Lecture 4
Single View Metrology

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Computational Vision and Geometry Lab

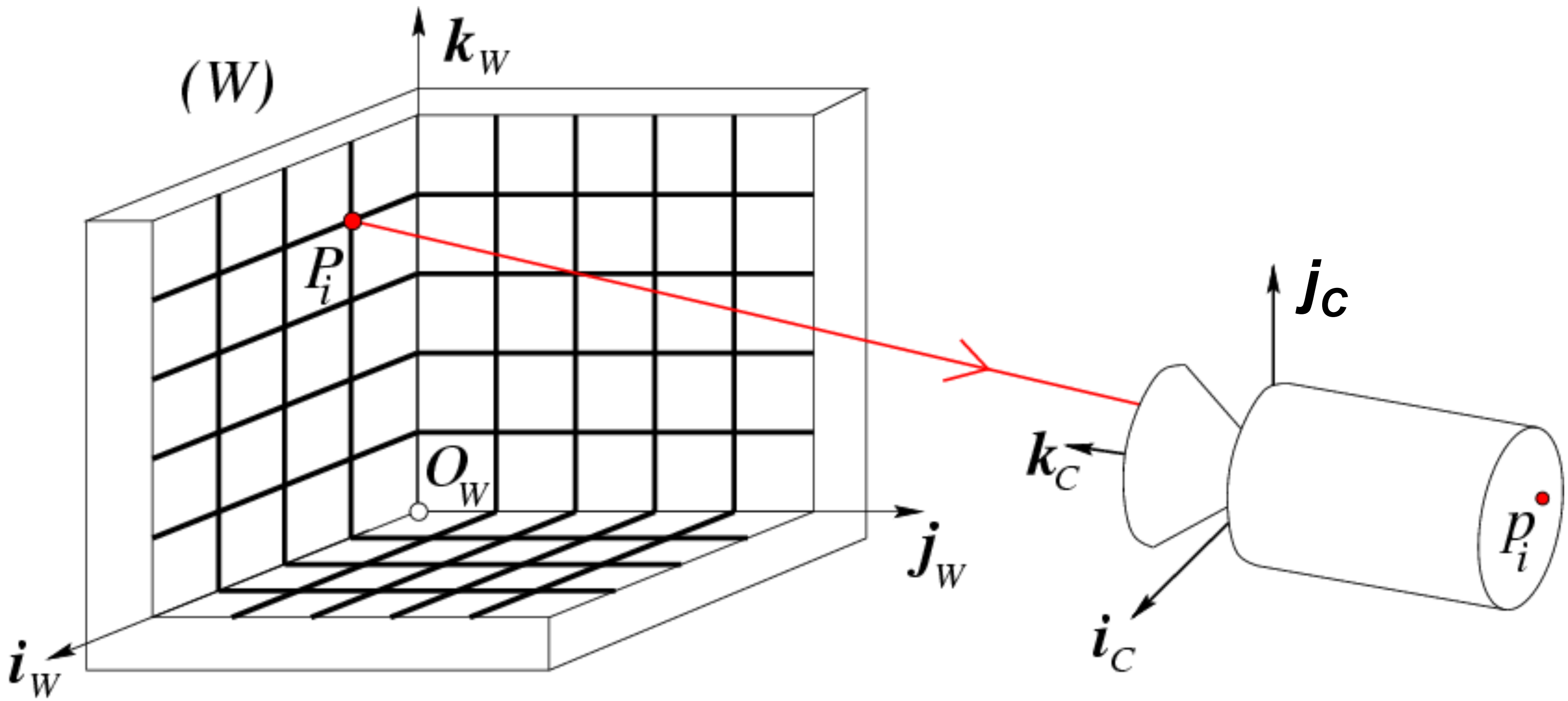
Lecture 4

Single View Metrology

- Review calibration and 2D transformations
- Vanishing points and lines
- Estimating geometry from a single image
- Extensions

Reading:
[HZ] Chapter 2 “Projective Geometry and Transformation in 2D”
[HZ] Chapter 3 “Projective Geometry and Transformation in 3D”
[HZ] Chapter 8 “More Single View Geometry”
[Hoeim & Savarese] Chapter 2

Calibration Problem



$$p_i = \begin{bmatrix} u_i \\ v_i \end{bmatrix} = M\ P_i$$

In pixels

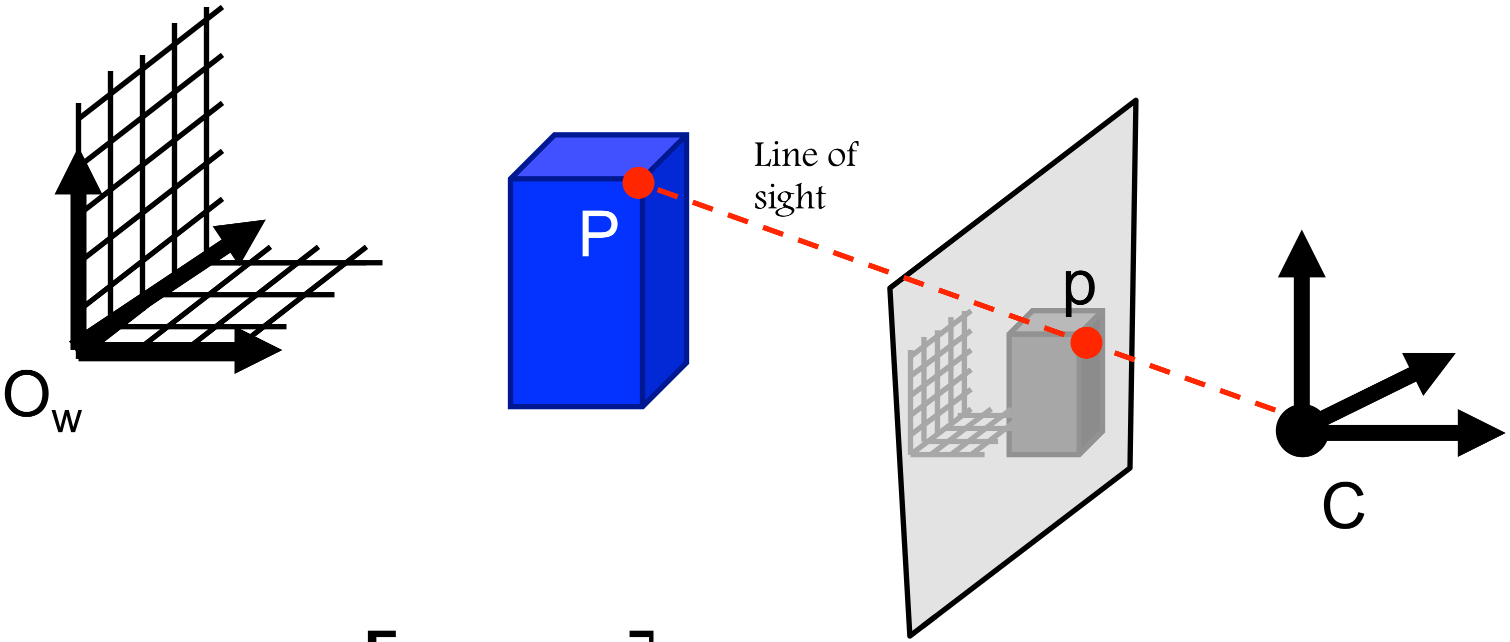
World ref. system

$$M = K\begin{bmatrix} R & T \end{bmatrix}$$

11 unknowns

Need at least 6 correspondences

Once the camera is calibrated...



$$M = K\begin{bmatrix} R & T \end{bmatrix}$$

-Internal parameters K are known

-R, T are known – but these can only relate C to the calibration rig

Can I estimate P from the measurement p from a single image?

No - in general ☹ (P can be anywhere along the line defined by C and p)

Recovering structure from a single view

http://www.robots.ox.ac.uk/~vgg/projects/SingleView/models/hut/hutme.wrl

Transformation in 2D

-Isometries

-Similarities

-Affinity

-Projective

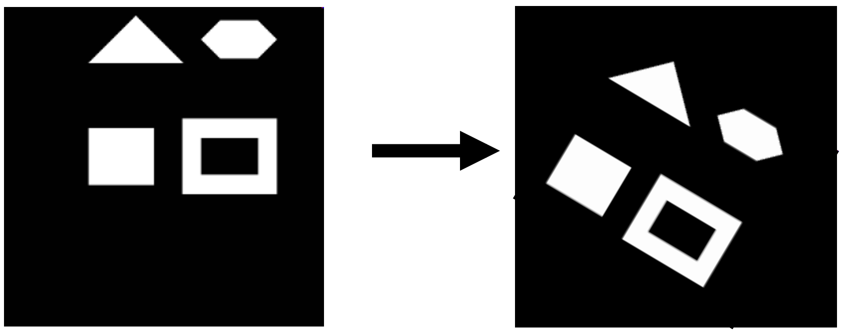
Transformation in 2D

Isometries:

[Euclideans]

$$\begin{bmatrix} x' \\ y' \\ 1 \end{bmatrix} = \begin{bmatrix} R & t \\ 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} = H_e \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} \quad \text{[Eq. 4]}$$

- Preserve distance (areas)
- 3 DOF
- Regulate motion of rigid object



Transformation in 2D

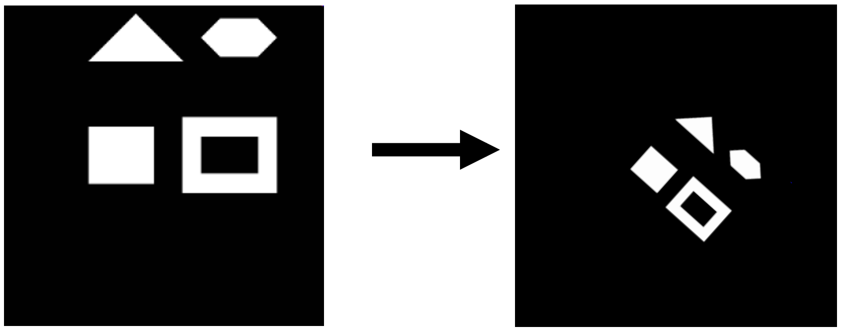
Similarities:

$$\begin{bmatrix} x' \\ y' \\ 1 \end{bmatrix} = \begin{bmatrix} S\,R & t \\ 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} = H_s \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$$

$$S = \begin{bmatrix} s & 0 \\ 0 & s \end{bmatrix}$$

[Eq. 5]

- Preserve
  - ratio of lengths
  - angles
- 4 DOF



Transformation in 2D

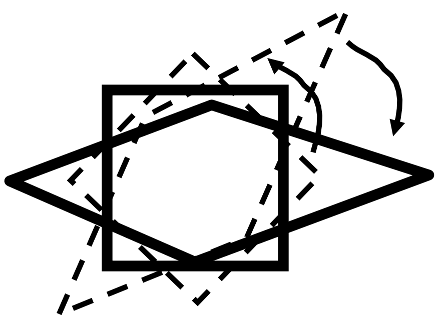
Affinities:

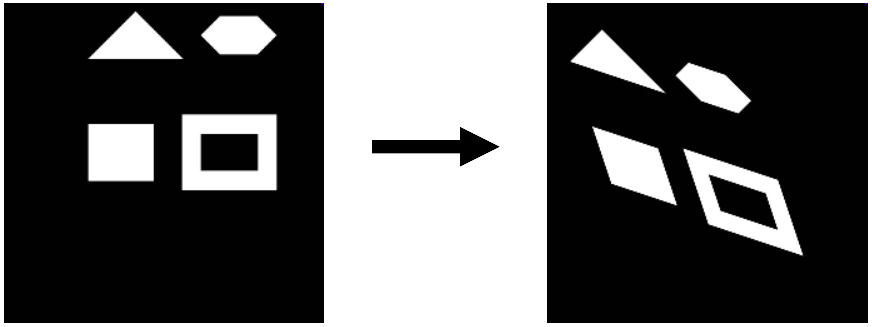
$$\begin{bmatrix} x' \\ y' \\ 1 \end{bmatrix} = \begin{bmatrix} A & t \\ 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} = H_a \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$$

[Eq. 6]

$$A = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} = R(\boldsymbol{\theta}) \cdot R(-\boldsymbol{\phi}) \cdot D \cdot R(\boldsymbol{\phi}) \qquad D = \begin{bmatrix} s_x & 0 \\ 0 & s_y \end{bmatrix}$$

[Eq. 7]





Transformation in 2D

Affinities:

$$\begin{bmatrix} x' \\ y' \\ 1 \end{bmatrix} = \begin{bmatrix} A & t \\ 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} = H_a \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$$

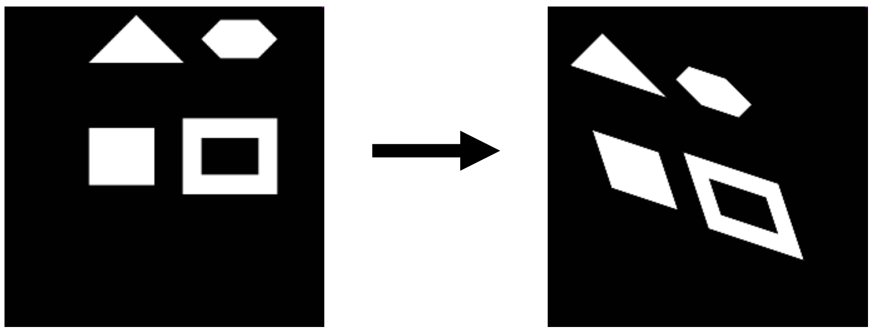
[Eq. 6]

$$A = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} = R(\theta) \cdot R(-\phi) \cdot D \cdot R(\phi) \qquad D = \begin{bmatrix} s_x & 0 \\ 0 & s_y \end{bmatrix}$$

[Eq. 7]

-Preserve:
- Parallel lines
- Ratio of areas
- Ratio of lengths on collinear lines
- others…

- 6 DOF

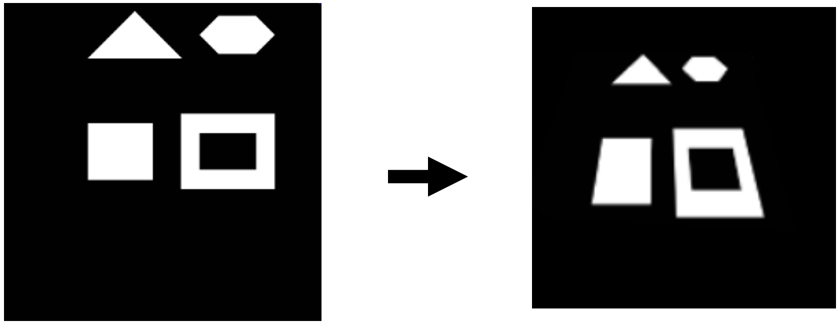


Transformation in 2D

Projective:

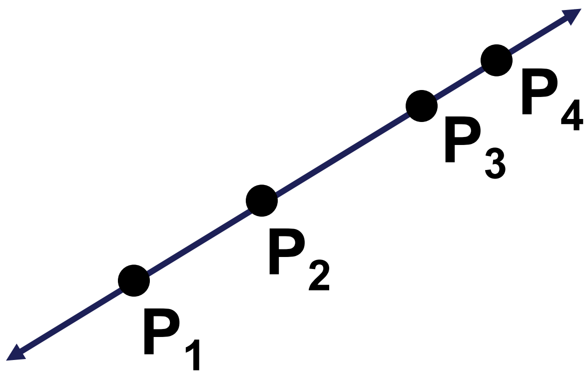
$$\begin{bmatrix} x' \\ y' \\ 1 \end{bmatrix} = \begin{bmatrix} A & t \\ \boxed{v} & b \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} = H_p \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$$ [Eq. 8]

- 8 DOF
- Preserve:
  - cross ratio of 4 collinear points
  - collinearity
  - and a few others…



The cross ratio

The cross-ratio of 4 collinear points is defined as



[Eq. 9]

$$\frac{\|\mathbf{P}_3 - \mathbf{P}_1\| \, \|\mathbf{P}_4 - \mathbf{P}_2\|}{\|\mathbf{P}_3 - \mathbf{P}_2\| \, \|\mathbf{P}_4 - \mathbf{P}_1\|}$$

$$\mathbf{P}_i = \begin{bmatrix} X_i \\ Y_i \\ Z_i \\ 1 \end{bmatrix}$$

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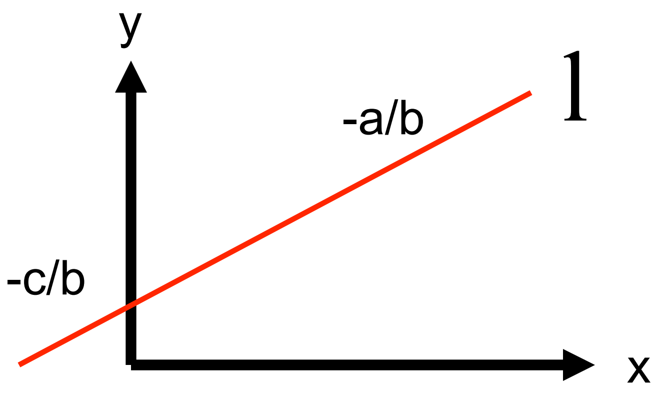
Lines in a 2D plane

$$ax + by + c = 0$$



$$\mathbf{l} = \begin{bmatrix} a \\ b \\ c \end{bmatrix}$$

If $x = [\, x_1, x_2]^T \in \mathbf{l}$

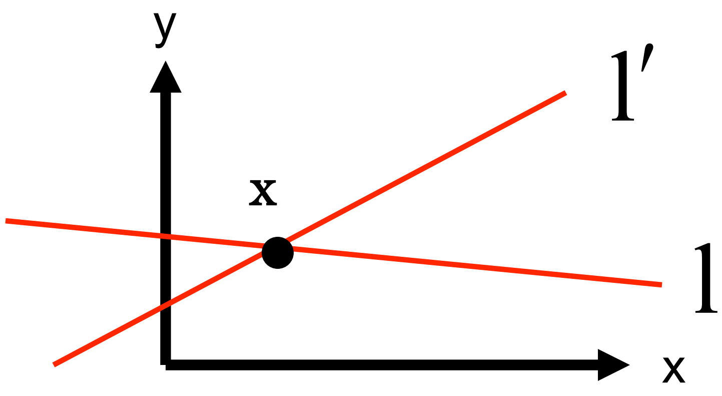
$$\begin{bmatrix} x_1 \\ x_2 \\ 1 \end{bmatrix}^T \begin{bmatrix} a \\ b \\ c \end{bmatrix} = 0$$

[Eq. 10]

Lines in a 2D plane

Intersecting lines

$$\mathbf{x} = \mathbf{l} \times \mathbf{l}' \quad \text{[Eq. 11]}$$



Proof

$$\mathbf{l} \times \mathbf{l}' \perp \mathbf{l} \quad \rightarrow (\mathbf{l} \times \mathbf{l}') \cdot \mathbf{l} = 0 \quad \rightarrow x \in l \quad \text{[Eq. 12]}$$

$$\mathbf{l} \times \mathbf{l}' \perp \mathbf{l}' \quad \rightarrow \underbrace{(\mathbf{l} \times \mathbf{l}')}_{\mathbf{x}} \cdot \mathbf{l}' = 0 \quad \rightarrow x \in l' \quad \text{[Eq. 13]}$$

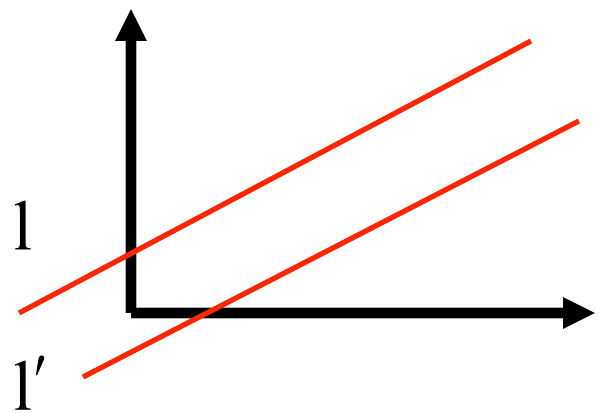
$\rightarrow$ x is the intersecting point

2D Points at infinity (ideal points)

$$\mathrm{x} = \begin{bmatrix} \mathrm{x}_1 \\ \mathrm{x}_2 \\ \mathrm{x}_3 \end{bmatrix}, \mathrm{x}_3 \neq 0$$

$$x_\infty = \begin{bmatrix} x'_1 \\ x'_2 \\ 0 \end{bmatrix}$$

$$-a/b = -a'/b'$$



$$\mathrm{l} = \begin{bmatrix} \mathrm{a} \\ \mathrm{b} \\ \mathrm{c} \end{bmatrix}$$

$$l' = \begin{bmatrix} a' \\ b' \\ c' \end{bmatrix}$$

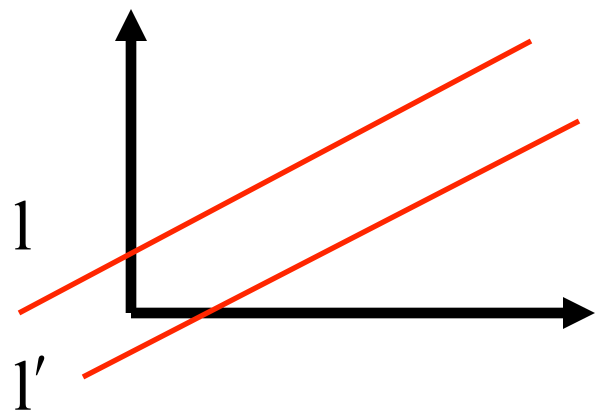
Let's intersect two parallel lines: $\rightarrow l \times l' \propto \begin{bmatrix} b \\ -a \\ 0 \end{bmatrix} = x_\infty$ Eq.13]

- In Euclidian coordinates this point is at infinity
- Agree with the general idea of two lines intersecting at infinity

2D Points at infinity (ideal points)

$$\mathrm{x} = \begin{bmatrix} \mathrm{x}_1 \\ \mathrm{x}_2 \\ \mathrm{x}_3 \end{bmatrix}, \mathrm{x}_3 \neq 0$$

$$-a/b = -a'/b'$$



$$\mathrm{l} = \begin{bmatrix} \mathrm{a} \\ \mathrm{b} \\ \mathrm{c} \end{bmatrix}$$

$$l' = \begin{bmatrix} a' \\ b' \\ c' \end{bmatrix}$$

Note: the line l = [a b c]^T pass trough the ideal point x_∞

$$\mathrm{l}^{\mathrm{T}}\ x_\infty = \begin{bmatrix} a & b & c \end{bmatrix} \begin{bmatrix} b \\ -a \\ 0 \end{bmatrix} = 0 \quad \text{[Eq. 15]}$$

