UNIVERSITÉ Concordia UNIVERSITY
FACULTY OF ENGINEERING AND COMPUTER SCIENCE
Department of Computer Science and Software Engineering

COMP498G/691G COMPUTER VISION

LECTURE 12
EPIPOLAR GEOMETRY

Administrative

- Tonight's tutorial topics
    - Camera calibration (review)
    - Stereo

Concordia

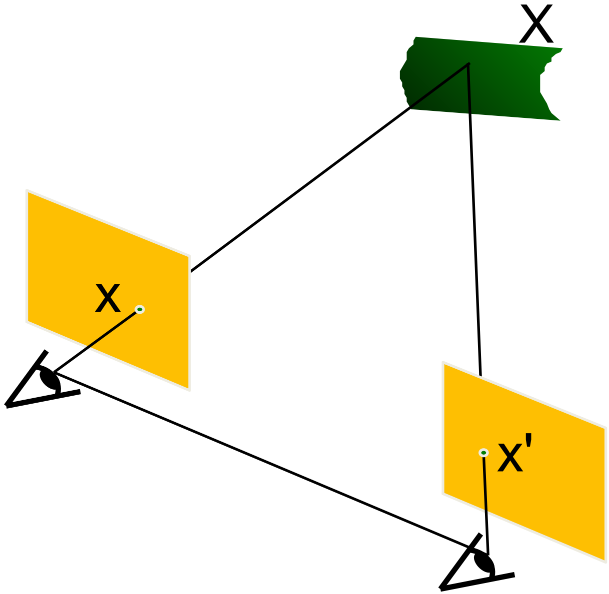
Today's Lecture

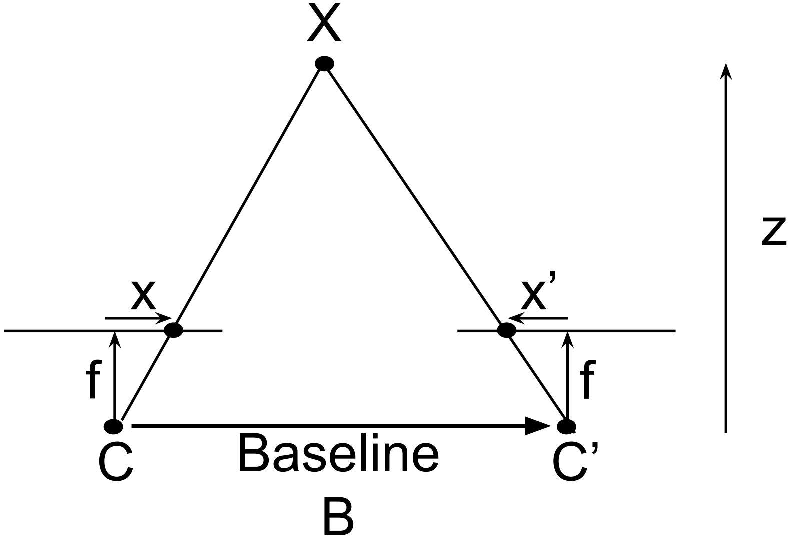
- Epipolar Geometry
  - General case with calibrated cameras
  - Slides acknowledgment: J. Hays, Derek Hoiem, Lana Lazebnik, Silvio Saverese, Steve Seitz.
  - Many figures from Hartley & Zisserman
- Questions

- Epipolar geometry
  - Relates cameras from two positions

Depth from Stereo

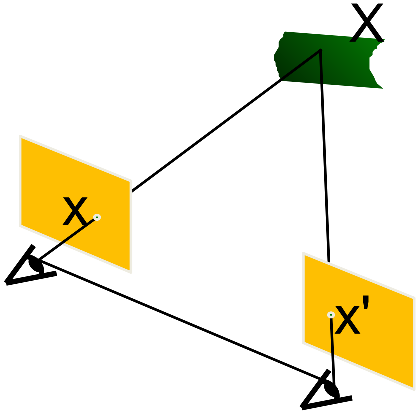
- **Goal**: recover depth by finding image coordinate x’ that corresponds to x



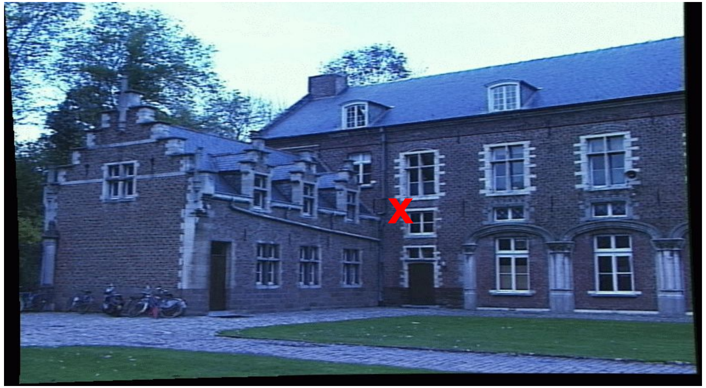


Depth from Stereo

- **Goal**: recover depth by finding image coordinate x' that corresponds to x
- Sub-Problems
  1. **Calibration**: How do we recover the relation of the cameras (if not already known)?
  2. **Correspondence**: How do we search for the matching point x'?



Correspondence Problem



- We have two images taken from cameras with different intrinsic and extrinsic parameters

- How do we match a point in the first image to a point in the second? How can we constrain our search?

Where do we need to search?

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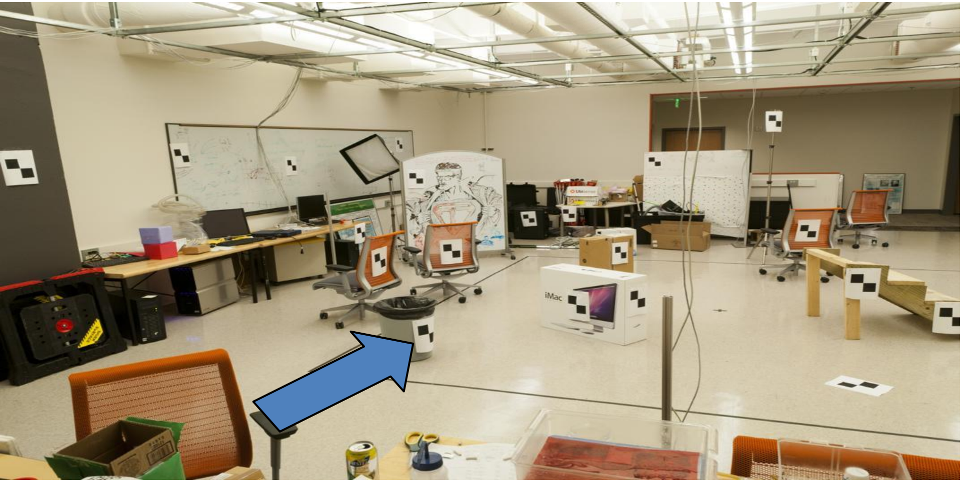

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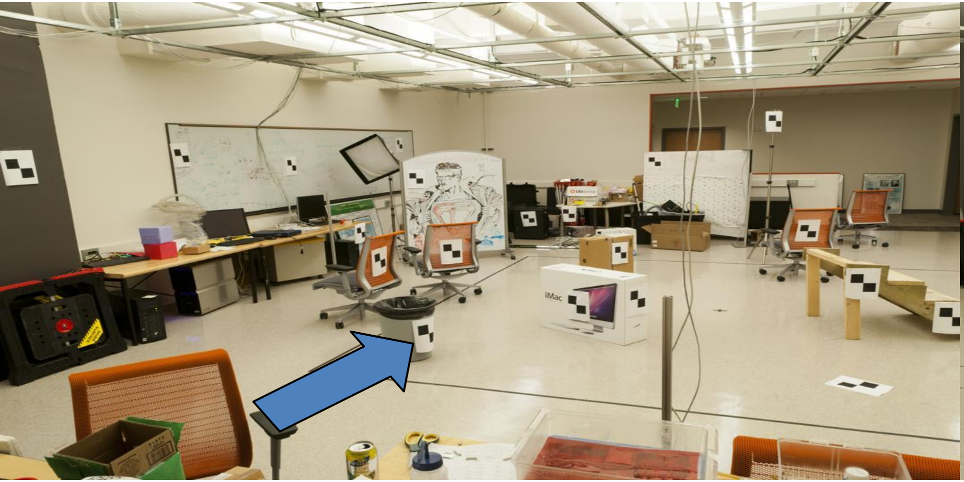

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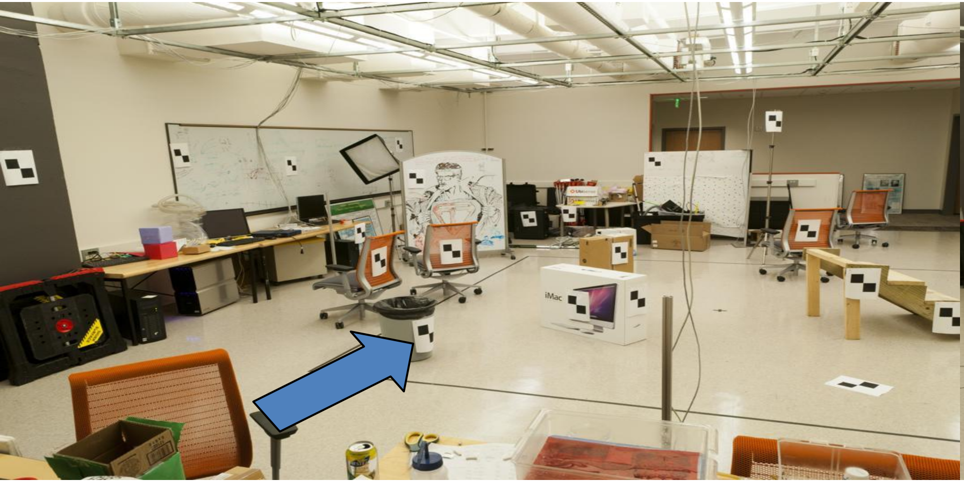

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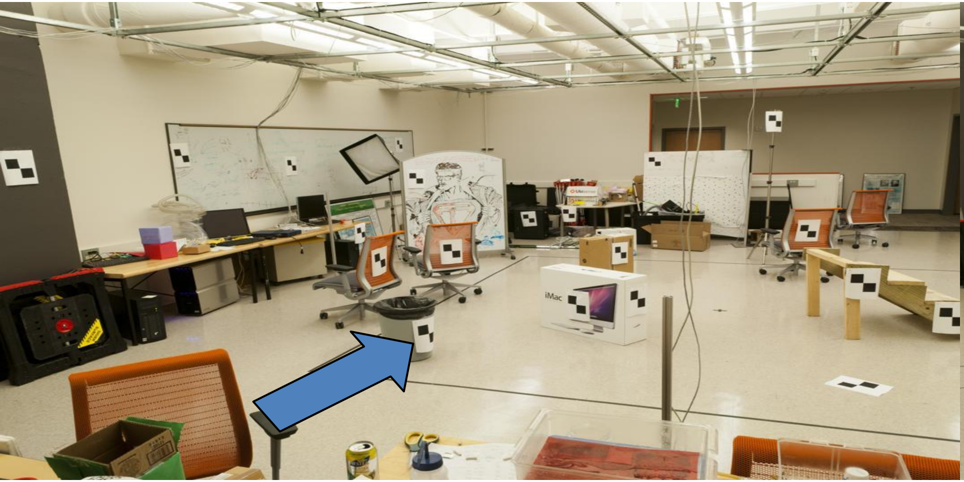

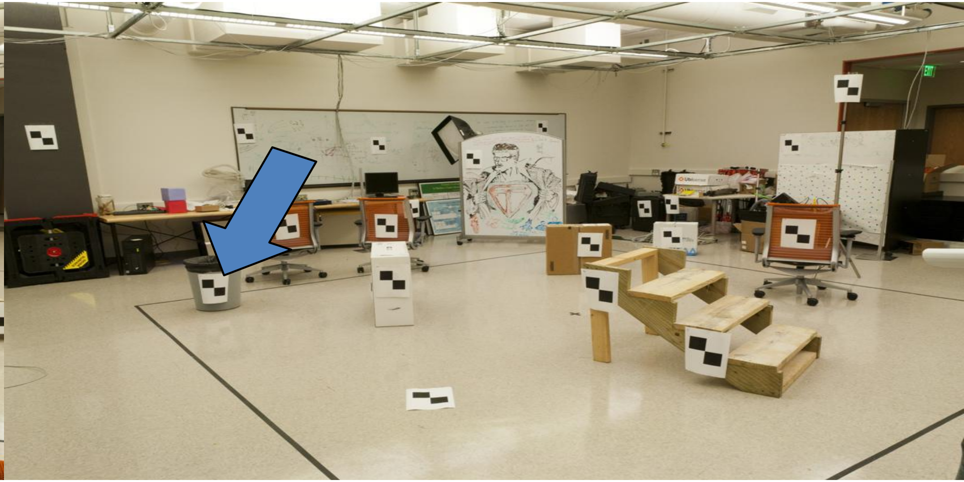

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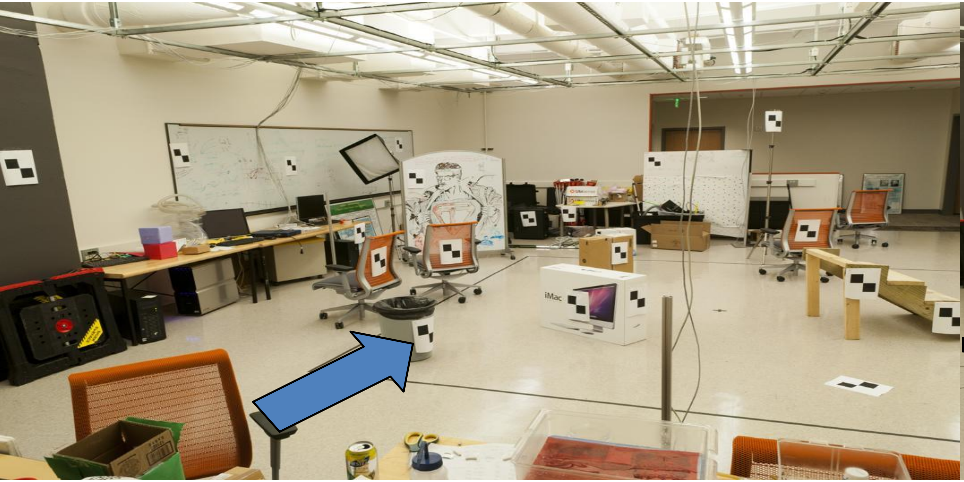

