COMPUTER VISION AND PHOTOGRAMMETRY

TWO VIEW GEOMETRY

CONTENTS TODAY

- Quick review, Camera Geometry and Homographies
- Epipolar Geometry (review)
- Fundamental Matrix
- Projective Invariance and Projective Ambiguity
- Essential Matrix
- Computing F and E
- Canonical Cameras from F
- Triangulation

LET'S RECAP…

LAB 1
QUESTIONS?
PROBLEMS?

CAMERA PARAMETERS – NOTATION AND RELATIONSHIPS

- P
- K
- R
- T
- Q
- C
- k1, k2, k…

CAMERA PARAMETERS – NOTATION AND RELATIONSHIPS

- P = Projection matrix (pinhole camera model)
- takes a 3D point in world homogeneous coordinates
- gives a 2D point in image homogeneous coordinates
- includes intrinsic and extrinsic parameters
- 11 degres of freedom K[R | T]
- doesn’t include lens distortion

CAMERA PARAMETERS – NOTATION AND RELATIONSHIPS

- K = intrinsic matrix is 3x3 upper diagonal (calibration)
- focal length (in pixels)
  - how to calculate? Sensor size = 20mm X 20mm / focal length f = 10mm
    - image size 1000 by 1000, then 1pixel =20/1000 mm,
    - f = 10mm = 10 / (20/1000) = 500 pixels
- pixel aspect ratio (non-squared pixels) (different x,and y, f)
  - not related to the image aspect ratio
- skew: non-rectangular pixels
- Uo and Vo center of the image (in pixels) near w/2 h/2

CAMERA PARAMETERS – NOTATION AND RELATIONSHIPS

- R
- rotation matrix, 3x3
- orthogonal matrix: change points in 3D world to points in camera world orientation

CAMERA PARAMETERS – NOTATION AND RELATIONSHIPS

- T and C
- T is Translation matrix 3x1
- is the (0,0,0) in the world coordinates in camera coordinates
- C is the center of the camera in world coordinates
- $T = -RC \; \rightarrow \; C = -R^{-1}T$
- RT transforms a point in the world coordinates to camera coordinates and projected into an ideal camera with K = diag(1,1,1) *normalized coordinates*
- RT X = x-vector is the direction of that point towards X
- Kx-vector = x in image coordinates -> $K^{-1}x$ = x-vector

CAMERA PARAMETERS – NOTATION AND RELATIONSHIPS

- P - K,R,T,C
- Q is the left 3x3 matrix of P
- Lets call P4 the last column of P
- $C = -Q^{-1}P4$
- K,R = rq-factorization of (Q) upper diagonal and orthogonal
- $T = K^{-1}P4$
- $C = -R^{-1}T$

CAMERA PARAMETERS – NOTATION AND RELATIONSHIPS

- k1, k2 are the first two parameters for lens distortion
- usually enough
- x-distorted = x + (x-Uo)(k1r^2 + k2r^4 +…)
- r^2 and r^4 are calculated in *normalized coordinates* (x-vector)

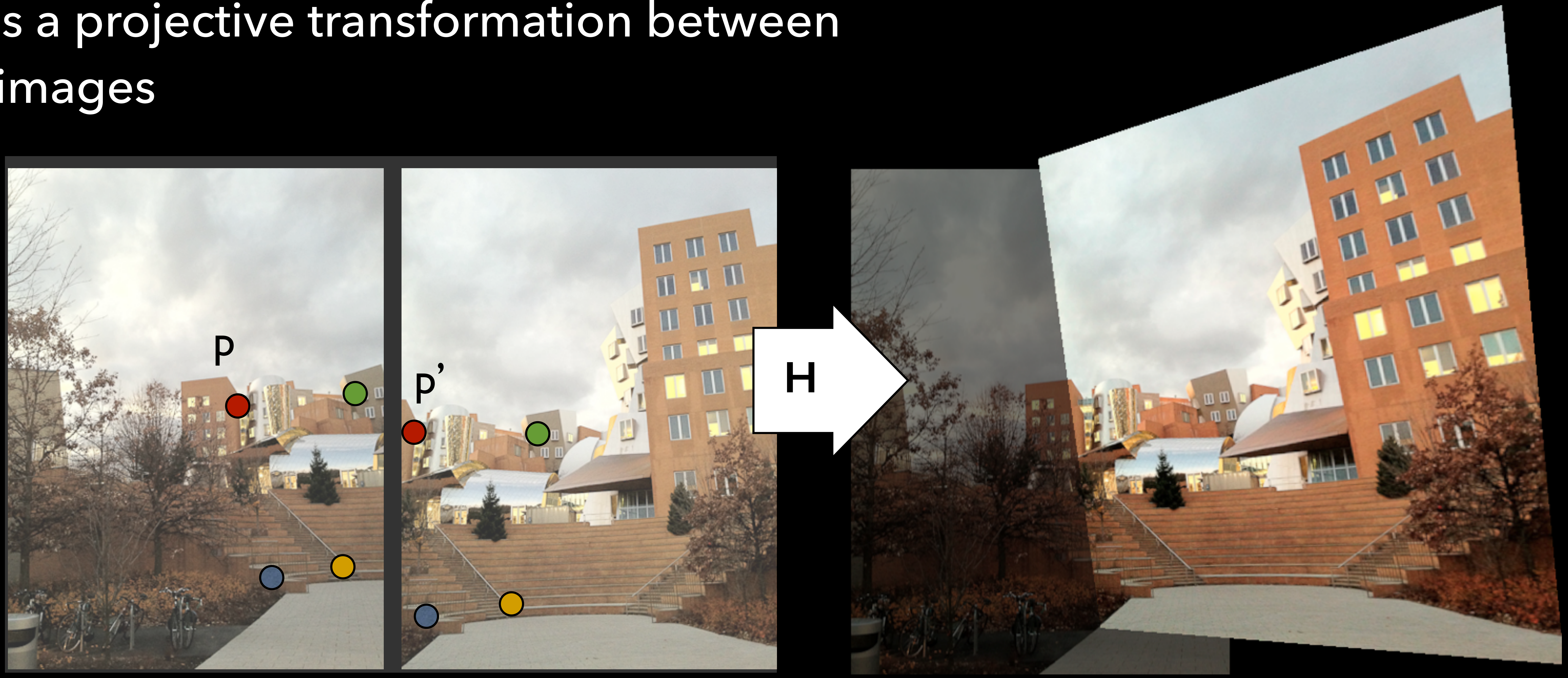
CAMERA PARAMETERS – NOTATION AND RELATIONSHIPS

- P can be calculated from 3D to 2D correspondences
- K, R, and T, can be recovered from P using RQ Factorization.
- k1, k2 can be calculated from disparity between P and projections
- Non-linear iterative methods allow for adding known constraints and include Lens distortion in the model.

HOMOGRAPHIES

HOMOGRAPHIES

- 3x3 matrix
- Gives a projective transformation between two images



CORRECT PERSPECTIVE

- We will use it for stereo rectification

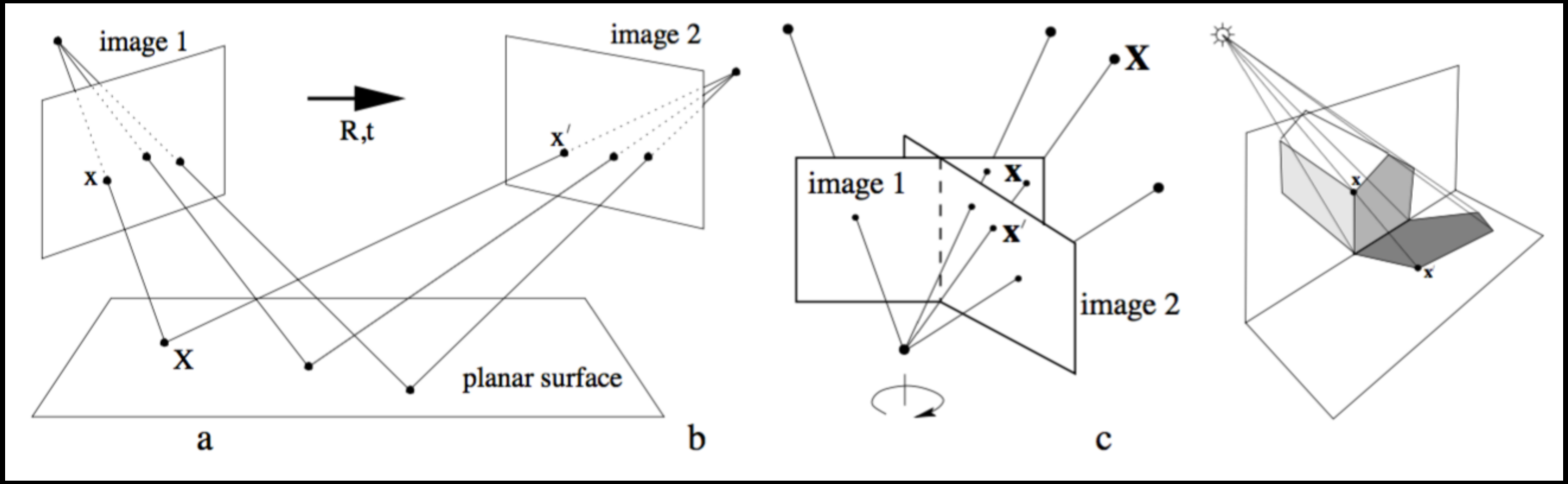
SCALE

- Homographies are defined up to a scale
- H and kH represent the same 2D transformation
- because (w'x', w'y', w') and (kw'x', kw'y', kw') represent the same point

$$\underbrace{\begin{bmatrix} wx' \\ wy' \\ w \end{bmatrix}}_{\mathbf{p'}} = \underbrace{\begin{bmatrix} * & * & * \\ * & * & * \\ * & * & * \end{bmatrix}}_{\mathbf{H}} \underbrace{\begin{bmatrix} x \\ y \\ 1 \end{bmatrix}}_{\mathbf{p}}$$

EXAMPLES OF HOMOGRAPHIES

- Rotation and Translation in 3D
- Rotation on camera center
- Shadows from a point light-source



CALCULATING AN HOMOGRAPHY

- Given correspondences
- Find homography matrix H that maps the p_i to p_i'

HOMOGRAPHY EQUATION

- We are given pairs of corresponding points
  - x, y, x′, y′ are known
- Unknowns: matrix coefficients and w′
- (the order in Y and X is only for convenience when

$$\begin{pmatrix} a & b & c \\ d & e & f \\ g & h & i \end{pmatrix} \begin{pmatrix} y \\ x \\ 1 \end{pmatrix} = \begin{pmatrix} y'w' \\ x'w' \\ w' \end{pmatrix}$$

LINEAR SYSTEM

$$ay + bx + c = y'(gy + hx + i)$$

$$dy + ex + f = x'(gy + hx + i)$$

$$\begin{array}{c} \begin{array}{ccccccccc} a & b & c & d & e & f & g & h & i \end{array} \\ \left(\begin{array}{ccccccccc} & & & & \cdots\cdots & & & & \\ y & x & 1 & 0 & 0 & 0 & -yy' & -xy' & -y' \\ & & & & \cdots\cdots & & & & \\ & & & & \cdots\cdots & & & & \end{array}\right) \end{array} \begin{pmatrix} a \\ b \\ c \\ d \\ e \\ f \\ g \\ h \\ i \end{pmatrix} = \begin{array}{c} \cdot \\ \cdot \\ \cdot \\ 0 \\ \cdot \\ \cdot \\ \cdot \end{array}$$

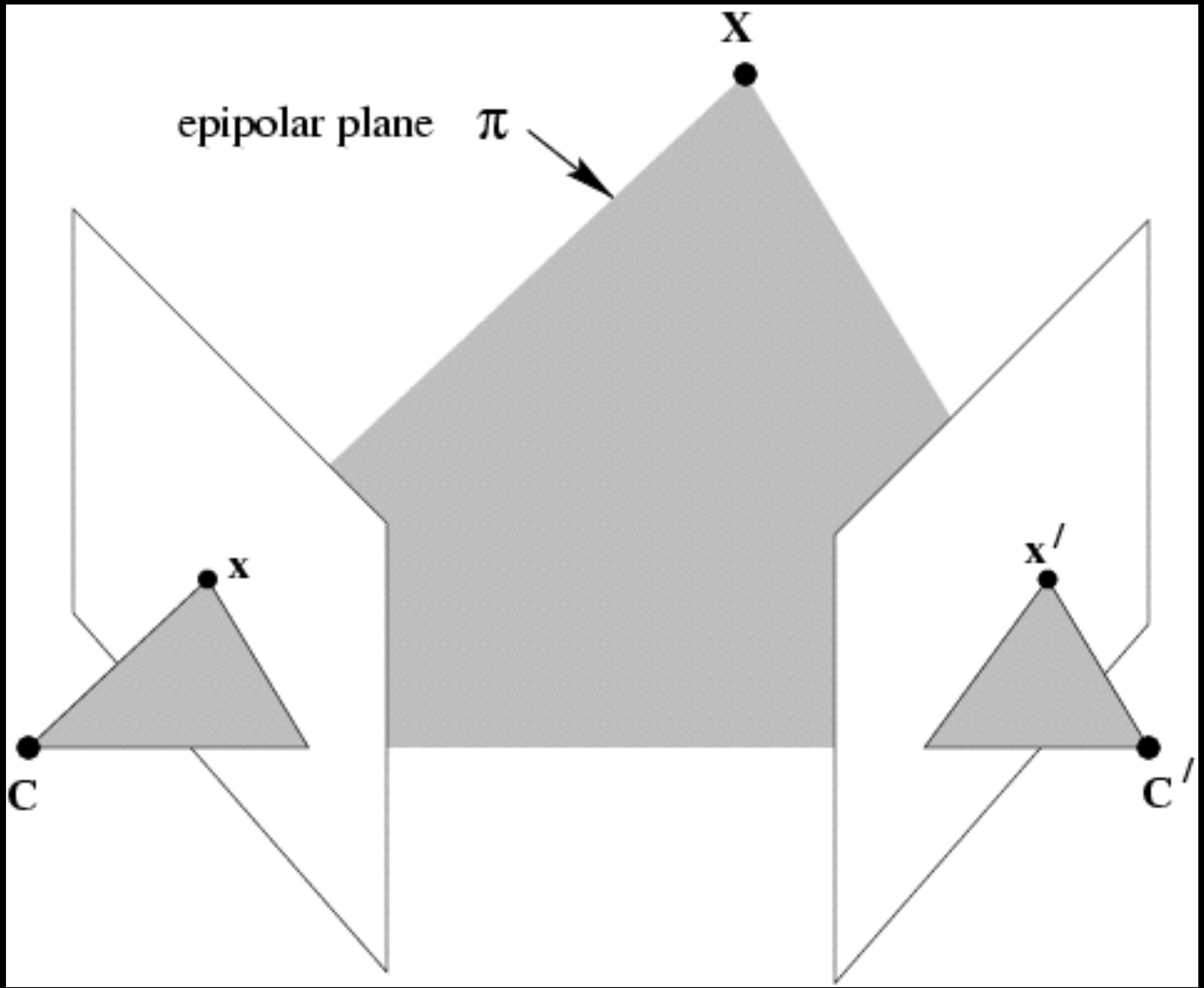
SOLVE THE SYSTEM USING LEAST SQUARES

- 4 points - 8 equations will suffice
- Use SVD -> UsV or UsV^T
- The singular vector with singular value 0 is a solution
- This is a good solving method for homogeneous systems

?

