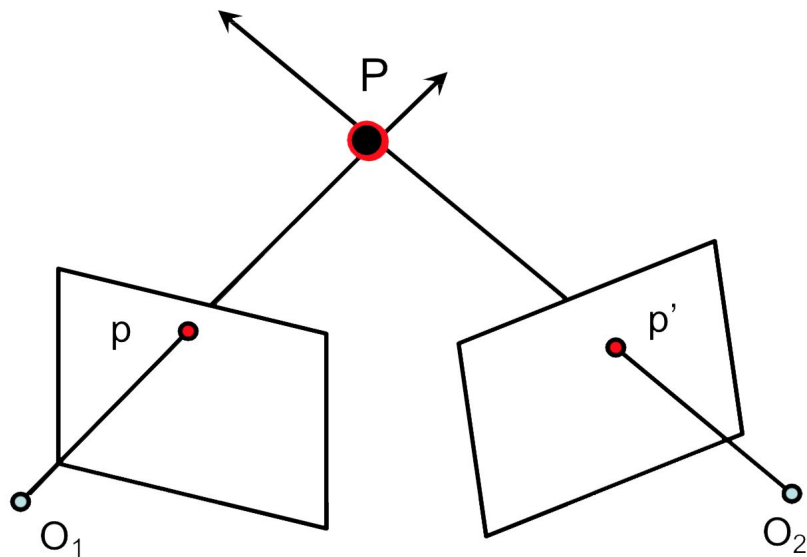


CSE 152 Section 7
HW3: Epipolar Geometry

November 16, 2018

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Epipolar Geometry



P arbitrary 3D point

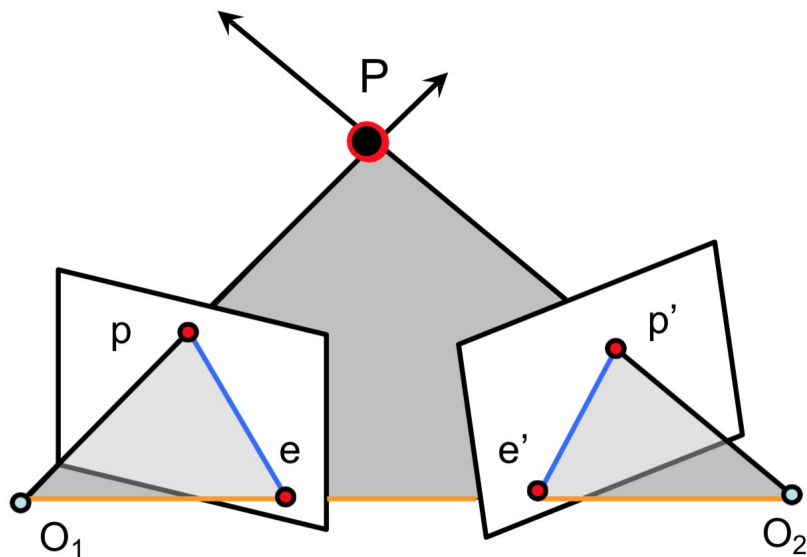
p projection of P onto image 1

p' projection of P onto image 2

O_1 pinhole (center of projection) of camera 1

O_2 pinhole (center of projection) of camera 2

Epipolar Geometry



P arbitrary 3D point

p projection of P onto image 1

p' projection of P onto image 2

O_1 pinhole (center of projection) of camera 1

O_2 pinhole (center of projection) of camera 2

e epipole 1 (projection of O_2 onto image 1)

e' epipole 2 (projection of O_1 onto image 2)

gray plane

epipolar plane (defined by P , O_1 , O_2)

