COS 429: COMPUTER VISON

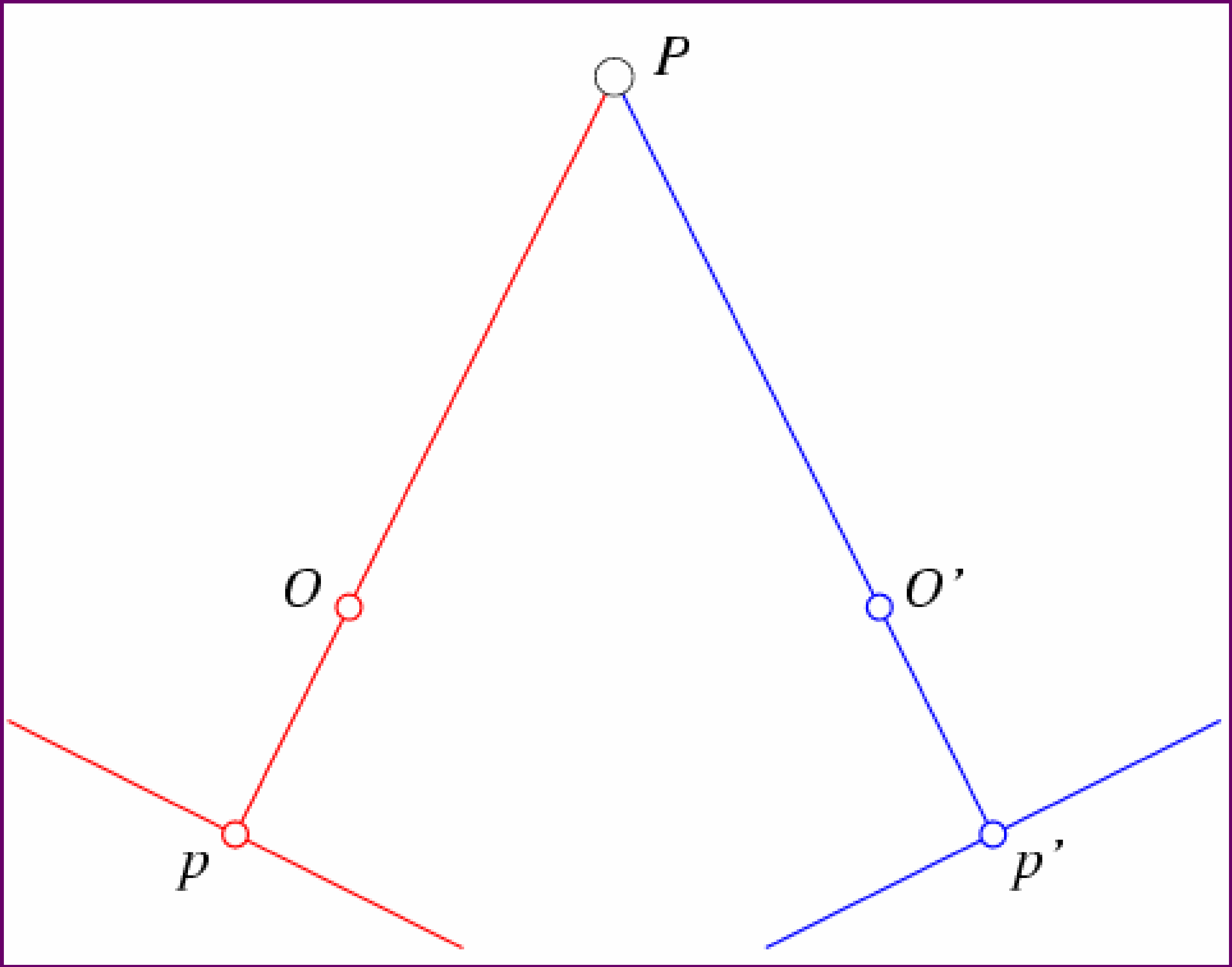
MULTI-VIEW GEOMETRY (1 lecture)

- Epipolar Geometry
- The Essential and Fundamental Matrices
- The 8-Point Algorithm
- Trifocal tensor

