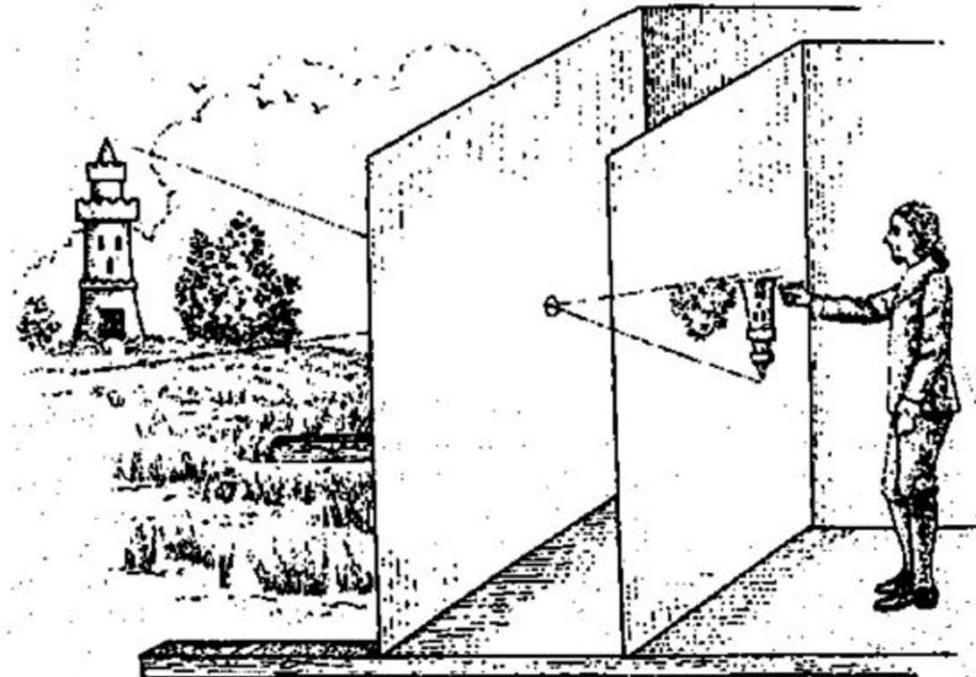


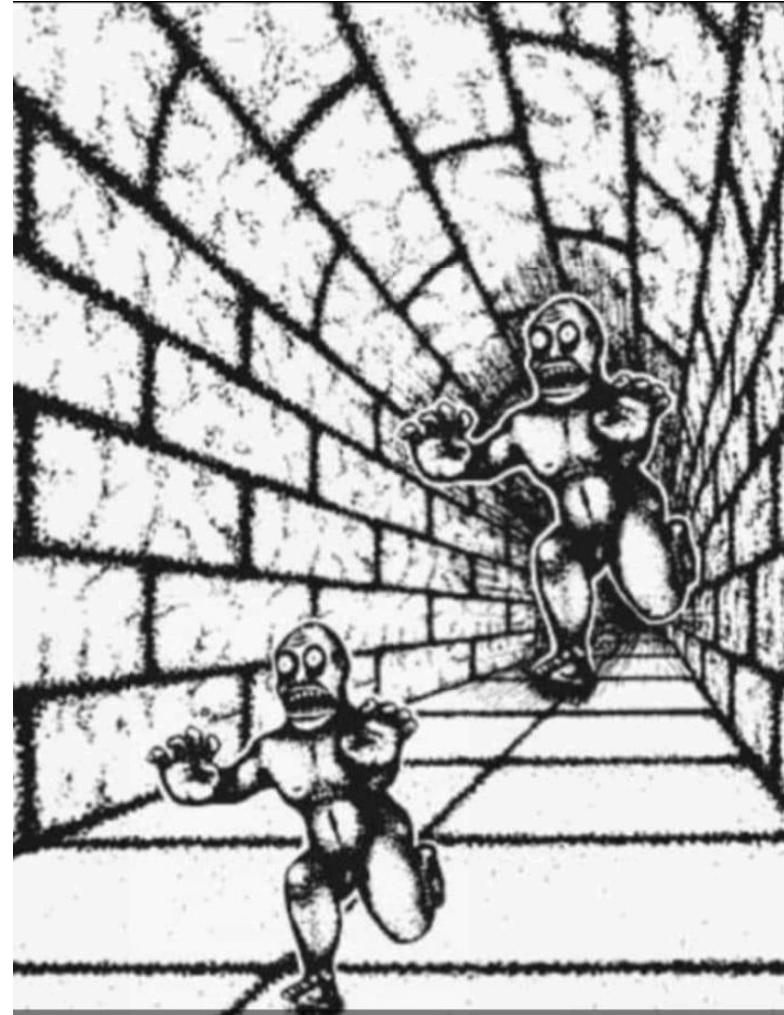
It's a 3D World, After All



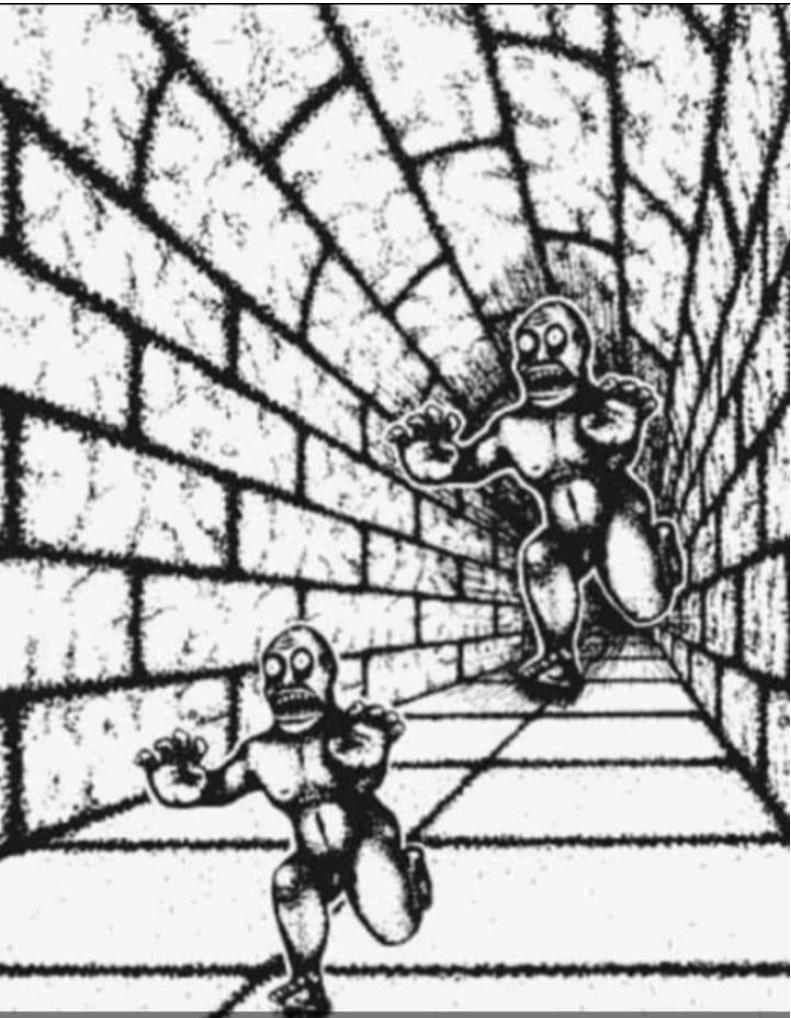
3D Computer Vision

Elliott Wu

We're good at seeing 3D!



We're good at seeing 3D!

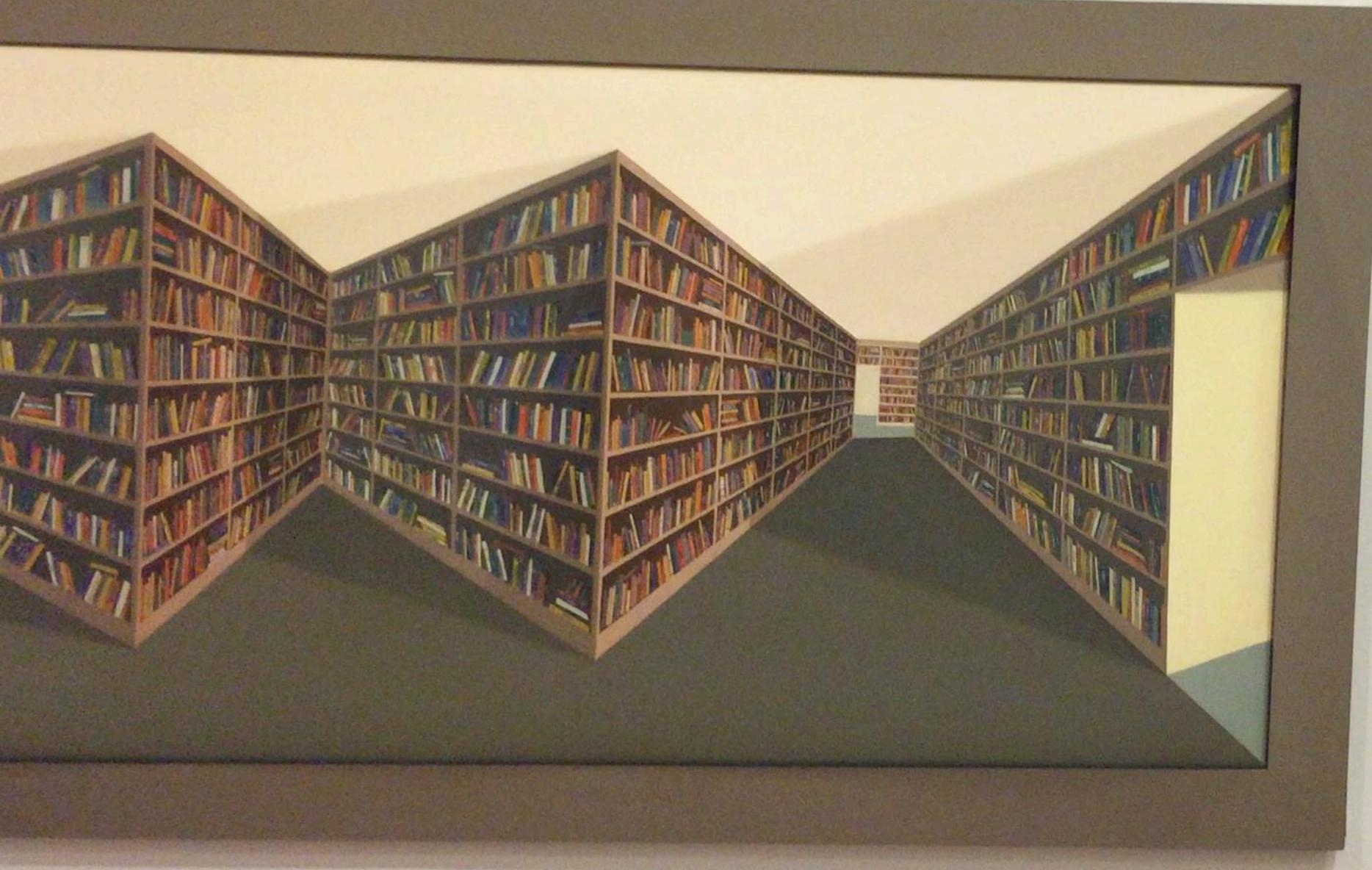


And sometimes too good..



And sometimes too good..





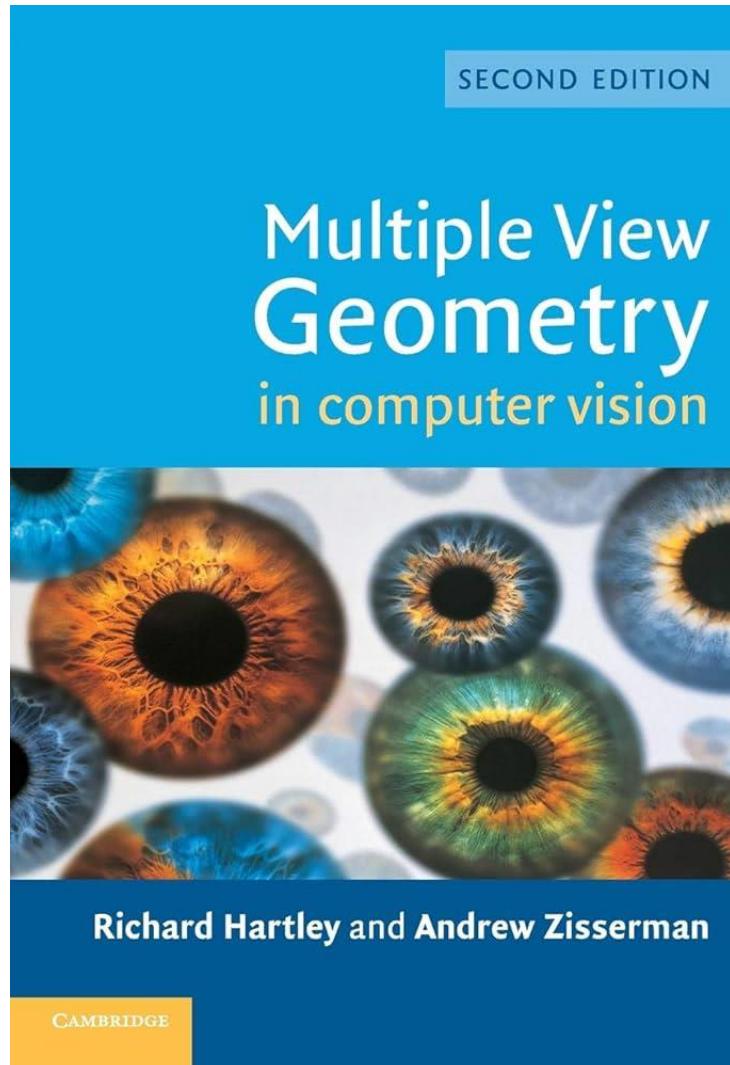


These 'Reverspective' paintings are mind-boggling. <https://youtu.be/fzZy1FtYsVM>

3D Computer Vision – Outline

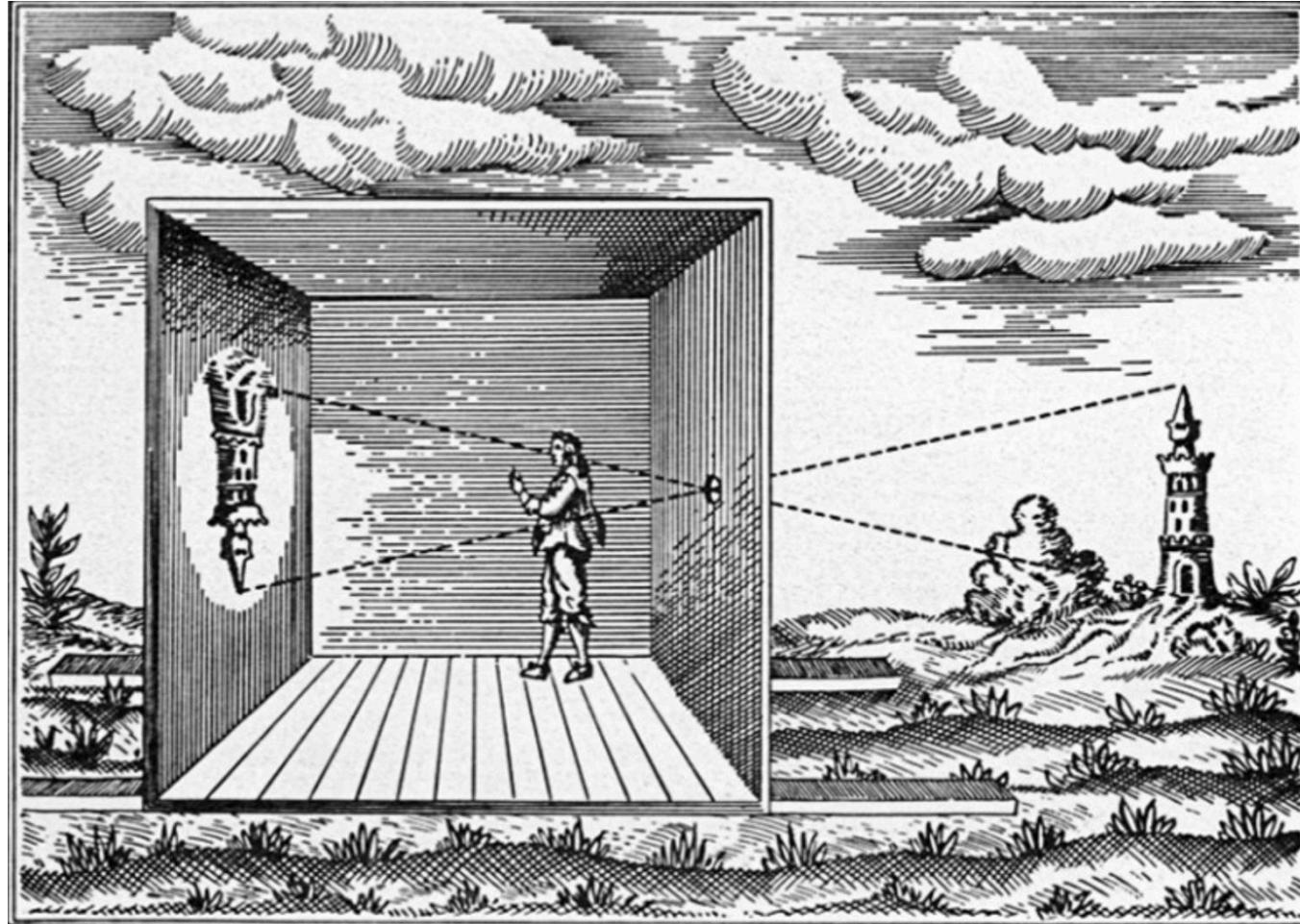
- Part 1 – Camera Model & Projection
- Part 2 – Multi-view Geometry
- Part 3 – 3D Representations & Rendering
- Part 4 – Learning-based 3D Modeling

Multi-view Geometry “Bible”



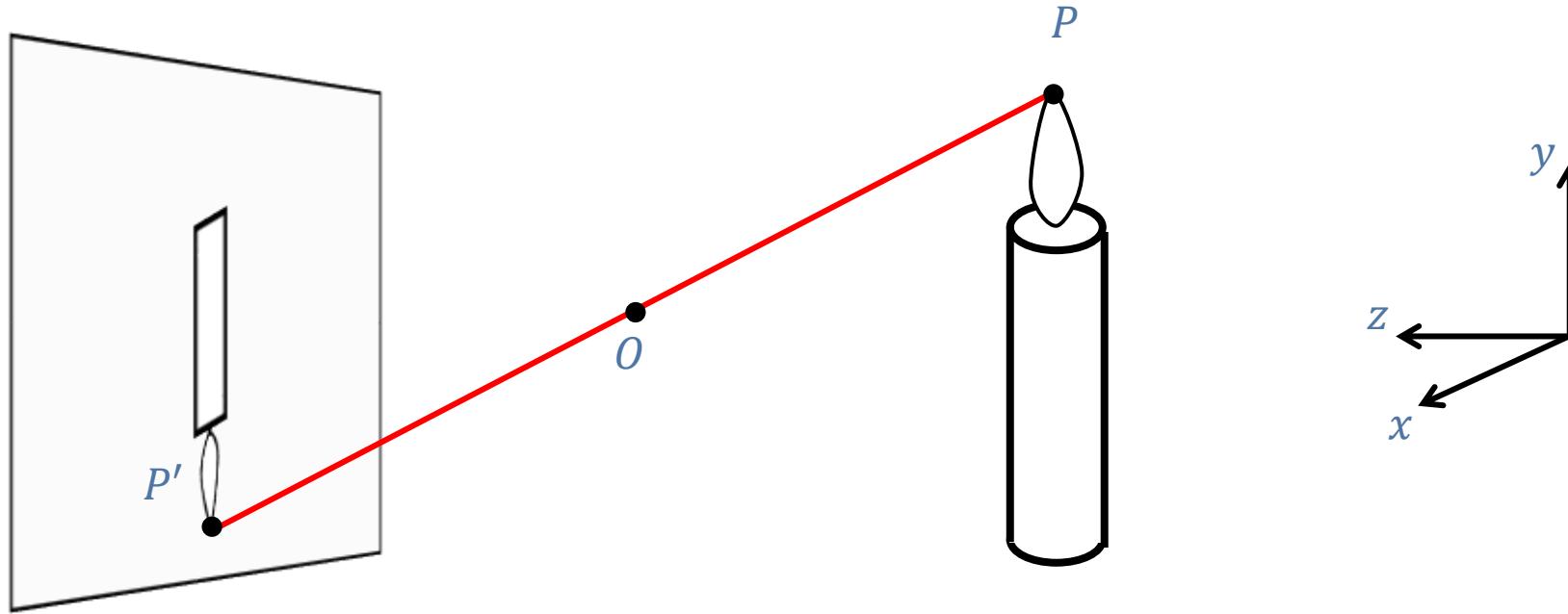
Part 1 – Camera Model & Projection

Image Formation – Camera Obscura



- Basic principle known to Mozi (470-390 BCE), Aristotle (384-322 BCE)
- Drawing aid for artists: described by Leonardo da Vinci (1452-1519)

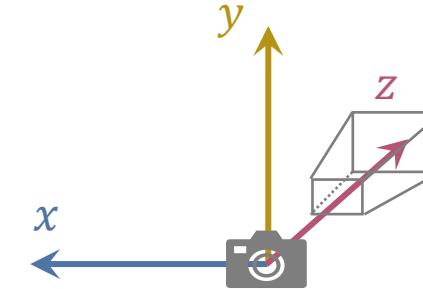
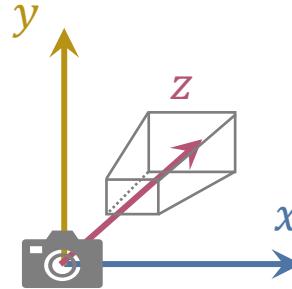
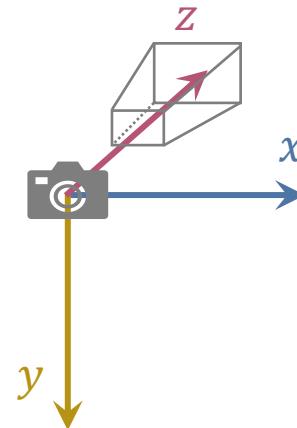
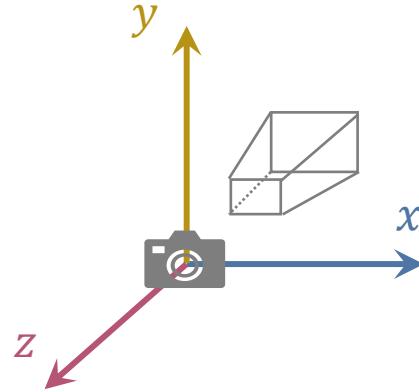
Pinhole Camera



Canonical coordinate system

- The optical center (O) is at the origin
- The z axis is the optical axis perpendicular to the image plane
- The xy plane is parallel to the image plane, x and y axes are horizontal and vertical directions of the image plane

Everybody Agrees... Except on the Axes



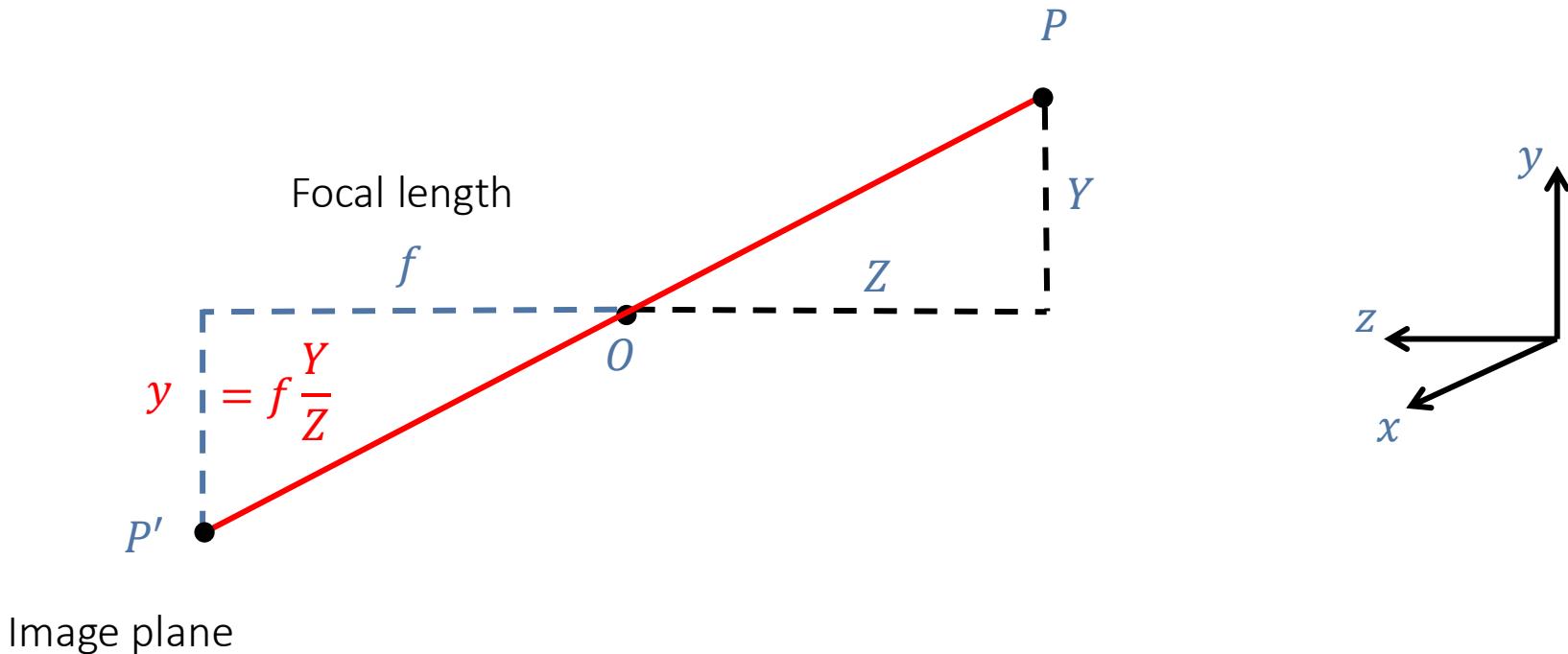
- OpenGL
- Blender
- ARKit
- Three.js
- Nerfstudio
- ...

