Lecture 18

Binocular Stereo 1:
Epipolar Geometry

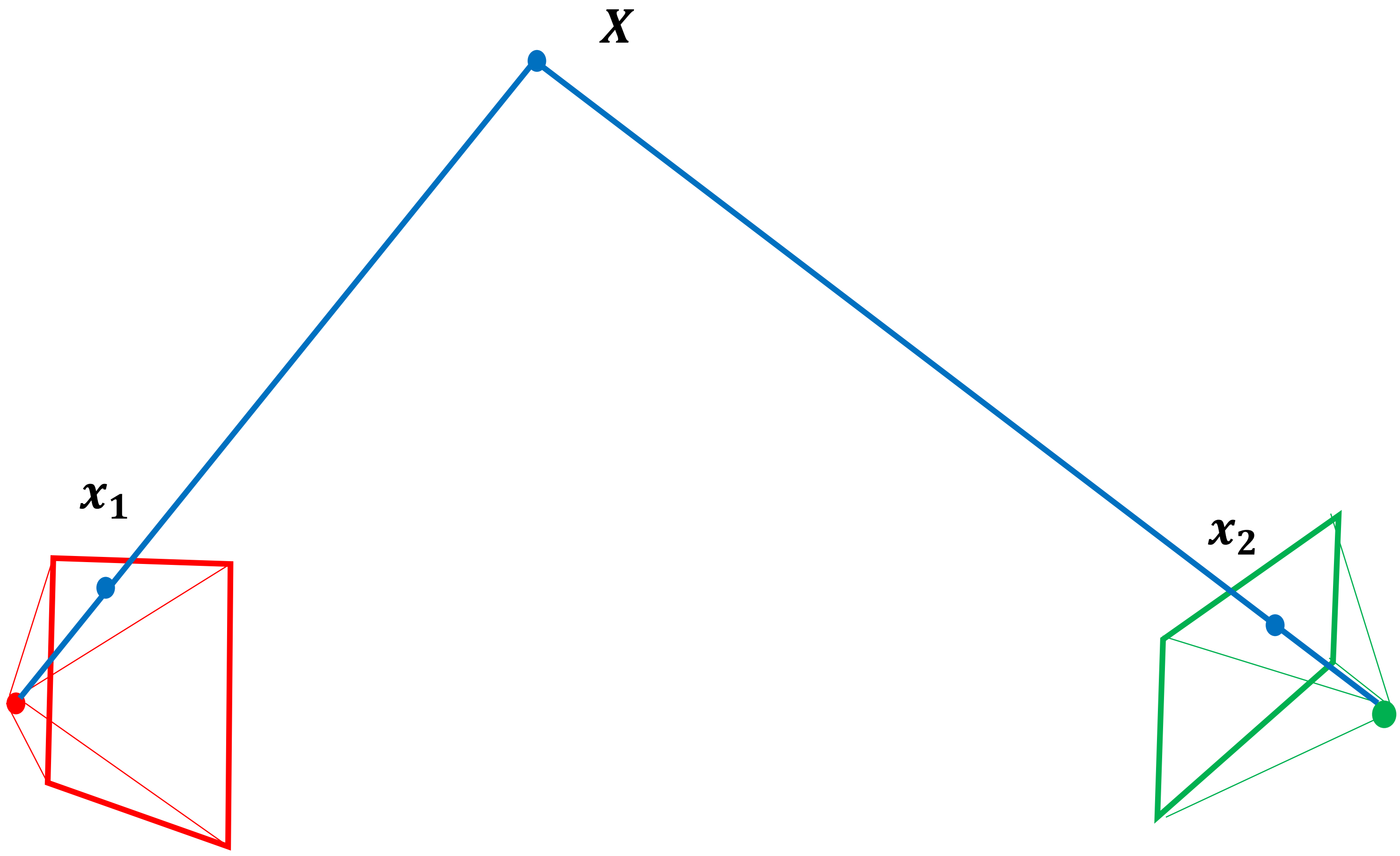
November 9, 2020

reminder – record lecture

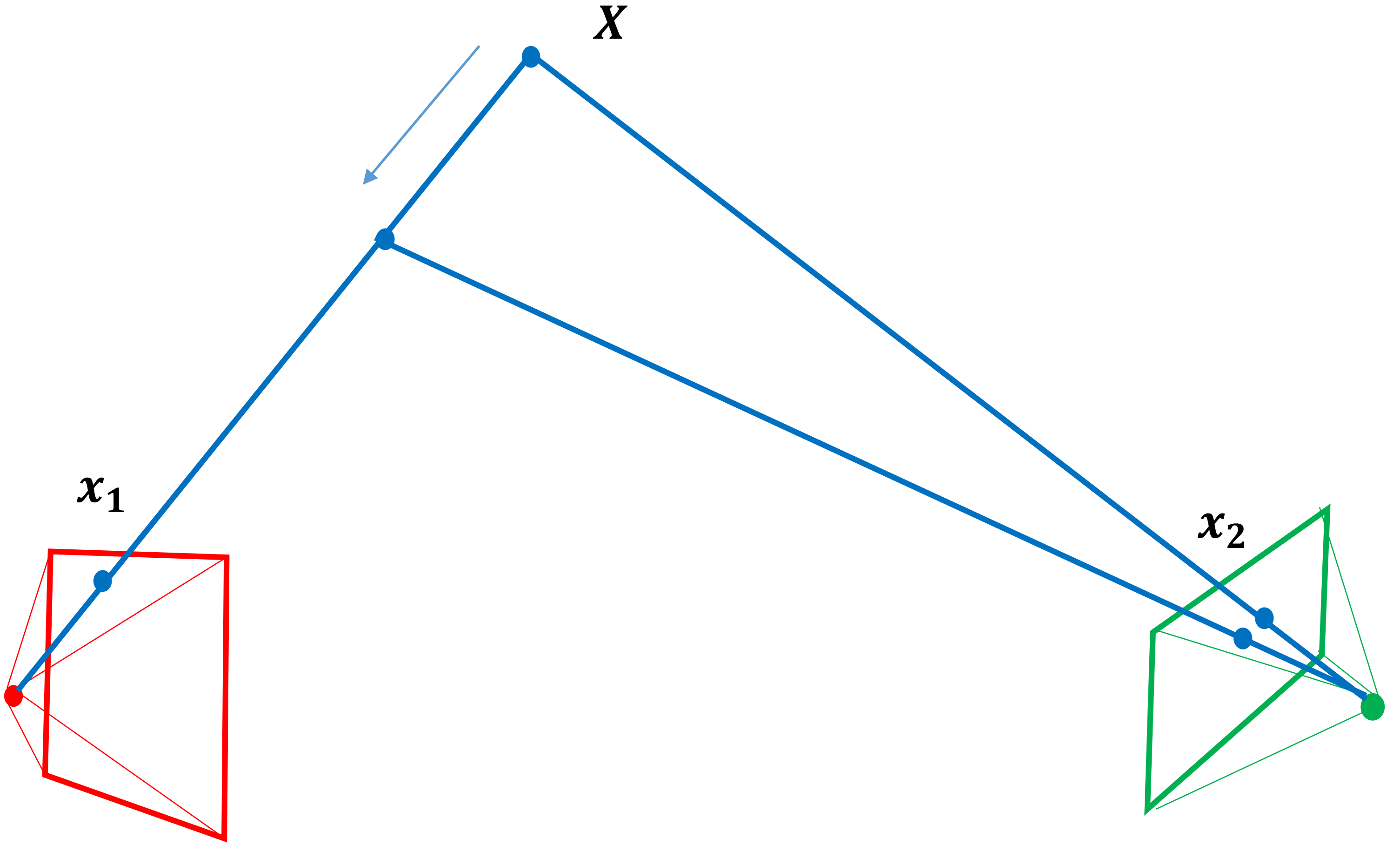
"Binocular" vision – two cameras

Camera i has a $\boldsymbol{P_i}$ matrix with internals $\boldsymbol{K_i}$ and externals $\boldsymbol{R_i}$ and $\boldsymbol{C_i}$. Today we assume that these are all *unknown.*)

A 3D point $\boldsymbol{X}$ at depth $Z_i > 0$ in camera i will project to camera i's image plane at position $\boldsymbol{x_i}$. This point might not lie within the camera's field of view (as determined by the camera matrix $\boldsymbol{K_i}$ and the range of pixel indices).



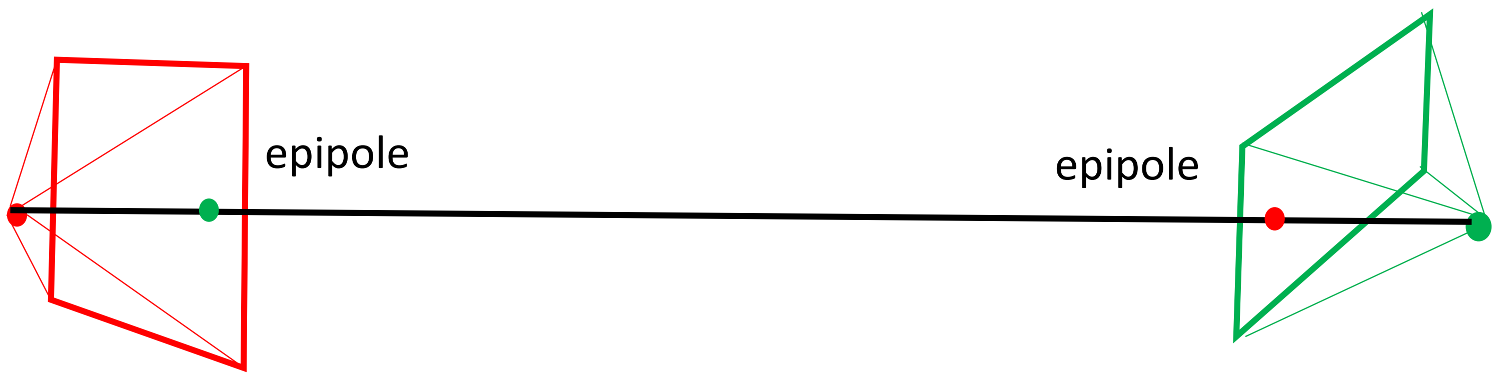
Moving the 3D point $\boldsymbol{X}$ along the projection ray toward the left camera doesn't change its position in the left image. But it does change its position in the right image.



Epipole

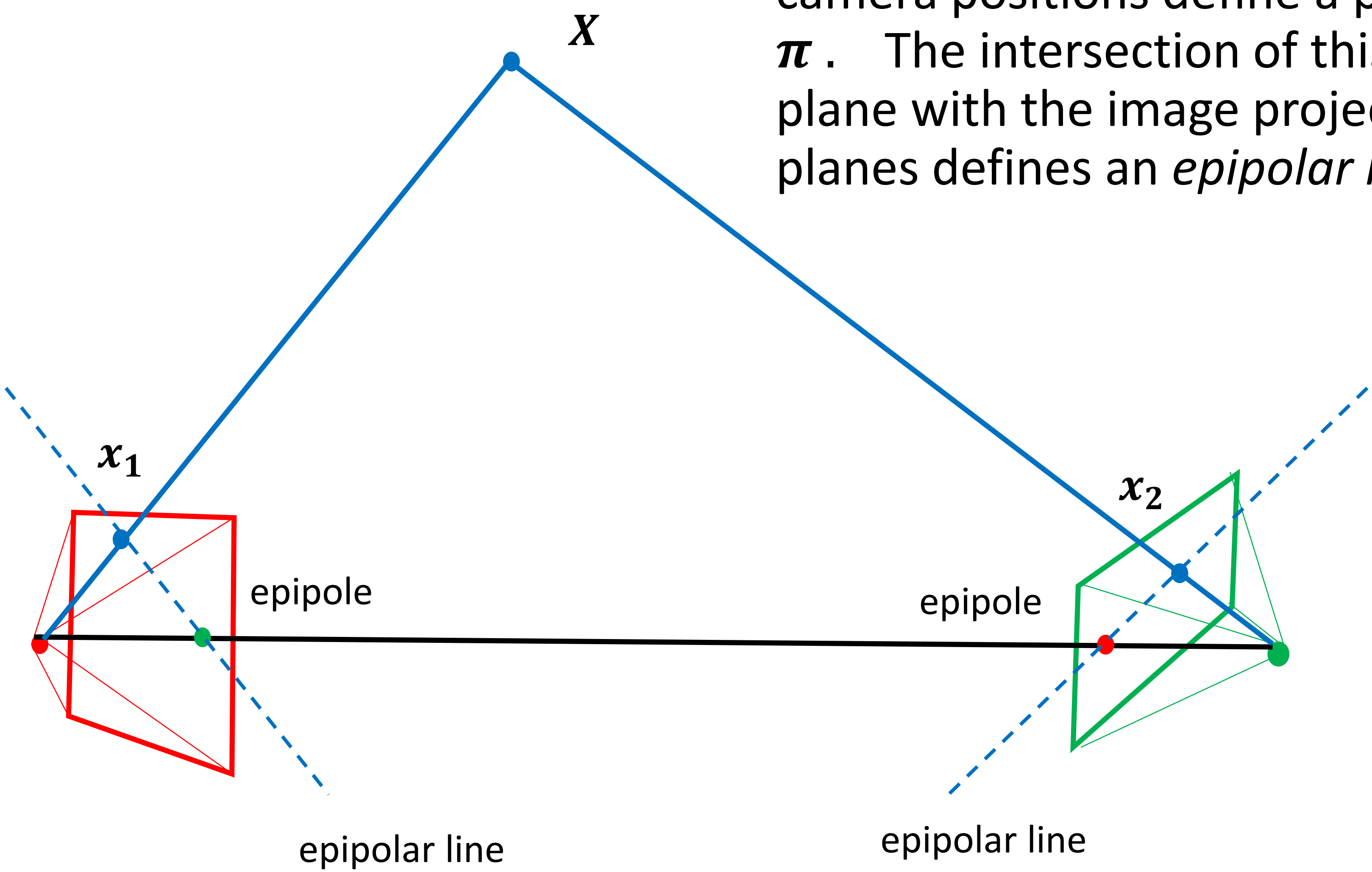
Each camera position is a 3D point. So each camera position defines an image position (possibly at infinity) in the other camera's projection plane. Such a position in called an *epipole*.