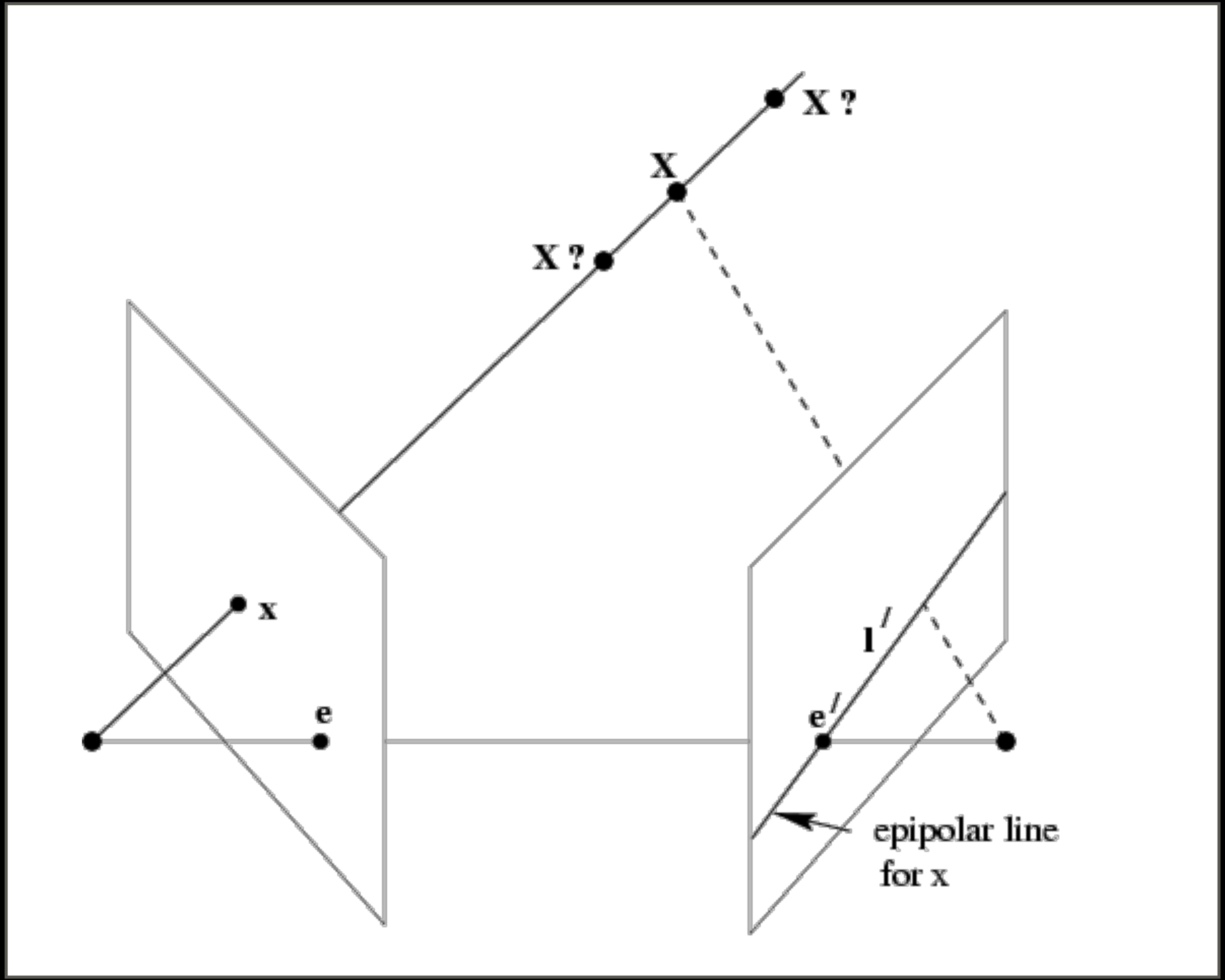
EPIPOLAR GEOMETRY

THE EPIPOLAR GEOMETRY



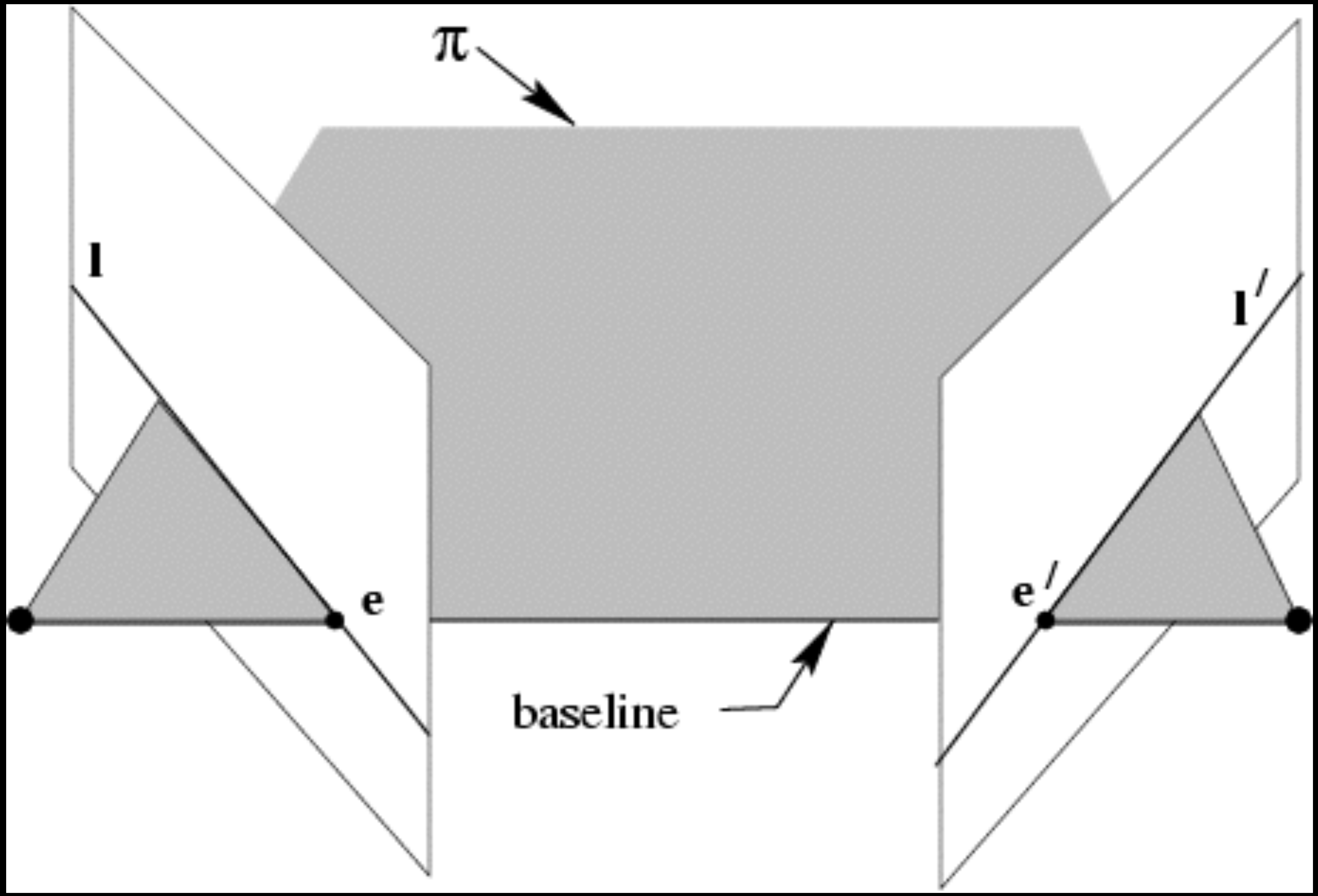
C,C',X,X' AND X ARE COPLANAR

THE EPIPOLAR GEOMETRY



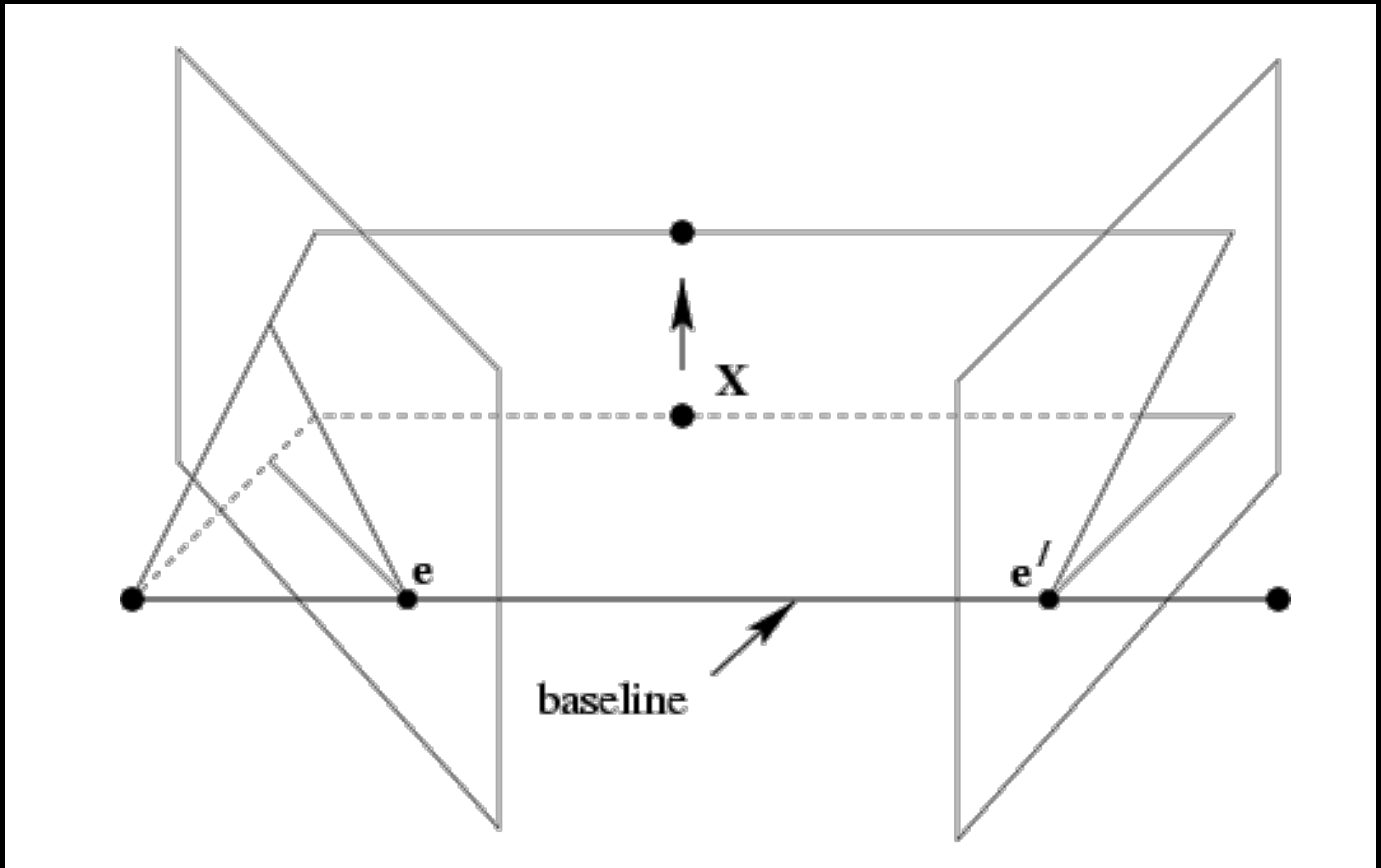
WHAT IF ONLY C,C',X ARE KNOWN?