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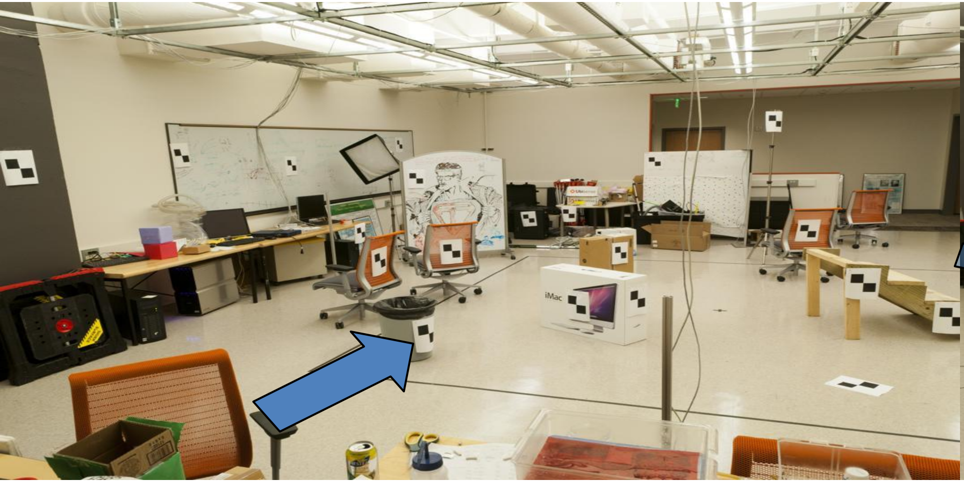

Key idea: Epipolar constraint

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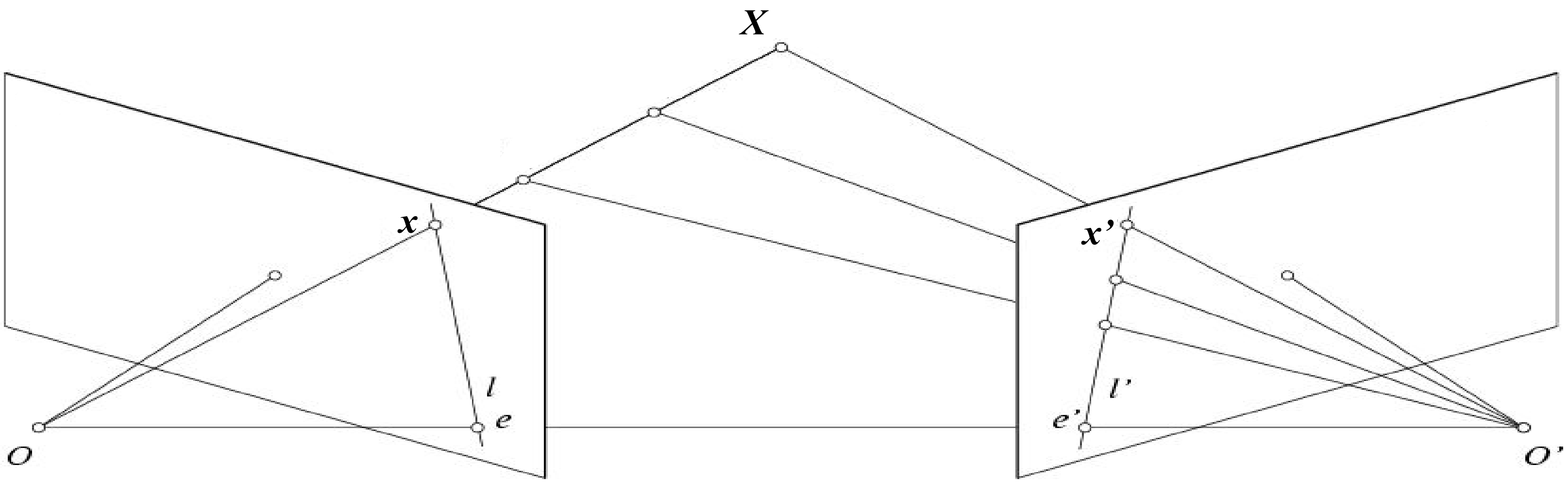
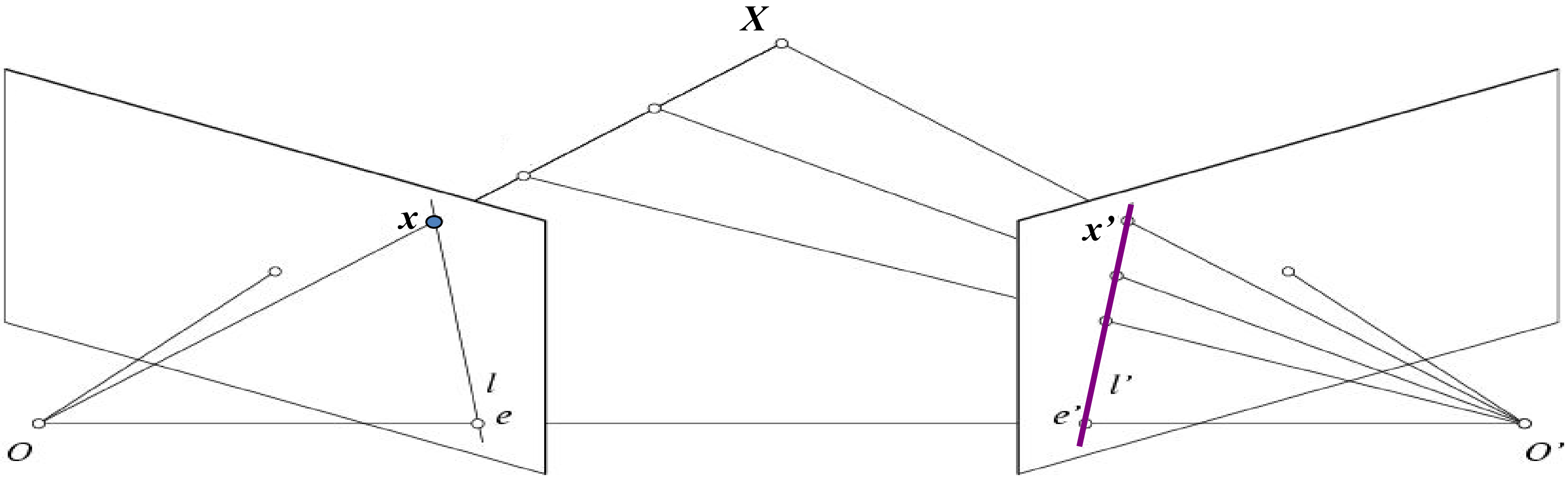
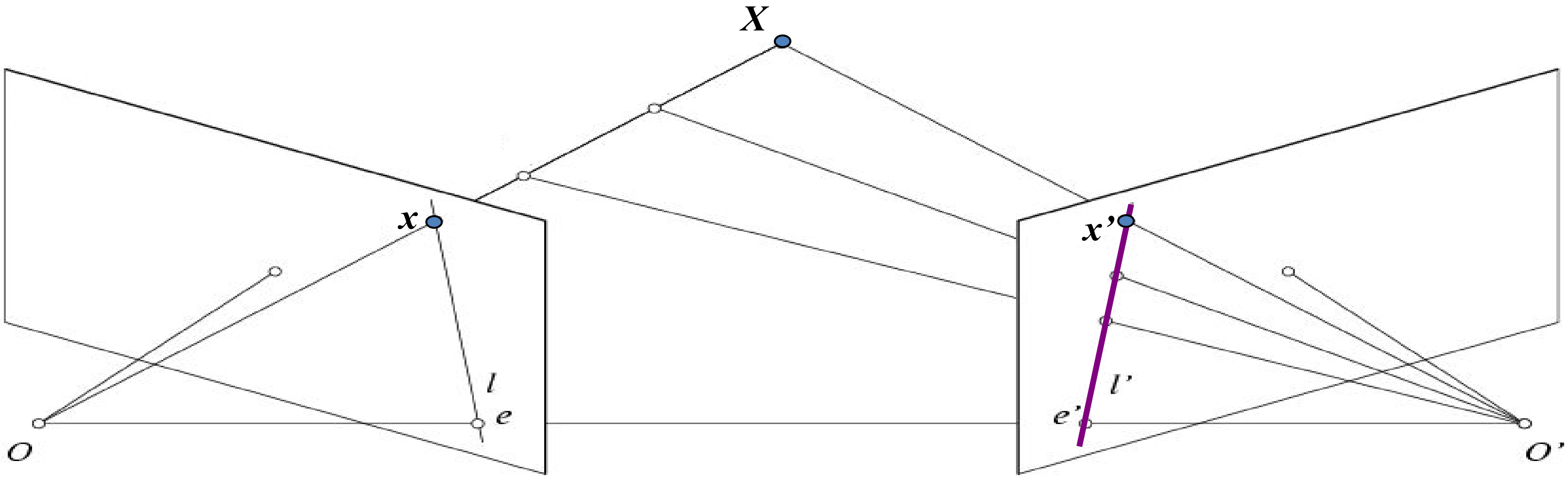


Key idea: Epipolar constraint



Potential matches for *x* have to lie on the corresponding line *l'*.

Key idea: Epipolar constraint



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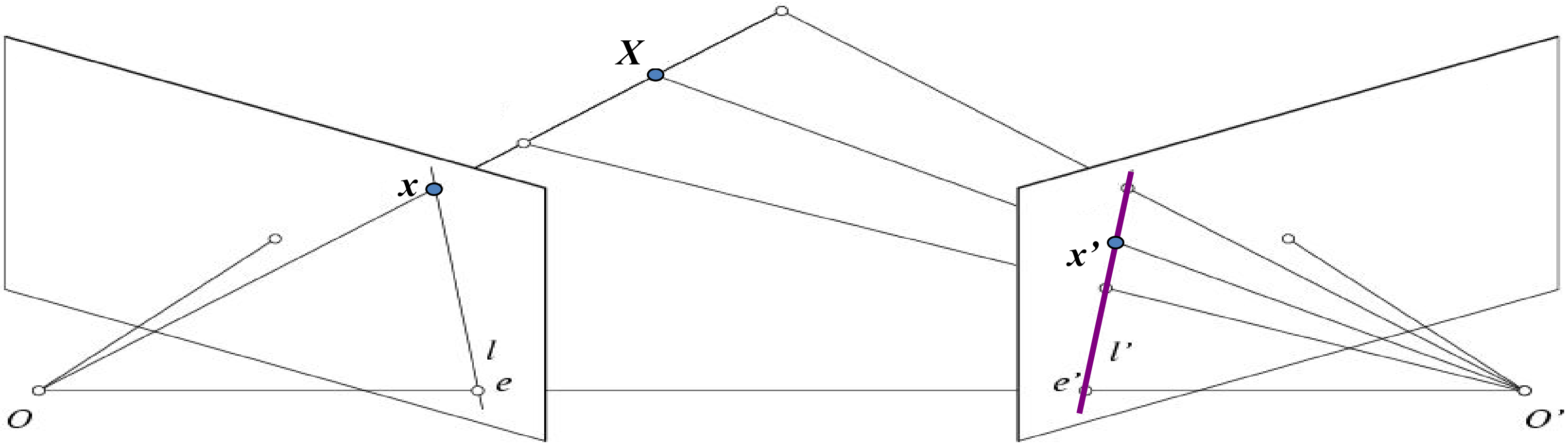

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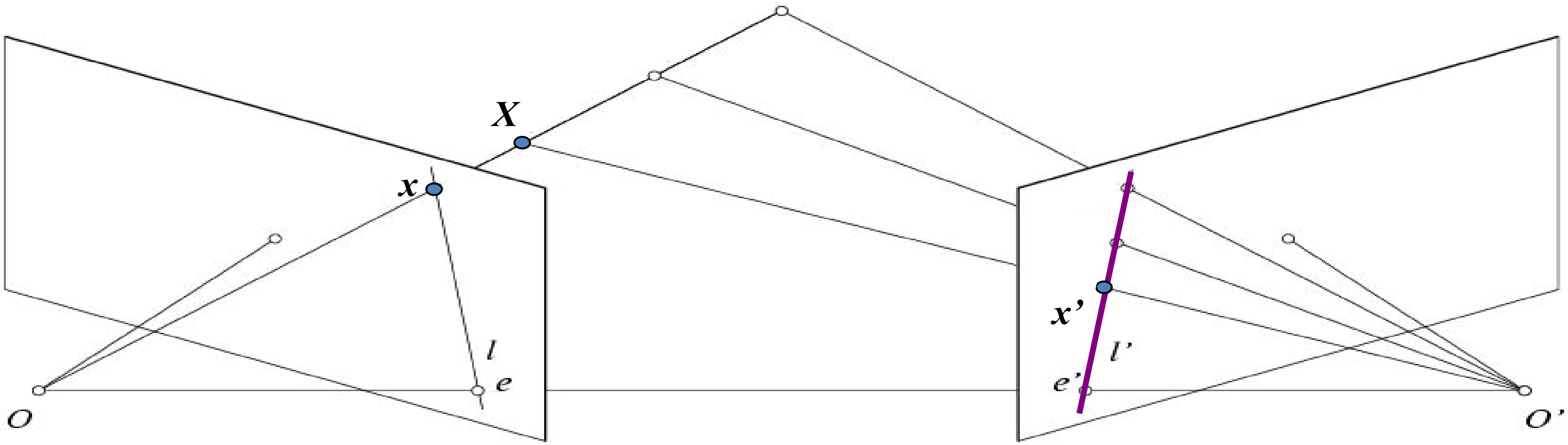

