



Multi-View Geometry Part II (Ch7 New book. Ch 10/11 old book)

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Credits: M. Shah, UCF CAP5415, lecture 23

<http://www.cs.ucf.edu/courses/cap6411/cap5415/>, Trevor Darrell, Berkeley, C280, Marc Pollefeys



Multi-View Geometry

Relates



Multi-View Geometry

Relates

- 3D World Points

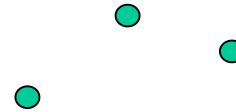




Multi-View Geometry

Relates

- 3D World Points
- Camera Centers

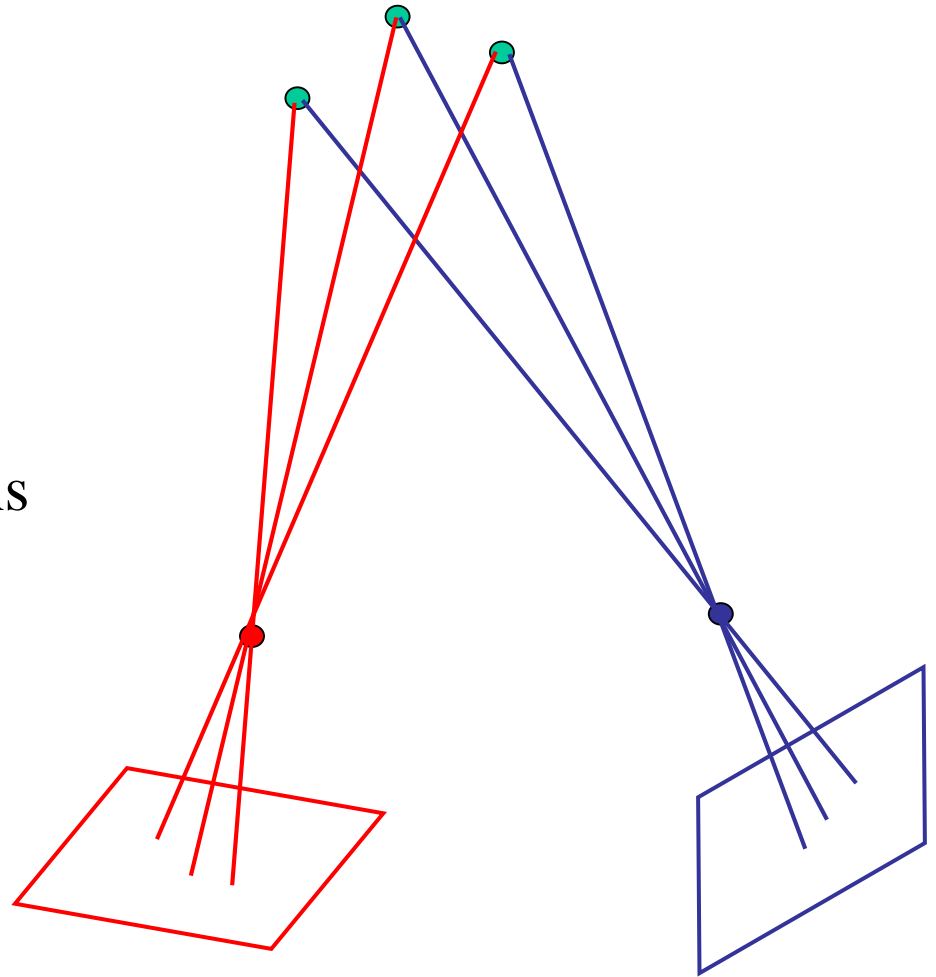




Multi-View Geometry

Relates

- 3D World Points
- Camera Centers
- Camera Orientations

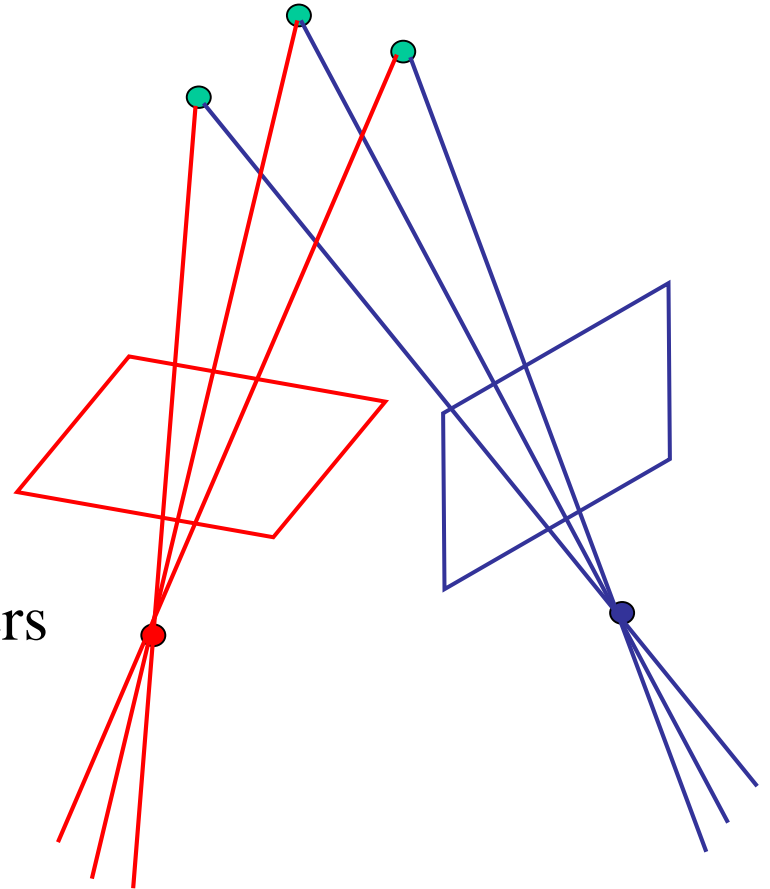




Multi-View Geometry

Relates

- 3D World Points
- Camera Centers
- Camera Orientations
- Camera Intrinsic Parameters

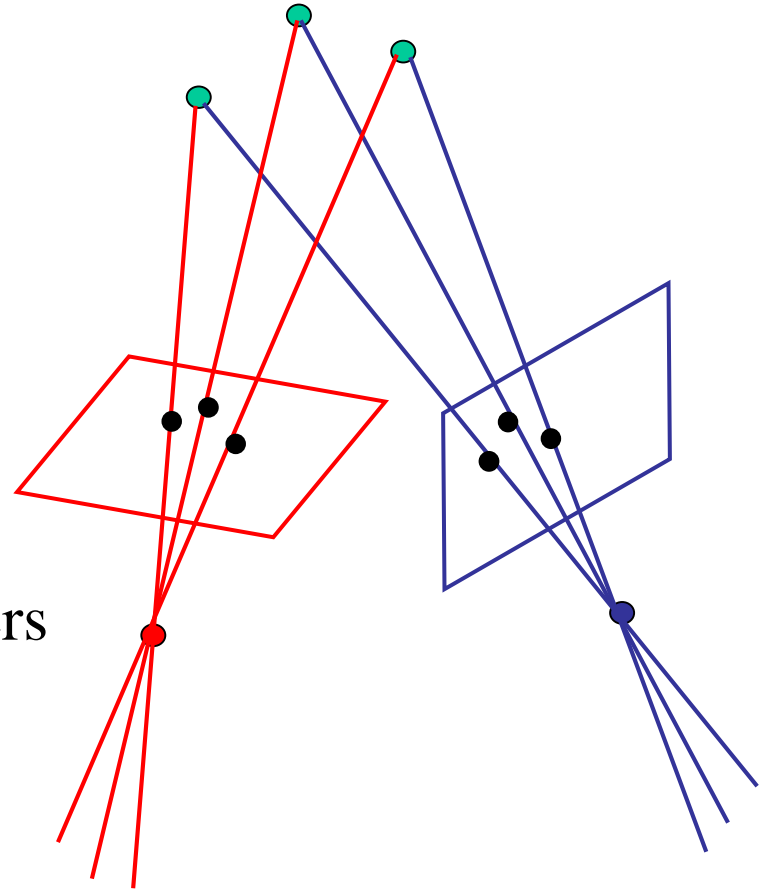




Multi-View Geometry

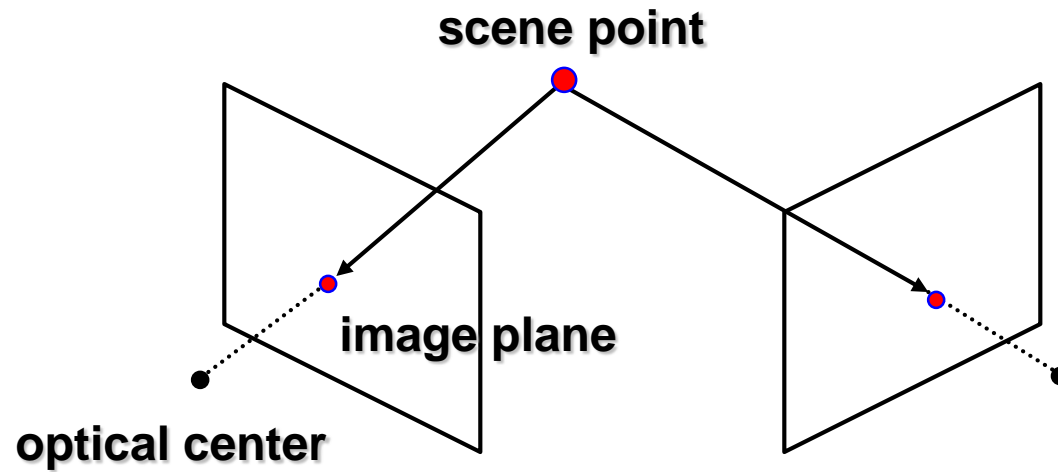
Relates

- 3D World Points
- Camera Centers
- Camera Orientations
- Camera Intrinsic Parameters
- Image Points



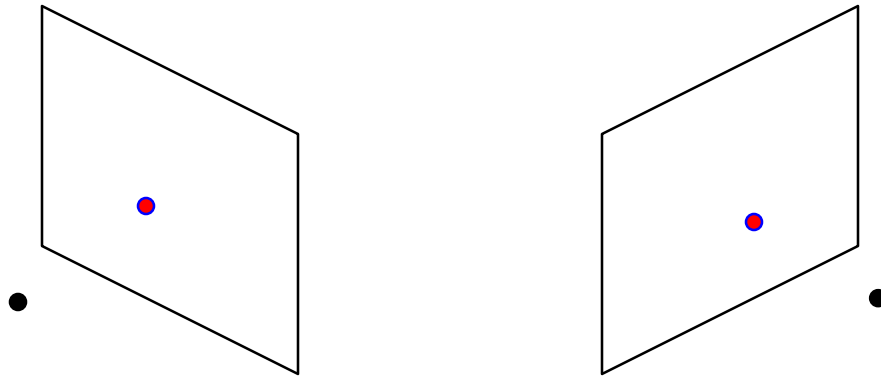


Stereo





Stereo

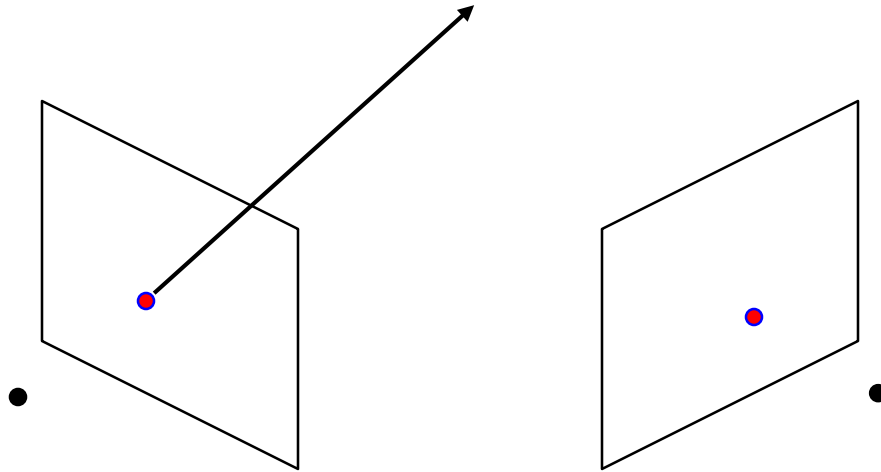


Basic Principle: Triangulation

- Gives reconstruction as intersection of two rays



Stereo

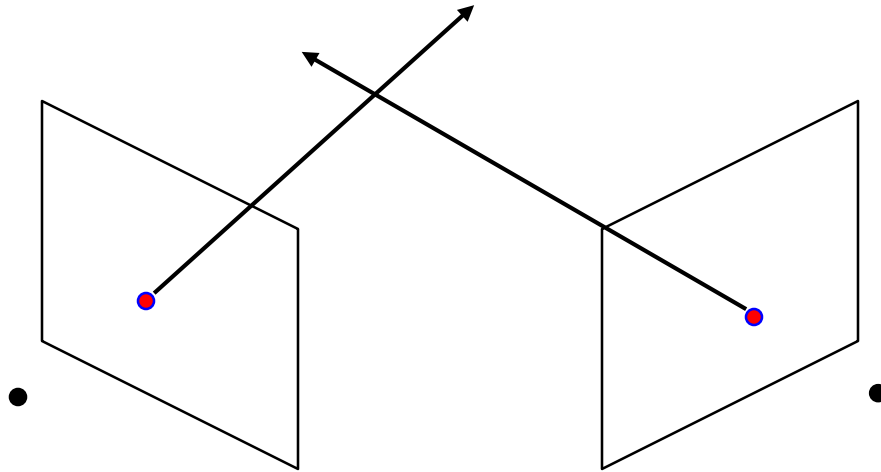


Basic Principle: Triangulation

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Stereo

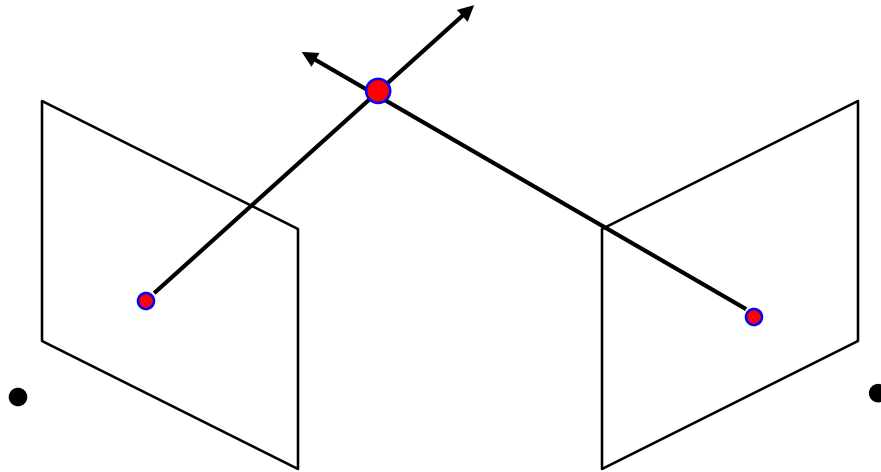


Basic Principle: Triangulation

- Gives reconstruction as intersection of two rays



Stereo

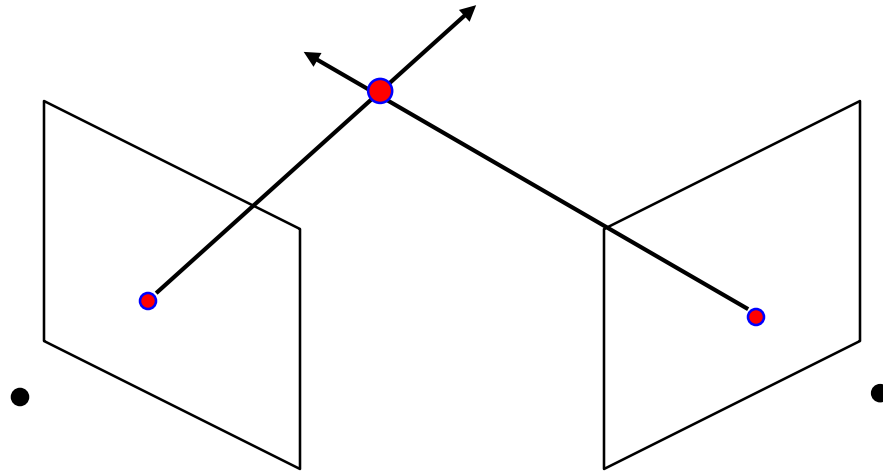


Basic Principle: Triangulation

- Gives reconstruction as intersection of two rays



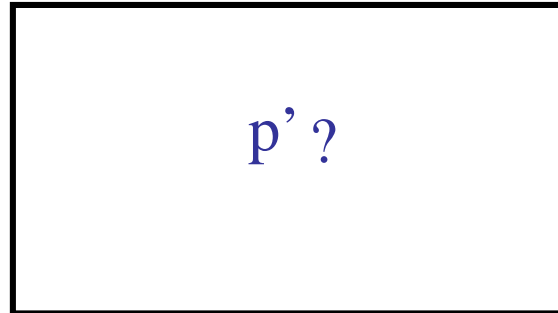
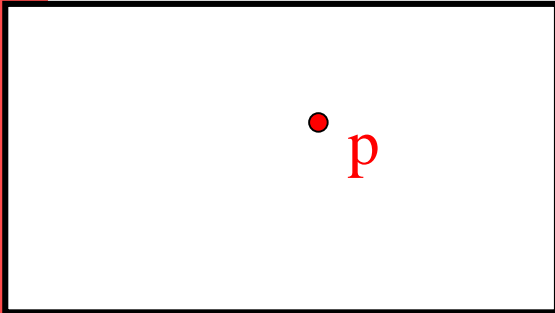
Stereo