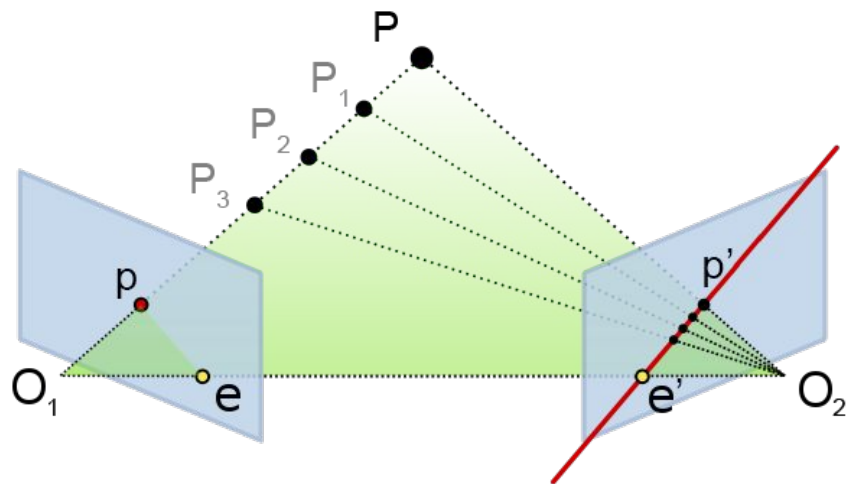
orange line

baseline (defined by O_1 , O_2)

blue line

epipolar line (intersection of
epipolar plane with image)

Epipolar Geometry



Epipolar constraint:

the point p' which corresponds to p
must lie on the epipolar line for image 2

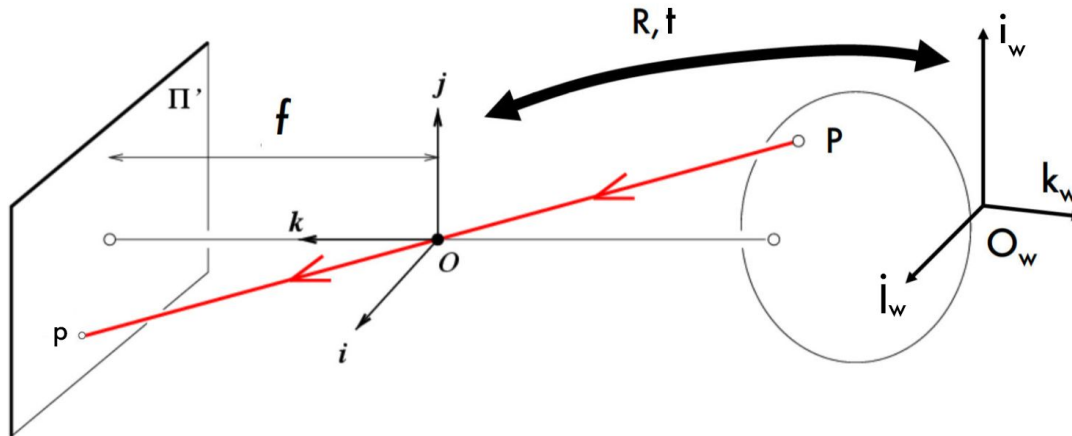
an alternative interpretation of this epipolar line:
the projection of the line $O_1 - P$ onto image 2

3D \rightarrow 2D

Recall from the calibration lecture:

$$\mathbf{p} = \mathbf{M} \mathbf{P} = \mathbf{K} [\mathbf{R} \ \mathbf{t}] \mathbf{P}$$

for \mathbf{K} the 3x3 intrinsic (camera projection) matrix, $[\mathbf{R} \ \mathbf{t}]$ the 3x4 extrinsic (camera pose) matrix



3D \rightarrow 2D

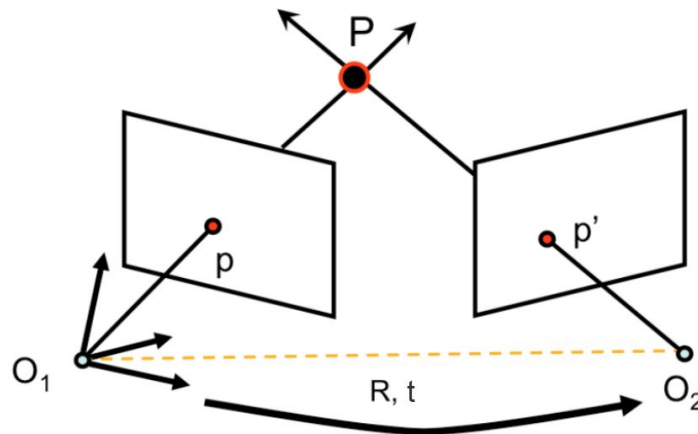
Let

$$\mathbf{M} \text{ (mapping for camera 1)} = \mathbf{K} \begin{bmatrix} \mathbf{I} & \mathbf{0} \end{bmatrix}$$

$$\mathbf{M}' \text{ (mapping for camera 2)} = \mathbf{K}' \begin{bmatrix} \mathbf{R} & \mathbf{t} \end{bmatrix}$$

i.e.