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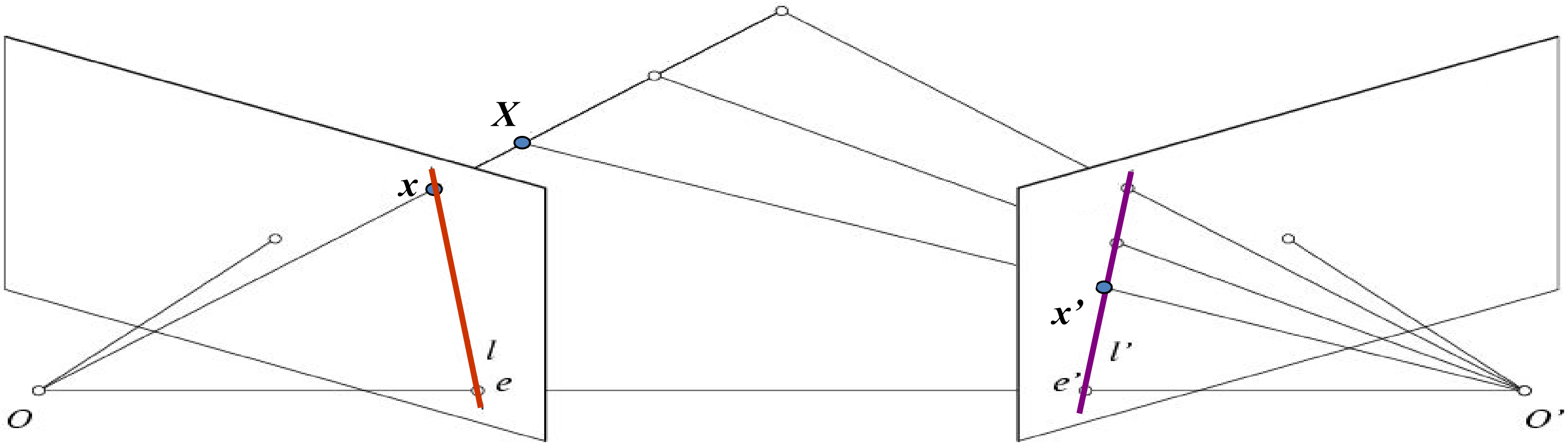
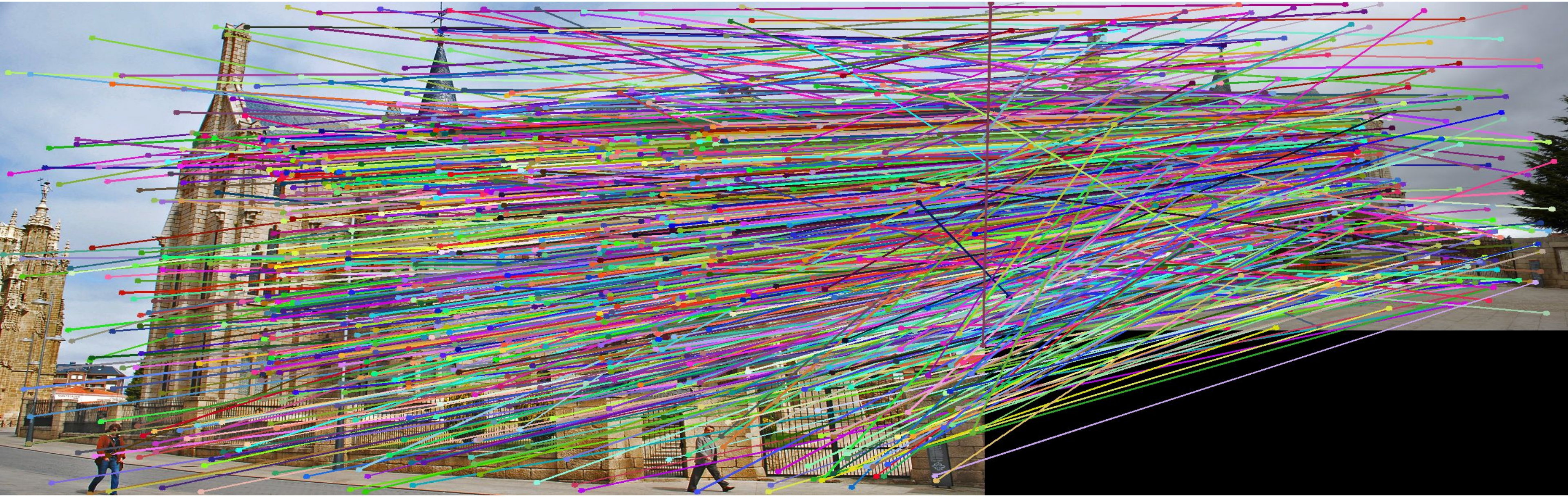


Potential matches for *x* have to lie on the corresponding line *l'*.

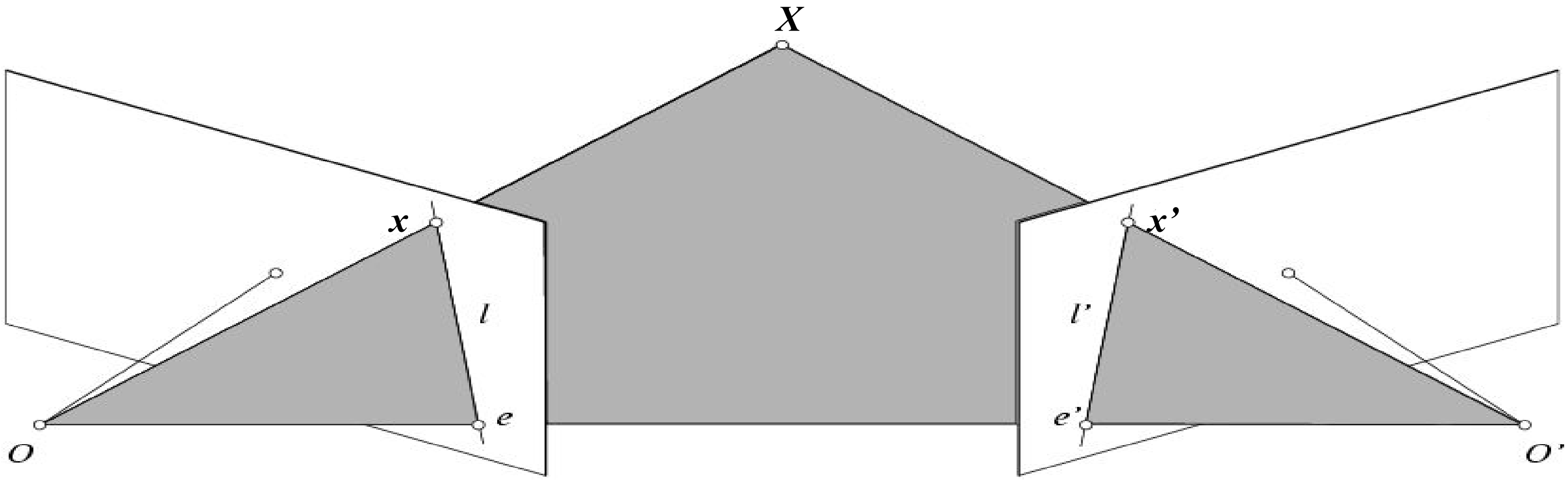
Potential matches for *x'* have to lie on the corresponding line *l*.

Wouldn’t it be nice to know where matches can live? To constrain our 2d search to 1d.

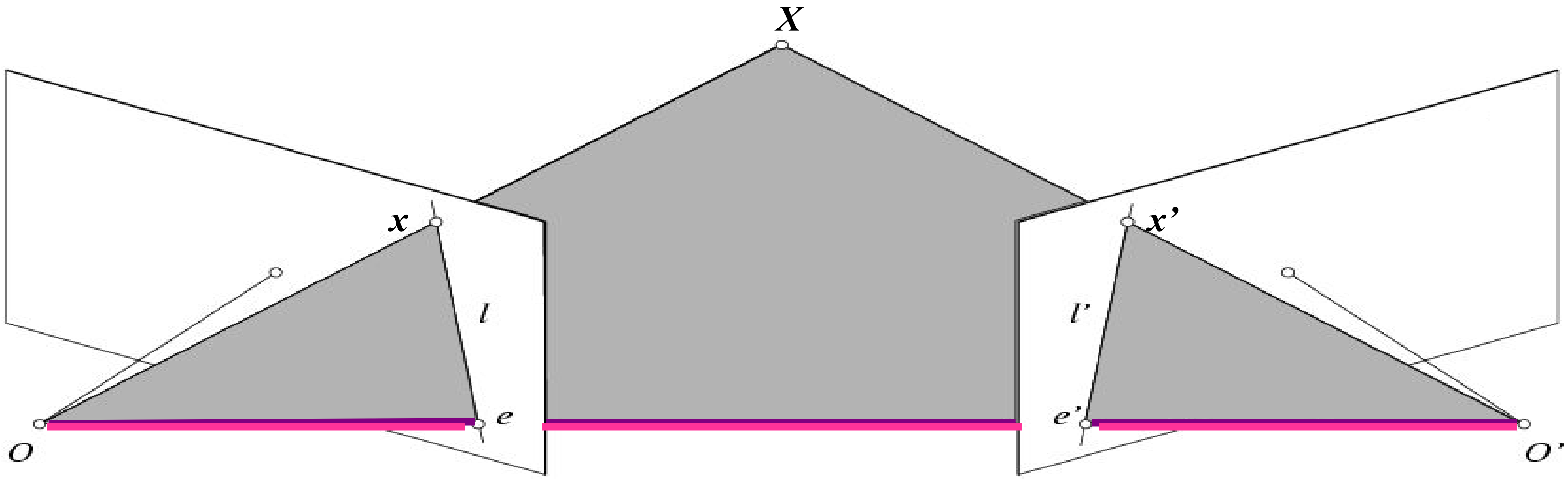
VLFeat’s 800 most confident matches among 10,000+ local features.



Epipolar geometry: notation

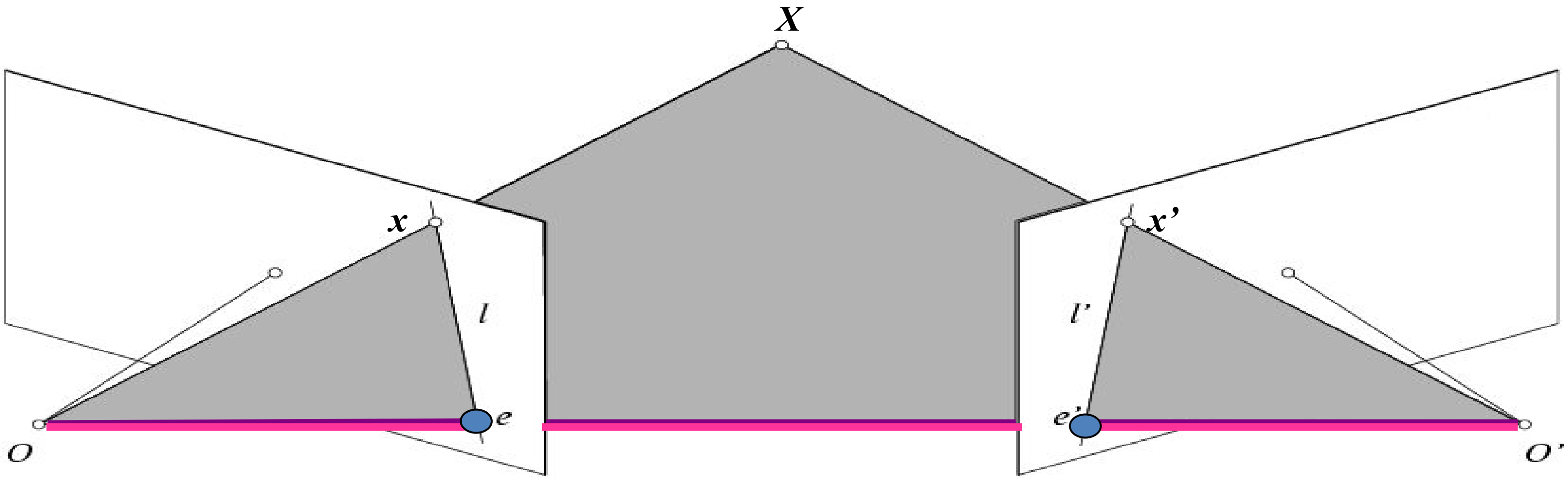


Epipolar geometry: notation



- **Baseline** – line connecting the two camera centers

Epipolar geometry: notation

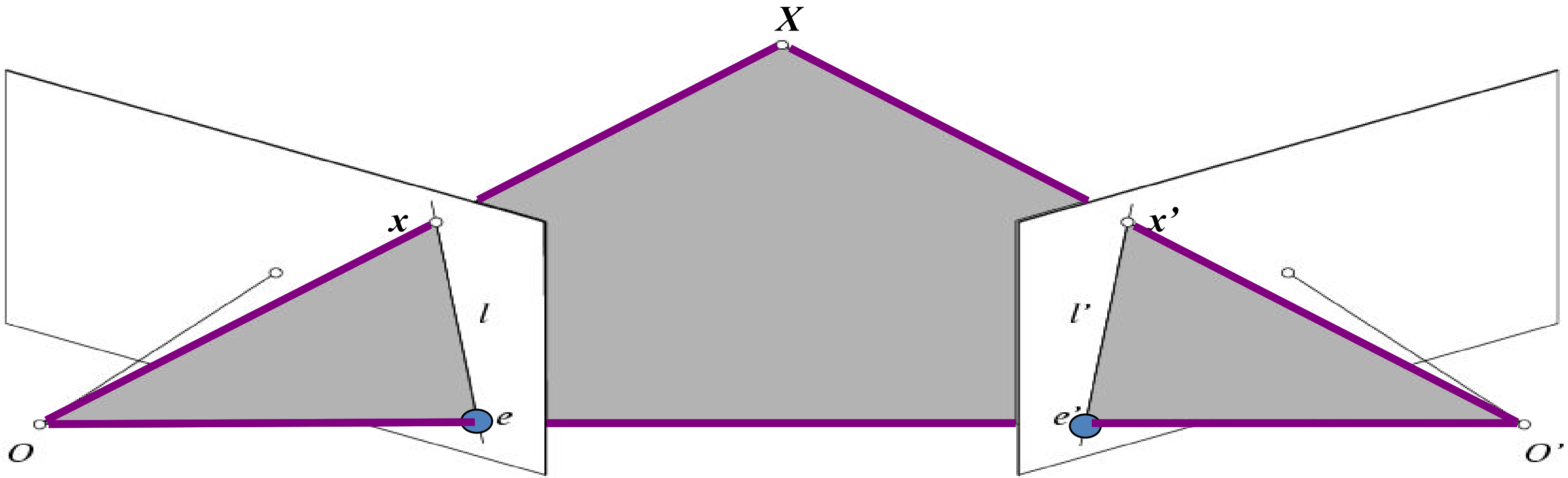


- **Baseline** – line connecting the two camera centers
- **Epipoles**

= intersections of baseline with image planes

= projections of the other camera center

Epipolar geometry: notation



- **Baseline** – line connecting the two camera centers
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= intersections of baseline with image planes