The cameras typically do not see each other. So the epipoles typically lie outside the field of view (unlike what is shown below):

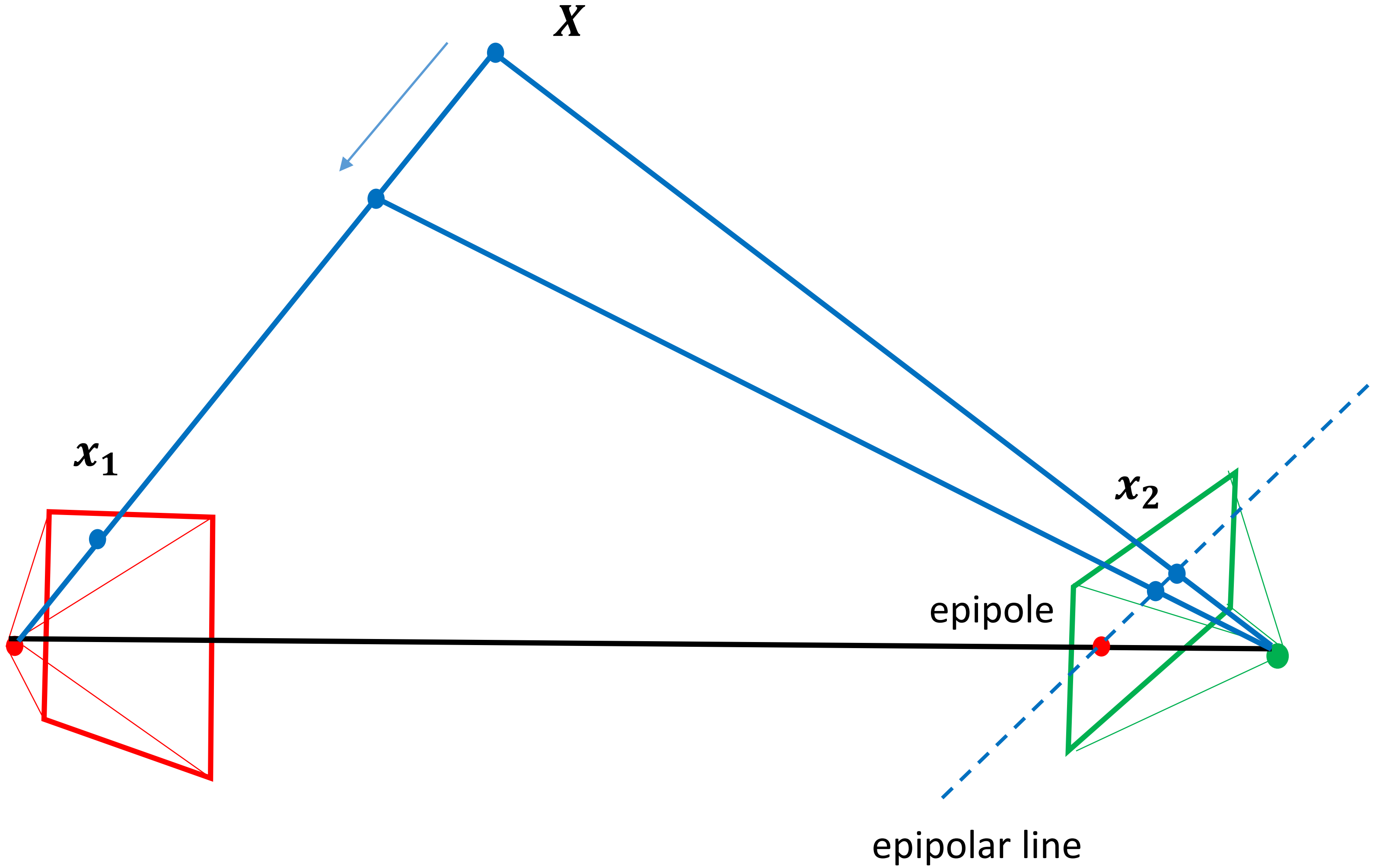


Epipolar Line

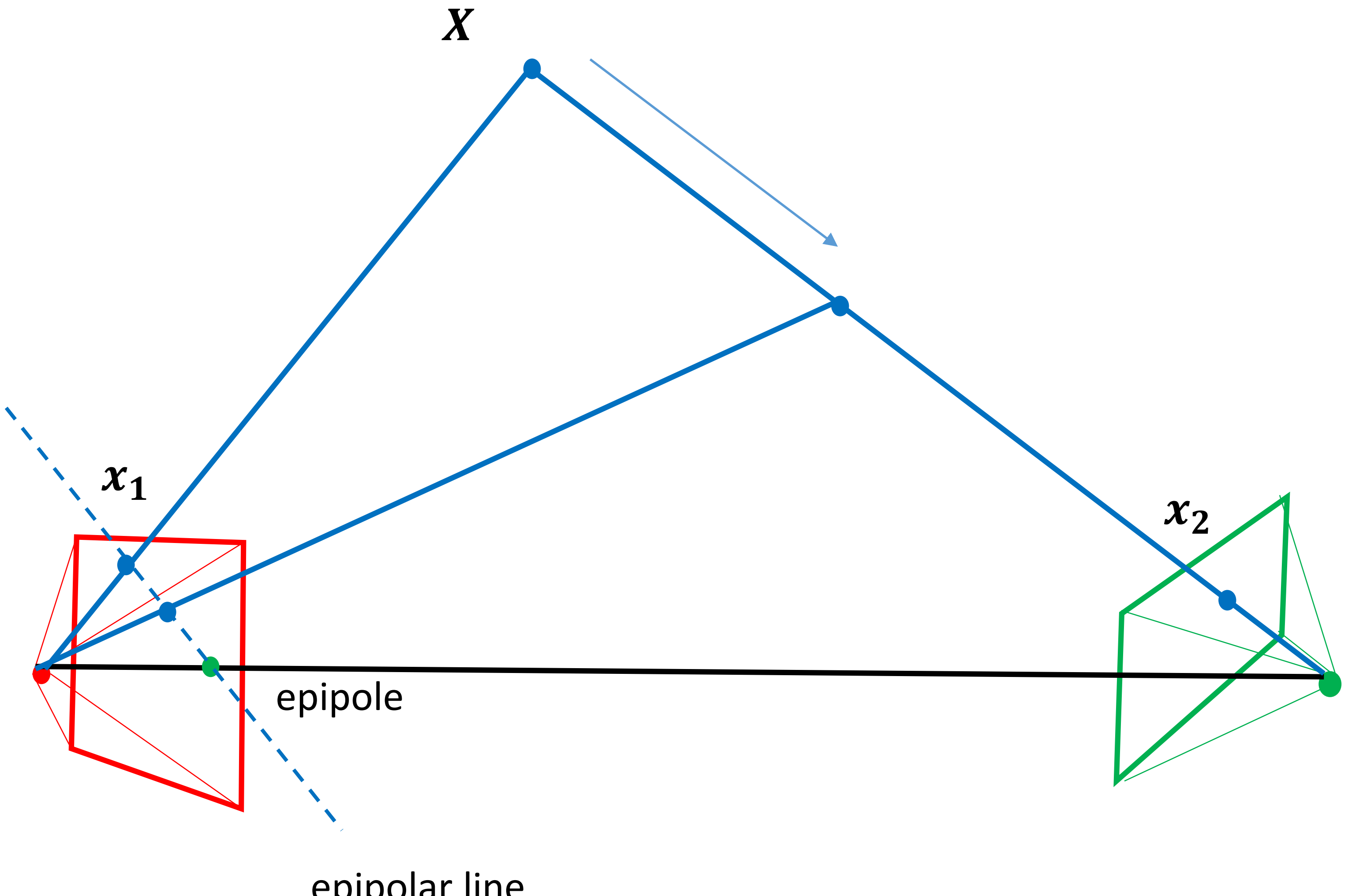
A 3D point $\boldsymbol{X}$ and the two camera positions define a plane $\boldsymbol{\pi}$. The intersection of this plane with the image projection planes defines an *epipolar line*.



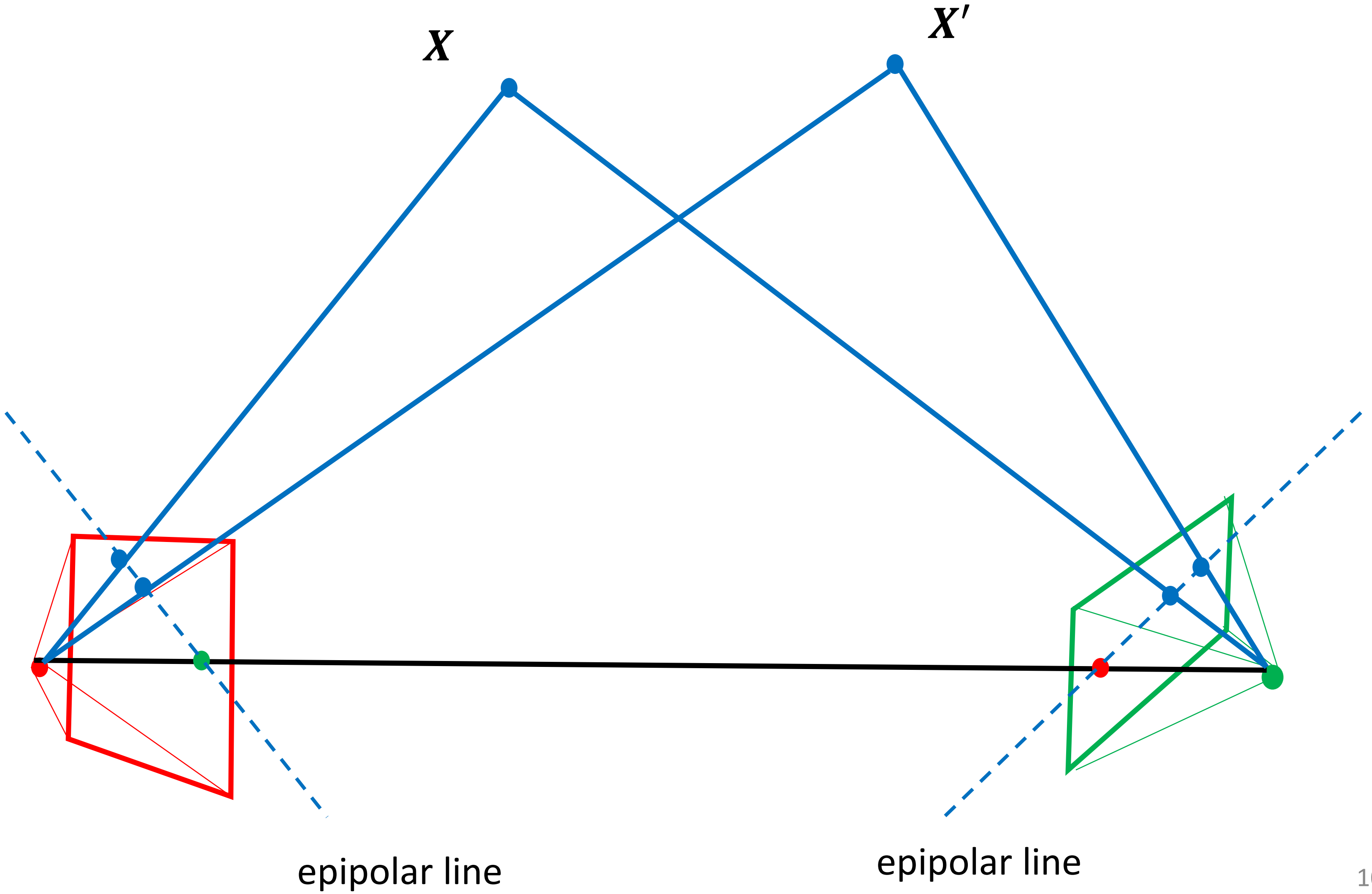
Moving the 3D point $\boldsymbol{X}$ along the projection ray toward the left camera doesn't change its position in the left image. In the right image, the point moves along the epipolar line.



Moving the 3D point $\boldsymbol{X}$ along the projection ray toward the right camera doesn't change its position in the right image. In the left image the point moves along the epipolar line.