- OpenCV
- Open3D
- COLMAP
- gsplat
- ...

- Unity
- ...

- PyTorch3D
- ?

Perspective Projection

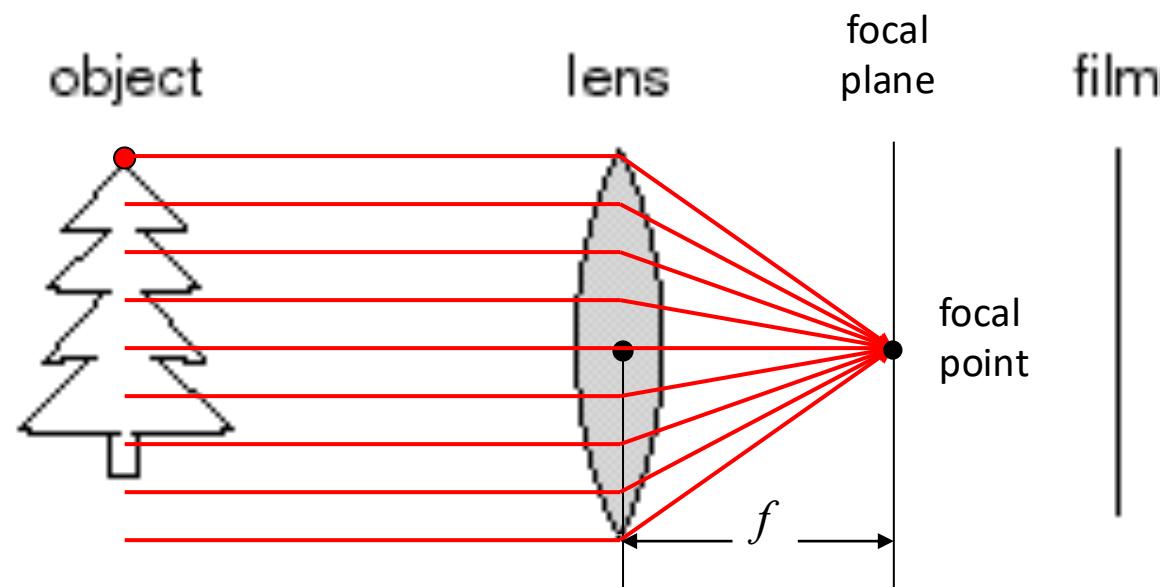


$$(X, Y, Z) \rightarrow \left(f \frac{X}{Z}, f \frac{Y}{Z} \right)$$

3D point 2D point

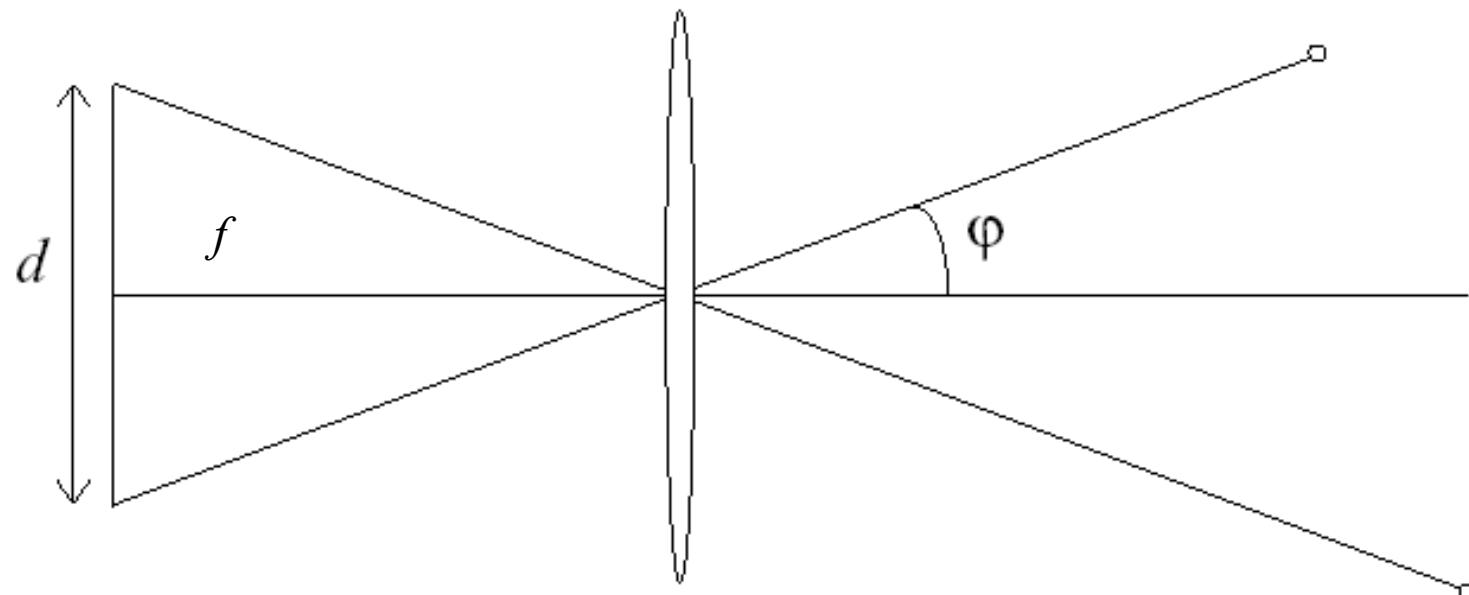
Focal Length of Lenses

- In practice, most cameras use lenses, and the focal length is determined by the physical properties of the lens, such as refraction index, thickness, curvature etc.



Field of View (FOV)

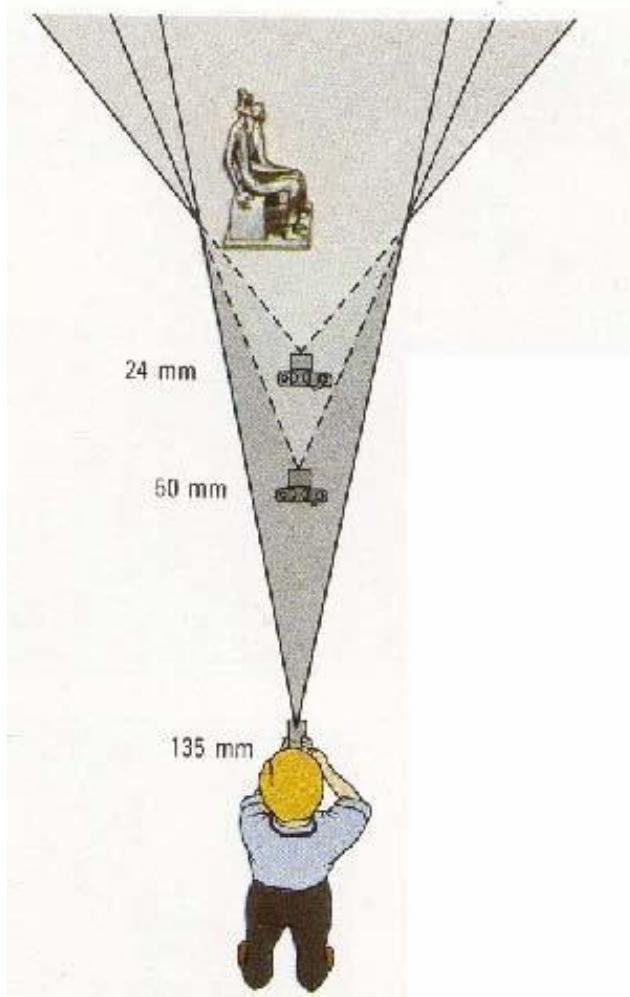
- The field of view is the angular extent of the world observed by the camera.
- Focal length (f), length of the sensor (d):



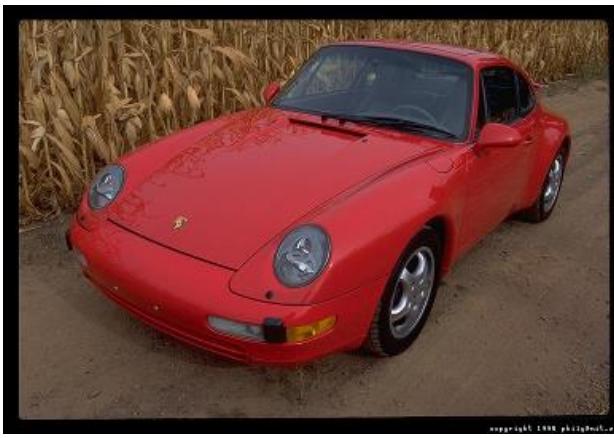
$$\varphi = \tan^{-1} \frac{d}{2f}$$

- Larger focal length = smaller FOV (assuming a constant sensor size)

Field of View / Focal Length Ambiguity



Large FOV, small f
Camera close to car



Small FOV, large f
Camera far from the car

Field of View / Focal Length Ambiguity



wide-angle



standard



telephoto

- What would happen when reconstructing 3D shapes from a single image with *unknown* focal length/FOV?

Field of View / Focal Length Ambiguity



wide-angle



standard



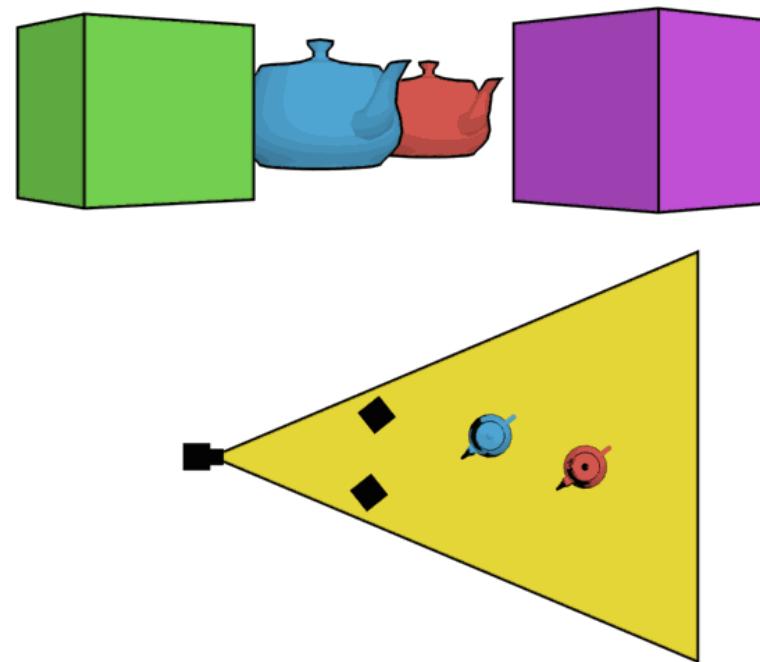
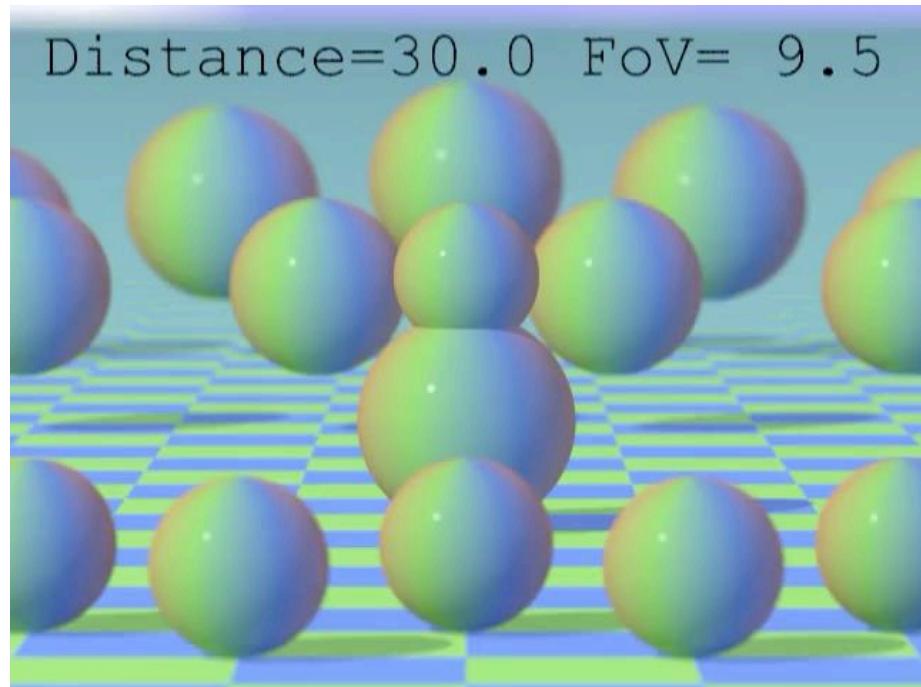
telephoto

(reconstructed by Hunyuan3D V3.1)

- What would happen when reconstructing 3D shapes from a single image with *unknown* focal length/FOV?

Dolly Zoom Effect

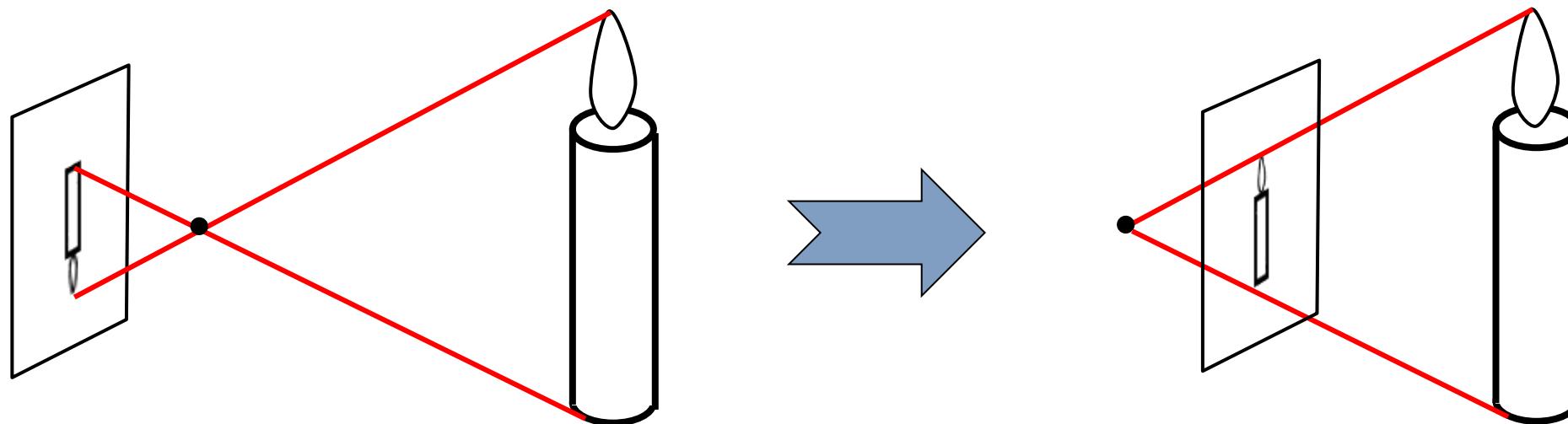
- Continuously adjusting the focal length, while dollying toward or away from the subject.



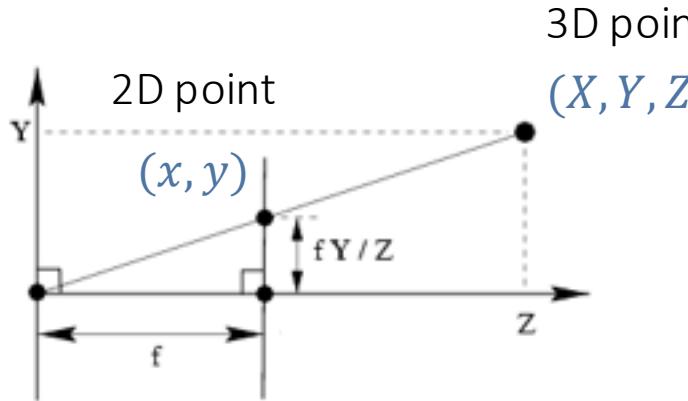
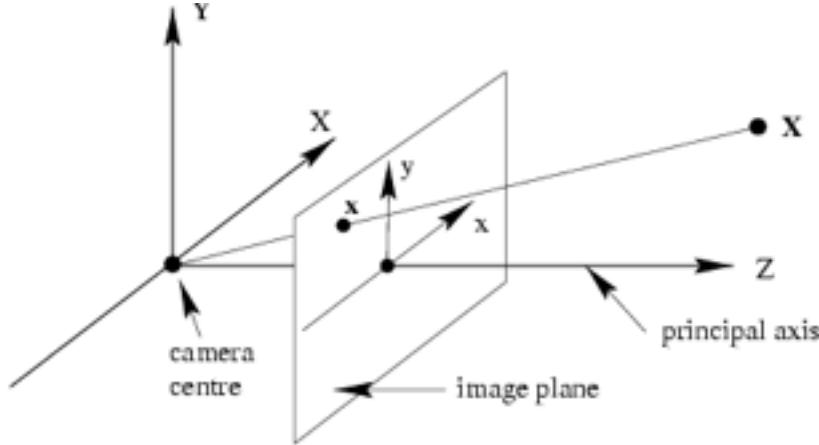
https://en.wikipedia.org/wiki/Dolly_zoom

Perspective Projection

- Instead of dealing with an image that is upside down, most of the time we will pretend that the image plane is in front of the camera center.



Perspective Projection



$$(X, Y, Z) \rightarrow (x, y)$$

$$x = f \frac{X}{Z}, y = f \frac{Y}{Z}$$

- Perspective projection is not a linear transformation!
- But most other transformations we will be dealing with are linear.
- Projective geometry provides a handy mathematical tool to unify them.

Homogeneous Coordinates

- To form homogeneous coordinates from Euclidean coordinates, append 1 as the last entry:

$$(x, y) \Rightarrow \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$$

homogeneous coordinates
of a 2D point (x, y)

$$(X, Y, Z) \Rightarrow \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix}$$

homogeneous coordinates
of a 3D point (X, Y, Z)

- To convert homogeneous coordinates to Euclidean coordinates, divide by the last entry:

$$\begin{bmatrix} x \\ y \\ w \end{bmatrix} \Rightarrow (x/w, y/w)$$

$$\begin{bmatrix} X \\ Y \\ Z \\ W \end{bmatrix} \Rightarrow (X/W, Y/W, Z/W)$$

- All scalar multiples represent the same point!

$$\begin{bmatrix} x \\ y \\ w \end{bmatrix} \sim \lambda \begin{bmatrix} x \\ y \\ w \end{bmatrix}, \quad \lambda \neq 0$$

Homogeneous Coordinates

2D	3D
2D point (x, y)	$\mathbf{x} = \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$
2D line \mathbf{l}	$\mathbf{l} = \begin{bmatrix} a \\ b \\ c \end{bmatrix}$ $\mathbf{l}^\top \mathbf{x} = ax + by + c = 0$
2 points $\mathbf{x}_1, \mathbf{x}_2$ form a line \mathbf{l}	$\mathbf{l} = \mathbf{x}_1 \times \mathbf{x}_2$
2 lines $\mathbf{l}_1, \mathbf{l}_2$ intersect at point \mathbf{x}	$\mathbf{x} = \mathbf{l}_1 \times \mathbf{l}_2$
	3D point (x, y, z)
	$\mathbf{X} = \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix}$
	3D plane $\boldsymbol{\pi}$
	$\boldsymbol{\pi} = \begin{bmatrix} a \\ b \\ c \\ d \end{bmatrix}$ $\boldsymbol{\pi}^\top \mathbf{X} = aX + bY + cZ + d = 0$
	3 points $\mathbf{X}_1, \mathbf{X}_2, \mathbf{X}_3$ form a plane $\boldsymbol{\pi}$
	$\boldsymbol{\pi} = \mathbf{x}_1 \times \mathbf{x}_2 \times \mathbf{x}_3$
	3 planes $\boldsymbol{\pi}_1, \boldsymbol{\pi}_2, \boldsymbol{\pi}_3$ intersect at point \mathbf{X}
	$\mathbf{X} = \boldsymbol{\pi}_1 \times \boldsymbol{\pi}_2 \times \boldsymbol{\pi}_3$

Perspective Projection Matrix

- Projection is a matrix multiplication using homogeneous coordinates:

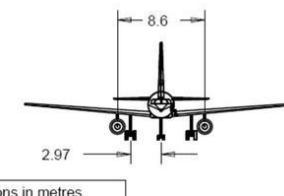
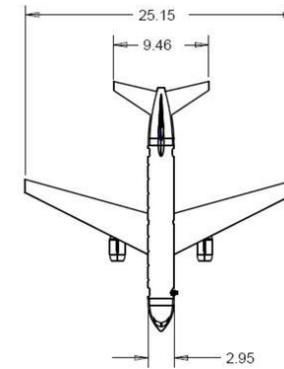
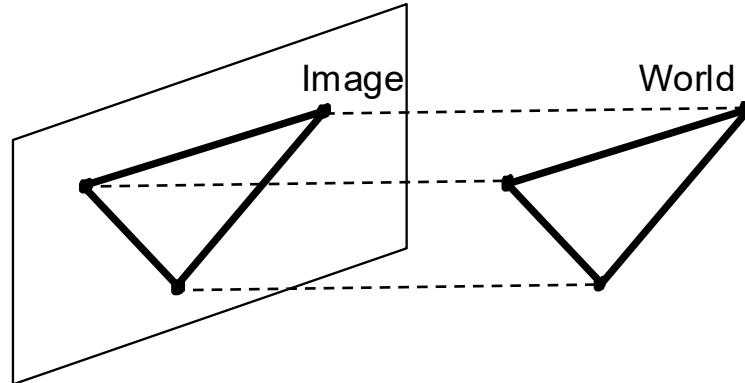
$$\begin{bmatrix} & & \\ & & \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix} = \begin{bmatrix} & & \\ & & \end{bmatrix} \Rightarrow \left(f \frac{X}{Z}, f \frac{Y}{Z} \right)$$

divide by the third coordinate

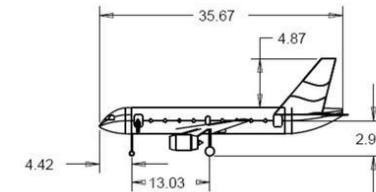
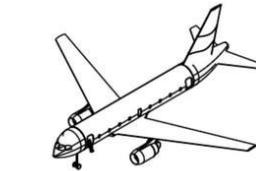
- What will happen if f is very large?

Orthographic Projection

- A form of *parallel projection* where the projection axis is orthogonal to image plane.



