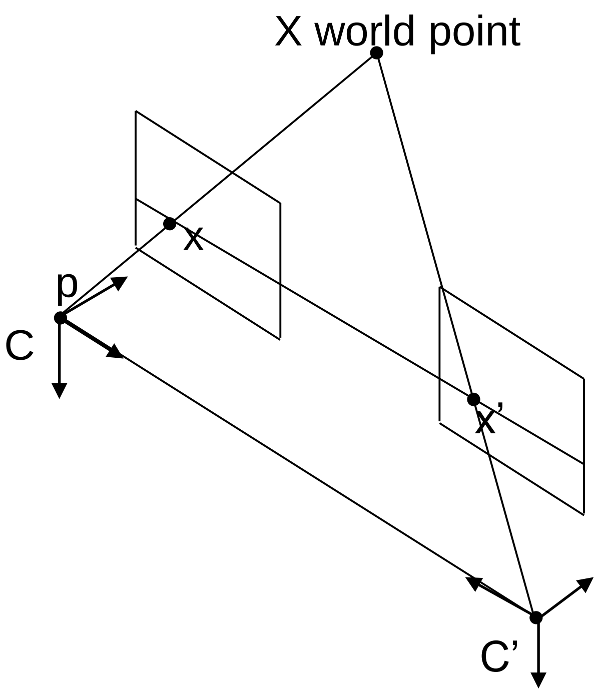


Stereo case



$$R = I_{3x3} \qquad T = [T_x \quad 0 \quad 0]^T$$

Stereo case



$$R = I_{3x3} \qquad T = [T_x \quad 0 \quad 0]^T$$

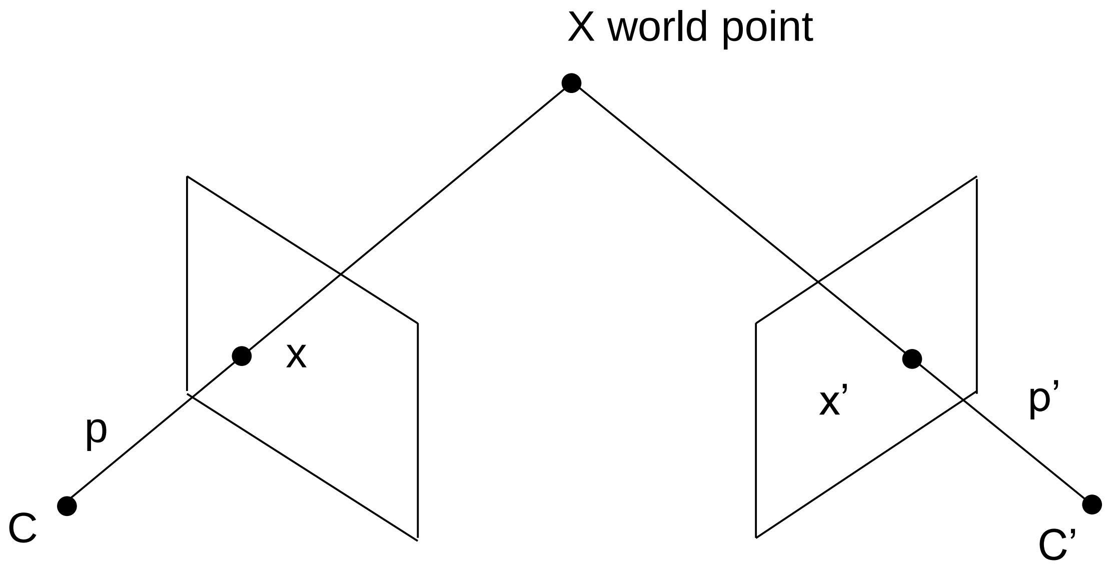
$$E = [T]_x R = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & -T_x \\ 0 & T_x & 0 \end{bmatrix}$$

$$[x' \quad y' \quad 1] \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & -T_x \\ 0 & T_x & 0 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} = 0$$