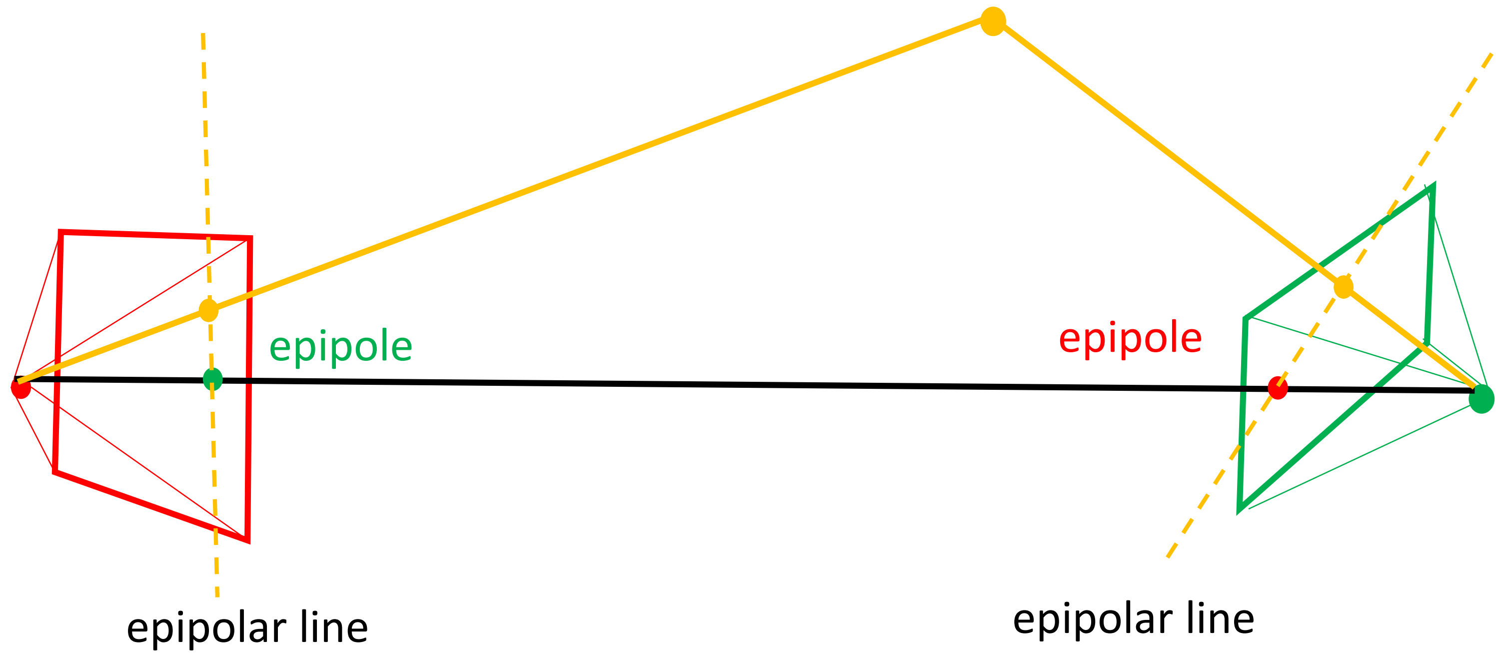


Any 3D point within the same plane $\boldsymbol{\pi}$ will project to the same epipolar lines.

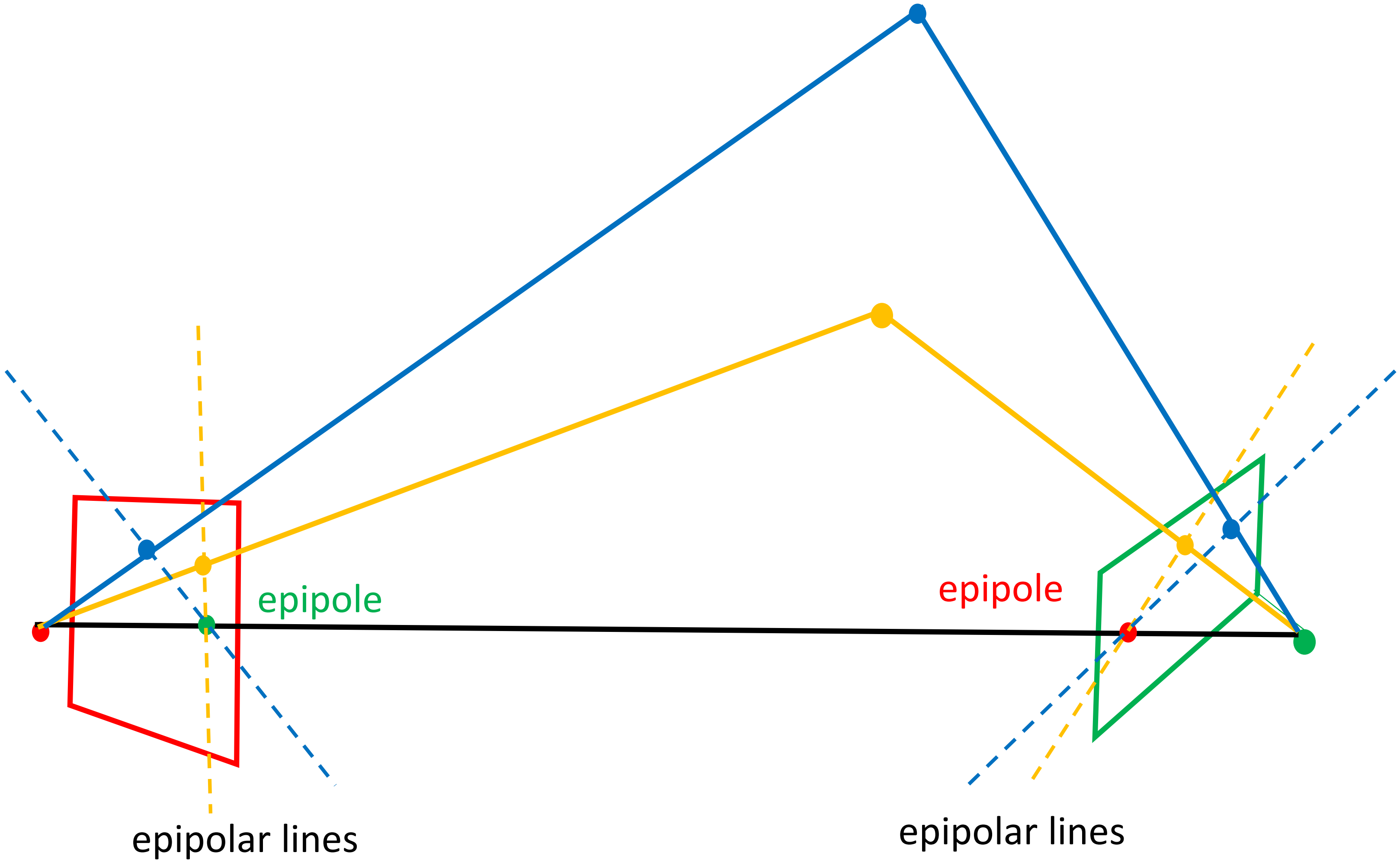


A 3D point within a *different* plane will project to different epipolar lines.

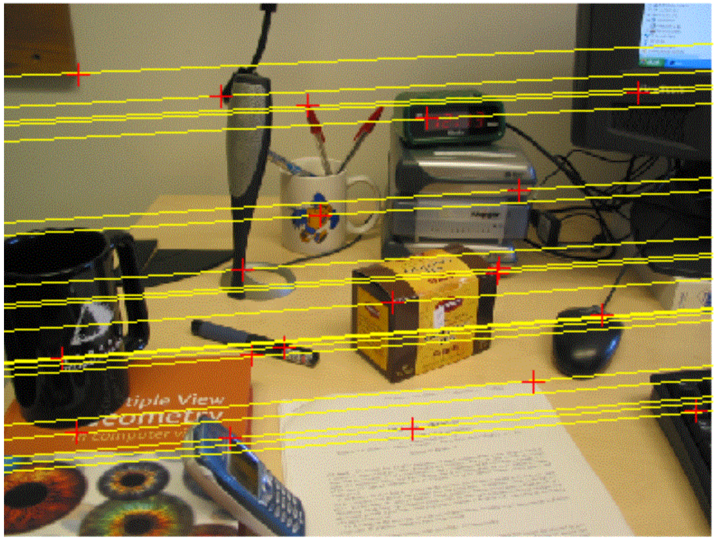
The epipoles do not change since they depend on cameras only.

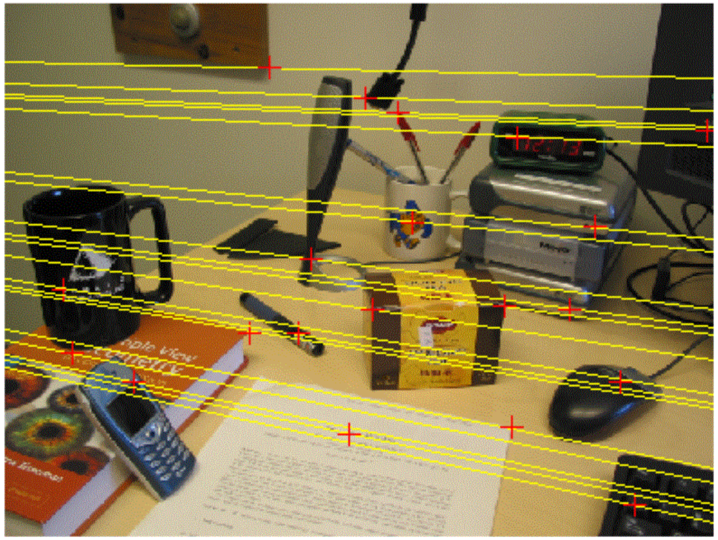


Epipolar lines always contain the epipoles (hence, the name).



Example

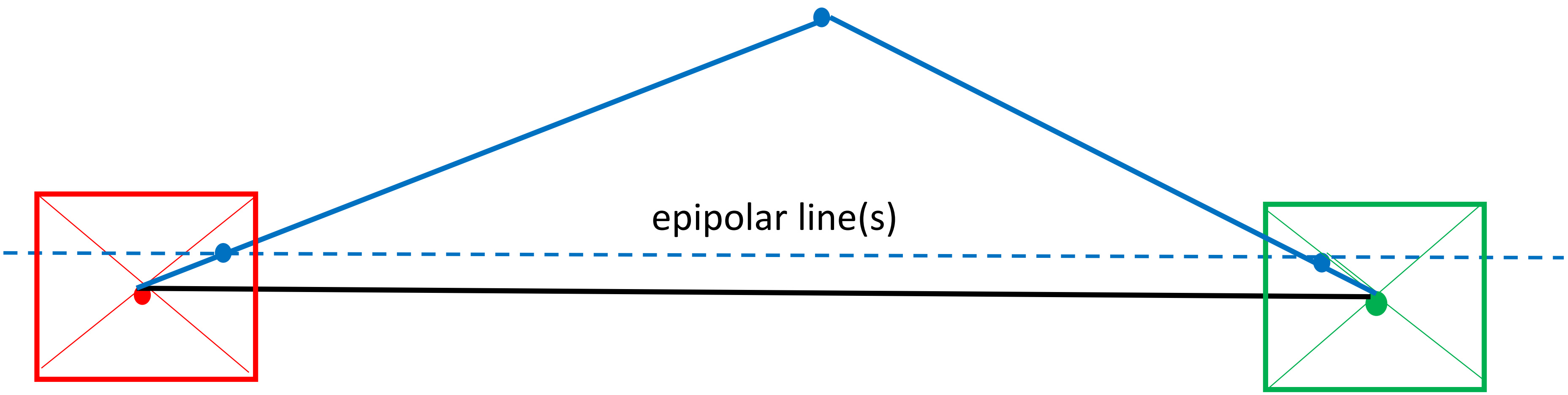




Some epipolar lines are shown.
In this example, the epipoles are outside the field of view.

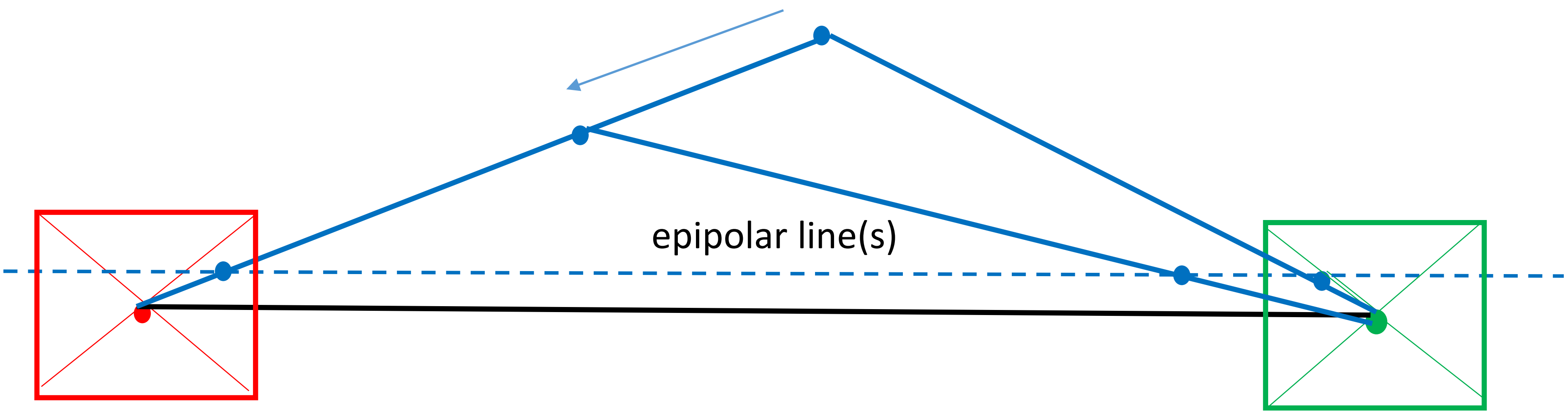
Special case: rectified cameras

The cameras are rectified if their $\boldsymbol{XYZ}$ axes are parallel to each other, and the epipoles are in the direction of the $\boldsymbol{X}$ axes. In this case, the epipolar line(s) are the same in the two images.