- world coordinates = camera 1 coordinates
- the transformation from a point \mathbf{p}_1 in camera 1 coords to a point \mathbf{p}_2 in camera 2 coords is $\mathbf{p}_2 = \mathbf{R}\mathbf{p}_1 + \mathbf{t}$ [$\rightarrow \mathbf{p}_1 = \mathbf{R}^T(\mathbf{p}_2 - \mathbf{t})$]
- \mathbf{p}' in camera 1 coordinates is $\mathbf{R}^T[(\mathbf{K}')^{-1}\mathbf{p}' - \mathbf{t}]$



Fundamental Matrix

Then the fundamental matrix is

$$\mathbf{F} = (\mathbf{K}')^{-T} \mathbf{T}_x \mathbf{R} \mathbf{K}^{-1}$$

where \mathbf{T}_x is a skew-symmetric matrix corresponding to the translation vector \mathbf{t} :

$$\begin{bmatrix} 0 & -t_z & t_y \\ t_z & 0 & -t_x \\ -t_y & t_x & 0 \end{bmatrix}$$

- 3x3, rank 2, seven degrees of freedom
- relates corresponding points \mathbf{p}, \mathbf{p}' according to $(\mathbf{p}')^T \mathbf{F} \mathbf{p} = 0$ (epipolar constraint)
 - note that \mathbf{p} is in homogeneous image 1 coords, \mathbf{p}' is in homogeneous image 2 coords
- gives epipolar line in image 1 as $\{\mathbf{x} : (\mathbf{F}^T \mathbf{p}')^T \mathbf{x} = 0\}$
- gives epipolar line in image 2 as $\{\mathbf{x} : (\mathbf{F} \mathbf{p})^T \mathbf{x} = 0\}$
- $\mathbf{F}^T \mathbf{e}' = 0, \mathbf{F} \mathbf{e} = 0$
 - [epipolar point is on every epipolar line, so $(\mathbf{p}')^T \mathbf{F} \mathbf{e} = 0$ for all \mathbf{p}' and $(\mathbf{e}')^T \mathbf{F} \mathbf{p} = 0$ for all \mathbf{p}]

Eight-Point Algorithm

We can estimate the fundamental matrix using the **eight-point algorithm**.

Input: 8+ pairs of corresponding points $\mathbf{p}_i = (u_i, v_i, 1)$, $\mathbf{p}_i' = (u_i', v_i', 1)$

Output: fundamental matrix \mathbf{F}

each correspondence is 1 equation $(\mathbf{p}_i')^T \mathbf{F} \mathbf{p}_i = 0$

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

$$u_i u_i' F_{11} + v_i u_i' F_{12} + u_i' F_{13} + u_i v_i' F_{21} + v_i v_i' F_{22} + v_i' F_{23} + u_i F_{31} + v_i F_{32} + F_{33} = 0$$

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

Eight-Point Algorithm

We use 8+ equations to solve for the 8 independent entries in \mathbf{F} (the ninth entry is a scaling factor).

$$\begin{bmatrix} u_1 u'_1 & v_1 u'_1 & u'_1 & u_1 v'_1 & v_1 v'_1 & v'_1 & u_1 & v_1 & 1 \\ u_2 u'_2 & v_2 u'_2 & u'_2 & u_2 v'_2 & v_2 v'_2 & v'_2 & u_2 & v_2 & 1 \\ u_3 u'_3 & v_3 u'_3 & u'_3 & u_3 v'_3 & v_3 v'_3 & v'_3 & u_3 & v_3 & 1 \\ u_4 u'_4 & v_4 u'_4 & u'_4 & u_4 v'_4 & v_4 v'_4 & v'_4 & u_4 & v_4 & 1 \\ u_5 u'_5 & v_5 u'_5 & u'_5 & u_5 v'_5 & v_5 v'_5 & v'_5 & u_5 & v_5 & 1 \\ u_6 u'_6 & v_6 u'_6 & u'_6 & u_6 v'_6 & v_6 v'_6 & v'_6 & u_6 & v_6 & 1 \\ u_7 u'_7 & v_7 u'_7 & u'_7 & u_7 v'_7 & v_7 v'_7 & v'_7 & u_7 & v_7 & 1 \\ u_8 u'_8 & v_8 u'_8 & u'_8 & u_8 v'_8 & v_8 v'_8 & v'_8 & u_8 & v_8 & 1 \end{bmatrix} \begin{bmatrix} F_{11} \\ F_{12} \\ F_{13} \\ F_{21} \\ F_{22} \\ F_{23} \\ F_{31} \\ F_{32} \\ F_{33} \end{bmatrix} = 0$$