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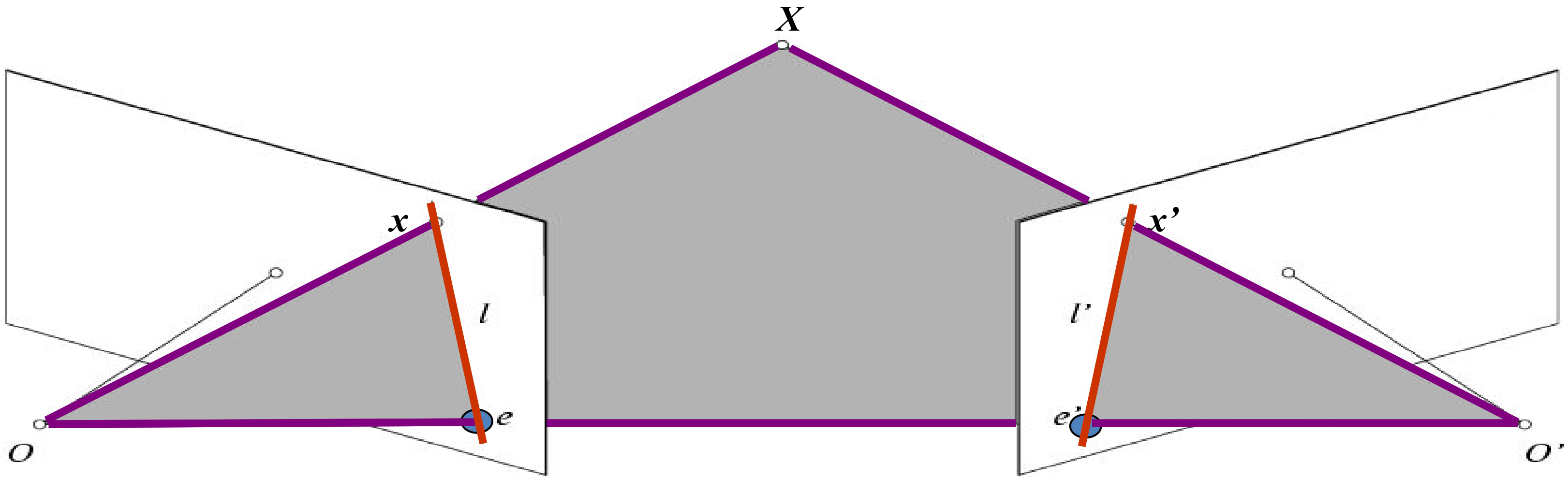
- **Epipolar Plane** – plane containing baseline (1D family)

Epipolar geometry: notation



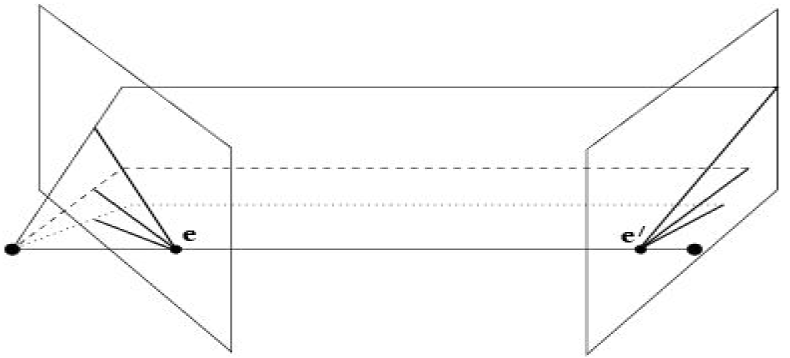
- **Baseline** – line connecting the two camera centers
- **Epipoles**

= intersections of baseline with image planes

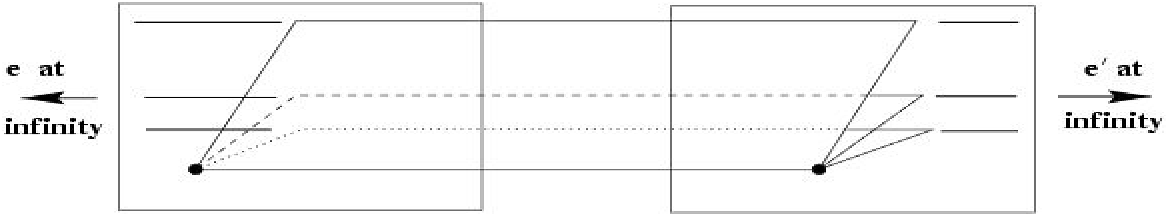
= projections of the other camera center

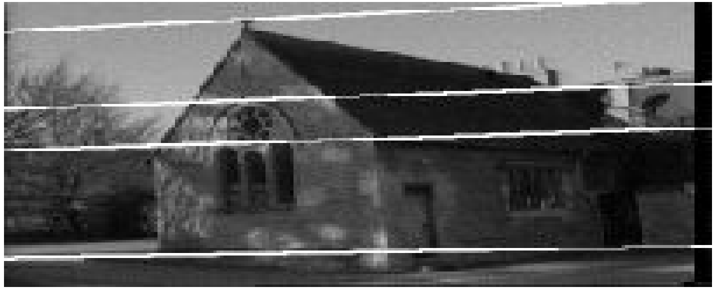
- **Epipolar Plane** – plane containing baseline (1D family)
- **Epipolar Lines** - intersections of epipolar plane with image planes (always come in corresponding pairs)

Example: Converging cameras



Example: Motion parallel to image plane

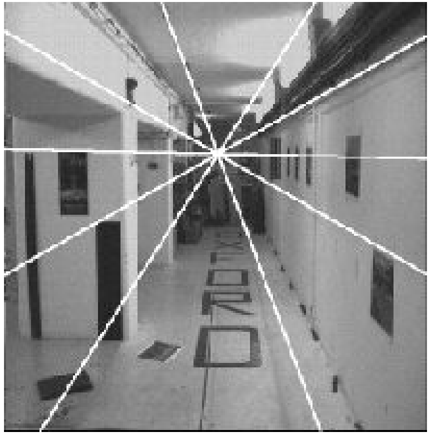


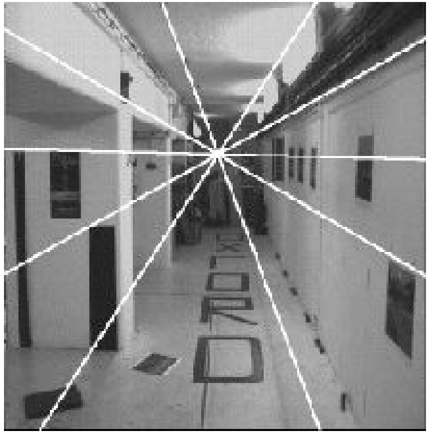


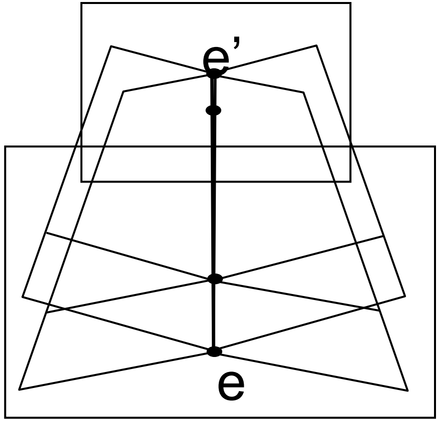
Example: Forward motion

What would the epipolar lines look like if the camera moves directly forward?

Example: Forward motion

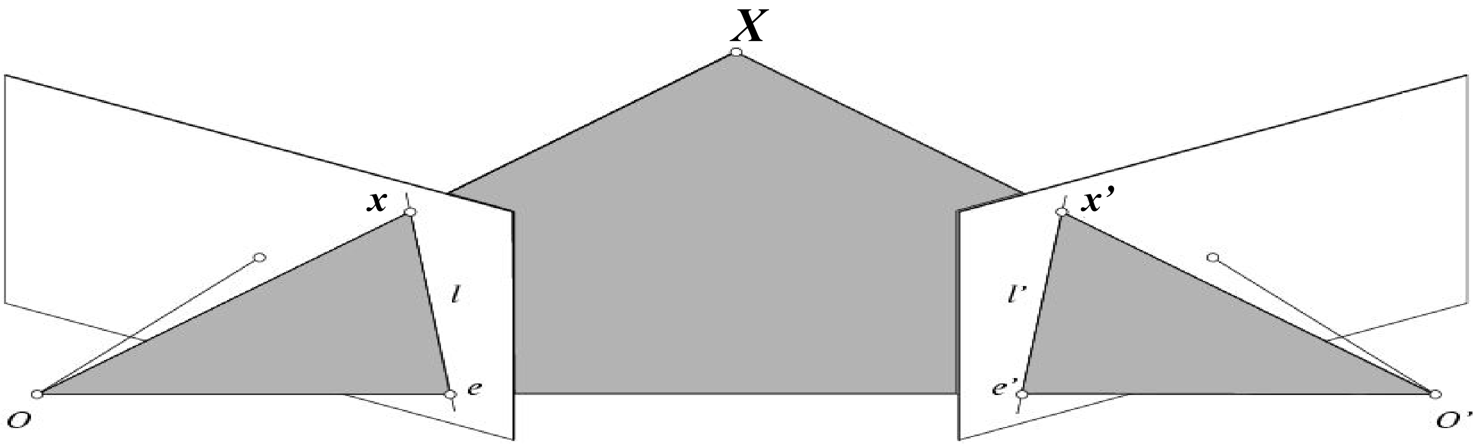






Epipole has same coordinates in both images.
Points move along lines radiating from e: "Focus of expansion"

Epipolar constraint: Calibrated case



Given the intrinsic parameters of the cameras:

1. Convert to normalized coordinates by pre-multiplying all points with the inverse of the calibration matrix; set first camera's coordinate system to world coordinates

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

3D scene point

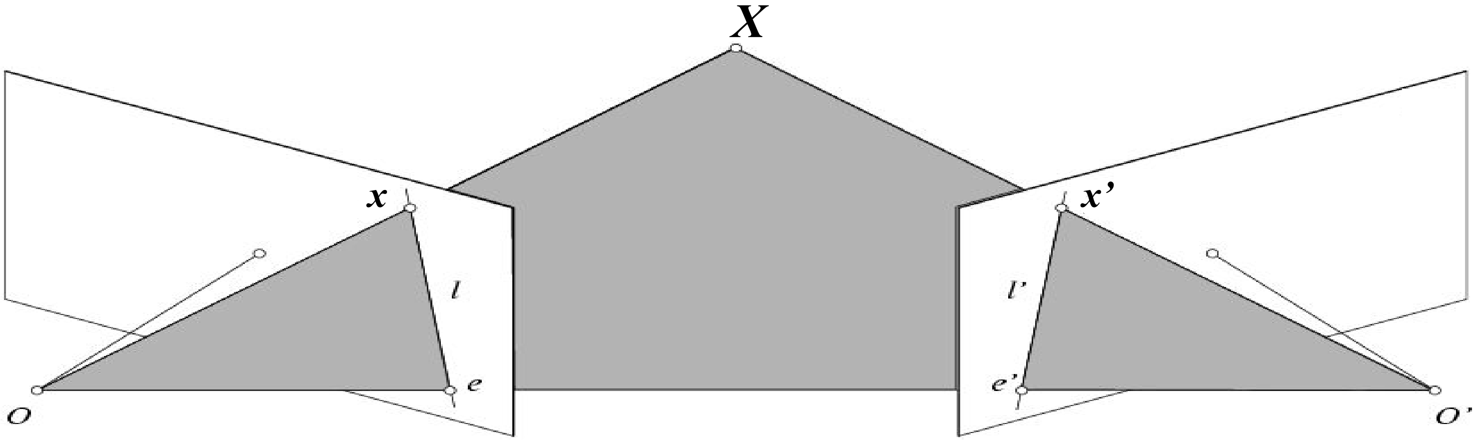
$$\hat{x}' = K'^{-1}x' = X'$$

Homogeneous 2d point
(3D ray towards X)

2D pixel coordinate
(homogeneous)

3D scene point in 2nd
camera's 3D coordinates

Epipolar constraint: Calibrated case



Given the intrinsic parameters of the cameras:

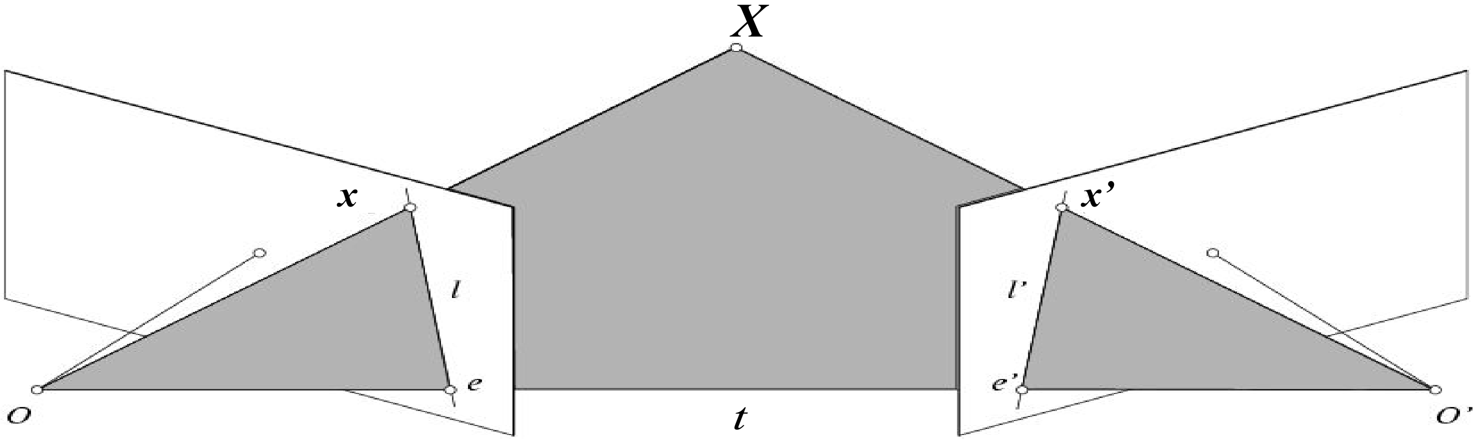
1. Convert to normalized coordinates by pre-multiplying all points with the inverse of the calibration matrix; set first camera's coordinate system to world coordinates
2. Define some *R* and *t* that relate X to X' as below