Special case: rectified cameras

Moving the scene point toward the left camera along a line does not affect the position in the left image. But it does affect the position in the right image: the point leaves the right image!



Overview of today

- Epipolar geometry
- Essential matrix (algebra)

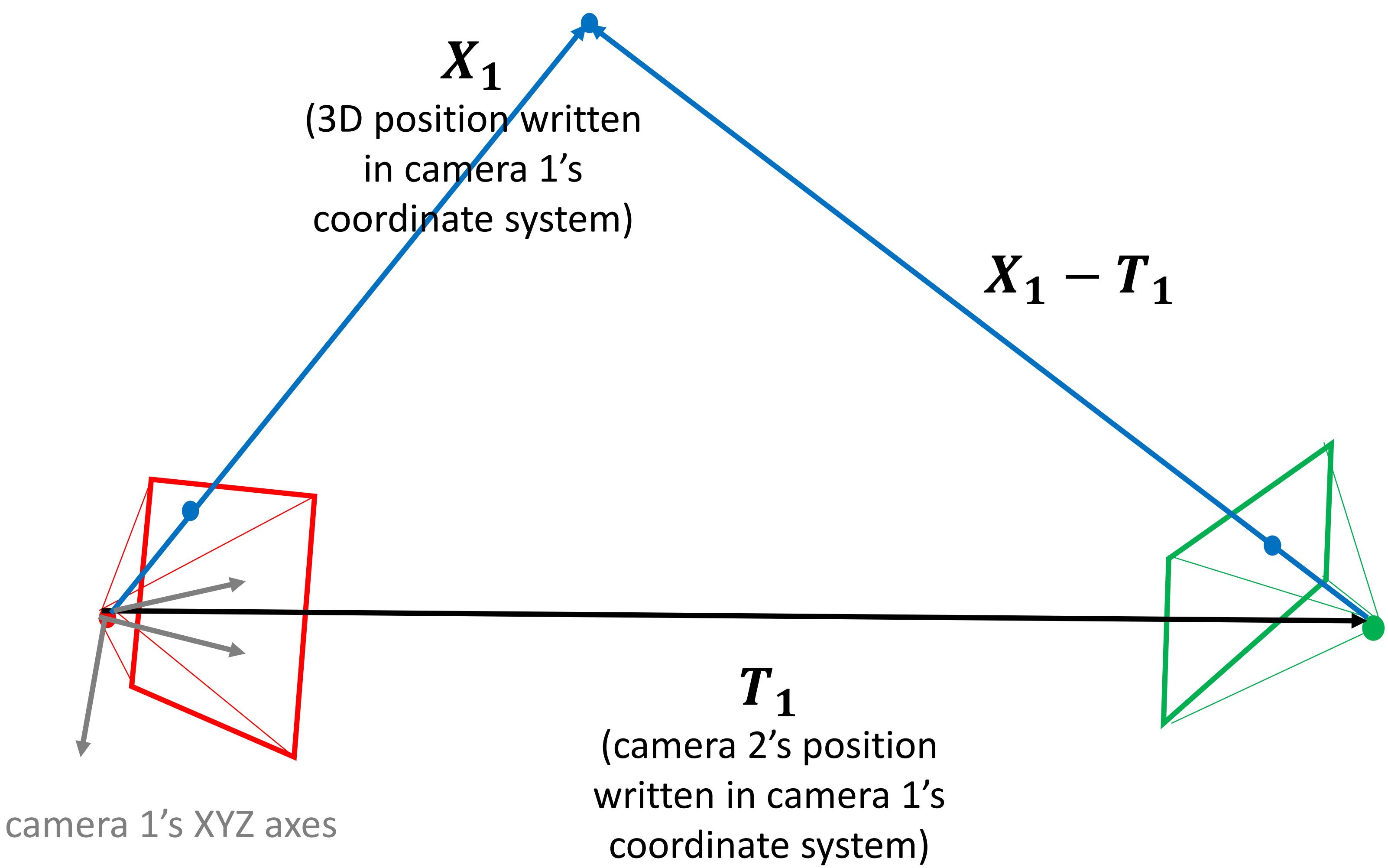
  Uses projection plane coordinates, not pixel coordinates.

- Fundamental matrix (algebra)

  Uses pixel coordinates.

The three vectors $\boldsymbol{X_1}, \boldsymbol{T_1}, \boldsymbol{X_1} - \boldsymbol{T_1}$ form a triangle in the figure.

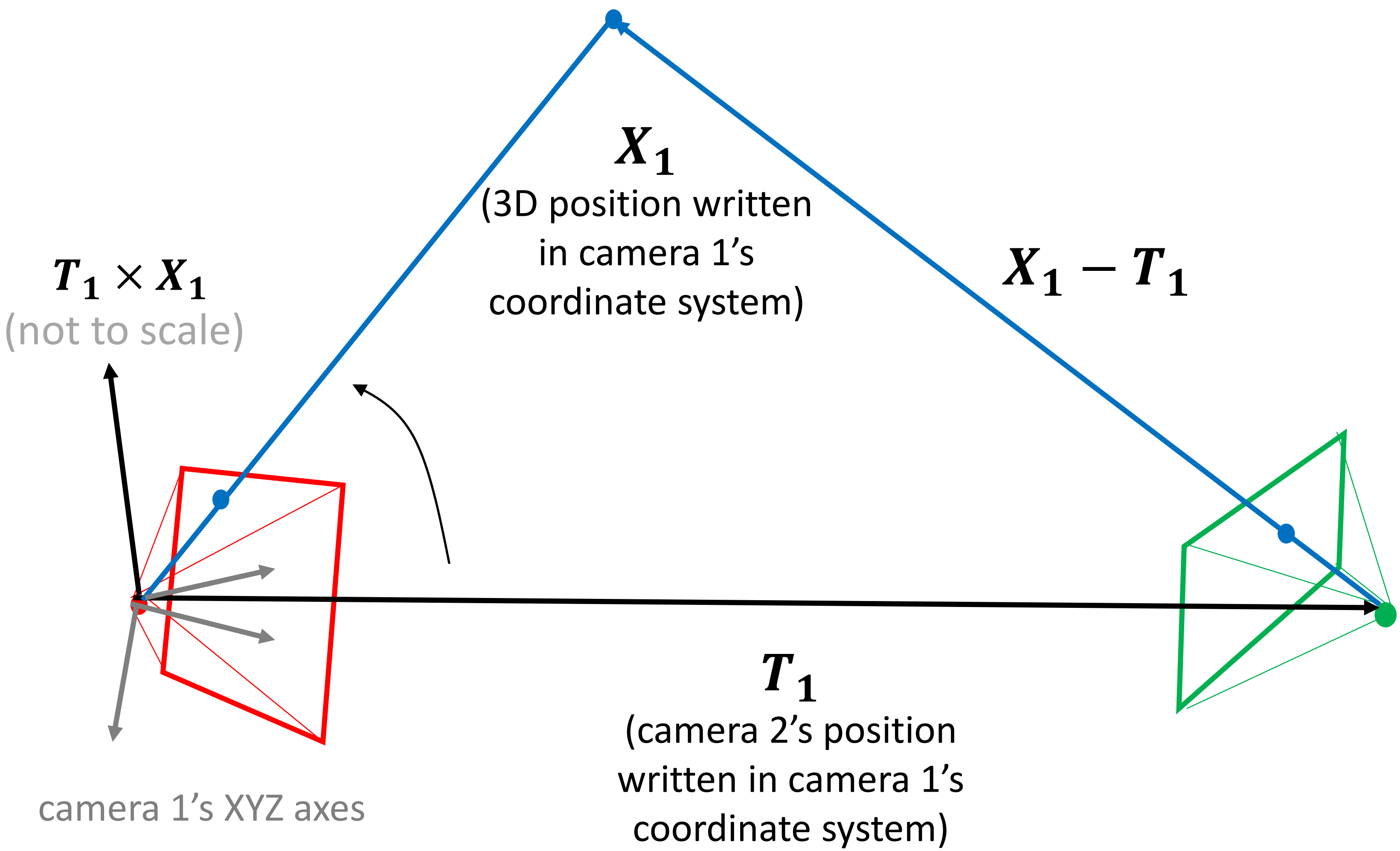
These vectors are all expressed in camera 1's coordinate system.



The three vectors $X_1, T_1, X_1 - T_1$ form a triangle in the figure.

$\boldsymbol{T_1} \times \boldsymbol{X_1}$ is perpendicular to this triangle.

In particular, $(\boldsymbol{X_1} - \boldsymbol{T_1}) \cdot (\boldsymbol{T_1} \times \boldsymbol{X_1}) = \boldsymbol{0}$. ← main equation of today



Recall: Cross Product
lecture 13, slide 26

$$\boldsymbol{T_1} \times \boldsymbol{X_1} = \begin{bmatrix} 0 & -T_Z & T_Y \\ T_Z & 0 & -T_X \\ -T_Y & T_X & 0 \end{bmatrix} \begin{bmatrix} X_1 \\ Y_1 \\ Z_1 \end{bmatrix}$$

We will write $\boldsymbol{T_1} \times \boldsymbol{X_1}$ as $[\boldsymbol{T_1}]_\times \boldsymbol{X_1}$.

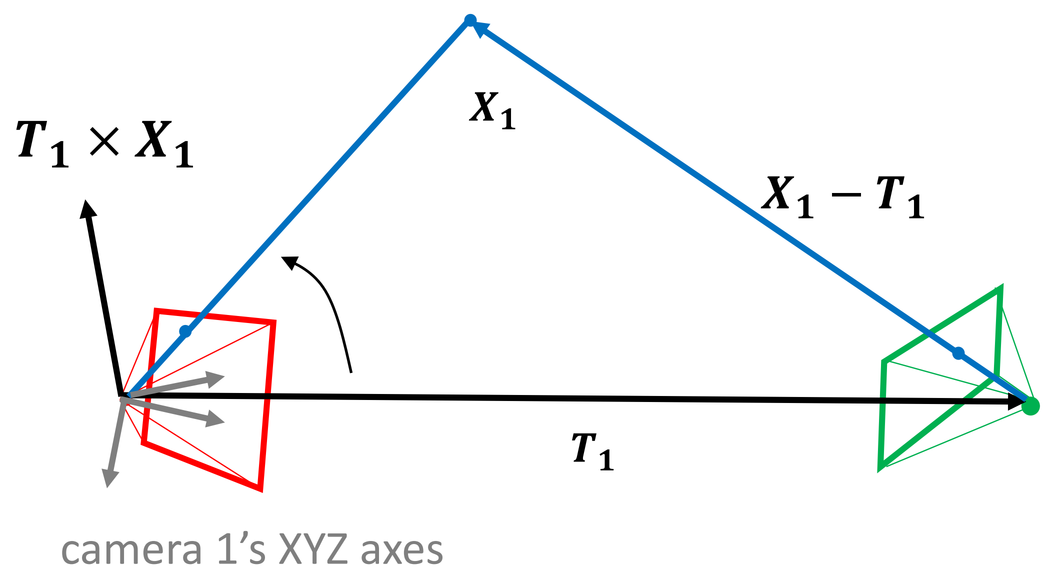
This expresses the cross product as a linear transformation defined by $\boldsymbol{T_1}$ and applied to vector $\boldsymbol{X_1}$.

$$(\boldsymbol{X_1} - \boldsymbol{T_1}) \cdot (\boldsymbol{T_1} \times \boldsymbol{X_1}) = \mathbf{0}$$

$$\boldsymbol{T_1} \times \boldsymbol{X_1} \equiv [\boldsymbol{T_1}]_\times \ \boldsymbol{X_1}$$