THE EPIPOLAR GEOMETRY



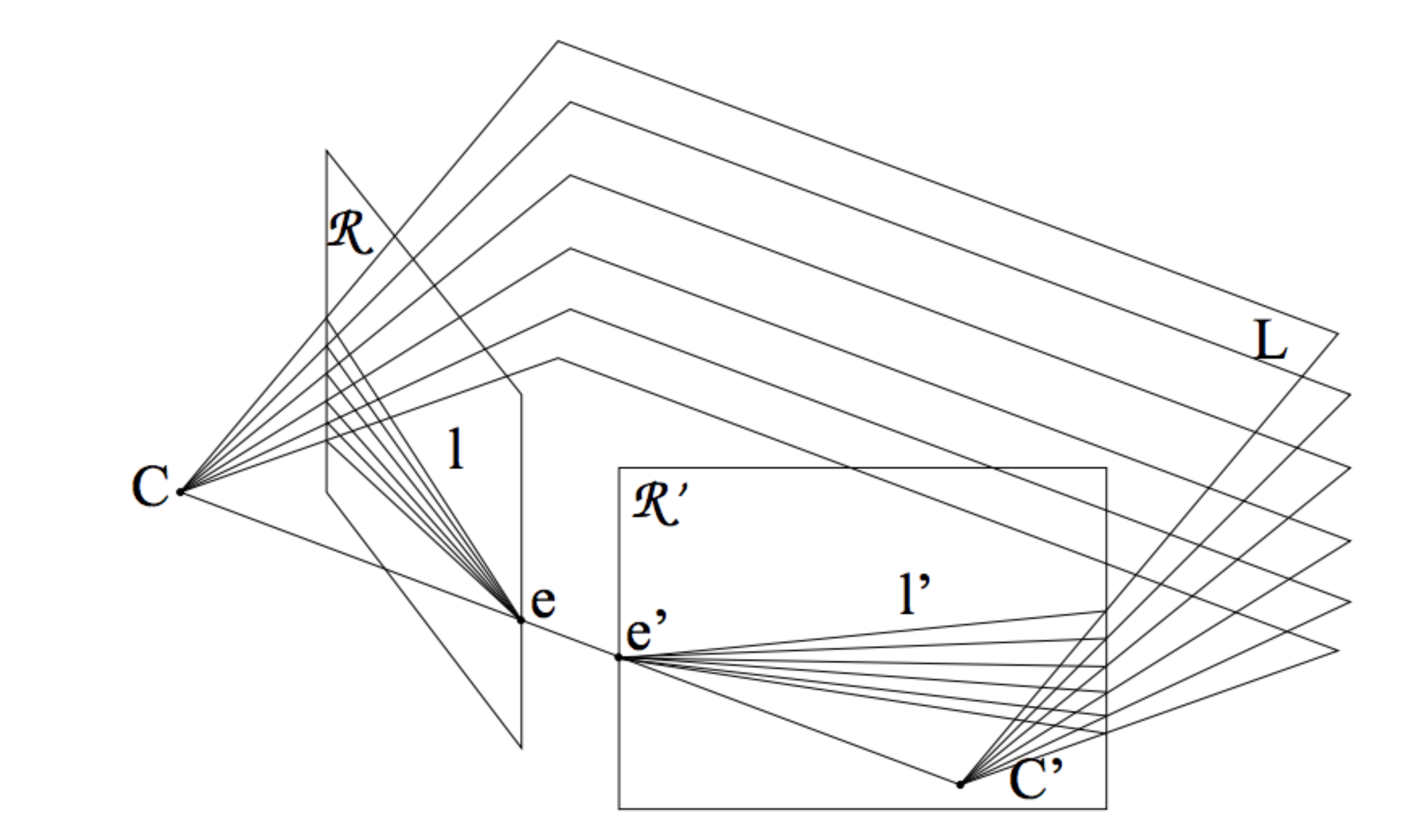
ALL POINTS ON Π PROJECT ON L AND L’

THE EPIPOLAR GEOMETRY



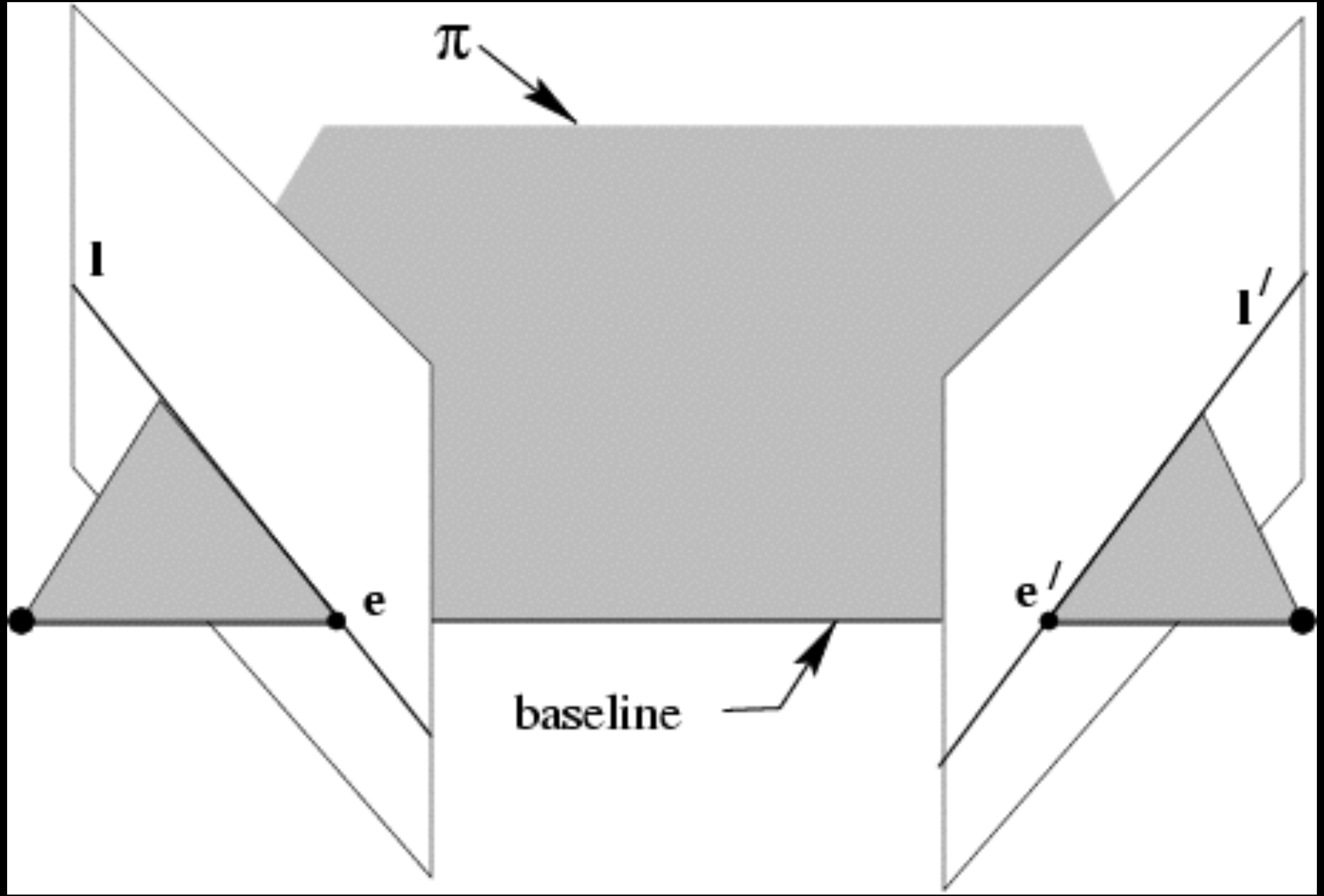
FAMILY OF PLANES Π AND LINES L AND L’
INTERSECTION IN E AND E’

EPIPOLAR GEOMETRY: NOTATION



PENCIL OF PLANES OF THE BASELINE DEFINE EPIPOLAR LINES AND EPIPOLES

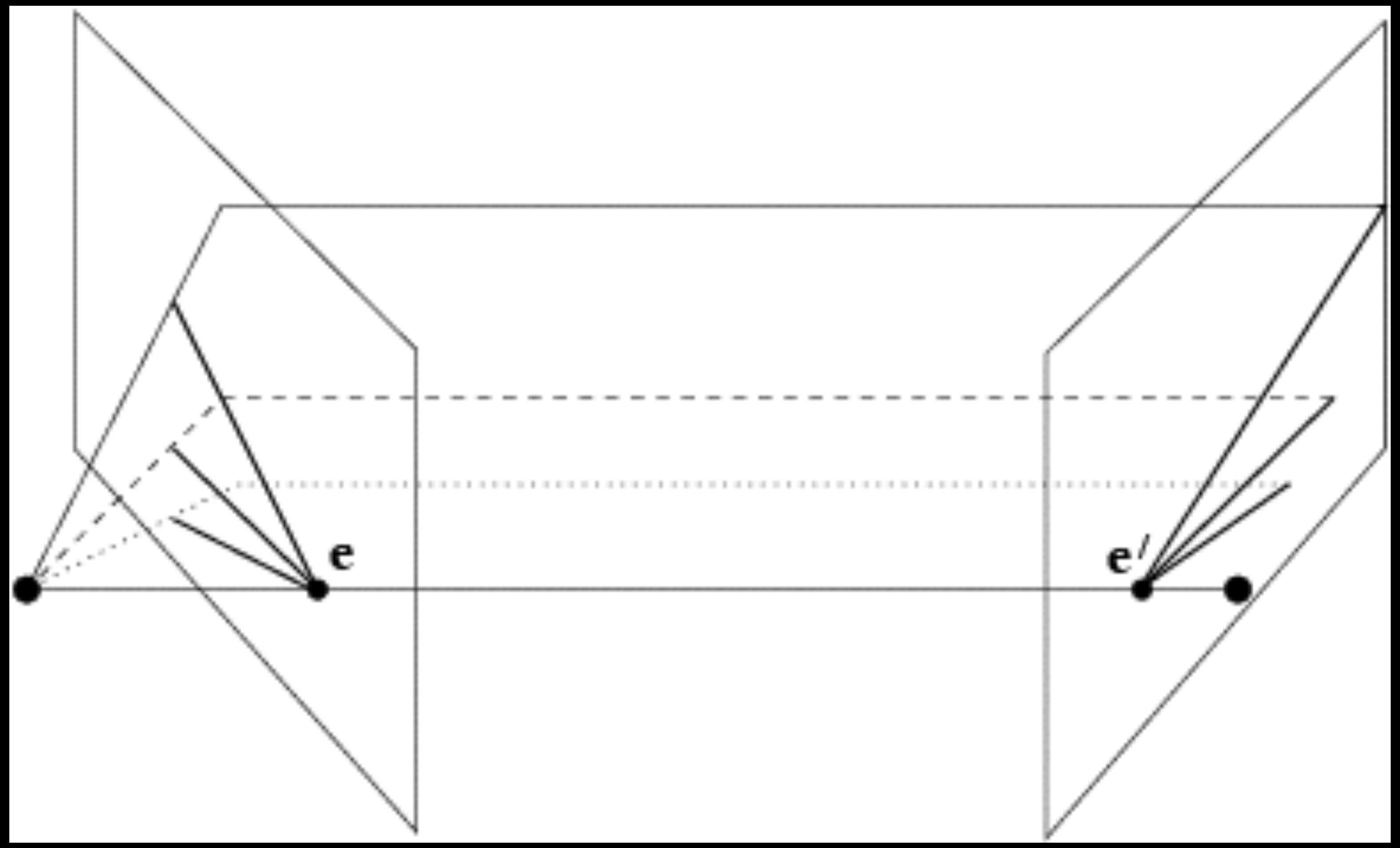
EPIPOLES E,E′
= INTERSECTION OF BASELINE WITH IMAGE PLANE
= PROJECTION OF PROJECTION CENTER IN OTHER IMAGE
= VANISHING POINT OF CAMERA MOTION DIRECTION

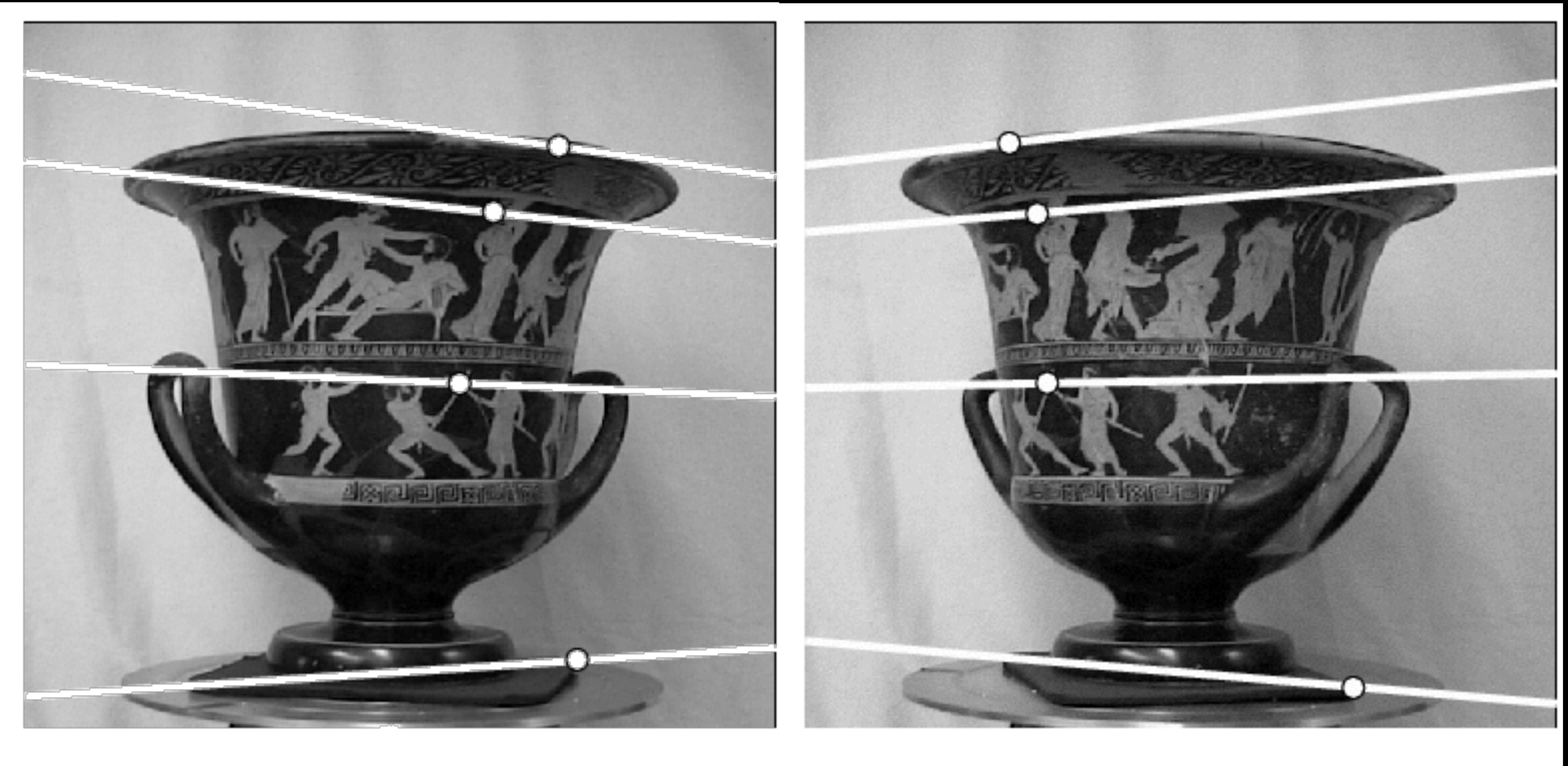


AN EPIPOLAR PLANE = PLANE CONTAINING BASELINE (1-D FAMILY)