Basic Principle: Triangulation

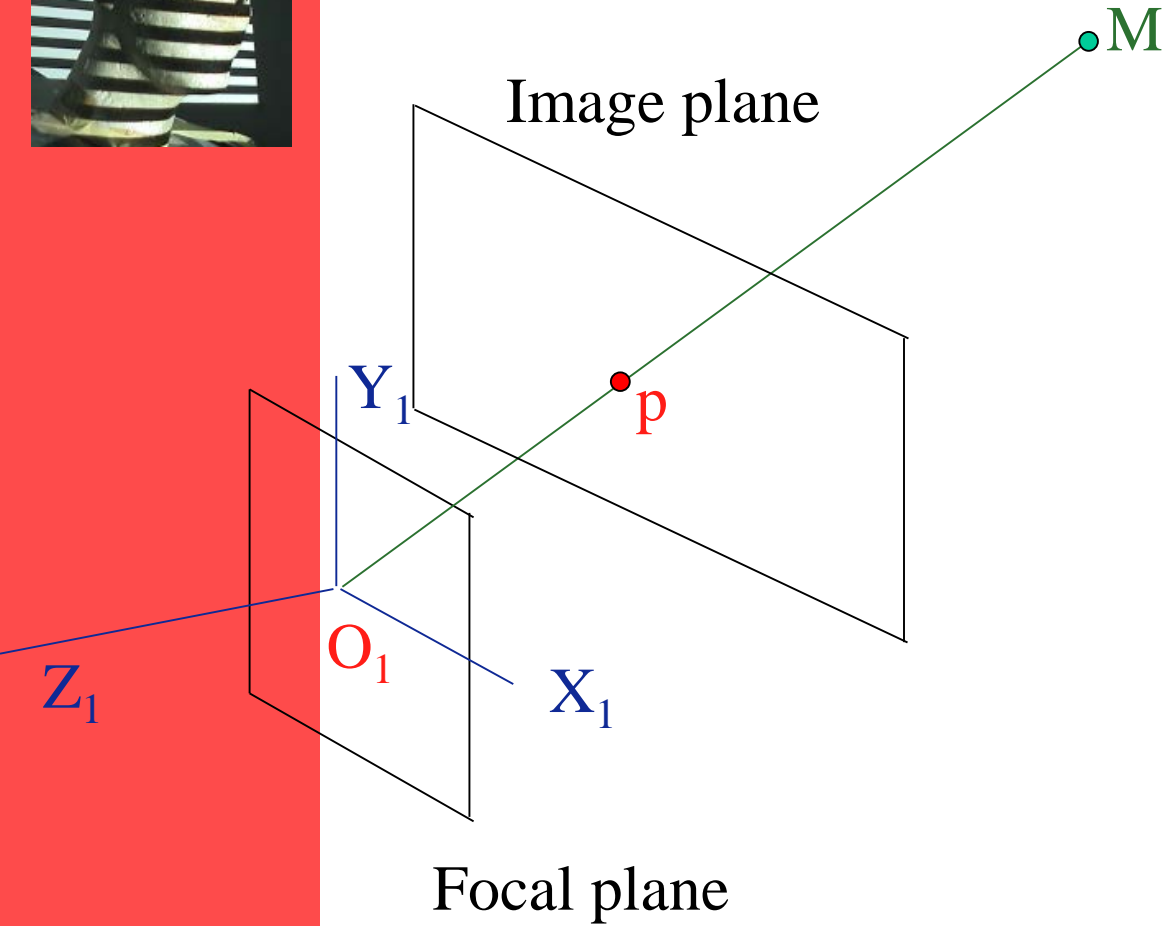
- Gives reconstruction as intersection of two rays
- Requires
 - calibration
 - ***point correspondence***

Stereo Constraints



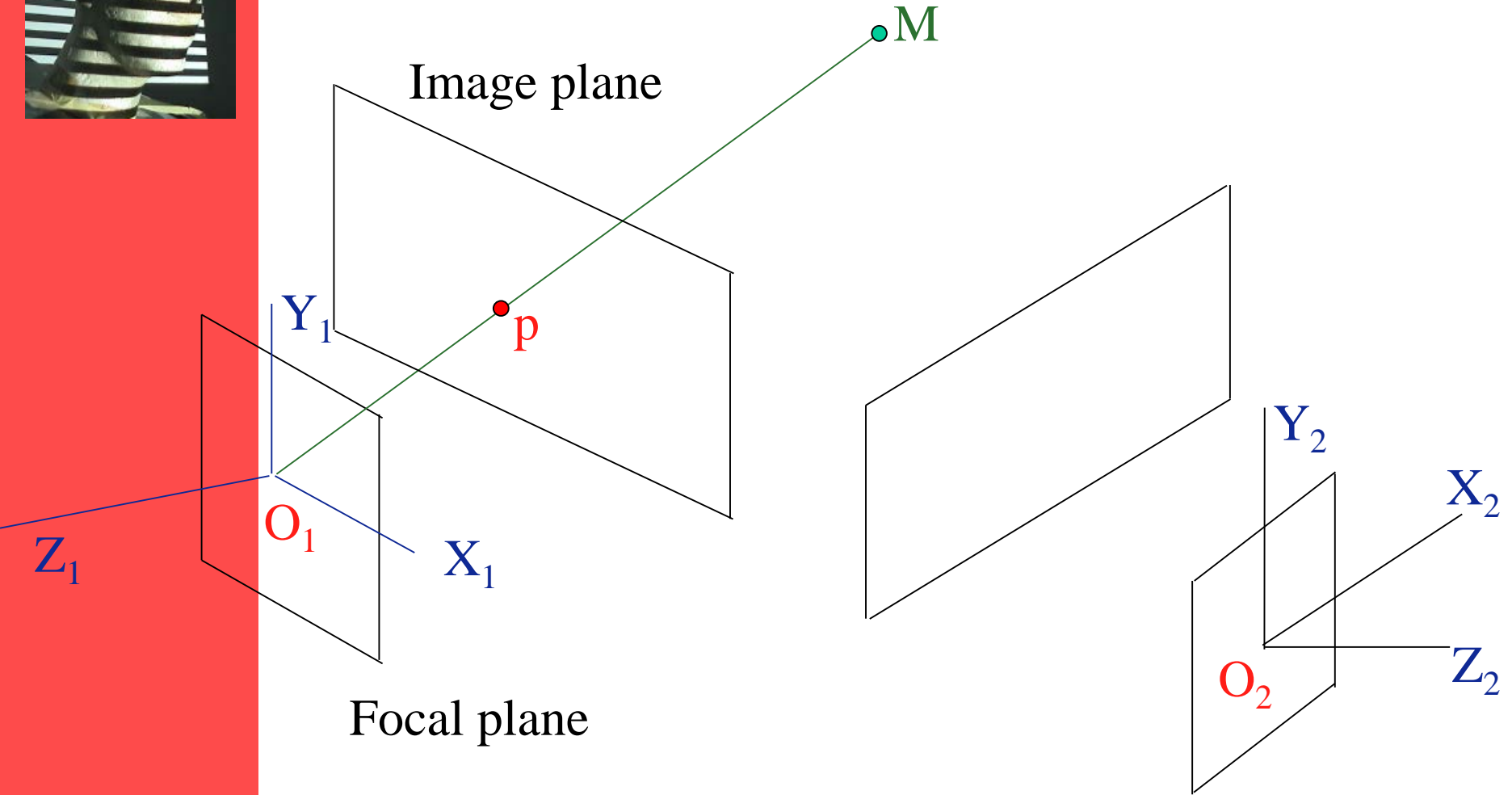
Given p in left image, where can the corresponding point p' in right image be?