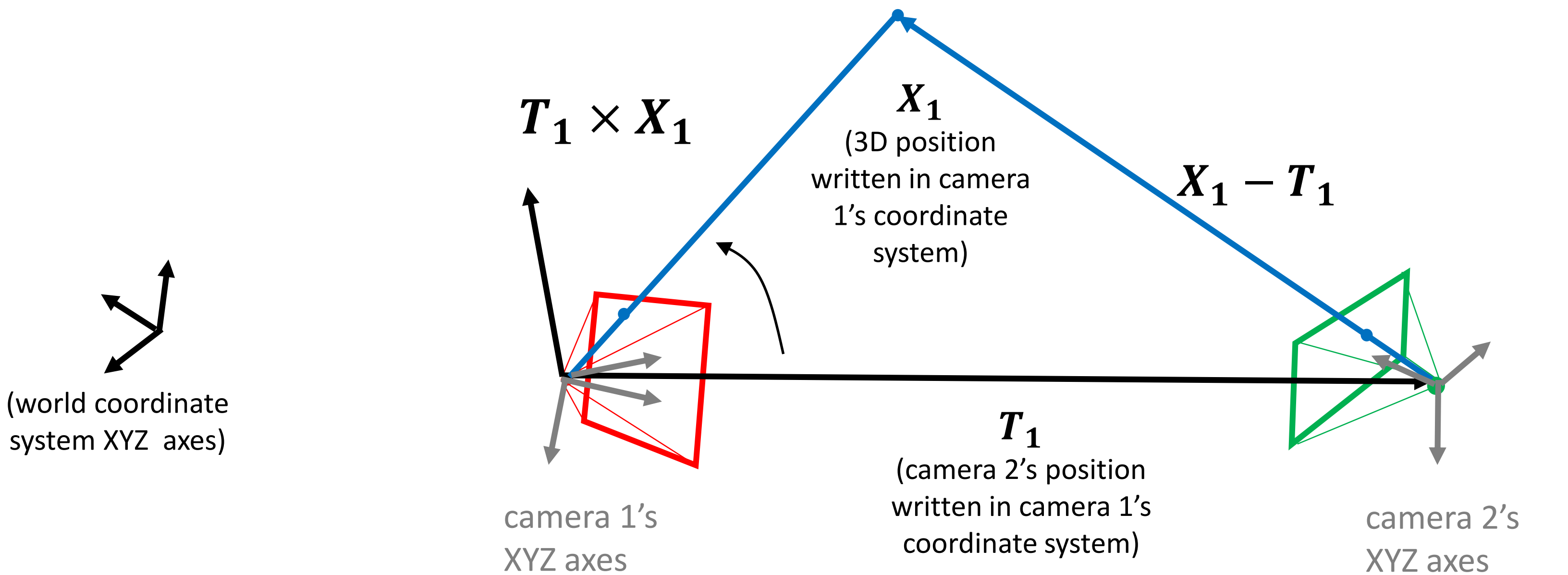
So, $(\boldsymbol{X_1} - \boldsymbol{T_1})^T \, [\boldsymbol{T_1}]_\times \, \boldsymbol{X_1} = \mathbf{0}$

This just says again that $\boldsymbol{T_1} \times \boldsymbol{X_1}$ is perpendicular to the triangle.



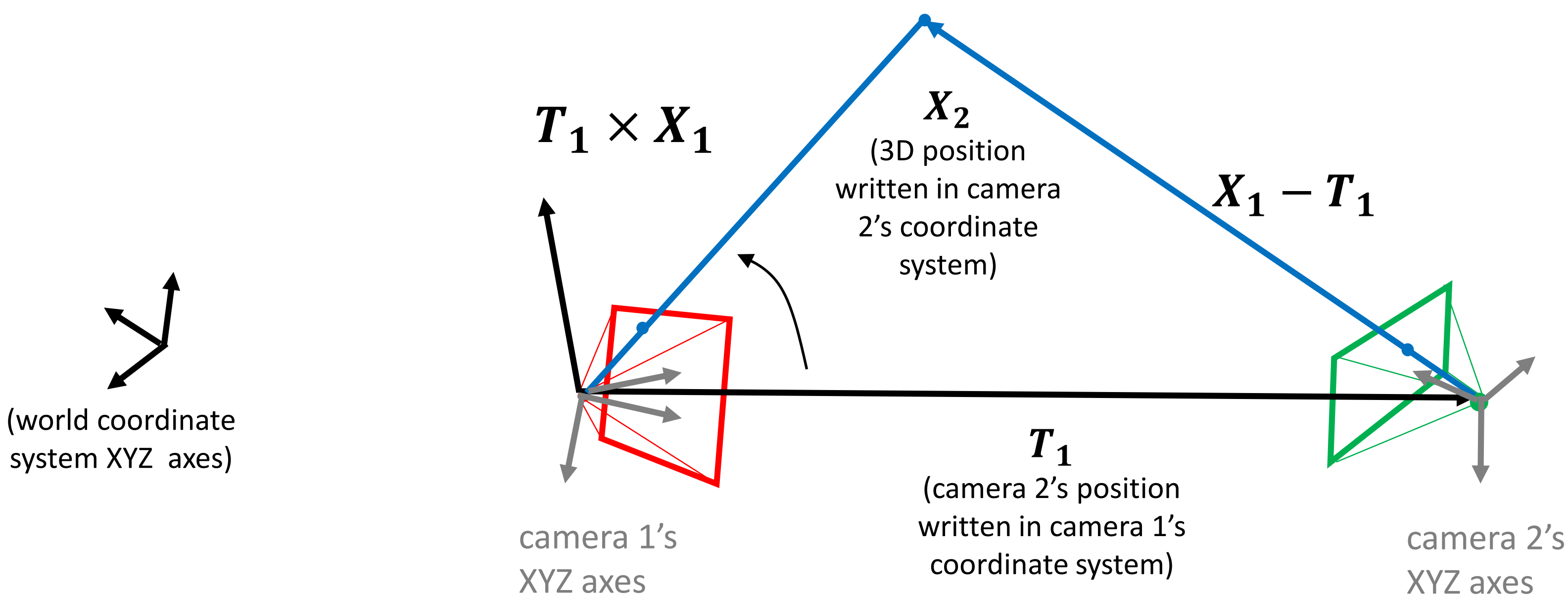
We would like to write $\boldsymbol{X_1} - \boldsymbol{T_1}$ in camera 2's coordinate system, so that we can say where the 3D point in question appears in camera 2's image plane.

How ?



We would like to write $\boldsymbol{X_1} - \boldsymbol{T_1}$ in camera 2's coordinate system, so that we can say where the 3D point in question appears in camera 2's image plane.

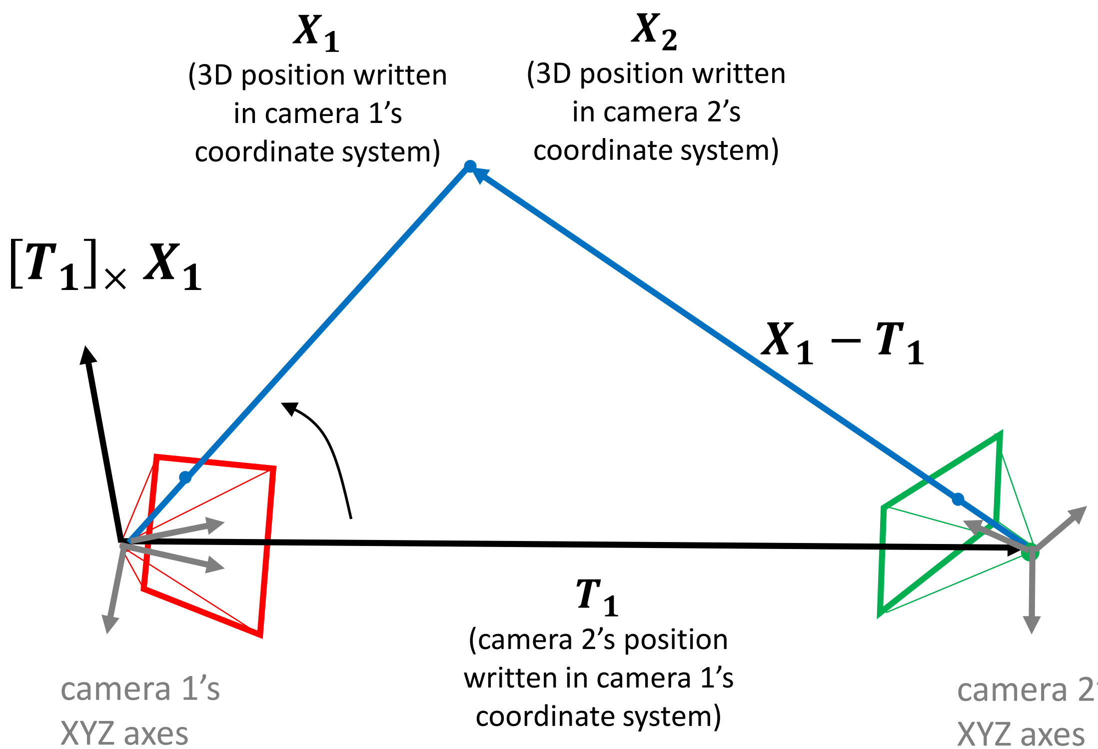
$\boldsymbol{X_2} = \boldsymbol{R_2}\,\boldsymbol{R_1^{\mathrm{T}}}\,(\boldsymbol{X_1} - \boldsymbol{T_1})$ or equivalently $\boldsymbol{R_1}\,\boldsymbol{R_2^{\mathrm{T}}}\,\boldsymbol{X_2} = \boldsymbol{X_1} - \boldsymbol{T_1}$



Substituting into $(\boldsymbol{X_1} - \boldsymbol{T_1})^T \, [\boldsymbol{T_1}]_\times \, \boldsymbol{X_1} = \boldsymbol{0}$, we get

$$\left(\boldsymbol{R_1}\,\boldsymbol{R_2^{\mathrm{T}}}\;\boldsymbol{X_2}\right)^T [\boldsymbol{T_1}]_\times \, \boldsymbol{X_1} = \boldsymbol{0}\ .$$

This gives us a constraint on the image position of this 3D point in the left and right camera's coordinate systems.

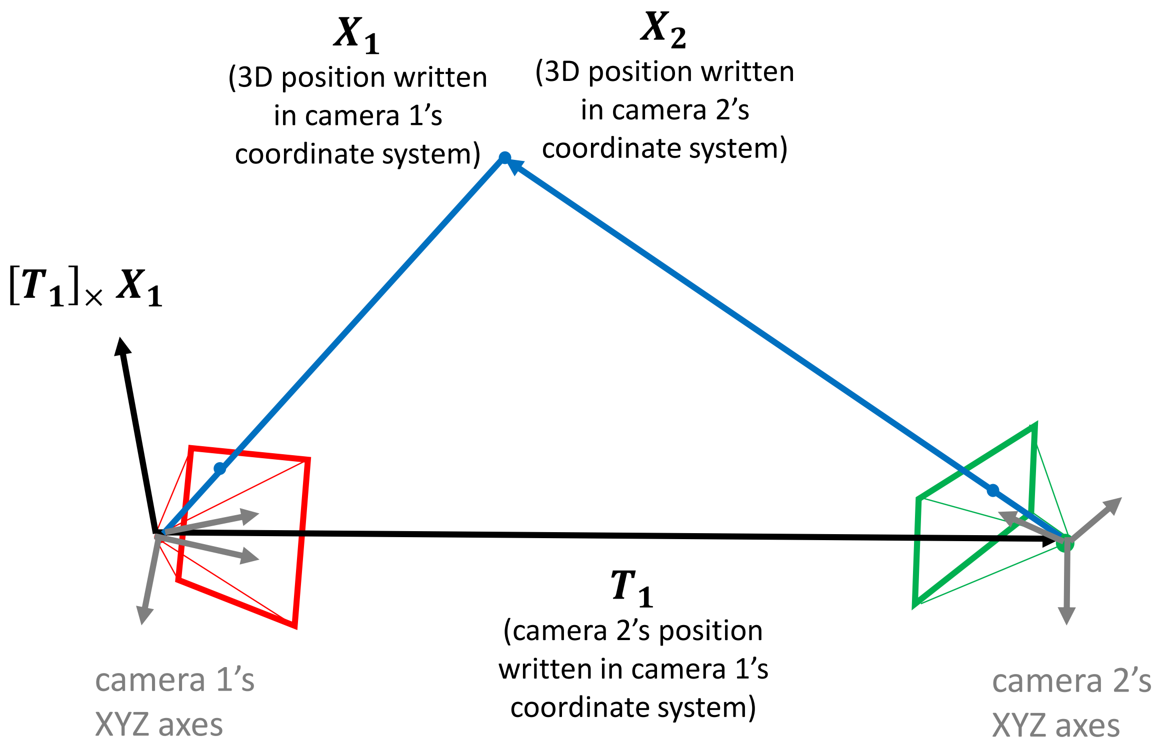


Essential Matrix $\boldsymbol{E}$ (definition)

$$\left(\boldsymbol{R}_1\,\boldsymbol{R}_2^{\mathrm{T}}\ \boldsymbol{X}_2\right)^T [\boldsymbol{T}_1]_\times\,\boldsymbol{X}_1 = \boldsymbol{0}$$

$$\boldsymbol{X}_2^{\mathrm{T}}\,\boldsymbol{E}\,\boldsymbol{X}_1 = \boldsymbol{0}$$