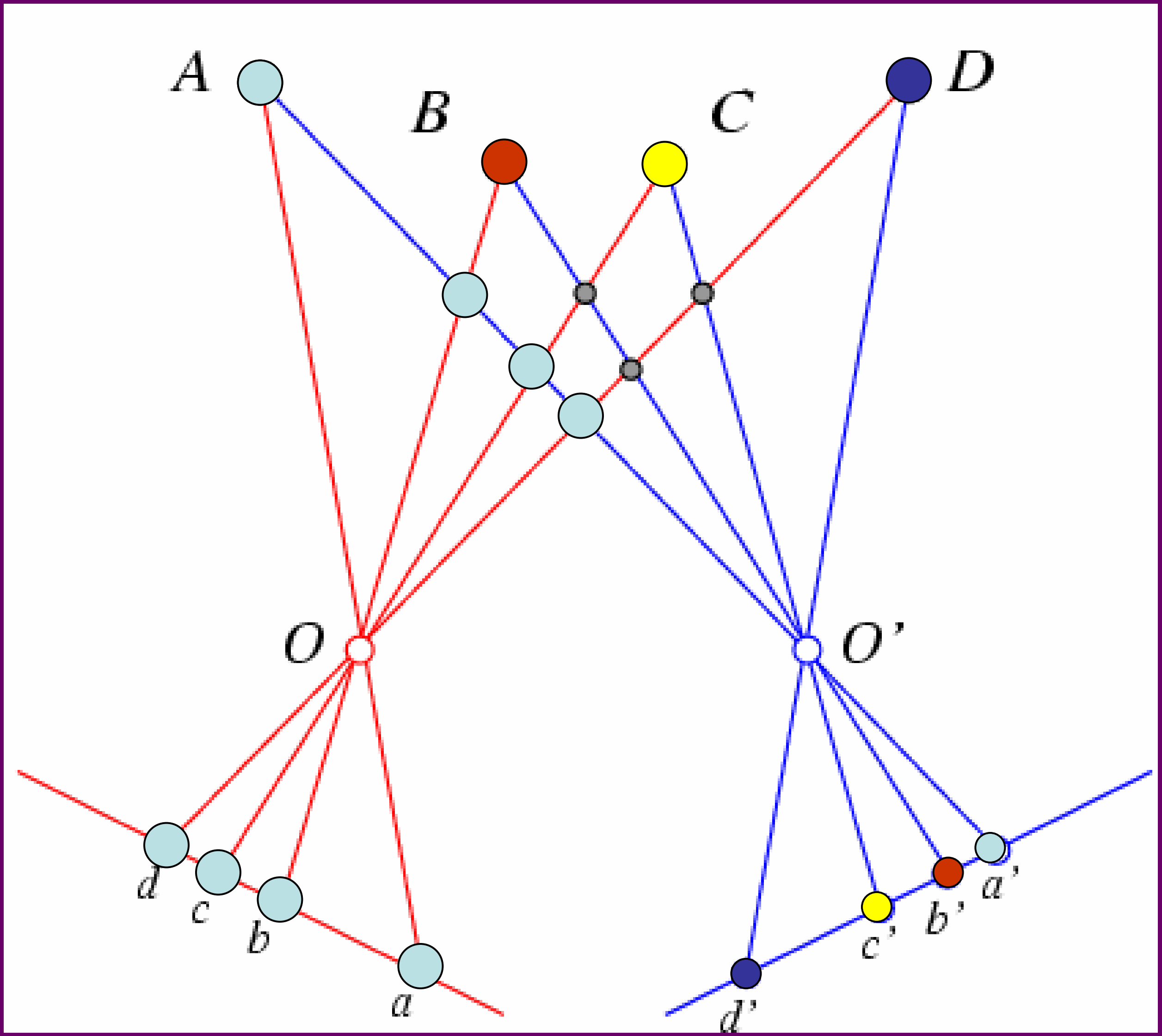
- Reading: Chapter 10

Many of the slides in this lecture are courtesy to Prof. J. Ponce

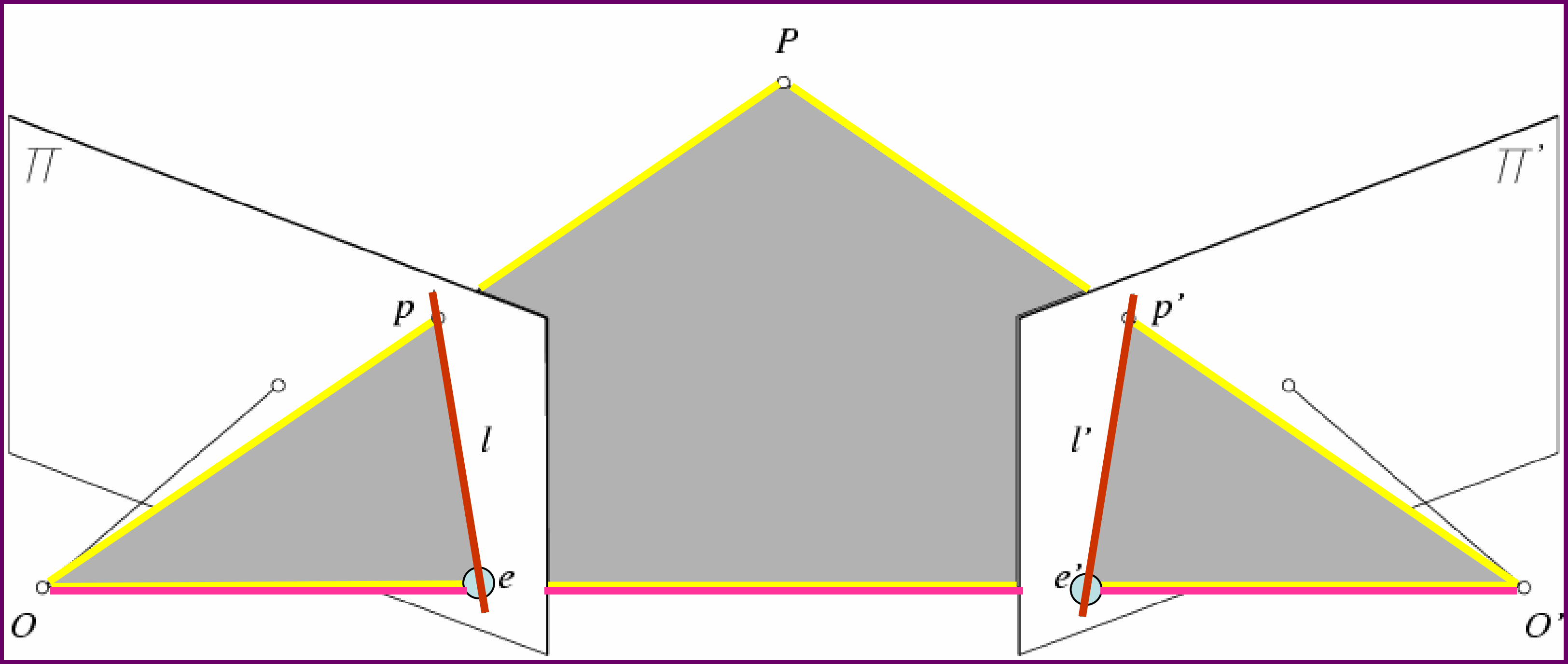
Reconstruction / Triangulation



(Binocular) Fusion

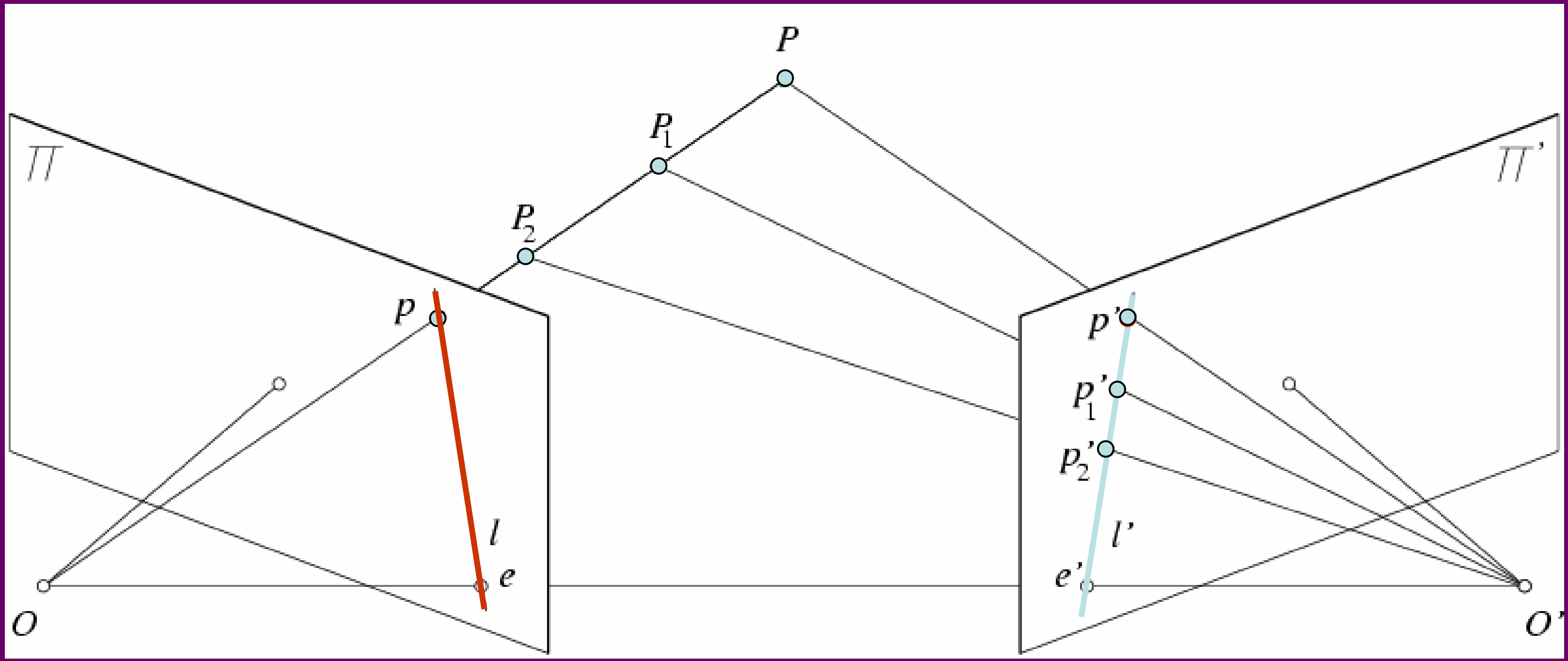


Epipolar Geometry



- Epipolar Plane
- Baseline
- Epipoles
- Epipolar Lines

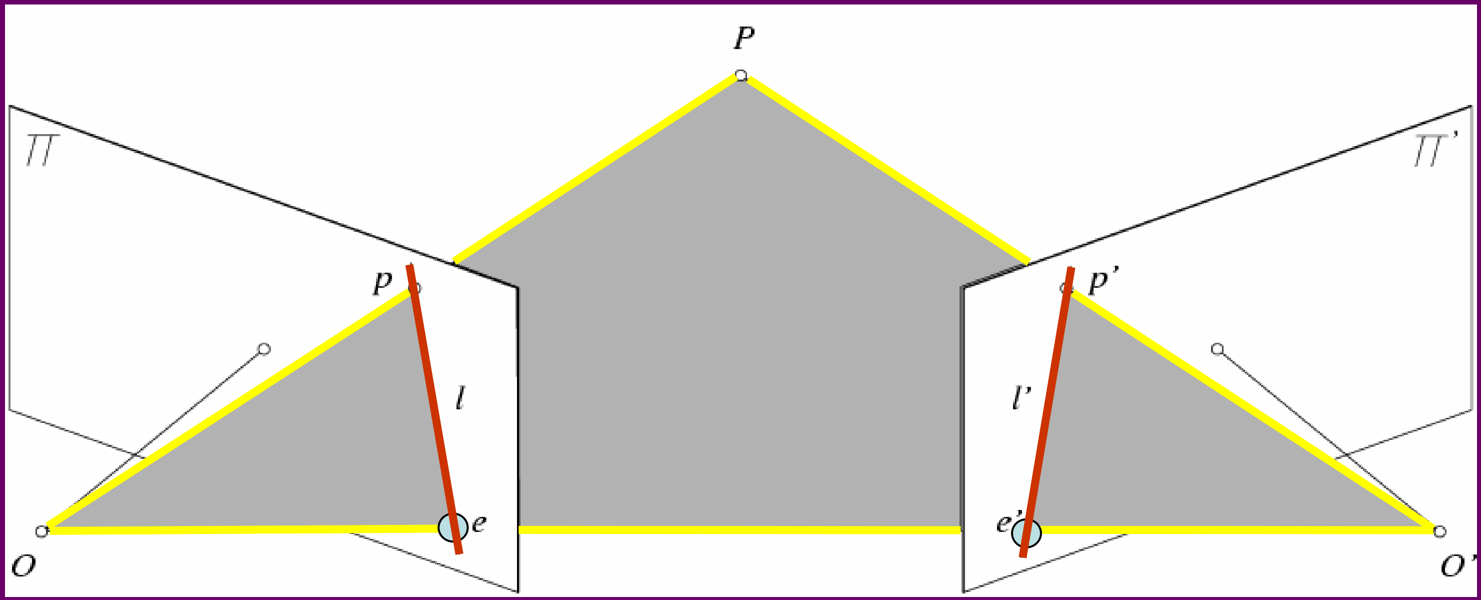
Epipolar Constraint



- Potential matches for *p* have to lie on the corresponding epipolar line *l'*.

- Potential matches for *p'* have to lie on the corresponding epipolar line *l*.

Epipolar Constraint: Calibrated Case



$$\overrightarrow{Op} \cdot [\overrightarrow{OO'} \times \overrightarrow{O'p'}] = 0$$

$$\boldsymbol{p} \cdot [\boldsymbol{t} \times (\mathcal{R}\boldsymbol{p}')] = 0 \quad \text{with} \begin{cases} \boldsymbol{p} = (u, v, 1)^T \\ \boldsymbol{p}' = (u', v', 1)^T \\ \mathcal{M} = (\text{Id} \quad \boldsymbol{0}) \\ \mathcal{M}' = (\mathcal{R}^T, -\mathcal{R}^T\boldsymbol{t}) \end{cases}$$

$$\boldsymbol{p}^T \mathcal{E} \boldsymbol{p}' = 0 \quad \text{with} \quad \mathcal{E} = [\boldsymbol{t}_\times]\mathcal{R}$$

Essential Matrix

(Longuet-Higgins, 1981)

Properties of the Essential Matrix

- $\mathcal{E}$ p' is the epipolar line associated with p'.
- $\mathcal{E}^T$ p is the epipolar line associated with p.
- $\mathcal{E}$ e'=0 and $\mathcal{E}^T$e=0.
- $\mathcal{E}$ is singular.
- $\mathcal{E}$ has two equal non-zero singular values (Huang and Faugeras, 1989).