Stereo Constraints



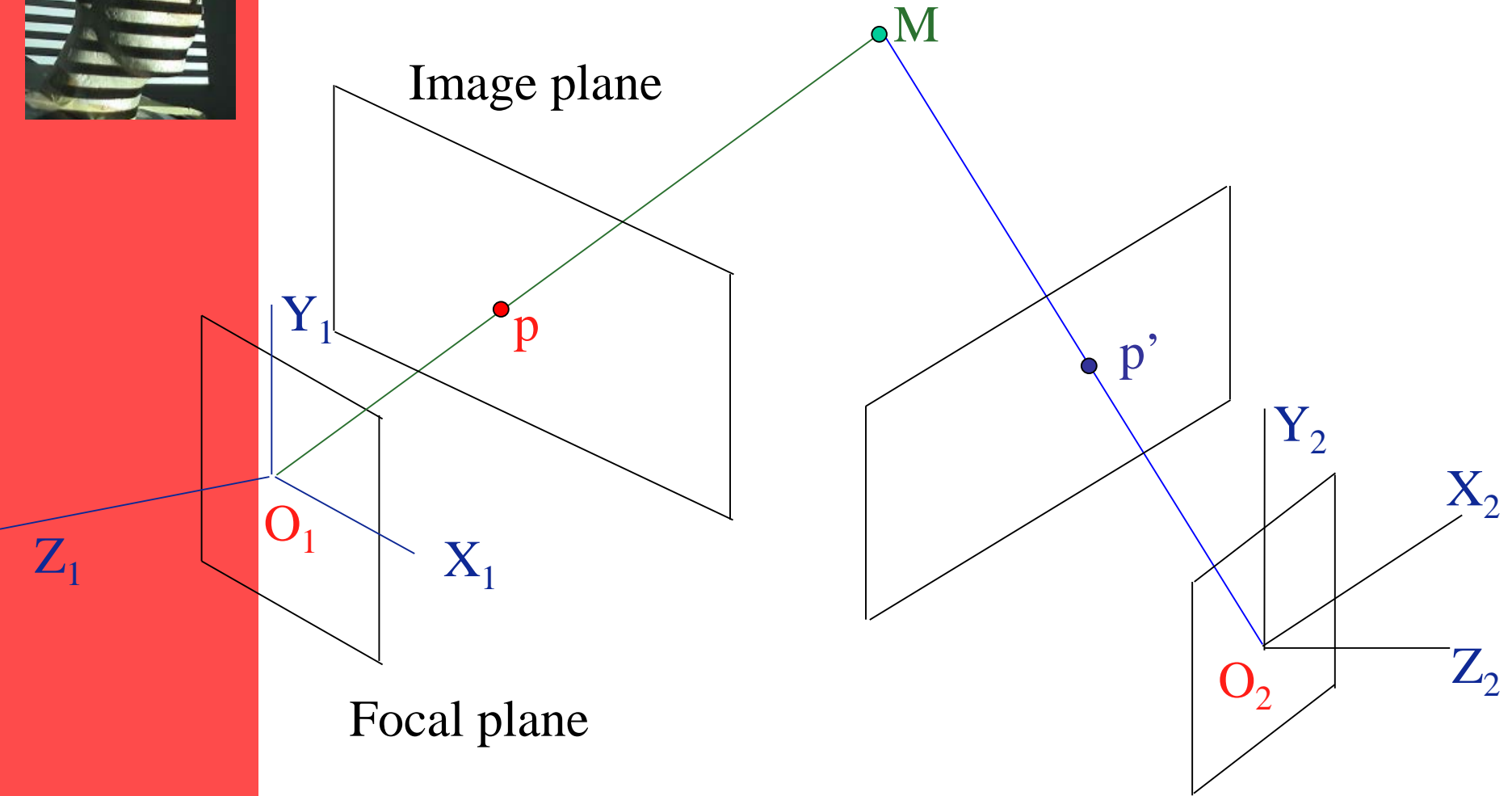


Stereo Constraints



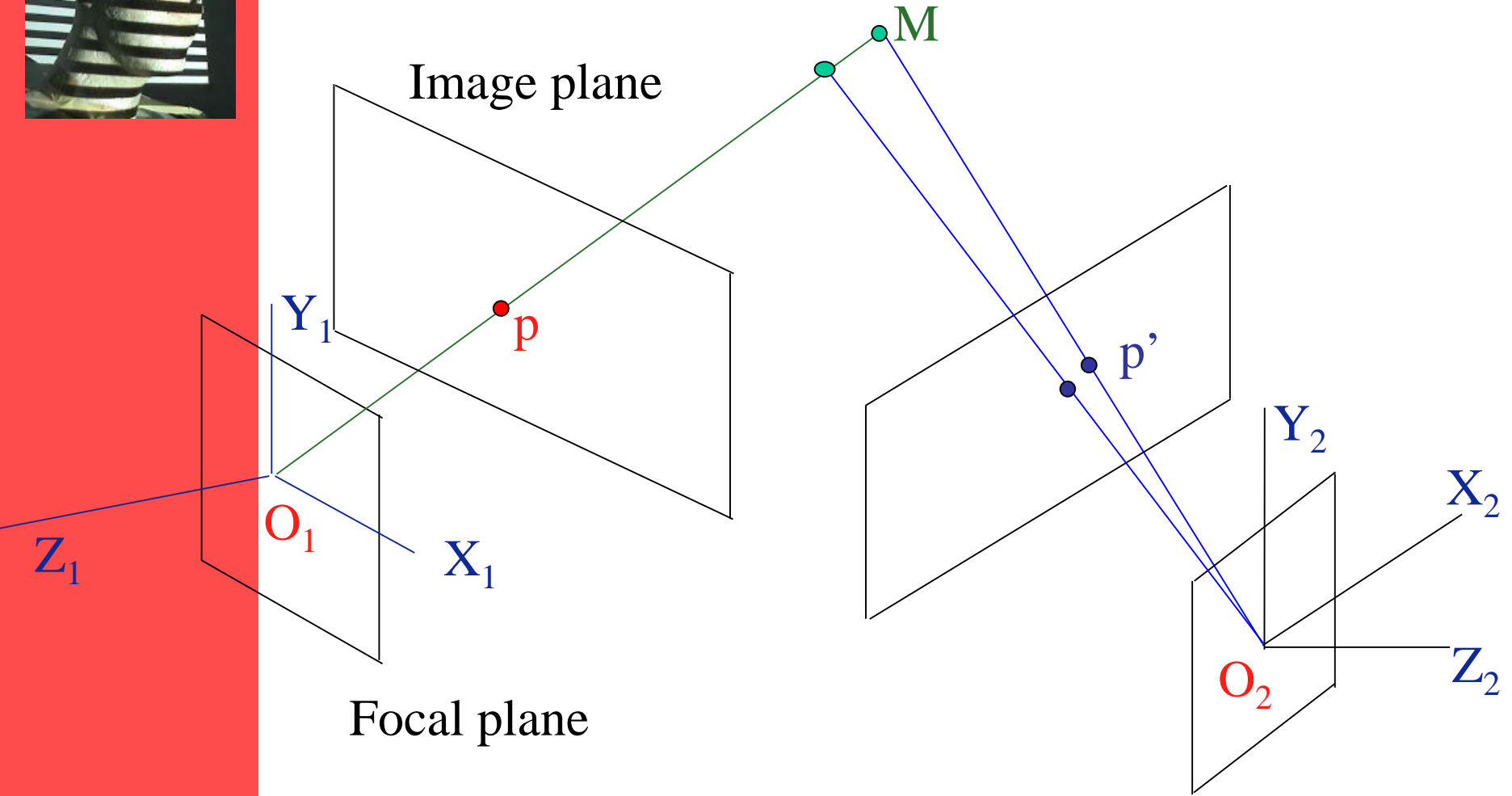


Stereo Constraints



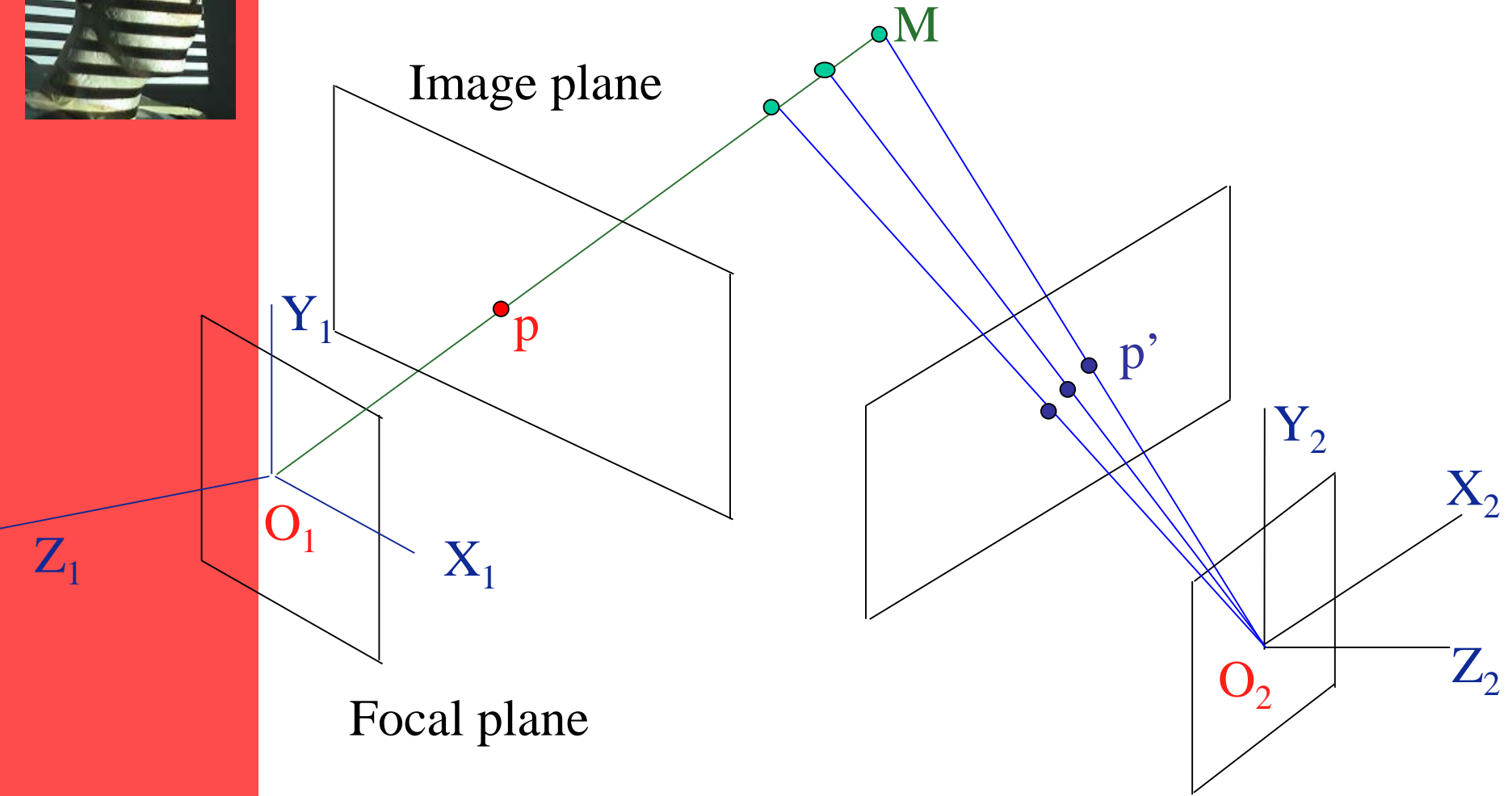


Stereo Constraints



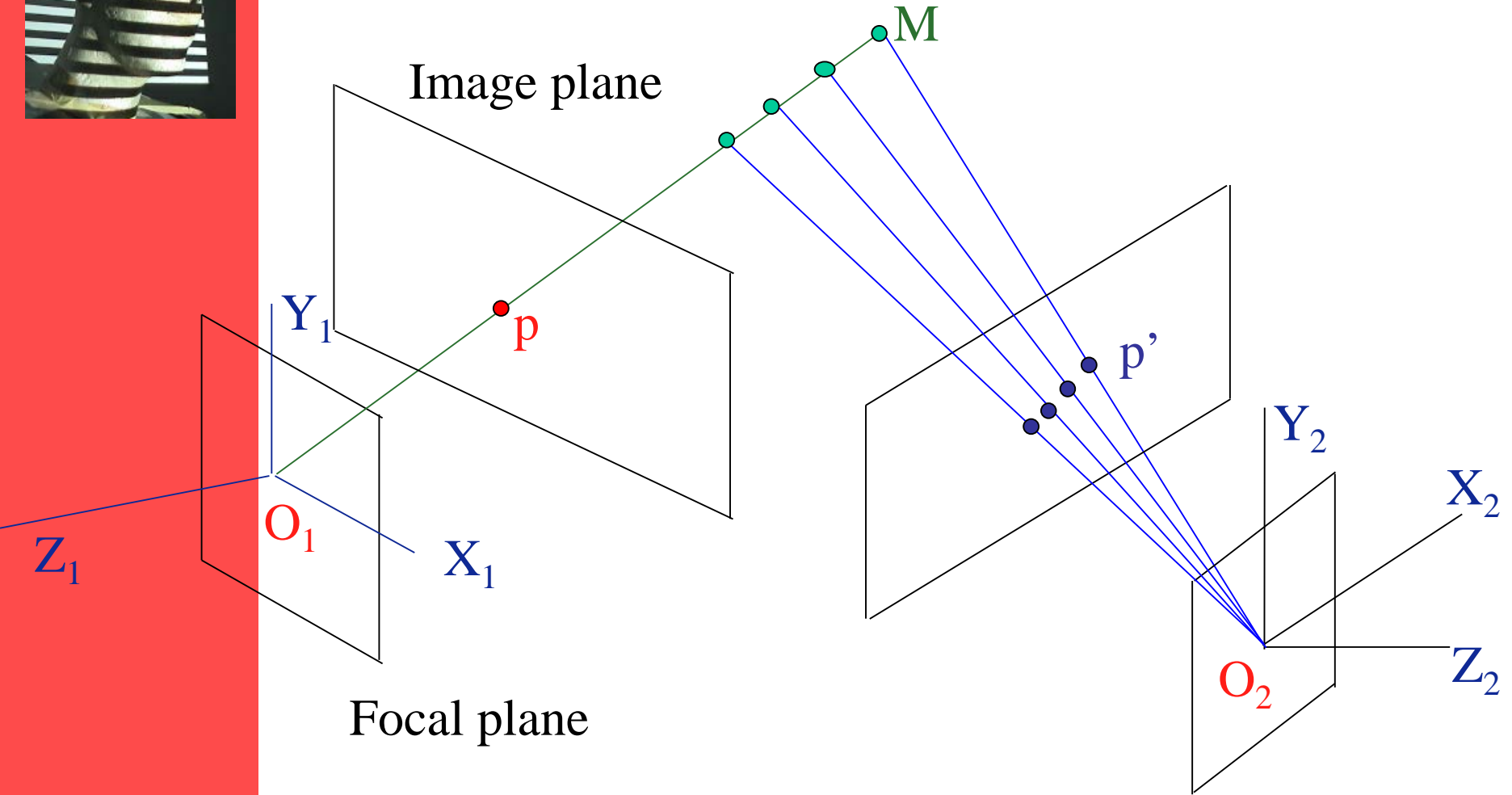


Stereo Constraints



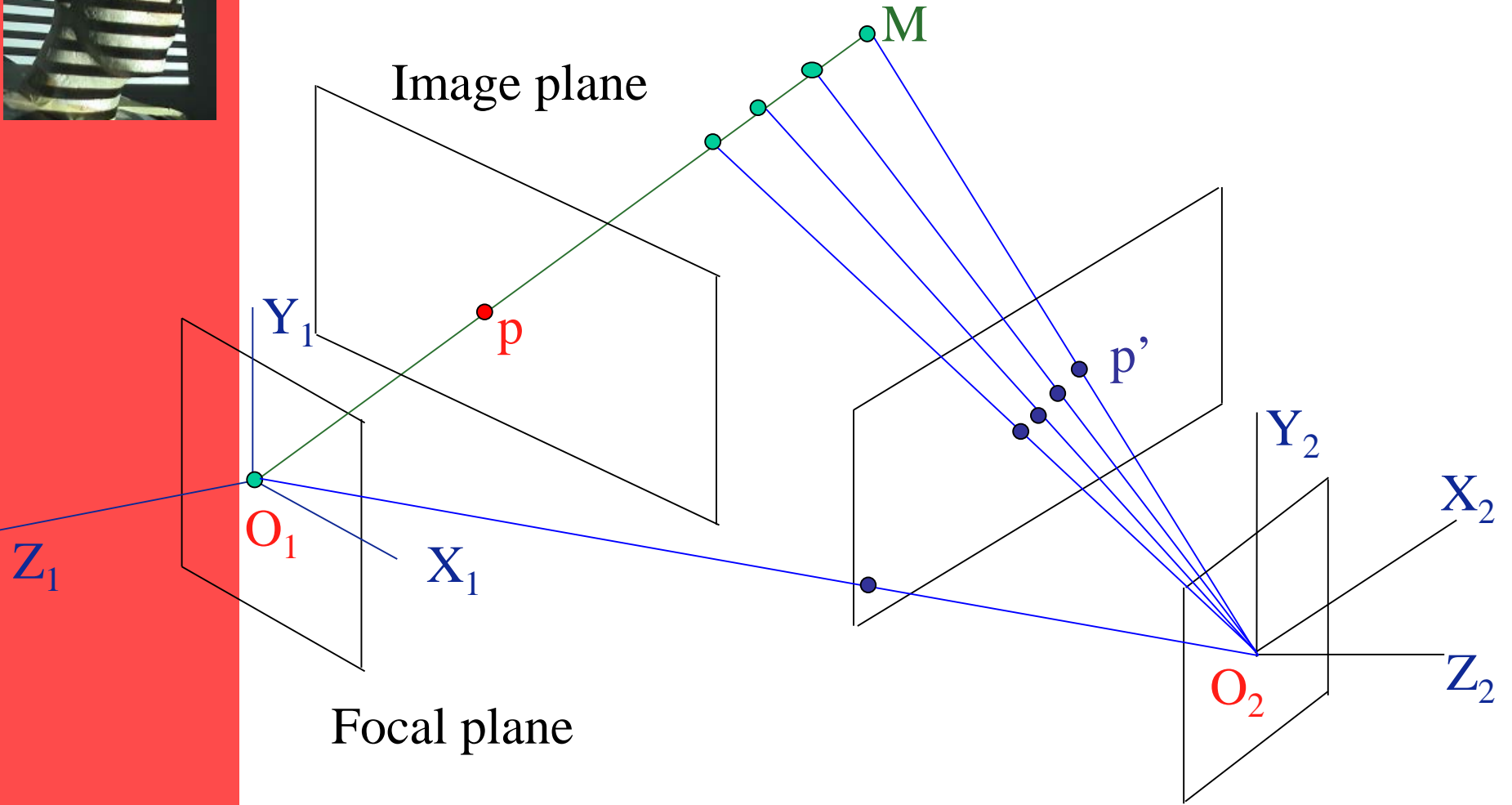


Stereo Constraints



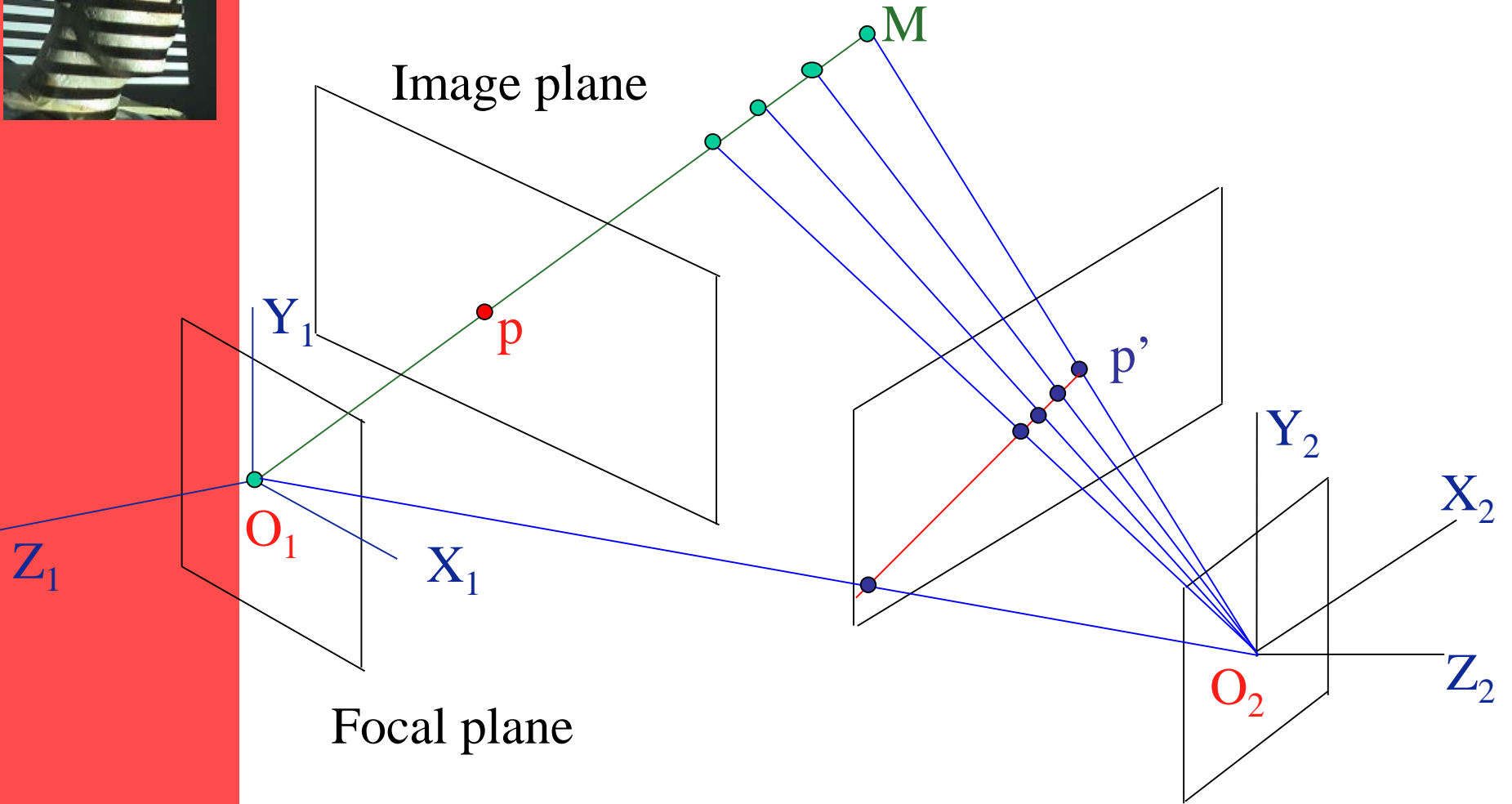


Stereo Constraints



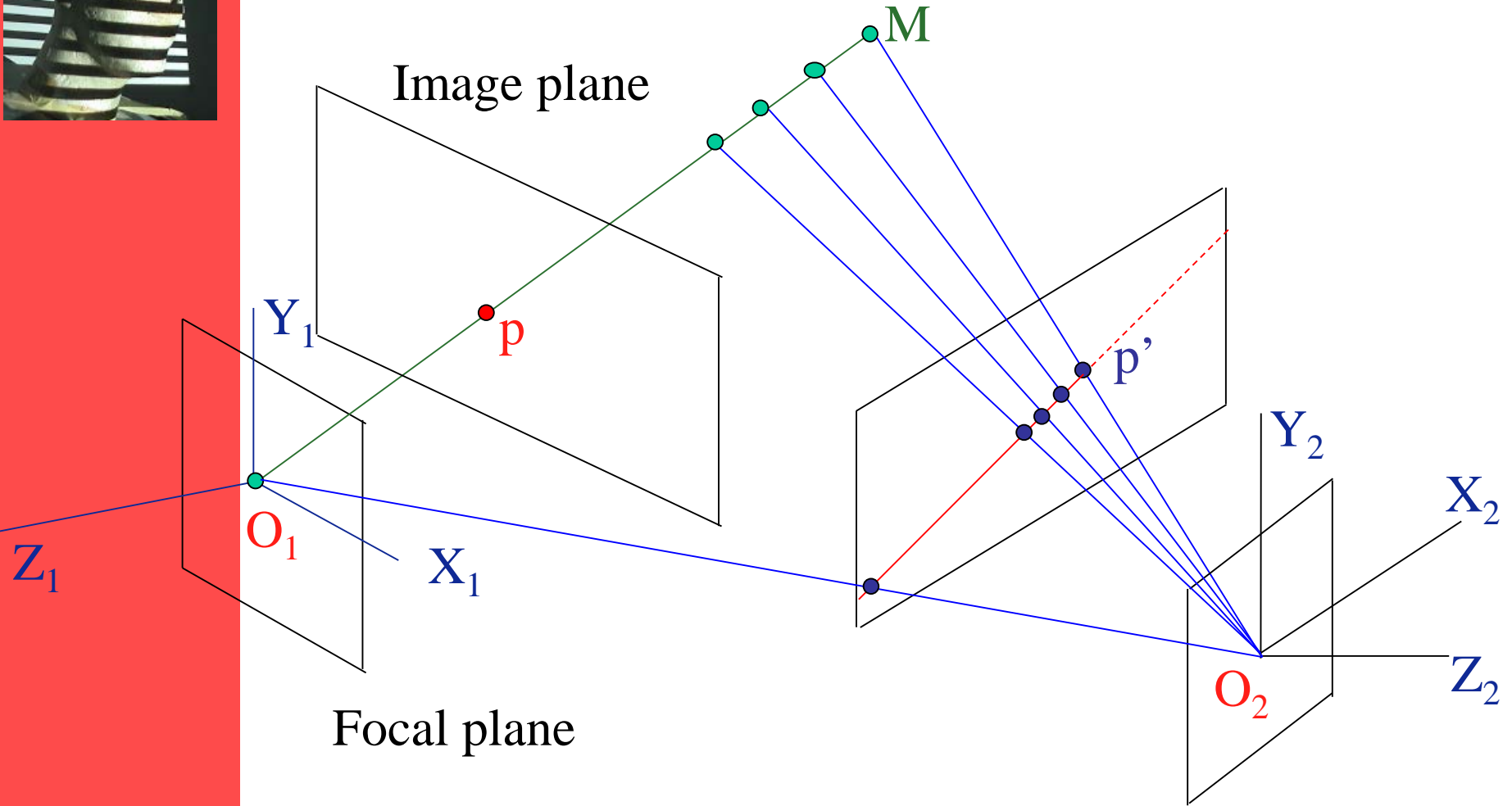


Stereo Constraints



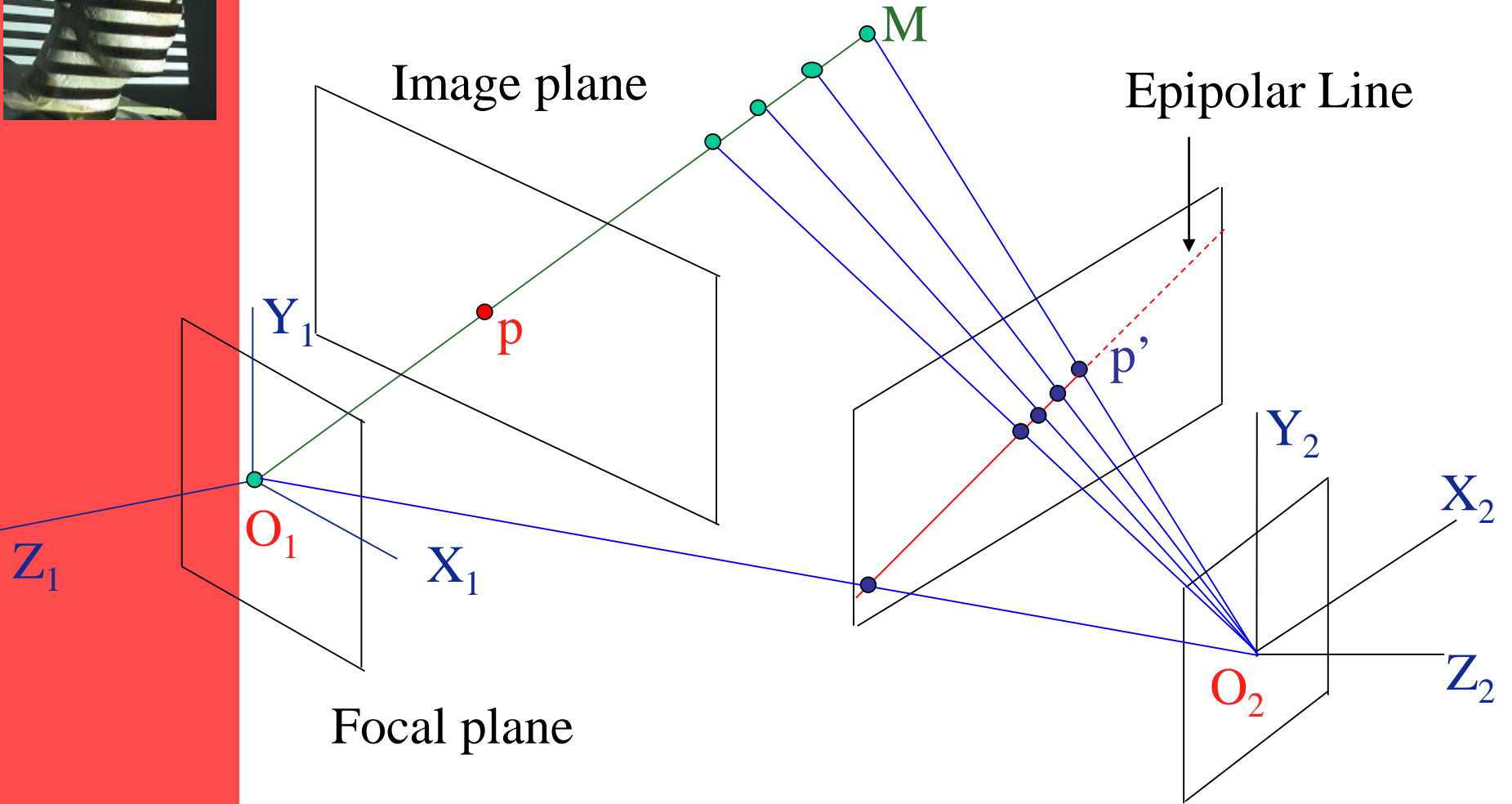


Stereo Constraints



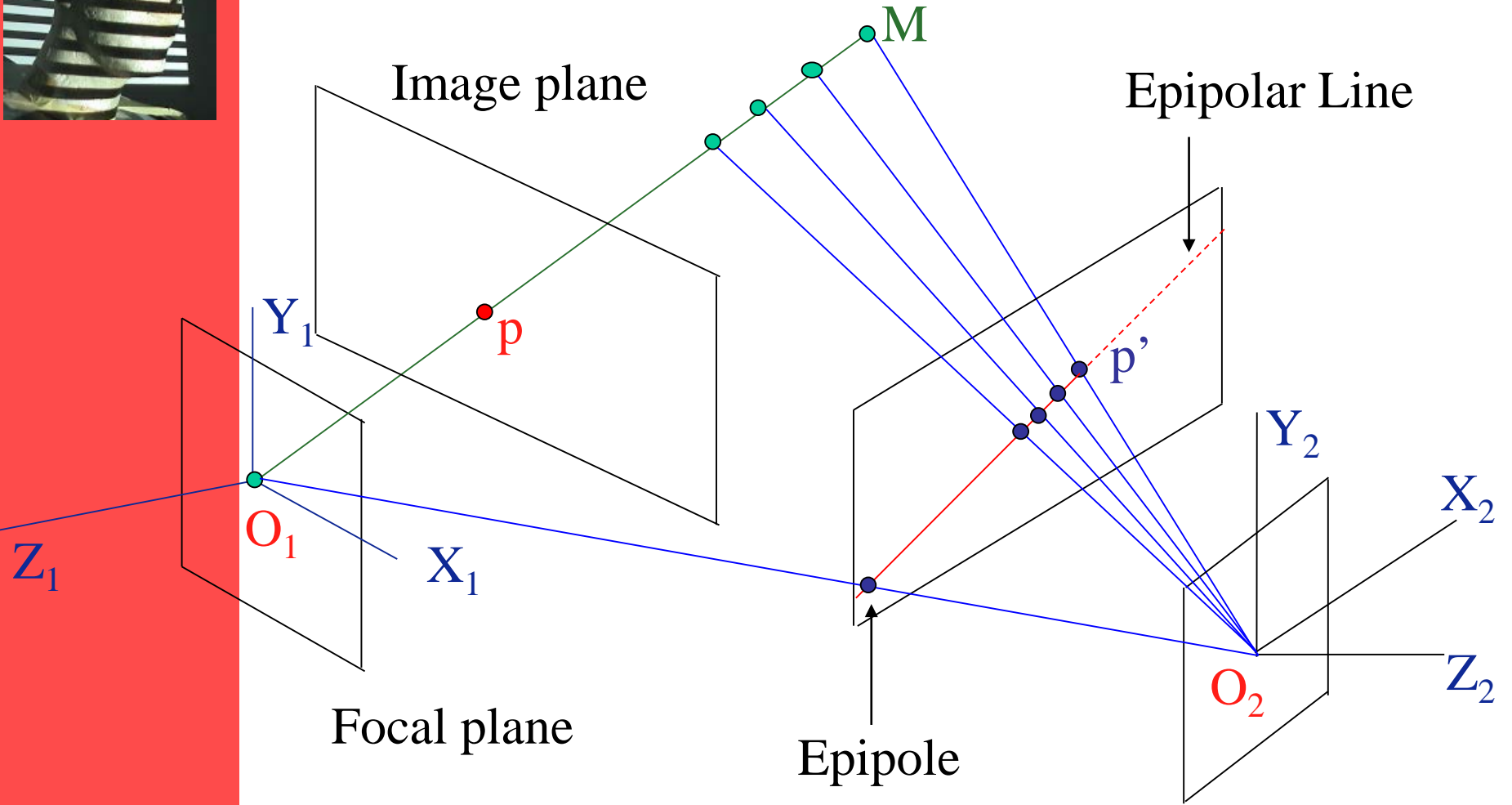


Stereo Constraints





Stereo Constraints



Demo Epipolar Geometry

[Java Applet](#)

credit to:

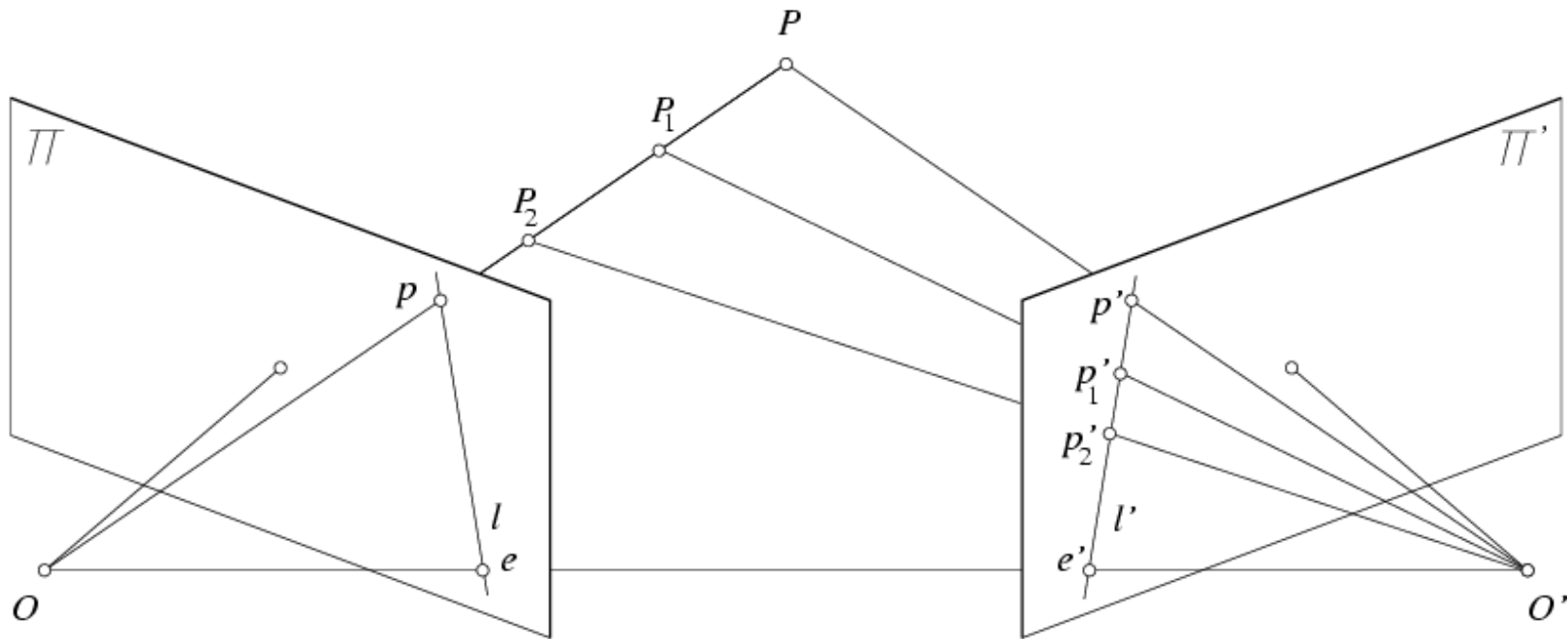
Quang-Tuan Luong

SRI Int.

Sylvain Bougnoux

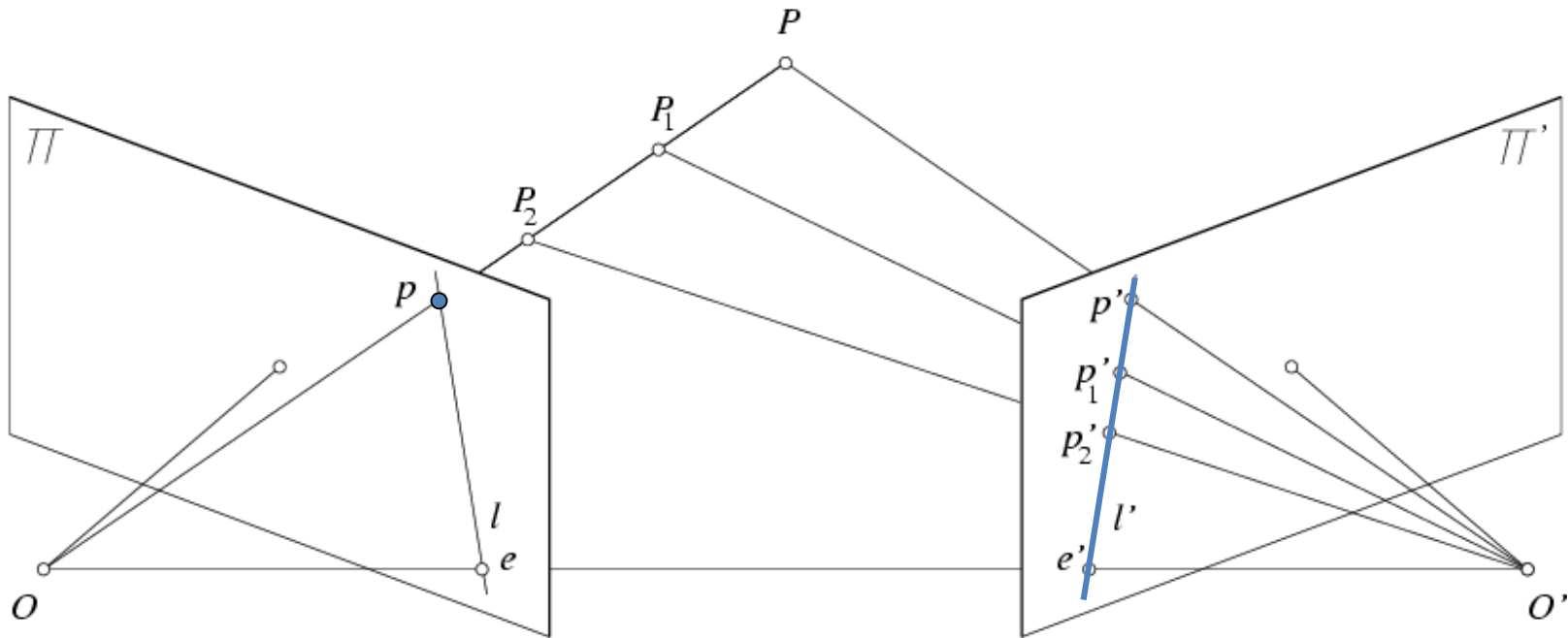


Epipolar constraint



<http://www.ai.sri.com/~luong/research/Meta3DViewer/EpipolarGeo.html>

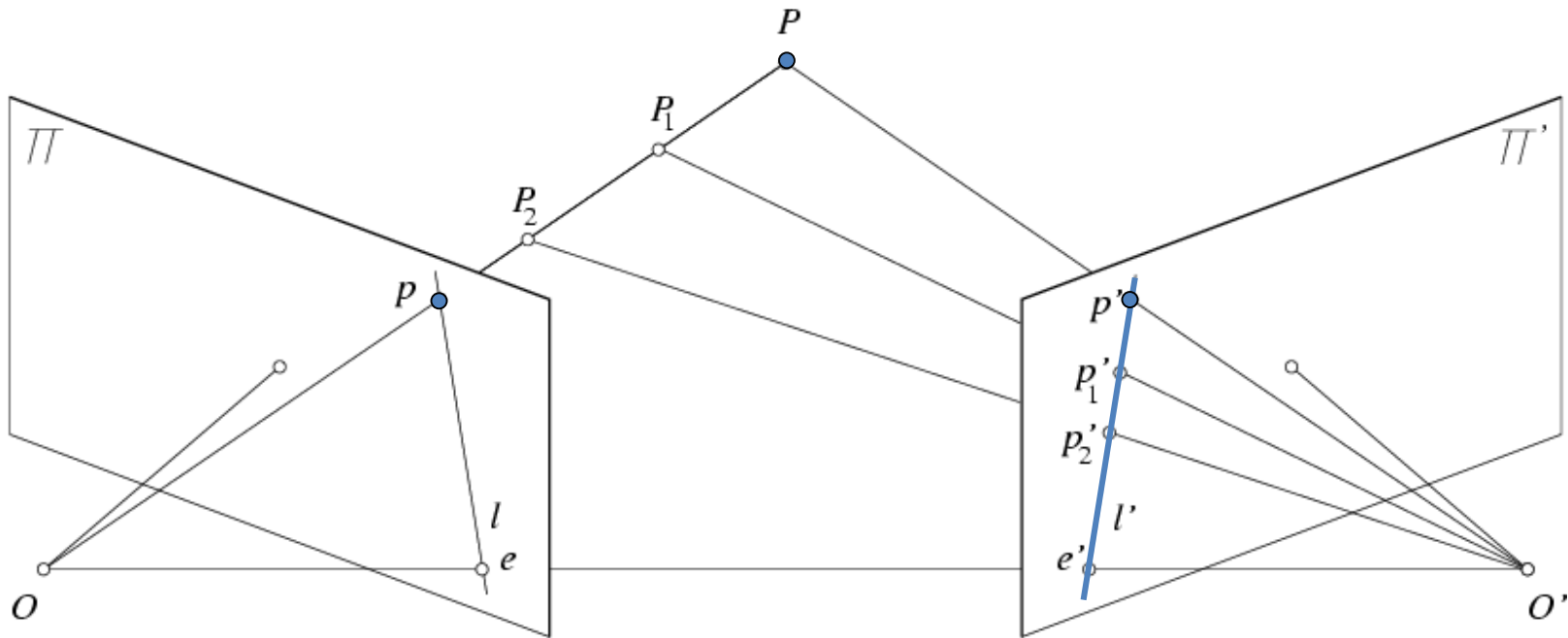
Epipolar constraint



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

<http://www.ai.sri.com/~luong/research/Meta3DViewer/EpipolarGeo.html>

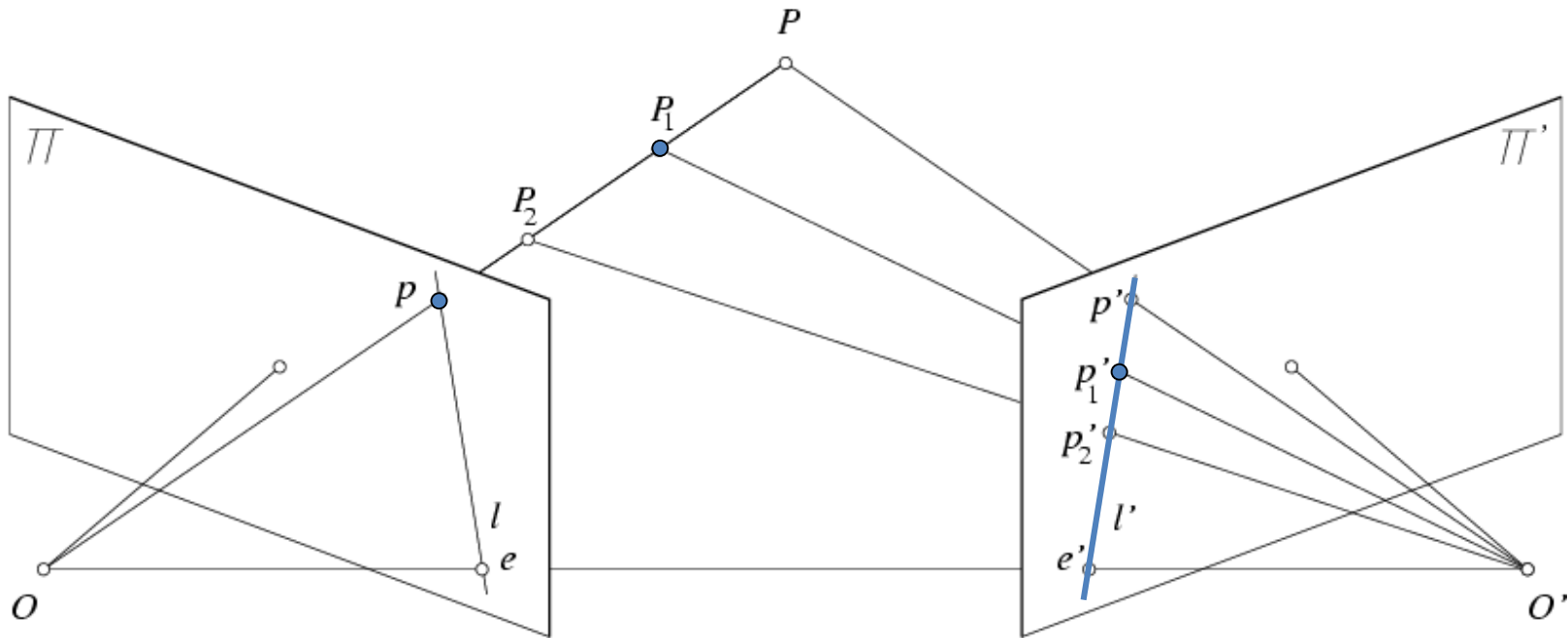
Epipolar constraint



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<http://www.ai.sri.com/~luong/research/Meta3DViewer/EpipolarGeo.html>

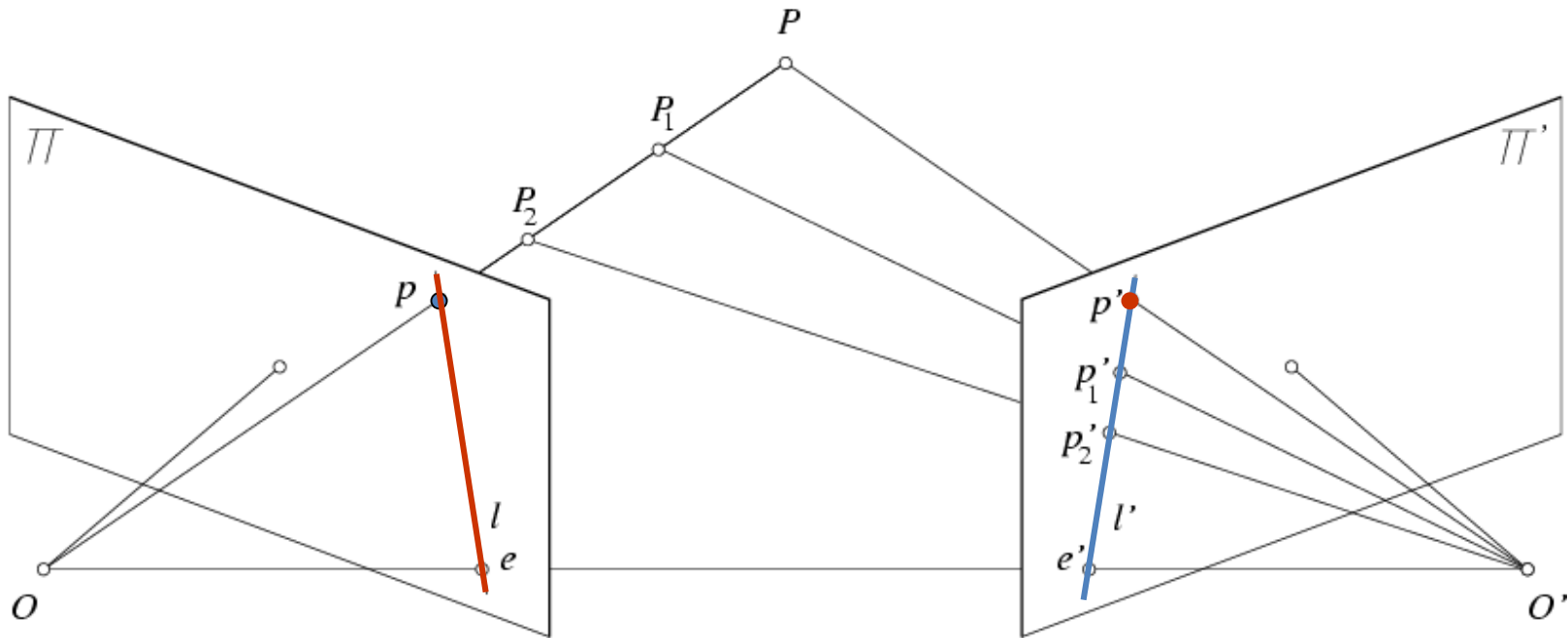
Epipolar constraint



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<http://www.ai.sri.com/~luong/research/Meta3DViewer/EpipolarGeo.html>

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 .

<http://www.ai.sri.com/~luong/research/Meta3DViewer/EpipolarGeo.html>



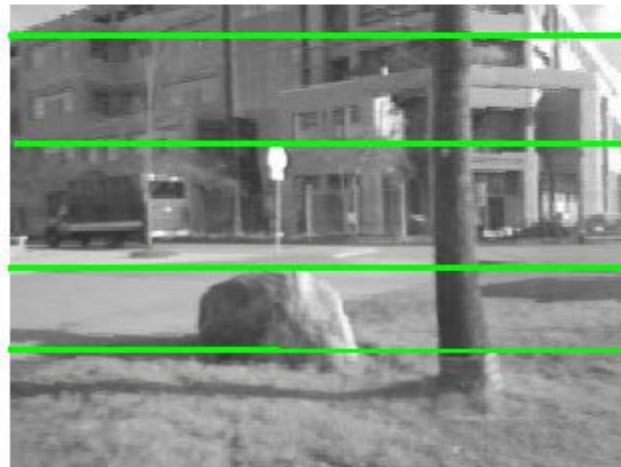
Finding Correspondences



Andrea Fusiello, CVonline

Strong constraints for searching for corresponding points!

Example



Parallel Cameras:
Corresponding
points on
horizontal lines.