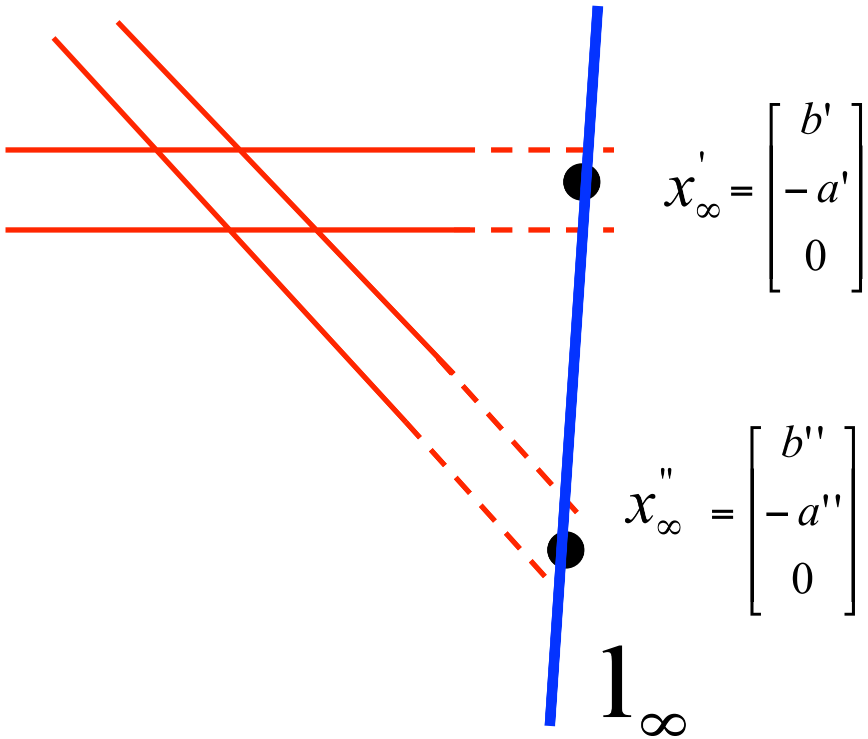
So does the line l' since a b' = a' b

Lines infinity l_∞

Set of ideal points lies on a line called the line at infinity.
How does it look like?

$$l_\infty = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$$

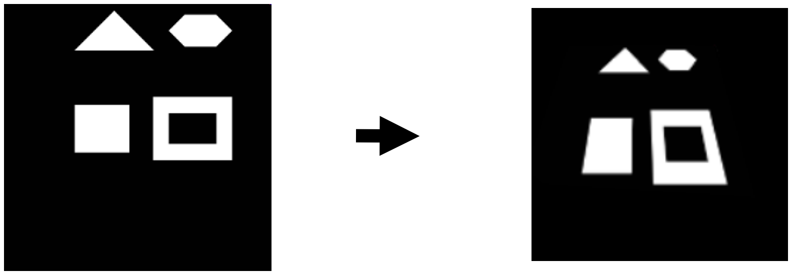
Indeed: $\begin{bmatrix} x_1 \\ x_2 \\ 0 \end{bmatrix}^T \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} = 0$



A line at infinity can be thought of the set of "directions" of lines in the plane

Projective transformation of a point at infinity

$$H = \begin{bmatrix} A & t \\ v & b \end{bmatrix}$$



$$p' = H\ p$$

is it a point at infinity?

$$H\ p_\infty = ? = \begin{bmatrix} A & t \\ v & b \end{bmatrix} \begin{bmatrix} 1 \\ 1 \\ 0 \end{bmatrix} = \begin{bmatrix} p'_x \\ p'_y \\ p'_z \end{bmatrix}$$

…no!

[Eq. 17]

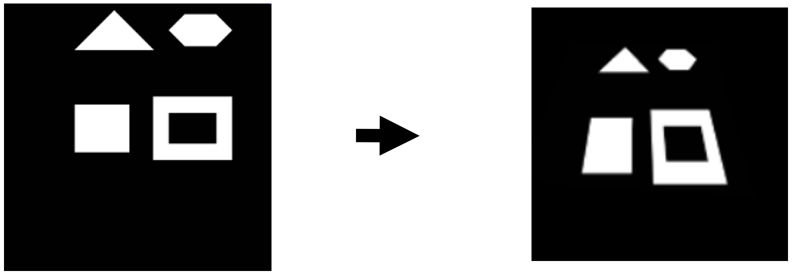
$$H_A\ p_\infty = ? = \begin{bmatrix} A & t \\ 0 & b \end{bmatrix} \begin{bmatrix} 1 \\ 1 \\ 0 \end{bmatrix} = \begin{bmatrix} p'_x \\ p'_y \\ 0 \end{bmatrix}$$

An affine transformation of a point at infinity is still a point at infinity

[Eq. 18]

Projective transformation of a line (in 2D)

$$\mathrm{H} = \begin{bmatrix} \mathrm{A} & \mathrm{t} \\ \mathrm{v} & \mathrm{b} \end{bmatrix}$$



$$\mathrm{l}' = \mathrm{H}^{-\mathrm{T}}\ \mathrm{l}$$

[Eq. 19]

is it a line at infinity?

$$\mathrm{H}^{-\mathrm{T}}\ \mathrm{l}_{\infty} = ? = \begin{bmatrix} \mathrm{A} & \mathrm{t} \\ \mathrm{v} & \mathrm{b} \end{bmatrix}^{-\mathrm{T}} \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} = \begin{bmatrix} \mathrm{t}_{\mathrm{x}} \\ \mathrm{t}_{\mathrm{y}} \\ \mathrm{b} \end{bmatrix}$$

…no!

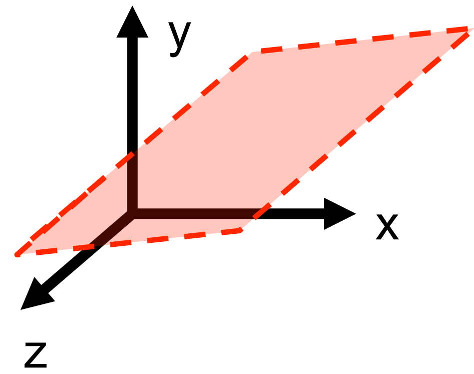
[Eq. 20]

$$\mathrm{H}_{\mathrm{A}}^{-\mathrm{T}}\ \mathrm{l}_{\infty} = ? \quad = \begin{bmatrix} A & t \\ 0 & 1 \end{bmatrix}^{-T} \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} = \begin{bmatrix} A^{-T} & 0 \\ -t^{T} A^{-T} & 1 \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$$

[Eq. 21]

Points and planes in 3D

$$x = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ 1 \end{bmatrix} \qquad \Pi = \begin{bmatrix} a \\ b \\ c \\ d \end{bmatrix}$$



$$x \in \Pi \leftrightarrow x^T \Pi = 0$$

[Eq. 22]

$$ax + by + cz + d = 0$$

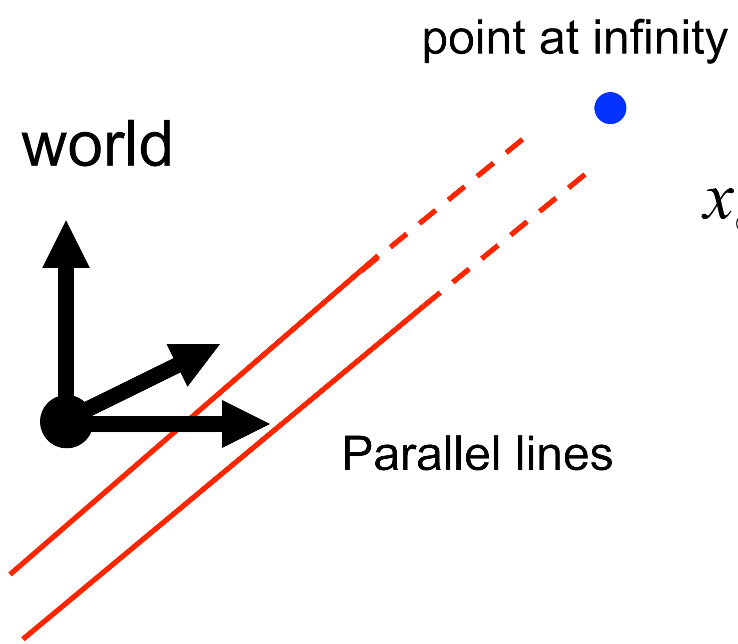
[Eq. 23]

How about lines in 3D?

- Lines have 4 degrees of freedom - hard to represent in 3D-space
- Can be defined as intersection of 2 planes

Points at infinity in 3D

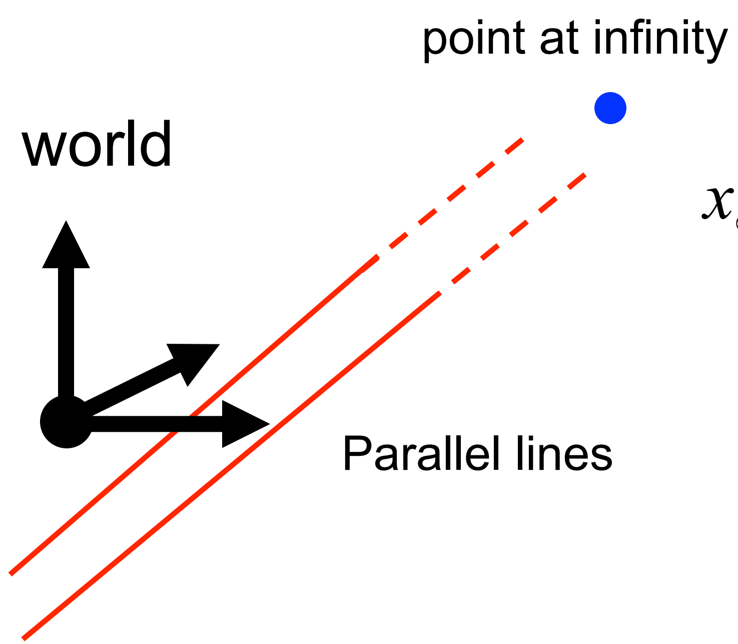
Points where parallel lines intersect in 3D



$$x_\infty = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ 0 \end{bmatrix}$$

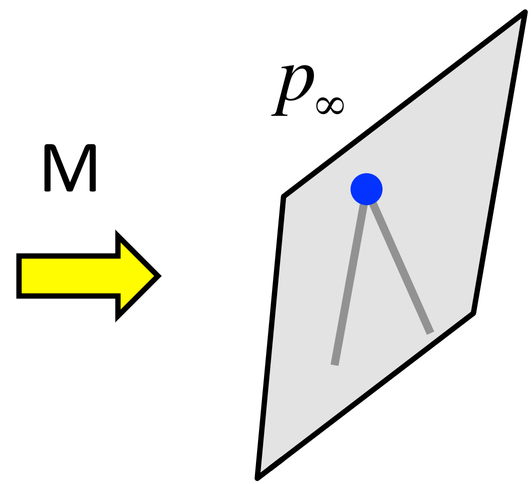
Vanishing points

The projective projection of a point at infinity into the image plane defines a vanishing point.