Epipolar Constraint: Small Motions

$$\mathcal{R}(\boldsymbol{a},\theta) = e^{\theta[\boldsymbol{a}_\times]} \stackrel{\text{def}}{=} \sum_{i=0}^{+\infty} \frac{1}{i!}(\theta[\boldsymbol{a}_\times])^i$$

To First-Order:

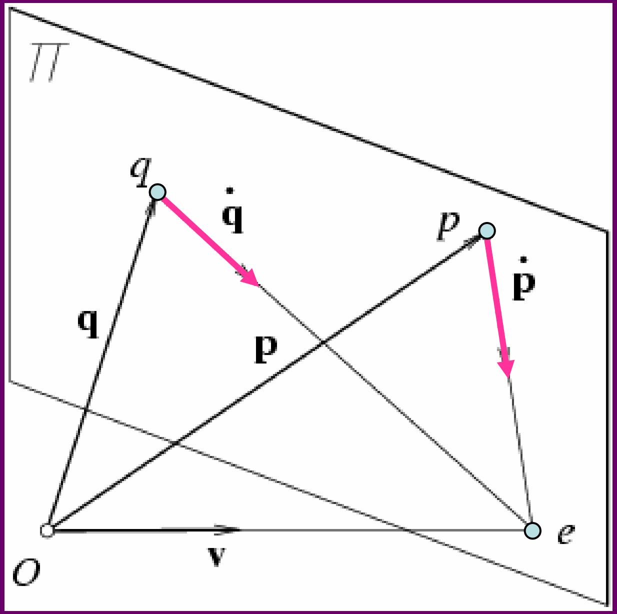
$$\begin{cases} \boldsymbol{t} = \delta t\, \boldsymbol{v} \\ \mathcal{R} = \mathrm{Id} + \delta t\, [\boldsymbol{\omega}_\times] \\ \boldsymbol{p}' = \boldsymbol{p} + \delta t\, \dot{\boldsymbol{p}} \end{cases}$$

$$\boldsymbol{p}^T \mathcal{E} \boldsymbol{p}' = 0 \quad \text{with} \quad \mathcal{E} = [\boldsymbol{t}_\times]\mathcal{R}$$

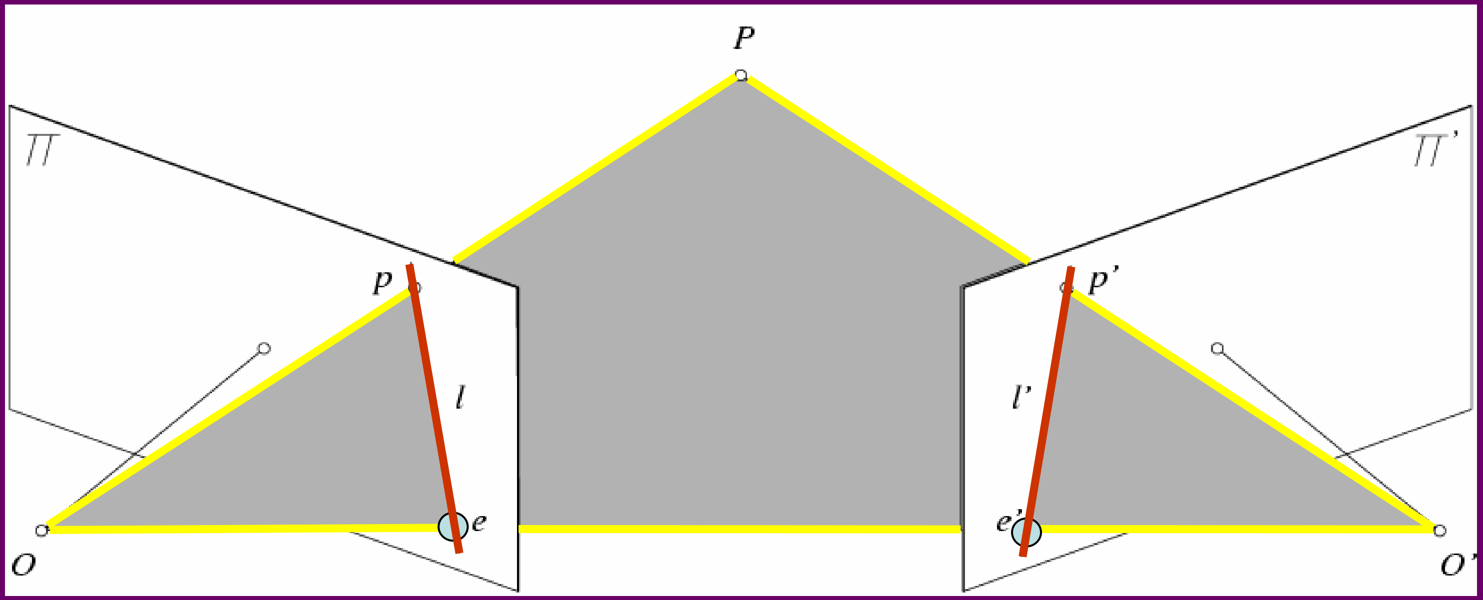
$$\boldsymbol{p}^T[\boldsymbol{v}_\times](\mathrm{Id} + \delta t\, [\boldsymbol{\omega}_\times])(\boldsymbol{p} + \delta t\, \dot{\boldsymbol{p}}) = 0$$

$$\boldsymbol{p}^T([\boldsymbol{v}_\times][\boldsymbol{\omega}_\times])\boldsymbol{p} - (\boldsymbol{p} \times \dot{\boldsymbol{p}}) \cdot \boldsymbol{v} = 0$$

Pure translation:
Focus of Expansion



Epipolar Constraint: Uncalibrated Case



$$\hat{\boldsymbol{p}}^T \mathcal{E} \hat{\boldsymbol{p}}' = 0$$

$$\boldsymbol{p} = \mathcal{K} \hat{\boldsymbol{p}}$$

$$\boldsymbol{p}' = \mathcal{K}' \hat{\boldsymbol{p}}'$$

$$\boldsymbol{p}^T \mathcal{F} \boldsymbol{p}' = 0 \quad \text{with} \quad \mathcal{F} = \mathcal{K}^{-T} \mathcal{E} \mathcal{K}'^{-1}$$

Fundamental Matrix

(Faugeras and Luong, 1992)

Properties of the Fundamental Matrix

- $\mathcal{F}$ p' is the epipolar line associated with p'.
- $\mathcal{F}^T$ p is the epipolar line associated with p.
- $\mathcal{F}$ e'=0 and $\mathcal{F}^T$ e=0.
- $\mathcal{F}$ is singular.

The Eight-Point Algorithm (Longuet-Higgins, 1981)

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

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

$$\begin{pmatrix} u_1u_1' & u_1v_1' & u_1 & v_1u_1' & v_1v_1' & v_1 & u_1' & v_1' \\ u_2u_2' & u_2v_2' & u_2 & v_2u_2' & v_2v_2' & v_2 & u_2' & v_2' \\ u_3u_3' & u_3v_3' & u_3 & v_3u_3' & v_3v_3' & v_3 & u_3' & v_3' \\ u_4u_4' & u_4v_4' & u_4 & v_4u_4' & v_4v_4' & v_4 & u_4' & v_4' \\ u_5u_5' & u_5v_5' & u_5 & v_5u_5' & v_5v_5' & v_5 & u_5' & v_5' \\ u_6u_6' & u_6v_6' & u_6 & v_6u_6' & v_6v_6' & v_6 & u_6' & v_6' \\ u_7u_7' & u_7v_7' & u_7 & v_7u_7' & v_7v_7' & v_7 & u_7' & v_7' \\ u_8u_8' & u_8v_8' & u_8 & v_8u_8' & v_8v_8' & v_8 & u_8' & v_8' \end{pmatrix}\begin{pmatrix} F_{11} \\ F_{12} \\ F_{13} \\ F_{21} \\ F_{22} \\ F_{23} \\ F_{31} \\ F_{32} \end{pmatrix} = -\begin{pmatrix} 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \end{pmatrix}$$

Minimize:

$$\sum_{i=1}^{n} (\boldsymbol{p}_i^T \mathcal{F} \boldsymbol{p}_i')^2$$

under the constraint

$|\mathcal{F}|^2 = 1.$

Non-Linear Least-Squares Approach (Luong et al., 1993)