for some scale factor

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

$$\hat{x} = R\hat{x}' + t$$

Epipolar constraint: Calibrated case

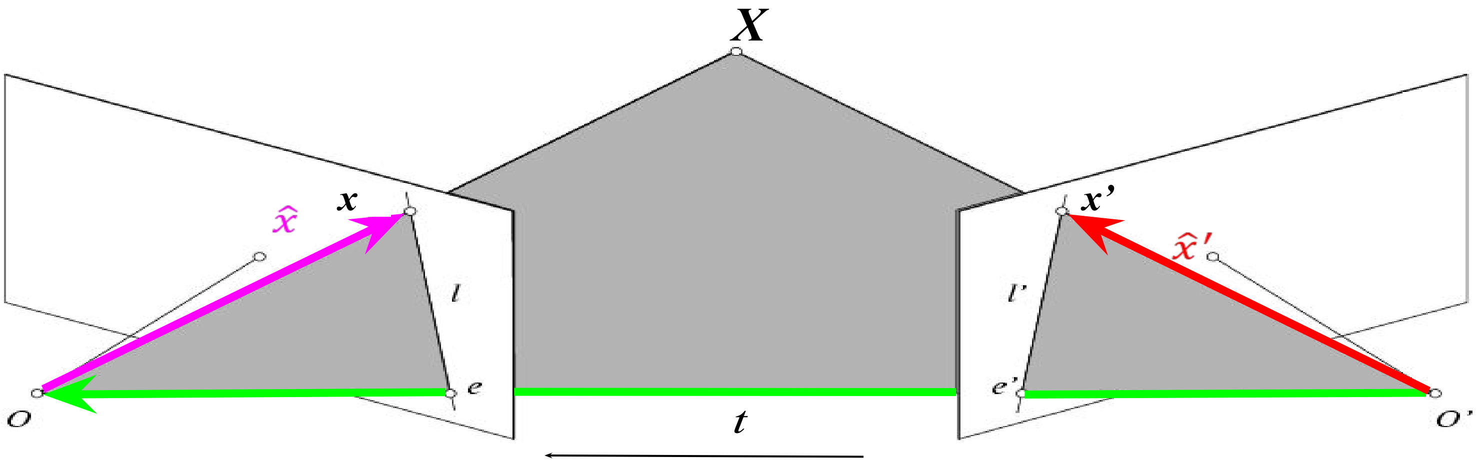


$$\hat{x} = K^{-1}x = X \qquad \hat{x}' = K'^{-1}x' = X'$$

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

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

Epipolar constraint: Calibrated case



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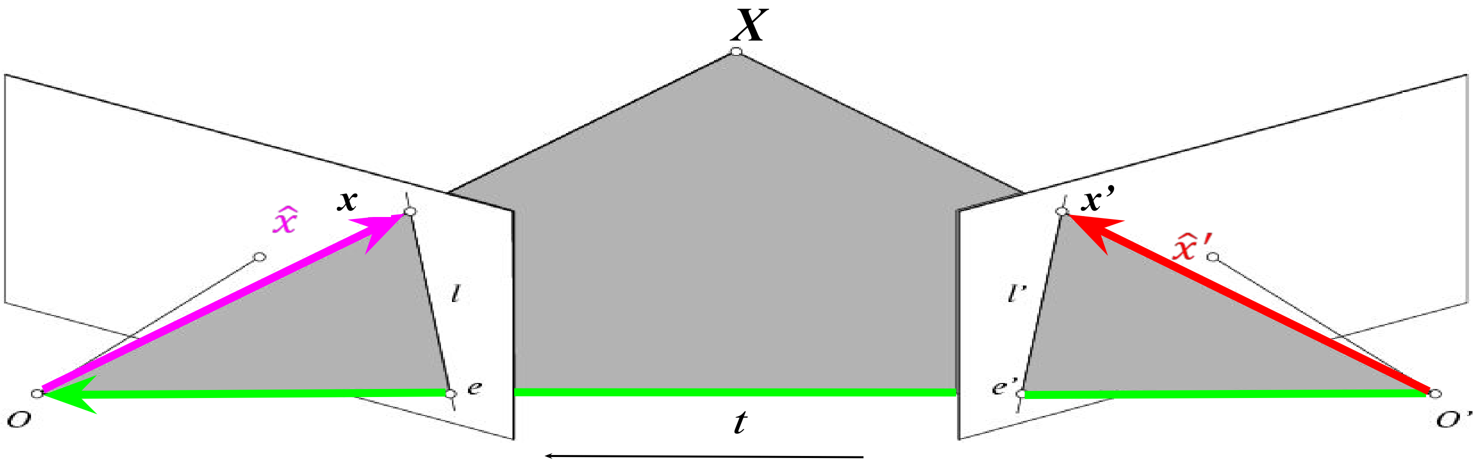

$$\hat{x} = K^{-1}x = X \qquad \hat{x}' = K'^{-1}x' = X'$$

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

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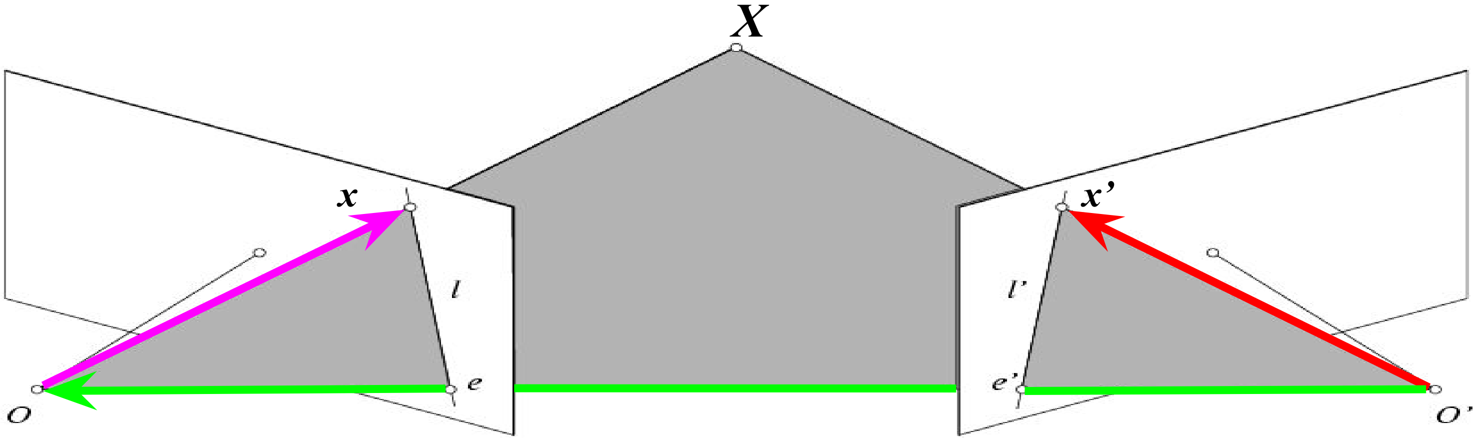
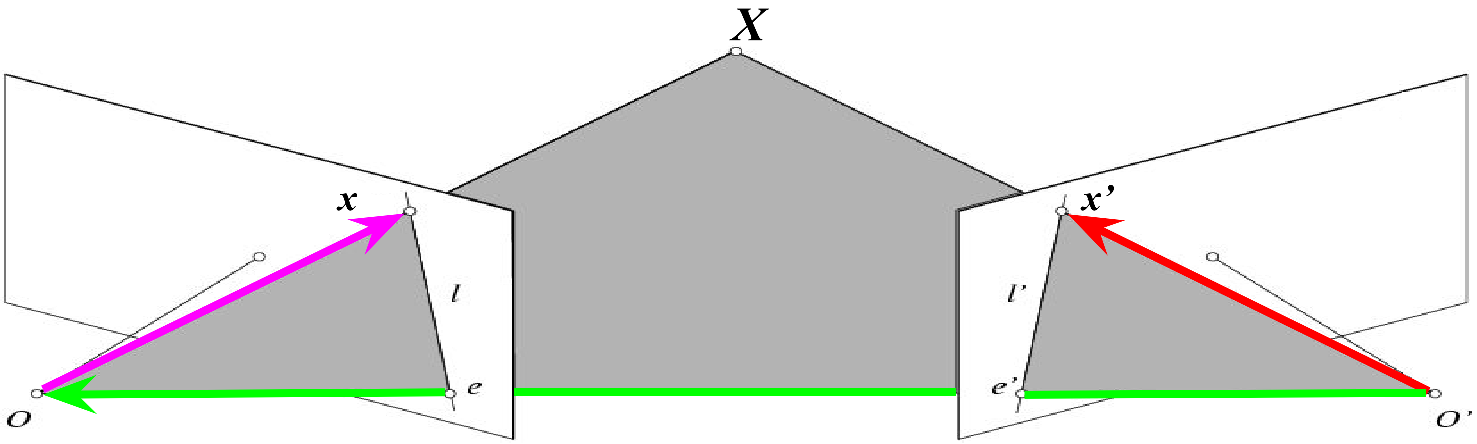
Essential matrix



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

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

Essential matrix



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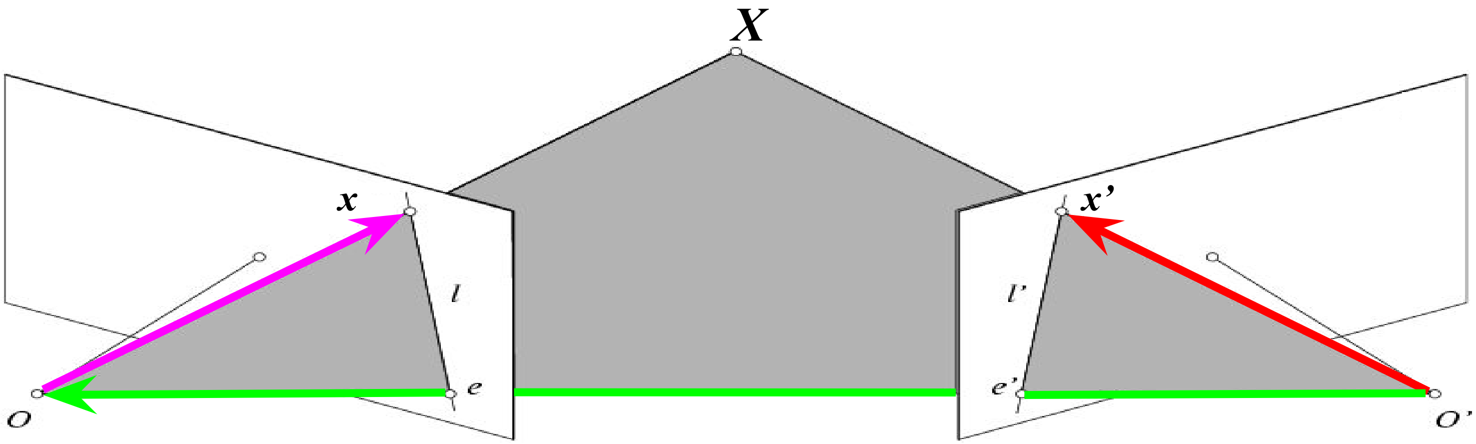
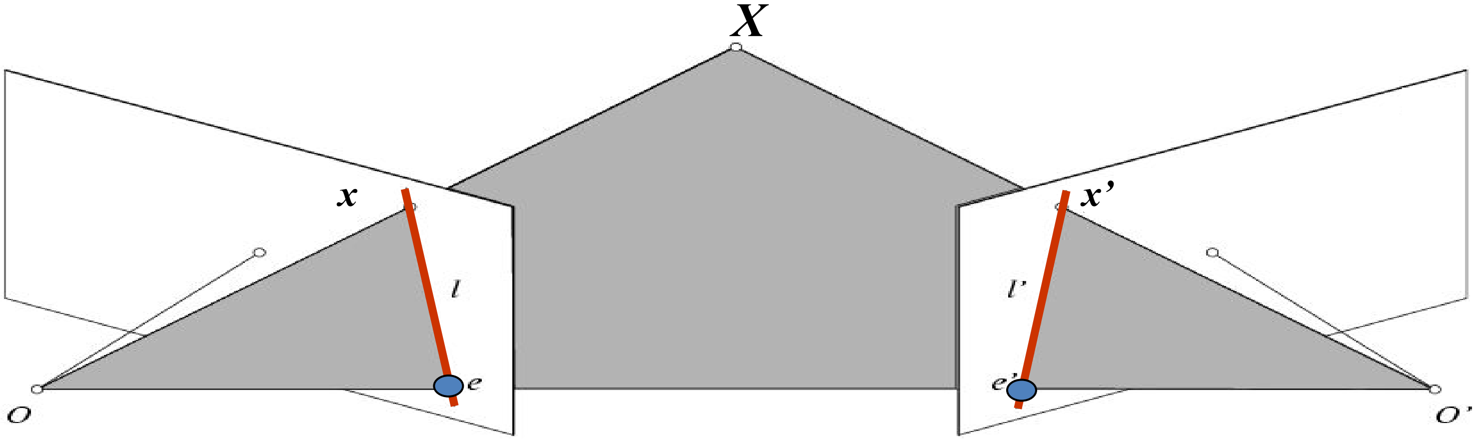


$\hat{x} \cdot [t \times (R\hat{x}')] = 0$ $\Rightarrow$ $\hat{x}^T E \hat{x}' = 0$ with $E = [t]_\times R$

Essential Matrix
(Longuet-Higgins, 1981)

Properties of the Essential matrix



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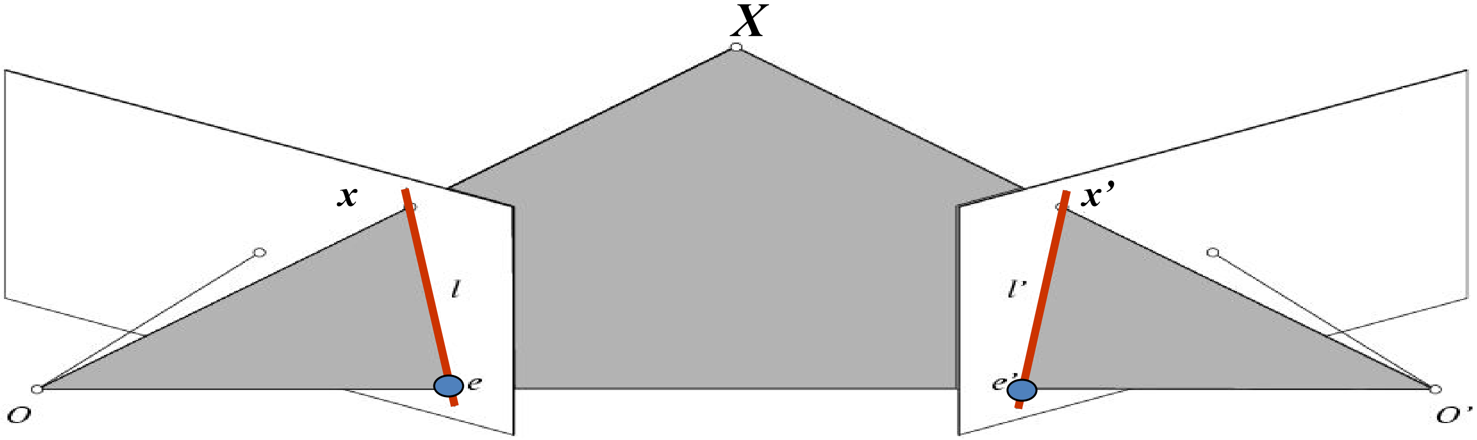
Drop ^ below to simplify notation