Dimensions in metres



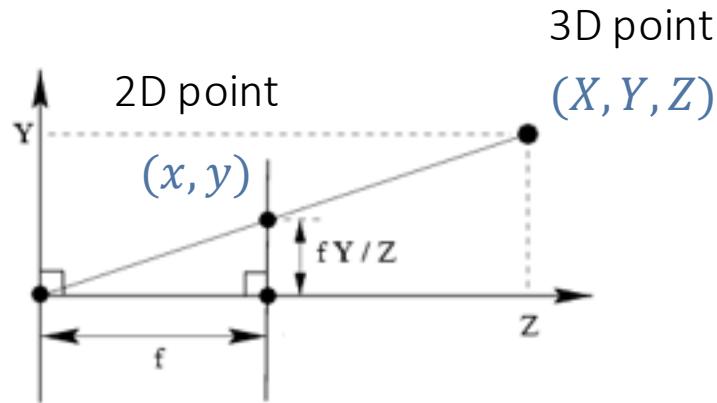
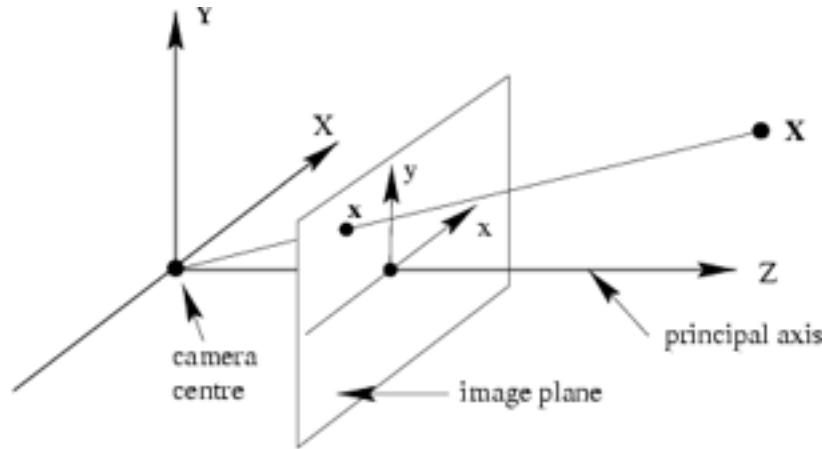
Three-view drawing

- Assuming projection along the z axis, what's the matrix?

$$\begin{bmatrix} & & \\ & & \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix} = \begin{bmatrix} & \\ & \end{bmatrix}$$

Perspective Projection *in Normalized Coordinates*

(assuming camera looking toward z axis and no scaling)



$$(X, Y, Z) \rightarrow (x, y)$$

$$x = f \frac{X}{Z}, y = f \frac{Y}{Z}$$

$$\begin{pmatrix} x \\ y \\ 1 \end{pmatrix} \cong \begin{pmatrix} fX \\ fY \\ Z \end{pmatrix} = \underbrace{\begin{bmatrix} f & 0 & 0 & 0 \\ 0 & f & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}}_{\mathbf{P}} \underbrace{\begin{pmatrix} X \\ Y \\ Z \\ 1 \end{pmatrix}}_{\mathbf{X}}$$

Homogeneous
coordinates of
image point

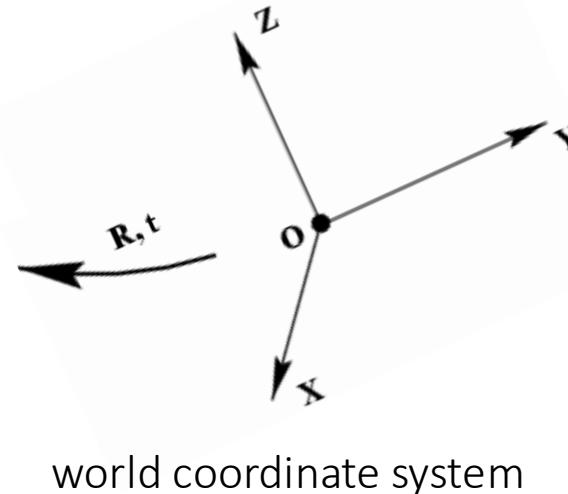
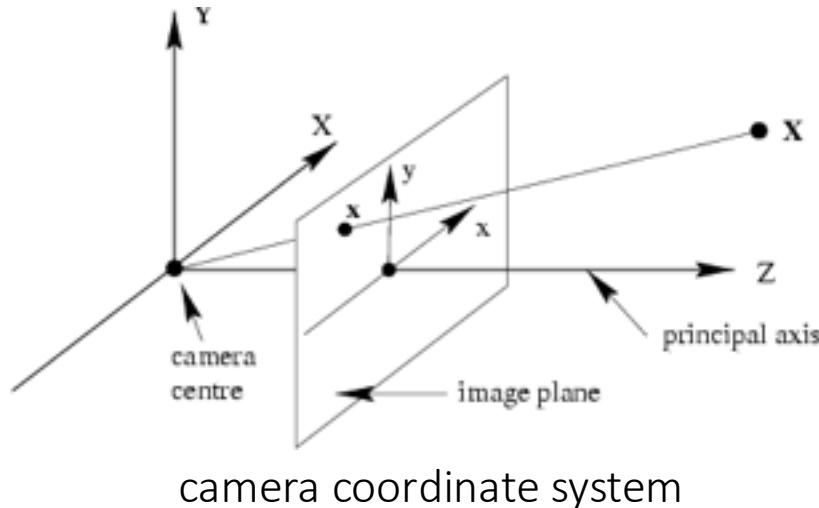
Camera
projection
matrix

Homogeneous
coordinates of
3D point

$$\mathbf{x} \cong \mathbf{P}\mathbf{X}$$

Equality up to scale

Camera Calibration



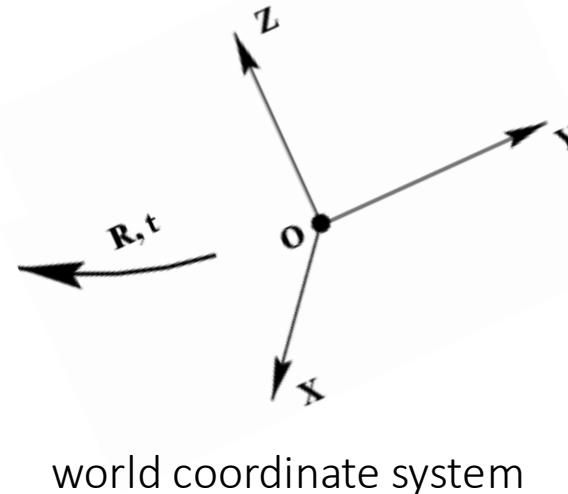
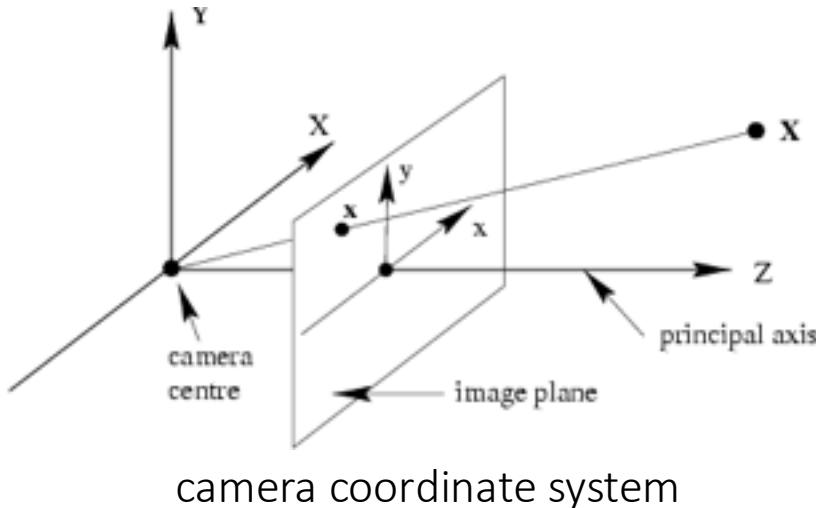
- **Camera calibration:** figuring out transformation from *world* coordinate system to *image* coordinate system

$$\begin{pmatrix} \text{2D point} \\ \mathbf{x} \\ (3 \times 1) \end{pmatrix} \approx \begin{pmatrix} \text{Camera to pixel coord. trans. matrix} \\ \mathbf{K} \\ (3 \times 3) \end{pmatrix} \left(\begin{array}{c} \text{Canonical projection matrix} \\ [\mathbf{I} \mid \mathbf{0}] \text{ (3x4)} \end{array} \right) \left(\begin{array}{c} \text{World to camera coord. trans. matrix} \\ [\mathbf{R} \mid \mathbf{t}] \text{ (4x4)} \\ [\mathbf{0}^T \mid 1] \end{array} \right) \begin{pmatrix} \text{3D point} \\ \mathbf{X} \\ (4 \times 1) \end{pmatrix}$$

Intrinsic camera parameters: principal point, scaling factors

Extrinsic camera parameters: rotation, translation

Camera Calibration

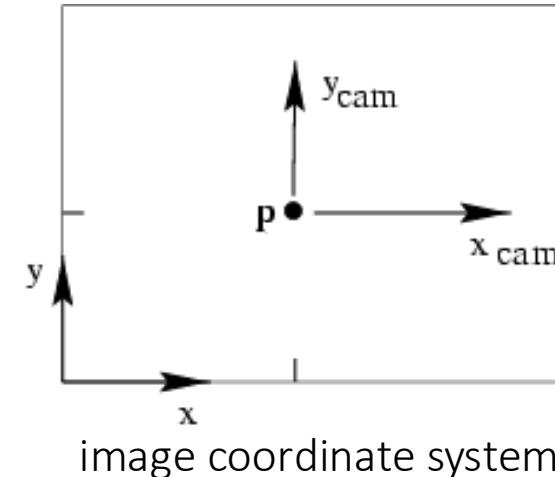
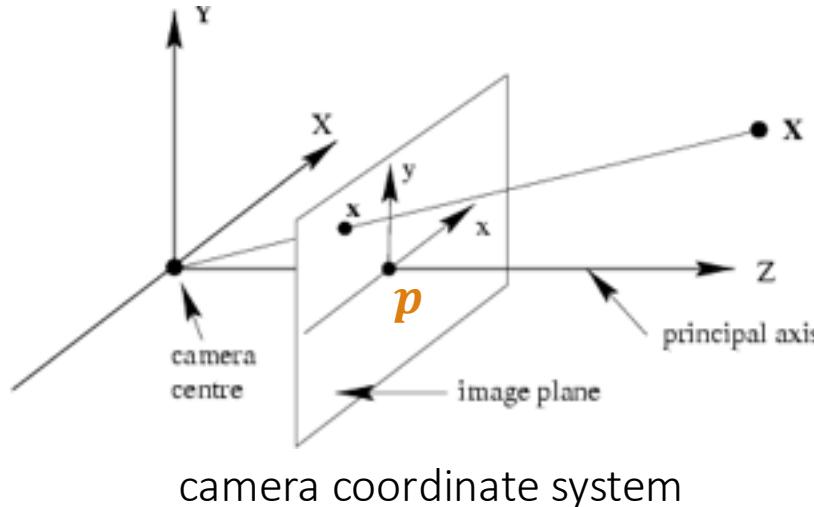


- **Camera calibration:** figuring out transformation from *world* coordinate system to *image* coordinate system

$$\begin{pmatrix} \text{2D point} \\ \textcolor{orange}{x} \\ (3 \times 1) \end{pmatrix} \approx \begin{pmatrix} \text{Camera to pixel coord. trans. matrix} \\ \textcolor{orange}{K} \ (3 \times 3) \end{pmatrix} \left(\begin{array}{c} \text{Canonical projection matrix} \\ [\mathbf{I} \ | \ \mathbf{0}] \ (3 \times 4) \end{array} \right) \left(\begin{array}{c} \text{World to camera coord. trans. matrix} \\ [\mathbf{R} \ | \ \mathbf{t}] \ (4 \times 4) \end{array} \right) \begin{pmatrix} \text{3D point} \\ \textcolor{orange}{X} \\ (4 \times 1) \end{pmatrix}$$

$\mathcal{P} = \mathbf{K}[\mathbf{R}|\mathbf{t}]$
General camera projection matrix

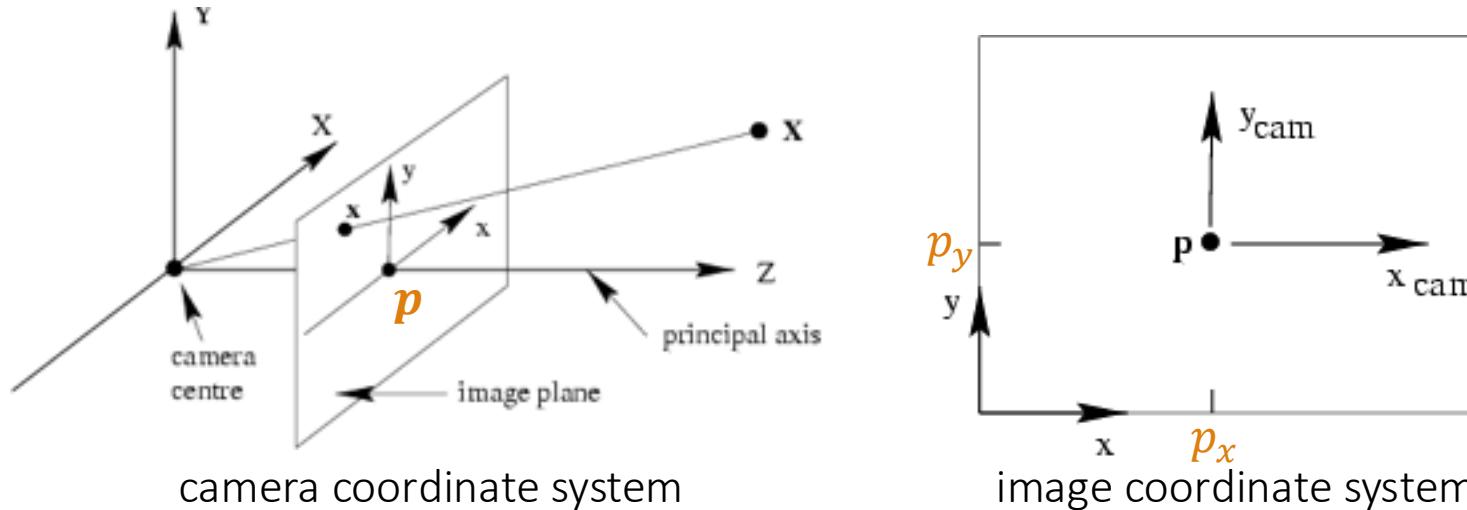
Intrinsic Parameters – Principal Point



Principal point (p): point where principal axis intersects the image plane

- In the *normalized* coordinate system, the **origin** is at the **principal point**.
- In the *image* coordinate system, the **origin** is in the **corner**.

Intrinsic Parameters – Principal Point

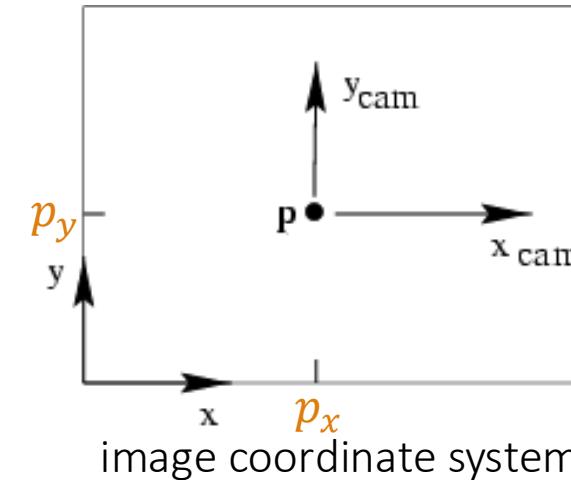
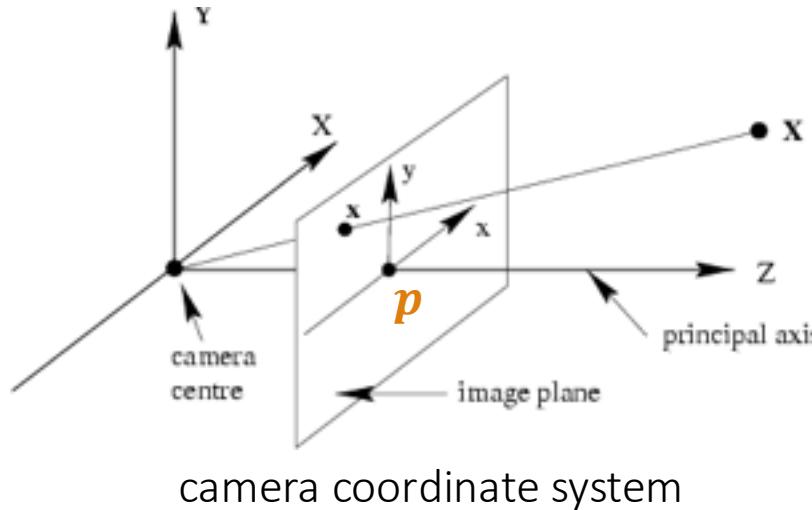


$$x = f \frac{X}{Z} + p_x, \quad y = f \frac{Y}{Z} + p_y$$

$$\begin{pmatrix} x \\ y \\ 1 \end{pmatrix} \cong \begin{pmatrix} fX + Zp_x \\ fY + Zp_y \\ Z \end{pmatrix} = \left[\begin{array}{c|c} & \begin{pmatrix} X \\ Y \\ Z \\ 1 \end{pmatrix} \\ \hline \mathbf{K} & \end{array} \right]$$

calibration matrix \mathbf{K}

Intrinsic Parameters – Scaling

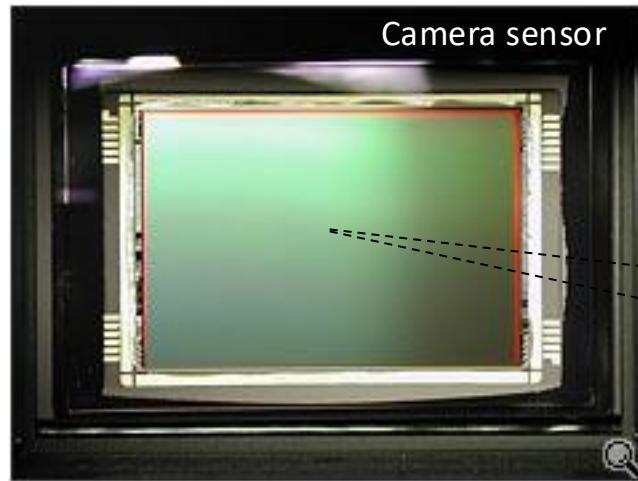


$$x = f \frac{X}{Z} + p_x, \quad y = f \frac{Y}{Z} + p_y$$

$$\begin{pmatrix} u \\ v \\ 1 \end{pmatrix} \xleftarrow[\text{pixels}]{}^{\alpha} \begin{pmatrix} x \\ y \\ 1 \end{pmatrix} \cong \begin{pmatrix} fX + Zp_x \\ fY + Zp_y \\ Z \end{pmatrix} = \begin{bmatrix} f & 0 & p_x & 0 \\ 0 & f & p_y & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{pmatrix} X \\ Y \\ Z \\ 1 \end{pmatrix}$$

calibration matrix \mathbf{K}

Intrinsic Parameters – Scaling



m_x pixels/m in horizontal direction
 m_y pixels/m in vertical direction

Pixel size (m): $\frac{1}{m_x} \times \frac{1}{m_y}$

Scaling factors

$$\begin{bmatrix} m_x & 0 & 0 \\ 0 & m_y & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

pixels/m

Calibration matrix
 K in metric units

$$\begin{bmatrix} f & 0 & p_x \\ 0 & f & p_y \\ 0 & 0 & 1 \end{bmatrix}$$

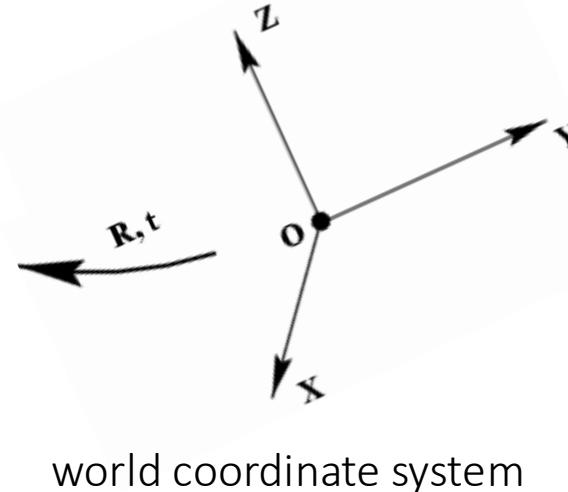
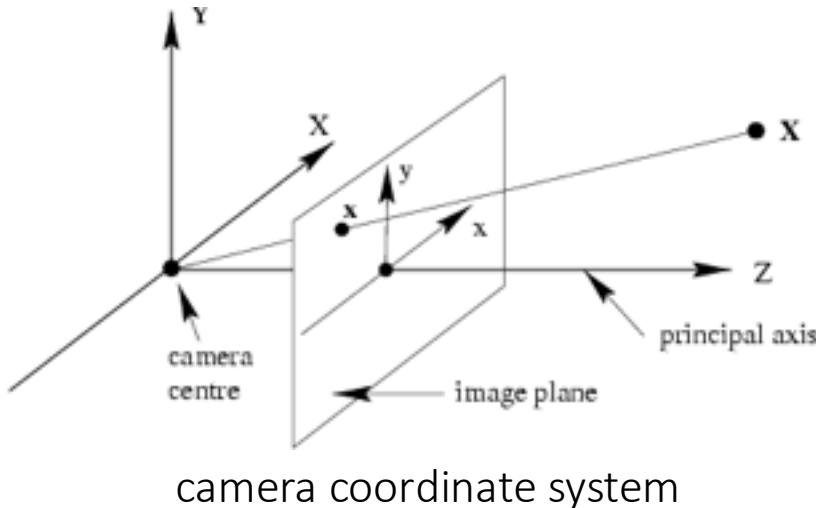
m

Calibration matrix
 K in pixel units

$$= \begin{bmatrix} \alpha_x & 0 & \beta_x \\ 0 & \alpha_y & \beta_y \\ 0 & 0 & 1 \end{bmatrix}$$

pixels

Camera Calibration

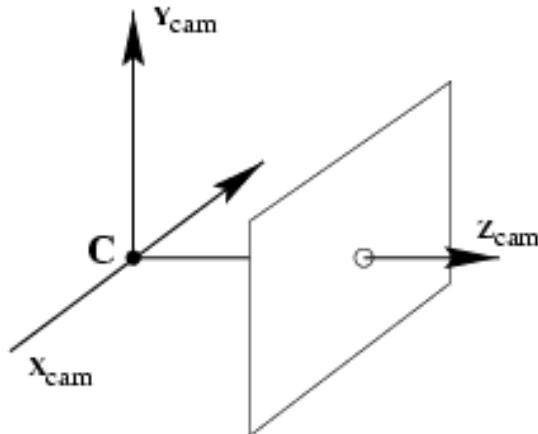


- **Camera calibration:** figuring out transformation from *world* coordinate system to *image* coordinate system

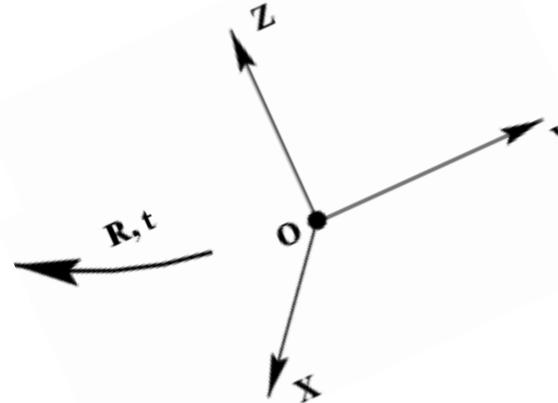
$$\begin{pmatrix} \text{2D point} \\ \mathbf{x} \\ (3 \times 1) \end{pmatrix} \approx \underbrace{\begin{pmatrix} \text{Camera to pixel coord. trans. matrix} \\ \mathbf{K} \quad (3 \times 3) \end{pmatrix}}_{\text{Canonical projection matrix } [\mathbf{I} \mid \mathbf{0}] \quad (3 \times 4)} \underbrace{\begin{pmatrix} \text{World to camera coord. trans. matrix} \\ [\mathbf{R} \quad \mathbf{t}] \quad (4 \times 4) \\ [\mathbf{0}^T \quad 1] \end{pmatrix}}_{\mathbf{P} = \mathbf{K}[\mathbf{R}|\mathbf{t}]} \begin{pmatrix} \text{3D point} \\ \mathbf{X} \\ (4 \times 1) \end{pmatrix}$$

$\mathbf{P} = \mathbf{K}[\mathbf{R}|\mathbf{t}]$
General camera projection matrix

Extrinsic Parameters



camera coordinate system



world coordinate system

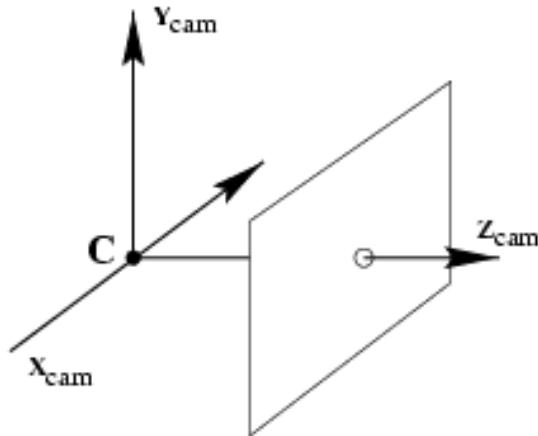
- In *non-homogeneous* coordinates, the transformation from world to normalized camera coordinate system is given by:

$$\tilde{X}_{cam} = R(\tilde{X} - \tilde{C}) = R\tilde{X} + t$$

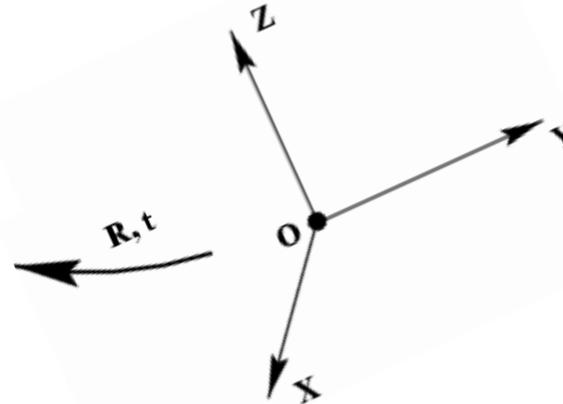
coords. of point in normalized camera frame 3x3 rotation matrix coords. of a point in world frame coords. of camera center in world frame

$$\text{W2C: } \tilde{X}_{cam} = R\tilde{X}_{world} + t$$
$$\text{C2W: } \tilde{X}_{world} = R^T\tilde{X}_{cam} - R^Tt$$

Extrinsic Parameters



camera coordinate system



world coordinate system

In non-homogeneous
coordinates:

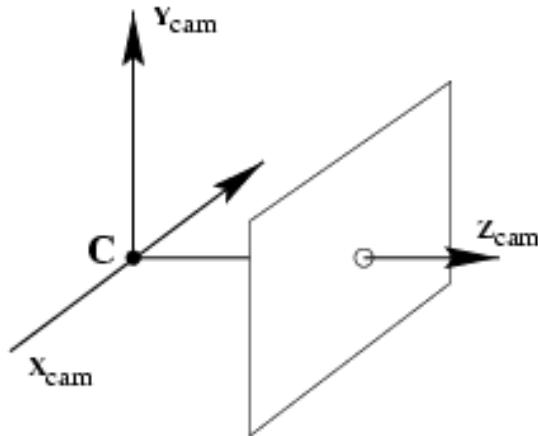
$$\tilde{X}_{cam} = \mathbf{R}\tilde{X} + \mathbf{t}$$