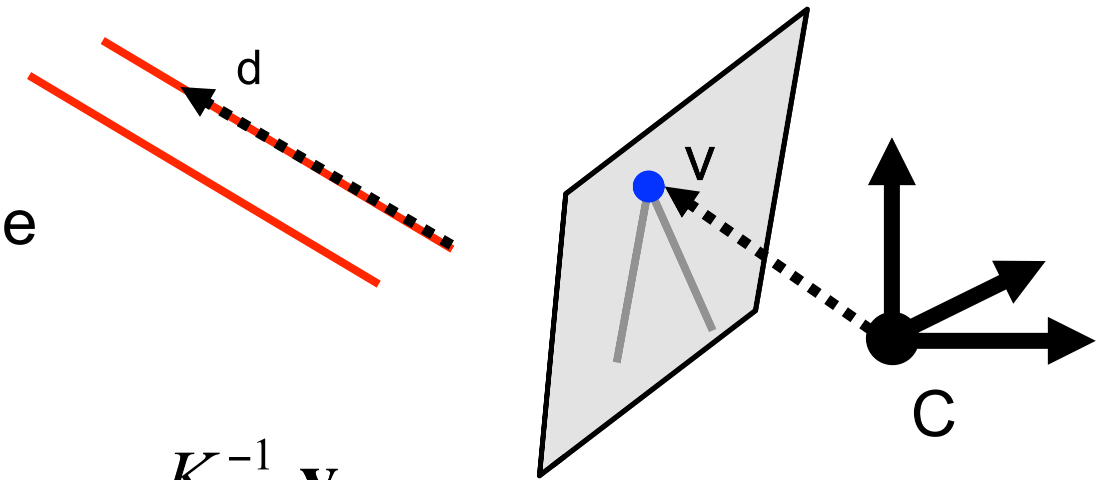
$$x_\infty = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ 0 \end{bmatrix}$$

= direction of corresponding parallel lines in 3D



$$p_\infty = \begin{bmatrix} p_1 \\ p_2 \\ p_3 \end{bmatrix}$$

Vanishing points and directions



d = direction of the line
= [a, b, c]^T

$$\mathbf{v} = K\,\mathbf{d}$$

[Eq. 24]

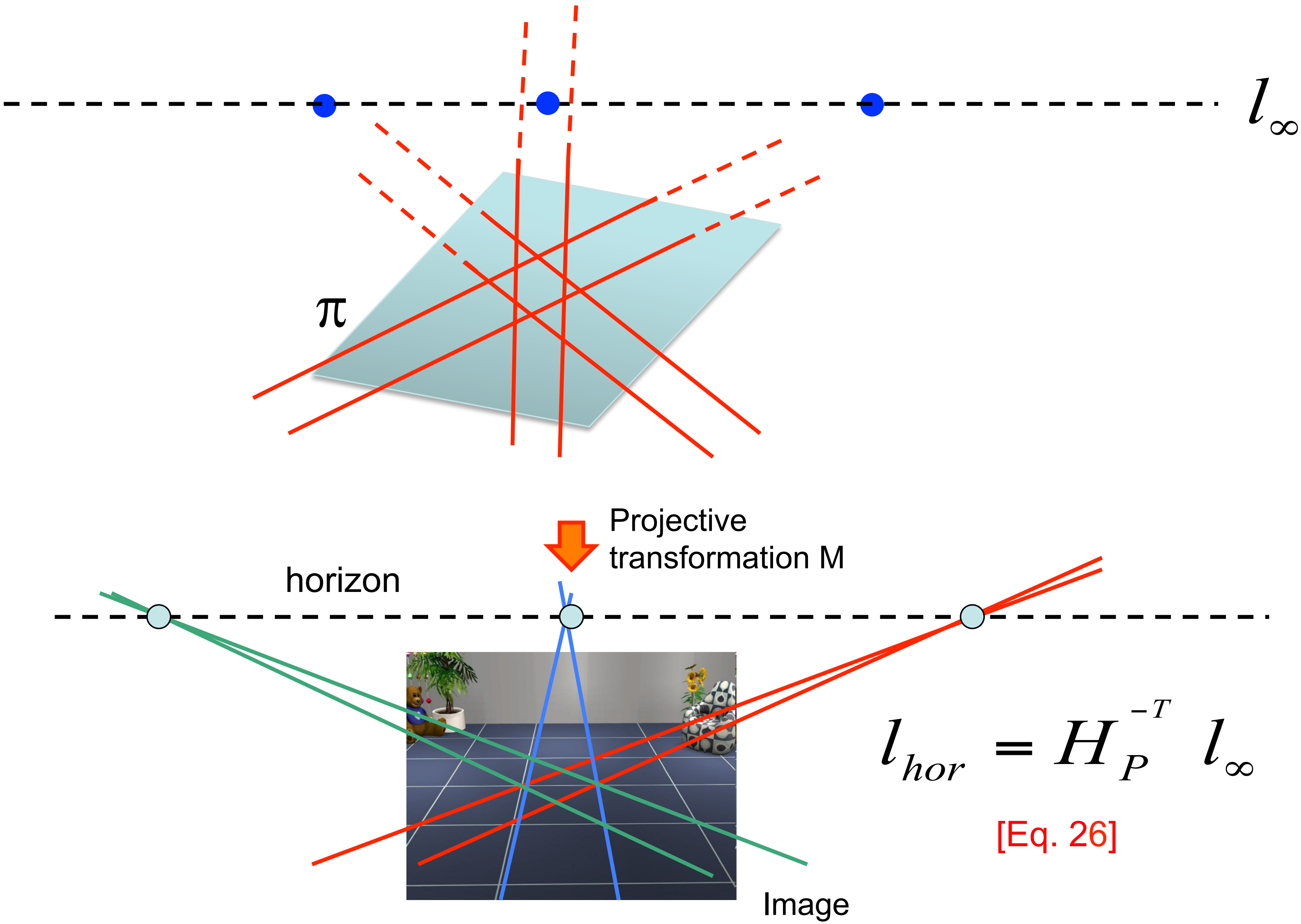
$$\mathbf{d} = \frac{K^{-1}\,\mathbf{v}}{\left\| K^{-1}\,\mathbf{v} \right\|}$$

[Eq. 25]

Proof:

$$X_\infty = \begin{bmatrix} a \\ b \\ c \\ 0 \end{bmatrix} \xrightarrow{\text{M}} \mathbf{v} = \mathbf{M}\,\mathbf{X}_\infty = \mathbf{K}\begin{bmatrix}\mathbf{I} & \mathbf{0}\end{bmatrix}\begin{bmatrix} a \\ b \\ c \\ 0 \end{bmatrix} = \mathbf{K}\begin{bmatrix} a \\ b \\ c \end{bmatrix}$$