Skew-sym
metric
matrix

Properties of the Essential matrix



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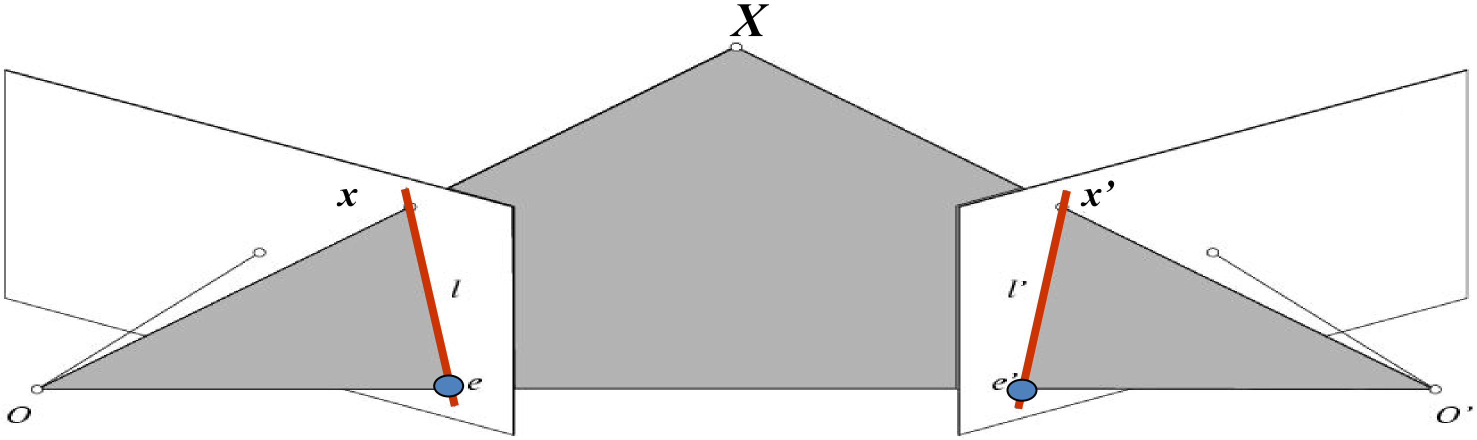
- *E x'* is the epipolar line associated with *x'* (*l* = *E x'*)

Skew-sym metric matrix

Properties of the Essential matrix



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Skew-sym metric matrix

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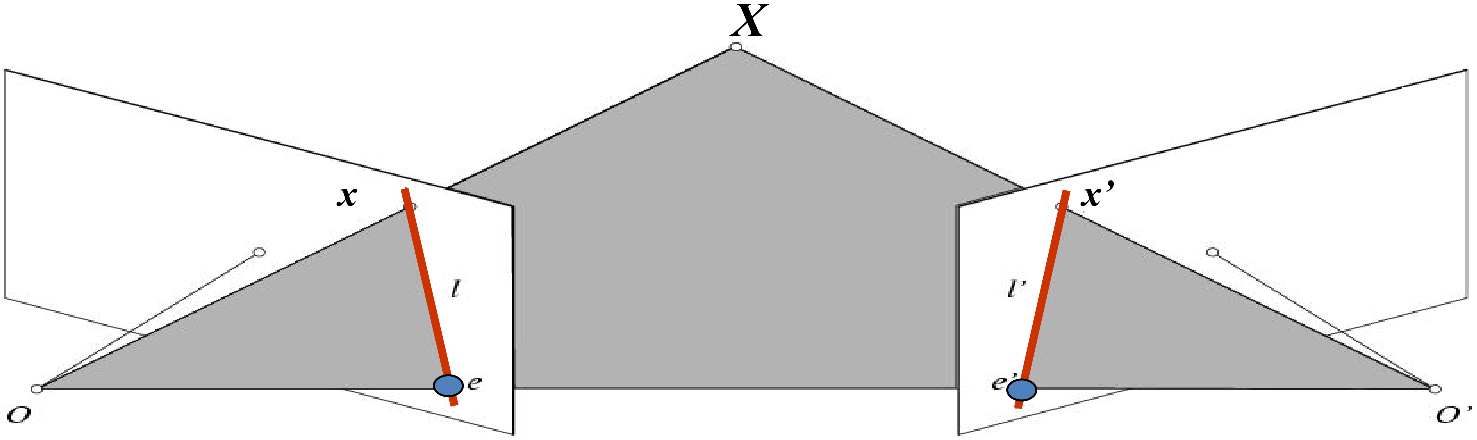
Properties of the Essential matrix



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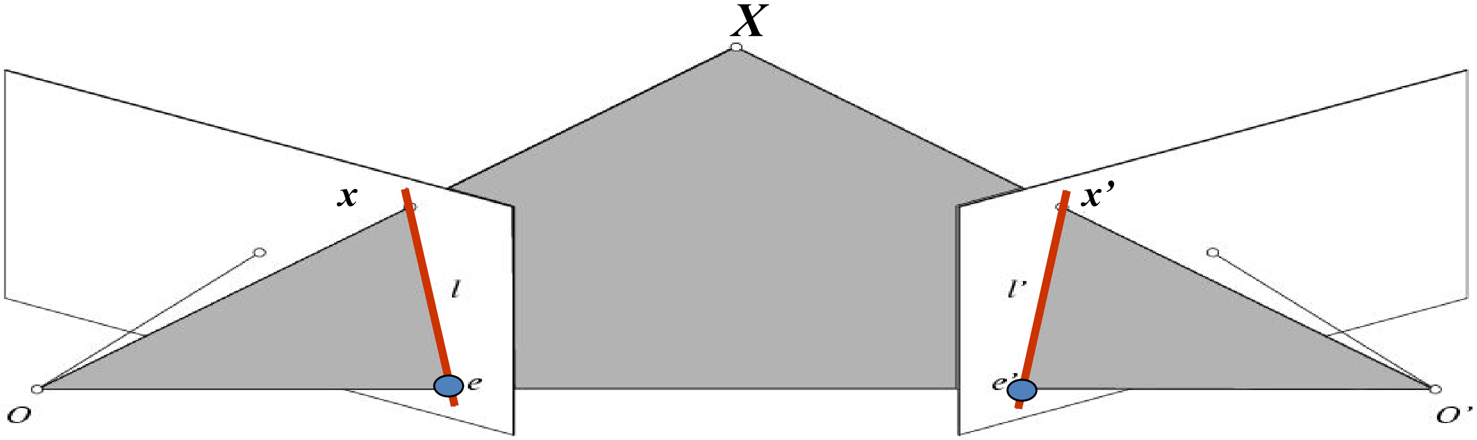

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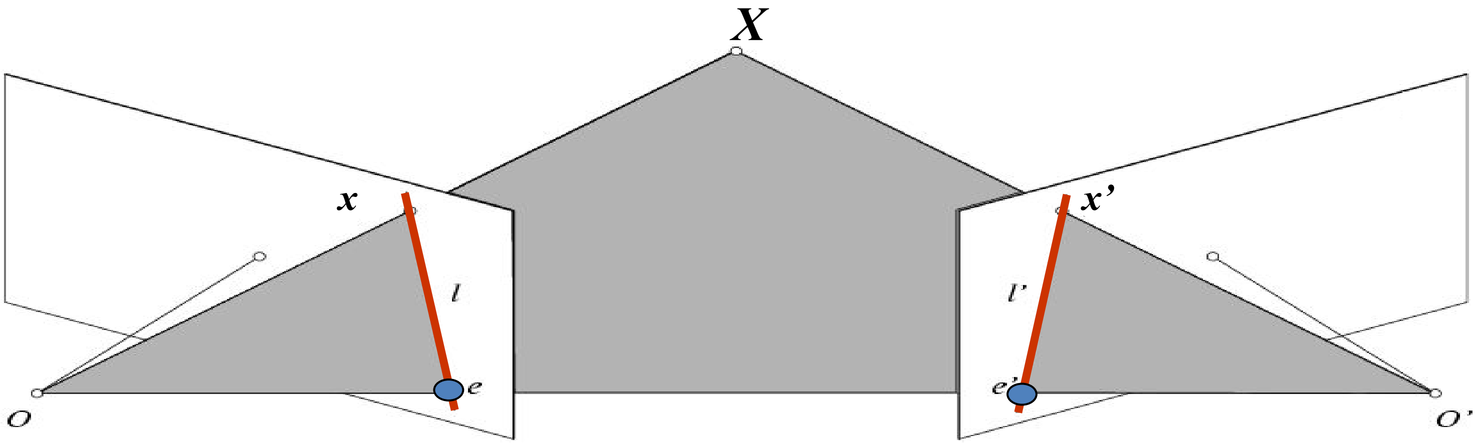
- E is singular (rank two)

Properties of the Essential matrix



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

Skew-sym metric matrix

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- $E x'$ is the epipolar line associated with x' ($l = E x'$)
- $E^T x$ is the epipolar line associated with x ($l' = E^T x$)
- $E e' = 0$ and $E^T e = 0$
- E is singular (rank two)
- E has five degrees of freedom
  - (3 for R, 2 for t because it's up to a scale)

The Fundamental Matrix

Without knowing K and K', we can define a similar relation using *unknown* normalized coordinates

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

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

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

$$x^T F x' = 0 \quad \textbf{with} \quad F = K^{-T} E K'^{-1}$$

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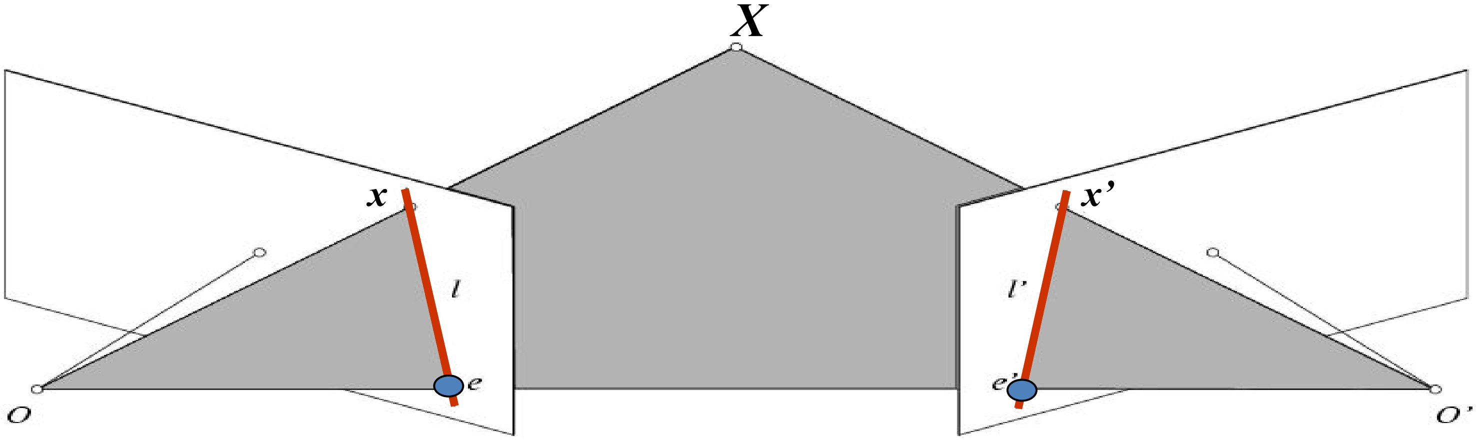
Fundamental Matrix
(Faugeras and Luong, 1992)

Properties of the Fundamental matrix



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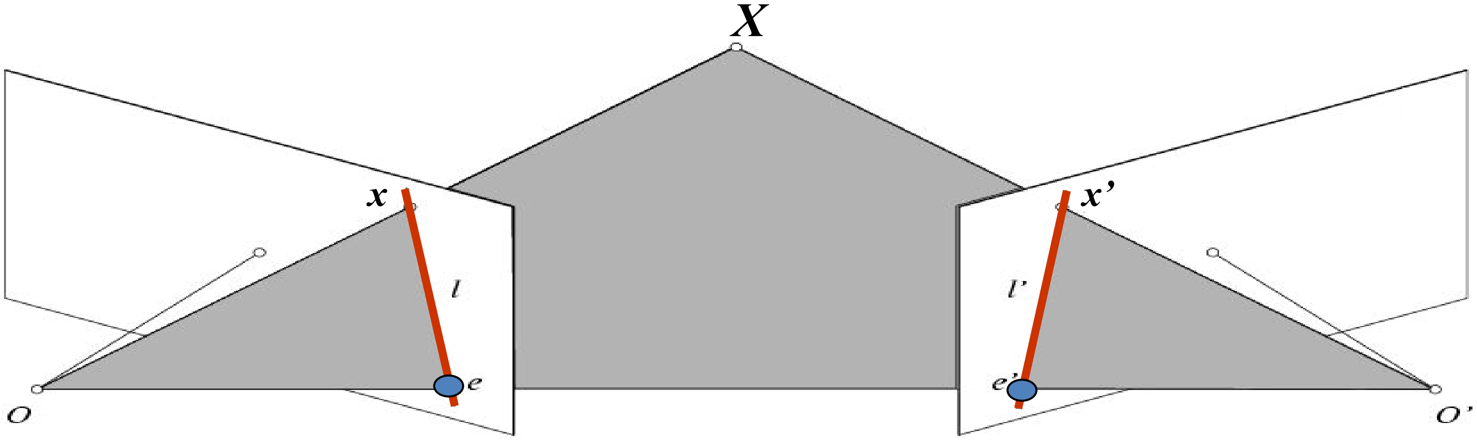
Properties of the Fundamental matrix