$$W\mathbf{f} = 0$$

Eight-Point Algorithm

Approach: find a least-squares solution to this system of equations. **Can use SVD for this!**

Might also want to normalize each \mathbf{p}_i and \mathbf{p}_i' for better results (must de-normalize resulting \mathbf{F} as well!).

1. Normalize points in each image according to \mathbf{T} and \mathbf{T}' , use normalized points to construct \mathbf{W} .
2. Compute the SVD of \mathbf{W} , reshape right singular vector into initial estimate of \mathbf{F} .
 - a. As reference, see sections 3 and 4 of [this document](#).
3. Enforce rank = 2 by taking another SVD, this time of \mathbf{F} , and zeroing out the last singular value.

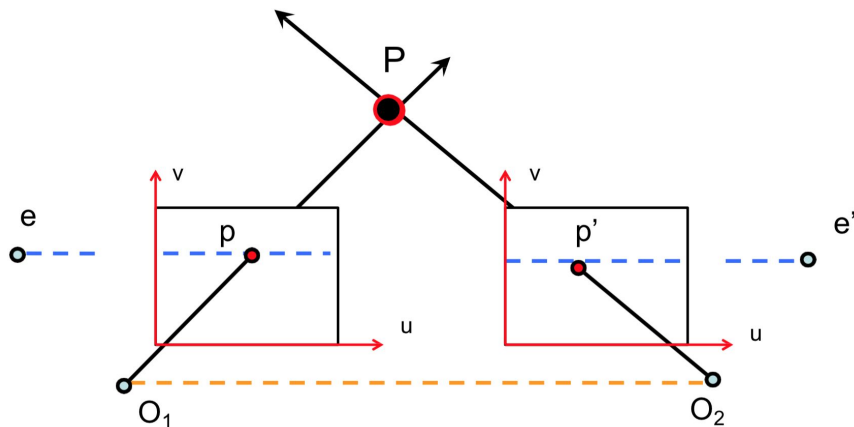
$$\mathbf{F} = \mathbf{U} \begin{bmatrix} s_1 & 0 & 0 \\ 0 & s_2 & 0 \\ 0 & 0 & 0 \end{bmatrix} \mathbf{V}^T$$

4. De-normalize \mathbf{F} .
 - a. Currently, $(\mathbf{T}'\mathbf{p}')^T \mathbf{F} (\mathbf{T}\mathbf{p}) = 0 \rightarrow (\mathbf{p}')^T (\mathbf{T}')^T \mathbf{F} \mathbf{T} \mathbf{p} = 0$, so $(\mathbf{T}')^T \mathbf{F} \mathbf{T}$ is the true fundamental matrix.

:)



Question 1.1



Notes:

- no rotation, only translation

Hints:

[option 1] argue geometrically that all of the epipolar lines are parallel to the baseline

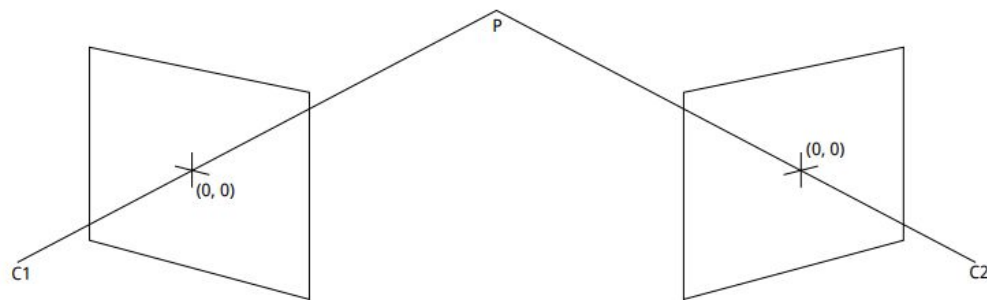
[option 2] compute the essential matrix $\mathbf{E} = \mathbf{T}_x \mathbf{R}$
(difference is that \mathbf{p}, \mathbf{p}' are now [normalized image coordinates](#))