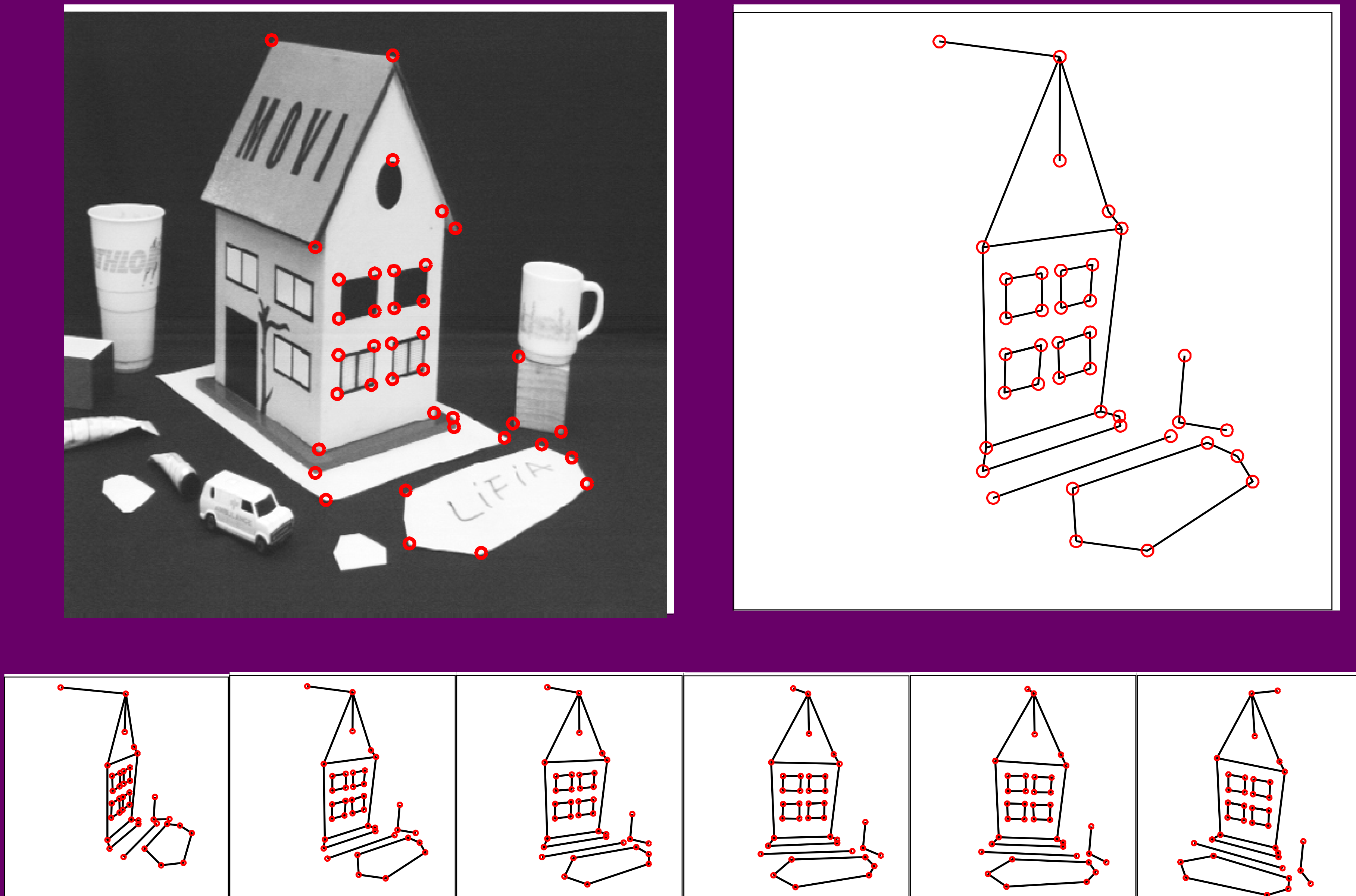
Minimize

$$\sum_{i=1}^{n}[\mathrm{d}^2(\boldsymbol{p}_i, \mathcal{F}\boldsymbol{p}'_i) + \mathrm{d}^2(\boldsymbol{p}'_i, \mathcal{F}^T\boldsymbol{p}_i)]$$

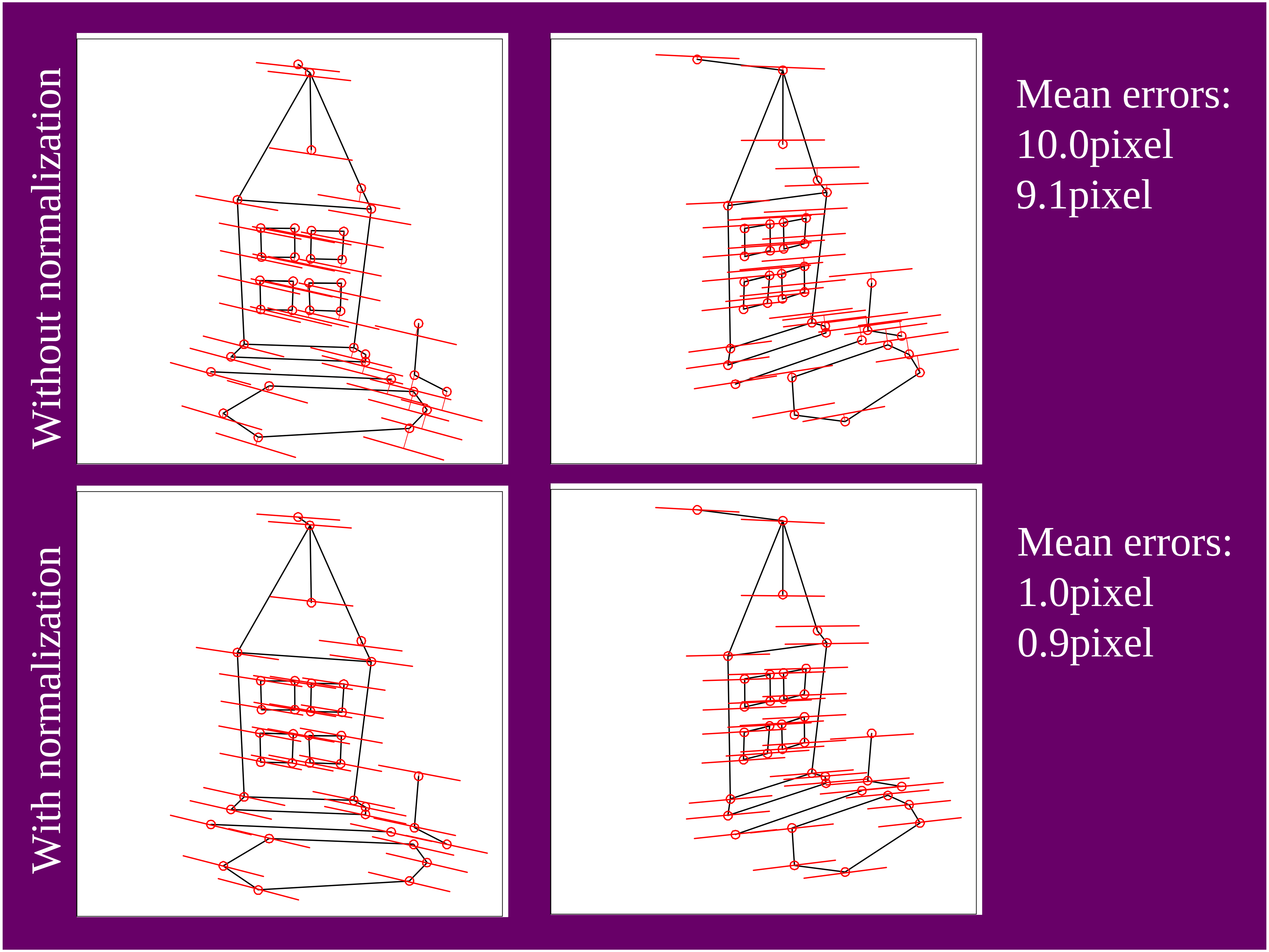
with respect to the coefficients of $\mathcal{F}$, using an appropriate rank-2 parameterization.

The Normalized Eight-Point Algorithm (Hartley, 1995)

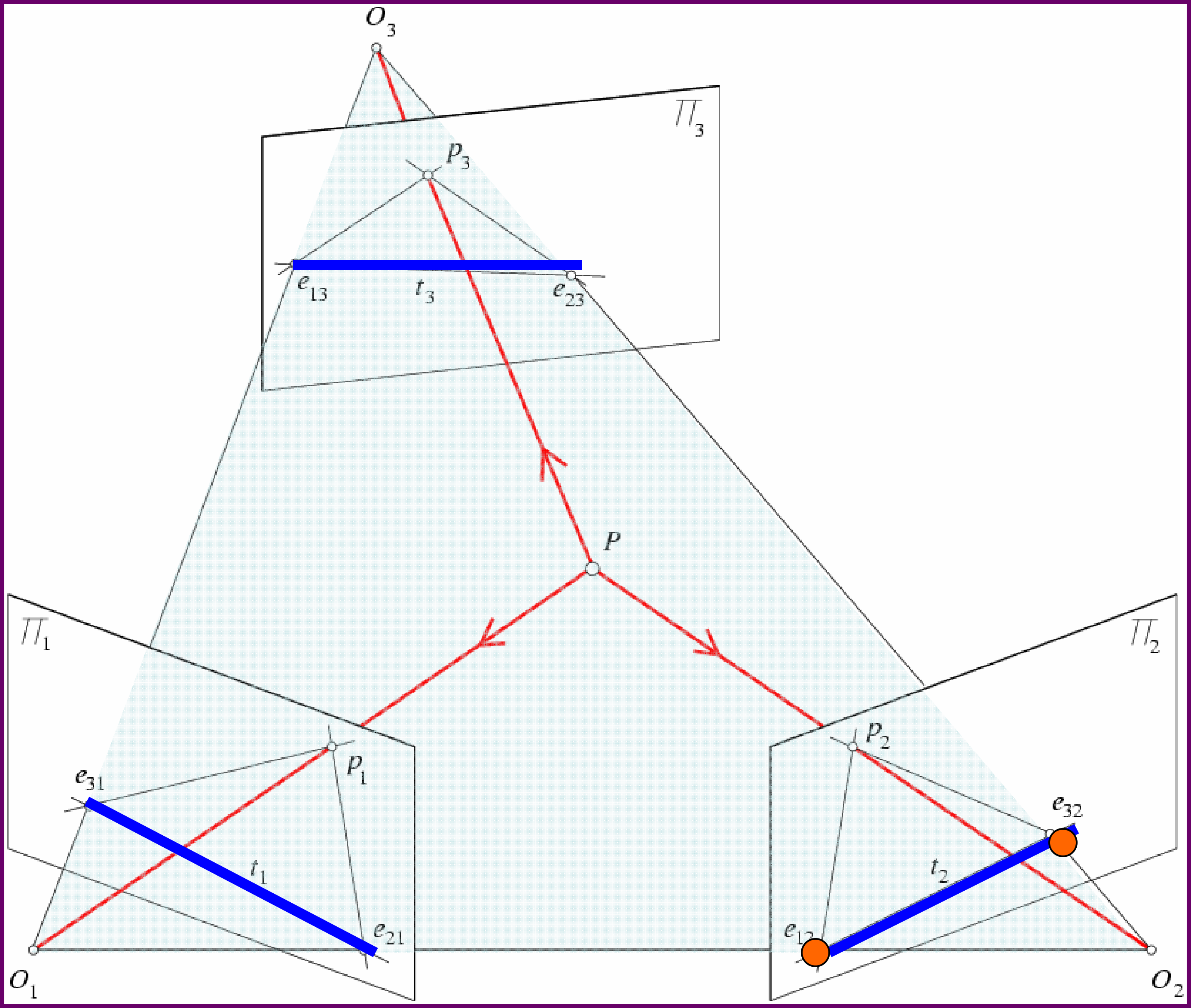
- Center the image data at the origin, and scale it so the mean squared distance between the origin and the data points is 2 pixels: $q_i = T p_i$, $q'_i = T' p'_i$.
- Use the eight-point algorithm to compute $\mathcal{F}$ from the points q_i and q'_i .
- Enforce the rank-2 constraint.
- Output $T^T \mathcal{F} T'$.