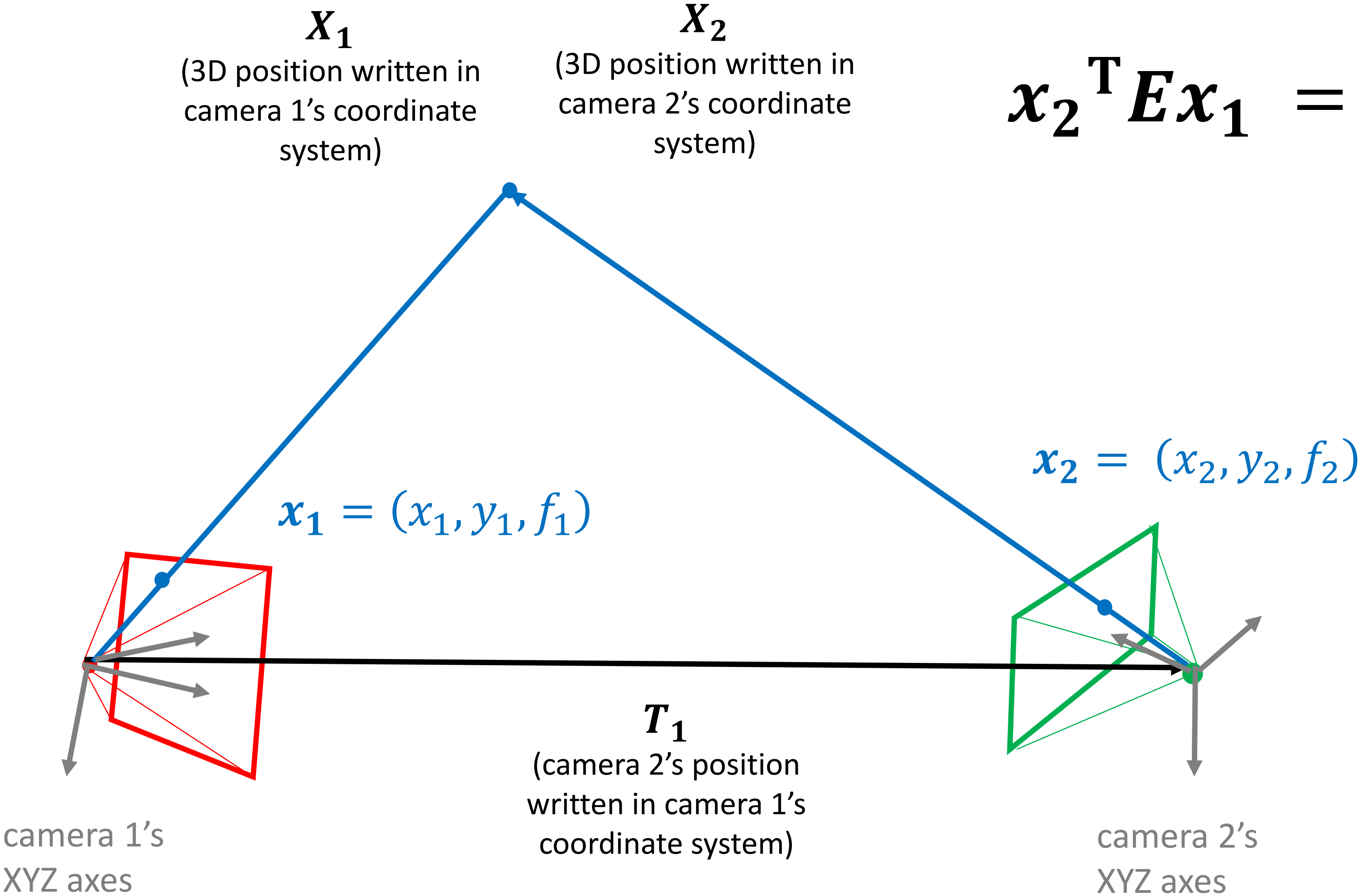
$$\boldsymbol{X}_2^{\mathrm{T}}\,\underbrace{\boldsymbol{R}_2\,\boldsymbol{R}_1^{\mathrm{T}}\,[\boldsymbol{T}_1]_\times}_{\boldsymbol{E}}\,\boldsymbol{X}_1 = \boldsymbol{0}$$



We can multiply $\boldsymbol{X_1}$ and $\boldsymbol{X_2}$ by constants and the equation still holds. Thus.....

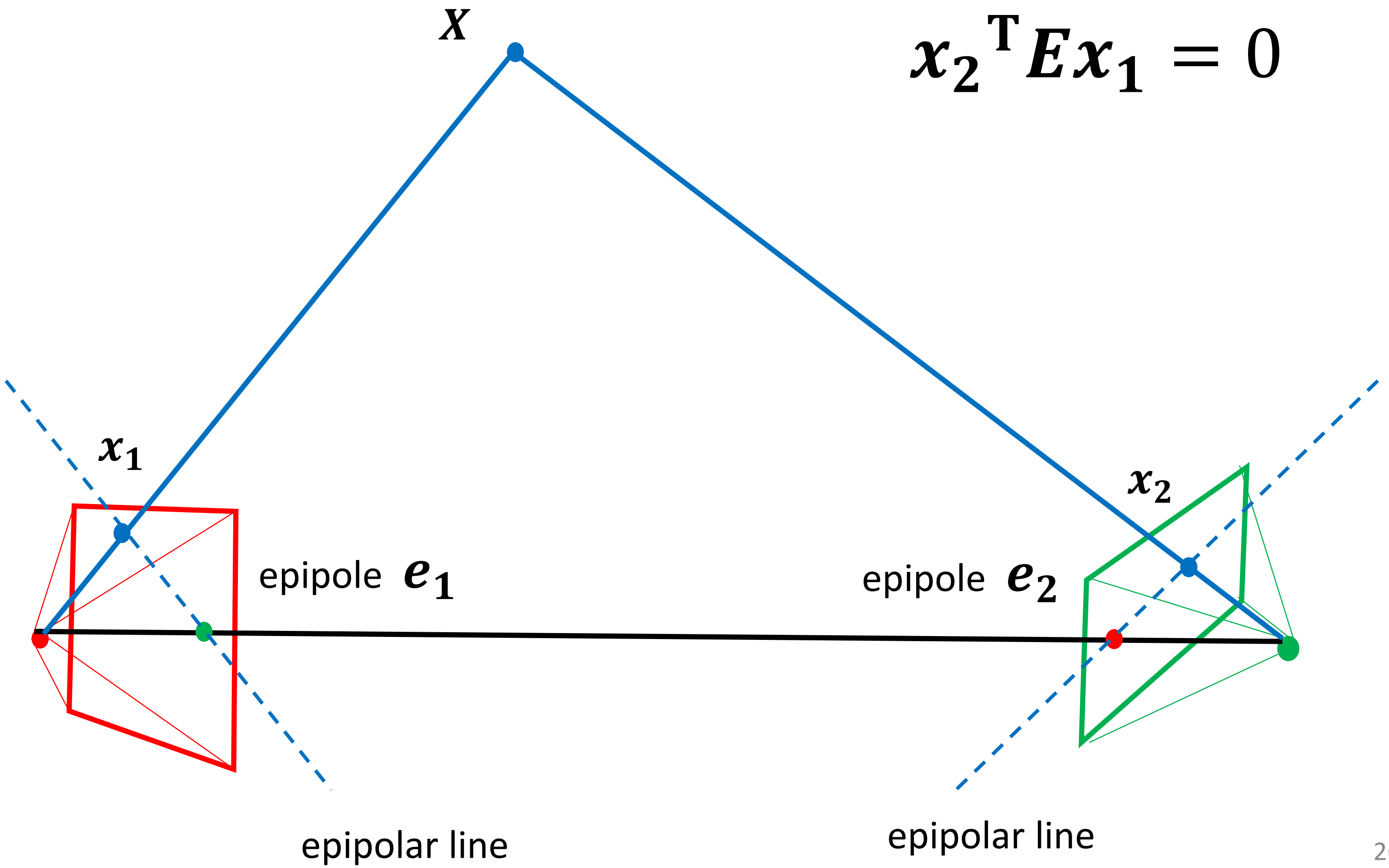
$$X_2^{\mathrm{T}} E\, X_1 = 0$$

$$\boldsymbol{x_2}^{\mathbf{T}} \boldsymbol{E} \boldsymbol{x_1} = 0$$

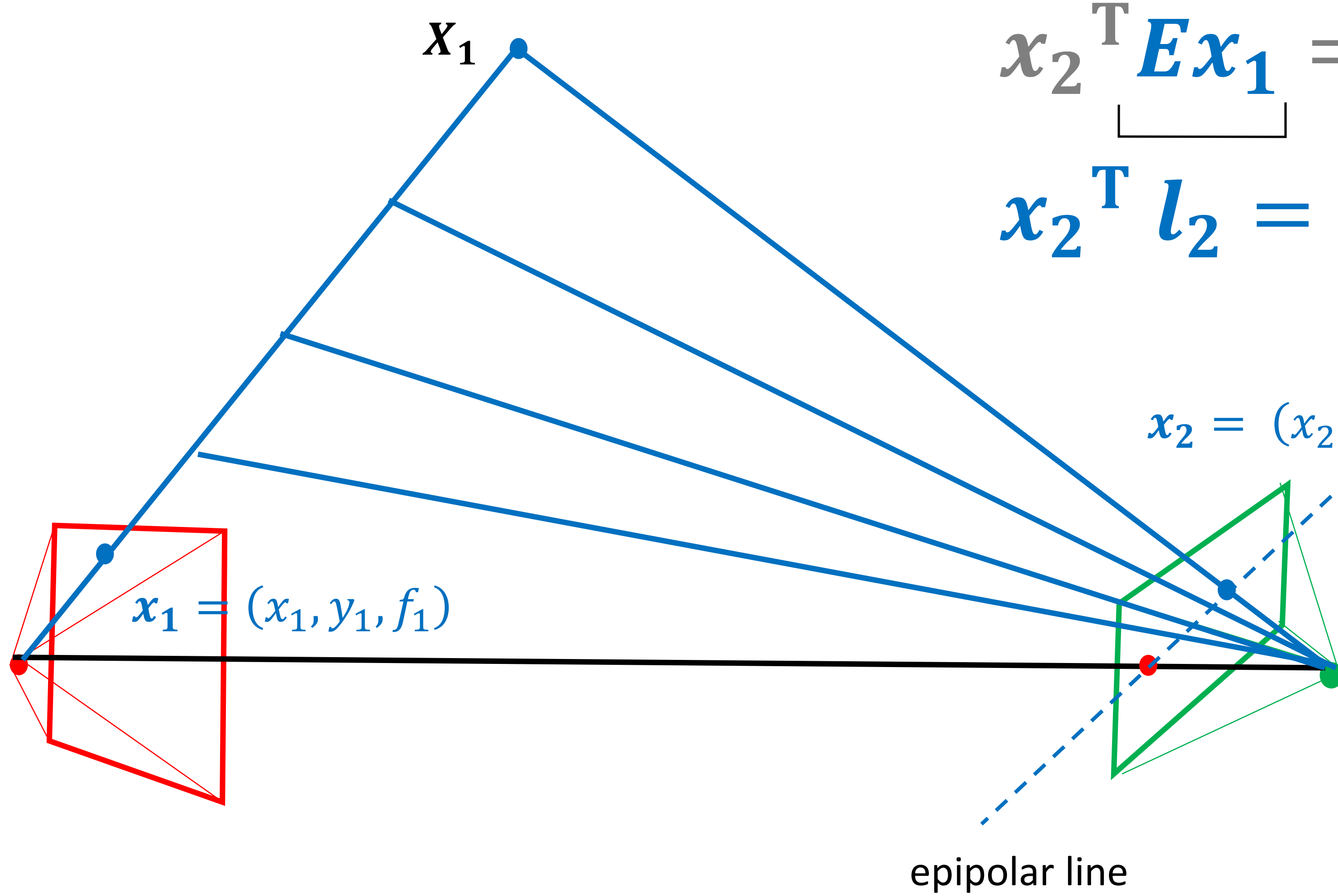


How to express epipolar lines and epipoles using the essential matrix?

$$\boldsymbol{x_2}^{\mathrm{T}} \boldsymbol{E} \boldsymbol{x_1} = 0$$



If we choose a point $\boldsymbol{x_1}$ in image 1, then this defines a line in image 2, namely the image of the ray from camera 1 through $\boldsymbol{x_1}$. This gives an epipolar line in image 2.