- what is the rotation matrix?
- what is the translation vector?
- what is the direction of each epipolar line?
 - $\mathbf{E}\mathbf{p}$ and $\mathbf{E}^T\mathbf{p}'$ give normals to lines
- what does $(\mathbf{p}')^T\mathbf{E}\mathbf{p} = 0$ tell us? (expand it)

Question 1.2

Hints:

- Under this setup,
 - what is the \mathbf{p} corresponding to \mathbf{P} ?
 - what is the \mathbf{p}' corresponding to \mathbf{P} ?
- What is the relationship between \mathbf{p} , \mathbf{p}' , and the fundamental matrix?



Question 2

1. Eight-point algorithm

Estimate the fundamental matrix given point correspondences.

for when you haven't done camera calibration and don't have the intrinsics/extrinsics

2. Metric reconstruction

Estimate the camera matrices, triangulate and visualize the 3D points.

3. 3D correspondence

Estimate corresponding points given the fundamental matrix.

2.1. Eight-Point Algorithm

Notes:

- See eight-point algorithm slides for outline.
- \mathbf{W} is an $\mathbf{n} \times 9$ matrix, where \mathbf{n} is the number of correspondences.
- As an alternative to using SVD,
you can define the initial \mathbf{F} estimate as the eigenvector of $\mathbf{W}^T \mathbf{W}$ with the smallest eigenvalue.

$$\begin{bmatrix} u_1 u'_1 & v_1 u'_1 & u'_1 & u_1 v'_1 & v_1 v'_1 & v'_1 & u_1 & v_1 & 1 \\ \vdots & & & & & & & & \\ u_n u'_n & v_n u'_n & u'_n & u_n v'_n & v_n v'_n & v'_n & u_n & v_n & 1 \end{bmatrix}$$

2.1. Eight-Point Algorithm

Normalization

Notes:

- Recall that we would like to precondition \mathbf{W} before SVD.
 - To do so, normalize the pixel point coordinates through scaling and/or translation.
 - Then construct \mathbf{W} from the normalized coordinates.
- In this homework, we suggest scaling by 1 / (the largest image dimension).
 - Although you shouldn't need to, you are free to do something else if you'd like.
 - For example, you can subtract the mean and divide by the standard deviation.
- **Don't forget to de-normalize the fundamental matrix at the end!**

2.2. Metric Reconstruction

1. Load K1 and K2.

- a. Load the intrinsic matrices **K1** and **K2** from **temple/intrinsics.mat**.
- b. Documentation: <https://www.mathworks.com/help/matlab/ref/load.html>

2.2. Metric Reconstruction

2. Find M_2 and M_1 .

- a. Recover camera 2's extrinsic matrix $[R \ t]$ using **camera2**.
 - i. To obtain the full $3D \rightarrow 2D$ matrix M_2 , multiply by the intrinsic matrix K_2 .
- b. Define camera 1's frame to be the world coordinate frame.
 - i. Don't forget to multiply by K_1 !

Notes:

- The spec says that **camera2** returns M_2 , but it only returns the extrinsic matrix.

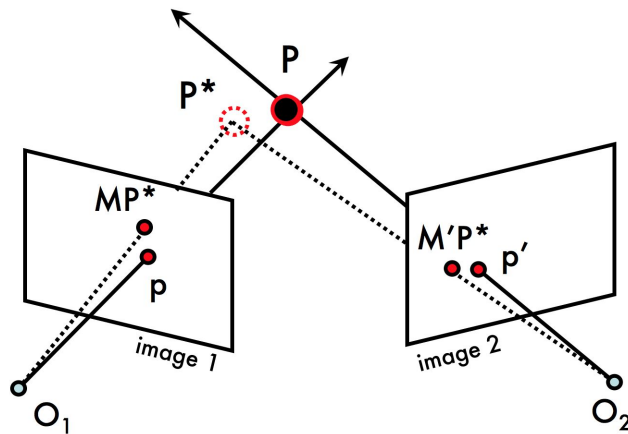
2.2. Metric Reconstruction

3. Load the correspondences for 3D visualization.
 - a. Load the correspondences **x1, y1, x2, y2** from **many_corresp.mat**.
 - b. Documentation: <https://www.mathworks.com/help/matlab/ref/load.html>