In homogeneous
coordinates:

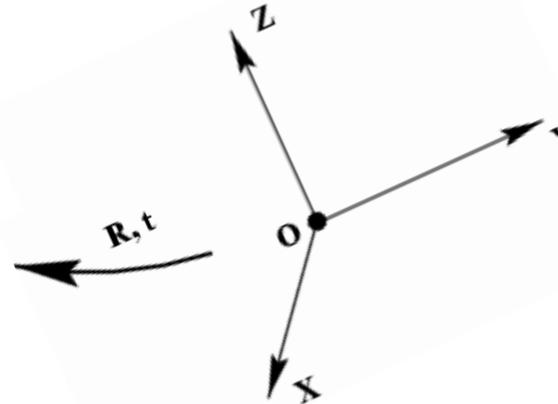
$$\begin{pmatrix} \tilde{X}_{cam} \\ 1 \end{pmatrix} = \begin{bmatrix} \mathbf{R} & \mathbf{t} \\ \mathbf{0}^T & 1 \end{bmatrix} \begin{pmatrix} \tilde{X} \\ 1 \end{pmatrix}$$

3D transformation
matrix (4 x 4)

Extrinsic Parameters



camera coordinate system



world coordinate system

In non-homogeneous
coordinates:

$$\tilde{X}_{cam} = R\tilde{X} + t$$

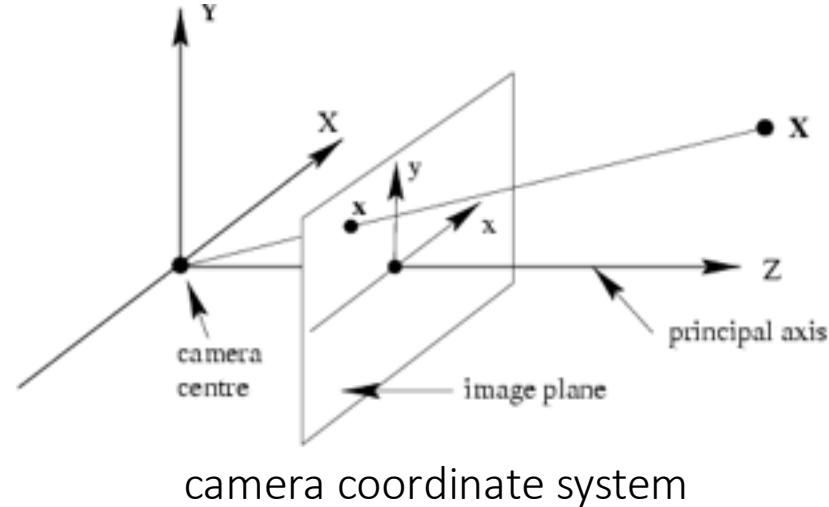
In homogeneous
coordinates:

$$X_{cam} = \begin{bmatrix} R & t \\ 0^T & 1 \end{bmatrix} X$$

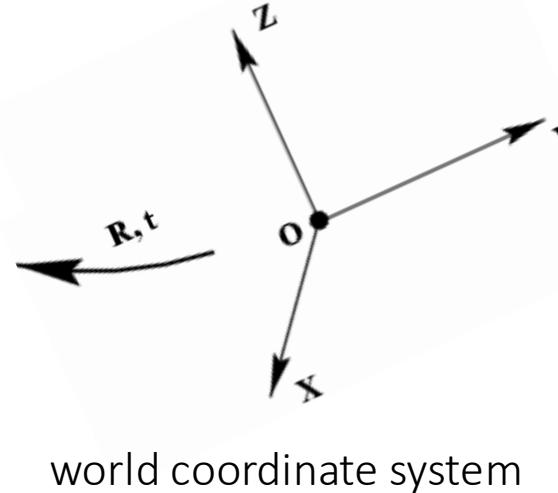
3D transformation
matrix (4 x 4)

And then to image coordinates: $\mathbf{x} \cong K[I|0]X_{cam}$

Camera Calibration



camera coordinate system



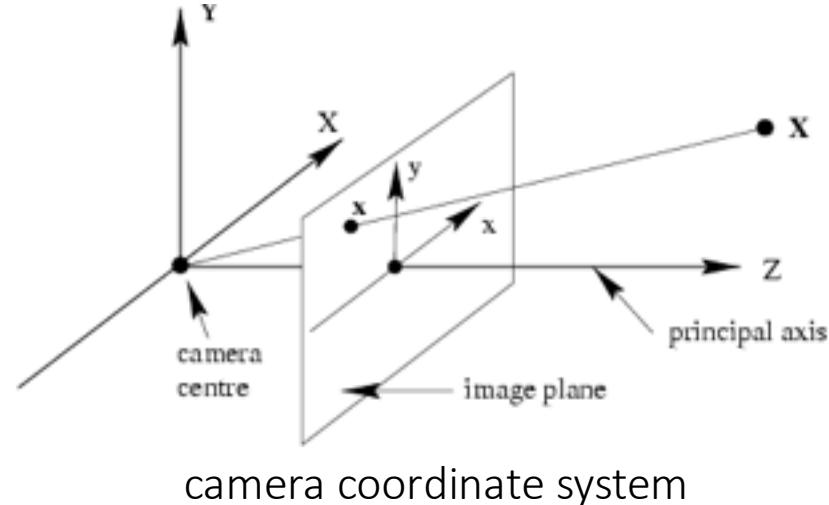
world coordinate system

$$\mathbf{x} \cong \mathbf{K}[\mathbf{R}|\mathbf{t}] \mathbf{X}$$

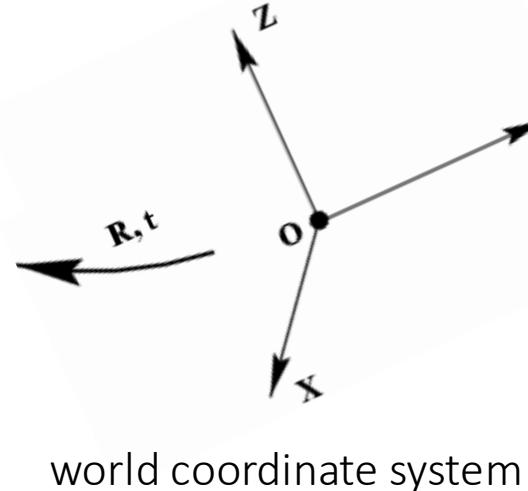
- **Camera calibration:** figuring out transformation from *world* coordinate system to *image* coordinate system

$$\begin{pmatrix} 2D \\ \text{point} \\ \mathbf{x} \\ (3x1) \end{pmatrix} \cong \underbrace{\begin{pmatrix} \text{Camera to} \\ \text{pixel coord.} \\ \text{trans. matrix} \\ \mathbf{K} \\ (3x3) \end{pmatrix}}_{\mathbf{P} = \mathbf{K}[\mathbf{R}|\mathbf{t}]} \underbrace{\begin{pmatrix} \text{Canonical} \\ \text{projection matrix} \\ [\mathbf{I} \mid \mathbf{0}] \\ (3x4) \end{pmatrix}}_{\text{General camera projection matrix}} \underbrace{\begin{pmatrix} \text{World to} \\ \text{camera coord.} \\ \text{trans. matrix} \\ [\mathbf{R} \mid \mathbf{t}] \\ (\mathbf{0}^T \mid 1) \\ (4x4) \end{pmatrix}}_{\text{3D point } \mathbf{X} \\ (4x1)}$$

Camera Calibration



camera coordinate system



world coordinate system

$$\mathbf{x} \cong K[R|t]\mathbf{X}$$

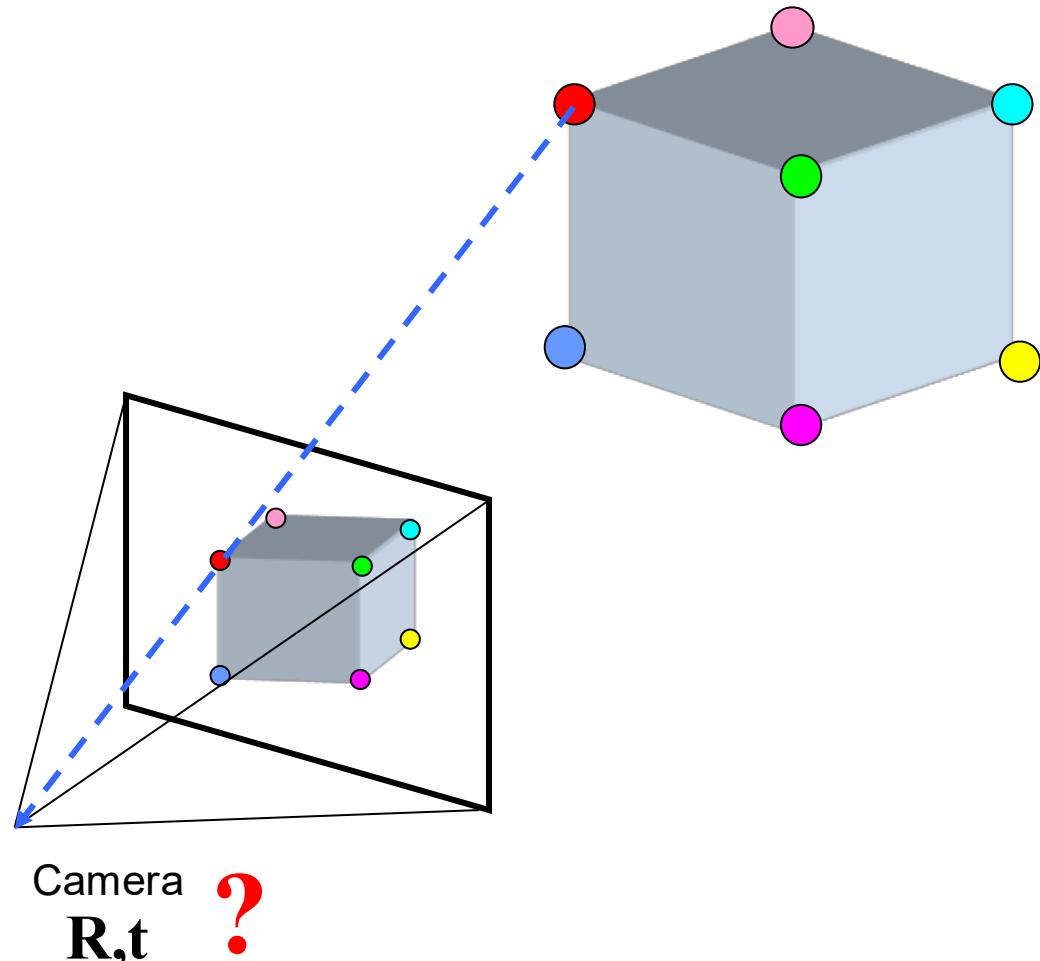
- **Camera calibration:** figuring out transformation from *world* coordinate system to *image* coordinate system

$$\begin{pmatrix} x \\ y \\ 1 \end{pmatrix} \cong \begin{bmatrix} p_{11} & p_{12} & p_{13} & p_{14} \\ p_{21} & p_{22} & p_{23} & p_{24} \\ p_{31} & p_{32} & p_{33} & p_{34} \end{bmatrix} \begin{pmatrix} X \\ Y \\ Z \\ 1 \end{pmatrix}$$

We could solve this as a linear system, then perform QR decomposition to get K, R, t .
(not robust in practice;
sensitive to noise)

Perspective-n-Point (PnP)

$$\mathbf{x} \cong \mathbf{K}[\mathbf{R}|\mathbf{t}]\mathbf{X}$$



Known:

- n 3D points \mathbf{X}
- Corresponding 2D pixel coordinates \mathbf{x}
- Camera intrinsics \mathbf{K}

Solve for:

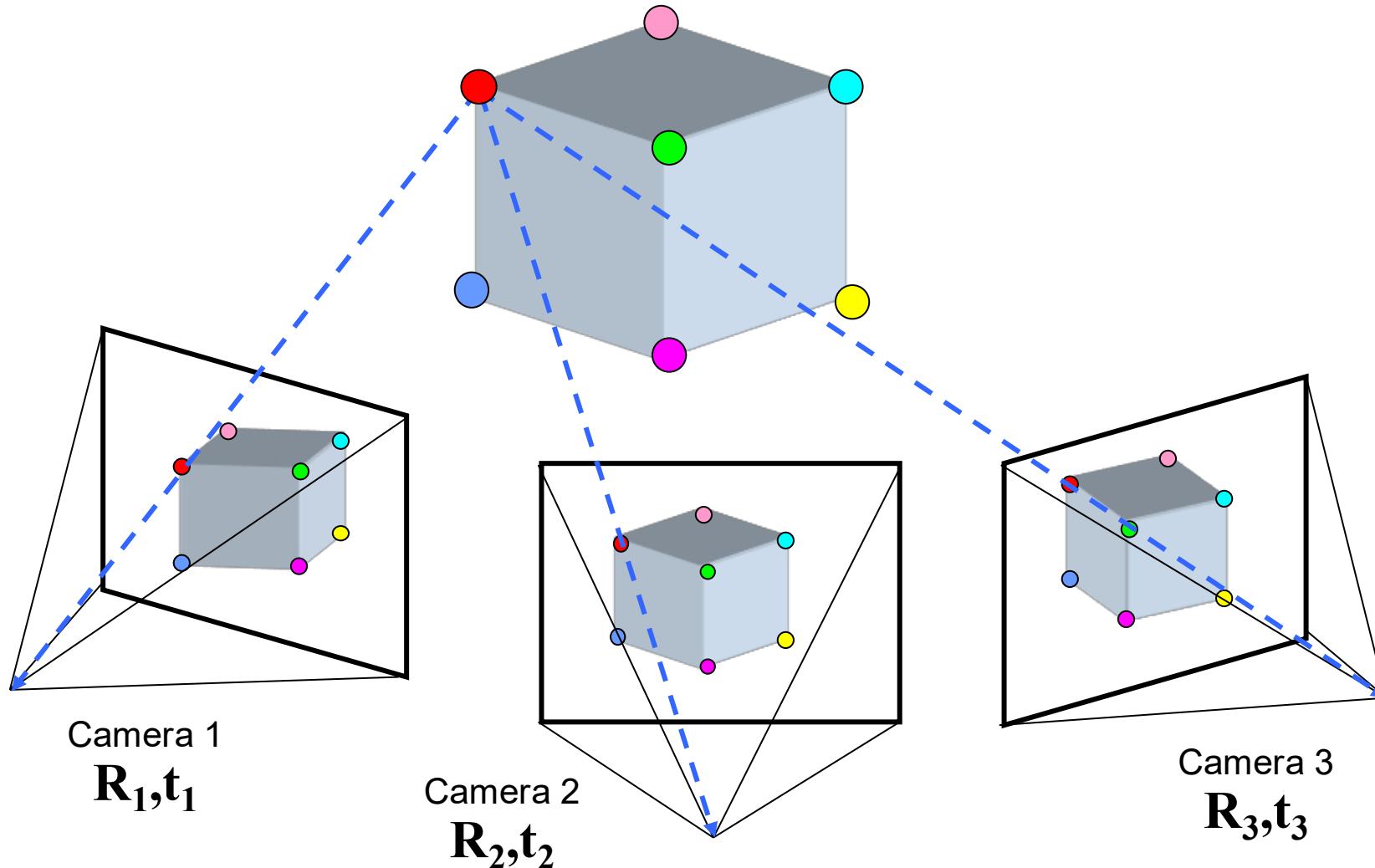
- Camera pose (extrinsics) \mathbf{R}, \mathbf{t}

Q: How many points at least do we need?

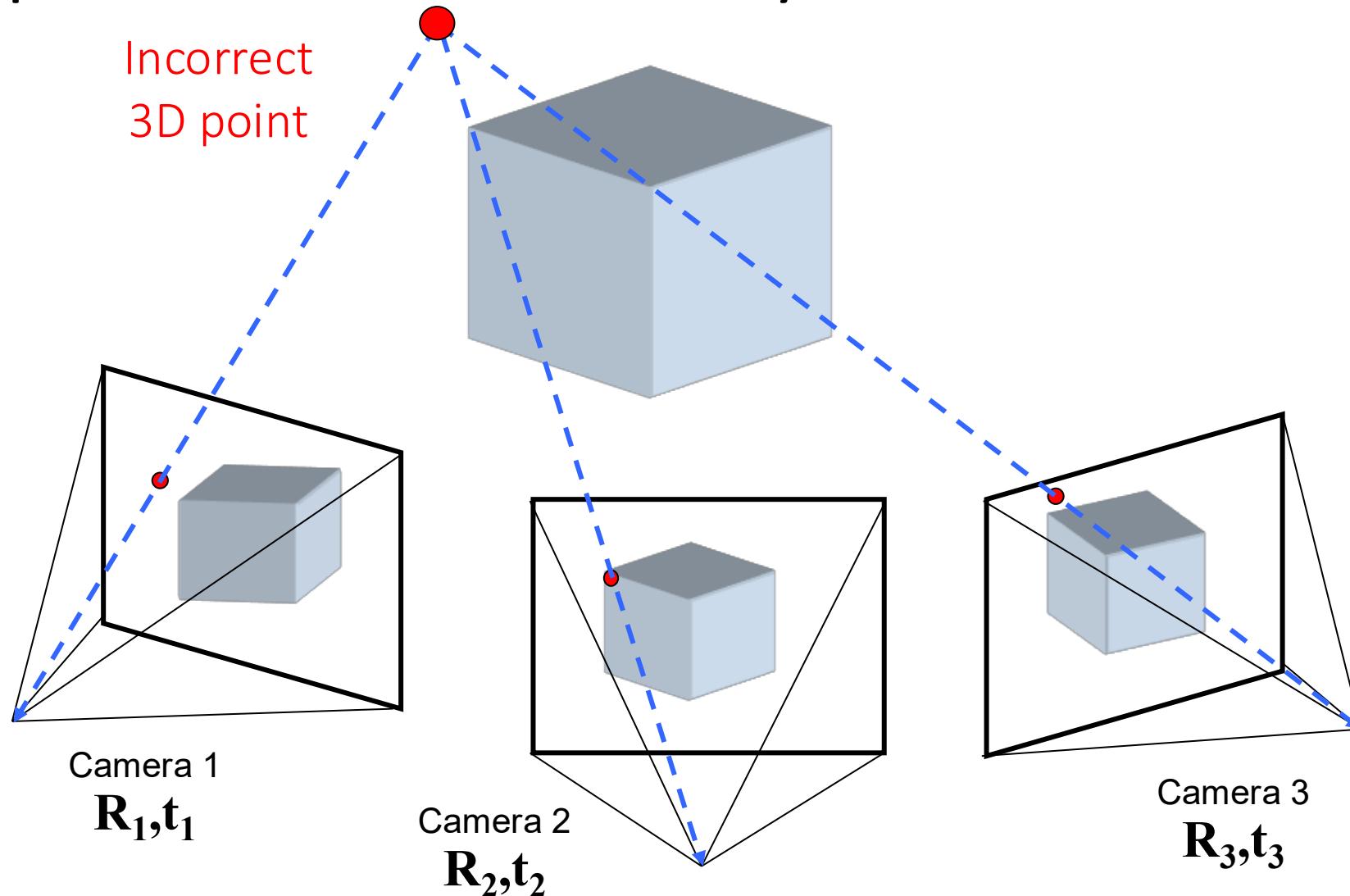
A: $n \geq 3$ (in general). We have 6 DoF unknowns \mathbf{R}, \mathbf{t} . Each point provides 2 constraints (2 equations for \mathbf{x} and \mathbf{y}).