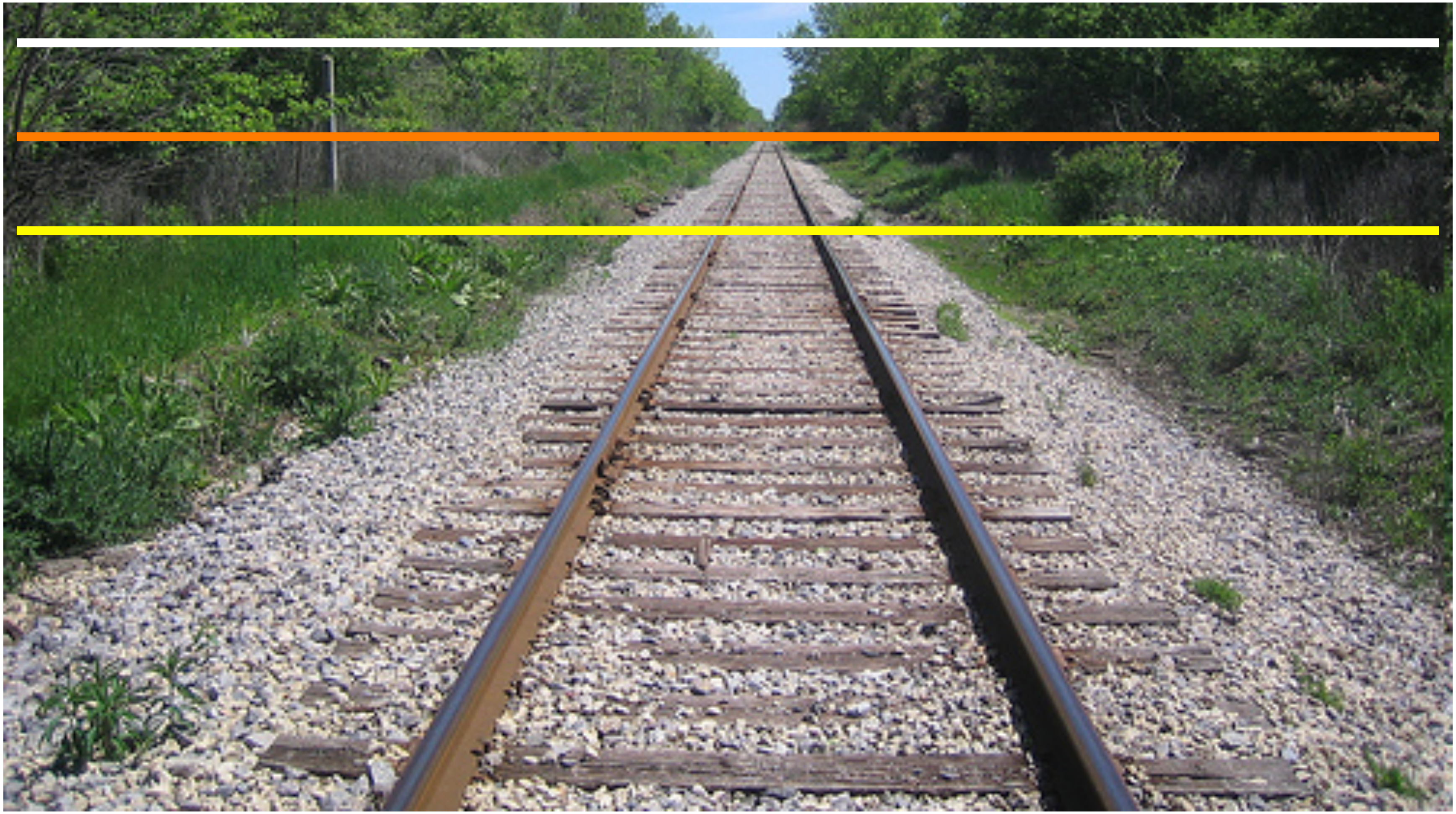
Vanishing (horizon) line



$$l_{hor} = H_P^{-T}\, l_\infty$$

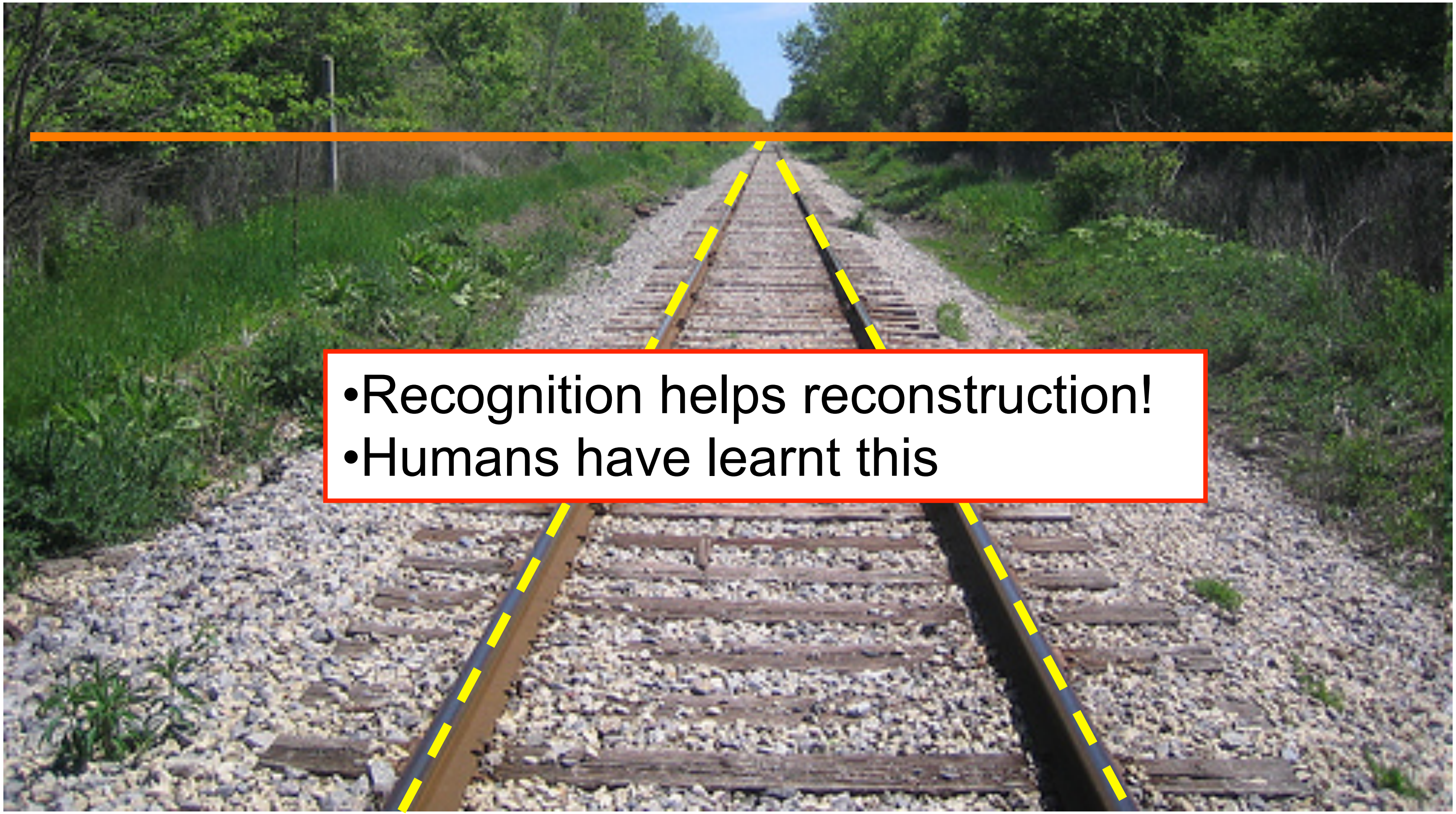
[Eq. 26]

Example of horizon line



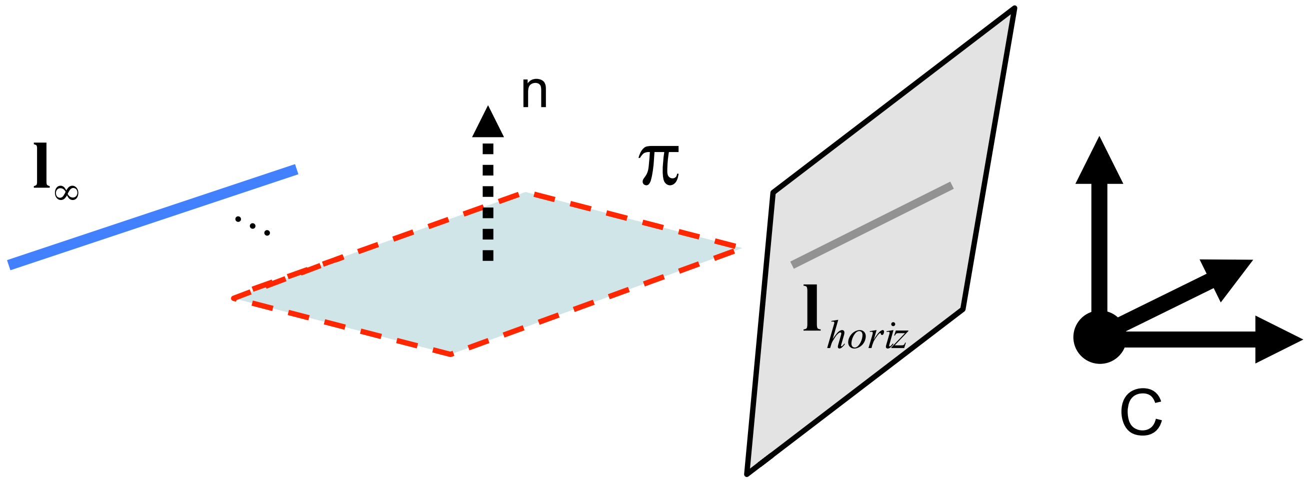
The orange line is the horizon!

Are these two lines parallel or not?



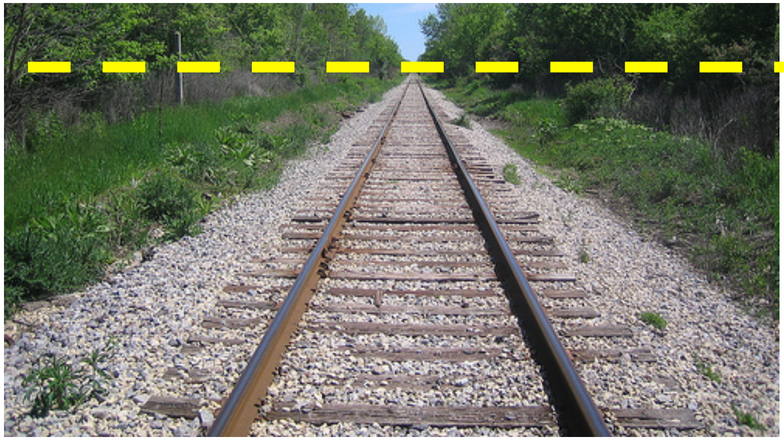
- Recognize the horizon line
- Measure if the 2 lines meet at the horizon
- if yes, these 2 lines are // in 3D

Vanishing points and planes

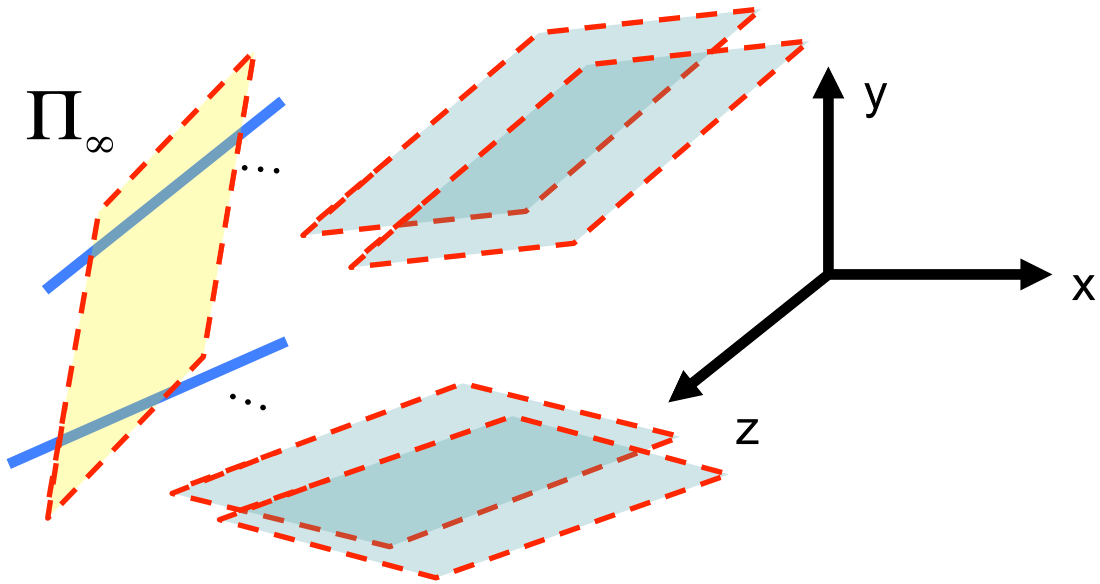


$$\mathbf{n} = K^T \mathbf{l}_{\text{horiz}}$$

[Eq. 27]



Planes at infinity

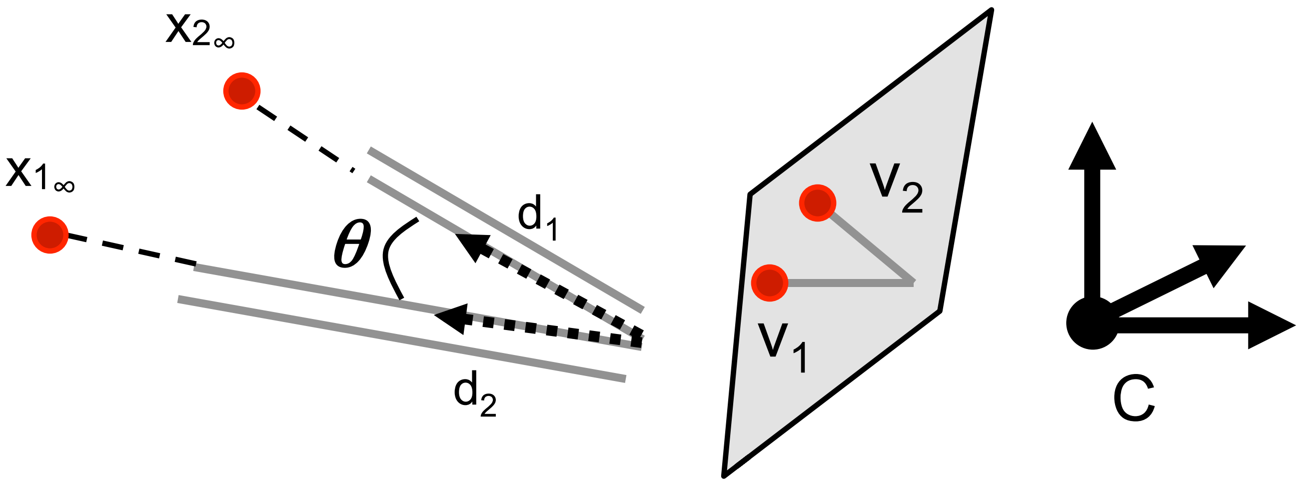


$$\Pi_\infty = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}$$

plane at infinity

- Parallel planes intersect at infinity in a common line **– the line at infinity**
- A set of 2 or more lines at infinity defines the plane at infinity Π_∞

Angle between 2 vanishing points



$$\cos\theta = \frac{v_1^T \omega\, v_2}{\sqrt{v_1^T \omega\, v_1}\sqrt{v_2^T \omega\, v_2}}$$