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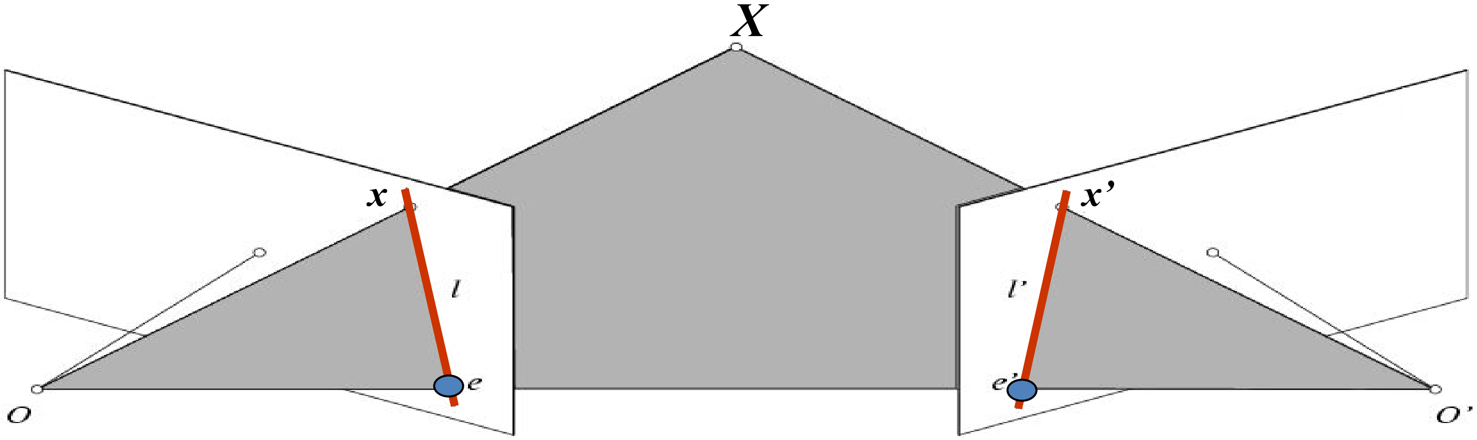
- *F x'* is the epipolar line associated with *x'* ($l = F x'$)

Properties of the Fundamental matrix



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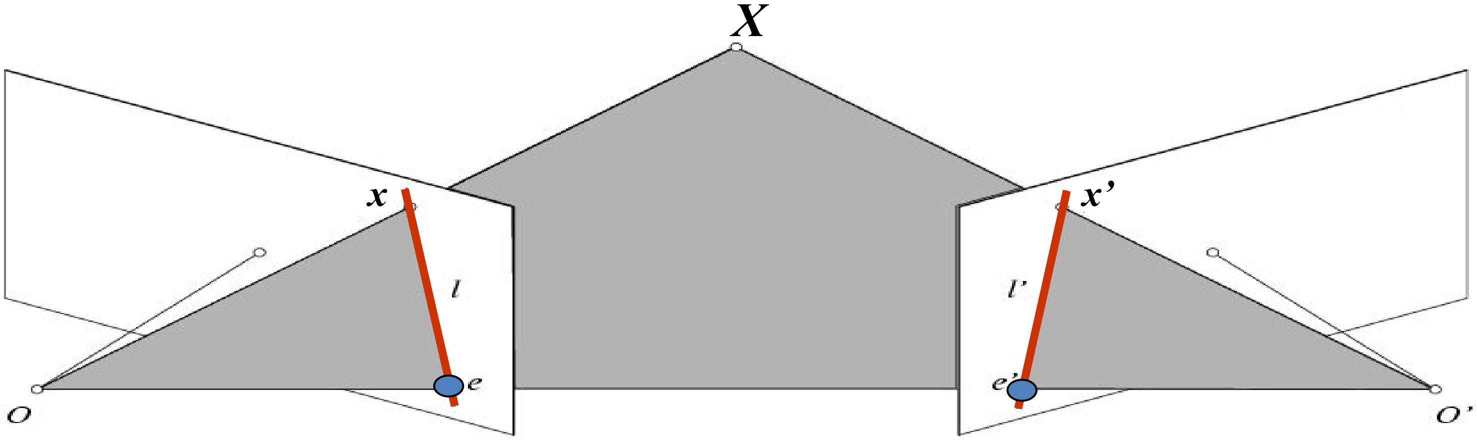

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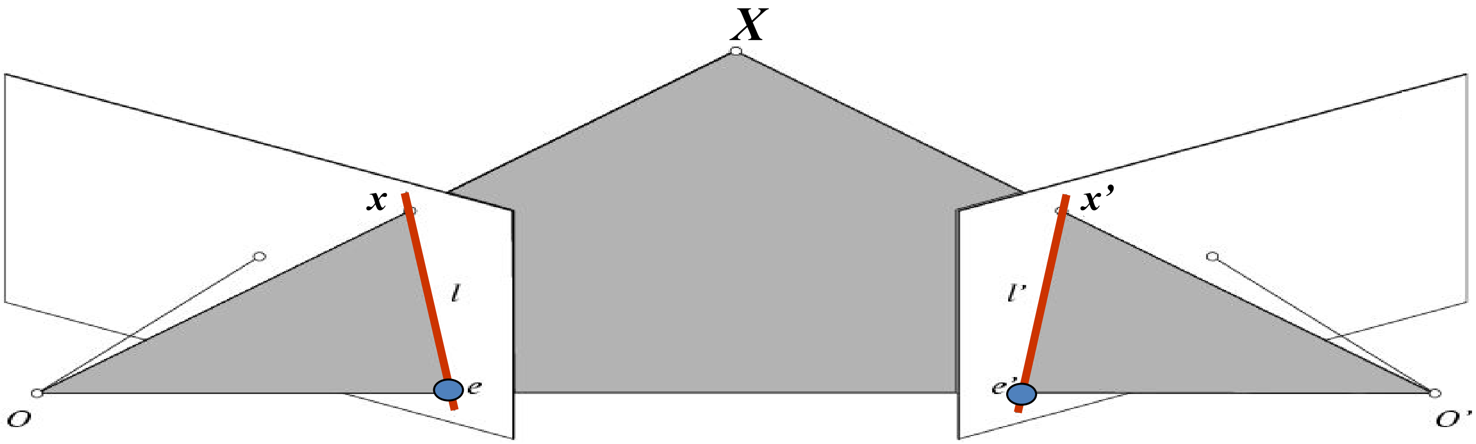
- $F e' = 0$ and $F^T e = 0$

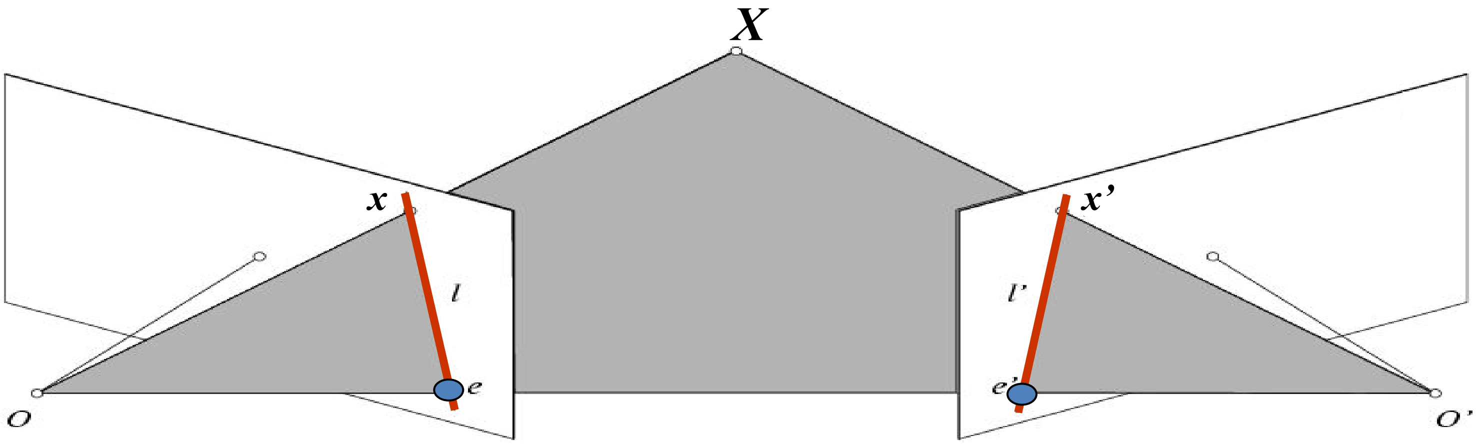
Properties of the Fundamental matrix



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

- $F x'$ is the epipolar line associated with x' ($l = F x'$)
- $F^T x$ is the epipolar line associated with x ($l' = F^T x$)
- $F e' = 0$ and $F^T e = 0$
- F is singular (rank two): det(F)=0

Properties of the Fundamental matrix



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

- $F x'$ is the epipolar line associated with x' ($l = F x'$)
- $F^T x$ is the epipolar line associated with x ($l' = F^T x$)
- $F e' = 0$ and $F^T e = 0$
- F is singular (rank two): det(F)=0
- F has seven degrees of freedom: 9 entries but defined up to scale, det(F)=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
- 7-point algorithm
  - Use least squares to solve for null space (two vectors) using SVD and 7 pairs of correspondences
  - Solve for linear combination of null space vectors that satisfies det(F)=0
- Minimize reprojection error
  - Non-linear least squares

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

8-point algorithm

1. Solve a system of homogeneous linear equations
   a. Write down the system of equations

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

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

$$\mathrm{A}\boldsymbol{f} = \begin{bmatrix} u_1 u_1' & u_1 v_1' & u_1 & v_1 u_1' & v_1 v_1' & v_1 & u_1' & v_1' & 1 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ u_n u_v' & u_n v_n' & u_n & v_n u_n' & v_n v_n' & v_n & u_n' & v_n' & 1 \end{bmatrix} \begin{bmatrix} f_{11} \\ f_{12} \\ f_{13} \\ f_{21} \\ \vdots \\ f_{33} \end{bmatrix} = \mathbf{0}$$

8-point algorithm

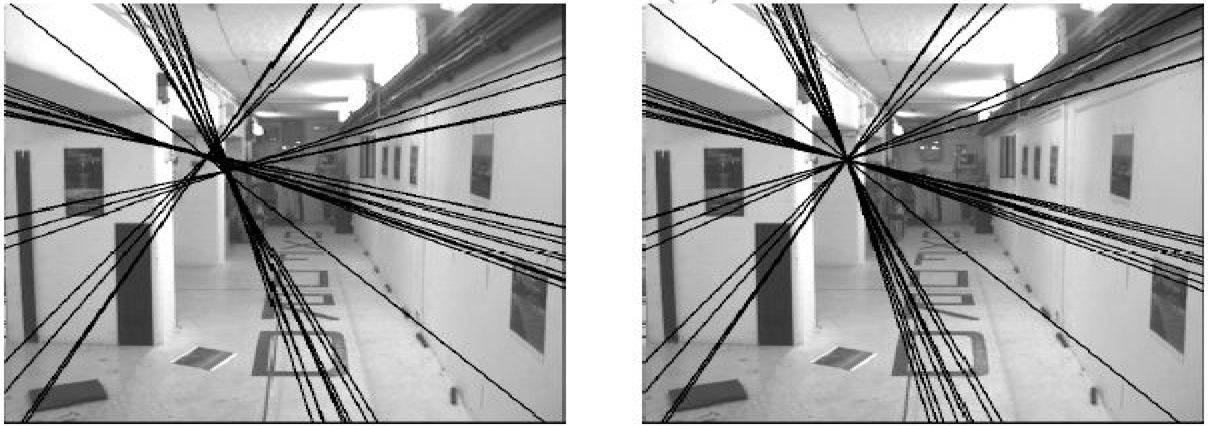
1. Solve a system of homogeneous linear equations
   a. Write down the system of equations
   b. Solve **f** from A**f**=**0** using SVD

      Matlab:

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

Need to enforce singularity constraint

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



Left : Uncorrected $\mathtt{F}$ – epipolar lines are not coincident.

Right : Epipolar lines from corrected $\mathtt{F}$.

8-point algorithm

1. Solve a system of homogeneous linear equations
   a. Write down the system of equations
   b. Solve **f** from A**f**=**0** using SVD

   Matlab:

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

2. Resolve det(F) = 0 constraint using SVD

   Matlab:

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

8-point algorithm

1. Solve a system of homogeneous linear equations
   a. Write down the system of equations
   b. Solve **f** from A**f**=**0** using SVD
2. Resolve det(F) = 0 constraint by SVD

Notes:

3. Use RANSAC to deal with outliers (sample 8 points)
   – How to test for outliers?

Problem with eight-point algorithm

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

Problem with eight-point algorithm

$$
\begin{bmatrix}
250906.36 & 183269.57 & 921.81 & 200931.10 & 146766.13 & 738.21 & 272.19 & 198.81 \\
2692.28 & 131633.03 & 176.27 & 6196.73 & 302975.59 & 405.71 & 15.27 & 746.79 \\
416374.23 & 871684.30 & 935.47 & 408110.89 & 854384.92 & 916.90 & 445.10 & 931.81 \\
191183.60 & 171759.40 & 410.27 & 416435.62 & 374125.90 & 893.65 & 465.99 & 418.65 \\
48988.86 & 30401.76 & 57.89 & 298604.57 & 185309.58 & 352.87 & 846.22 & 525.15 \\
164786.04 & 546559.67 & 813.17 & 1998.37 & 6628.15 & 9.86 & 202.65 & 672.14 \\
116407.01 & 2727.75 & 138.89 & 169941.27 & 3982.21 & 202.77 & 838.12 & 19.64 \\
135384.58 & 75411.13 & 198.72 & 411350.03 & 229127.78 & 603.79 & 681.28 & 379.48
\end{bmatrix}
\begin{bmatrix} f_{11} \\ f_{12} \\ f_{13} \\ f_{21} \\ f_{22} \\ f_{23} \\ f_{31} \\ f_{32} \end{bmatrix} = -1
$$

Problem with eight-point algorithm

250906.36	183269.57	921.81	200931.10	146766.13	738.21	272.19	198.81
2692.28	131633.03	176.27	6196.73	302975.59	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	846.22	525.15
164786.04	546559.67	813.17	1998.37	6628.15	9.86	202.65	672.14
116407.01	2727.75	138.89	169941.27	3982.21	202.77	838.12	19.64
135384.58	75411.13	198.72	411350.03	229127.78	603.79	681.28	379.48