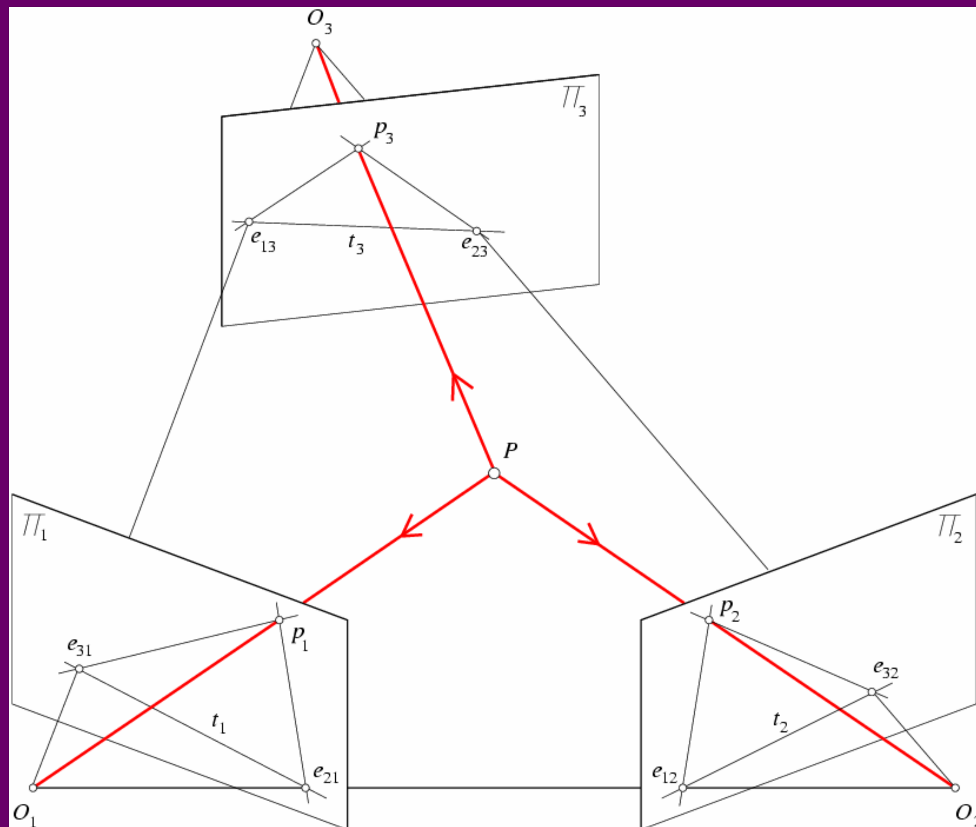
Data courtesy of R. Mohr and B. Boufama.


Without normalization
Mean errors:
10.0pixel
9.1pixel
With normalization
Mean errors:
1.0pixel
0.9pixel

Trinocular Epipolar Constraints



Trinocular Epipolar Constraints

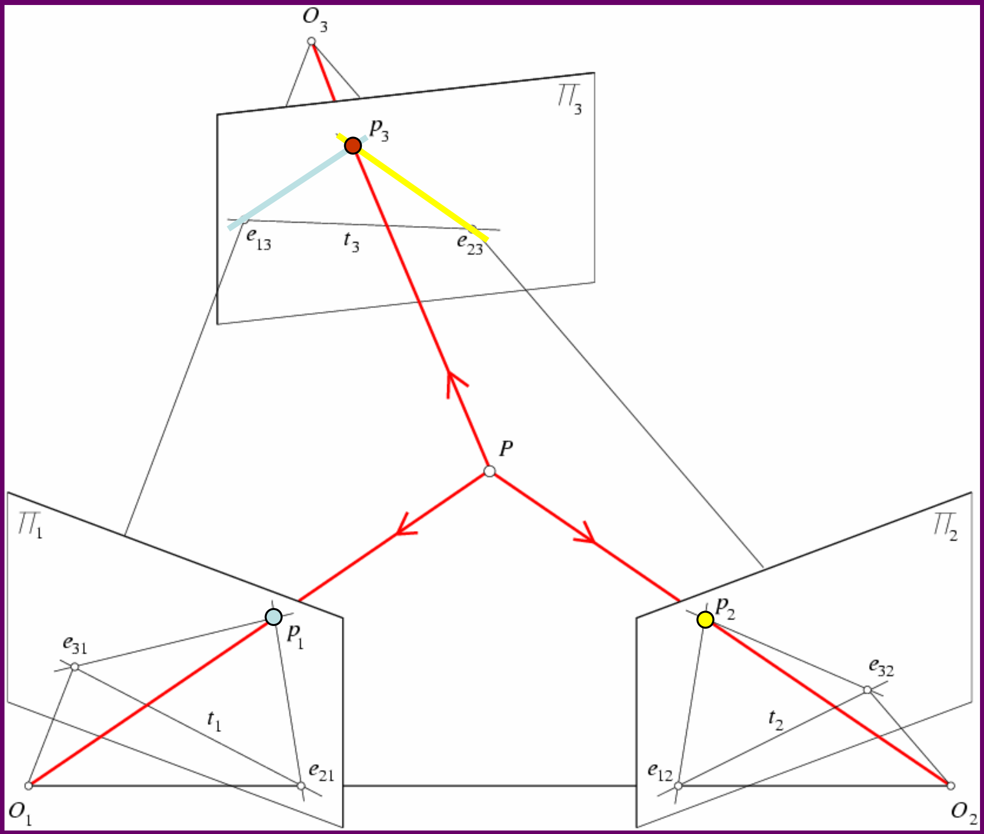


$$\begin{cases} \boldsymbol{p}_1^T \mathcal{E}_{12} \boldsymbol{p}_2 = 0 \\ \boldsymbol{p}_2^T \mathcal{E}_{23} \boldsymbol{p}_3 = 0 \\ \boldsymbol{p}_3^T \mathcal{E}_{31} \boldsymbol{p}_1 = 0 \end{cases}$$

These constraints are not independent!

$$\boldsymbol{e}_{31}^T \mathcal{E}_{12} \boldsymbol{e}_{32} = \boldsymbol{e}_{12}^T \mathcal{E}_{23} \boldsymbol{e}_{13} = \boldsymbol{e}_{23}^T \mathcal{E}_{31} \boldsymbol{e}_{21} = 0$$

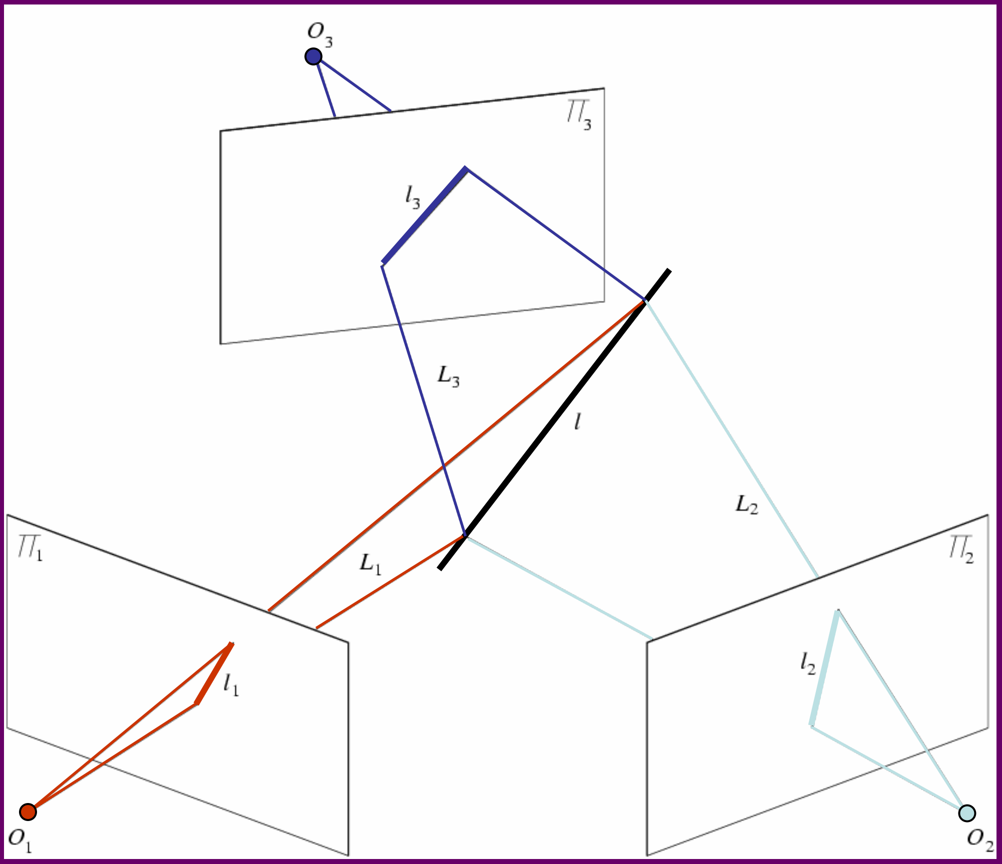
Trinocular Epipolar Constraints: Transfer



$$\begin{cases} \boldsymbol{p}_1^T \mathcal{E}_{12} \boldsymbol{p}_2 = 0 \\ \boldsymbol{p}_2^T \mathcal{E}_{23} \boldsymbol{p}_3 = 0 \\ \boldsymbol{p}_3^T \mathcal{E}_{31} \boldsymbol{p}_1 = 0 \end{cases}$$