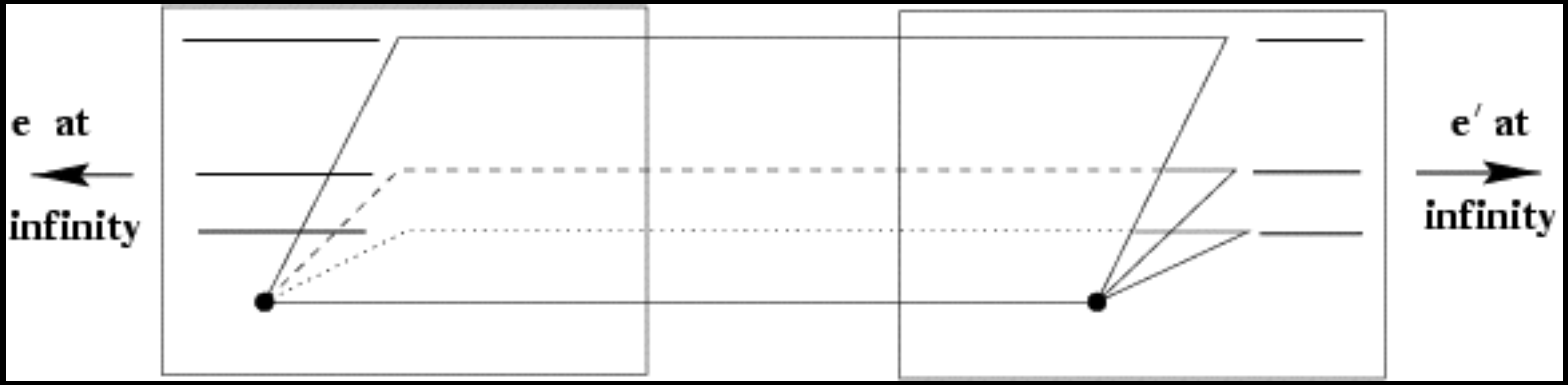
AN EPIPOLAR LINE = INTERSECTION OF EPIPOLAR PLANE WITH IMAGE
(ALWAYS COME IN CORRESPONDING PAIRS)