Epipolar Constraint

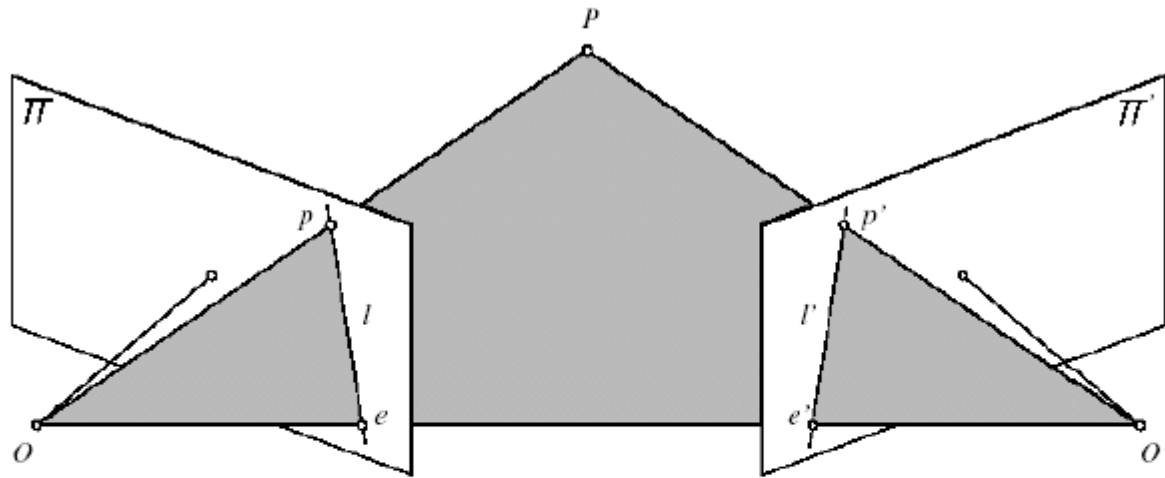


FIGURE 11.1: Epipolar geometry: the point P , the optical centers O and O' of the two cameras, and the two images p and p' of P all lie in the same plane.

All epipolar lines contain epipole, the image of other camera center.

From Geometry to Algebra

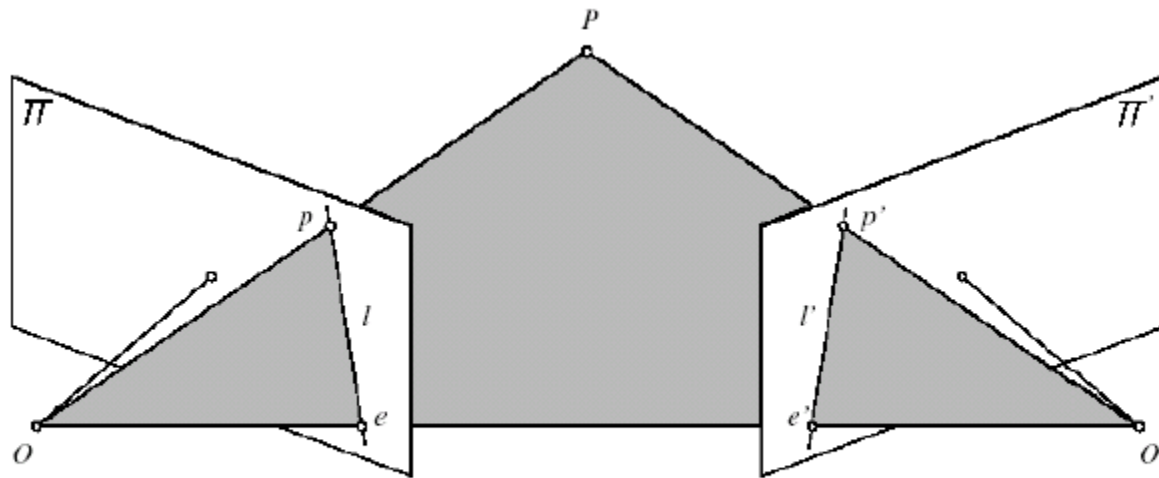


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From Geometry to Algebra

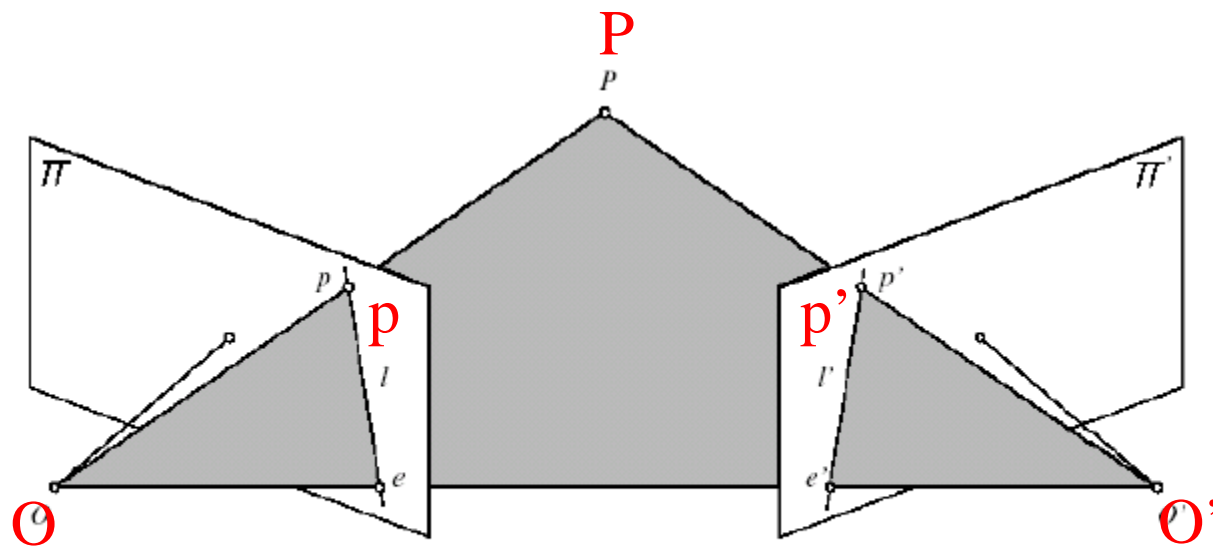


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From Geometry to Algebra

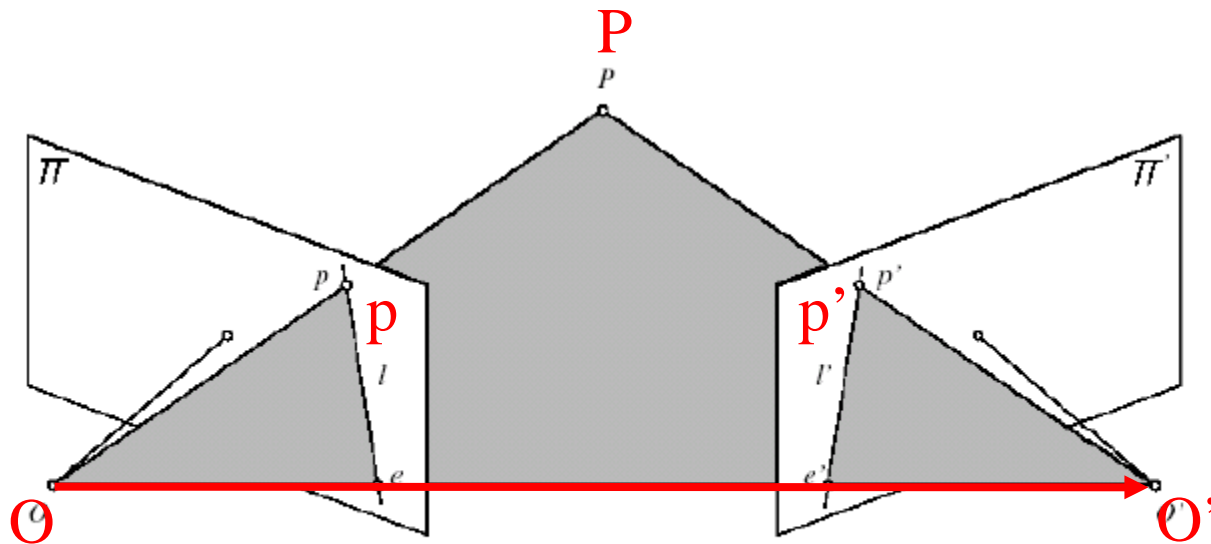


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From Geometry to Algebra

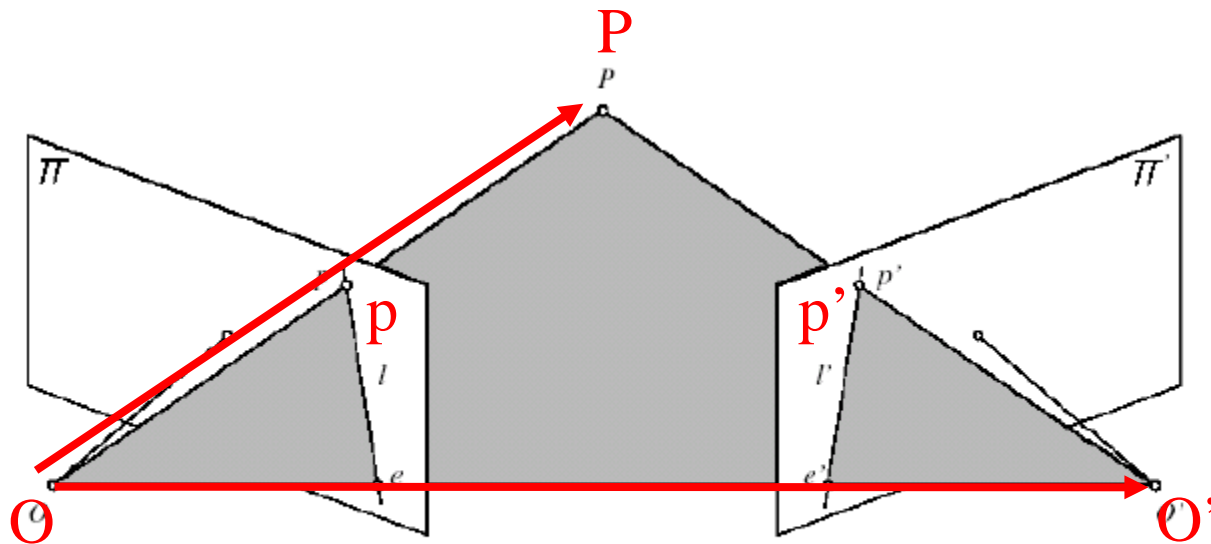


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From Geometry to Algebra

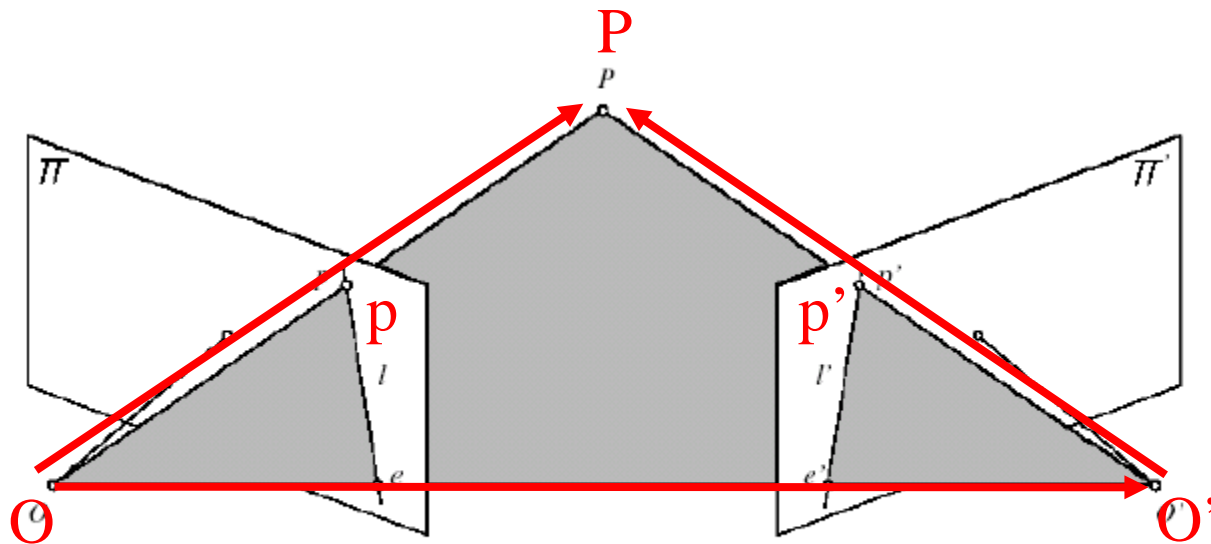


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From Geometry to Algebra

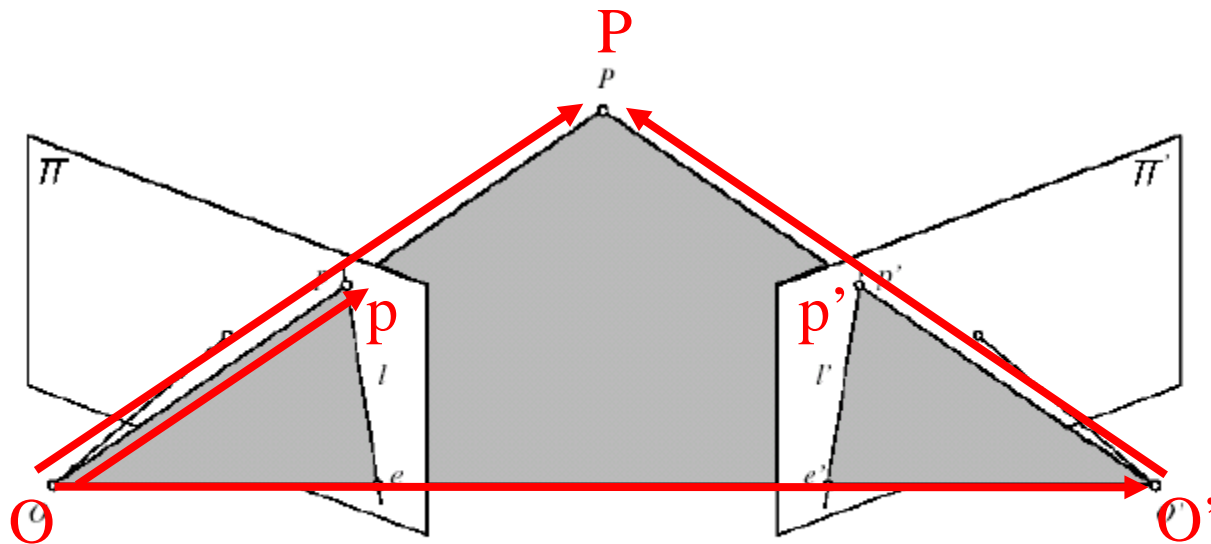


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From Geometry to Algebra

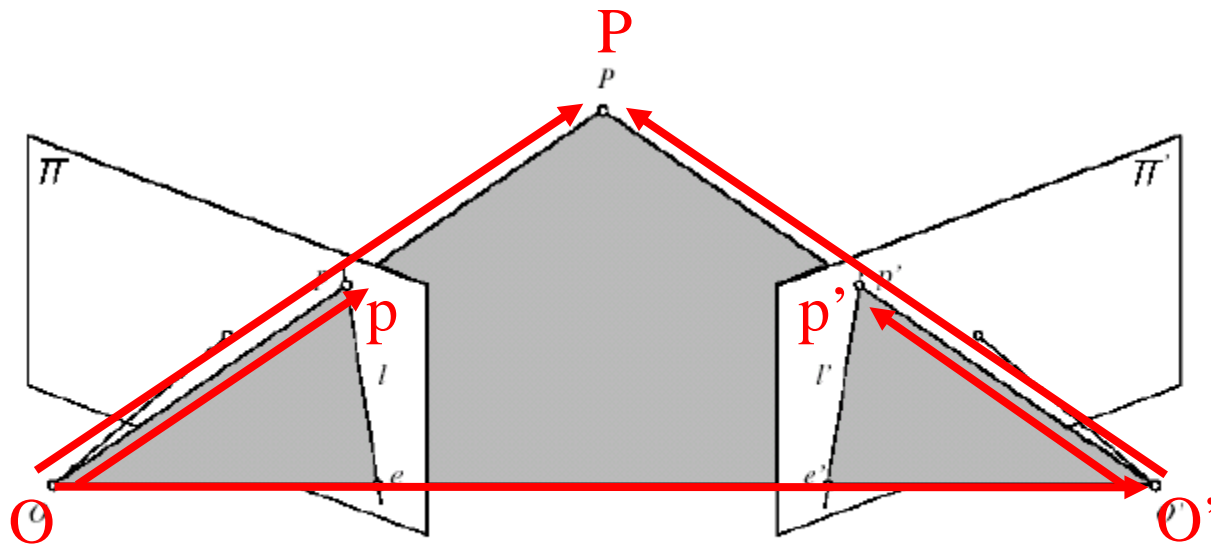
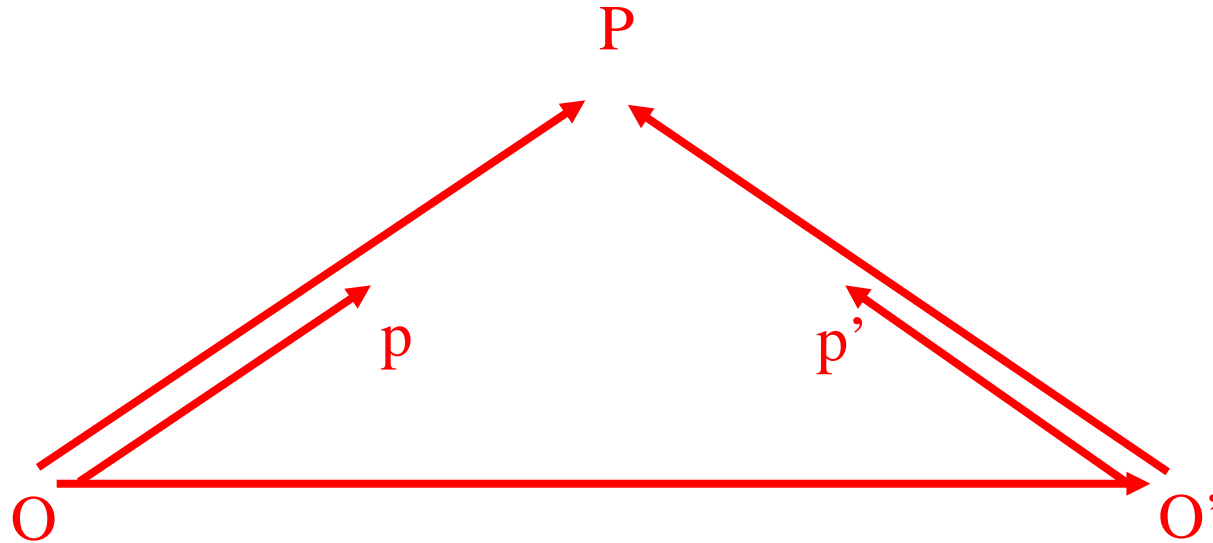