Given p_1 and p_2, p_3 can be computed as the solution of linear equations.

Trifocal Constraints



$$z\boldsymbol{p} = \mathcal{M}\boldsymbol{P} \Longleftrightarrow \boldsymbol{l}^T\mathcal{M}\boldsymbol{P} = 0 \Longleftrightarrow \boldsymbol{L}\cdot\boldsymbol{P} = 0 \text{ with } \boldsymbol{L} = \mathcal{M}^T\boldsymbol{l}$$

$$\begin{pmatrix} \boldsymbol{L}_1^T \\ \boldsymbol{L}_2^T \\ \boldsymbol{L}_3^T \end{pmatrix} \boldsymbol{P} = \boldsymbol{0}$$

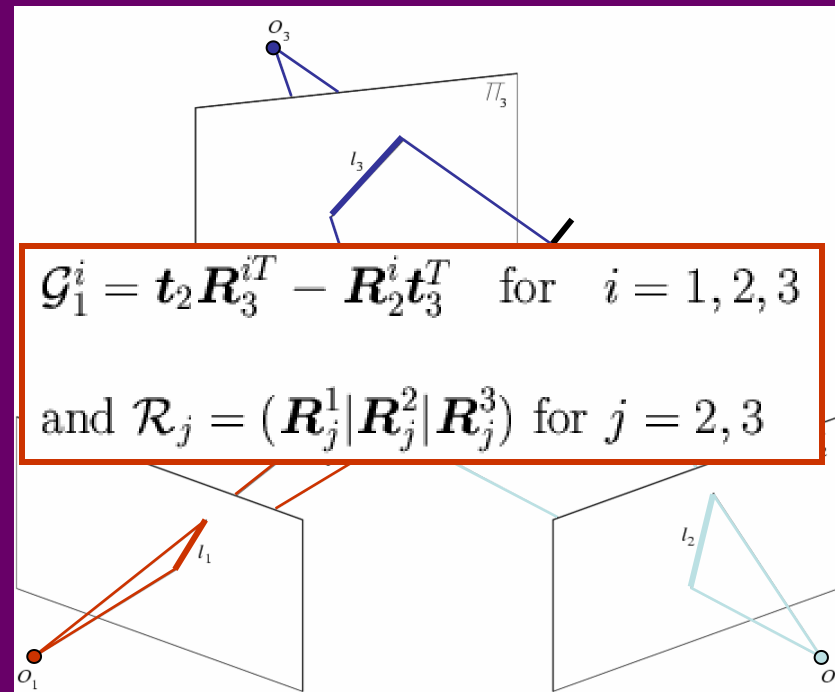
$$\text{Rank}(\mathcal{L}) = 2 \quad \text{where} \quad \mathcal{L} \stackrel{\text{def}}{=} \begin{pmatrix} \boldsymbol{l}_1^T\mathcal{M}_1 \\ \boldsymbol{l}_2^T\mathcal{M}_2 \\ \boldsymbol{l}_3^T\mathcal{M}_3 \end{pmatrix}$$

Trifocal Constraints

Calibrated Case

$$\text{Rank}(\mathcal{L}) = 2 \quad \text{where} \quad \mathcal{L} \stackrel{\text{def}}{=} \begin{pmatrix} \boldsymbol{l}_1^T \mathcal{M}_1 \\ \boldsymbol{l}_2^T \mathcal{M}_2 \\ \boldsymbol{l}_3^T \mathcal{M}_3 \end{pmatrix}$$

All 3x3 minors must be zero!



$$\mathcal{G}_1^i = \boldsymbol{t}_2 \boldsymbol{R}_3^{iT} - \boldsymbol{R}_2^i \boldsymbol{t}_3^T \quad \text{for} \quad i = 1, 2, 3$$

$$\text{and } \mathcal{R}_j = (\boldsymbol{R}_j^1 | \boldsymbol{R}_j^2 | \boldsymbol{R}_j^3) \text{ for } j = 2, 3$$

$$\text{Pick} \quad \mathcal{M}_1 = (\,\text{Id} \quad \boldsymbol{0}\,)\,, \quad \mathcal{M}_2 = (\,\mathcal{R}_2 \quad \boldsymbol{t}_2\,) \quad \text{and} \quad \mathcal{M}_3 = (\,\mathcal{R}_3 \quad \boldsymbol{t}_3\,)\,.$$

$$\mathcal{L} = \begin{pmatrix} \boldsymbol{l}_1^T & 0 \\ \boldsymbol{l}_2^T \mathcal{R}_2 & \boldsymbol{l}_2^T \boldsymbol{t}_2 \\ \boldsymbol{l}_3^T \mathcal{R}_3 & \boldsymbol{l}_3^T \boldsymbol{t}_3 \end{pmatrix}$$

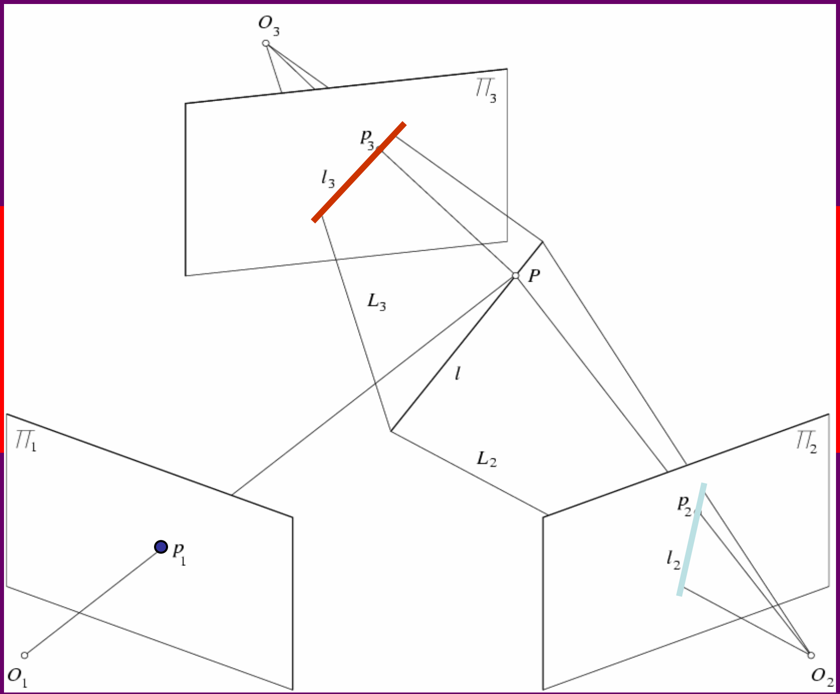
$$\boldsymbol{p}_1^T \begin{pmatrix} \boldsymbol{l}_2^T \mathcal{G}_1^1 \boldsymbol{l}_3 \\ \boldsymbol{l}_2^T \mathcal{G}_1^2 \boldsymbol{l}_3 \\ \boldsymbol{l}_2^T \mathcal{G}_1^3 \boldsymbol{l}_3 \end{pmatrix} = 0$$

$$\begin{matrix} \mathcal{G}_1^1 \\ \mathcal{G}_1^2 \\ \mathcal{G}_1^3 \end{matrix}$$

Trifocal Tensor

Trifocal Constraints

Uncalibrated Case



$$\text{Rank}(\mathcal{L}) = 2 \quad \text{where} \quad \mathcal{L} \stackrel{\text{def}}{=} \begin{pmatrix} \boldsymbol{l}_1^T \mathcal{M}_1 \\ \boldsymbol{l}_2^T \mathcal{M}_2 \\ \boldsymbol{l}_3^T \mathcal{M}_3 \end{pmatrix}$$

$$\mathcal{L} = \begin{pmatrix} \boldsymbol{l}_1^T \mathcal{K}_1 & 0 \\ \boldsymbol{l}_2^T \mathcal{K}_2 \mathcal{R}_2 & \boldsymbol{l}_2^T \mathcal{K}_2 \boldsymbol{t}_2 \\ \boldsymbol{l}_3^T \mathcal{K}_3 \mathcal{R}_3 & \boldsymbol{l}_3^T \mathcal{K}_3 \boldsymbol{t}_3 \end{pmatrix}$$