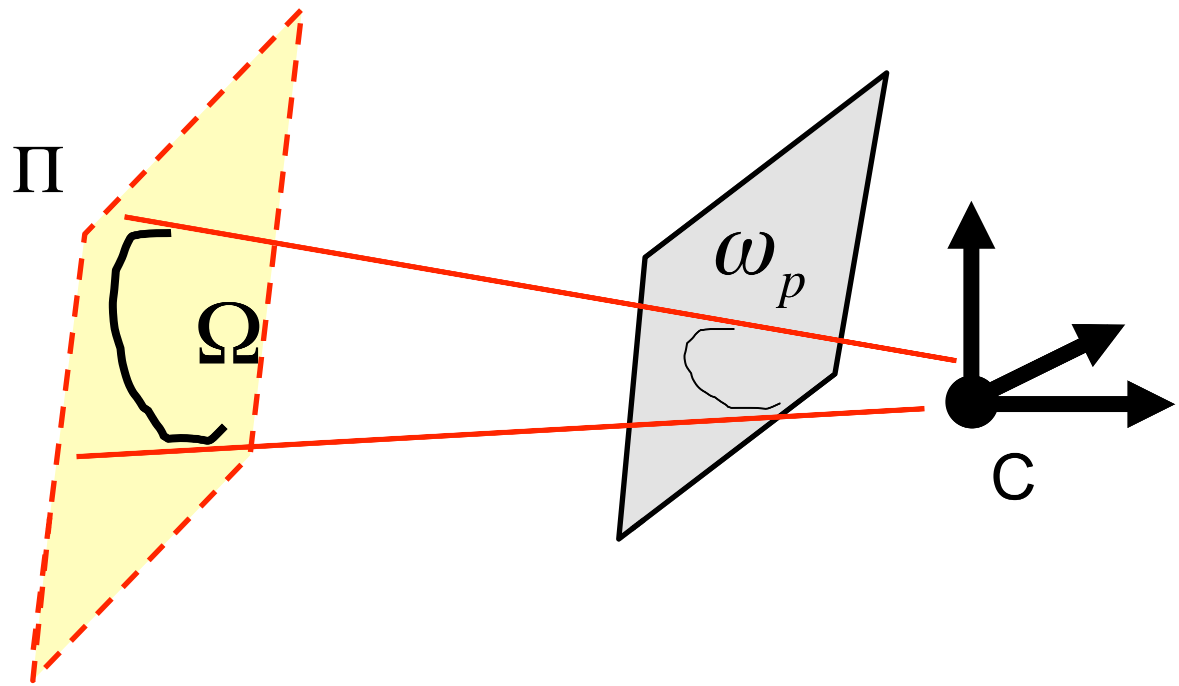
[Eq. 28]

$$\omega = (K\,K^T)^{-1}$$

If $\theta = 90 \rightarrow \boxed{v_1^T \omega\, v_2 = 0}$ [Eq. 29]

Scalar equation

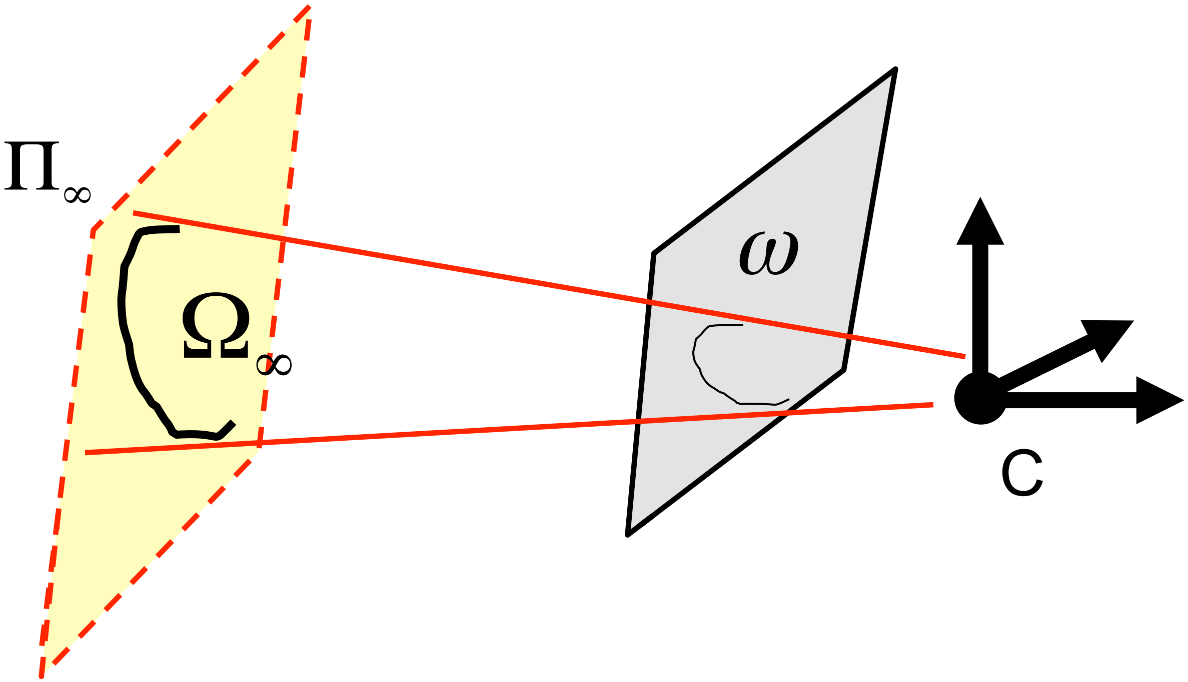
Projective transformation of a conic Ω



$$\omega_p = M^{-T}\Omega\ M^{-1}$$

HZ page 73, eq. 3.16

Projective transformation of Ω_∞ Absolute conic



$$\omega = M^{-T}\Omega_\infty M^{-1} = (K\,K^T)^{-1}$$

HZ page 73

Projective transformation of Ω_∞

Absolute conic

$$\boxed{\omega = M^{-T}\Omega_\infty M^{-1} = (K\,K^T)^{-1}} \quad \text{[Eq. 30]}$$

$$M = K\begin{bmatrix} R & T \end{bmatrix}$$

1. It is not function of R, T

2. $\omega = \begin{bmatrix} \omega_1 & \omega_2 & \omega_4 \\ \omega_2 & \omega_3 & \omega_5 \\ \omega_4 & \omega_5 & \omega_6 \end{bmatrix}$ symmetric and known up scale

3. $\omega_2 = 0$ zero-skew

4. $\omega_2 = 0$, $\omega_1 = \omega_3$ square pixel

Summary

$$\boxed{\mathbf{v} = K\,\mathbf{d}}$$

[Eq. 24]

$$\boxed{\mathbf{n} = \mathrm{K}^{\mathrm{T}}\mathbf{l}_{\mathrm{horiz}}}$$

[Eq. 27]

$$\cos\boldsymbol{\theta} = \frac{\mathrm{v}_1^{\mathrm{T}}\boldsymbol{\omega}\,\mathrm{v}_2}{\sqrt{\mathrm{v}_1^{\mathrm{T}}\boldsymbol{\omega}\,\mathrm{v}_1}\sqrt{\mathrm{v}_2^{\mathrm{T}}\boldsymbol{\omega}\,\mathrm{v}_2}} \xrightarrow{\boldsymbol{\theta}=90} \boxed{\mathrm{v}_1^{\mathrm{T}}\boldsymbol{\omega}\,\mathrm{v}_2 = 0}$$

[Eq. 28]

[Eq. 29]

$$\boxed{\omega = (K\,K^T)^{-1}}$$

Useful to:

- To calibrate the camera
- To estimate the geometry of the 3D world

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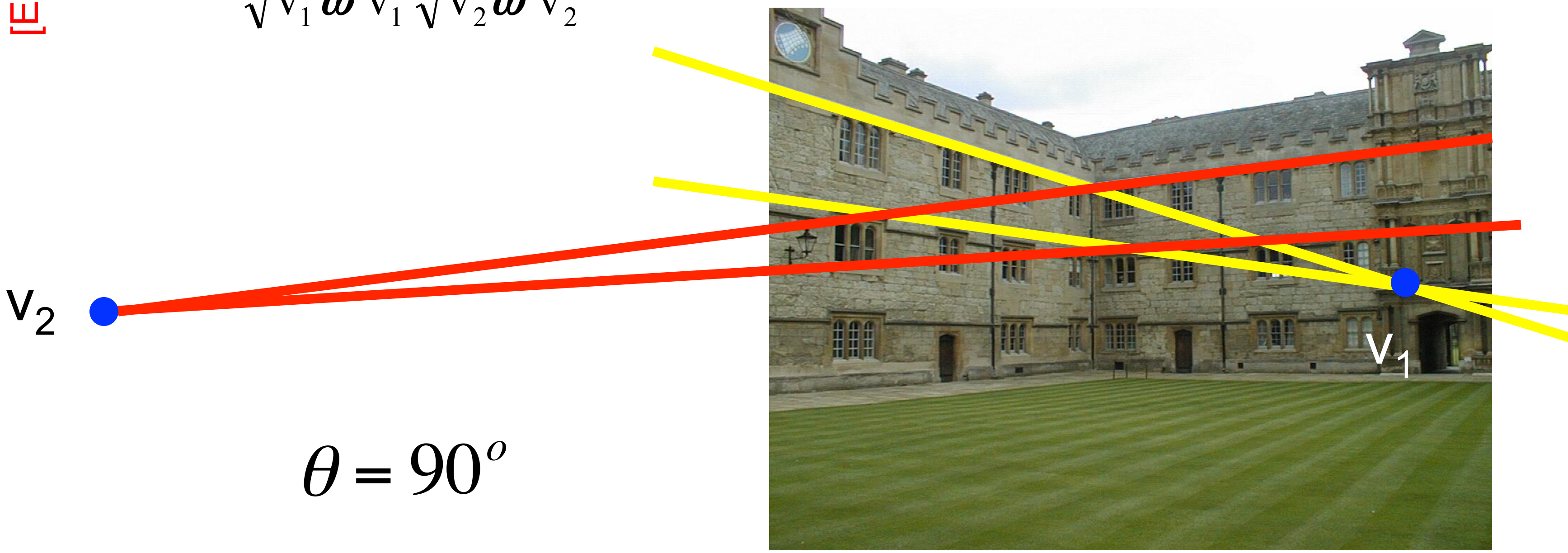
Single view calibration - example

[Eq. 28]

$$\cos\boldsymbol{\theta} = \frac{\mathrm{v}_1^{\mathrm{T}}\boldsymbol{\omega}\,\mathrm{v}_2}{\sqrt{\mathrm{v}_1^{\mathrm{T}}\boldsymbol{\omega}\,\mathrm{v}_1}\sqrt{\mathrm{v}_2^{\mathrm{T}}\boldsymbol{\omega}\,\mathrm{v}_2}}$$



$$\theta = 90^o$$

[Eq. 29]