2.2. Metric Reconstruction

4. Get 3D points given 2D point correspondences.
 - a. Use the [triangulate](#) function (provided).

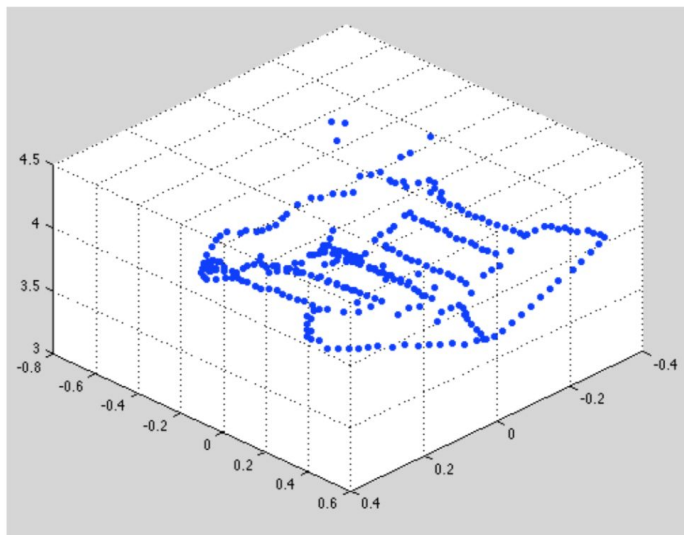
$$P = \text{triangulate}(M1, \text{pts1}, M2, \text{pts2})$$



2.2. Metric Reconstruction

5. Plot 3D points.

- Use the scatter3 function.
- Documentation: <https://www.mathworks.com/help/matlab/ref/scatter3.html>



2.3. 3D Correspondence

Notes:

- In this problem, we take advantage of the epipolar constraint to search for corresponding points.
- We are given $\mathbf{p} = (\mathbf{x1}, \mathbf{y1})$ in image 1, and we would like to find \mathbf{p}' in image 2.

Compare **the window around $(\mathbf{x1}, \mathbf{y1})$ in image 1**
to **the window around each point on the epipolar line in image 2.**

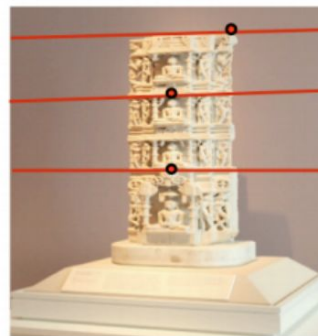
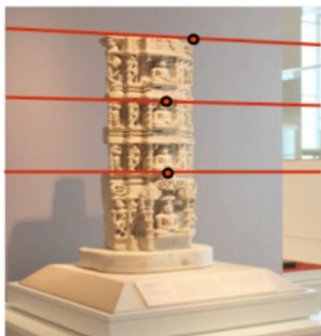
The point in image 2 with the minimum window distance is our match.

- We can weight the window according to a 2D Gaussian when computing the difference.
- To speed things up, we can look **only** at points along the line which are close to $(\mathbf{x1}, \mathbf{y1})$.

2.3. 3D Correspondence

Computing the epipolar line:

- The epipolar line associated with \mathbf{p} is $\ell = \mathbf{Fp}$.
- The equation of the line is $(\mathbf{Fp})^T \mathbf{x} = 0$.
 - i.e. if $\ell = [\ell_1, \ell_2, \ell_3]^T$ and $\mathbf{x} = [\mathbf{u}, \mathbf{v}, 1]$, then the equation of the line is $\ell_1 \mathbf{u} + \ell_2 \mathbf{v} + \ell_3 = 0$
 - in $\mathbf{y} = \mathbf{mx} + \mathbf{b}$ form, the equation of the line is $\mathbf{v} = \dots$ (you can figure this out)



Additional Readings

- [CS 231A course notes](#)
- [How to use SVD to solve homogeneous linear least-squares](#)