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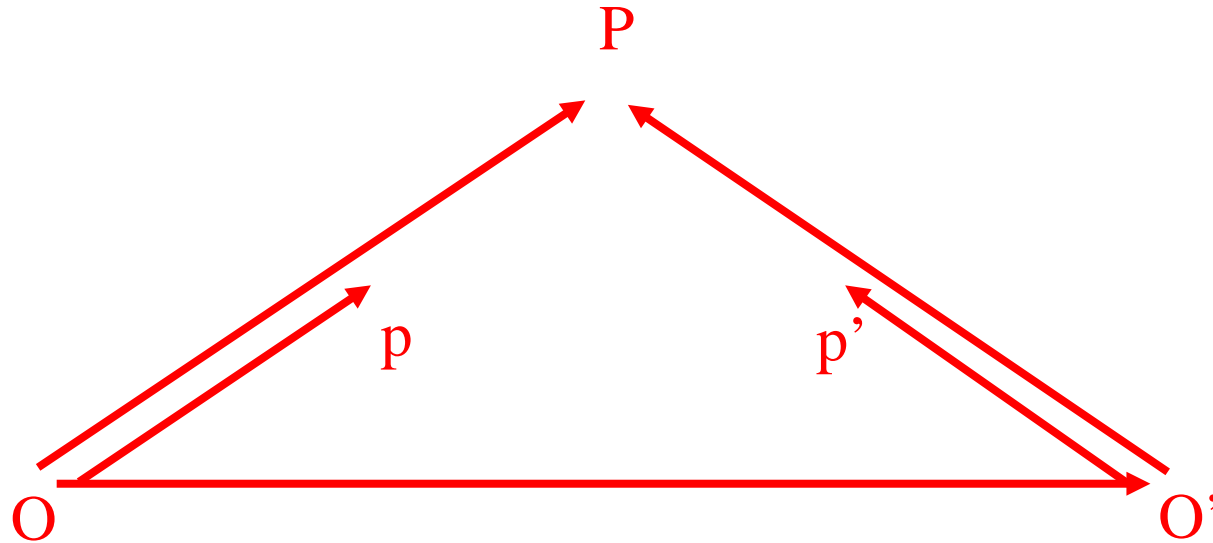
From Geometry to Algebra



The epipolar constraint: these vectors are coplanar:

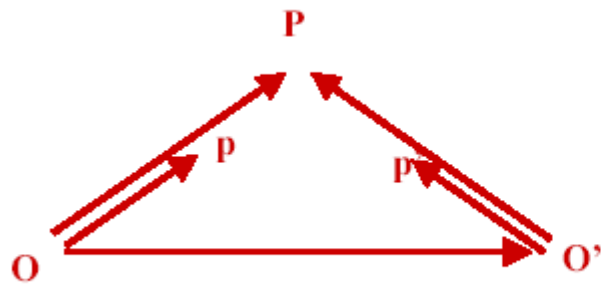


From Geometry to Algebra

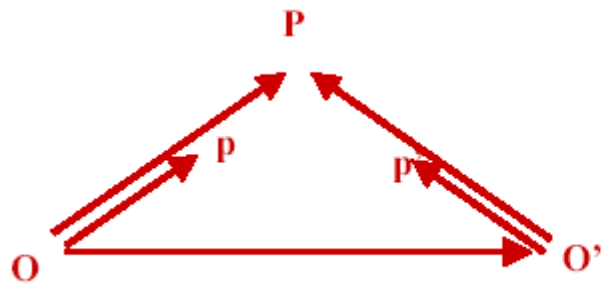


The epipolar constraint: these vectors are coplanar:

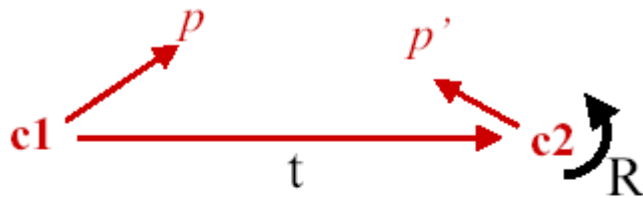
$$\overrightarrow{Op} \cdot [\overrightarrow{OO'} \times \overrightarrow{O'p'}] = 0$$



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

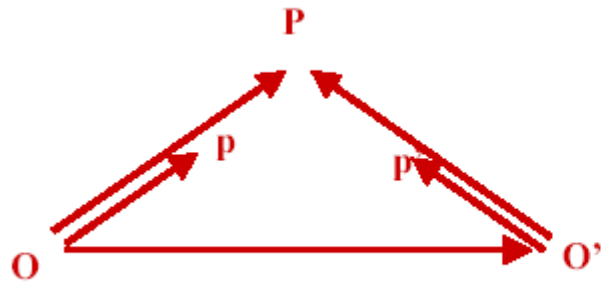


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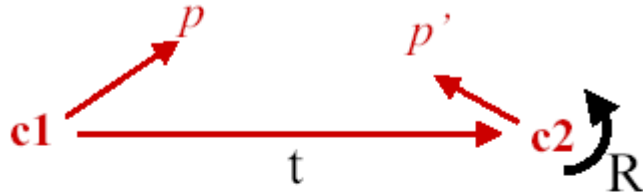


p, p' are image coordinates of P in c1 and c2...

c2 is related to c1 by rotation R and translation t



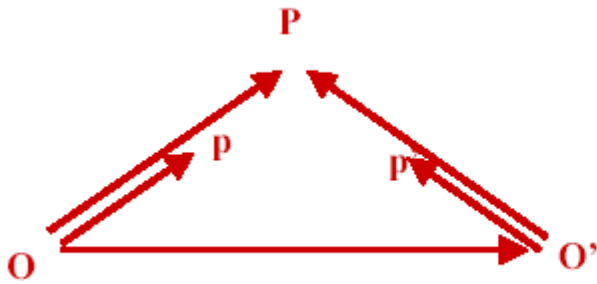
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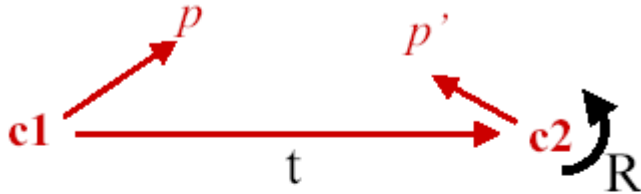
p, p' are image coordinates of P in c1 and c2...

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$$\mathbf{p} \cdot [\mathbf{t} \times (\mathcal{R}\mathbf{p}')] = 0$$



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



p, p' are image coordinates of P in c1 and c2...

c2 is related to c1 by rotation R and translation t

$$\mathbf{p} \cdot [\mathbf{t} \times (\mathcal{R}\mathbf{p}')] = 0$$

Linear Constraint:

Should be able to express as matrix multiplication.

Review: Matrix Form of Cross Product

The vector cross product also acts on two vectors and returns a third vector. Geometrically, this new vector is constructed such that its projection onto either of the two input vectors is zero.

$$\vec{a} \times \vec{b} = \begin{bmatrix} a_y b_z - a_z b_y \\ a_z b_x - a_x b_z \\ a_x b_y - a_y b_x \end{bmatrix}$$

$$\vec{a} \times \vec{b} = \begin{bmatrix} 0 & -a_z & a_y \\ a_z & 0 & -a_x \\ -a_y & a_x & 0 \end{bmatrix} \begin{bmatrix} b_x \\ b_y \\ b_z \end{bmatrix} = \vec{c} \quad \begin{array}{l} \vec{a} \cdot \vec{c} = 0 \\ \vec{b} \cdot \vec{c} = 0 \end{array}$$

Review: Matrix Form of Cross Product



$$\vec{a} \times \vec{b} = \begin{bmatrix} 0 & -a_z & a_y \\ a_z & 0 & -a_x \\ -a_y & a_x & 0 \end{bmatrix} \begin{bmatrix} b_x \\ b_y \\ b_z \end{bmatrix} = \vec{c} \quad \begin{array}{l} \vec{a} \cdot \vec{c} = 0 \\ \vec{b} \cdot \vec{c} = 0 \end{array}$$

$$[a_x] = \begin{bmatrix} 0 & -a_z & a_y \\ a_z & 0 & -a_x \\ -a_y & a_x & 0 \end{bmatrix}$$

$$\vec{a} \times \vec{b} = [a_x] \vec{b}$$

Matrix Form

$$\mathbf{p} \cdot [\mathbf{t} \times (\mathcal{R}\mathbf{p}')] = 0$$

$$\vec{a} \times \vec{b} = [a_x] \vec{b}$$

$$\mathbf{p}^T [\mathbf{t}_x] \mathcal{R} \mathbf{p}' = 0$$

$$\mathcal{E} = [\mathbf{t}_x] \mathcal{R}$$

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



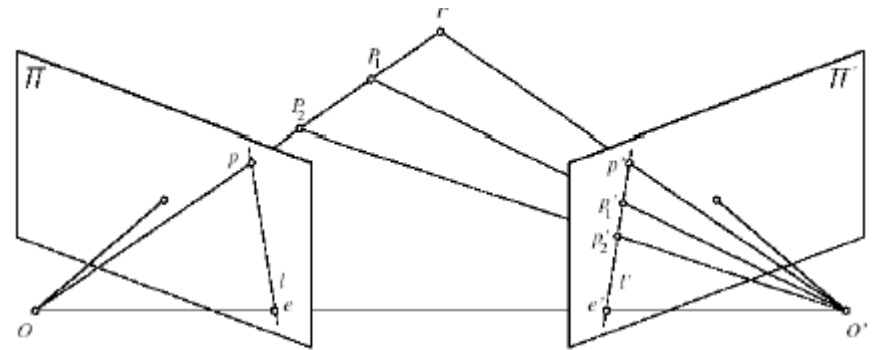


The Essential Matrix

Matrix that relates image of point in one camera to a second camera, given translation and rotation.

$$\mathcal{E} = [t_x] \mathfrak{R}$$

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



$$\vec{a} \times \vec{b} = [a_x] \vec{b}$$



The Essential Matrix

- Based on the Relative Geometry of the Cameras
- Assumes Cameras are calibrated (i.e., intrinsic parameters are known)
- Relates image of point in one camera to a second camera (points in camera coordinate system).
- Is defined up to scale
- 5 independent parameters



The Essential Matrix

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

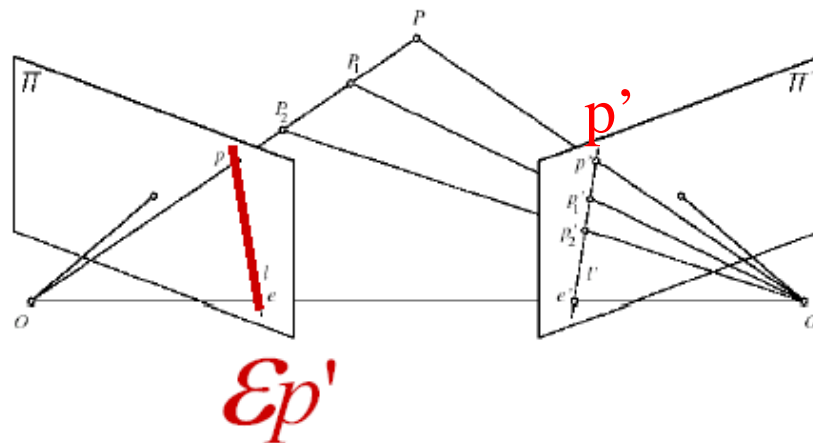
What is $\mathcal{E} \mathbf{p}'$?



The Essential Matrix

$\mathcal{E}p'$ is the epipolar line corresponding to p' in the left camera.

$$au + bv + c = 0$$



$$p = (u, v, 1)^T$$

$$l = (a, b, c)^T$$

$$l \cdot p = 0$$

$$\mathcal{E}p' \cdot p = 0$$

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

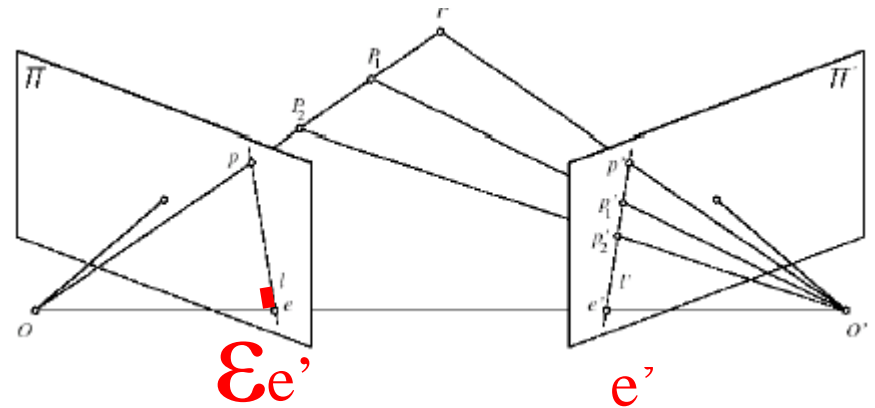
Similarly $\mathcal{E}^T p$ is the epipolar line corresponding to p in the right camera.



The Essential Matrix

$$e^T \mathcal{E} e' ?$$

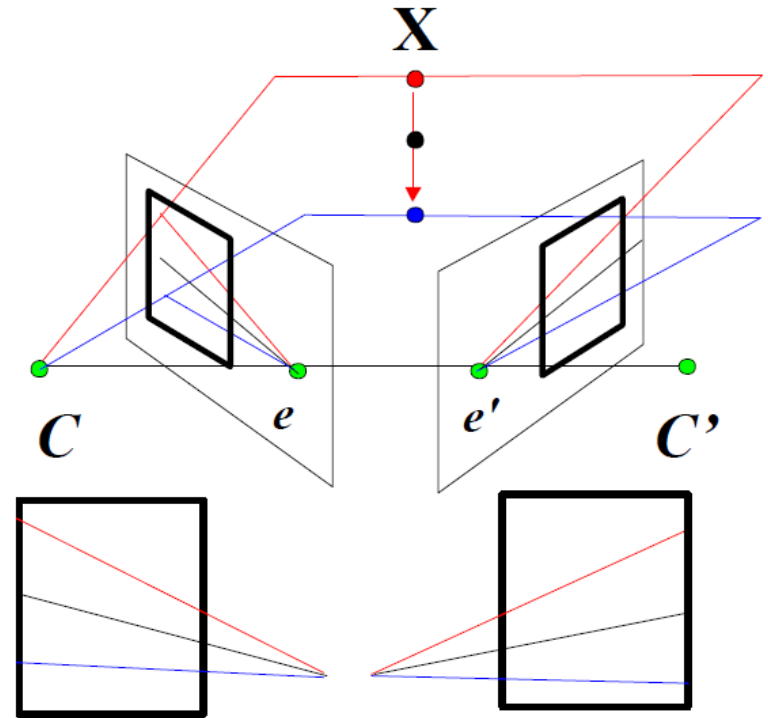
What is $\mathcal{E} e'$?



- line $\mathcal{E} p'$ converges to epipole e
- e' (center of camera C_2 expressed in frame C_1)



Pencil of epipolar lines



- The intersection points between the base line and the image planes are called *epipoles*.
- The epipole e' in image 2 is the mapping of the camera center C .
- The epipole e in image 1 is the mapping of the camera center C' .
- Since all epipolar planes intersect both camera centers, all epipolar lines will intersect the epipoles.



Pencil of epipolar lines

image1

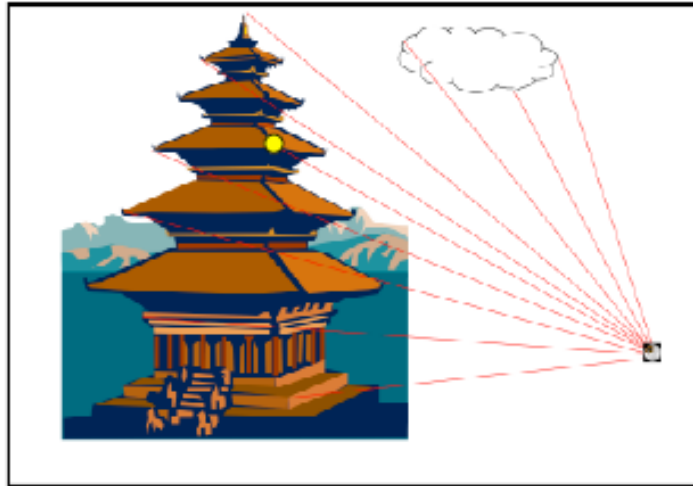
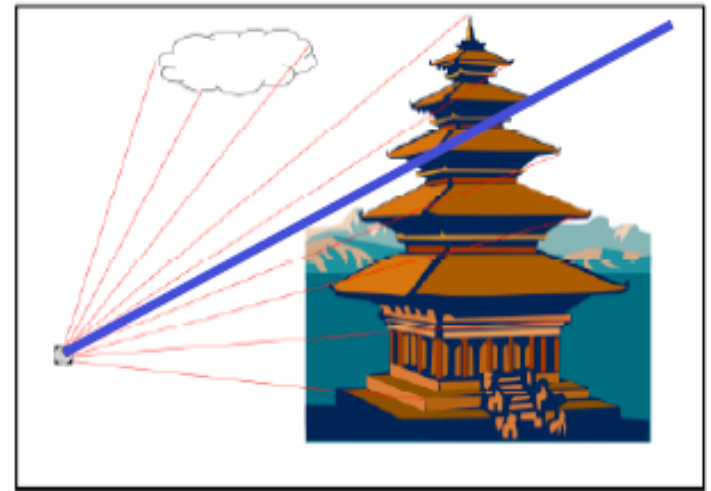


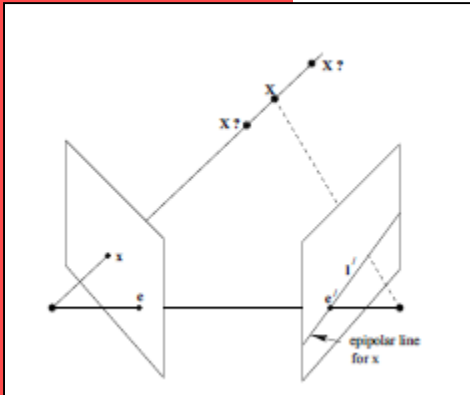
image 2



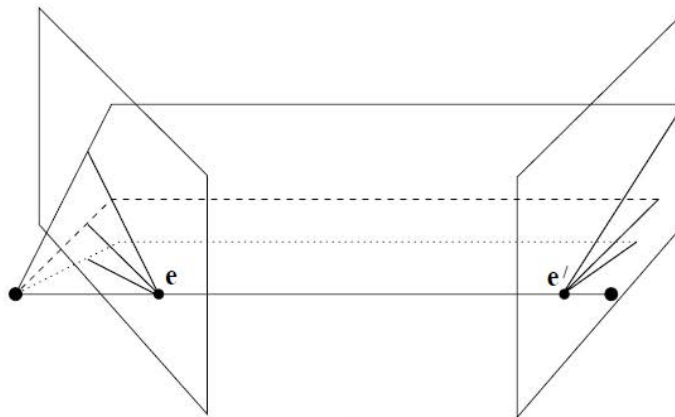
Given a point in one image, how do we determine the corresponding epipolar line to search along in the second image?