EXAMPLE: CONVERGING CAMERAS

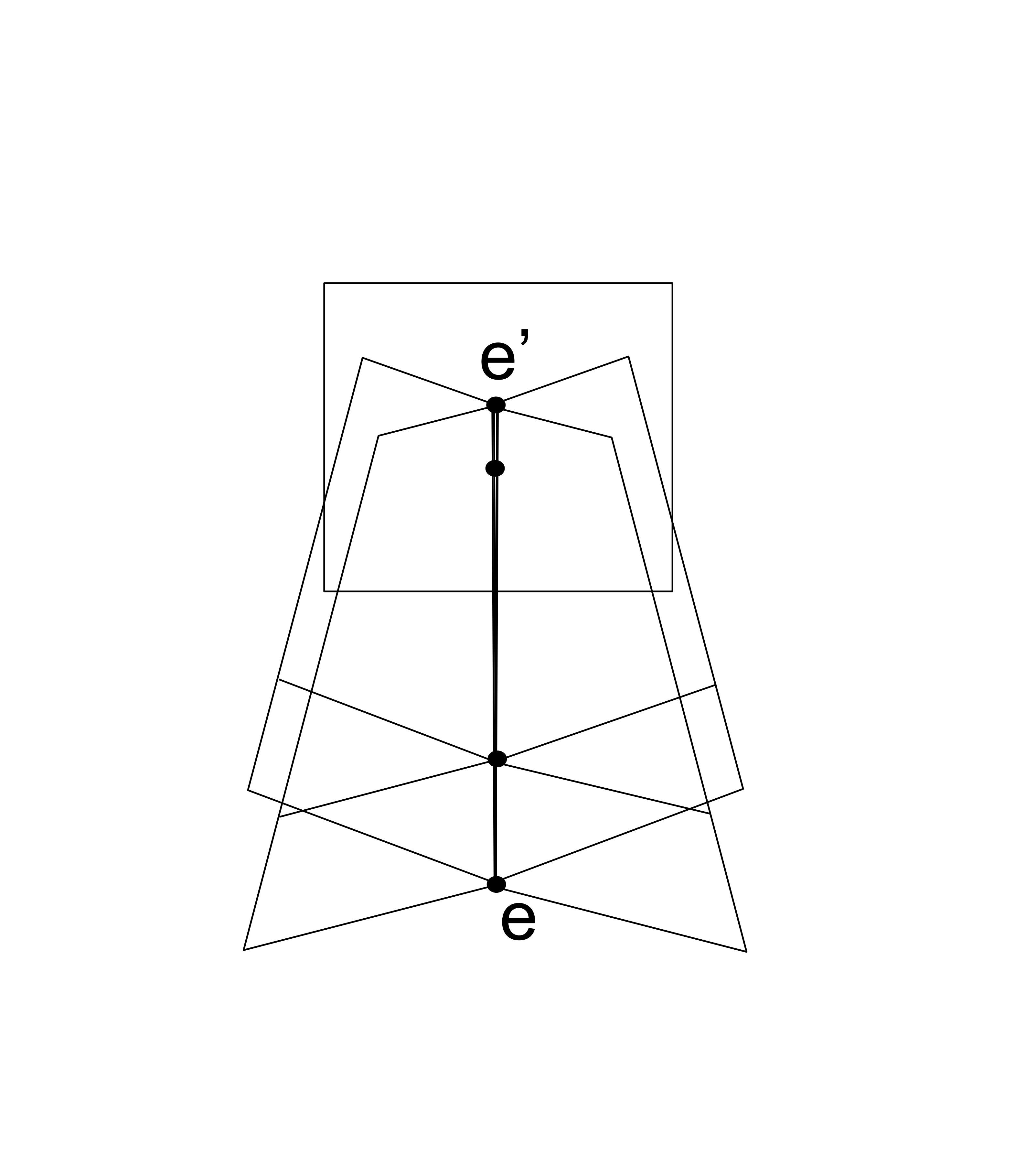


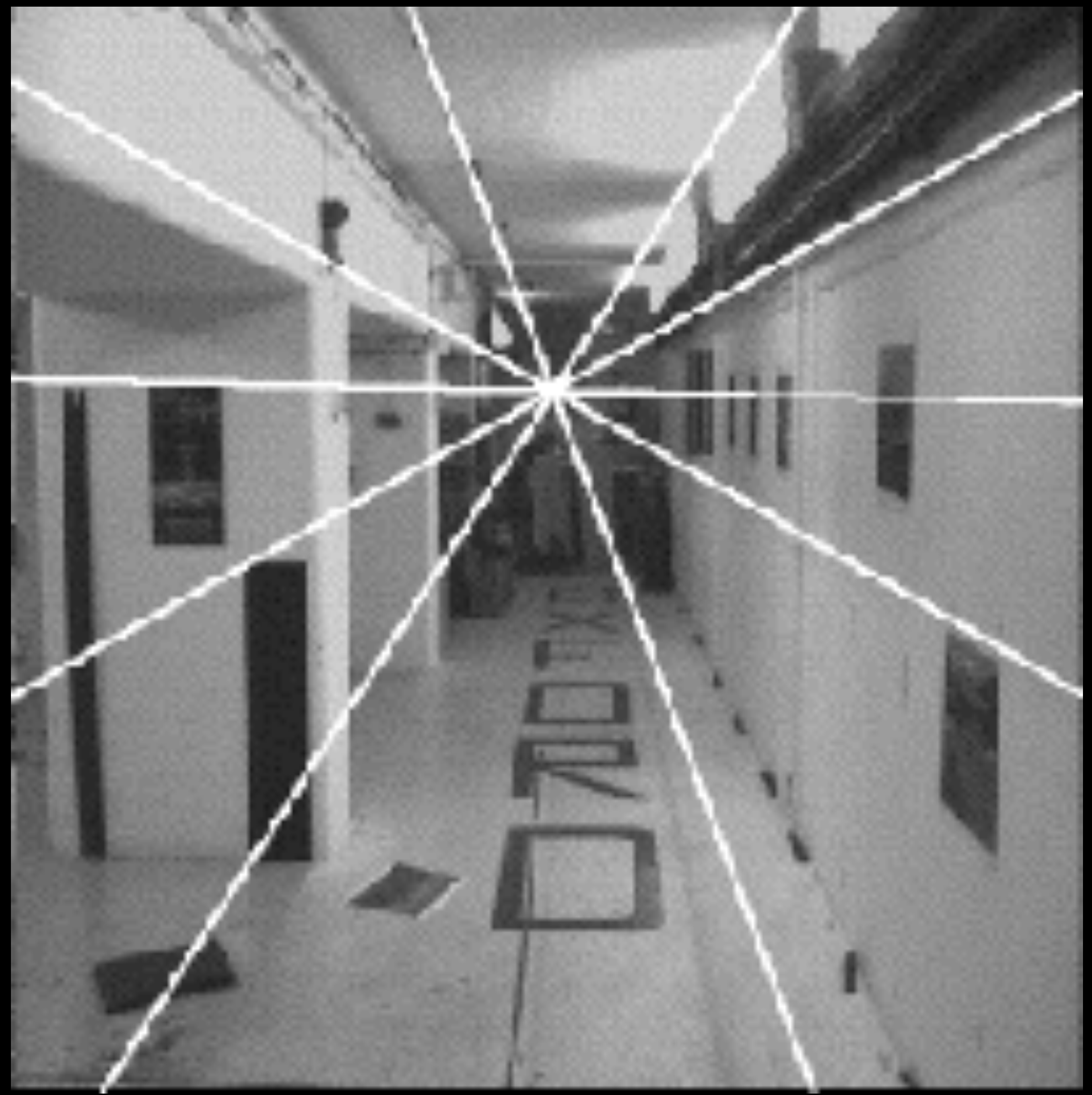


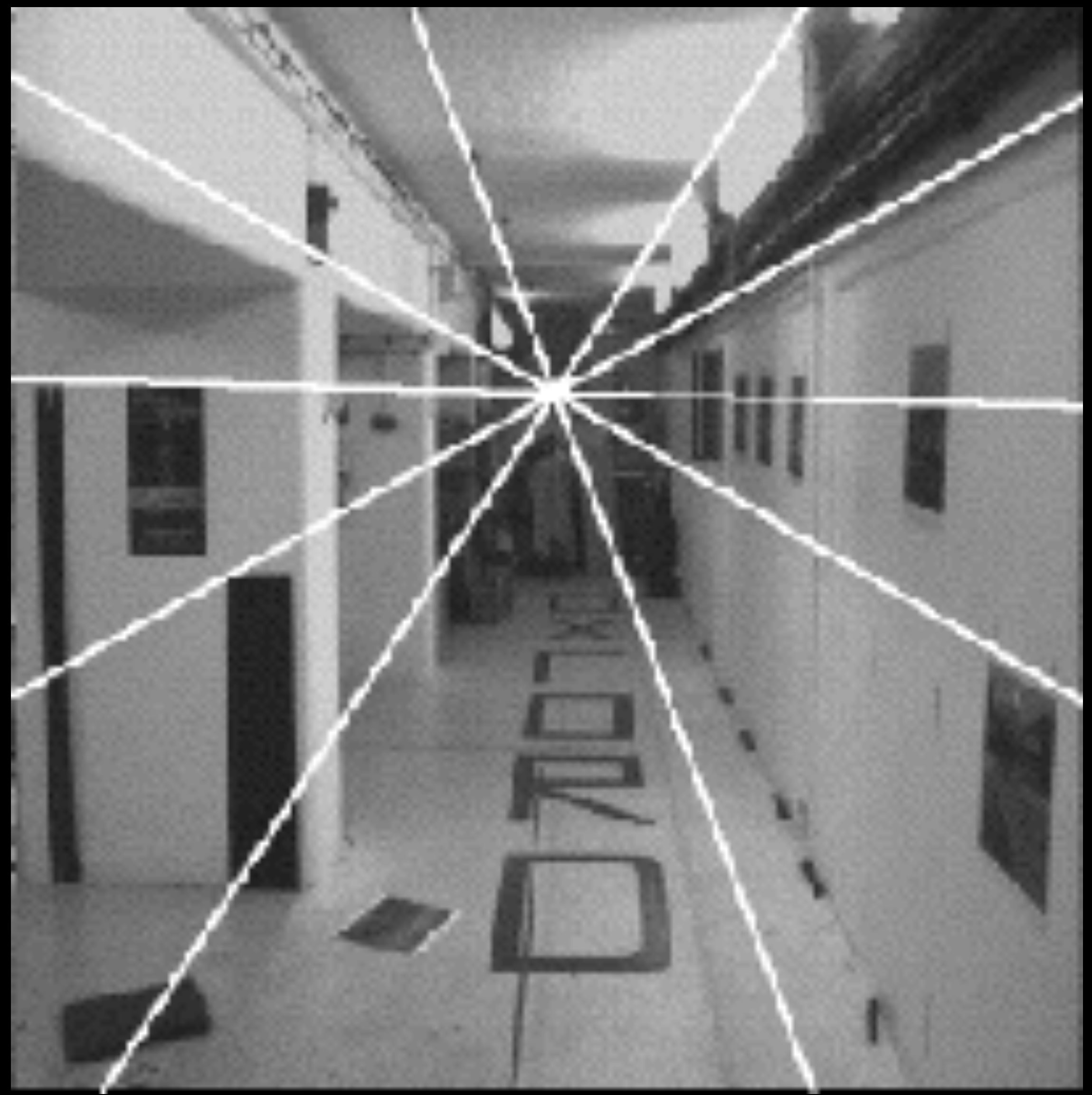
TEXT



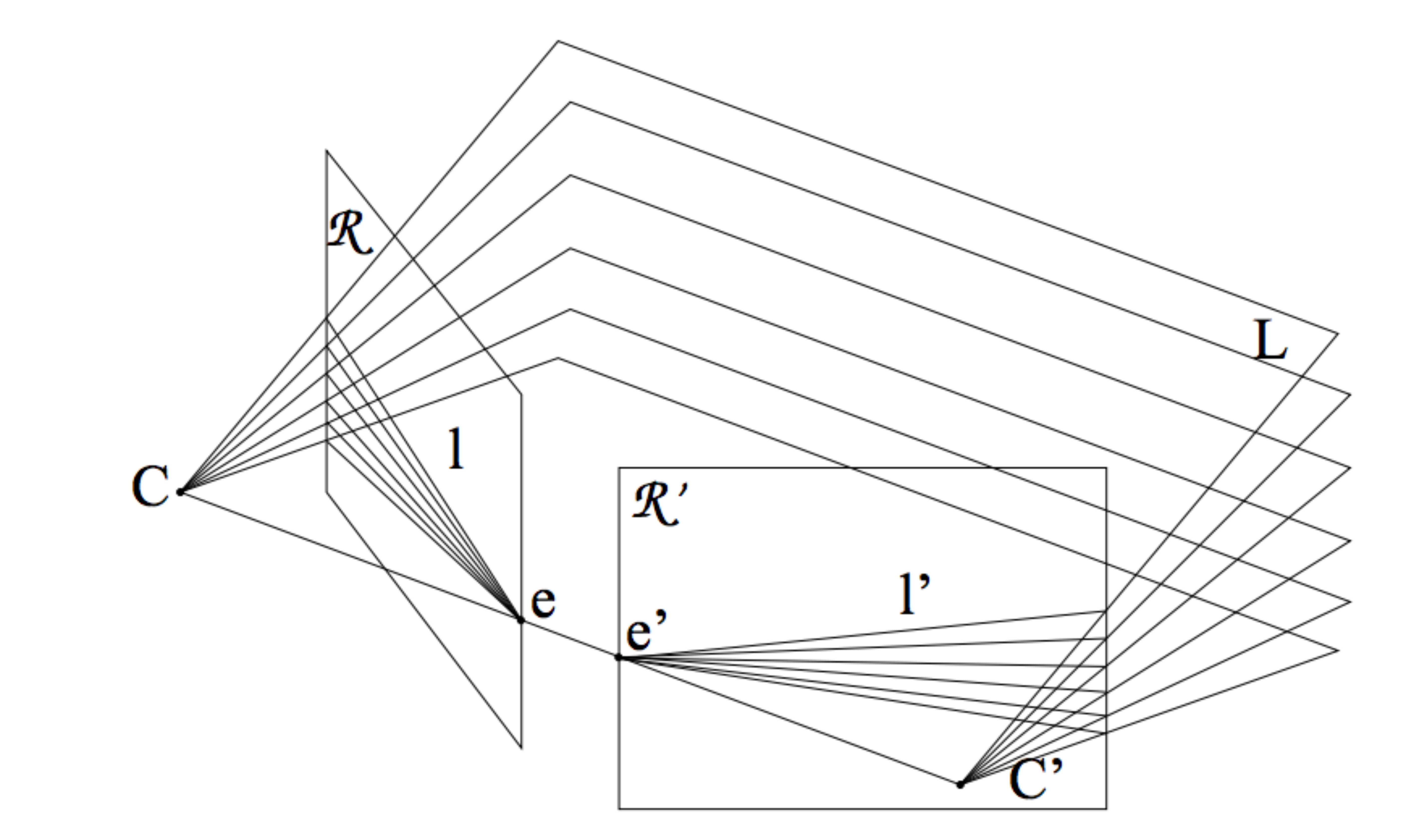
EXAMPLE: FORWARD MOTION







EPIPOLAR LINES CROSS AT THE EPIPOLE



BY DEFINITION, ALL EPIPOLAR LINES CROSS AT THE EPIPOLE

?

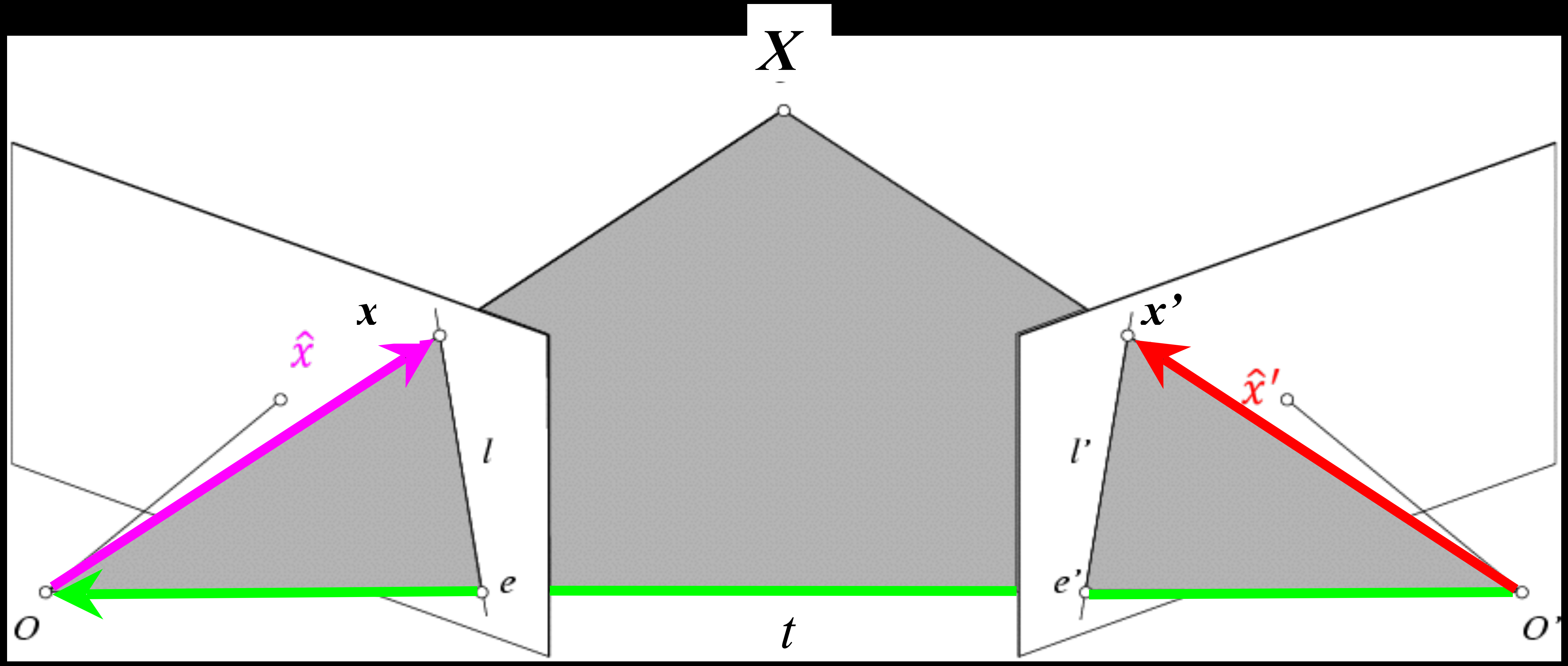
THE FUNDAMENTAL MATRIX F

ALGEBRAIC REPRESENTATION OF EPIPOLAR GEOMETRY

$$x \; ? \; l'$$

WE WILL SEE THAT MAPPING IS (SINGULAR) CORRELATION (I.E. PROJECTIVE MAPPING FROM POINTS TO LINES) REPRESENTED BY THE FUNDAMENTAL MATRIX F

EPIPOLAR CONSTRAINT: CALIBRATED CASE



$$\hat{x}' = K'^{-1}x' = X'$$

$$\hat{x} = K^{-1}x = X$$

$$\hat{x} = R\hat{x}' + t \quad \Rightarrow \quad \hat{x} \cdot [t \times (R\hat{x}')] = 0$$

(because $\hat{x}, R\hat{x}'$, and t are co-planar)

$$\hat{x} \cdot [t \times (R\hat{x}')] = 0 \quad \Rightarrow \quad \hat{x}^T E \hat{x}' = 0 \quad \text{with} \quad E = [t]_\times R$$

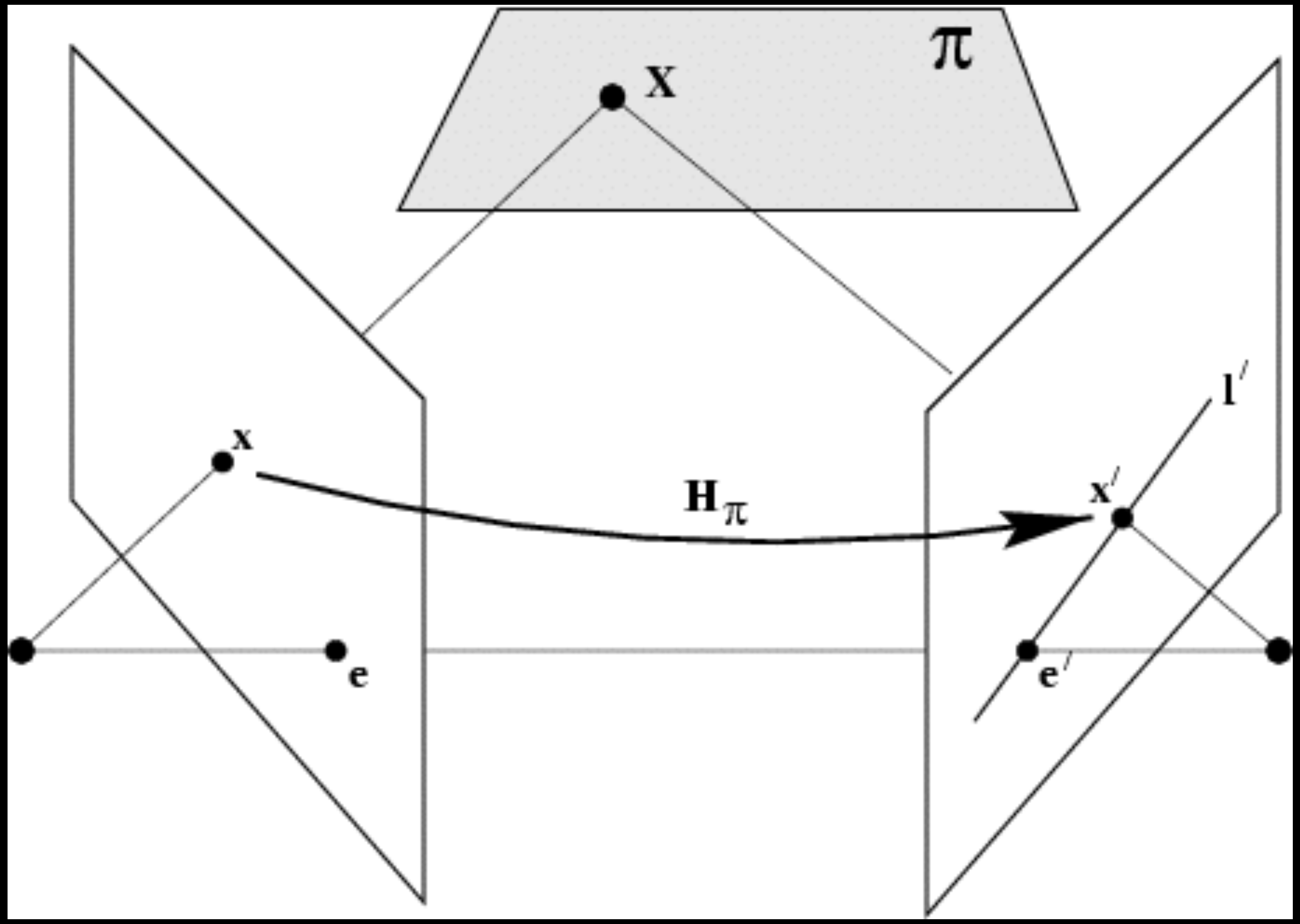
SKEW SYMMETRIC NOTATION

$$[\mathbf{a}]_\times = \begin{bmatrix} 0 & -a_3 & a_2 \\ a_3 & 0 & -a_1 \\ -a_2 & a_1 & 0 \end{bmatrix}.$$

$$\mathbf{a} \times \mathbf{b} = [\mathbf{a}]_\times \mathbf{b} = \left(\mathbf{a}^\mathsf{T}[\mathbf{b}]_\times\right)^\mathsf{T}.$$

THE FUNDAMENTAL MATRIX F

GEOMETRIC DERIVATION



$$x' = H_\pi x$$

$$l' = e' \times x' = [e']_\times H_\pi x = Fx$$

MAPPING FROM 2-D TO 1-D FAMILY (RANK 2)

THE FUNDAMENTAL MATRIX F

CORRESPONDENCE CONDITION

The fundamental matrix satisfies the condition that for any pair of corresponding points $x \leftrightarrow x'$ in the two images

$$x'^T F x = 0 \qquad \left(x'^T l' = 0\right)$$

THE FUNDAMENTAL MATRIX F

F is the unique 3x3 rank 2 matrix that satisfies $x'^T F x = 0$ for all $x \leftrightarrow x'$