Pick $\mathcal{M}_1 = (\,\mathcal{K}_1 \quad \boldsymbol{0}\,)$, $\mathcal{M}_2 = (\,\mathcal{A}_2\mathcal{K}_1 \quad \boldsymbol{a}_2\,)$ and $\mathcal{M}_3 = (\,\mathcal{A}_3\mathcal{K}_1 \quad \boldsymbol{a}_3\,)$.

$$\boldsymbol{l}_1 \propto \begin{pmatrix} \boldsymbol{l}_2^T \mathcal{G}_1^1 \boldsymbol{l}_3 \\ \boldsymbol{l}_2^T \mathcal{G}_1^2 \boldsymbol{l}_3 \\ \boldsymbol{l}_2^T \mathcal{G}_1^3 \boldsymbol{l}_3 \end{pmatrix} \Rightarrow \boldsymbol{p}_1^T \begin{pmatrix} \boldsymbol{l}_2^T \mathcal{G}_1^1 \boldsymbol{l}_3 \\ \boldsymbol{l}_2^T \mathcal{G}_1^2 \boldsymbol{l}_3 \\ \boldsymbol{l}_2^T \mathcal{G}_1^3 \boldsymbol{l}_3 \end{pmatrix} = 0 \Rightarrow \begin{matrix} \mathcal{G}_1^1 \\ \mathcal{G}_1^2 \\ \mathcal{G}_1^3 \end{matrix}$$

Trifocal Tensor

Properties of the Trifocal Tensor

- For any matching epipolar lines, $\boldsymbol{l}_2^{\mathrm{T}} \mathcal{G}_1^i \boldsymbol{l}_3 = 0$.

- The matrices $\mathcal{G}_1^i$ are singular.

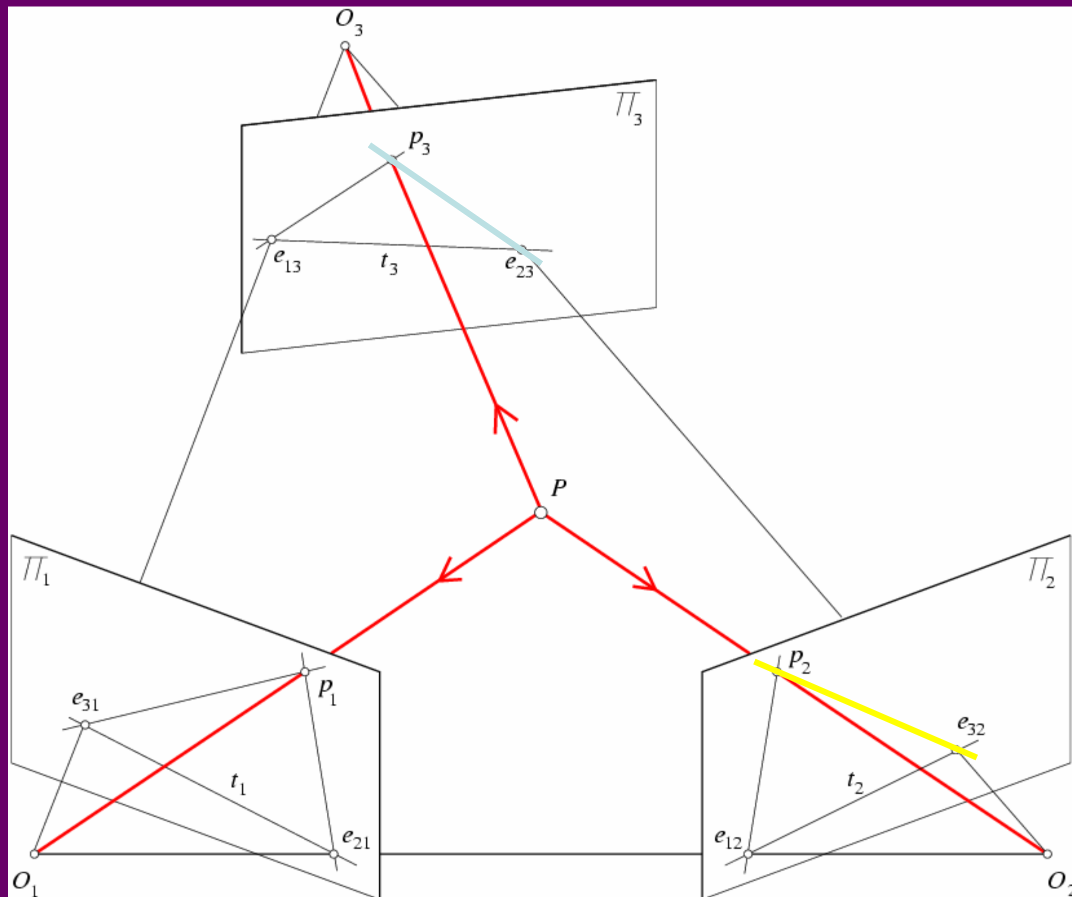
- They satisfy 8 independent constraints in the uncalibrated case (Faugeras and Mourrain, 1995).

Estimating the Trifocal Tensor

- Ignore the non-linear constraints and use linear least-squares a posteriori.

- Impose the constraints a posteriori.

For any matching epipolar lines, $\boldsymbol{l}_2^{\mathrm{T}} \mathcal{G}_1^i \boldsymbol{l}_3 = 0$.



The backprojections of the two lines do not define a line!

Multiple Views (Faugeras and Mourrain, 1995)

$$z\boldsymbol{p} = \mathcal{M}\boldsymbol{P} \Longleftrightarrow \boldsymbol{p} \times (\mathcal{M}\boldsymbol{P}) = ([\boldsymbol{p}_\times]\mathcal{M})\boldsymbol{P} = 0$$

$$\begin{pmatrix} u\mathcal{M}^3 - \mathcal{M}^1 \\ v\mathcal{M}^3 - \mathcal{M}^2 \end{pmatrix} \boldsymbol{P} = 0 \quad \text{where} \quad \mathcal{M} = \begin{pmatrix} \mathcal{M}^1 \\ \mathcal{M}^2 \\ \mathcal{M}^3 \end{pmatrix}$$

$$\mathcal{Q}\boldsymbol{P} = 0 \quad \text{where} \quad \mathcal{Q} \stackrel{\text{def}}{=} \begin{pmatrix} u_1\mathcal{M}_1^3 - \mathcal{M}_1^1 \\ v_1\mathcal{M}_1^3 - \mathcal{M}_1^2 \\ u_2\mathcal{M}_2^3 - \mathcal{M}_2^1 \\ v_2\mathcal{M}_2^3 - \mathcal{M}_2^2 \\ u_3\mathcal{M}_3^3 - \mathcal{M}_3^1 \\ v_3\mathcal{M}_3^3 - \mathcal{M}_3^2 \\ u_4\mathcal{M}_4^3 - \mathcal{M}_4^1 \\ v_4\mathcal{M}_4^3 - \mathcal{M}_4^2 \end{pmatrix} \Longrightarrow \boxed{\text{Rank}(\mathcal{Q}) \le 3}$$

Two Views

$$\mathcal{Q}\boldsymbol{P} = 0 \quad \text{where} \quad \mathcal{Q} \stackrel{\text{def}}{=} \begin{pmatrix} u_1\mathcal{M}_1^3 - \mathcal{M}_1^1 \\ v_1\mathcal{M}_1^3 - \mathcal{M}_1^2 \\ u_2\mathcal{M}_2^3 - \mathcal{M}_2^1 \\ v_2\mathcal{M}_2^3 - \mathcal{M}_2^2 \\ u_3\mathcal{M}_3^3 - \mathcal{M}_3^1 \\ v_3\mathcal{M}_3^3 - \mathcal{M}_3^2 \\ u_4\mathcal{M}_4^3 - \mathcal{M}_4^1 \\ v_4\mathcal{M}_4^3 - \mathcal{M}_4^2 \end{pmatrix} \implies \text{Rank}(\mathcal{Q}) \le 3$$

$$\text{Det}\begin{pmatrix} u_1\mathcal{M}_1^3 - \mathcal{M}_1^1 \\ v_1\mathcal{M}_1^3 - \mathcal{M}_1^2 \\ u_2\mathcal{M}_2^3 - \mathcal{M}_2^1 \\ v_2\mathcal{M}_2^3 - \mathcal{M}_2^2 \end{pmatrix} = 0$$

⇨ Epipolar Constraint

Three Views

$$\mathcal{Q}\boldsymbol{P} = 0 \quad \text{where} \quad \mathcal{Q} \stackrel{\text{def}}{=} \begin{pmatrix} u_1\mathcal{M}_1^3 - \mathcal{M}_1^1 \\ v_1\mathcal{M}_1^3 - \mathcal{M}_1^2 \\ u_2\mathcal{M}_2^3 - \mathcal{M}_2^1 \\ v_2\mathcal{M}_2^3 - \mathcal{M}_2^2 \\ u_3\mathcal{M}_3^3 - \mathcal{M}_3^1 \\ v_3\mathcal{M}_3^3 - \mathcal{M}_3^2 \\ u_4\mathcal{M}_4^3 - \mathcal{M}_4^1 \\ v_4\mathcal{M}_4^3 - \mathcal{M}_4^2 \end{pmatrix} \implies \text{Rank}(\mathcal{Q}) \leq 3$$

$$\text{Det}\begin{pmatrix} u_1\mathcal{M}_1^3 - \mathcal{M}_1^1 \\ v_1\mathcal{M}_1^3 - \mathcal{M}_1^2 \\ u_2\mathcal{M}_2^3 - \mathcal{M}_2^1 \\ v_3\mathcal{M}_3^3 - \mathcal{M}_3^2 \end{pmatrix} = 0$$