Epipoles



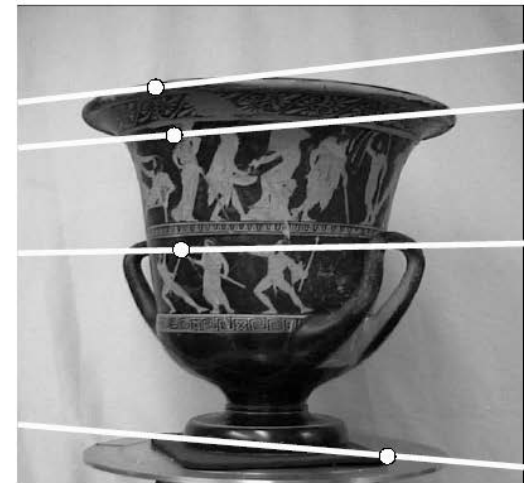
- The epipolar line $l' = \mathbf{E}x$ to each point x (except e) intersects the epipole e_0 . Thus e' satisfies $e'^T(\mathbf{E}x) = (e'^T \mathbf{E})x = 0$ for all x .
- This implies that $e'^T \mathbf{E} = 0^T$ or $\mathbf{E}^T e' = 0$. The epipole e' is thus a null vector to \mathbf{E}^T (in the left null-space of \mathbf{E}).
- Similarly, $\mathbf{E}e = 0$, i.e. e is a null-vector to \mathbf{E} (in the right null-space of \mathbf{E}).



a



b



c

Fig. 8.3. **Converging cameras.** (a) *Epipolar geometry for converging cameras.* (b) and (c) *A pair of images with superimposed corresponding points and their epipolar lines (in white). The motion between the views is a translation and rotation. In each image, the direction of the other camera may be inferred from the intersection of the pencil of epipolar lines. In this case, both epipoles lie outside of the visible image.*



Epipoles

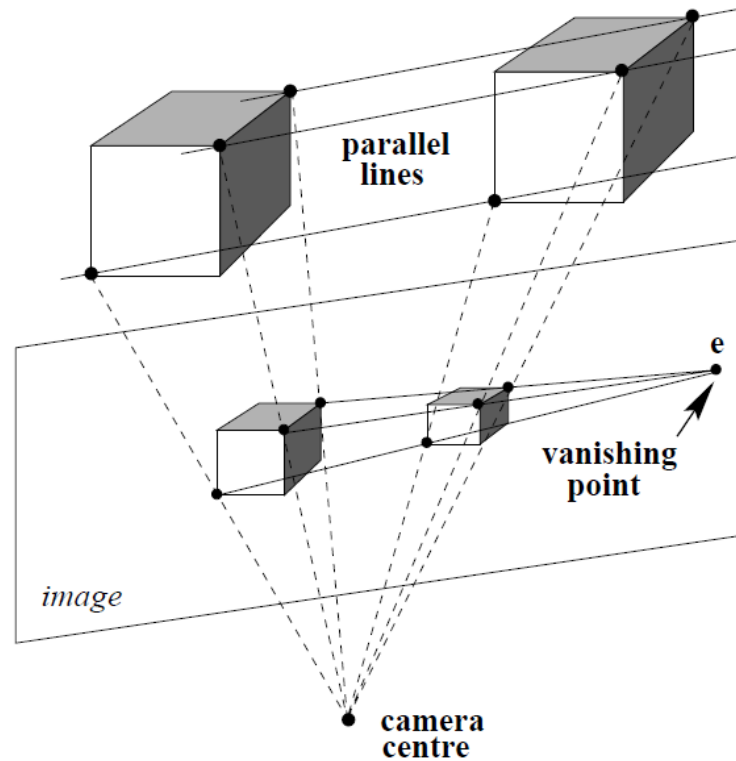


Fig. 8.7. Under a pure translational camera motion, 3D points appear to slide along parallel rails. The images of these parallel lines intersect in a vanishing point corresponding to the translation direction. The epipole e is the vanishing point.



The Essential Matrix

$$\mathcal{E}e' = [t_{\times}]Re' = 0$$

Similarly, $\mathcal{E}^T e = R^T [t_{\times}]^T e = -R^T [t_{\times}]e = 0$

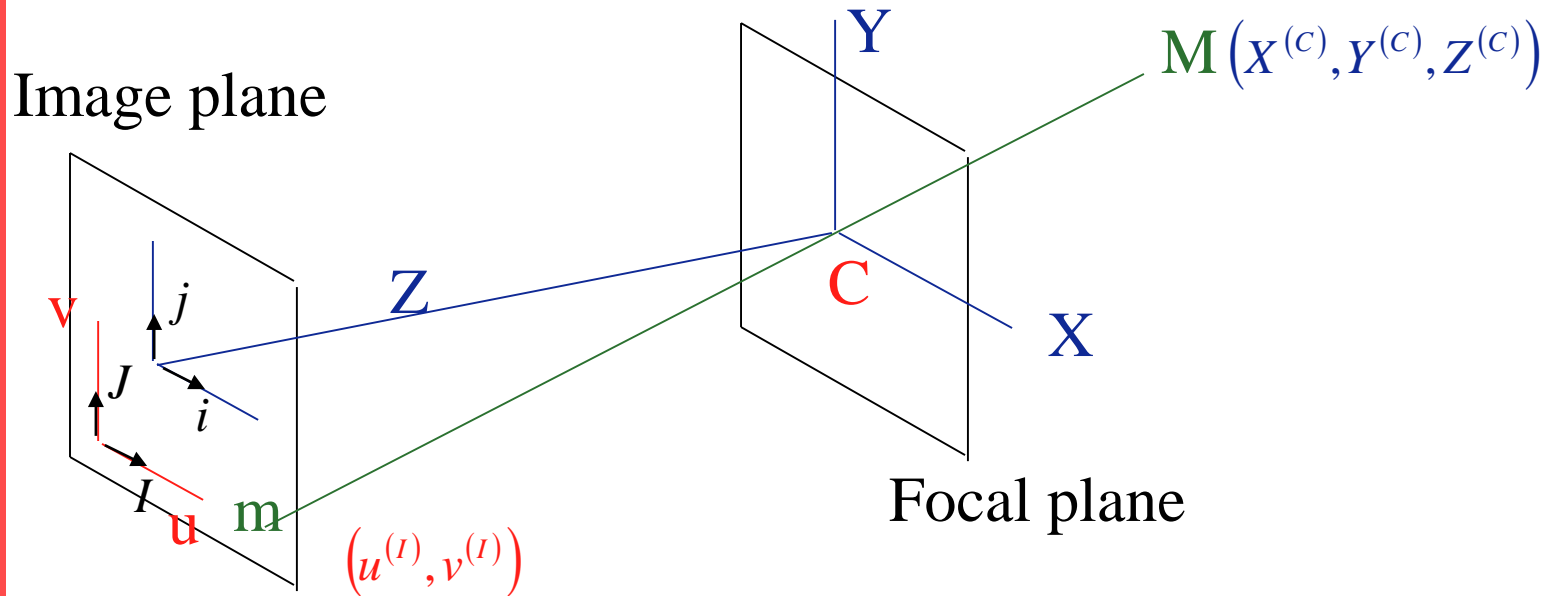
The essential matrix $\mathcal{E} = [t]_{\times}R$ has 5 degrees of freedom; 3 rotation angles in R , 3 elements in t , but arbitrary scale.

Essential Matrix is singular with rank 2.

What if Camera Calibration is not known



Review: Intrinsic Camera Parameters



$$\begin{bmatrix} u^{(I)} \\ v^{(I)} \\ S \end{bmatrix} = \begin{bmatrix} -f_u & 0 & u_0 & 0 \\ 0 & -f_v & v_0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} X^{(c)} \\ Y^{(c)} \\ Z^{(c)} \\ 1 \end{bmatrix} \quad \begin{aligned} f_u &= fk_u = \alpha \\ f_v &= fk_v = \beta \\ \Theta &= 90^\circ \end{aligned}$$

K



Fundamental Matrix

$p^T \mathcal{E} p' = 0$ p and p' are in camera coordinate system

If u and u' are corresponding image coordinates then we have:

$$\begin{array}{l} u = K_1 p \\ u' = K_2 p' \end{array} \quad \Longrightarrow \quad \begin{array}{l} p = K_1^{-1} u \rightarrow p^T = (K_1^{-1} u)^T = u^T K_1^{-T} \\ p' = K_2^{-1} u' \end{array}$$

$$u^T \boxed{K_1^{-T} \mathcal{E} K_2^{-1}} u' = 0$$

$$\Rightarrow u^T F u' = 0$$

$$F = K_1^{-T} \mathcal{E} K_2^{-1}$$



Fundamental Matrix

$$u^T F u' = 0 \quad F = K_1^{-T} \mathcal{E} K_2^{-1}$$

Fundamental Matrix is singular with rank 2.

The fundamental matrix F has 7 degrees of freedom: A 3×3 homogenous matrix has 8 degrees of freedom. The constraint $\text{rank}(F) = 2$ or $\det(F) = 0$ reduces the number to 7.

In principal F has 7 parameters up to scale and can be estimated from 7 point correspondences.

Direct Simpler Method requires 8 correspondences (Olivier Faugeras, Computer Vision textbook).



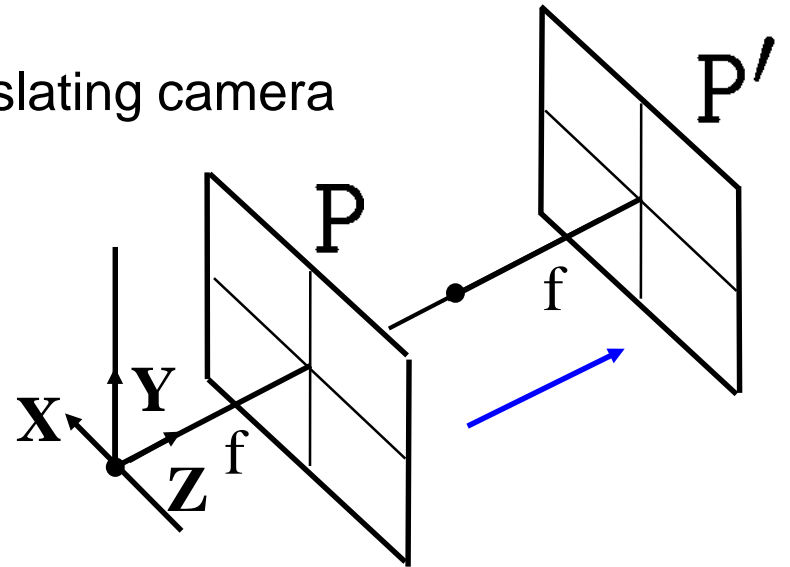


Example II: compute F for a forward translating camera

$$P = K[I \mid \mathbf{0}]$$

$$P' = K'[R \mid \mathbf{t}]$$

$$K = K' = \begin{bmatrix} f & 0 & 0 \\ 0 & f & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad R = I \quad \mathbf{t} = \begin{pmatrix} 0 \\ 0 \\ t_z \end{pmatrix}$$



$$F = K'^{-T} [\mathbf{t}]_{\times} R K^{-1}$$

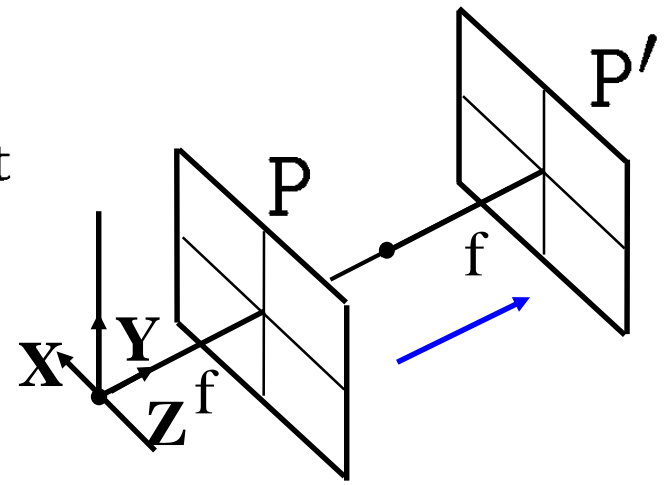
$$= \begin{bmatrix} 1/f & 0 & 0 \\ 0 & 1/f & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 0 & -t_z & 0 \\ t_z & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} 1/f & 0 & 0 \\ 0 & 1/f & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} 0 & -1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$



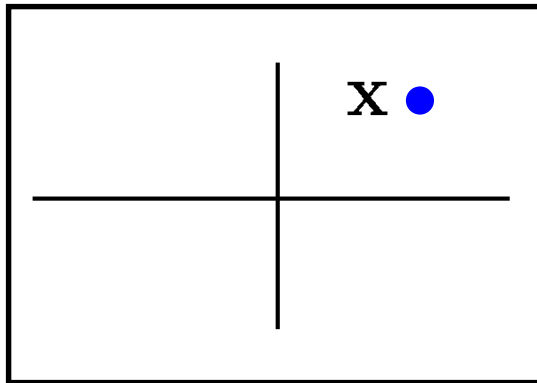
From $l' = Fx$ the epipolar line for the point $\mathbf{x} = (x, y, 1)^\top$ is

$$l' = \begin{bmatrix} 0 & -1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{pmatrix} x \\ y \\ 1 \end{pmatrix} = \begin{pmatrix} -y \\ x \\ 0 \end{pmatrix}$$