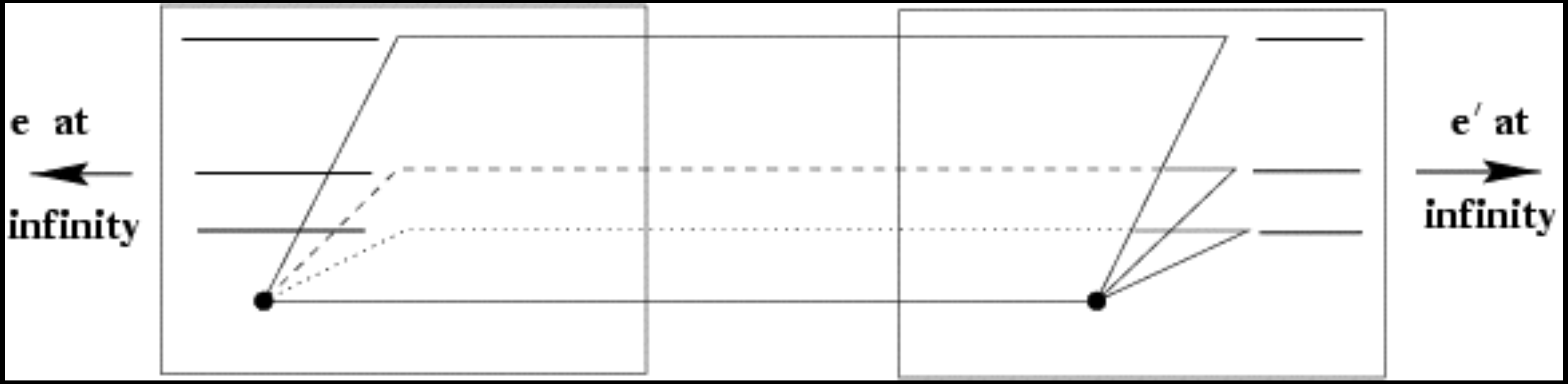
(i) **Transpose:** if F is fundamental matrix for (P,P'), then F^T is fundamental matrix for (P',P)

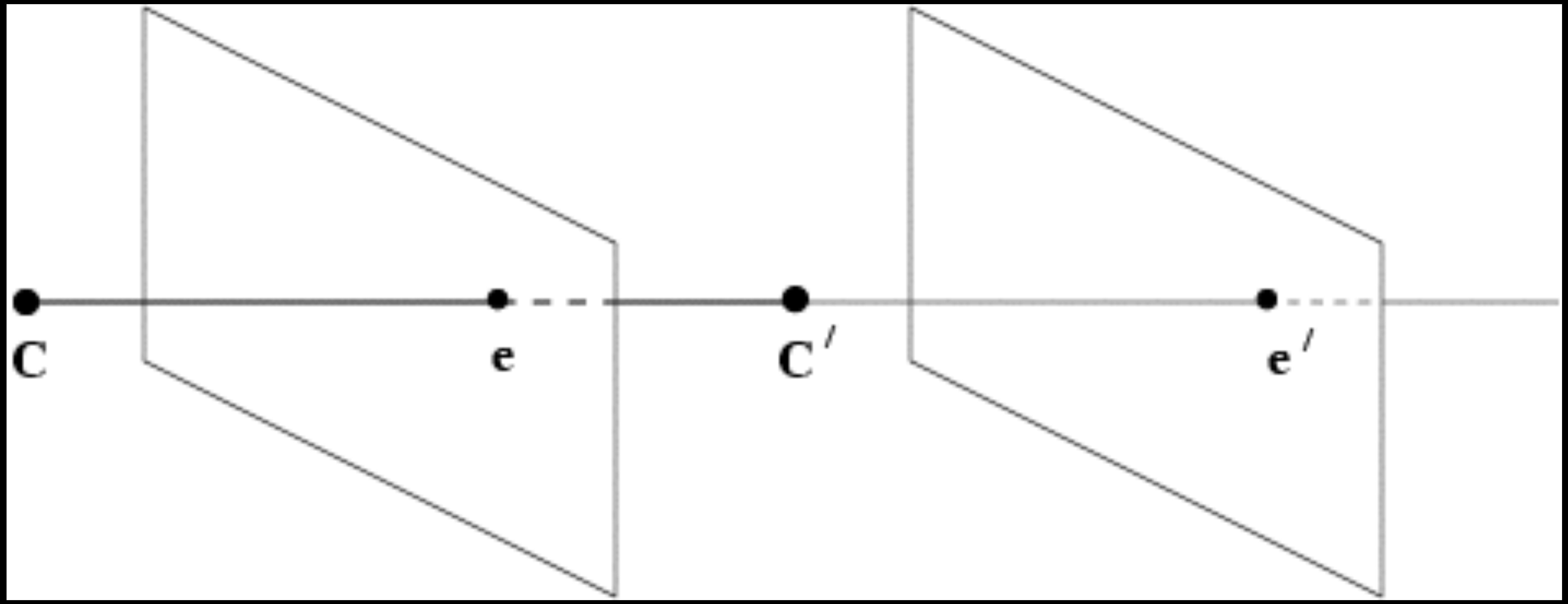
(ii) **Epipolar lines:** $l' = Fx$ & $l = F^T x'$

(iii) **Epipoles:** on all epipolar lines, thus $e'^T F x = 0, \forall x \Rightarrow e'^T F = 0$, similarly $Fe = 0$

(iv) **F** has 7 d.o.f. , i.e. 3x3-1(homogeneous)-1(rank2)

FUNDAMENTAL MATRIX FOR PURE TRANSLATION





FUNDAMENTAL MATRIX FOR PURE TRANSLATION

example:

$$e' = (1,0,0)^T \qquad F = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & -1 \\ 0 & 1 & 0 \end{bmatrix}_\times$$

$$x'^T F x = 0 \Leftrightarrow y = y'$$

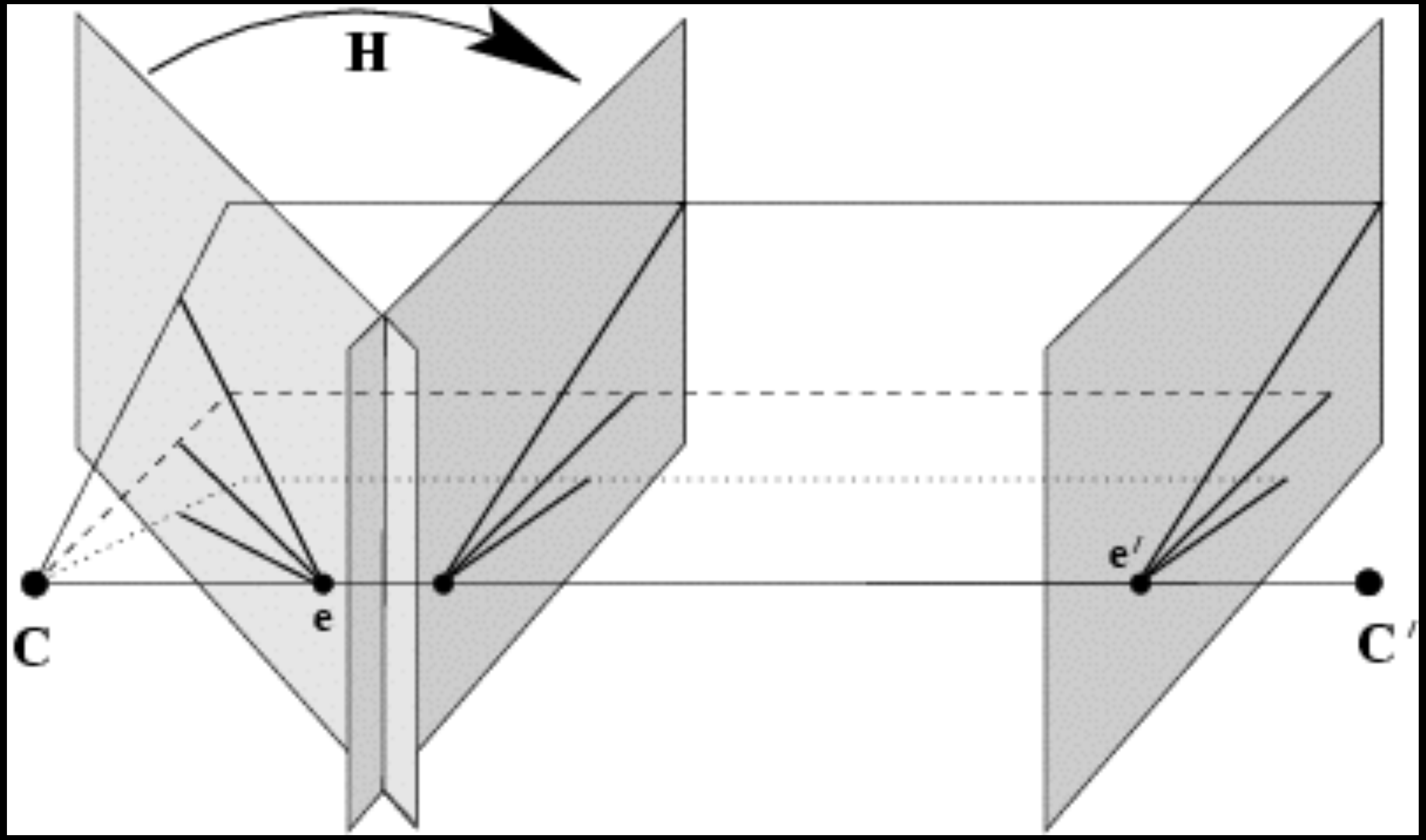
$$x = PX = K[I \mid 0]X \qquad (X,Y,Z)^T = K^{-1}x/Z$$

$$x' = P'X = K[I \mid t]\begin{bmatrix} K^{-1}x \\ Z \end{bmatrix} \qquad x' = x + Kt/Z$$

motion starts at x and moves towards e, faster depending on *Z*

pure translation: F only 2 d.o.f., $x^T[e]_x x=0 \Rightarrow$ auto-epipolar

GENERAL MOTION



$$x = PX = K[I \mid 0]X \qquad (X, Y, Z)^T = K^{-1}x/Z$$

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

$$x' = K'RK^{-1}x + K't/Z$$

- To this point we have examined the properties of F and of image relations for a point correspondence $x \leftrightarrow x'$. We now turn to one of the most significant properties of F, that the matrix may be used to determine the camera matrices of the two views.

WE CAN GET PROJECTION MATRICES P AND P' UP TO A PROJECTIVE AMBIGUITY

$$\mathbf{P} = [\mathbf{I} \mid \mathbf{0}] \quad \mathbf{P}' = [\underbrace{[\mathbf{e}']_\times \mathbf{F}}_{\text{K'*rotation}} \mid \underbrace{\mathbf{e}'}_{\text{K'*translation}}] \quad \mathbf{e}'^T \mathbf{F} = 0$$

SEE HZ P. 255-256

- Code:
- function P = vgg_P_from_F(F)
- [U,S,V] = svd(F);
- e = U(:,3);
- P = [-vgg_contreps(e)*F e];

PROJECTIVE TRANSFORMATION AND INVARIANCE

F invariant to transformations of projective 3-space

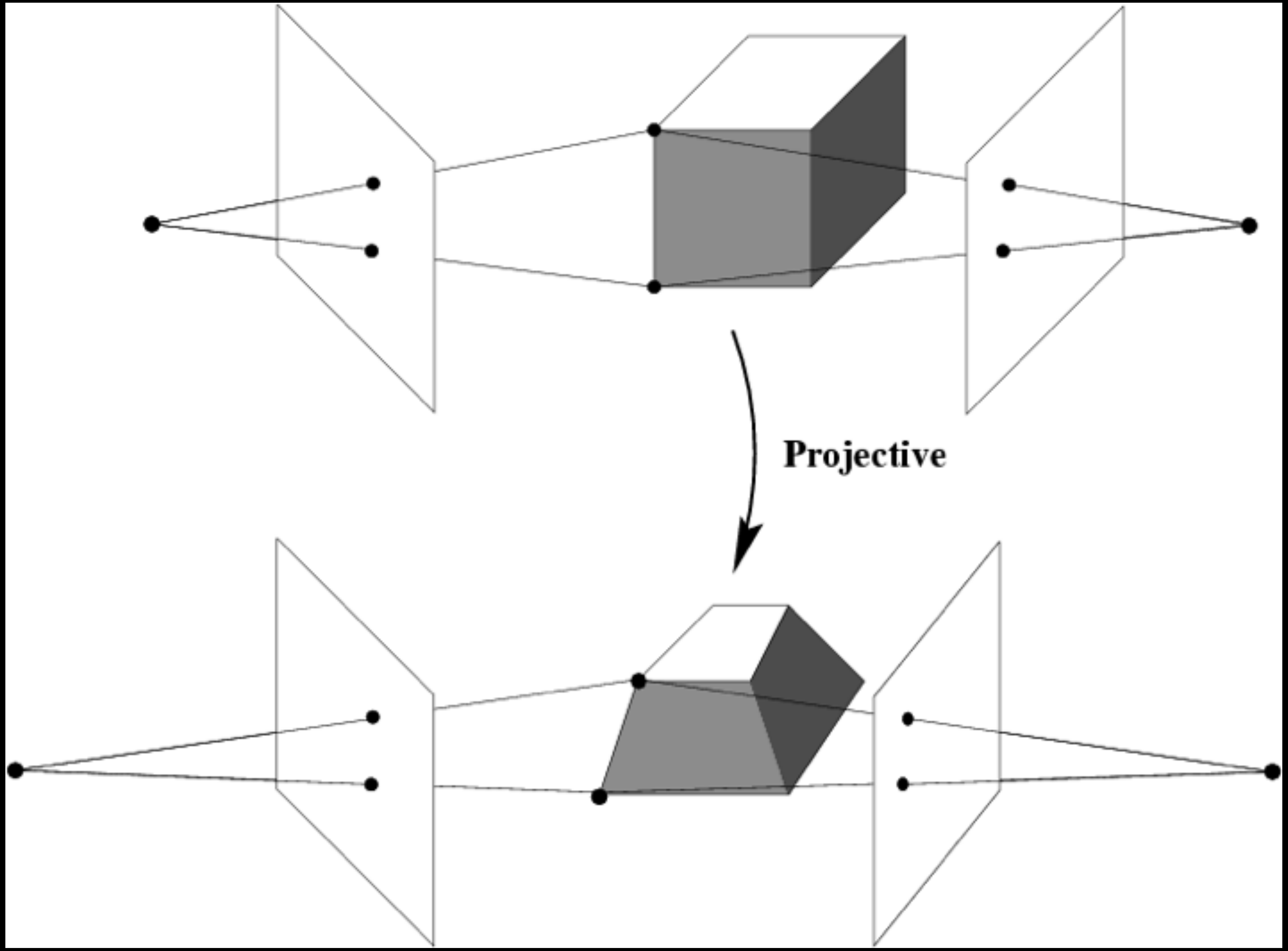
$$x = PX = (PH)(H^{-1}X) = \hat{P}\hat{X}$$