$$[x' \quad y' \quad 1] \begin{bmatrix} 0 \\ -T_x \\ T_x y \end{bmatrix} = 0$$

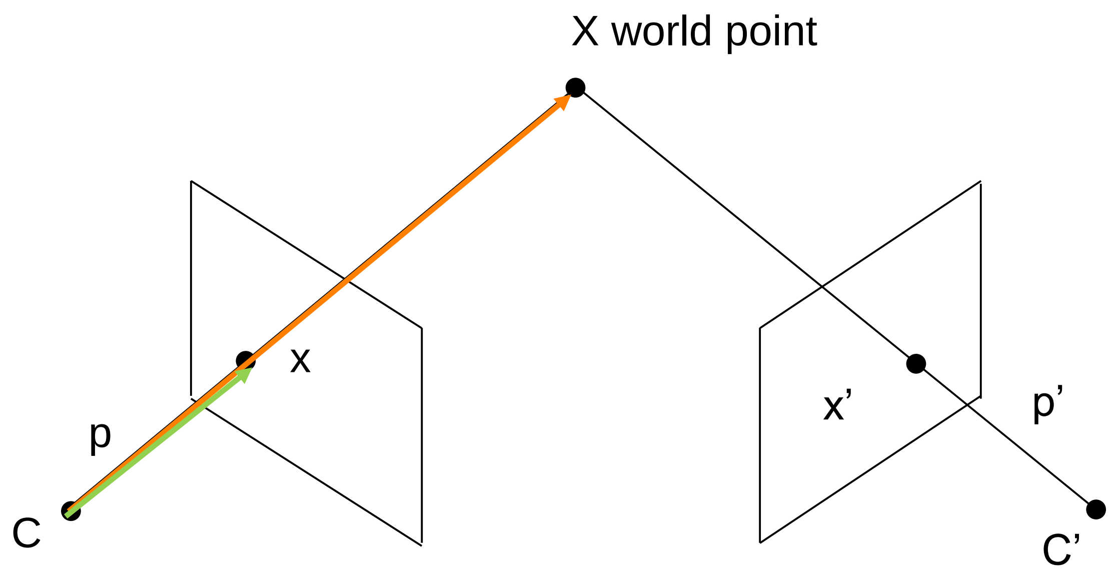
$$-y' T_x + T_x y = 0$$

Triangulation



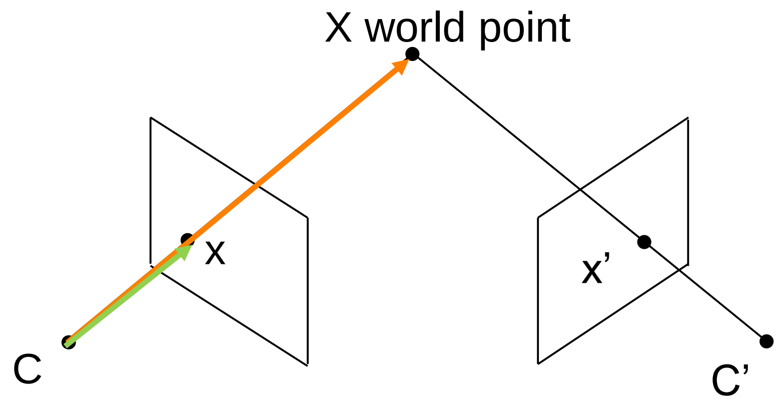
- Compute coordinates of world point X given the measurements x, x’ and the camera projection matrices P and P’

Triangulation



- Condition: Measurement vector x needs to have the same direction as projection of X (cross-product equals 0)
- $x \times (PX) = 0 \; and \; x' \times (P'X) = 0$
- Can be rewritten into equation system $AX = 0$ to solve for X