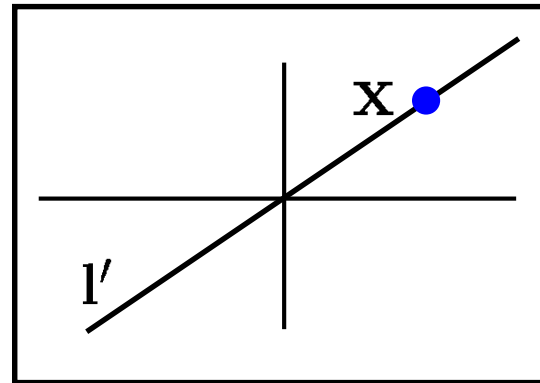


The points $(x, y, 1)^\top$ and $(0, 0, 1)^\top$ lie on this line

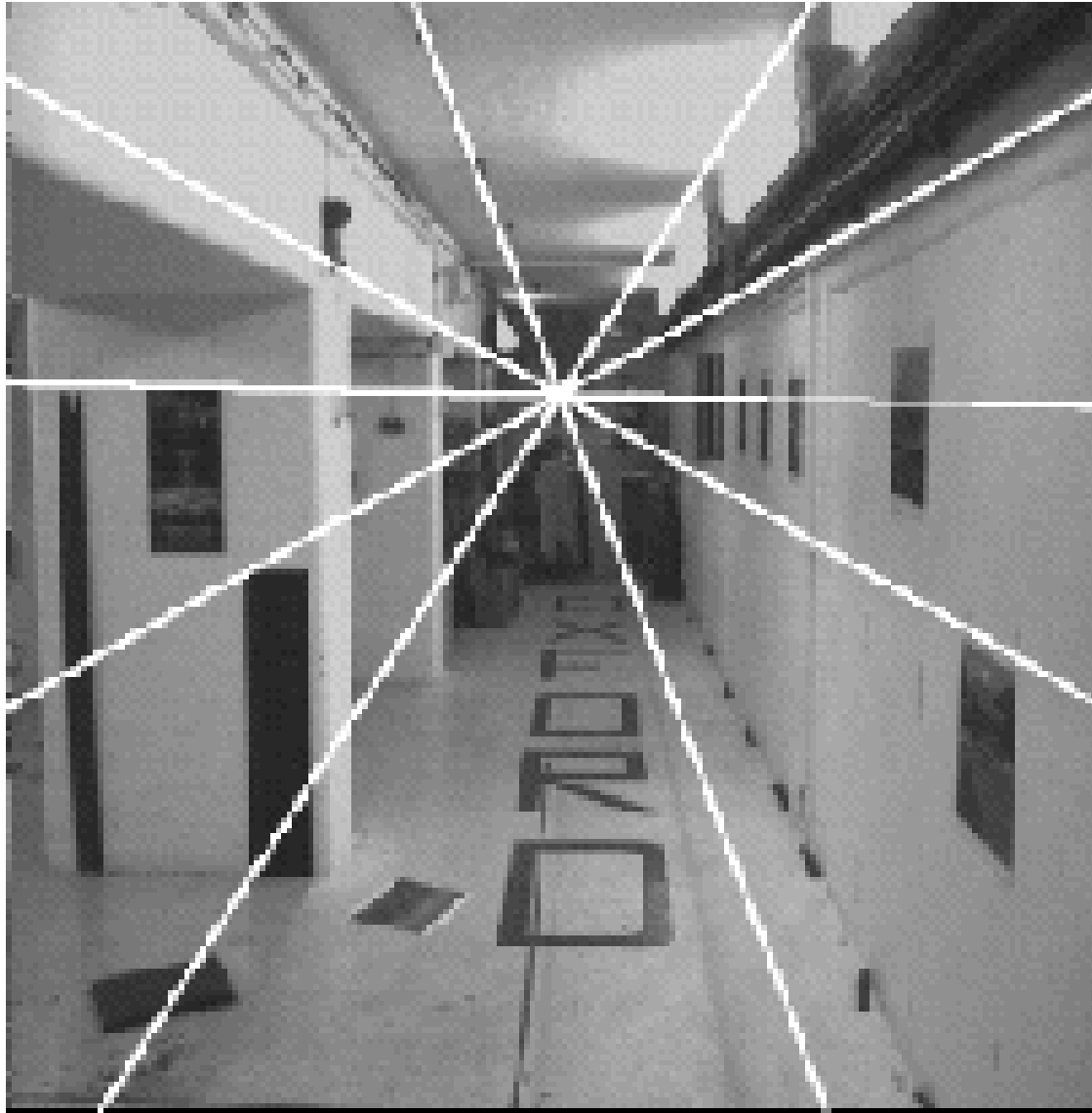
first image



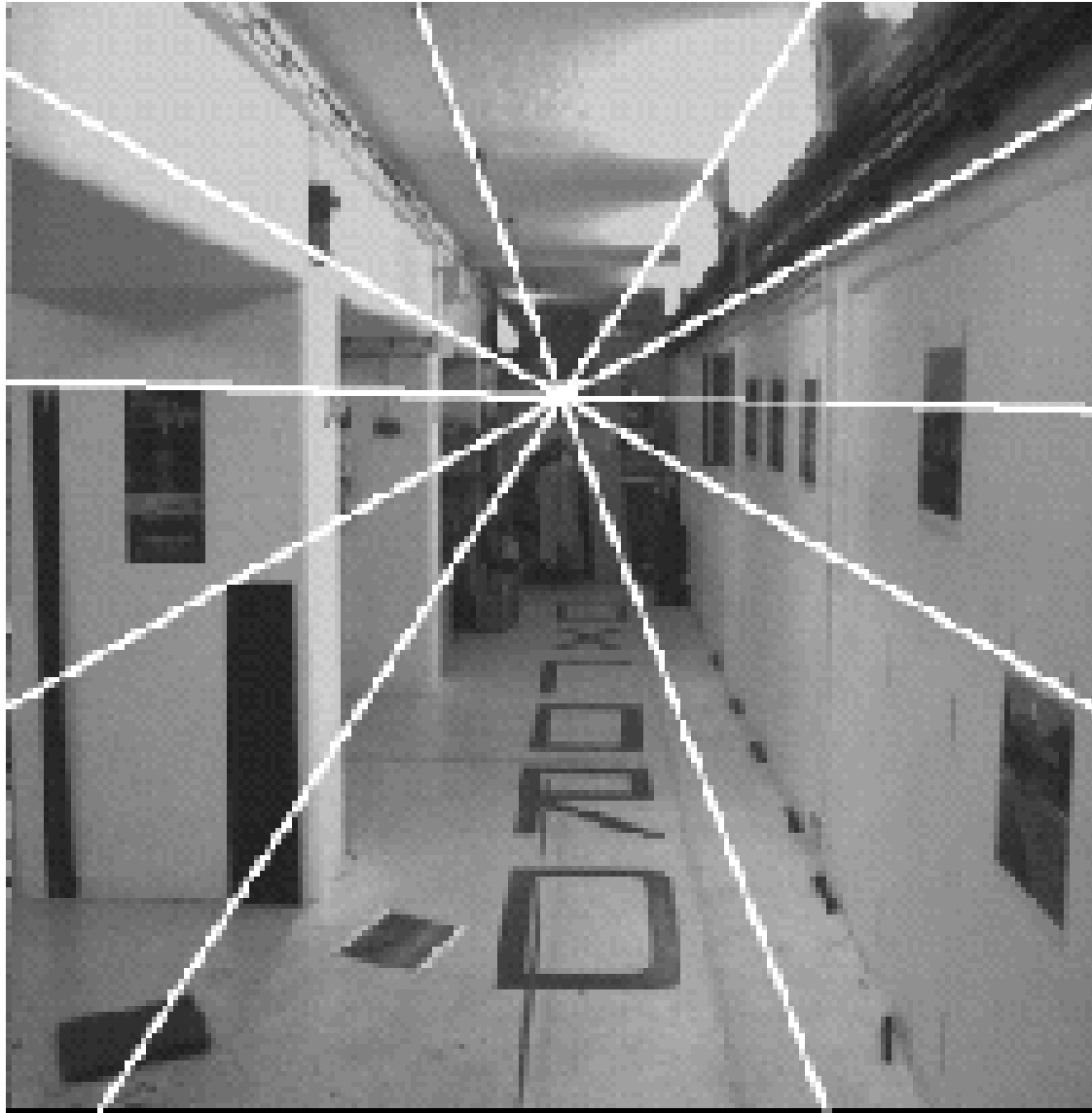
second image

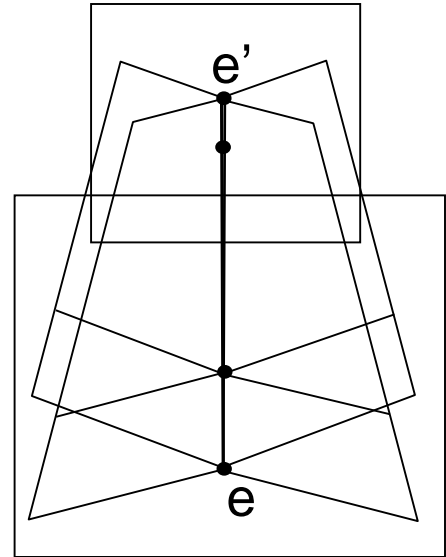
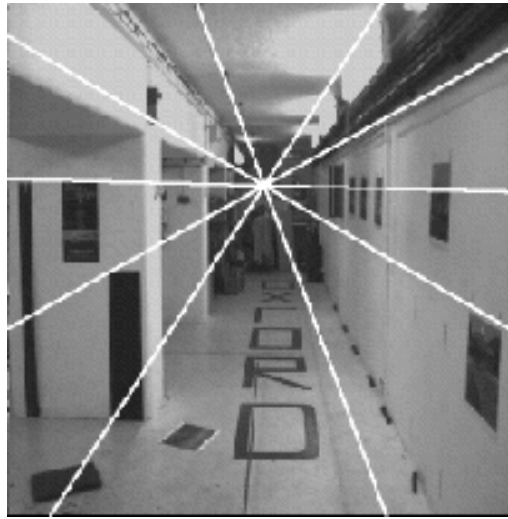
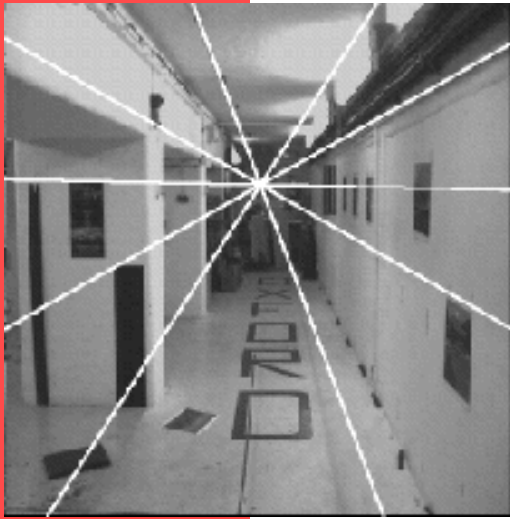


Example: forward motion



Example: forward motion





Estimating Fundamental Matrix

$$u^T F u' = 0$$

The 8-point algorithm (Faugeras)

Each point correspondence can be expressed as a linear equation:

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

$$\begin{bmatrix} uu' & uv' & u & u'v & vv' & v & u' & v' & 1 \end{bmatrix} \begin{bmatrix} F_{11} \\ F_{12} \\ F_{13} \\ F_{21} \\ F_{22} \\ F_{23} \\ F_{31} \\ F_{32} \\ F_{33} \end{bmatrix} = 0$$





The 8-point Algorithm

Scaling: Set F_{33} to 1 \rightarrow Solve for 8 parameters.

8 corresponding points, 8 equations.

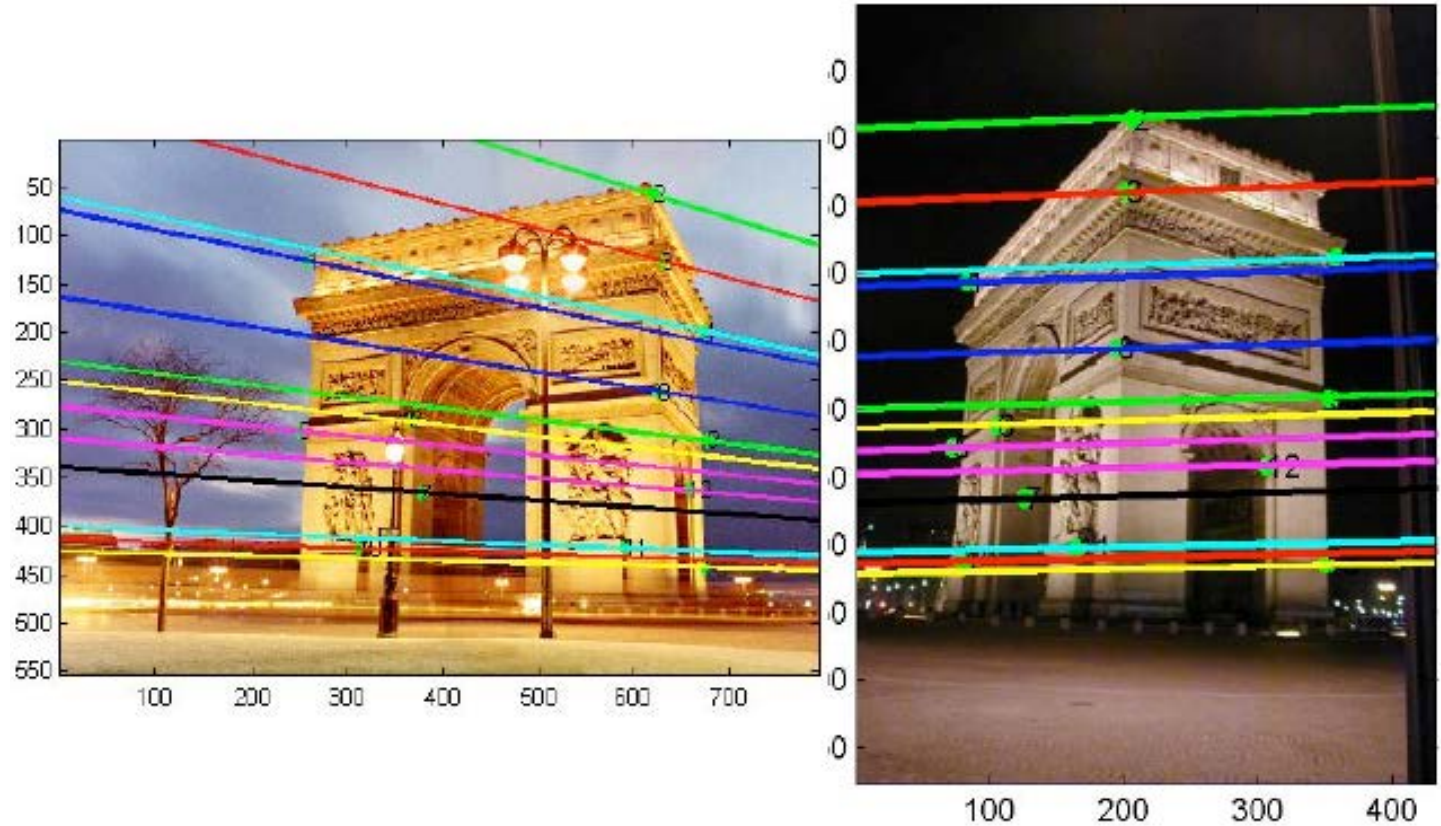
$$\begin{pmatrix} u_1 u'_1 & u_1 v'_1 & u_1 & v_1 u'_1 & v_1 v'_1 & v_1 & u'_1 & v'_1 \\ u_2 u'_2 & u_2 v'_2 & u_2 & v_2 u'_2 & v_2 v'_2 & v_2 & u'_2 & v'_2 \\ u_3 u'_3 & u_3 v'_3 & u_3 & v_3 u'_3 & v_3 v'_3 & v_3 & u'_3 & v'_3 \\ u_4 u'_4 & u_4 v'_4 & u_4 & v_4 u'_4 & v_4 v'_4 & v_4 & u'_4 & v'_4 \\ u_5 u'_5 & u_5 v'_5 & u_5 & v_5 u'_5 & v_5 v'_5 & v_5 & u'_5 & v'_5 \\ u_6 u'_6 & u_6 v'_6 & u_6 & v_6 u'_6 & v_6 v'_6 & v_6 & u'_6 & v'_6 \\ u_7 u'_7 & u_7 v'_7 & u_7 & v_7 u'_7 & v_7 v'_7 & v_7 & u'_7 & v'_7 \\ u_8 u'_8 & u_8 v'_8 & u_8 & v_8 u'_8 & v_8 v'_8 & v_8 & u'_8 & v'_8 \end{pmatrix} \begin{pmatrix} F_{11} \\ F_{12} \\ F_{13} \\ F_{21} \\ F_{22} \\ F_{23} \\ F_{31} \\ F_{32} \end{pmatrix} = - \begin{pmatrix} 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \end{pmatrix}$$

Invert and solve for \mathcal{F} .

(Use more points if available; find least-squares solution to minimize $\sum_{i=1}^n (\mathbf{p}_i^T \mathcal{F} \mathbf{p}'_i)^2$)



Example



$$F = \begin{pmatrix} -0.00310695 & -0.0025646 & 2.96584 \\ -0.028094 & -0.00771621 & 56.3813 \\ 13.1905 & -29.2007 & -9999.79 \end{pmatrix}$$

Example ctd.

$u^T F u' = 0 \rightarrow F u' = l'$, where l' is epipolar line associated to u .

$$F = \begin{pmatrix} -0.00310695 & -0.0025646 & 2.96584 \\ -0.028094 & -0.00771621 & 56.3813 \\ 13.1905 & -29.2007 & -9999.79 \end{pmatrix} \begin{pmatrix} 343.53 \\ 221.70 \\ 1.0 \end{pmatrix}$$



$x = 343.5300$ $y = 221.7005$

$$\begin{pmatrix} 0.0001 \\ 0.0045 \\ -1.1942 \end{pmatrix} \rightarrow \begin{pmatrix} 0.0295 \\ 0.9996 \\ -265.1531 \end{pmatrix}$$

normalize so sum of squares of first two terms is 1 (optional) *

* refers to normal form of line:
 $\rho = x \cos(\phi) + y \sin(\phi)$



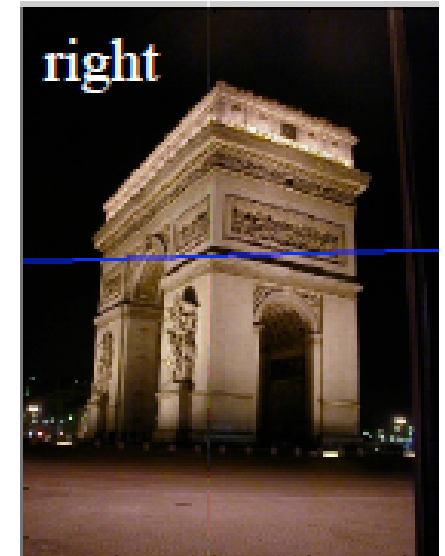
Example: Left to Right

$$F = \begin{pmatrix} -0.00310695 & -0.0025646 & 2.96584 \\ -0.028094 & -0.00771621 & 56.3813 \\ 13.1905 & -29.2007 & -9999.79 \end{pmatrix} \begin{pmatrix} 343.53 \\ 221.70 \\ 1.0 \end{pmatrix}$$



$x = 343.5300$ $y = 221.7005$

0.0295
0.9996
-265.1531

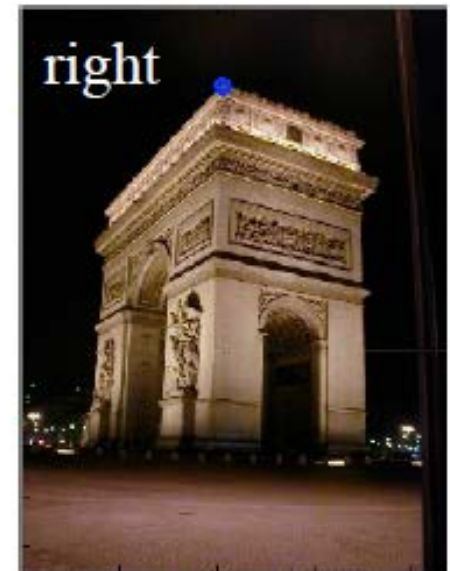
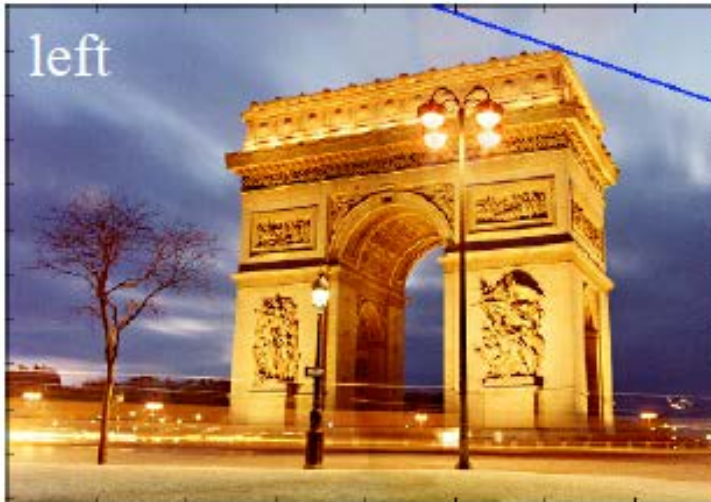




Example: Right to Left

$$(205.5526 \quad 80.5 \quad 1.0) \begin{pmatrix} -0.00310695 & -0.0025646 & 2.96584 \\ -0.028094 & -0.00771621 & 56.3813 \\ 13.1905 & -29.2007 & -9999.79 \end{pmatrix}$$

$$L = (0.3211 \quad -0.9470 \quad -151.39)$$

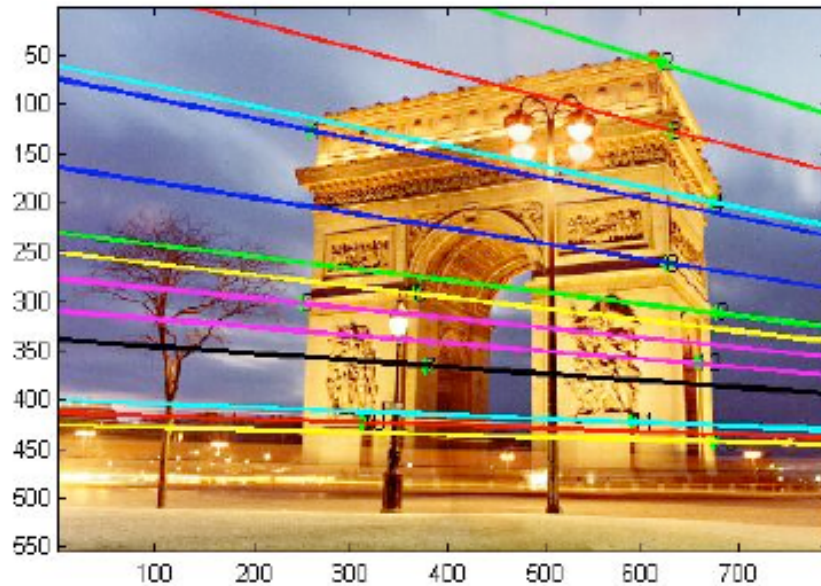


$$x = 205.5526 \quad y = 80.5000$$



Example: Epipoles?

where is the epipole?



$$F * e_L = 0$$

vector in the right
nullspace of matrix F

However, due to noise,
 F may not be singular.
So instead, next best
thing is eigenvector
associated with smallest
eigenvalue of F



Example: Epipoles?

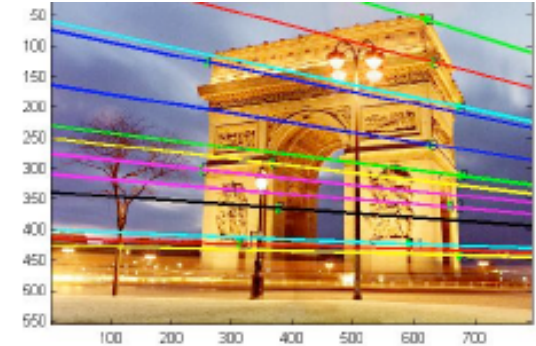
```
>> [u,d] = eigs(F' * F)
```

```
u =
```

-0.0013	0.2586	-0.9660	-1.0000	0	0
0.0029	-0.9660	-0.2586	0	-0.0000	0
1.0000	0.0032	-0.0005	0	0	-0.0000

```
d = 1.0e8*
```

-1.0000	0	0
0	-0.0000	0
0	0	-0.0000

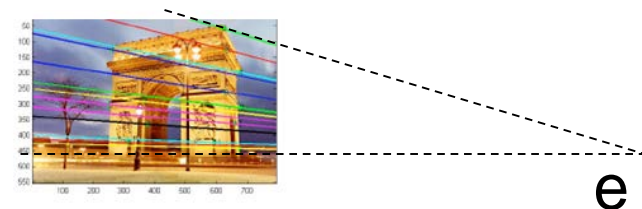


eigenvector associated with smallest eigenvalue

```
>> uu = u(:,3)
```

```
uu = ( -0.9660 -0.2586 -0.0005)
```

```
>> uu / uu(3) : to get pixel coords  
(1861.02 498.21 1.0)
```



Summary: Properties of the Fundamental matrix

- F is a rank 2 homogeneous matrix with 7 degrees of freedom.
- **Point correspondence:**
if \mathbf{x} and \mathbf{x}' are corresponding image points, then $\mathbf{x}'^T F \mathbf{x} = 0$.
- **Epipolar lines:**
 - ◇ $\mathbf{l}' = F \mathbf{x}$ is the epipolar line corresponding to \mathbf{x} .
 - ◇ $\mathbf{l} = F^T \mathbf{x}'$ is the epipolar line corresponding to \mathbf{x}' .
- **Epipoles:**
 - ◇ $F \mathbf{e} = \mathbf{0}$.
 - ◇ $F^T \mathbf{e}' = \mathbf{0}$.
- **Computation from camera matrices P, P' :**
 $P = K[I \mid \mathbf{0}]$, $P' = K'[R \mid \mathbf{t}]$, $F = K'^{-T}[\mathbf{t}]_{\times} R K^{-1}$