$$x' = P'X = (P'H)(H^{-1}X) = \hat{P}'\hat{X}$$

$$(P, P') \boxed{?} F \qquad \text{unique}$$

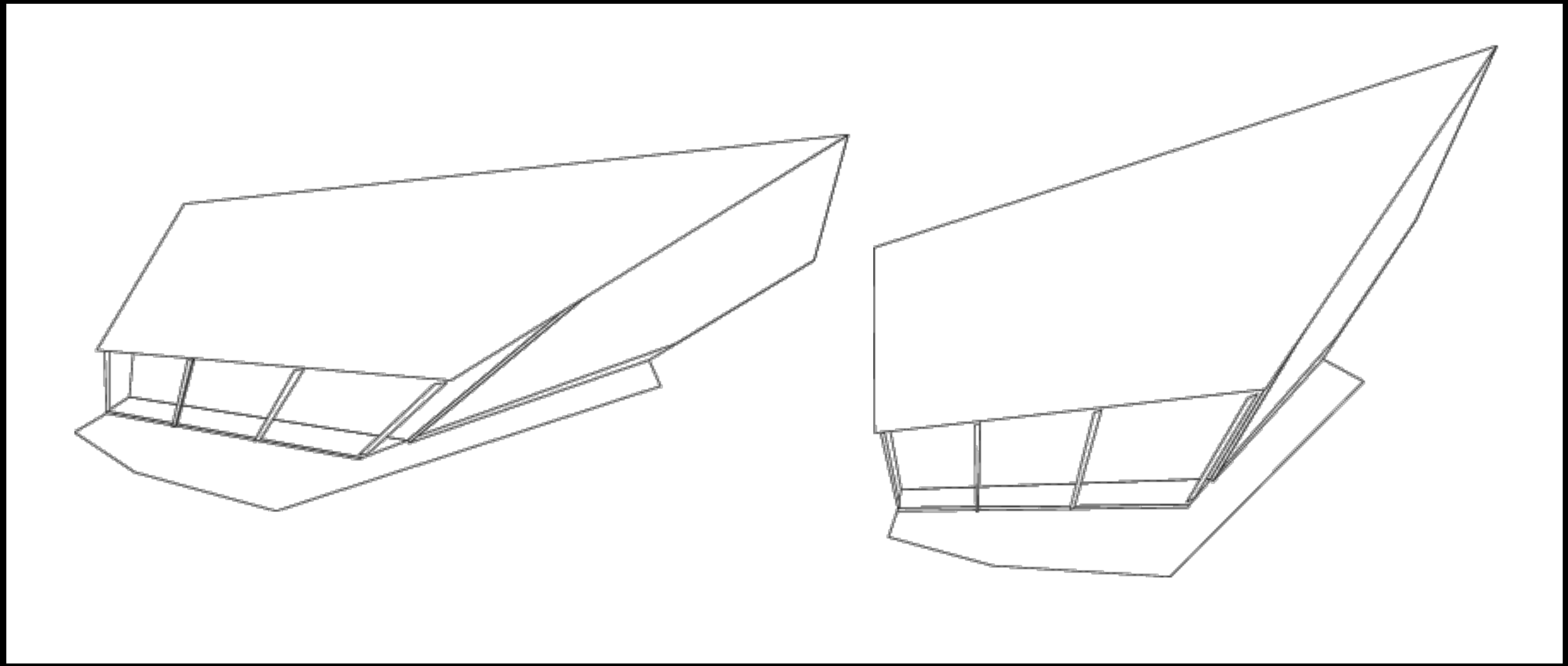
$$F \boxed{?} (P, P') \qquad \text{not unique}$$

RECONSTRUCTION AMBIGUITY: PROJECTIVE

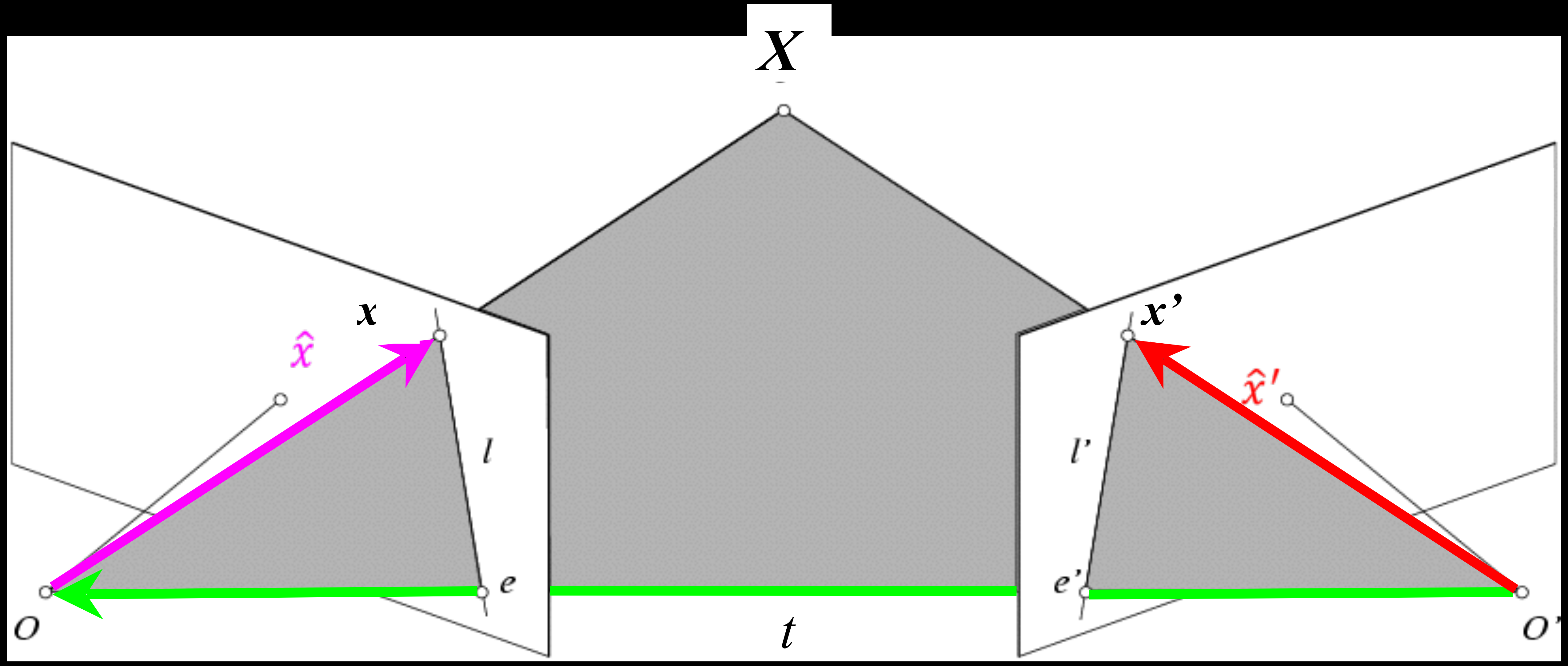


$$x_i = PX_i = \left(PH_P^{-1}\right)\left(H_P X_i\right)$$

TEXT



ESSENTIAL MATRIX



$$\hat{x} = K^{-1}x = X$$

$$\hat{x}' = K'^{-1}x' = X'$$

$$\hat{x} = R\hat{x}' + t \quad \Rightarrow \quad \hat{x} \cdot [t \times (R\hat{x}')] = 0$$

(because $\hat{x}, R\hat{x}'$, and t are co-planar)

$$\hat{x} \cdot [t \times (R\hat{x}')] = 0 \quad \Rightarrow \quad \hat{x}^T E \hat{x}' = 0 \quad \text{with} \quad E = [t]_\times R$$

THE ESSENTIAL MATRIX

~fundamental matrix for calibrated cameras (remove K)

$$E = [t]_\times R = R[R^T t]_\times$$

$$\hat{x}'^T E \hat{x} = 0 \qquad \left(\hat{x} = K^{-1}x;\ \hat{x}' = K^{-1}x'\right)$$

$$E = K'^T F K$$

5 d.o.f. (3 for R; 2 for t up to scale)

E is essential matrix if and only if
two singularvalues are equal (and third=0)

$$E = U\mathrm{diag}(1,1,0)V^T$$

THE ESSENTIAL MATRIX

$$\mathtt{W} = \begin{bmatrix} 0 & -1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad \text{and} \quad \mathtt{Z} = \begin{bmatrix} 0 & 1 & 0 \\ -1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

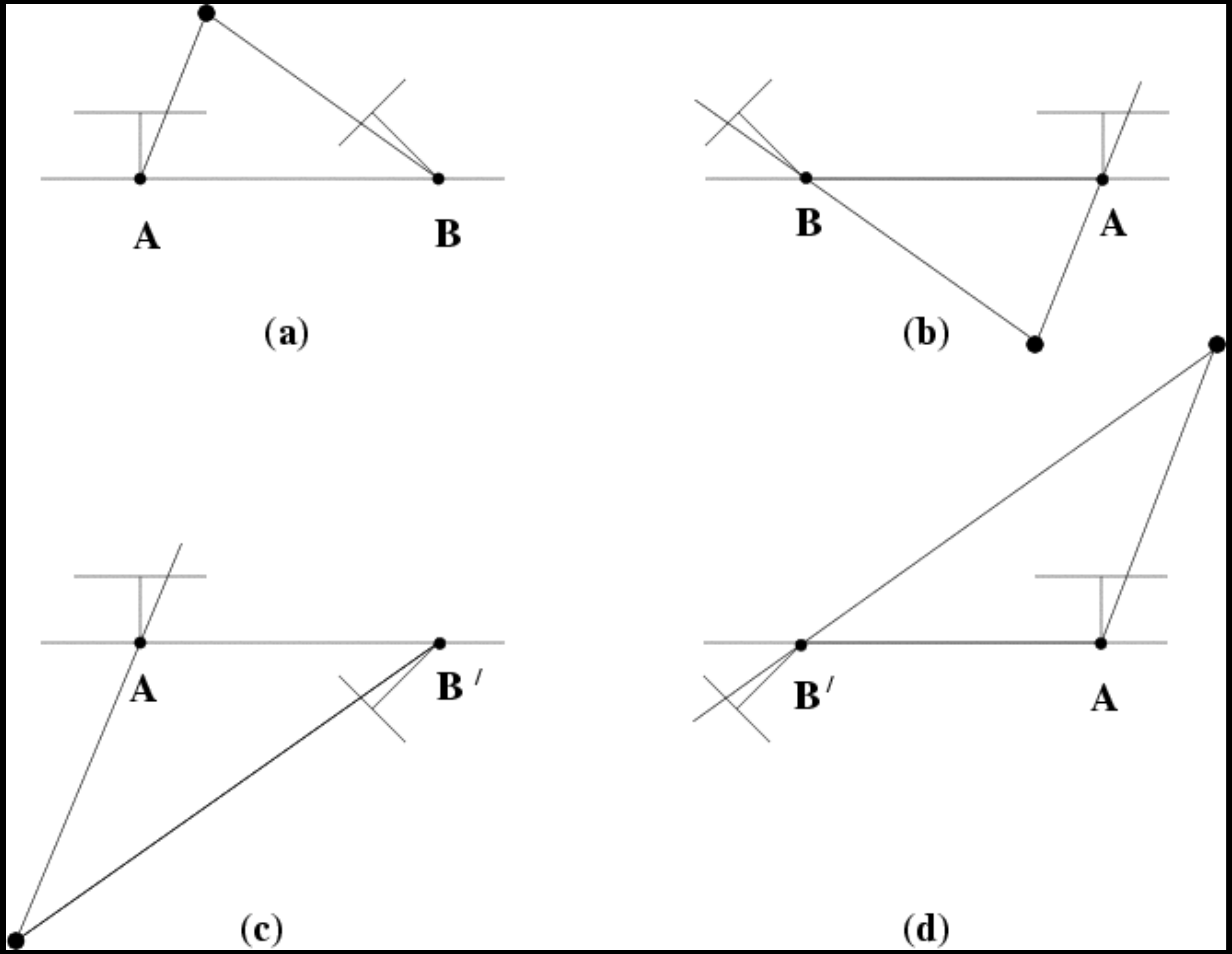
Result 9.18. *Suppose that the SVD of* $\mathtt{E}$ *is* $\mathtt{U}\,\mathrm{diag}(1,1,0)\mathtt{V}^\mathsf{T}$. *Using the notation of (9.13), there are (ignoring signs) two possible factorizations* $\mathtt{E} = \mathtt{SR}$ *as follows:*

$$\mathtt{S} = \mathtt{UZU}^\mathsf{T} \quad \mathtt{R} = \mathtt{UWV}^\mathsf{T} \quad \textit{or} \quad \mathtt{UW}^\mathsf{T}\mathtt{V}^\mathsf{T}\ . \tag{9.14}$$