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

Poor numerical conditioning

Problem with eight-point algorithm

250906.36	183269.57	921.81	200931.10	146766.13	738.21	272.19	198.81
2692.28	131633.03	176.27	6196.73	302975.59	405.71	15.27	746.79
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$$\begin{bmatrix} f_{11} \\ f_{12} \\ f_{13} \\ f_{21} \\ f_{22} \\ f_{23} \\ f_{31} \\ f_{32} \end{bmatrix} = -1$$

Poor numerical conditioning

Can be fixed by rescaling the data

The normalized eight-point algorithm

(Hartley, 1995)

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- 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

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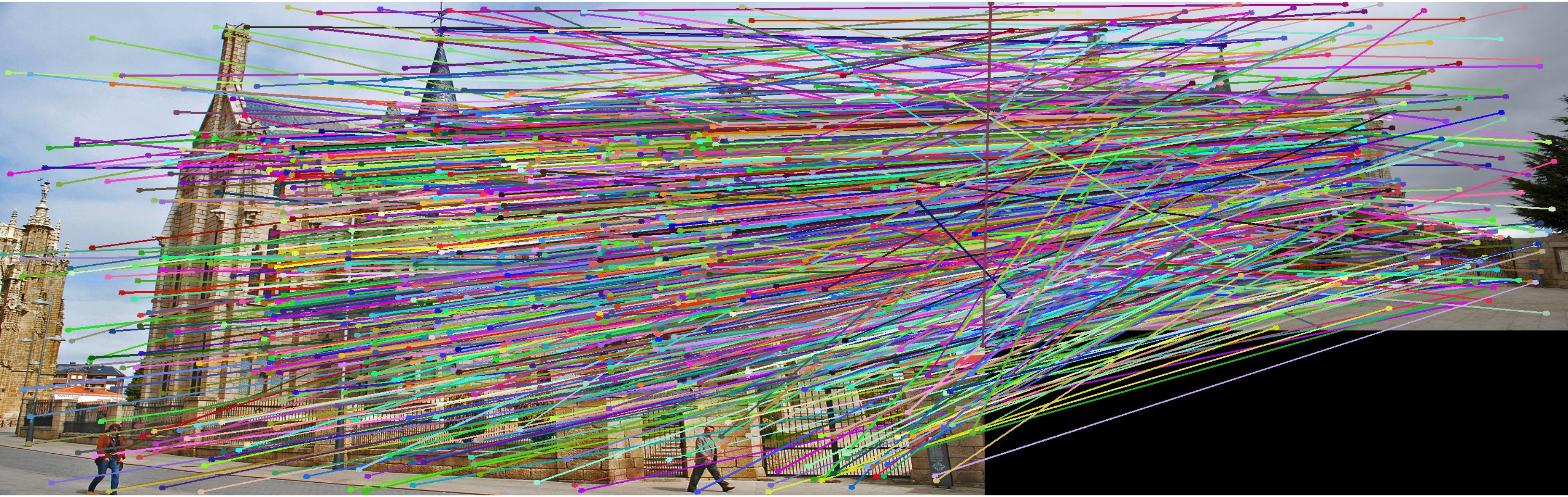
The normalized eight-point algorithm

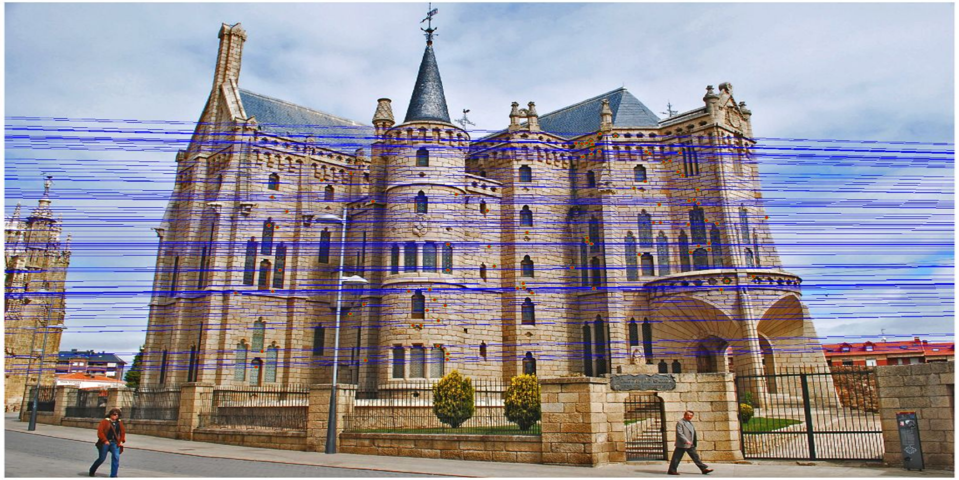
(Hartley, 1995)

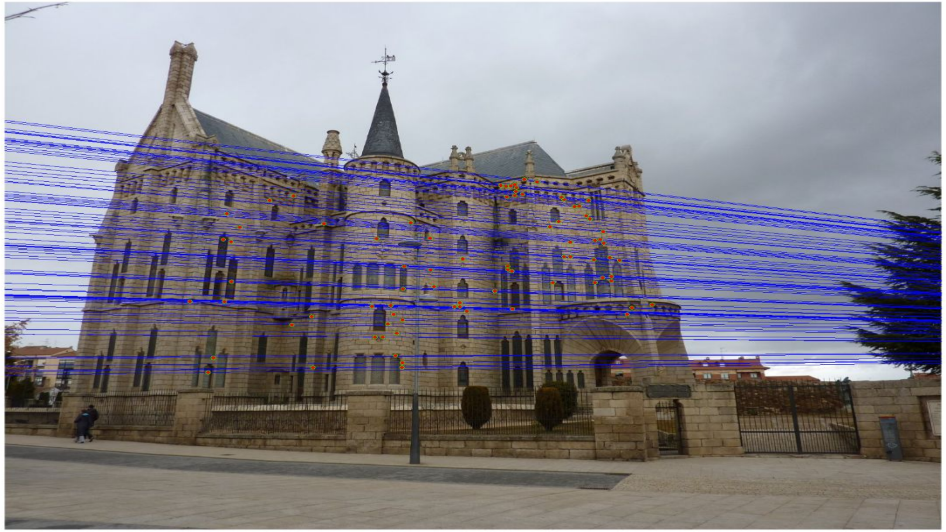
- Center the image data at the origin, and scale it so the mean squared distance between the origin and the data points is 2 pixels
- Use the eight-point algorithm to compute ***F*** from the normalized points
- Enforce the rank-2 constraint (for example, take SVD of ***F*** and throw out the smallest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

VLFeat’s 800 most confident matches among 10,000+ local features.

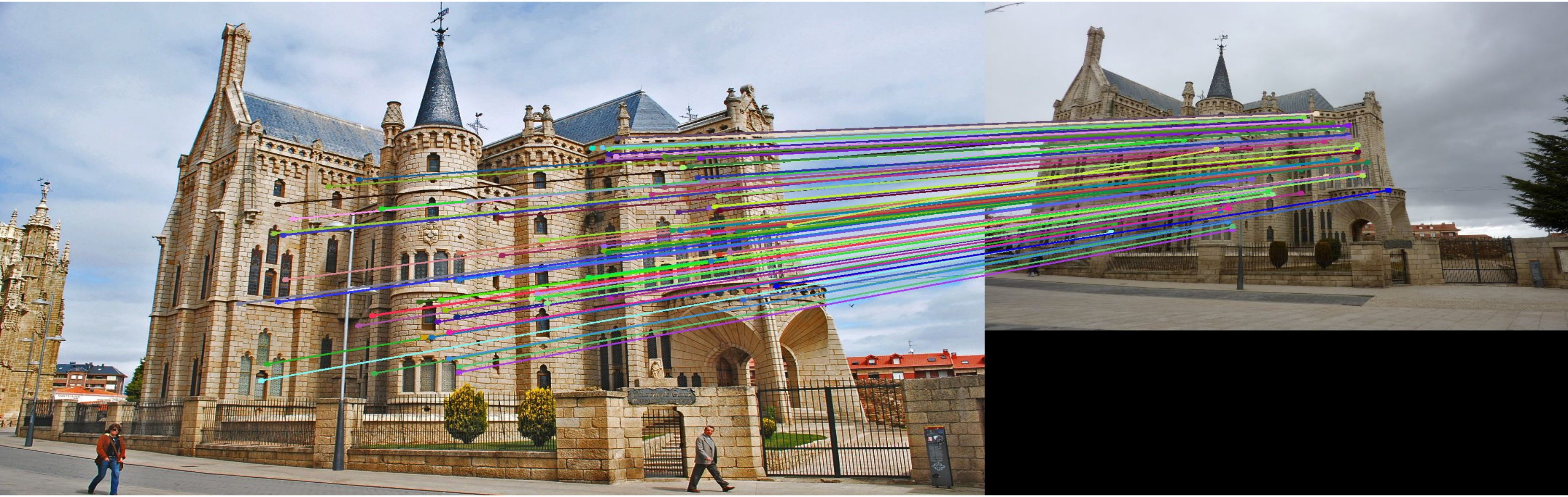


Epipolar lines





Keep only the matches at are "inliers" with respect to the "best" fundamental matrix



Review

- Depth from stereo: main idea is to triangulate from corresponding image points.
- Epipolar geometry defined by two cameras
  - We've assumed known extrinsic parameters relating their poses
- Epipolar constraint limits where points from one view will be imaged in the other
  - Makes search for correspondences quicker
- **Terms**: epipole, epipolar plane / lines, disparity, rectification, intrinsic/extrinsic parameters, essential matrix, baseline

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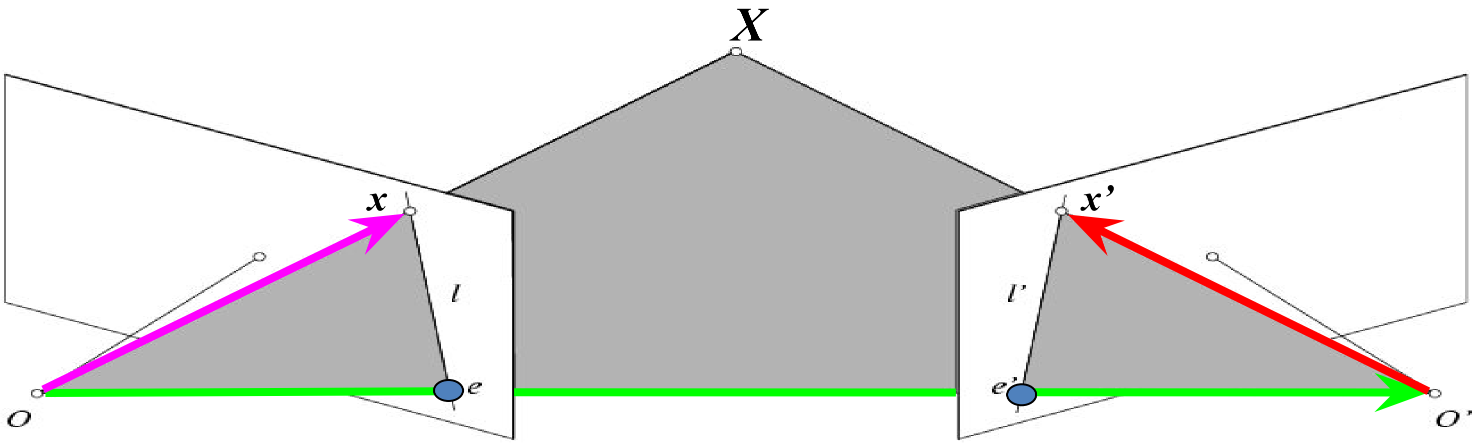
Epipolar constraint: Uncalibrated case



- If we don't know *K* and *K'*, then we can write the epipolar constraint in terms of *unknown* normalized coordinates:

$$\hat{x}^T E \hat{x}' = 0 \qquad\qquad x = K\hat{x}, \quad x' = K'\hat{x}'$$

7-point algorithm

Computation of $\mathtt{F}$ from 7 point correspondences

(i) Form the 7×9 set of equations $\mathtt{A}\mathbf{f} = 0$.

(ii) System has a 2-dimensional solution set.

(iii) General solution (use SVD) has form

$$\mathbf{f} = \lambda \mathbf{f}_0 + \mu \mathbf{f}_1$$

(iv) In matrix terms

$$\mathtt{F} = \lambda \mathtt{F}_0 + \mu \mathtt{F}_1$$

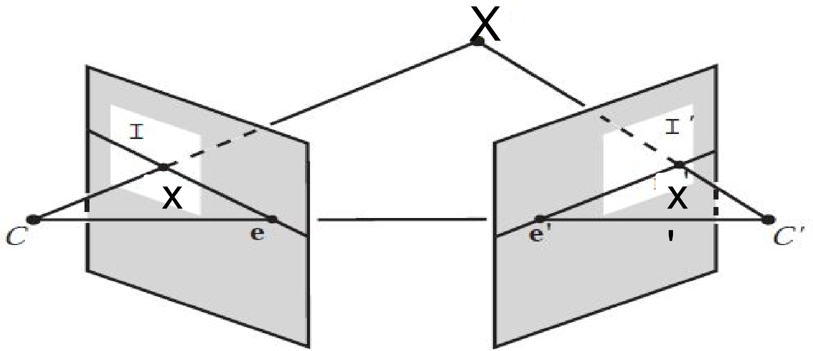
(v) Condition $\det \mathtt{F} = 0$ gives cubic equation in λ and μ.

(vi) Either one or three real solutions for ratio $\lambda : \mu$.

Faster (need fewer points) and could be more robust (fewer points), but also need to check for degenerate cases

“Gold standard” algorithm

- Use 8-point algorithm to get initial value of F
- Use F to solve for P and P’ (discussed later)
- Jointly solve for 3d points **X** and **F** that minimize error



See Algorithm 11.2 and Algorithm 11.3 in HZ (pages 284-285) for details

Comparison of estimation algorithms

	8-point	Normalized 8-point	Nonlinear least squares
Av. Dist. 1	2.33 pixels	0.92 pixel	0.86 pixel
Av. Dist. 2	2.18 pixels	0.85 pixel	0.80 pixel

We can get projection matrices P and P' up to a projective ambiguity

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

Code: See HZ p. 255-256

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

If we know the intrinsic matrices (K and K'), we can resolve the ambiguity

From epipolar geometry to camera calibration

- Estimating the fundamental matrix is known as "weak calibration"

- We cIf we know the calibration matrices of the two cameras, we can estimate the essential matrix: $E = K^T F K'$

- The essential matrix gives us the relative rotation and translation between the cameras, or their extrinsic parameters

Let’s recap…

- Fundamental matrix song