⇒ Trifocal Constraint

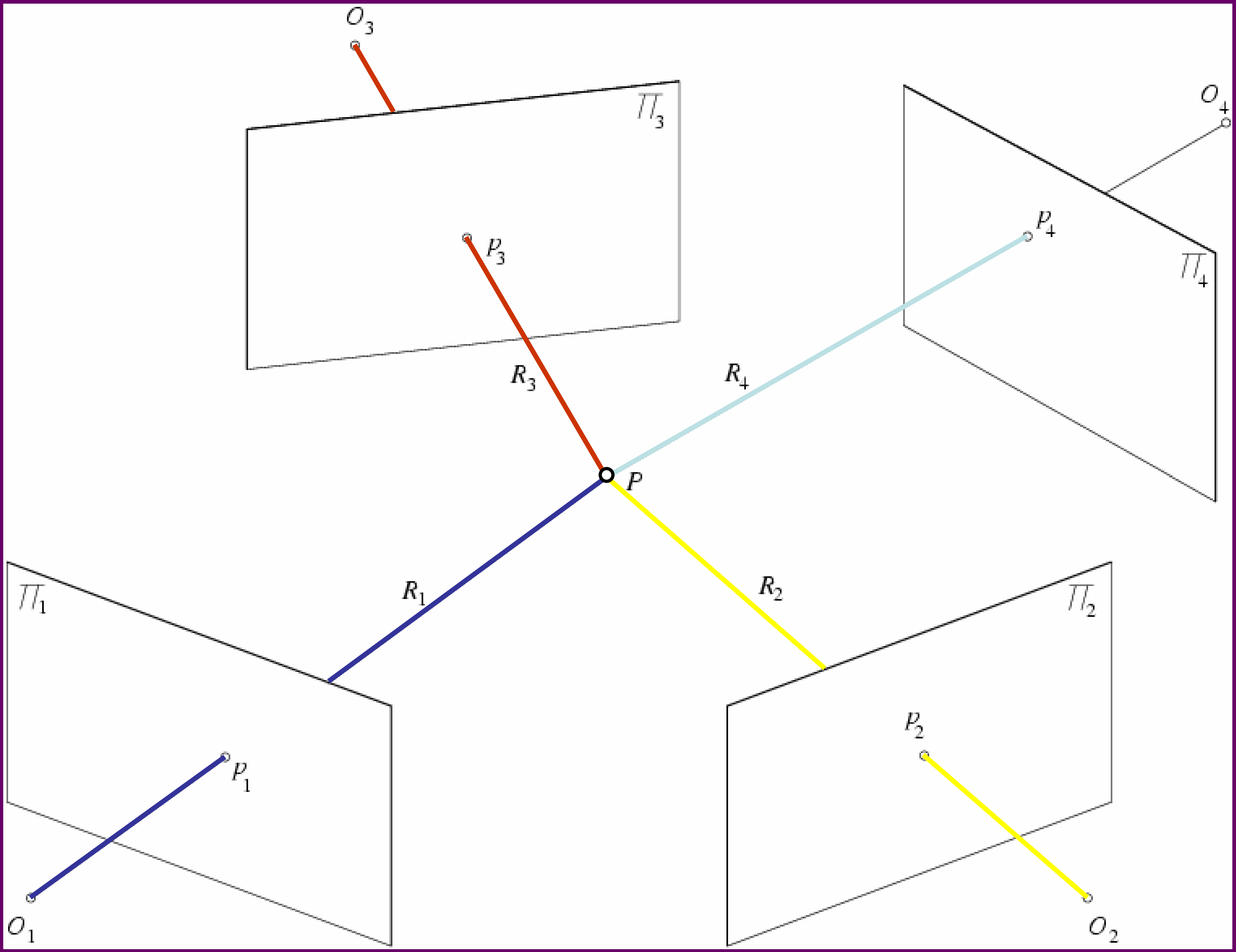
Four Views

$$\boldsymbol{\mathcal{Q}}\boldsymbol{P} = 0 \quad \text{where} \quad \boldsymbol{\mathcal{Q}} \stackrel{\text{def}}{=} \begin{pmatrix} u_1\mathcal{M}_1^3 - \mathcal{M}_1^1 \\ v_1\mathcal{M}_1^3 - \mathcal{M}_1^2 \\ u_2\mathcal{M}_2^3 - \mathcal{M}_2^1 \\ v_2\mathcal{M}_2^3 - \mathcal{M}_2^2 \\ u_3\mathcal{M}_3^3 - \mathcal{M}_3^1 \\ v_3\mathcal{M}_3^3 - \mathcal{M}_3^2 \\ u_4\mathcal{M}_4^3 - \mathcal{M}_4^1 \\ v_4\mathcal{M}_4^3 - \mathcal{M}_4^2 \end{pmatrix} \Longrightarrow \text{Rank}(\boldsymbol{\mathcal{Q}}) \leq 3$$

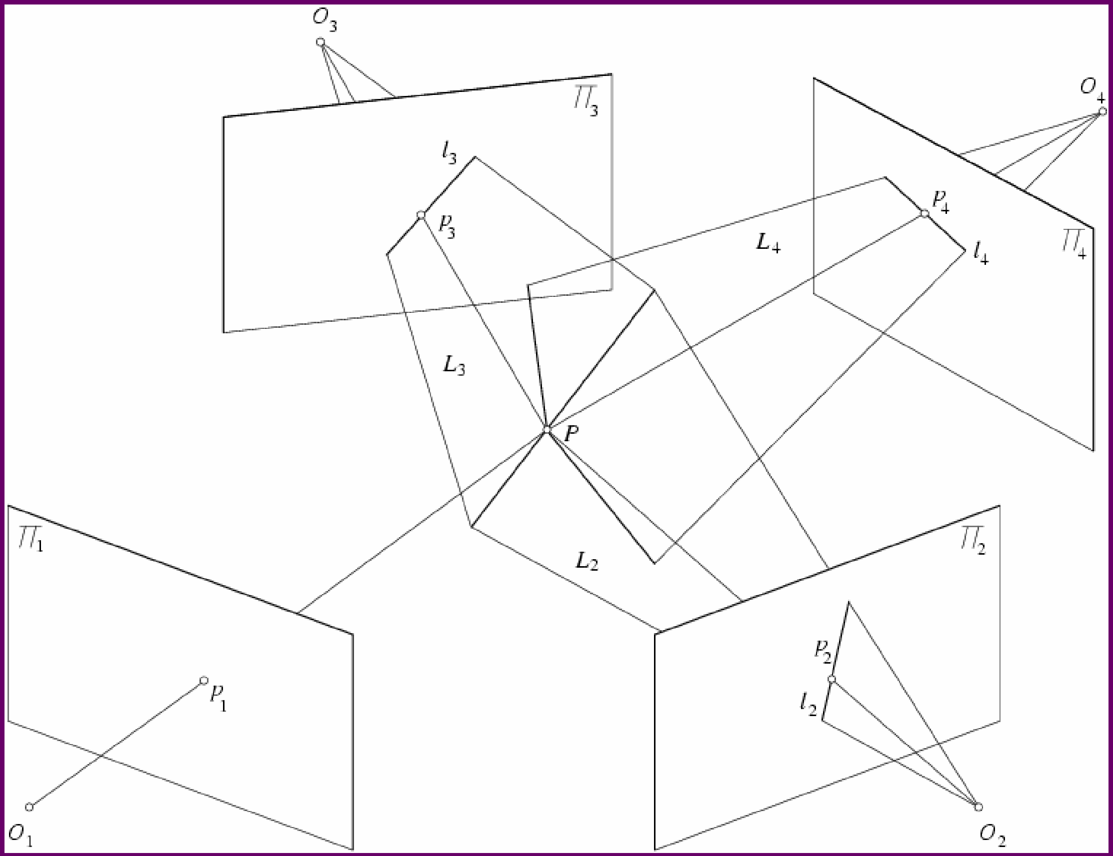
$$\text{Det}\begin{pmatrix} v_1\mathcal{M}_1^3 - \mathcal{M}_1^2 \\ u_2\mathcal{M}_2^3 - \mathcal{M}_2^1 \\ v_3\mathcal{M}_3^3 - \mathcal{M}_3^2 \\ v_4\mathcal{M}_4^3 - \mathcal{M}_4^2 \end{pmatrix} = 0$$

Quadrifocal Constraint
(Triggs, 1995)

Geometrically, the four rays must intersect in *P*..



Quadrifocal Tensor and Lines



$$z\boldsymbol{p} = \mathcal{M}\boldsymbol{P} \iff \boldsymbol{l}^T\mathcal{M}\boldsymbol{P} = 0 \iff \boldsymbol{L}\cdot\boldsymbol{P} = 0 \text{ with } \boldsymbol{L} = \mathcal{M}^T\boldsymbol{l}$$

$$\begin{pmatrix} \boldsymbol{L}_1^T \\ \boldsymbol{L}_2^T \\ \boldsymbol{L}_3^T \\ \boldsymbol{L}_4^T \end{pmatrix} \boldsymbol{P} = \boldsymbol{0}$$

$$\text{Rank}(\mathcal{L}) = 3 \quad \text{where} \quad \mathcal{L} \stackrel{\text{def}}{=} \begin{pmatrix} \boldsymbol{l}_1^T\mathcal{M}_1 \\ \boldsymbol{l}_2^T\mathcal{M}_2 \\ \boldsymbol{l}_3^T\mathcal{M}_3 \\ \boldsymbol{l}_3^T\mathcal{M}_4 \end{pmatrix}$$

Scale-Restraint Condition from Photogrammetry