Triangulation

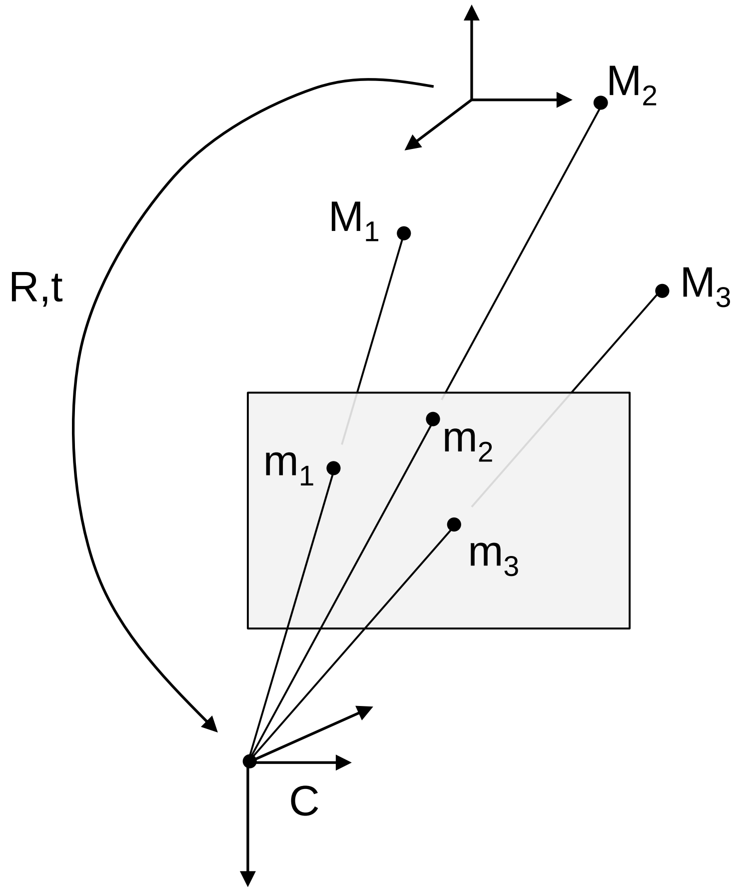


$$P = \begin{bmatrix} P_1^T \\ P_2^T \\ P_3^T \end{bmatrix}$$

$$x \times (PX) = 0 \; and \; x' \times (P'X) = 0$$
$$x(P_3^T X) - (P_1^T X) = 0$$
$$y(P_3^T X) - (P_2^T X) = 0$$
$$x(P_2^T X) - y(P_1^T X) = 0$$

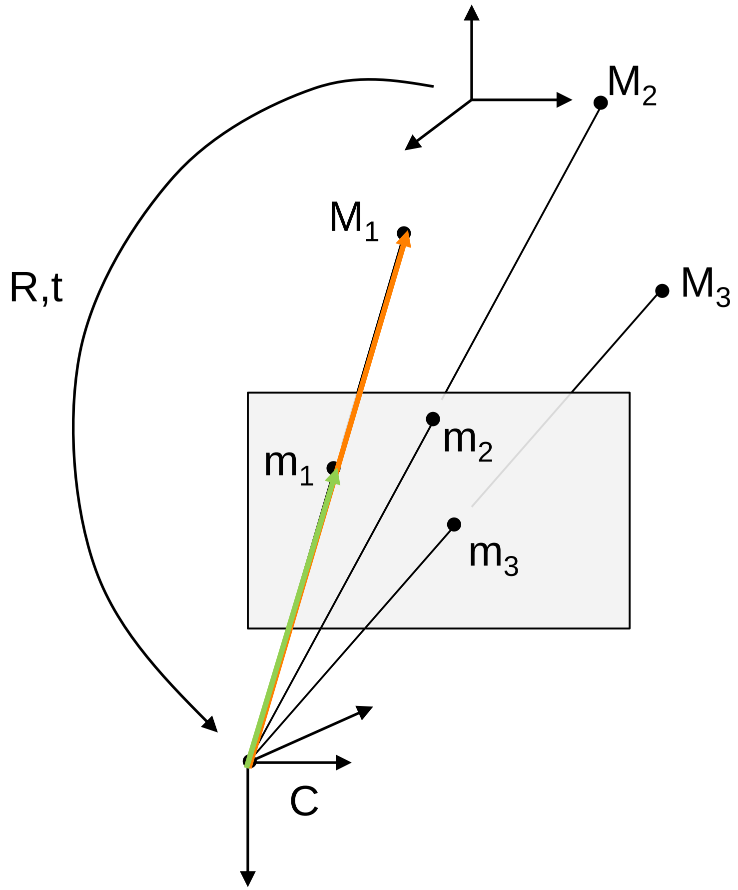
$$\begin{bmatrix} xP_3^T - P_1^T \\ yP_3^T - P_2^T \\ x'P'^T_3 - P'^T_1 \\ y'P'^T_3 - P'^T_2 \end{bmatrix} X = 0$$