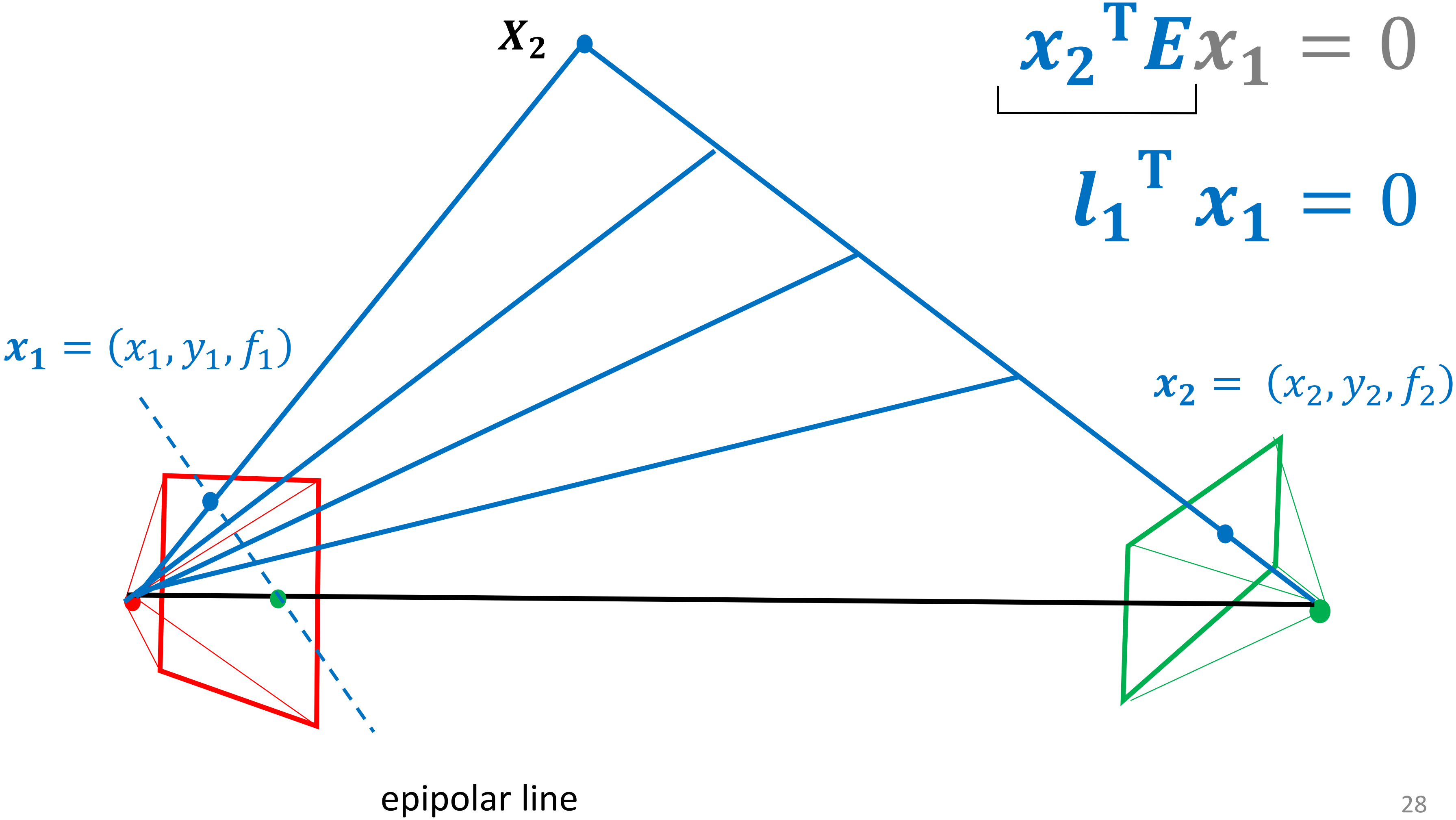
$$x_2^{\mathrm{T}} \underbrace{\boldsymbol{E}\boldsymbol{x_1}} = 0$$

$$\boldsymbol{x_2}^{\mathrm{T}} \boldsymbol{l_2} = 0$$

If we choose a point $\boldsymbol{x_2}$ in image 2, then this defines a line in image 1, namely the image of the ray from camera 2 through $\boldsymbol{x_2}$. This gives an epipolar line in image 1.

$$\underbrace{\boldsymbol{x_2}^{\mathrm{T}}\boldsymbol{E}}\boldsymbol{x_1} = 0$$

$$\boldsymbol{l_1}^{\mathrm{T}}\boldsymbol{x_1} = 0$$



Properties of Essential Matrix $\boldsymbol{E}$

$\boldsymbol{E} \equiv \boldsymbol{R_2}\, \boldsymbol{R_1^{\mathrm{T}}}\, [\boldsymbol{T_1}]_\times$ where $[\boldsymbol{T_1}]_\times \boldsymbol{X_1} \equiv \boldsymbol{T_1} \times \boldsymbol{X_1}$

$\boldsymbol{E}$ is a 3x3 matrix. It has rank 2. Why?

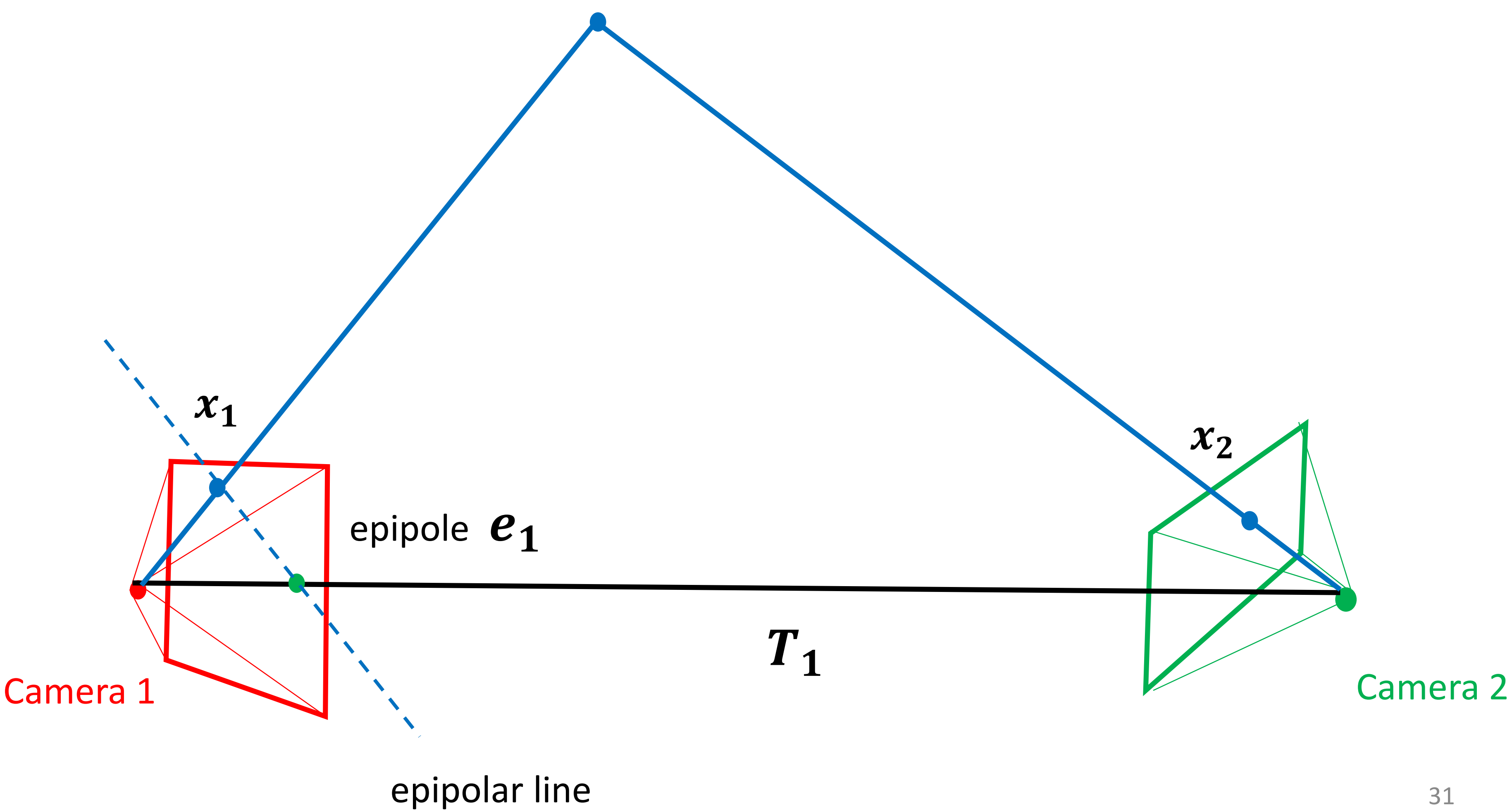
Properties of Essential Matrix $\boldsymbol{E}$

$\boldsymbol{E} \equiv \boldsymbol{R_2}\,\boldsymbol{R_1^{\mathrm{T}}}\,[\boldsymbol{T_1}]_\times$ where $[\boldsymbol{T_1}]_\times\,\boldsymbol{X_1} \equiv \boldsymbol{T_1} \times \boldsymbol{X_1}$

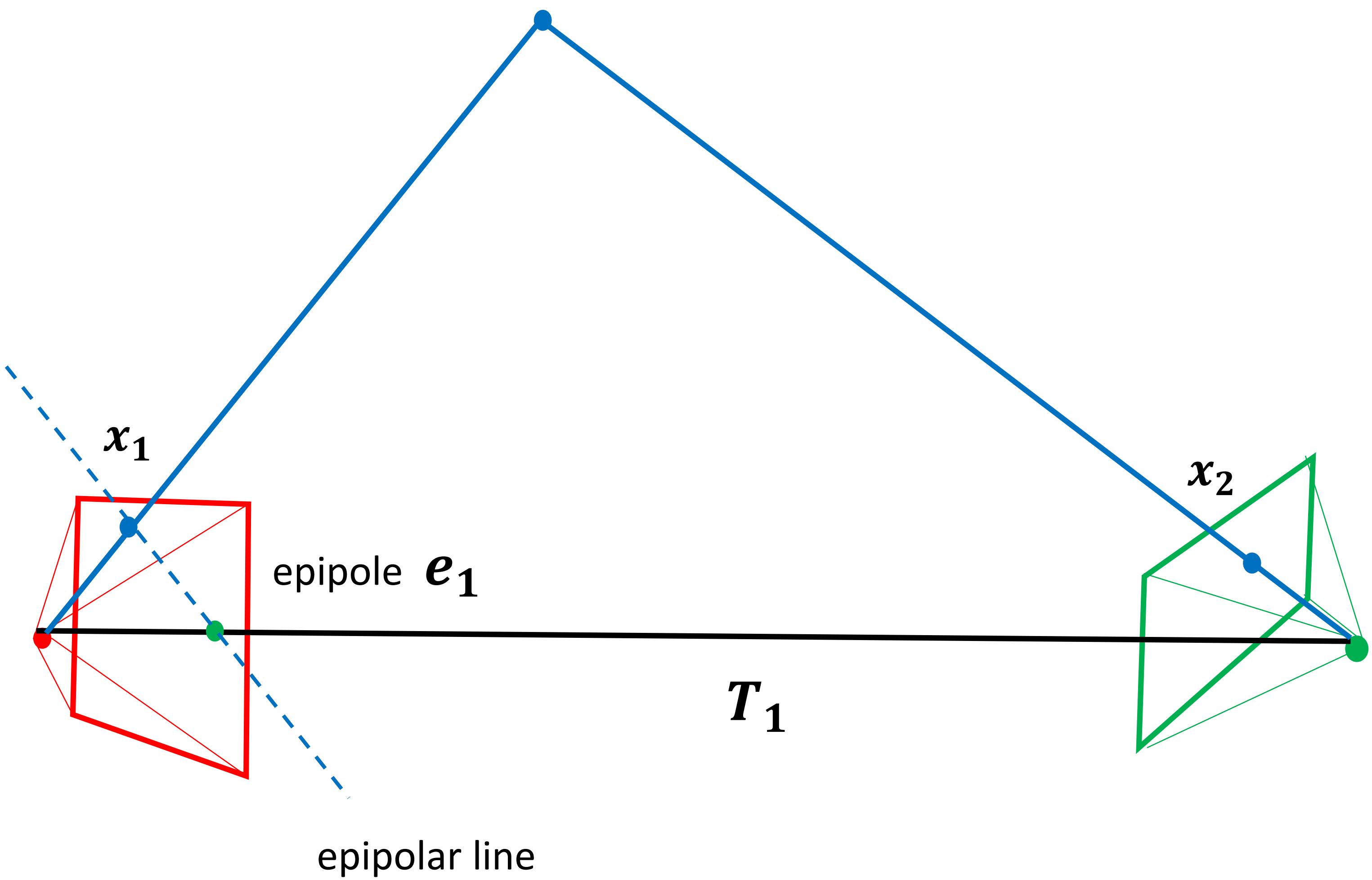
$\boldsymbol{E}$ is a 3x3 matrix. It has rank 2. Why?

$\boldsymbol{E}\ \boldsymbol{T_1}$ = 0, and by inspection $\boldsymbol{E}\,\boldsymbol{X_1} \neq \boldsymbol{0}$ for any vector $\boldsymbol{X_1}$ that isn't parallel to $\boldsymbol{T_1}$.

The epipole $\boldsymbol{e_1}$ is the position of camera 2 in camera 1 image position. It has the same direction as $\boldsymbol{T_1}$. Thus $\boldsymbol{Ee_1} = 0$.



The epipole $\boldsymbol{e_1}$ is the position of camera 2 in camera 1 image position. It has the same direction as $\boldsymbol{T_1}$. Thus $\boldsymbol{E}\boldsymbol{e_1} = 0$. Thus, for any $\boldsymbol{x_2}$ in image 2, $\boldsymbol{x_2}^{\mathrm{T}}\boldsymbol{E}\boldsymbol{e_1} = 0$. Equivalently, the epipole $\boldsymbol{e_1}$ lies on all epipolar lines $\boldsymbol{l_1}^{\mathrm{T}}\boldsymbol{x_1} = 0$.