Part 2 – Multi-view Geometry

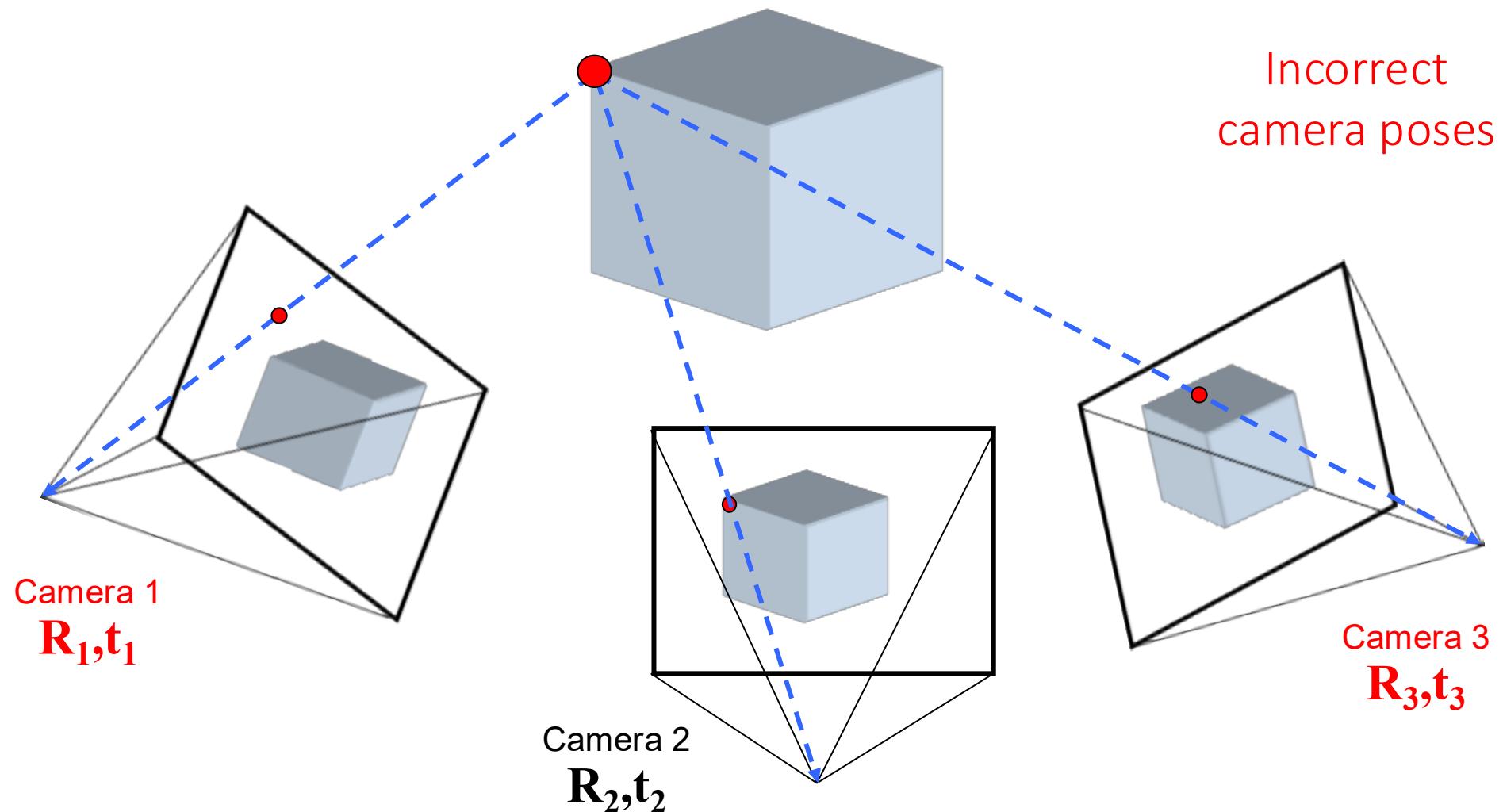
Multiple View Geometry



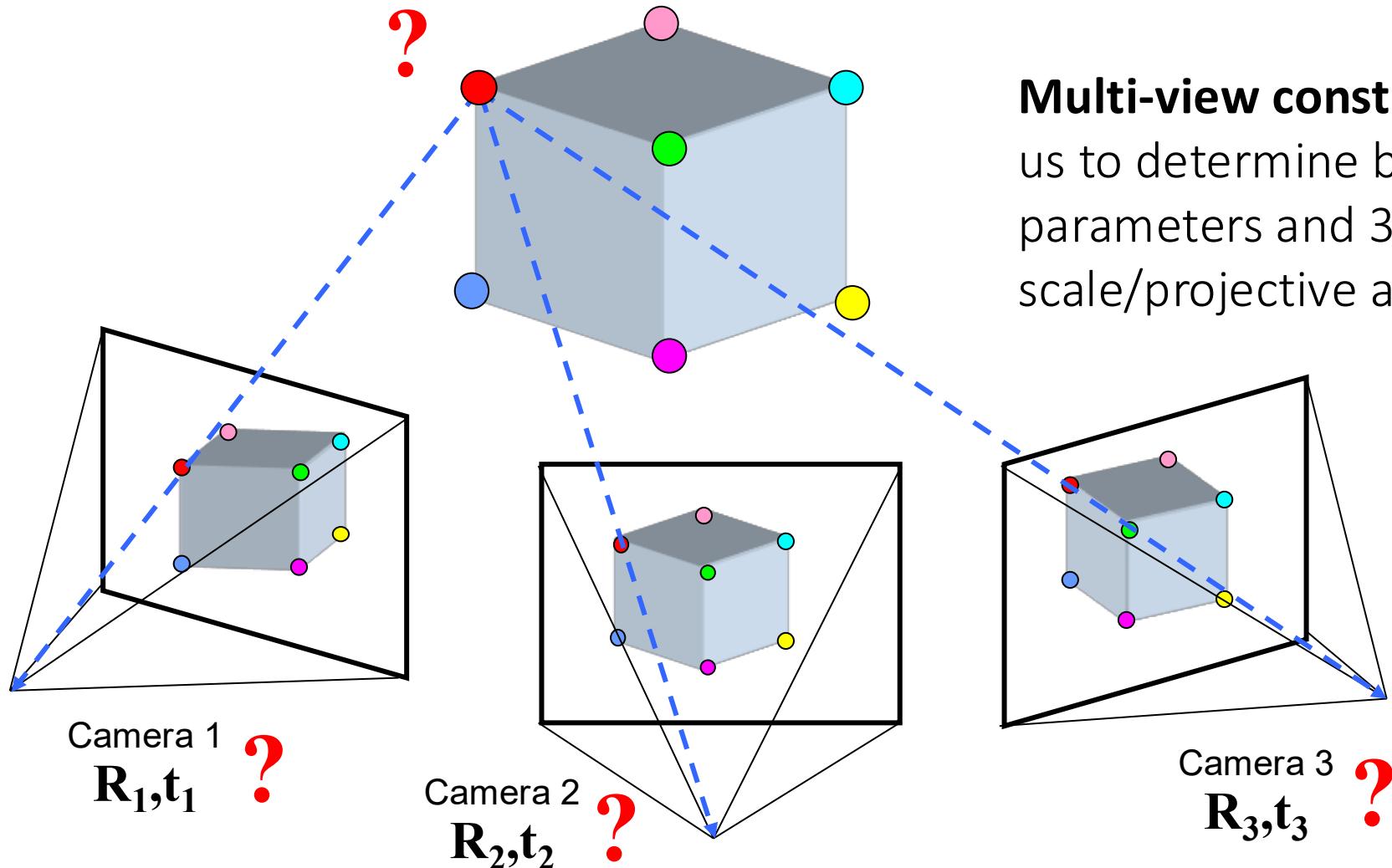
Multiple View Geometry



Multiple View Geometry

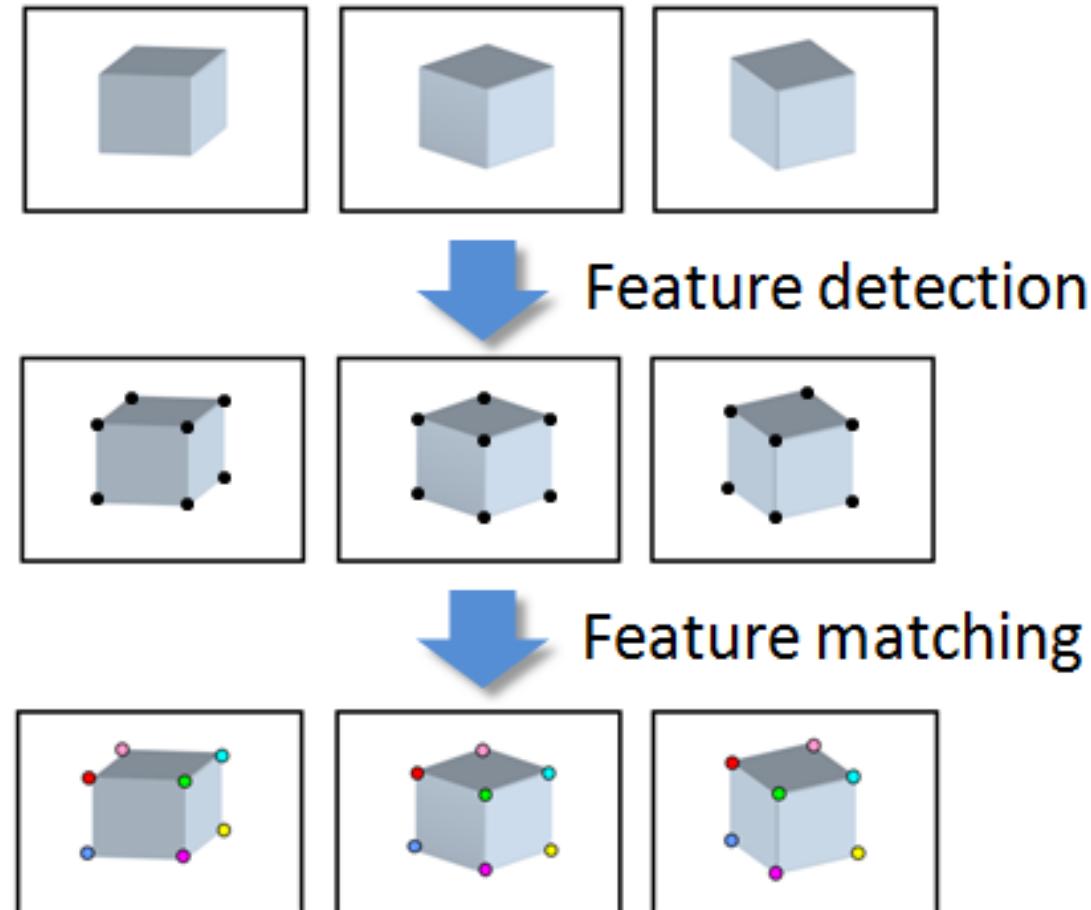


Multiple View Geometry

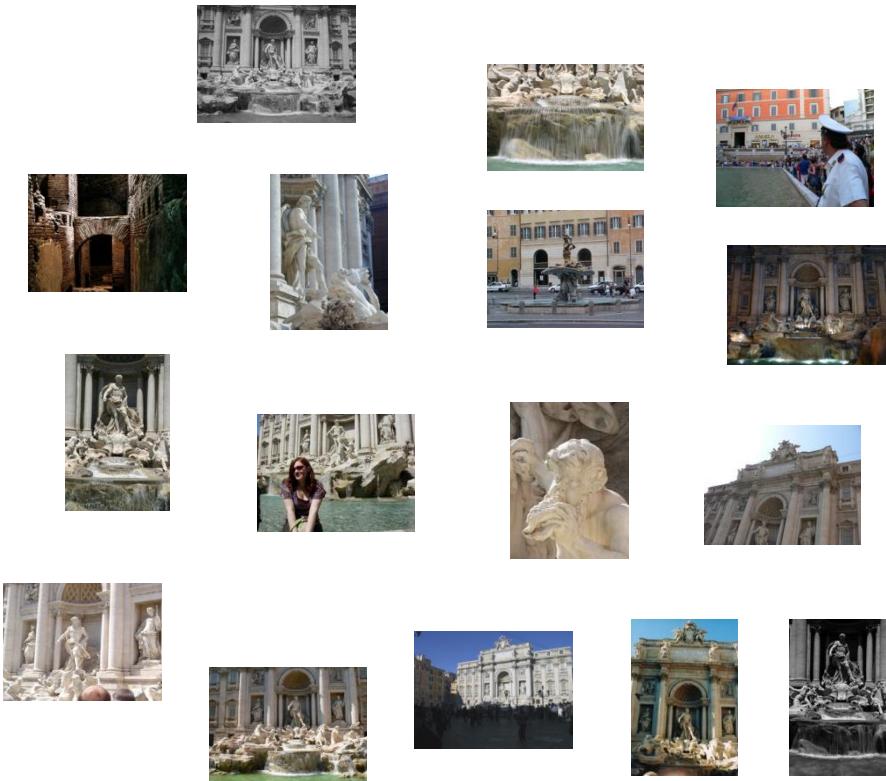


Multi-view constraints allow us to determine both camera parameters and 3D (up to scale/projective ambiguities)

Estimating Correspondences



Estimating Correspondences



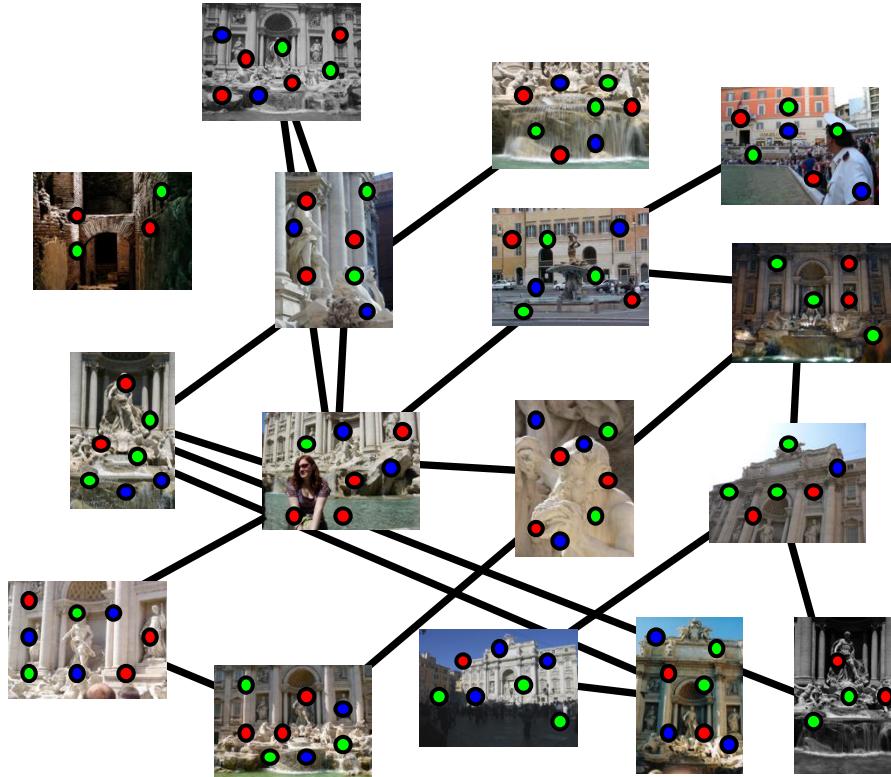
Estimating Correspondences



- **Detect feature points**

- SIFT descriptors [Lowe, 2004]
- Learned features – SuperPoint [DeTone, 2018])

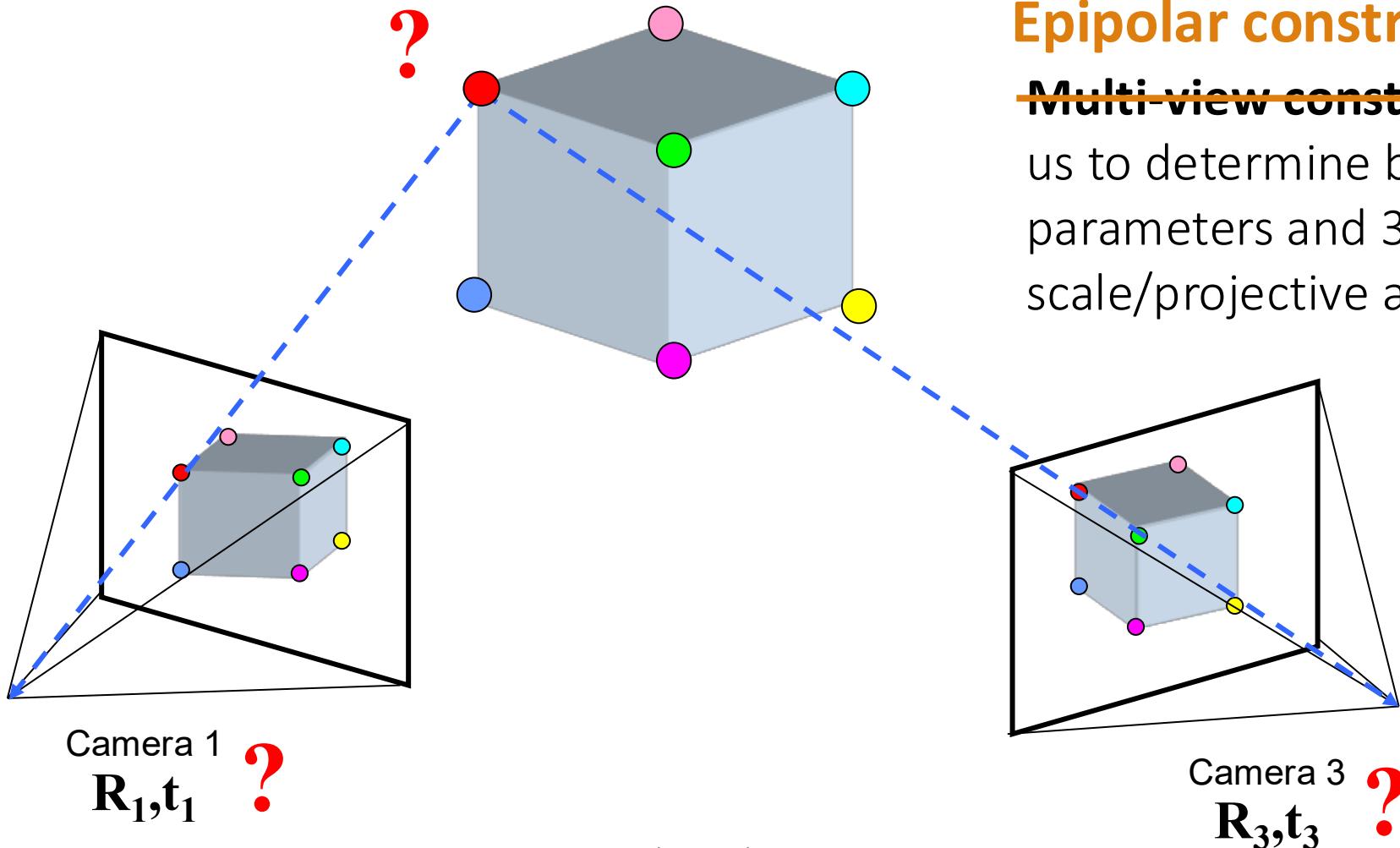
Estimating Correspondences



- **Detect feature points**
 - SIFT descriptors [Lowe, 2004]
 - Learned features – SuperPoint [DeTone, 2018])
- **Match features** between pair of images
 - Use RANSAC to filter outliers
 - Learned matching – SuperGlue [Sarlin, 2020]

Let's Start with Two Views – Epipolar Geometry

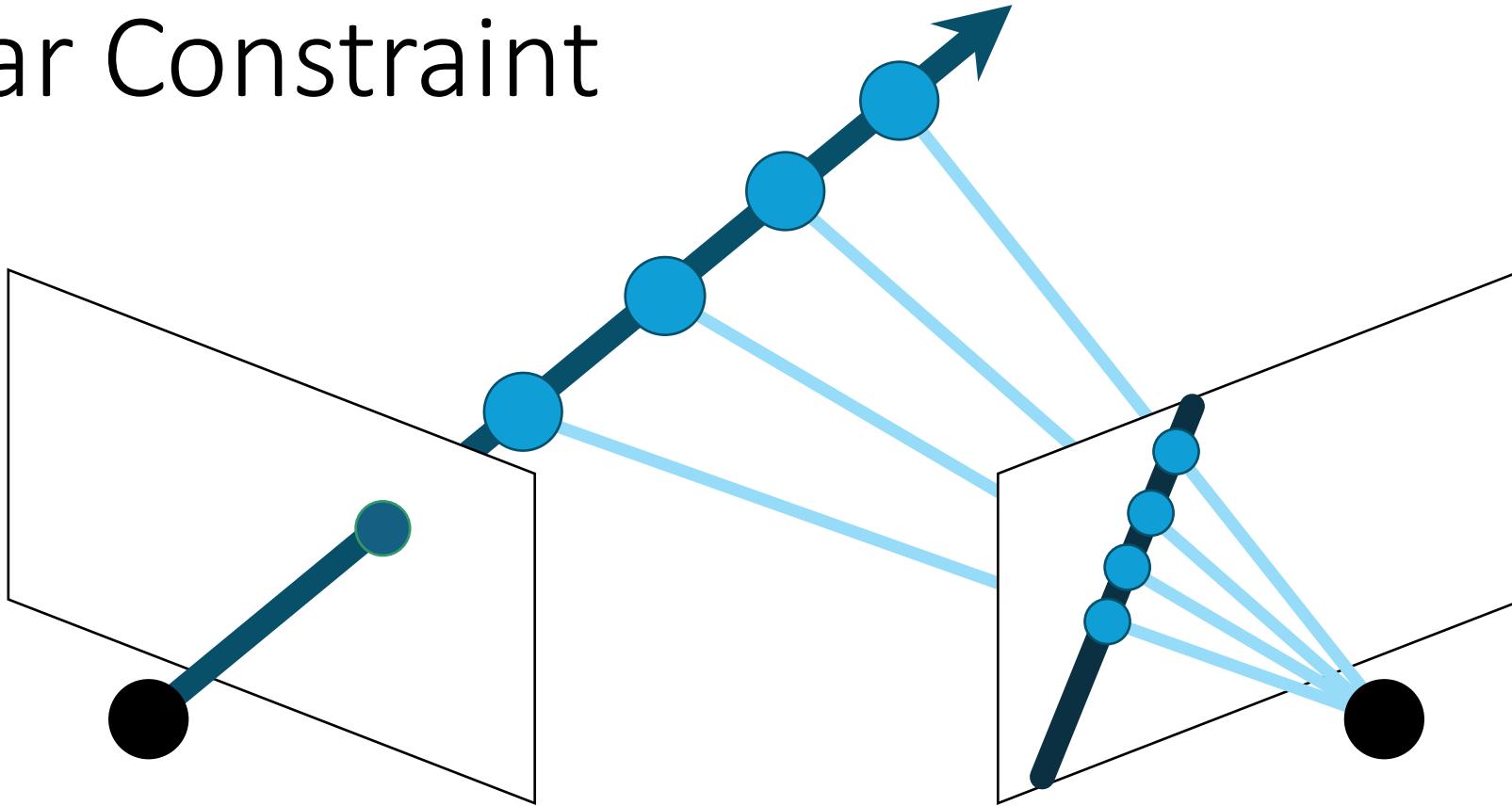
“epi-pole” \approx upon the pole/pivot



Epipolar constraints

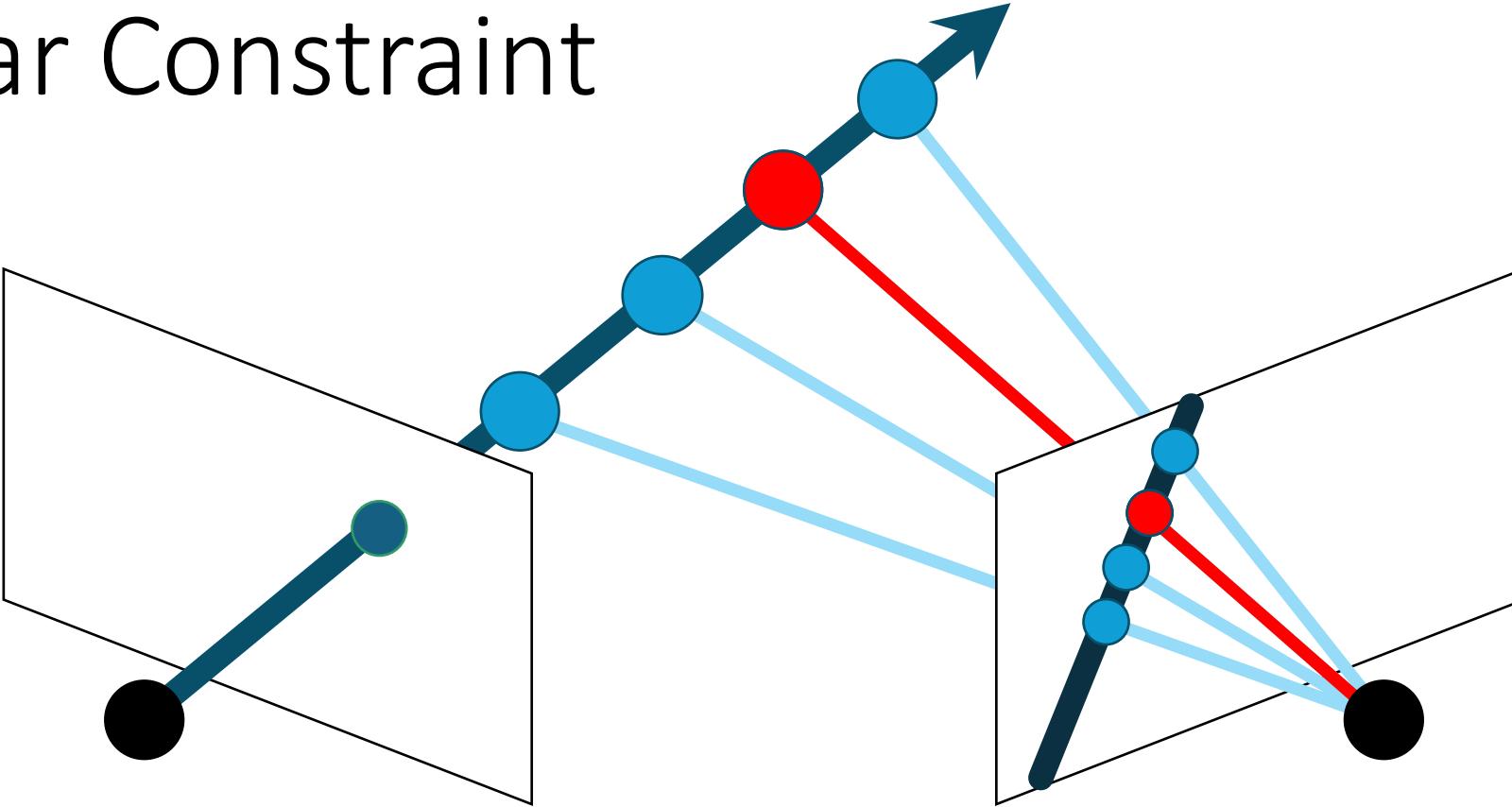
Multi-view constraints allow us to determine both camera parameters and 3D (up to scale/projective ambiguities)

Epipolar Constraint



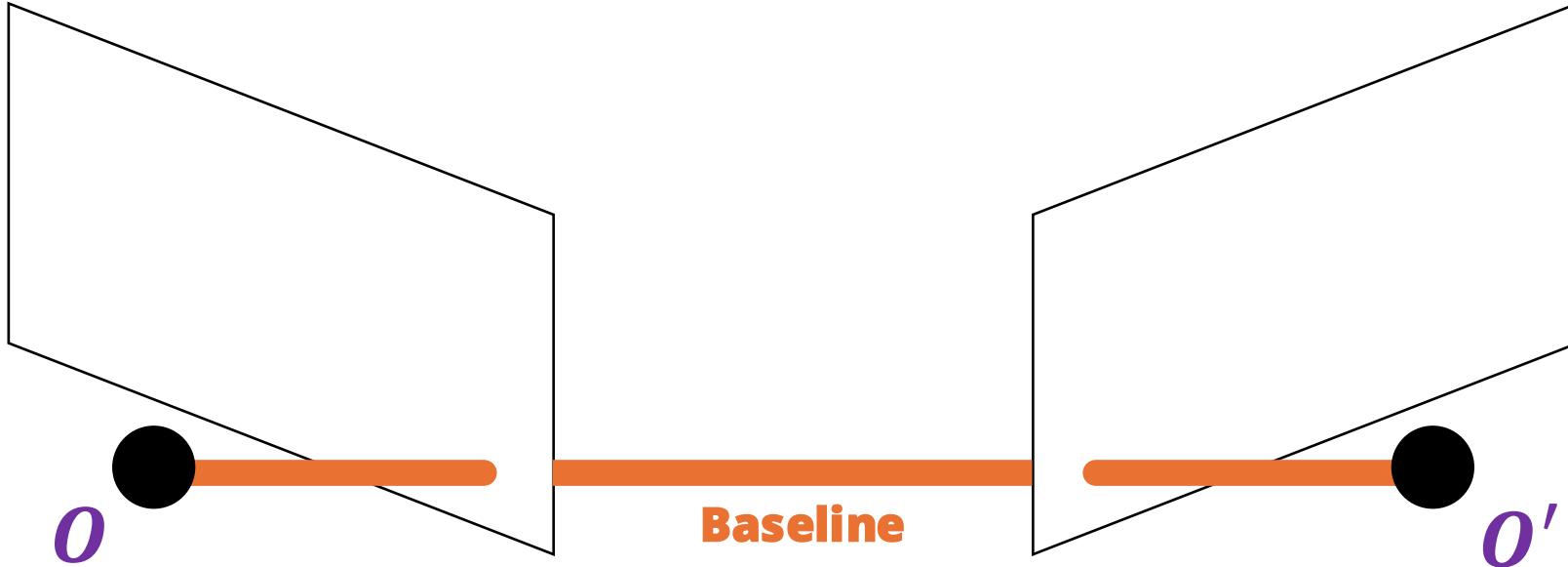
- Projecting points on a ray to another camera forms a **line**, i.e., the corresponding point on the second image *must* lie on this line