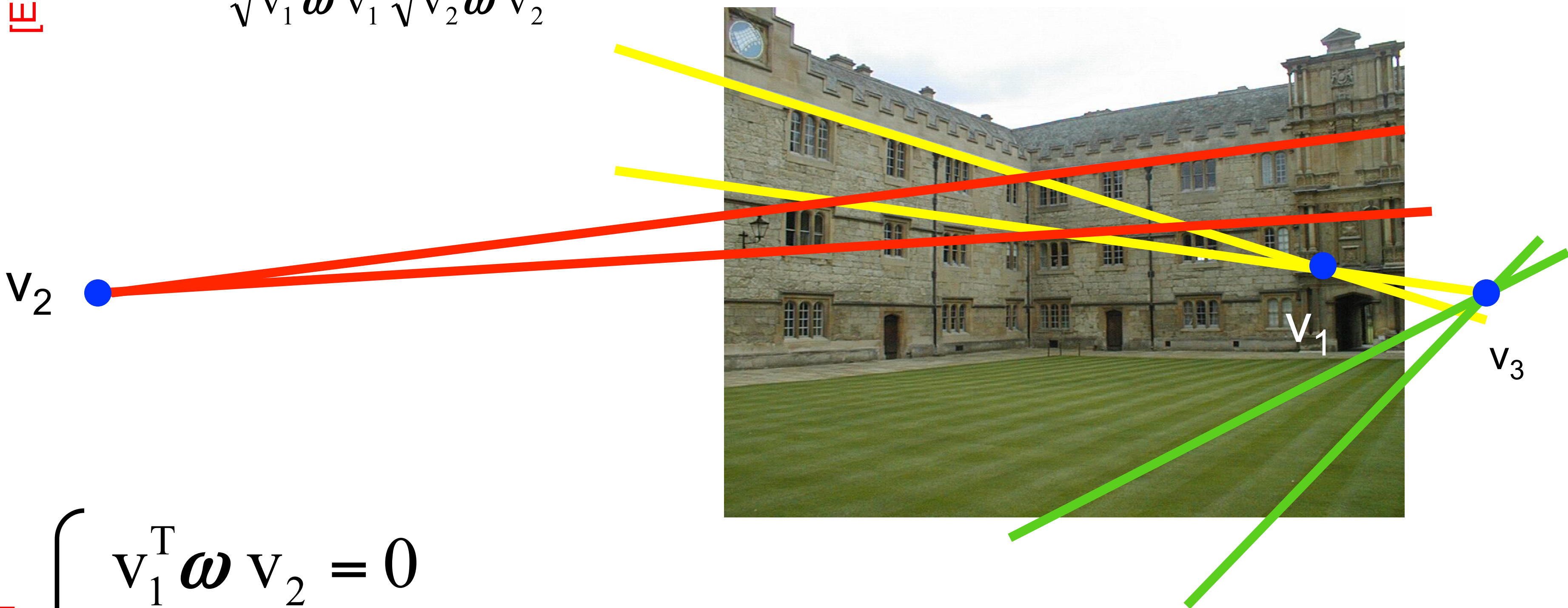
$$\begin{cases} \mathrm{v}_1^{\mathrm{T}}\boldsymbol{\omega}\,\mathrm{v}_2 = 0 \\ \omega = (K\,K^T)^{-1} \end{cases}$$

Do we have enough constraints to estimate K?
K has 5 degrees of freedom and Eq.29 is a scalar equation ☹

Single view calibration - example

[Eq. 28]

$$\cos\theta = \frac{v_1^T \boldsymbol{\omega}\, v_2}{\sqrt{v_1^T \boldsymbol{\omega}\, v_1}\sqrt{v_2^T \boldsymbol{\omega}\, v_2}}$$

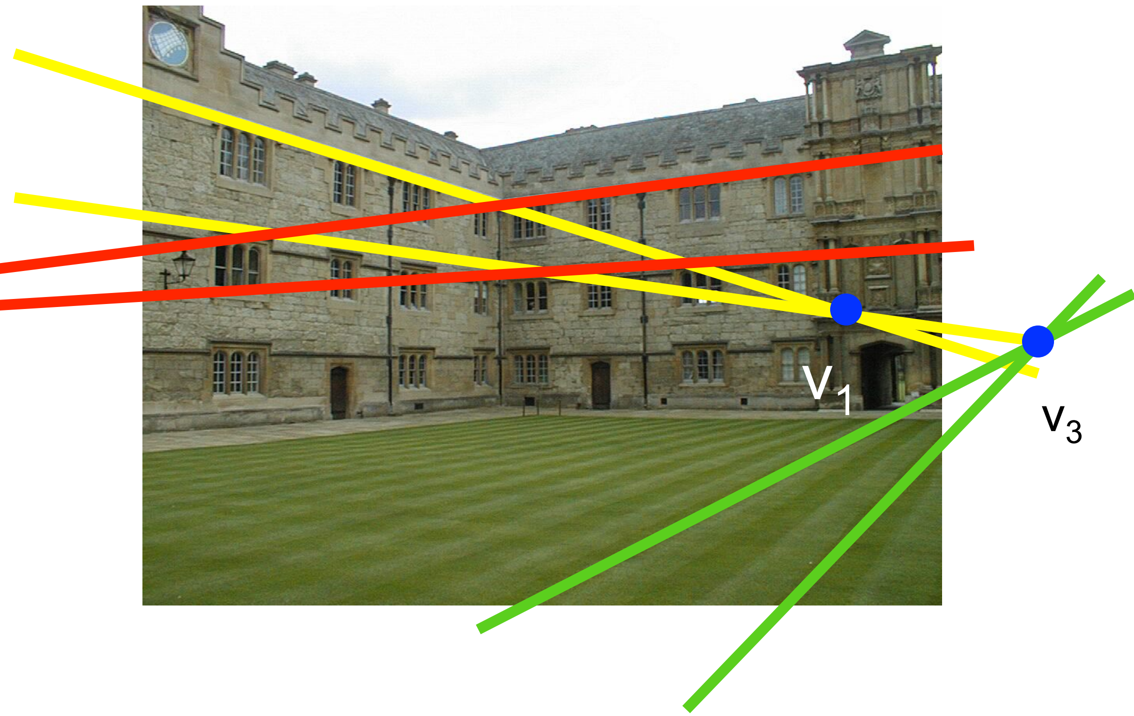


[Eqs. 31]

$$\begin{cases} v_1^T \boldsymbol{\omega}\, v_2 = 0 \\ v_1^T \boldsymbol{\omega}\, v_3 = 0 \\ v_2^T \boldsymbol{\omega}\, v_3 = 0 \end{cases}$$

Single view calibration - example

$$\omega = \begin{bmatrix} \omega_1 & \omega_2 & \omega_4 \\ \omega_2 & \omega_3 & \omega_5 \\ \omega_4 & \omega_5 & \omega_6 \end{bmatrix}$$



v_2

- Square pixels
- No skew

$\rightarrow$ $\omega_2 = 0$

$\omega_1 = \omega_3$

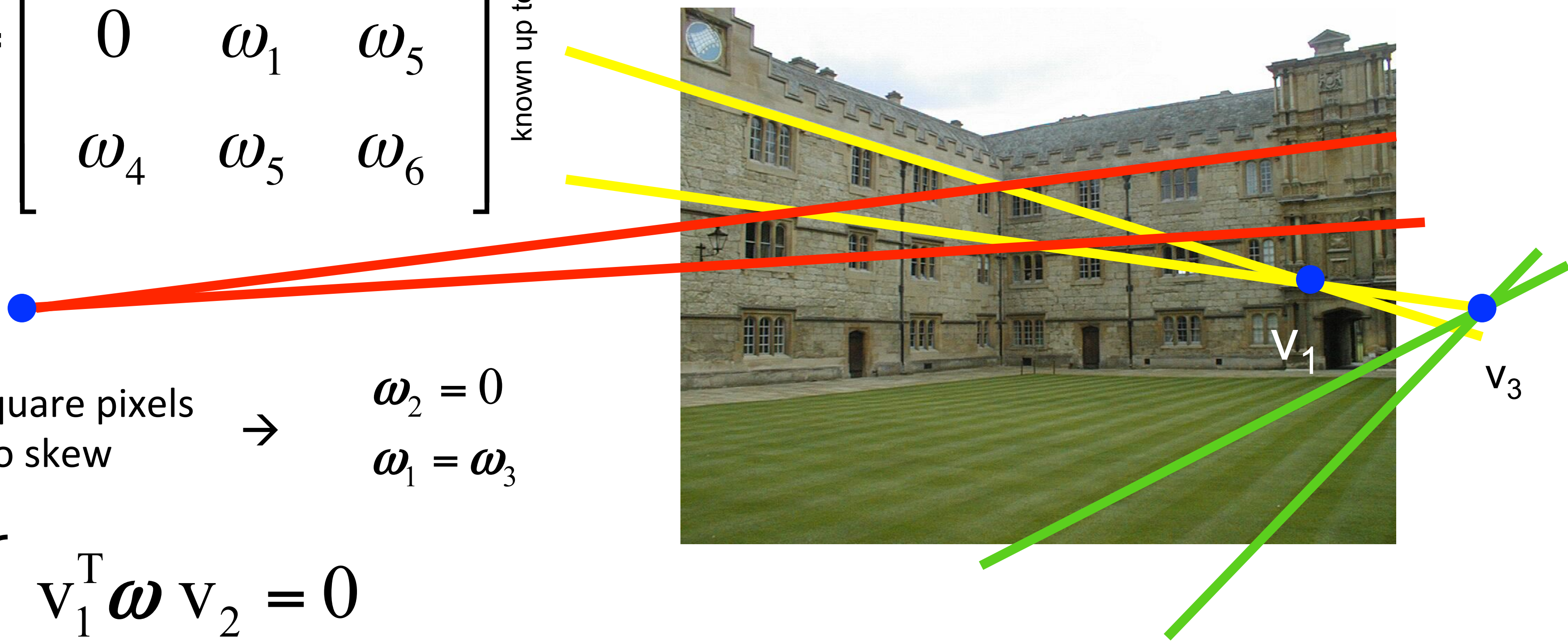
[Eqs. 31]

$$\begin{cases} v_1^T \omega \, v_2 = 0 \\ v_1^T \omega \, v_3 = 0 \\ v_2^T \omega \, v_3 = 0 \end{cases}$$

Single view calibration - example

$$\omega = \begin{bmatrix} \omega_1 & 0 & \omega_4 \\ 0 & \omega_1 & \omega_5 \\ \omega_4 & \omega_5 & \omega_6 \end{bmatrix}$$

known up to scale



- Square pixels
- No skew

→ $\omega_2 = 0$, $\omega_1 = \omega_3$

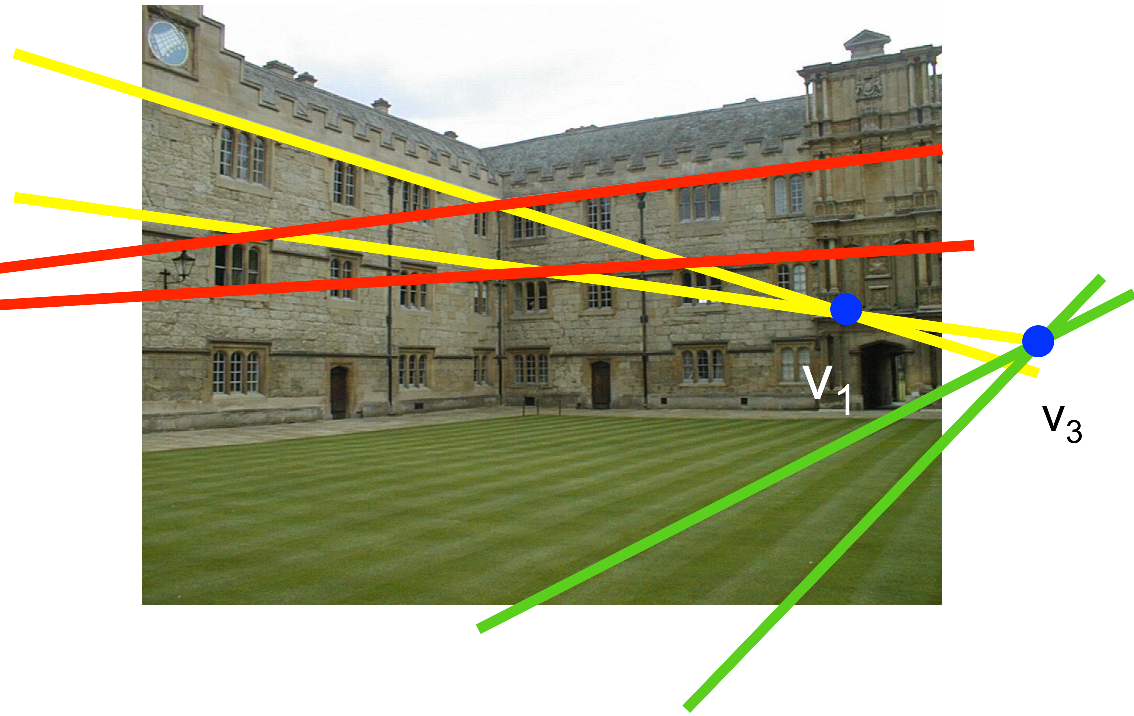
[Eqs. 31]

$$\begin{cases} v_1^T \omega \, v_2 = 0 \\ v_1^T \omega \, v_3 = 0 \\ v_2^T \omega \, v_3 = 0 \end{cases}$$

→ Compute ω !