Camera pose estimation



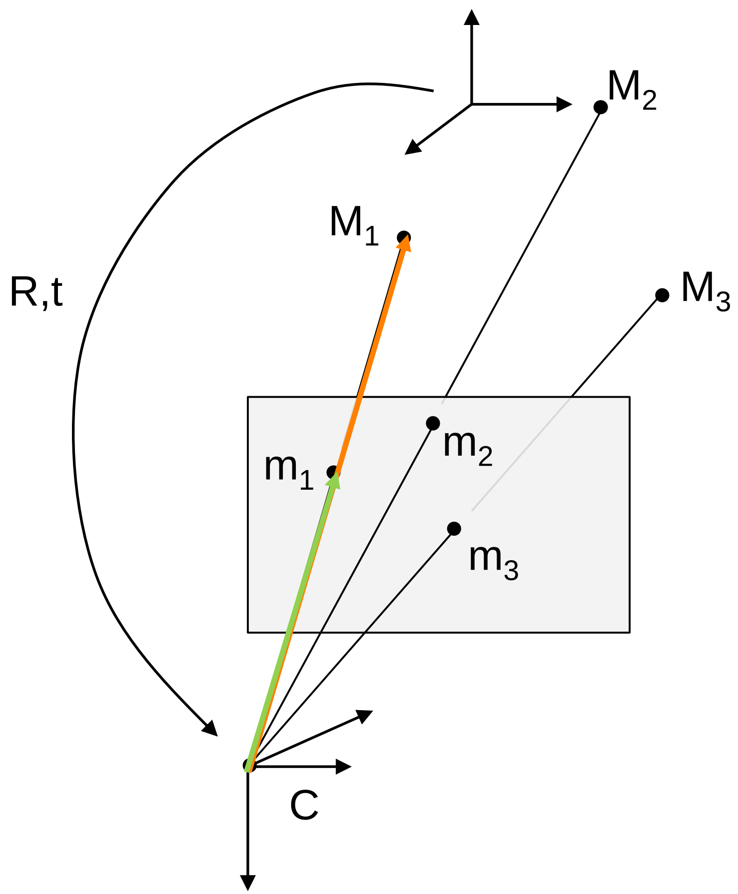
- perspective-n-point problem
- Goal is to estimate camera matrix P such that $m_1=PM_1$
- m_1,M_1,m_2,M_2,m_3,M_3 are known
- Algebraic linear solution requires 6 3D-2D point correspondences, minimal nonlinear solution requires only 3

Camera pose estimation



- Derivation similar to Triangulation, but now entries of P are the unknowns instead of X
- Condition: Measurement vector x needs to have the same direction as projection of X (cross-product equals 0)

Camera pose estimation



- Derivation similar to Triangulation, bot now entries of P are the unknowns instead of X
- Condition: Measurement vector x needs to have the same direction as projection of X (cross-product equals 0)

$$x \times (PX) = 0 \; for \; all \; pairs \; x \leftrightarrow X$$
$$y(P_3^T X) - w(P_2^T X) = 0$$
$$x(P_3^T X) - w(P_1^T X) = 0$$
$$x(P_2^T X) - y(P_1^T X) = 0$$

$$\begin{bmatrix} 0 & -wX^T & yX^T \\ -wX^T & 0 & xX^T \\ -yX^T & xX^T & 0 \end{bmatrix} \begin{bmatrix} P_1 \\ P_2 \\ P_3 \end{bmatrix} = 0$$

Recap - Learning goals

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