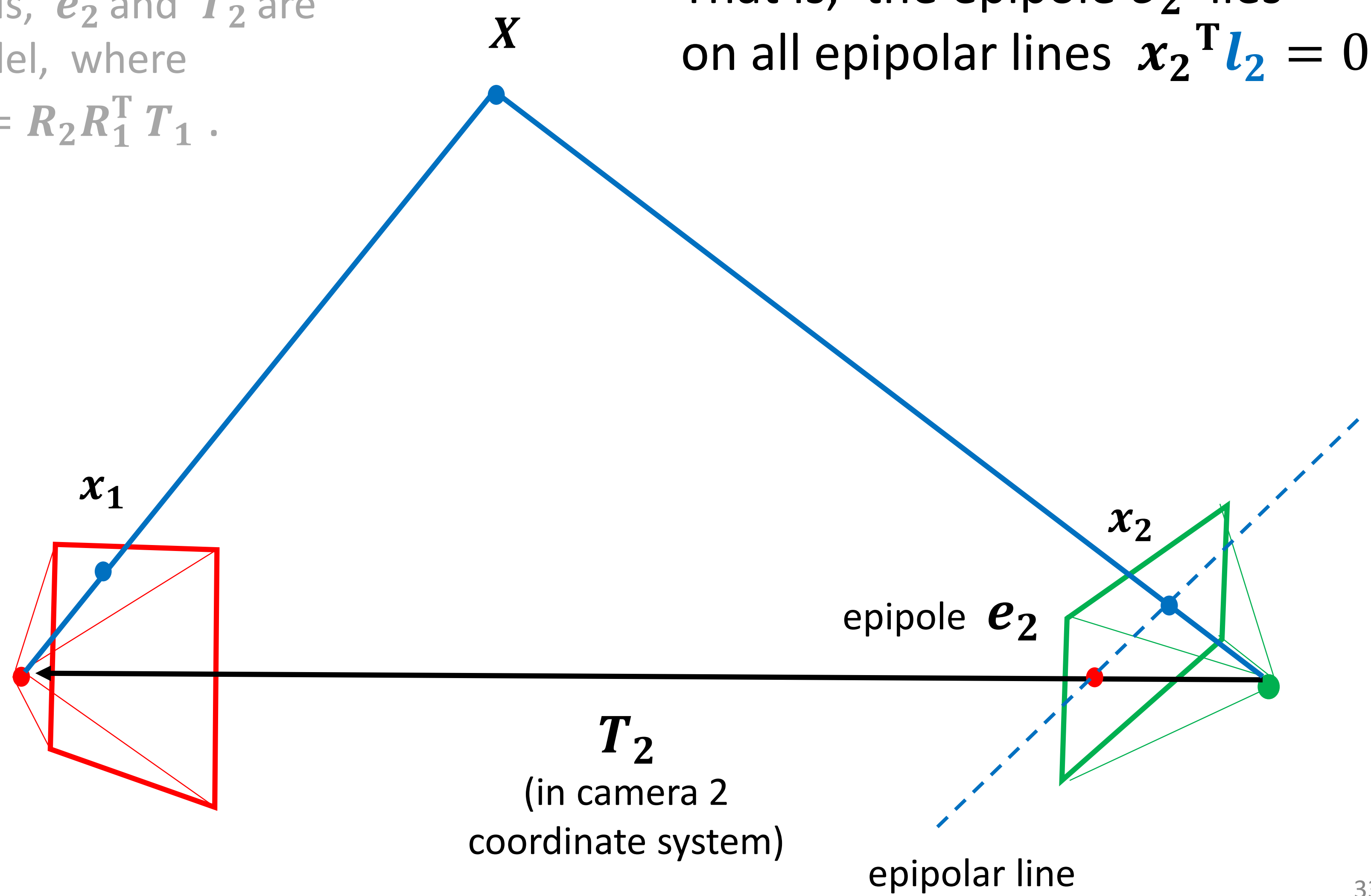


See lecture notes for the calculation. Use the fact that $R_1 R_2^{\mathrm{T}} e_2$ is parallel to T_1 .

That is, e_2 and T_2 are parallel, where $T_2 = R_2 R_1^{\mathrm{T}} T_1$.

One can similarly show that $e_2{}^{\mathrm{T}} E x_1 = 0$ for any x_1 in image 1.

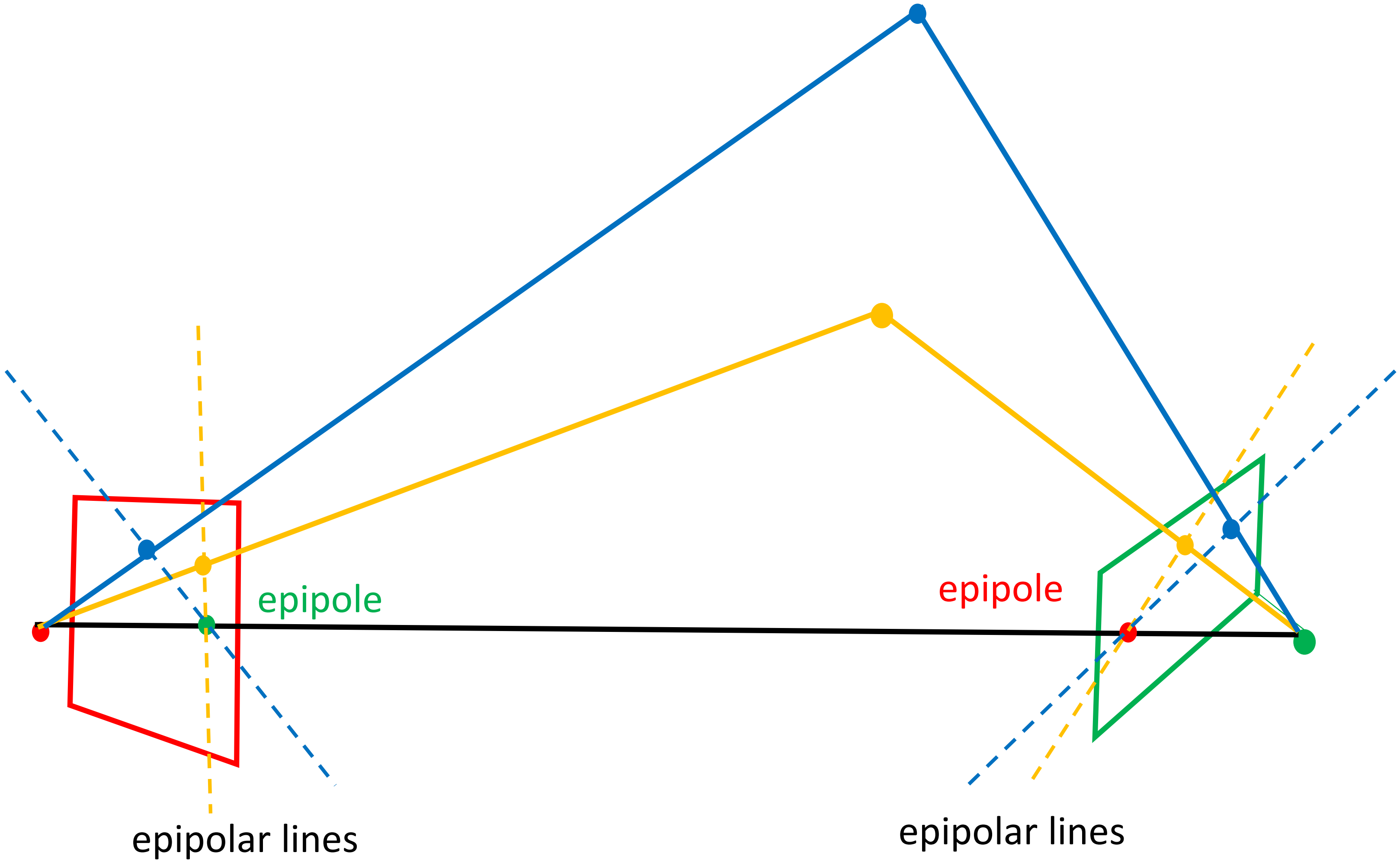
That is, the epipole e_2 lies on all epipolar lines $x_2{}^{\mathrm{T}} l_2 = 0$.



Summary: All epipolar lines pass through the epipoles.

Equivalently, the epipoles are where the epipolar lines intersect.

We have given both geometric and algebraic arguments.



Overview of today

- Epipolar geometry
- Essential matrix (algebra)

  Uses projection plane coordinates, not pixel coordinates.

- Fundamental matrix (algebra)

  Uses pixel coordinates.

$$\boldsymbol{X}_2^{\mathrm{T}} \boldsymbol{E}\, \boldsymbol{X}_1 = \boldsymbol{0}$$

$$\boldsymbol{x}_2^{\mathrm{T}} \boldsymbol{E}\, \boldsymbol{x}_1 = \boldsymbol{0}$$

Recall that we can write either since $\boldsymbol{X_i}$ and $\boldsymbol{x_i}$ differ only by multiplicative constants.

How can we write out this constraint in terms of *pixel* positions $\widetilde{\boldsymbol{x}}_{\mathbf{1}}$ and $\widetilde{\boldsymbol{x}}_{\mathbf{2}}$?

Use this trick:

$$\left(\boldsymbol{K}_2^{-1} \boldsymbol{K}_2 \boldsymbol{x}_2 \right)^{\mathrm{T}} \boldsymbol{E}\, \boldsymbol{K}_1^{-1} \boldsymbol{K}_1 \boldsymbol{x}_1 = \boldsymbol{0}$$

Fundamental Matrix $\boldsymbol{F}$

$$\boldsymbol{x_2^{\mathrm{T}} E \, x_1 = 0}$$

$$\left(\boldsymbol{K_2^{-1} K_2 x_2} \right)^{\mathrm{T}} \boldsymbol{E \, K_1^{-1} K_1 x_1 = 0}$$

$$\boldsymbol{\widetilde{x}_2^{\mathrm{T}} \underbrace{\left(K_2{}^{-1} \right)^{\mathrm{T}} E \;\; K_1{}^{-1}}_{F} \widetilde{x}_1 = 0}$$

$$\boldsymbol{\widetilde{x}_1} = \begin{bmatrix} \tilde{x}_1 \\ \tilde{x}_2 \\ 1 \end{bmatrix}$$

pixel position
in image 1

$$\boldsymbol{\widetilde{x}_2} = \begin{bmatrix} \tilde{x}_2 \\ \tilde{y}_2 \\ 1 \end{bmatrix}$$

pixel position
in image 2

Fundamental Matrix $\boldsymbol{F}$

$$\boldsymbol{x}_2^{\mathrm{T}} \boldsymbol{E}\, \boldsymbol{x}_1 = \boldsymbol{0}$$

$$\widetilde{\boldsymbol{x}}_2^{\mathrm{T}} \boldsymbol{F}\, \widetilde{\boldsymbol{x}}_1 = \boldsymbol{0}$$

$\widetilde{\boldsymbol{x}}_2 = \begin{bmatrix} \tilde{x}_2 \\ \tilde{y}_2 \\ 1 \end{bmatrix}$

pixel position in image 2

pixel position in image 1

$\widetilde{\boldsymbol{x}}_1 = \begin{bmatrix} \tilde{x}_1 \\ \tilde{x}_2 \\ 1 \end{bmatrix}$

Epipolar lines in pixel space

If we choose a pixel $\tilde{\boldsymbol{x}}_2$ in image 2, then this defines an epipolar line in image 1, namely the image of the ray from camera 2 through $\tilde{\boldsymbol{x}}_2$.

$$\underbrace{\tilde{\boldsymbol{x}}_2^{\mathrm{T}}\, \boldsymbol{F}}\, \tilde{\boldsymbol{x}}_1 = \mathbf{0}$$

$$\boldsymbol{l}_1^{\mathrm{T}}\, \tilde{\boldsymbol{x}}_1 = \mathbf{0}$$

$$\tilde{\boldsymbol{x}}_1 = \begin{bmatrix} x_1 \\ y_1 \\ 1 \end{bmatrix} \qquad \tilde{\boldsymbol{x}}_2 = \begin{bmatrix} \tilde{x}_2 \\ \tilde{y}_2 \\ 1 \end{bmatrix}$$

If we choose a pixel $\tilde{\boldsymbol{x}}_1$ in image 1, then this defines an epipolar line in image 2, namely the image of the ray from camera 1 through $\tilde{\boldsymbol{x}}_1$.

$$\tilde{\boldsymbol{x}}_2^{\mathrm{T}}\, \underbrace{\boldsymbol{F}\, \tilde{\boldsymbol{x}}_1} = \mathbf{0}$$

$$\tilde{\boldsymbol{x}}_2^{\mathrm{T}}\, \boldsymbol{l}_2 = \mathbf{0}$$

Epipoles in pixel space

$\boldsymbol{e_1}$ and $\boldsymbol{e_2}$ are the epipoles in the image projection plane of camera's 1 and 2.

By definition, the epipoles in pixel units are
$\tilde{\boldsymbol{e}}_{\boldsymbol{1}} = \boldsymbol{K}_1 \boldsymbol{e}_{\boldsymbol{1}}$ and $\tilde{\boldsymbol{e}}_2 = \boldsymbol{K}_2 \boldsymbol{e}_2$.

Verify for yourself that $\boldsymbol{F}\tilde{\boldsymbol{e}}_{\boldsymbol{1}} = \boldsymbol{0}$ and $\tilde{\boldsymbol{e}}_{\boldsymbol{2}}^{\mathbf{T}} \boldsymbol{F} = \boldsymbol{0}$.

Again, the epipoles lie on all epipolar lines. They are the intersection of the epipolar lines.

Next lecture

- Given two images and set of corresponding points (e.g. SIFT features), how can one estimate the fundamental matrix $\boldsymbol{F}$?
  - Least squares
  - exact solution + RANSAC

- 3D reconstruction from two images

Reminder: Quiz 4 is Wednesday