Result 9.19. *For a given essential matrix* $\mathtt{E} = \mathtt{U}\,\mathrm{diag}(1,1,0)\mathtt{V}^\mathsf{T}$, *and first camera matrix* $\mathtt{P} = [\mathtt{I} \mid \mathbf{0}]$, *there are four possible choices for the second camera matrix* $\mathtt{P}'$, *namely*

$$\mathtt{P}' = [\mathtt{UWV}^\mathsf{T} \mid +\mathbf{u}_3] \text{ or } [\mathtt{UWV}^\mathsf{T} \mid -\mathbf{u}_3] \text{ or } [\mathtt{UW}^\mathsf{T}\mathtt{V}^\mathsf{T} \mid +\mathbf{u}_3] \text{ or } [\mathtt{UW}^\mathsf{T}\mathtt{V}^\mathsf{T} \mid -\mathbf{u}_3].$$

FOUR POSSIBLE RECONSTRUCTIONS FROM E



(ONLY ONE SOLUTION WHERE POINTS IS IN FRONT OF BOTH CAMERAS)

COMPUTING F

EQUATIONS

- Solve a system of homogeneous linear equations
  - Write down the system of equations

$$\mathbf{x}^T F \mathbf{x}' = 0$$

$$uu'f_{11} + uv'f_{12} + uf_{13} + vu'f_{21} + vv'f_{22} + vf_{23} + u'f_{31} + v'f_{32} + f_{33} = 0$$

$$\mathrm{A}\boldsymbol{f} = \begin{bmatrix} u_1u_1' & u_1v_1' & u_1 & v_1u_1' & v_1v_1' & v_1 & u_1' & v_1' & 1 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ u_nu_v' & u_nv_n' & u_n & v_nu_n' & v_nv_n' & v_n & u_n' & v_n' & 1 \end{bmatrix} \begin{bmatrix} f_{11} \\ f_{12} \\ f_{13} \\ f_{21} \\ \vdots \\ f_{33} \end{bmatrix} = \mathbf{0}$$

ESTIMATING THE FUNDAMENTAL MATRIX

- 8-point algorithm
  - Least squares solution using SVD on equations from 8 pairs of correspondences
  - Enforce det(F)=0 constraint using SVD on F
- Minimize reprojection error
  - Non-linear least squares

Note: estimation of F (or E) is degenerate for a planar scene.

8-POINT ALGORITHM

- Solve a system of homogeneous linear equations
  - Write down the system of equations
  - Solve f from Af=0 using SVD

Matlab:

```
[U, S, V] = svd(A);
f = V(:, end);
F = reshape(f, [3 3])';
```

THE SINGULARITY CONSTRAINT

$$e'^{T} F = 0 \qquad Fe = 0 \qquad \det F = 0 \qquad \operatorname{rank} F = 2$$

SVD from linearly computed F matrix (rank 3)

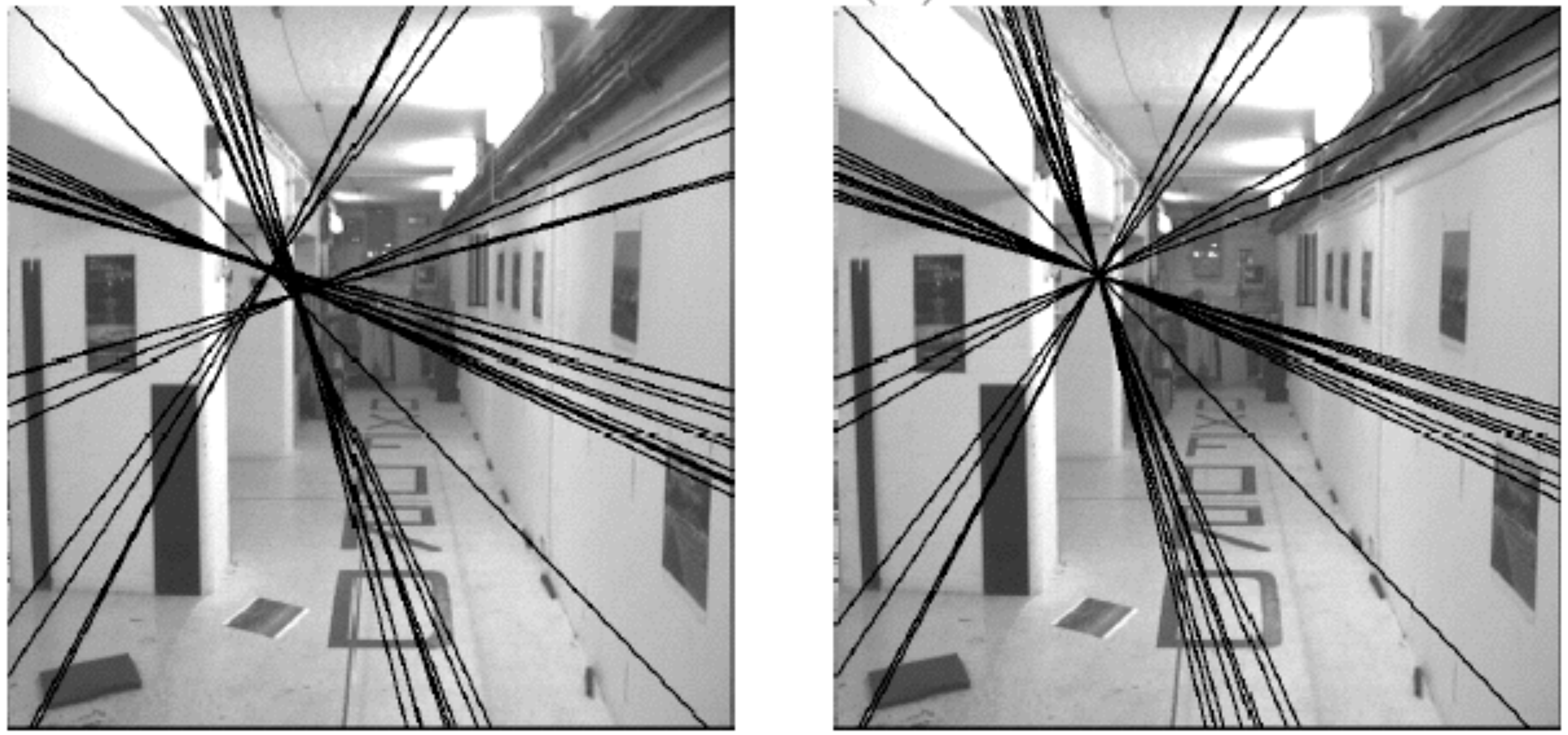
$$F = U \begin{bmatrix} \sigma_1 & & \\ & \sigma_2 & \\ & & \sigma_3 \end{bmatrix} V^T = U_1 \sigma_1 V_1^T + U_2 \sigma_2 V_2^T + U_3 \sigma_3 V_3^T$$

Compute closest rank-2 approximation $\min \|F - F'\|_F$

$$F' = U \begin{bmatrix} \sigma_1 & & \\ & \sigma_2 & \\ & & 0 \end{bmatrix} V^T = U_1 \sigma_1 V_1^T + U_2 \sigma_2 V_2^T$$

NEED TO ENFORCE SINGULARITY CONSTRAINT

Fundamental matrix has rank 2 : $\det(\mathbf{F}) = 0$.



Left : Uncorrected F – epipolar lines are not coincident.

Right : Epipolar lines from corrected F.

8-POINT ALGORITHM

- Solve a system of homogeneous linear equations
  - Write down the system of equations
  - Solve f from $Af=0$ using SVD

Matlab:

```
[U, S, V] = svd(A);
f = V(:, end);
F = reshape(f, [3 3])';
```

Matlab:

```
[U, S, V] = svd(F);
S(3,3) = 0;
F = U*S*V';
```

- Resolve $\det(F) = 0$ constraint using SVD

8-POINT ALGORITHM

- Solve a system of homogeneous linear equations
  - Write down the system of equations
  - Solve f from Af=0 using SVD
- Resolve det(F) = 0 constraint by SVD

- Notes:
- Use RANSAC to deal with outliers (sample 8 points)
  - How to test for outliers?

PROBLEM WITH EIGHT-POINT ALGORITHM

$$\begin{array}{c} \begin{bmatrix} x_1x_1' & y_1x_1' & x_1' & x_1y_1' & y_1y_1' & y_1' & x_1 & y_1 & 1 \\ x_2x_2' & y_2x_2' & x_2' & x_2y_2' & y_2y_2' & y_2' & x_2 & y_2 & 1 \\ \boxed{?} & \boxed{?} & \boxed{?} & \boxed{?} & \boxed{?} & \boxed{?} & \boxed{?} & \boxed{?} & \boxed{?} \\ x_nx_n' & y_nx_n' & x_n' & x_ny_n' & y_ny_n' & y_n' & x_n & y_n & 1 \end{bmatrix} \\ \begin{matrix} \sim 10000 & \sim 10000 & \sim 100 & \sim 10000 & \sim 10000 & \sim 100 & \sim 100 & \sim 100 & 1 \end{matrix} \end{array} \begin{bmatrix} f_{11} \\ f_{12} \\ f_{13} \\ f_{21} \\ f_{22} \\ f_{23} \\ f_{31} \\ f_{32} \\ f_{33} \end{bmatrix} = 0$$

Orders of magnitude difference

Between column of data matrix

$\longrightarrow$ least-squares yields poor results

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
- Use the eight-point algorithm to compute $\boldsymbol{F}$ from the normalized points
- Enforce the rank-2 constraint (for example, take SVD of $\boldsymbol{F}$ and throw out the smallest singular value)
- Transform fundamental matrix back to original units: if $\boldsymbol{T}$ and $\boldsymbol{T}'$ are the normalizing transformations in the two images, than the fundamental matrix in original coordinates is $\boldsymbol{T}'^{T} \boldsymbol{F} \boldsymbol{T}$

LET'S RECAP…

- Fundamental matrix song

TRIANGULATION

EQUATIONS

$$x_j = \frac{p_{00}^{(j)} X + p_{01}^{(j)} Y + p_{02}^{(j)} Z + p_{03}^{(j)} W}{p_{20}^{(j)} X + p_{21}^{(j)} Y + p_{22}^{(j)} Z + p_{23}^{(j)} W}$$

$$y_j = \frac{p_{10}^{(j)} X + p_{11}^{(j)} Y + p_{12}^{(j)} Z + p_{13}^{(j)} W}{p_{20}^{(j)} X + p_{21}^{(j)} Y + p_{22}^{(j)} Z + p_{23}^{(j)} W},$$

$$\begin{aligned} x(\mathbf{p}^{3\top}\mathbf{X}) - (\mathbf{p}^{1\top}\mathbf{X}) &= 0 \\ y(\mathbf{p}^{3\top}\mathbf{X}) - (\mathbf{p}^{2\top}\mathbf{X}) &= 0 \end{aligned}$$

$$\mathtt{A} = \begin{bmatrix} x\mathbf{p}^{3\top} - \mathbf{p}^{1\top} \\ y\mathbf{p}^{3\top} - \mathbf{p}^{2\top} \\ x'\mathbf{p}'^{3\top} - \mathbf{p}'^{1\top} \\ y'\mathbf{p}'^{3\top} - \mathbf{p}'^{2\top} \end{bmatrix}$$

Solve the sytem with the same methods as before

MORE ACCURATE

- Geometric error cost function
  - Given a measured point correspondence x ↔ x′, and a fundamental matrix F, compute the corrected correspondences xˆ ↔ xˆ′ that minimize the geometric error (C(x,x′)) subject to the epipolar constraint xˆ′TFxˆ = 0. (d() is the Euclidian distance)

$$\mathcal{C}(\mathbf{x}, \mathbf{x}') = d(\mathbf{x}, \hat{\mathbf{x}})^2 + d(\mathbf{x}', \hat{\mathbf{x}}')^2 \quad \text{subject to} \quad \hat{\mathbf{x}}'^{\mathsf{T}} \mathbf{F} \hat{\mathbf{x}} = 0$$

AN OPTIMAL SOLUTION

$$\min_{\hat{\mathbf{x}}} \mathcal{C} = d(\mathbf{x}, \hat{\mathbf{x}})^2 + d(\mathbf{x}', \hat{\mathbf{x}}')^2 = \min_t \mathcal{C} = d(\mathbf{x}, \mathbf{l}(t))^2 + d(\mathbf{x}', \mathbf{l}'(t))^2.$$

- Parametrize the pencil of epipolar lines in the first image by a parameter t. Thus an epipolar line in the first image may be written as l(t).
- Using the fundamental matrix F, compute the corresponding epipolar line l'(t) in the second image.
- Express the distance function d(x, l(t))2 + d(x', l'(t))2 explicitly as a function of t.
- Find the value of t that minimizes this function
- Finding the real roots of a polynomial of degree 6

Hartley & Sturm [Hartley-97b].

OUTLINE OF RECONSTRUCTION

(i) Compute F from correspondences
(ii) Compute camera matrices from F
(iii) Compute 3D point for each pair of corresponding points

computation of F
8+ (least-squares) (more on this next class)

computation of camera matrices
use

$$P = [I \mid 0] \quad P' = [[e']_{\times} F + e' v^{T} \mid \lambda e']$$

triangulation
compute intersection of two backprojected rays

FROM EPIPOLAR GEOMETRY TO CAMERA CALIBRATION

- Estimating the fundamental matrix is known as “weak calibration”
- We know the calibration matrices of the two cameras, we can estimate the essential matrix: $E = K^{T}FK'$
- The essential matrix gives us the relative rotation and translation between the cameras, or their extrinsic parameters

LAB 2

COMPUTE THE FUNDAMENTAL MATRIX

- 8-point algorithm
- Normalized 8-point algorithm
- Draw epipolar lines
- Compute Essential Matrix
- Compute Canonical P1 and P2
- Triangulate Points
- Reprojection error

REFERENCES AND FURTHER READING

- Computer Vision: Algorithms and Applications. Richard Szeliski
- Multiple View Geometry in Computer Vision. Hartley and Zisserman.