Epipolar Constraint



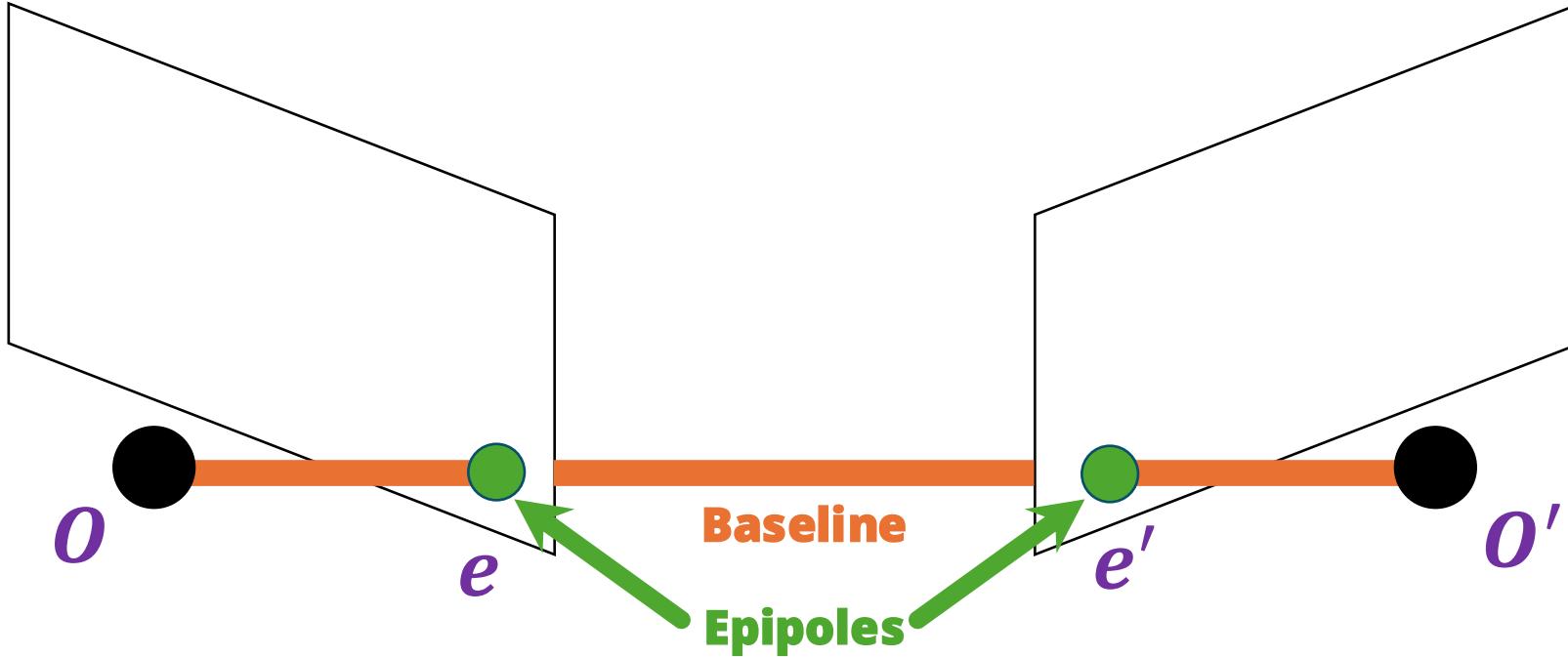
- Projecting points on a ray to another camera forms a **line**, i.e., the corresponding point on the second image *must* lie on this line
- Hence, if the *matched* 2D point is found along this line, we can determine its 3D location

Epipolar Geometry



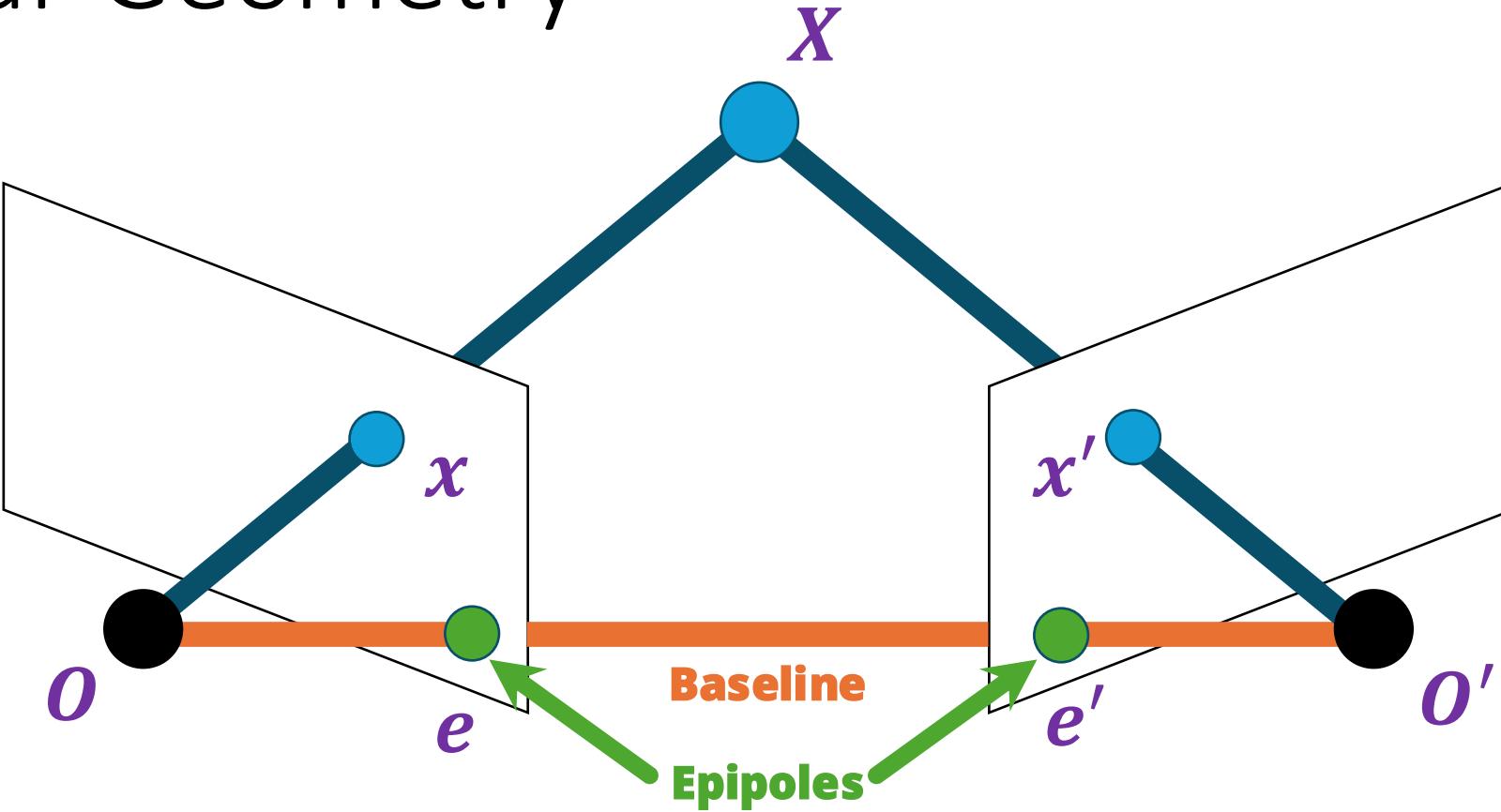
- Suppose we have two cameras with centers \mathbf{o}, \mathbf{o}'
- The **baseline** is the line connecting the origins

Epipolar Geometry



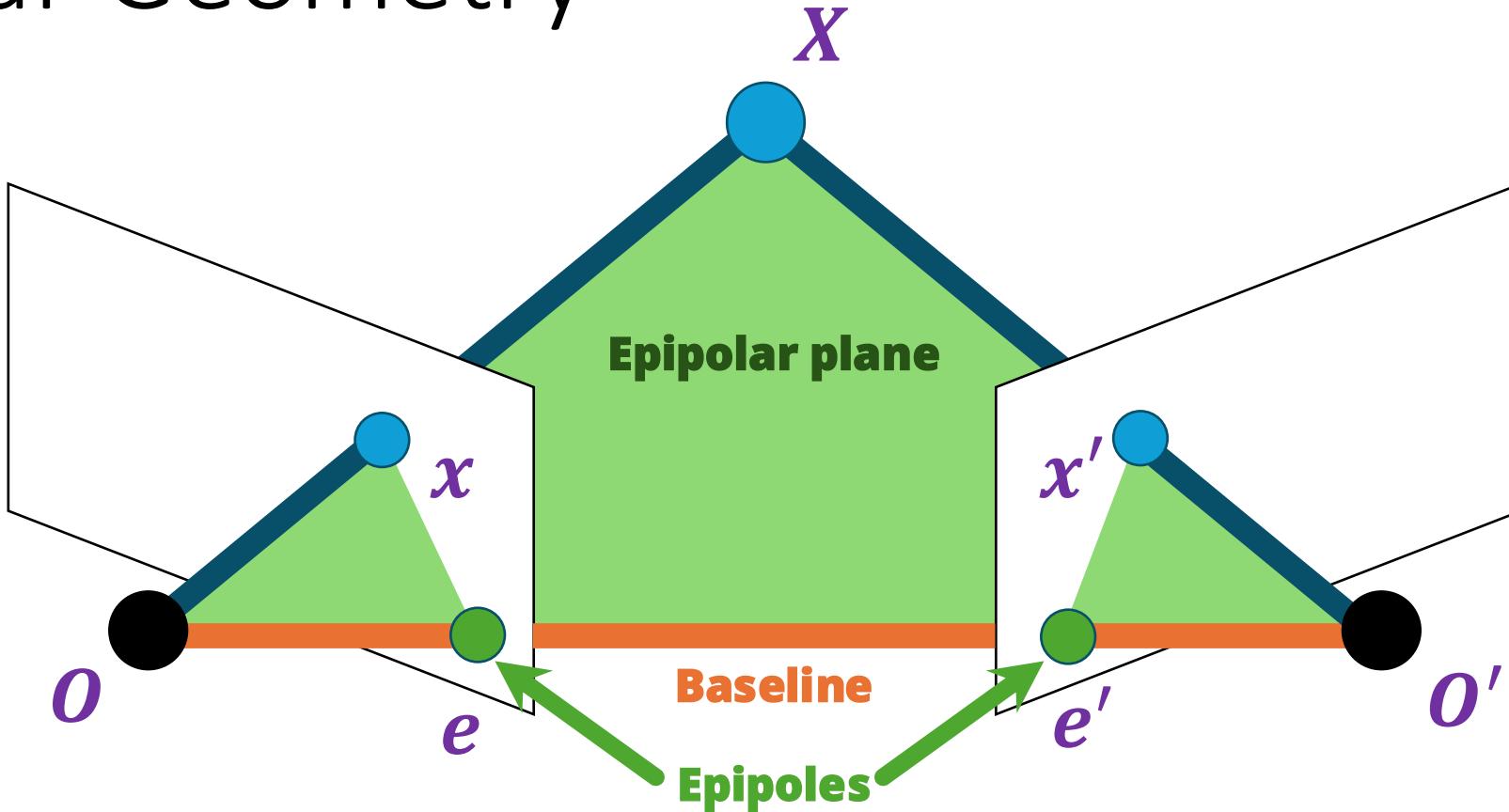
- **Epipoles** e, e' are where the baseline intersects the image planes, or projections of the other camera in each view

Epipolar Geometry



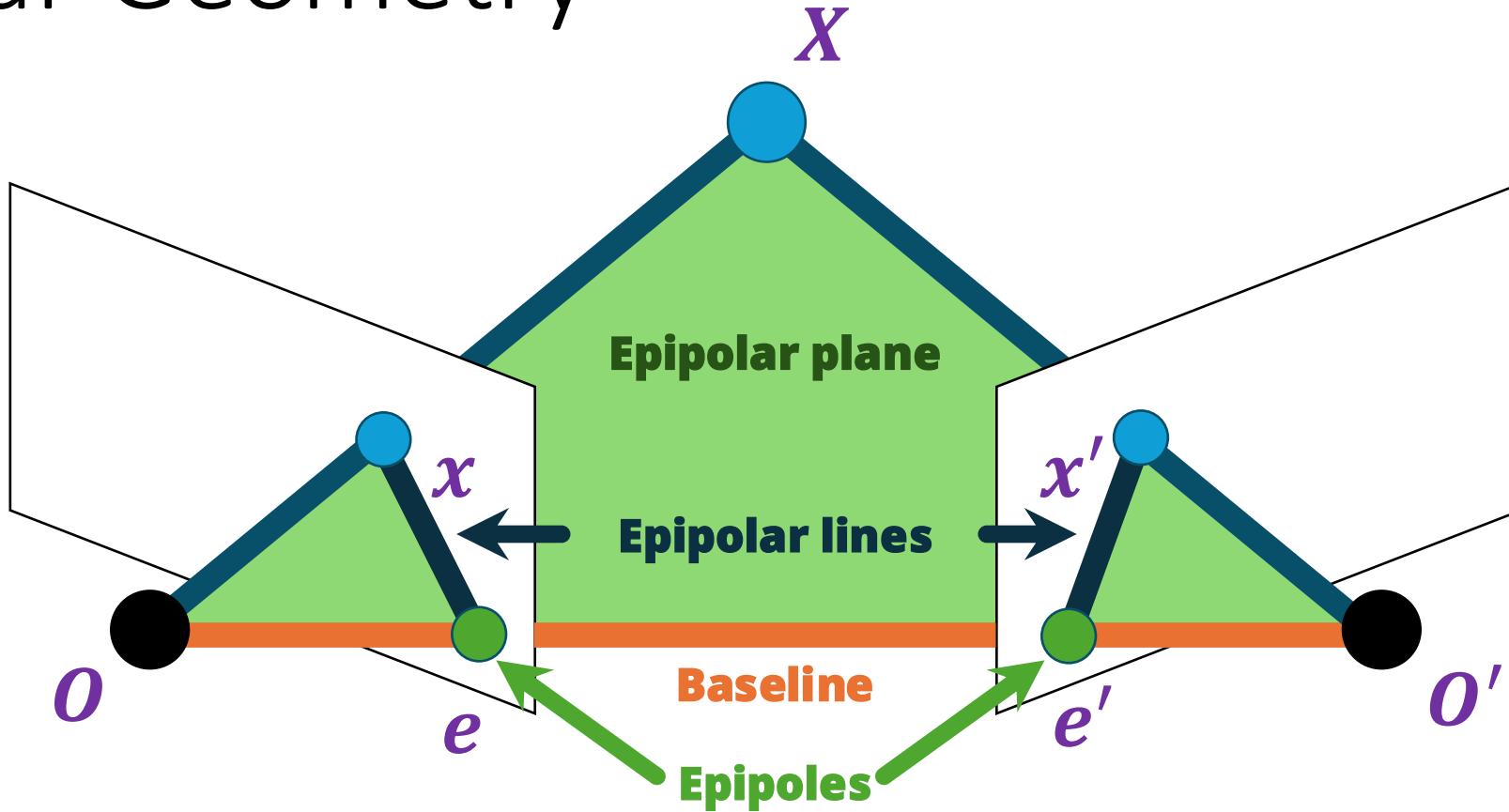
- Consider a **point X** , which projects to x and x'

Epipolar Geometry



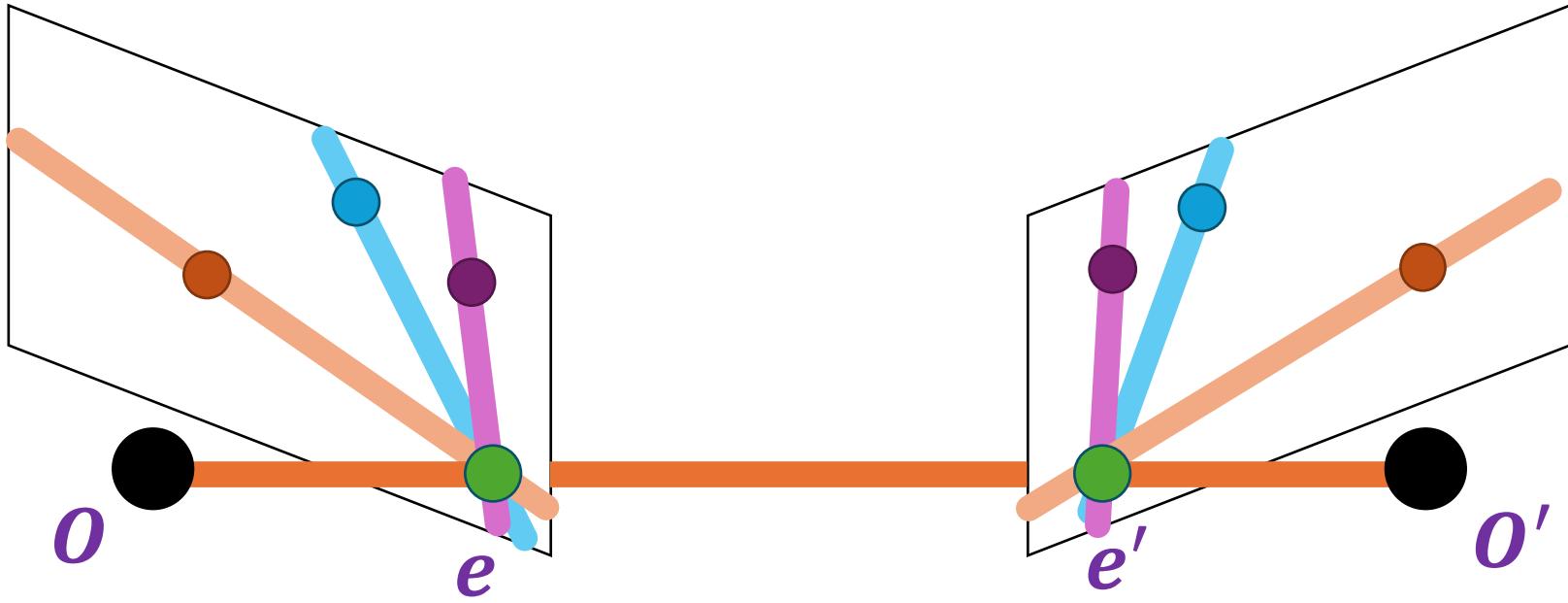
- The plane formed by X , O , and O' is called an **epipolar plane**
- There is a family of planes passing through O and O'

Epipolar Geometry



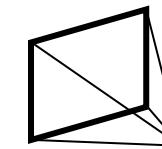
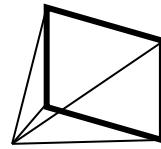
- **Epipolar lines** connect the epipoles to the projections of $\textcolor{violet}{X}$
- Equivalently, they are intersections of the epipolar plane with the image planes – thus, they come in matching pairs

Epipolar Geometry

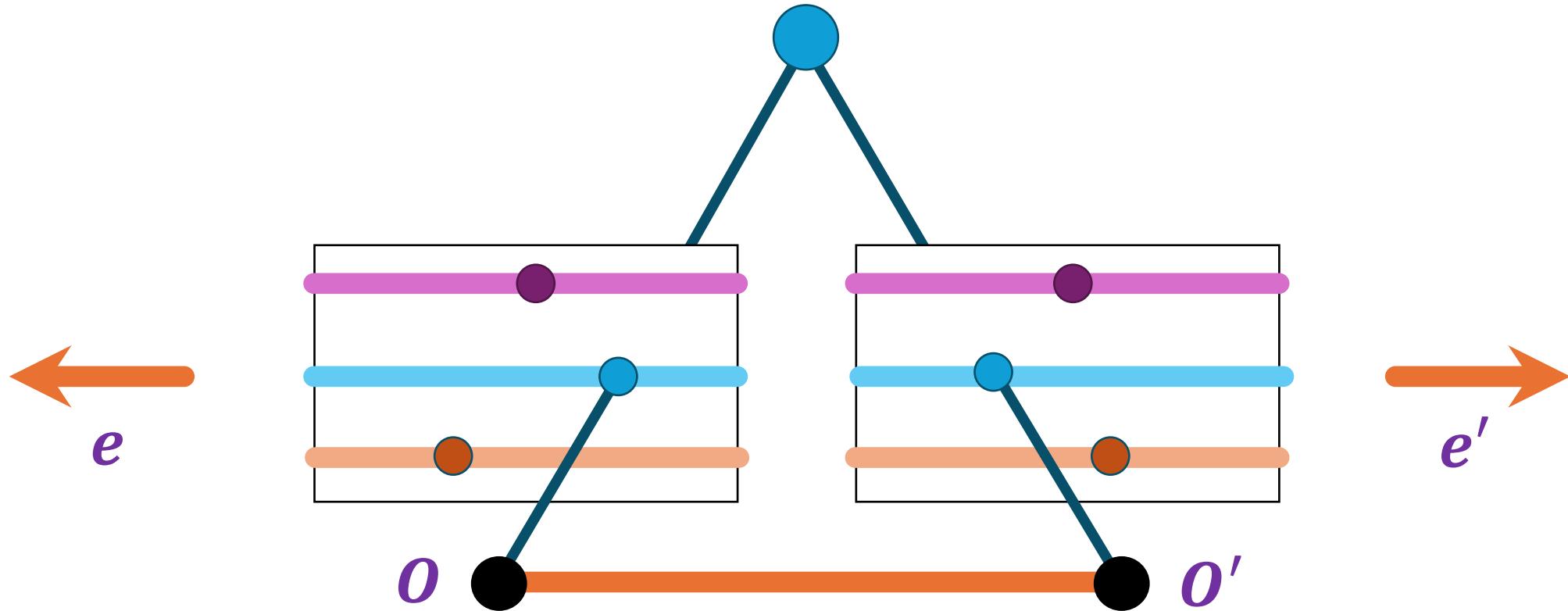


- All **epipolar lines** pass through the **epipoles**
- **Epipoles** can lie outside of the image

Example of Epipolar Lines

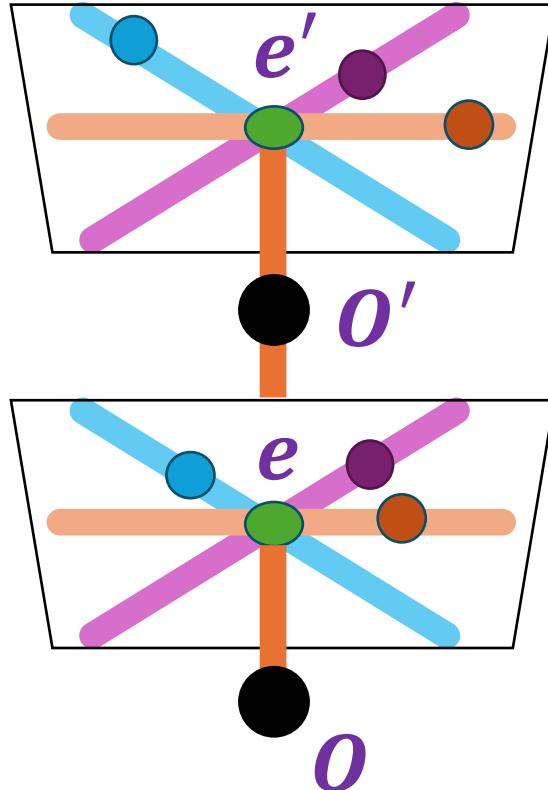


Parallel to Image Plane



- Where are the epipoles and what do the epipolar lines look like?
- Epipoles **infinitely** far away, epipolar lines parallel

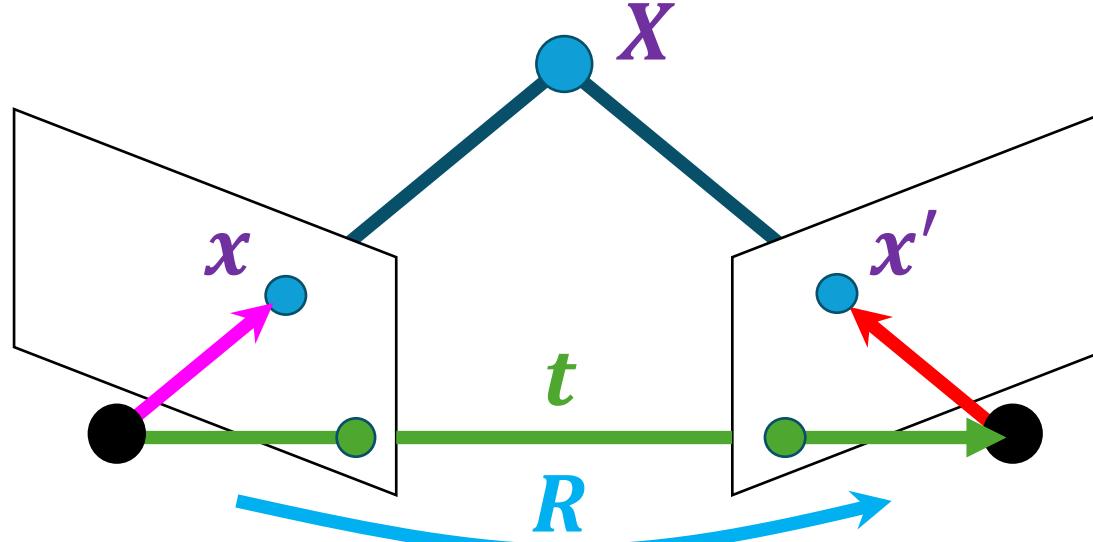
Perpendicular to Image Plane



- Where are the epipoles and what do the epipolar lines look like?
- Epipole is “focus of expansion” and coincides with the principal point of the camera
- Epipolar lines go out from principal point

Epipolar Constraint: Calibrated Case

$$\mathbf{x} \cong \mathbf{K}[\mathbf{R}|\mathbf{t}]X$$



- Assume the intrinsic and extrinsic parameters of the cameras are known (*calibrated*), and world coordinate system is set to that of the first camera
- Then the projection matrices are given by $\mathbf{K}[\mathbf{I} | \mathbf{0}]$ and $\mathbf{K}'[\mathbf{R} | \mathbf{t}]$
- We can pre-multiply the projection matrices (and the image points) by the inverse calibration matrices to get *normalized* image coordinates:

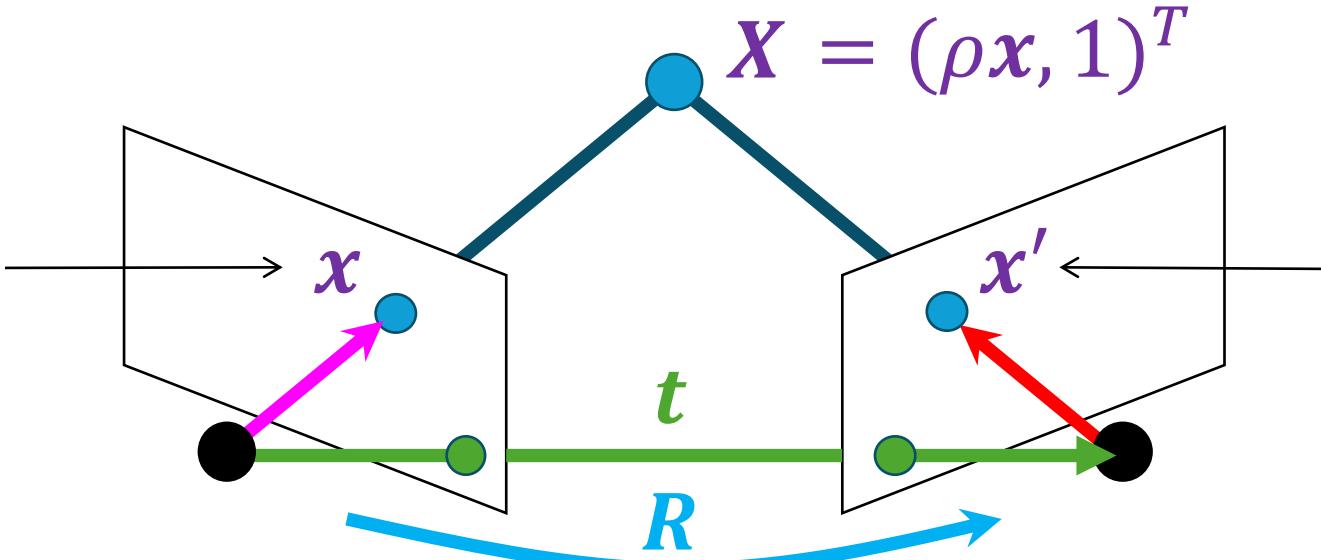
$$\mathbf{x}_{\text{norm}} = \mathbf{K}^{-1}\mathbf{x}_{\text{pixel}} \cong [\mathbf{I} | \mathbf{0}]X, \quad \mathbf{x'}_{\text{norm}} = \mathbf{K}'^{-1}\mathbf{x'}_{\text{pixel}} \cong [\mathbf{R} | \mathbf{t}]X$$

Epipolar Constraint: Calibrated Case

$$\mathbf{x} \cong K[R|t]\mathbf{X}$$

$$\mathbf{x}_{\text{norm}} \cong [\mathbf{I} | \mathbf{0}]\mathbf{X}$$

$$[\mathbf{I} | \mathbf{0}] \begin{pmatrix} \rho \mathbf{x} \\ 1 \end{pmatrix}$$



$$\mathbf{x'}_{\text{norm}} \cong [\mathbf{R} | \mathbf{t}]\mathbf{X}$$

$$[\mathbf{R} | \mathbf{t}] \begin{pmatrix} \rho \mathbf{x} \\ 1 \end{pmatrix} = \rho \mathbf{R}\mathbf{x} + \mathbf{t}$$

$$\mathbf{x}' \cong \rho \mathbf{R}\mathbf{x} + \mathbf{t} \implies \mathbf{x}' \cdot [\mathbf{t} \times (\mathbf{R}\mathbf{x})] = 0$$

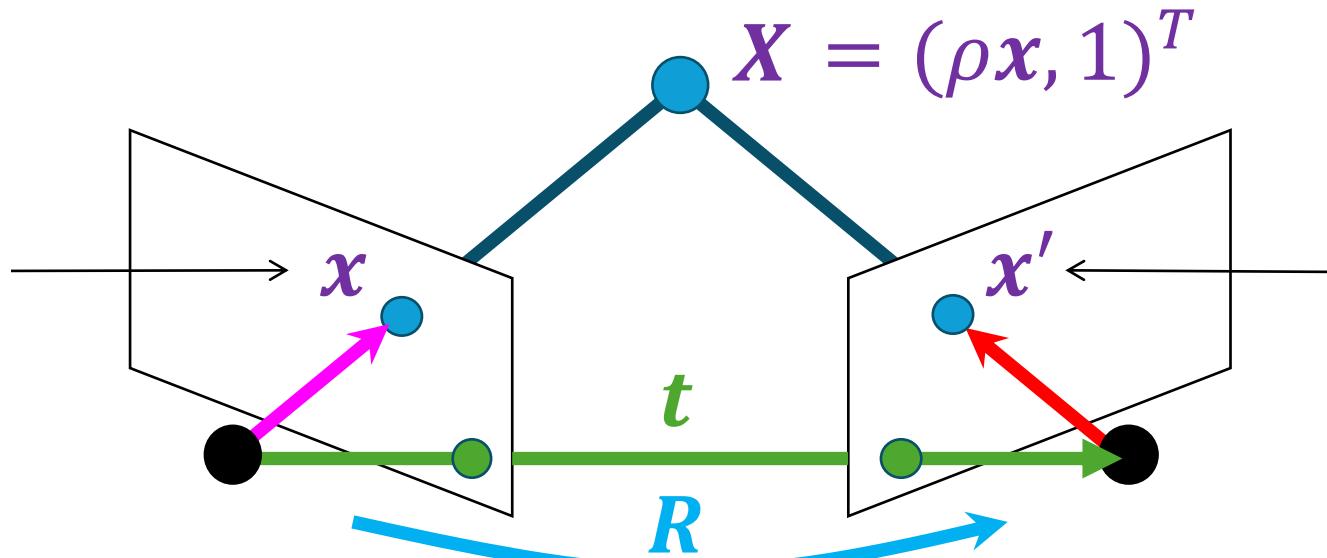
- This means the three vectors \mathbf{x}' , $\mathbf{R}\mathbf{x}$, and \mathbf{t} are linearly dependent, i.e., lying on the same plane
- This constraint can be written using the *triple product*

Epipolar Constraint: Calibrated Case

$$\mathbf{x} \cong \mathbf{K}[\mathbf{R}|\mathbf{t}]X$$

$$\mathbf{x}_{\text{norm}} \cong [\mathbf{I} | \mathbf{0}]X$$

$$[\mathbf{I} | \mathbf{0}] \begin{pmatrix} \rho \mathbf{x} \\ 1 \end{pmatrix}$$



$$\mathbf{x'}_{\text{norm}} \cong [\mathbf{R} | \mathbf{t}]X$$

$$[\mathbf{R} | \mathbf{t}] \begin{pmatrix} \rho \mathbf{x} \\ 1 \end{pmatrix} = \rho \mathbf{R} \mathbf{x} + \mathbf{t}$$

$$\mathbf{x}' \cong \rho \mathbf{R} \mathbf{x} + \mathbf{t} \implies \mathbf{x}' \cdot [\mathbf{t} \times (\mathbf{R} \mathbf{x})] = 0 \implies \mathbf{x}'^T [\mathbf{t}_x] \mathbf{R} \mathbf{x} = 0$$

Recall: $\mathbf{a} \times \mathbf{b} = \begin{bmatrix} 0 & -a_3 & a_2 \\ a_3 & 0 & -a_1 \\ -a_2 & a_1 & 0 \end{bmatrix} \begin{pmatrix} b_1 \\ b_2 \\ b_3 \end{pmatrix} = [\mathbf{a}_\times] \mathbf{b}$

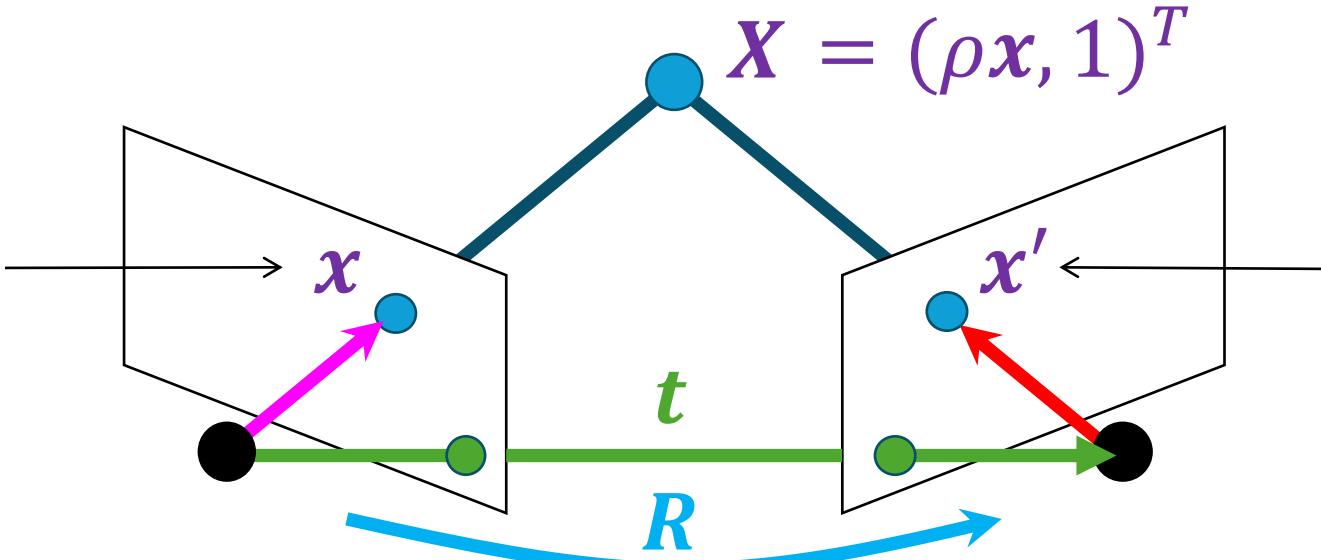
skew-symmetric matrix:
 $\mathbf{A}^T = -\mathbf{A}$

Epipolar Constraint: Calibrated Case

$$x \cong K[R|t]X$$

$$x_{\text{norm}} \cong [I | 0]X$$

$$[I | 0] \begin{pmatrix} \rho x \\ 1 \end{pmatrix}$$



$$x'_{\text{norm}} \cong [R | t]X$$

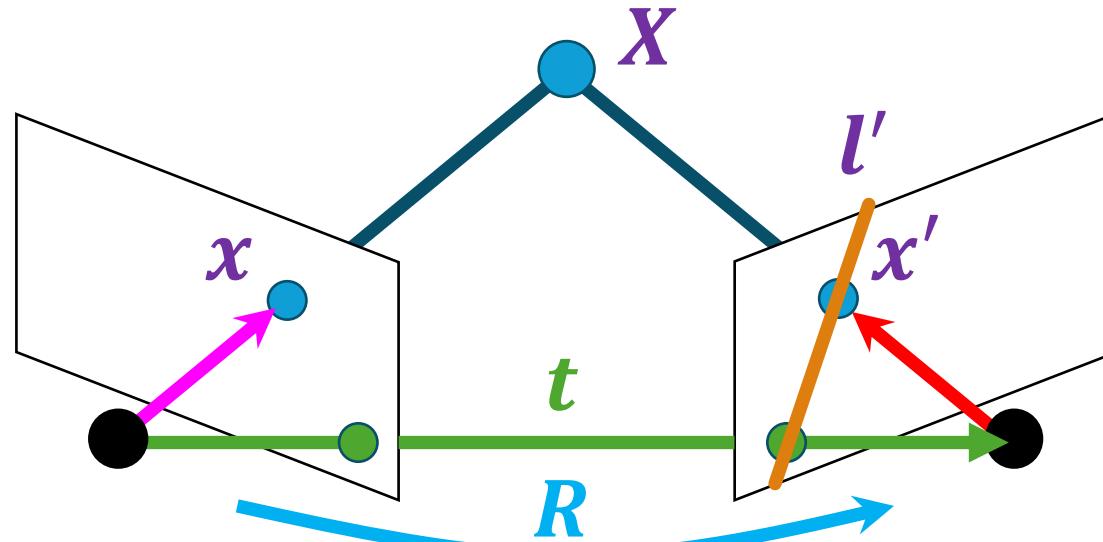
$$[R | t] \begin{pmatrix} \rho x \\ 1 \end{pmatrix} = \rho Rx + t$$

$$x' \cong \rho Rx + t \implies x' \cdot [t \times (Rx)] = 0 \implies x'^T [t_x] Rx = 0 \implies x'^T E x = 0$$



Essential Matrix

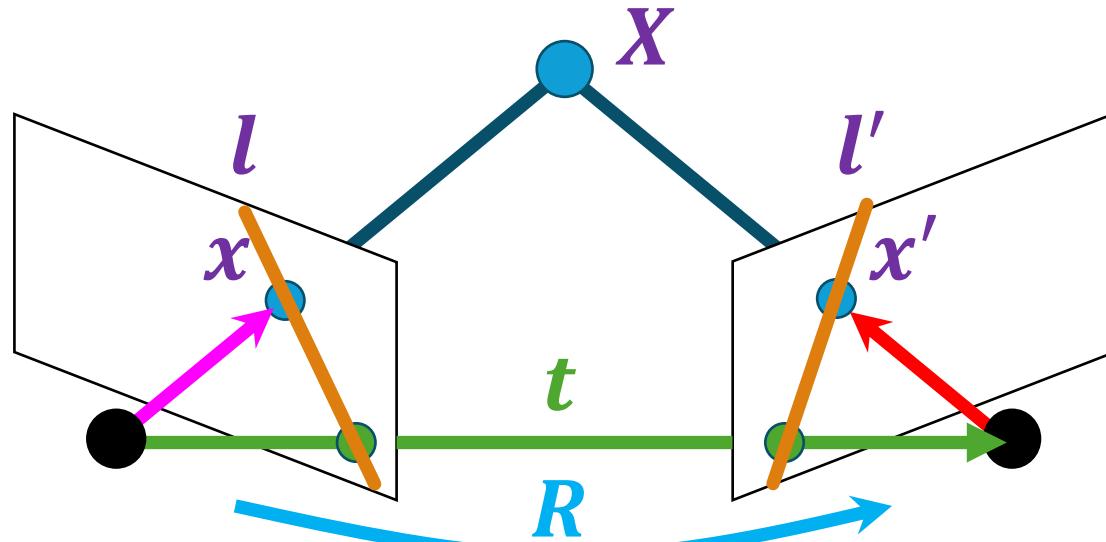
The Essential Matrix



$$\mathbf{l}' = \mathbf{E}^T \mathbf{x}$$
$$\mathbf{x}'^T \boxed{\mathbf{E} \mathbf{x}} = 0$$
$$(x', y', 1) \begin{bmatrix} e_{11} & e_{12} & e_{13} \\ e_{21} & e_{22} & e_{23} \\ e_{31} & e_{32} & e_{33} \end{bmatrix} \begin{pmatrix} x \\ y \\ 1 \end{pmatrix} = 0$$

- \mathbf{Ex} is the **epipolar line** associated with \mathbf{x} ($\mathbf{l}' = \mathbf{Ex}$)
- Recall: a line is given by $ax + by + c = 0$ or $\mathbf{l}^T \mathbf{x} = 0$ in homogeneous coordinates, where $\mathbf{l} = (a, b, c)^T$ and $\mathbf{x} = (x, y, 1)^T$
- $\mathbf{x}'^T \mathbf{E} \mathbf{x} = \mathbf{x}'^T \mathbf{l}' = 0$ means \mathbf{x}' lies on the epipolar line \mathbf{l}'

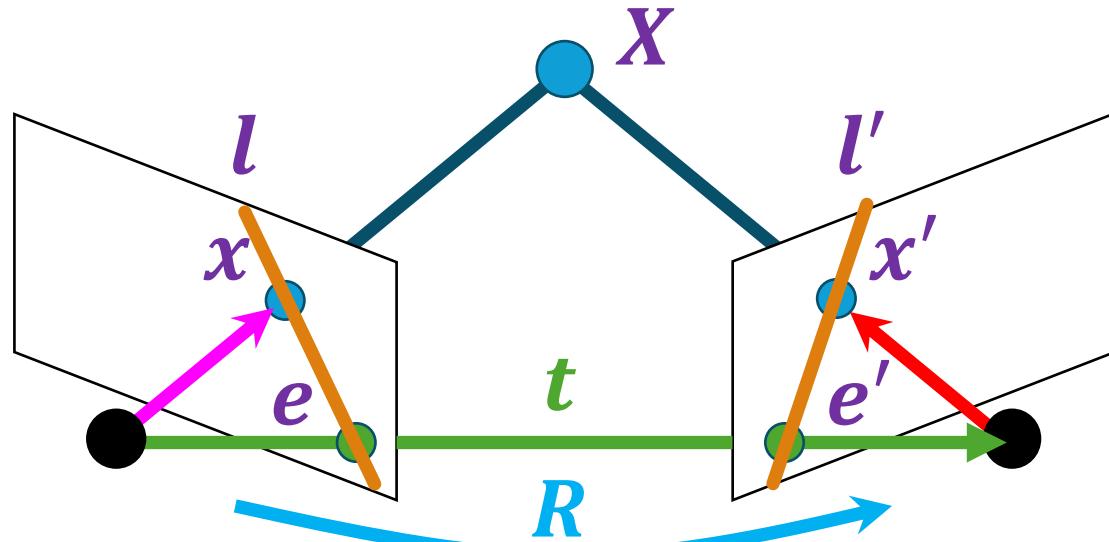
The Essential Matrix



$$\begin{aligned} \mathbf{l} &= E^T \mathbf{x}' \\ \boxed{\mathbf{x}'^T E \mathbf{x}} &= 0 \\ (x', y', 1) \begin{bmatrix} e_{11} & e_{12} & e_{13} \\ e_{21} & e_{22} & e_{23} \\ e_{31} & e_{32} & e_{33} \end{bmatrix} \begin{pmatrix} x \\ y \\ 1 \end{pmatrix} &= 0 \end{aligned}$$

- $E\mathbf{x}$ is the **epipolar line** associated with \mathbf{x} ($\mathbf{l}' = E\mathbf{x}$)
- $\mathbf{x}'^T E \mathbf{x} = \mathbf{x}'^T \mathbf{l}' = 0$ means \mathbf{x}' lies on the epipolar line \mathbf{l}'
- Equivalently, $E^T \mathbf{x}'$ is the **epipolar line** associated with \mathbf{x}' ($\mathbf{l} = E^T \mathbf{x}'$)
- $\mathbf{x}'^T E \mathbf{x} = \mathbf{l} \mathbf{x} = 0$ means \mathbf{x} lies on the epipolar line \mathbf{l}

The Essential Matrix

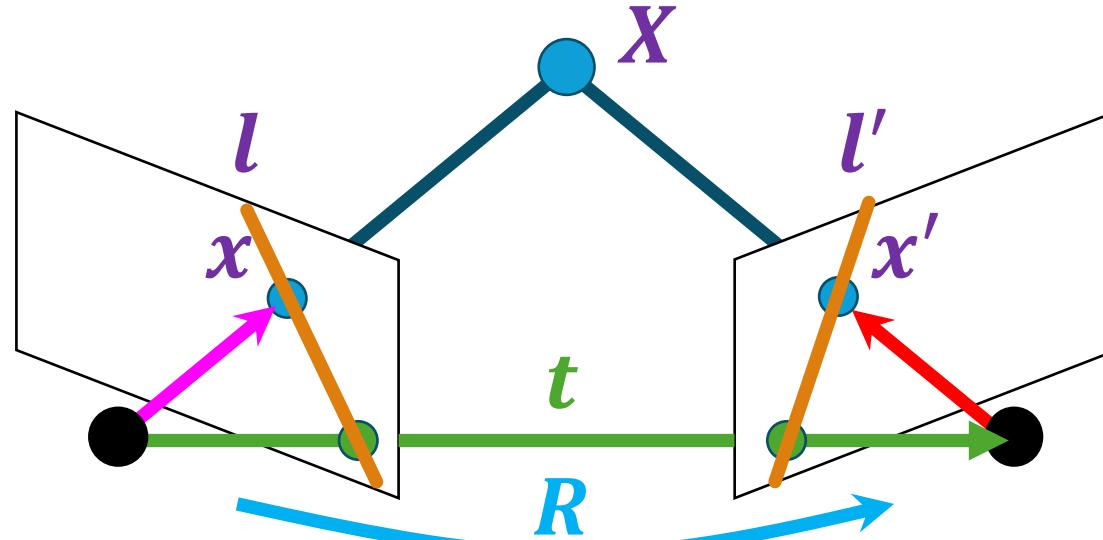


$$\mathbf{x}'^T \mathbf{E} \mathbf{x} = 0$$
$$(x', y', 1) \begin{bmatrix} e_{11} & e_{12} & e_{13} \\ e_{21} & e_{22} & e_{23} \\ e_{31} & e_{32} & e_{33} \end{bmatrix} \begin{pmatrix} x \\ y \\ 1 \end{pmatrix} = 0$$

- \mathbf{Ex} is the **epipolar line** associated with \mathbf{x} ($\mathbf{l}' = \mathbf{Ex}$)
- $\mathbf{E}^T \mathbf{x}'$ is the **epipolar line** associated with \mathbf{x}' ($\mathbf{l} = \mathbf{E}^T \mathbf{x}'$)
- $\mathbf{Ee} = \mathbf{0}$ and $\mathbf{E}^T \mathbf{e}' = \mathbf{0}$, where \mathbf{e}, \mathbf{e}' are the epipoles
- \mathbf{E} is singular (rank two) and has five degrees of freedom => why?
 - $\mathbf{E} = [\mathbf{t}_x] \mathbf{R}$! $[\mathbf{t}_x]$ is skew-symmetric; has rank 2
 - \mathbf{R} : 3 DoF, \mathbf{t} : 3 DoF, but we lost 1 DoF due to scale; move along \mathbf{t} doesn't change \mathbf{l}

Epipolar Constraint: Uncalibrated

$$\mathbf{x} \cong \mathbf{K}[\mathbf{R}|\mathbf{t}] \mathbf{X}$$



$$\mathbf{x}'^T \mathbf{E} \mathbf{x} = 0$$
$$(x', y', 1) \begin{bmatrix} e_{11} & e_{12} & e_{13} \\ e_{21} & e_{22} & e_{23} \\ e_{31} & e_{32} & e_{33} \end{bmatrix} \begin{pmatrix} x \\ y \\ 1 \end{pmatrix} = 0$$

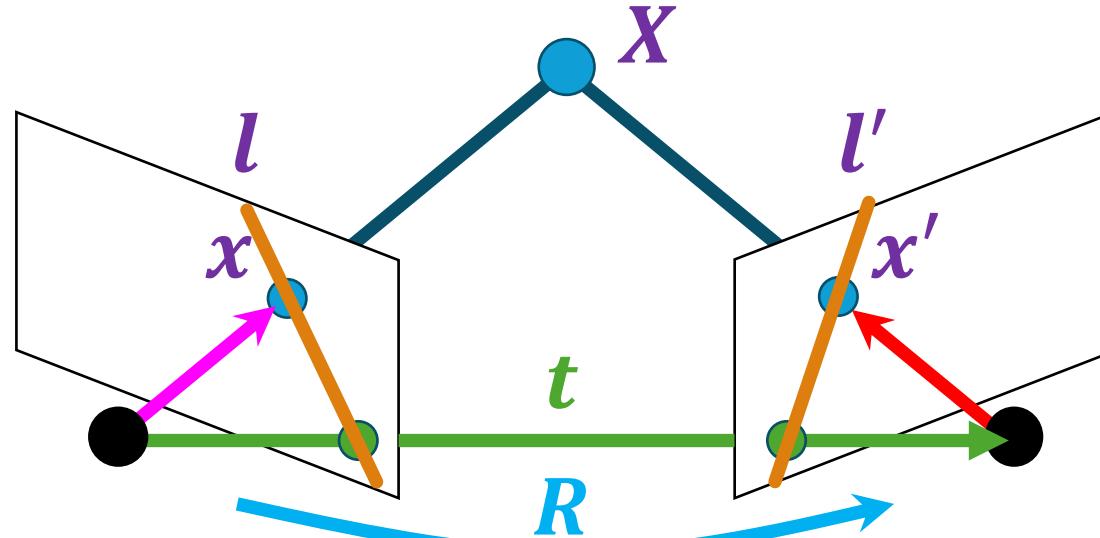
- What if camera intrinsics \mathbf{K}, \mathbf{K}' are unknown?
- We can write the epipolar constraint:

$$\mathbf{x}'_{\text{norm}}^T \mathbf{E} \mathbf{x}_{\text{norm}} = 0$$

where $\mathbf{x}_{\text{norm}} = \mathbf{K}^{-1} \mathbf{x}$, $\mathbf{x}'_{\text{norm}} = \mathbf{K}'^{-1} \mathbf{x}'$

Epipolar Constraint: Uncalibrated

$$\mathbf{x} \cong \mathbf{K}[\mathbf{R}|\mathbf{t}] \mathbf{X}$$



$$\mathbf{x}'^T \mathbf{E} \mathbf{x} = 0$$
$$(x', y', 1) \begin{bmatrix} e_{11} & e_{12} & e_{13} \\ e_{21} & e_{22} & e_{23} \\ e_{31} & e_{32} & e_{33} \end{bmatrix} \begin{pmatrix} x \\ y \\ 1 \end{pmatrix} = 0$$

- What if camera intrinsics \mathbf{K}, \mathbf{K}' are unknown?
- We can write the epipolar constraint:

Fundamental Matrix

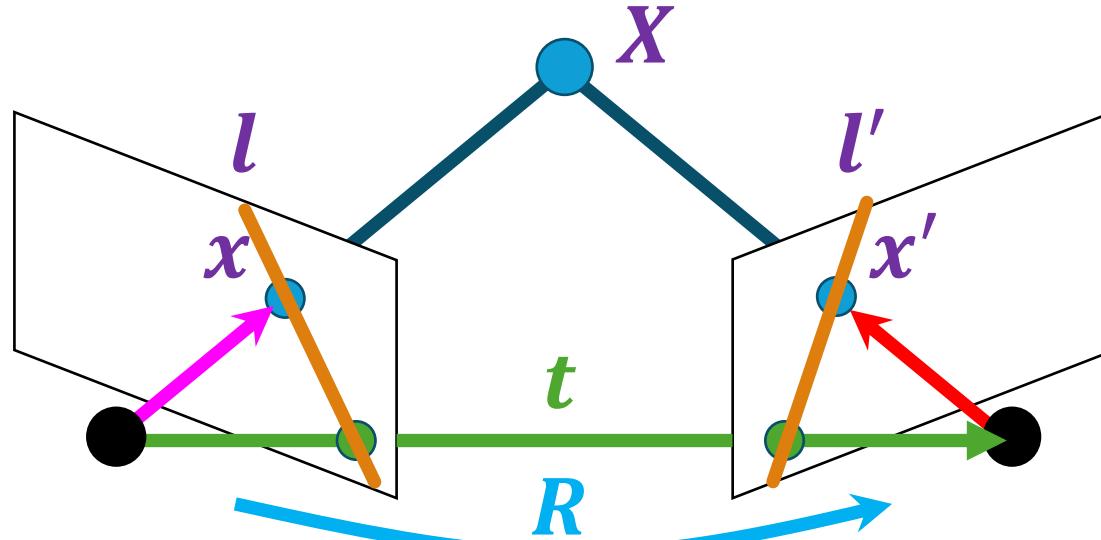
$$\mathbf{F} = \mathbf{K}'^{-T} \mathbf{E} \mathbf{K}^{-1}$$

$$\mathbf{x}'^T \mathbf{E} \mathbf{x} = \mathbf{x}'^T \boxed{\mathbf{K}'^{-T} \mathbf{E} \mathbf{K}^{-1}} \mathbf{x} = 0$$

where $\mathbf{x}_{\text{norm}} = \mathbf{K}^{-1} \mathbf{x}$, $\mathbf{x}'_{\text{norm}} = \mathbf{K}'^{-1} \mathbf{x}'$

The Fundamental Matrix

$$\mathbf{x} \cong \mathbf{K}[\mathbf{R}|\mathbf{t}]\mathbf{X}$$



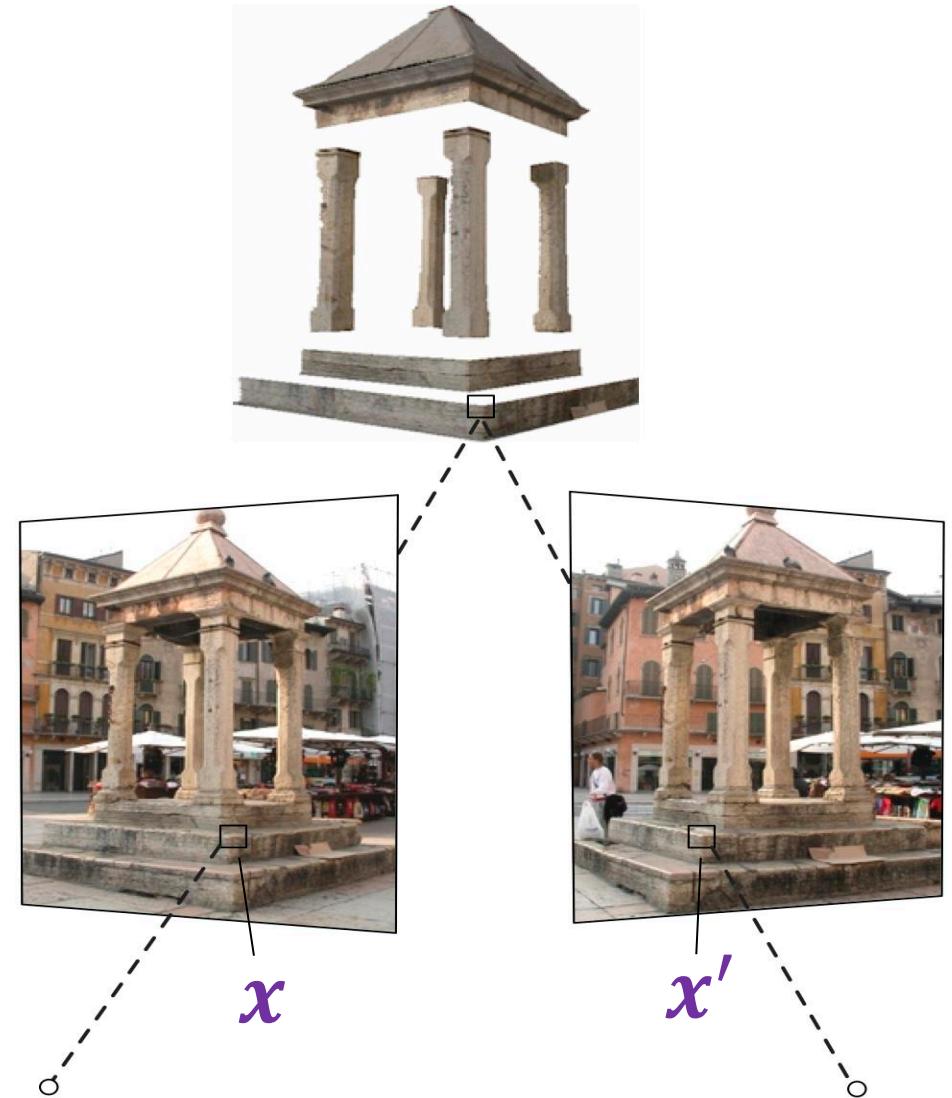
$$\mathbf{x}'^T \mathbf{F} \mathbf{x} = 0$$

$$(x', y', 1) \begin{bmatrix} f_{11} & f_{12} & f_{13} \\ f_{21} & f_{22} & f_{23} \\ f_{31} & f_{32} & f_{33} \end{bmatrix} \begin{pmatrix} x \\ y \\ 1 \end{pmatrix} = 0$$

- $\mathbf{F}\mathbf{x}$ is the **epipolar line** associated with \mathbf{x} ($\mathbf{l}' = \mathbf{F}\mathbf{x}$)
- $\mathbf{F}^T\mathbf{x}'$ is the **epipolar line** associated with \mathbf{x}' ($\mathbf{l} = \mathbf{F}^T\mathbf{x}'$)
- $\mathbf{F}\mathbf{e} = \mathbf{0}$ and $\mathbf{F}^T\mathbf{e}' = \mathbf{0}$, where \mathbf{e}, \mathbf{e}' are the epipoles
- \mathbf{F} is singular (rank **two**) and has **seven** degrees of freedom => why?
 - $\mathbf{F} = \mathbf{K}'^{-T} [\mathbf{t}_x] \mathbf{R} \mathbf{K}^{-1}$! $[\mathbf{t}_x]$ is skew-symmetric; has rank 2
 - 9 elements, but we lost 1 DoF to scale, and 1 DoF to rank constraint

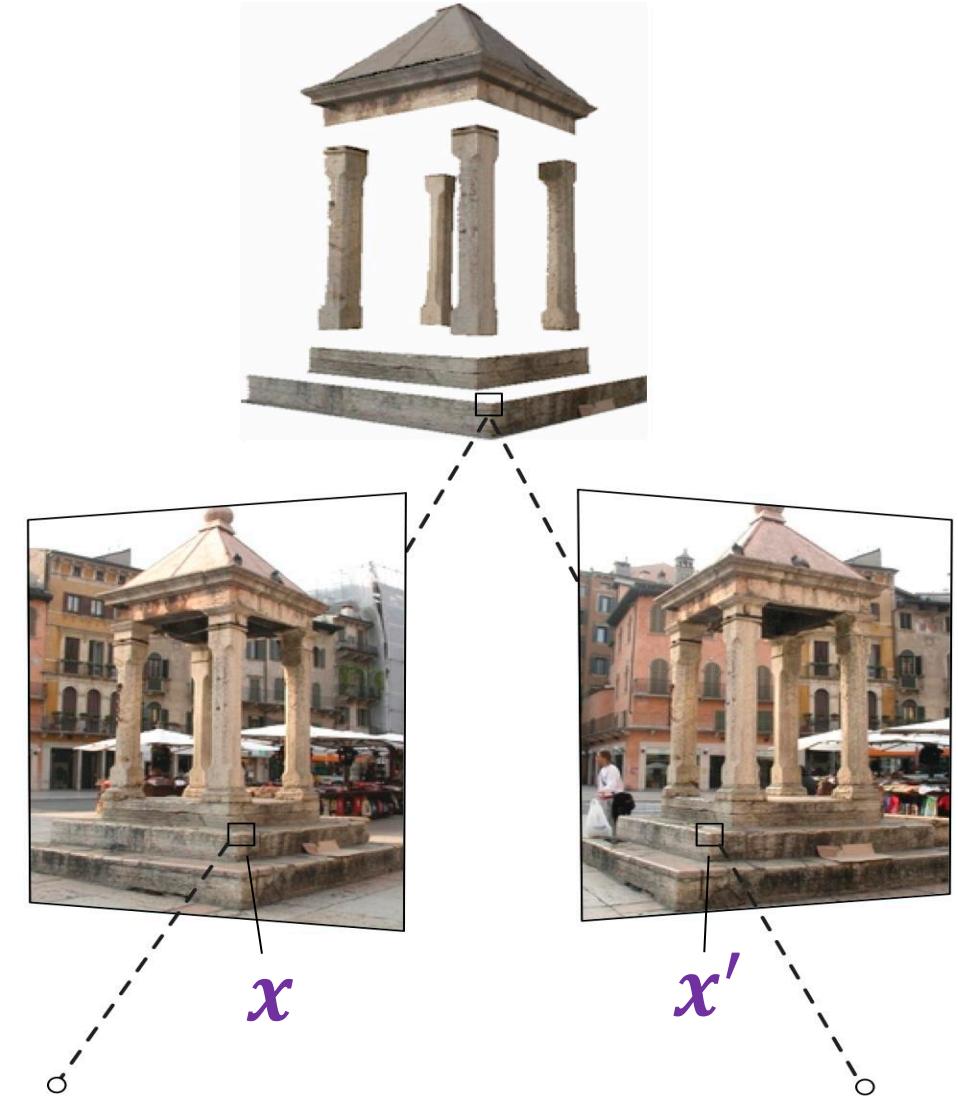
How Can We Use the Epipolar Constraint?

- **Given:** F , \mathbf{x} , \mathbf{x}'
- **Q:** does there exist a 3D point that projects to \mathbf{x} and \mathbf{x}' ?
- **A:** Yes, if $\text{residual}(\mathbf{x}'^T F \mathbf{x})$ is sufficiently low
- Note: the interpretation of $\text{residual}(\mathbf{x}'^T F \mathbf{x})$ is the distance (geometric or algebraic) between \mathbf{x} and $\mathbf{l} = F^T \mathbf{x}'$, or \mathbf{x}' and $\mathbf{l}' = F \mathbf{x}$



How Can We Use the Epipolar Constraint?

- **Given:** \mathbf{F}
- **Q:** how do we find \mathbf{R}, \mathbf{t} ?
- **A:**
 - **Step 0:** estimate \mathbf{K}, \mathbf{K}' if not known (self-calibration)
 - **Step 1:** compute $\mathbf{E} = \mathbf{K}'^T \mathbf{F} \mathbf{K}$
 - **Step 2:** since $\mathbf{E} = [\mathbf{t}_x] \mathbf{R}$, perform SVD on $\mathbf{E} = \mathbf{U} \mathbf{\Sigma} \mathbf{V}^T$. We have 4 solutions $(\mathbf{R}_1, \pm \mathbf{t}), (\mathbf{R}_2, \pm \mathbf{t})$, where $\mathbf{t} = \mathbf{U}[:, 3]$, $\mathbf{R}_1 = \mathbf{U} \mathbf{W} \mathbf{V}^T$, $\mathbf{R}_2 = \mathbf{U} \mathbf{W}^T \mathbf{V}^T$, and \mathbf{W} is the matrix that rotates 90° about z-axis.
 - **Step 3:** pick the one that gives 3D points in front of both cameras (cheirality check).



How to Estimate the Fundamental Matrix?

- **Given:** correspondences $\mathbf{x}_i = (x_i, y_i, 1)^T$ and $\mathbf{x}'_i = (x'_i, y'_i, 1)^T$
- **Constraint:** $\mathbf{x}'^T \mathbf{F} \mathbf{x} = 0$

$$(x', y', 1) \begin{bmatrix} f_{11} & f_{12} & f_{13} \\ f_{21} & f_{22} & f_{23} \\ f_{31} & f_{32} & f_{33} \end{bmatrix} \begin{pmatrix} x \\ y \\ 1 \end{pmatrix} = 0 \rightarrow (x'x, x'y, x', y'x, y'y, y', x, y, 1) \begin{pmatrix} f_{11} \\ f_{12} \\ f_{13} \\ f_{21} \\ f_{22} \\ f_{23} \\ f_{31} \\ f_{32} \\ f_{33} \end{pmatrix} = 0$$

How to Estimate the Fundamental Matrix?

- **Given:** correspondences $\mathbf{x}_i = (x_i, y_i, 1)^T$ and $\mathbf{x}'_i = (x'_i, y'_i, 1)^T$
- **Constraint:** $\mathbf{x}'^T \mathbf{F} \mathbf{x} = 0$

$$\underbrace{\begin{bmatrix} x'_1 x_1 & x'_1 y_1 & x'_1 & y'_1 x_1 & y'_1 y_1 & y'_1 & x_1 & y_1 & 1 \\ \vdots & \vdots \\ x'_n x_n & x'_n y_n & x'_n & y'_n x_n & y'_n y_n & y'_n & x_n & y_n & 1 \end{bmatrix}}_{\mathbf{A}} \underbrace{\begin{pmatrix} f_{11} \\ f_{12} \\ f_{13} \\ f_{21} \\ f_{22} \\ f_{23} \\ f_{31} \\ f_{32} \\ f_{33} \end{pmatrix}}_{= \mathbf{0}} = \mathbf{0}$$

Homogeneous least squares to find \mathbf{f} :

$$\arg \min_{\|\mathbf{f}\|=1} \|\mathbf{A}\mathbf{f}\|_2^2 \quad \rightarrow \quad \text{Least eigenvector of } \mathbf{A}^T \mathbf{A}$$

Small Trick to Enforce Rank-2 Constraint

- We know \mathbf{F} must be singular/rank 2. How do we force that?
- **Solution:** take SVD of the initial estimate and throw out the smallest singular value

$$\mathbf{F}_{\text{init}} = \mathbf{U}\Sigma\mathbf{V}^T$$

$$\downarrow$$
$$\Sigma = \begin{bmatrix} \sigma_1 & 0 & 0 \\ 0 & \sigma_2 & 0 \\ 0 & 0 & \cancel{\sigma_3} \end{bmatrix} \longrightarrow \Sigma' = \begin{bmatrix} \sigma_1 & 0 & 0 \\ 0 & \sigma_2 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$
$$\downarrow$$
$$\mathbf{F} = \mathbf{U}\Sigma'\mathbf{V}^T$$

The Fundamental Matrix Song



By Daniel Wedge: <https://danielwedge.com/fmatrix/>

The Fundamental Matrix Song – Live!

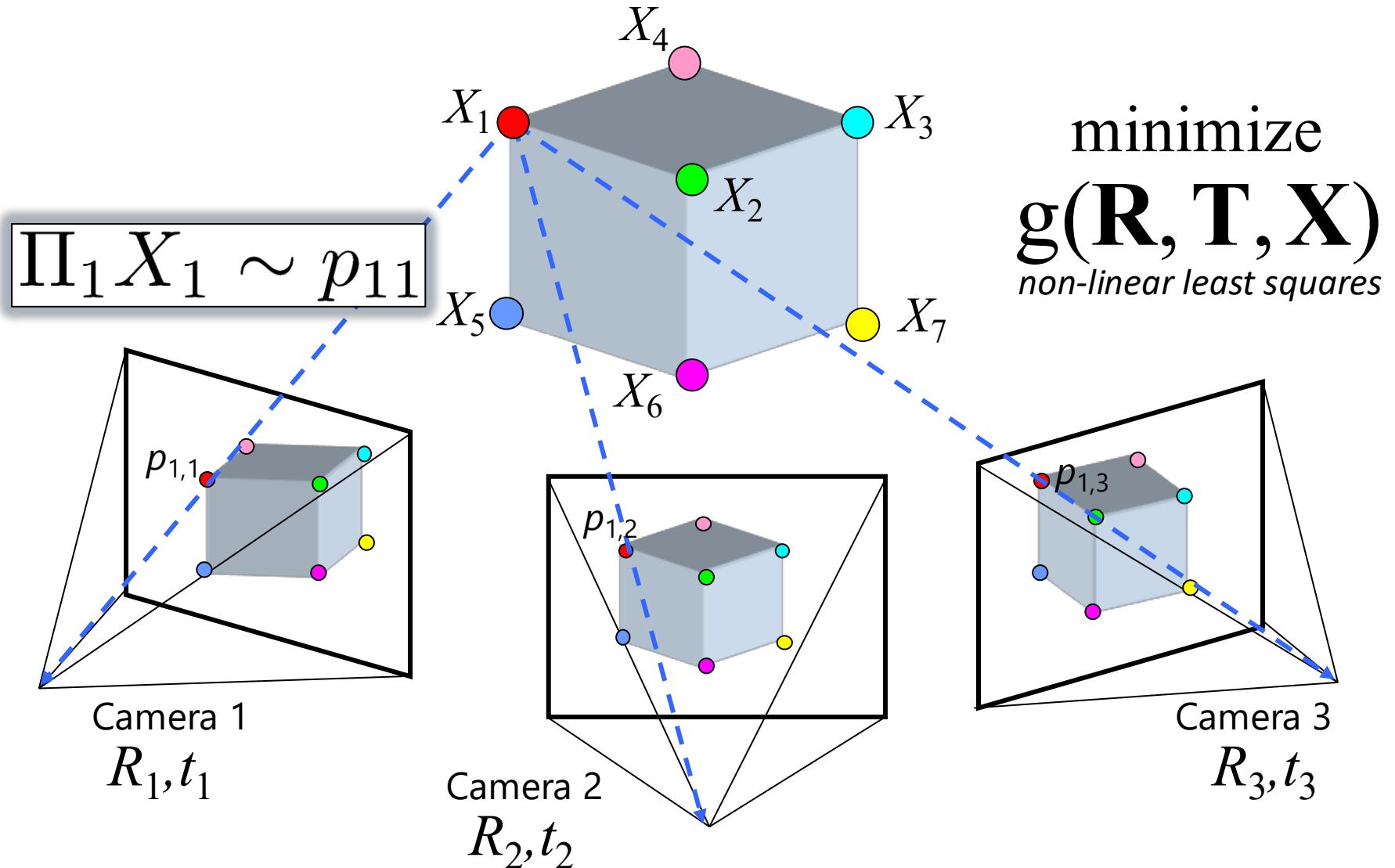


Daniel Wedge and the CVPR house band at CVPR 2023 in Vancouver

More Than Two Views?

- The geometry of three views is described by a $3 \times 3 \times 3$ tensor called the *trifocal tensor*
- The geometry of four views is described by a $3 \times 3 \times 3 \times 3$ tensor called the *quadrifocal tensor*
- After this it starts to get complicated...
- Or we can pose it as an optimization problem

Structure from Motion (SfM)



Bundle Adjustment

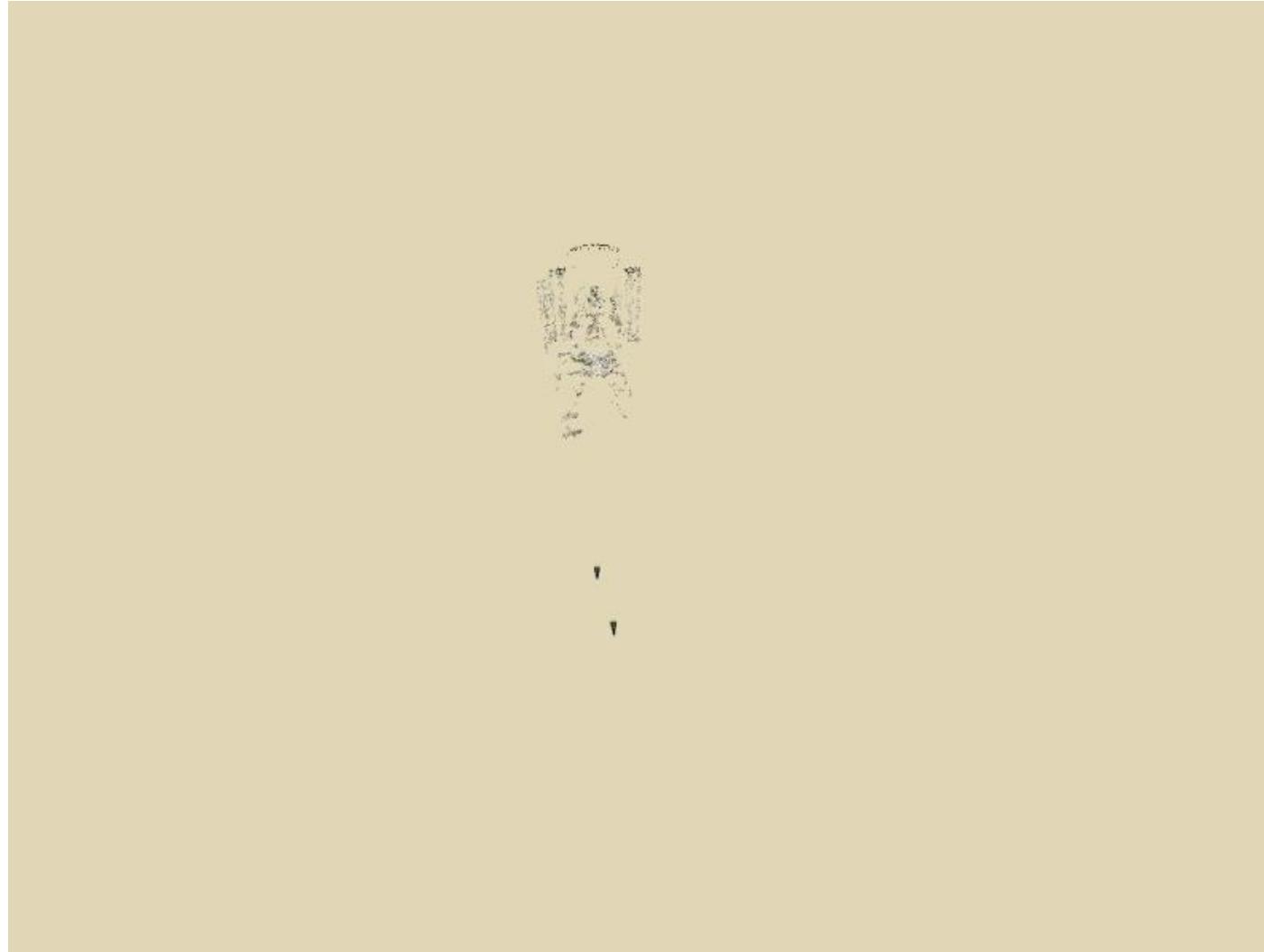
- Minimize reprojection errors:

$$g(\mathbf{X}, \mathbf{R}, \mathbf{T}) = \sum_{i=1}^m \sum_{j=1}^n w_{ij} \cdot \left\| \underbrace{\mathbf{P}(\mathbf{x}_i, \mathbf{R}_j, \mathbf{t}_j)}_{\substack{\text{predicted} \\ \text{image location}}} - \underbrace{\begin{bmatrix} u_{i,j} \\ v_{i,j} \end{bmatrix}}_{\substack{\text{observed} \\ \text{image location}}} \right\|^2$$

indicator variable:
is point i visible in image j ?

- Optimized using non-linear least squares, e.g., Levenberg-Marquardt algorithm
- Susceptible to local minima; requires careful initialization

Incremental Structure from Motion



- Photo Tourism (Snavely et al., SIGGAPH'06)
- Trevi Fountain, Rome
 - 466 Internet photos
 - > 100,000 3D points
 - Very large optimization problem

Practical SfM Tools

- COLMAP (by Schönberger et al.): <https://colmap.github.io/>
- nerfstudio COLMAP Python wrapper:
https://docs.nerf.studio/quickstart/custom_dataset.html
- Still, with thousands of images, it can take many hours or even days!
- There's a family of methods optimized for efficiency and continuous streams, often referred to as *Simultaneous Localization and Mapping (SLAM)*, particularly useful for robot navigation for instance
 - One classic, widely-used system is *ORB-SLAM* (Mur-Artal et al., 2015)
- We will discuss learning-based approaches later

Part 1&2 Summary – Multi-view Geometry

- Camera model and projection
 - Homogeneous coordinates
 - Pinhole camera, perspective projection $\mathbf{x} \cong \mathbf{K}[\mathbf{R}|\mathbf{t}]X$
 - Intrinsics \mathbf{K} , extrinsics $[\mathbf{R}|\mathbf{t}]$
 - Camera calibration
- Epipolar geometry
 - Epipolar plane, epipolar lines
 - Essential matrix $\mathbf{E} \Rightarrow \mathbf{x}'^T \mathbf{E} \mathbf{x}_{\text{norm}} = 0$ (calibrated)
 - Fundamental matrix $\mathbf{F} \Rightarrow \mathbf{x}'^T \mathbf{F} \mathbf{x} = 0$ (uncalibrated)
- Structure from Motion (SfM)
 - Bundle adjustment