Single view calibration - example

$$\omega = \begin{bmatrix} \omega_1 & 0 & \omega_4 \\ 0 & \omega_1 & \omega_5 \\ \omega_4 & \omega_5 & \omega_6 \end{bmatrix}$$



- Square pixels
- No skew

$\rightarrow$ $\omega_2 = 0$, $\omega_1 = \omega_3$

[Eqs. 31]

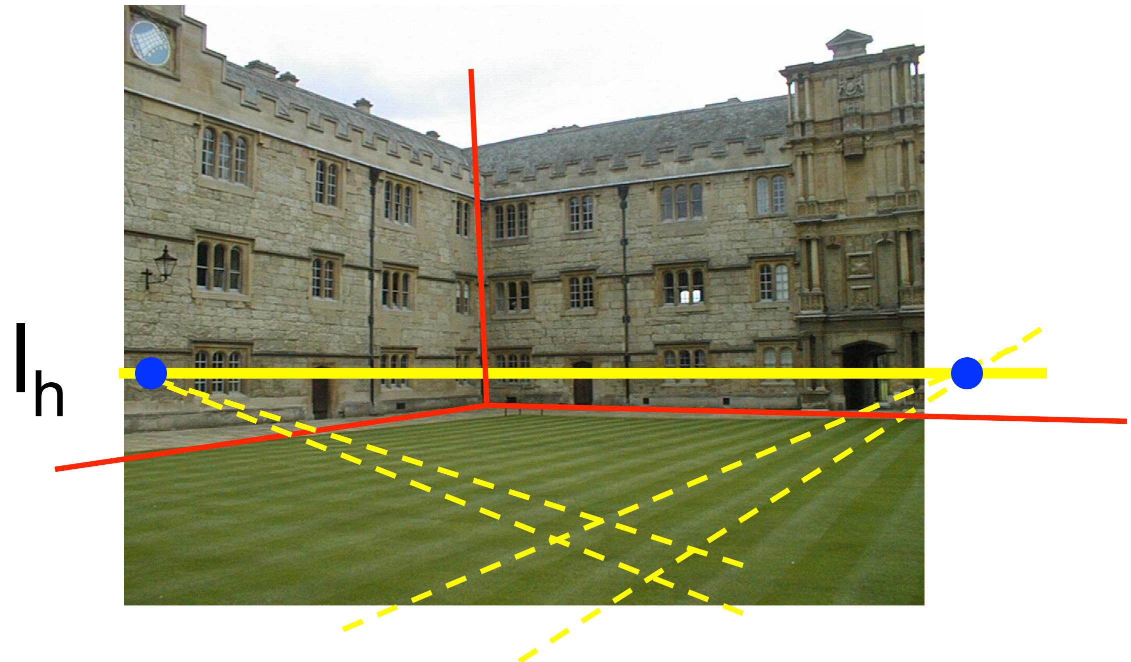
$$\begin{cases} \mathrm{v}_1^{\mathrm{T}} \boldsymbol{\omega}\, \mathrm{v}_2 = 0 \\ \mathrm{v}_1^{\mathrm{T}} \boldsymbol{\omega}\, \mathrm{v}_3 = 0 \\ \mathrm{v}_2^{\mathrm{T}} \boldsymbol{\omega}\, \mathrm{v}_3 = 0 \end{cases}$$

Once ω is calculated, we get K:

$$\omega = (K\,K^T)^{-1} \longrightarrow \mathrm{K}$$

(Cholesky factorization; HZ pag 582)

Single view reconstruction - example

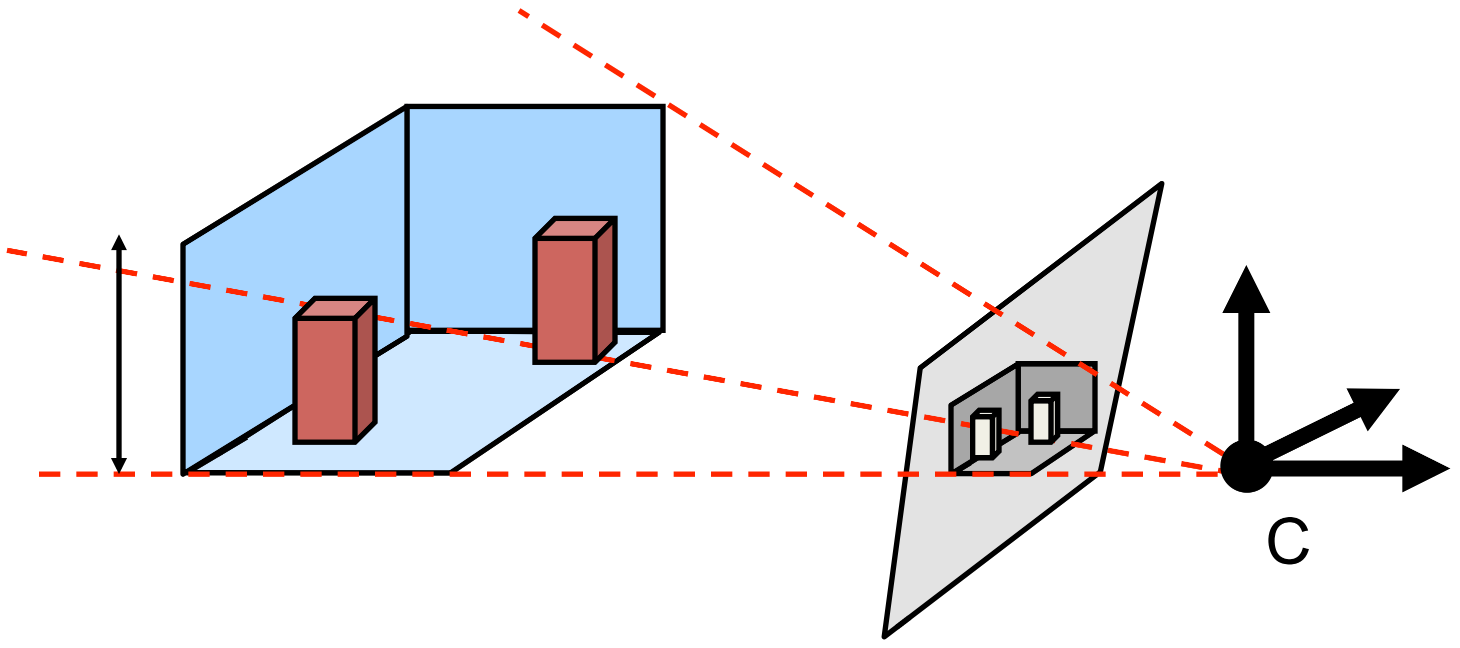


[Eq. 27]

K known $\longrightarrow$ $$\mathbf{n} = K^T \mathbf{l}_{horiz}$$ = Scene plane orientation in the camera reference system

Select orientation discontinuities

Single view reconstruction - example



Recover the structure within the camera reference system

Notice: the actual scale of the scene is NOT recovered

- Recognition helps reconstruction!
- Humans have learnt this

Lecture 4

Single View Metrology

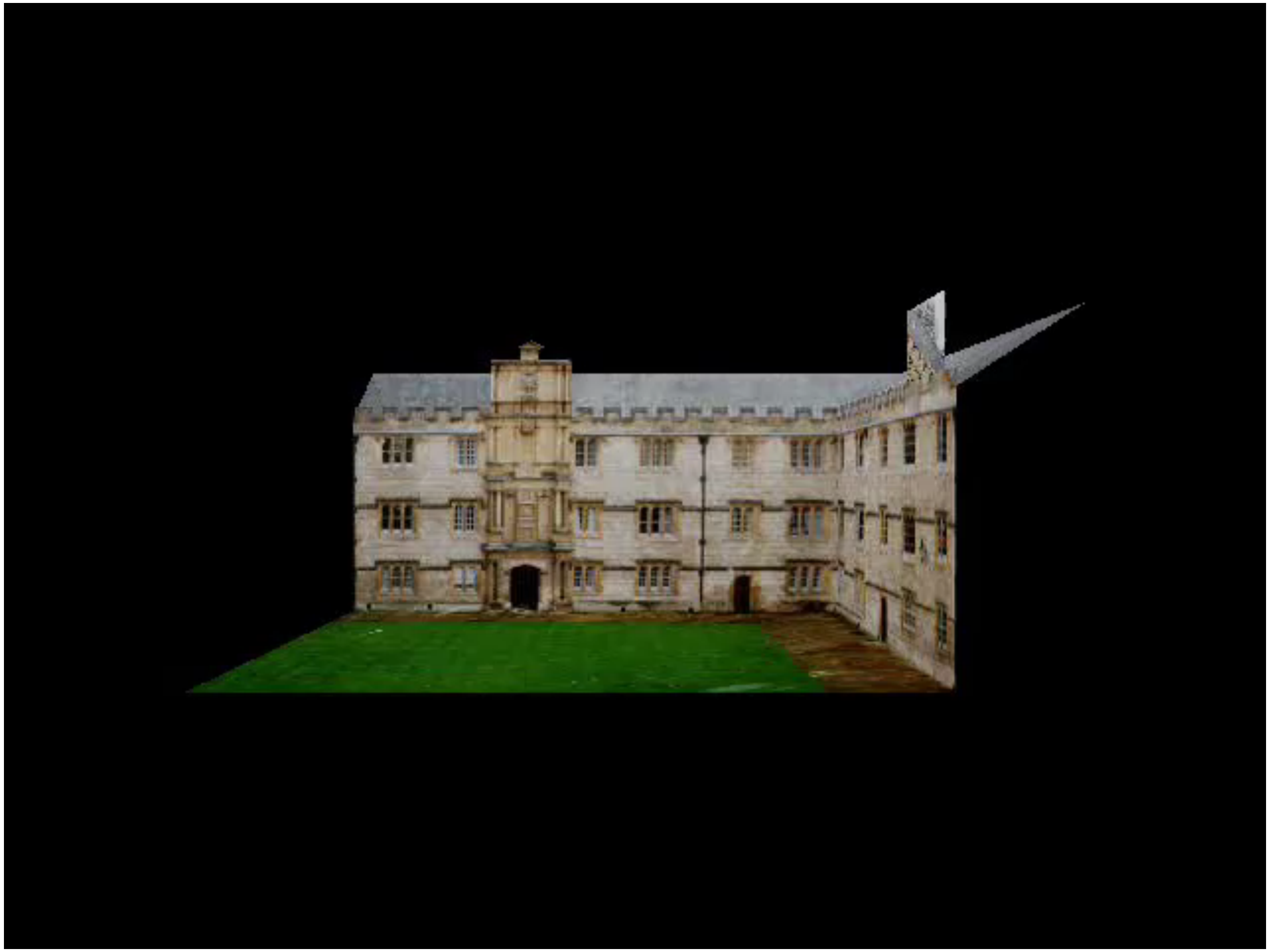
- Review calibration
- Vanishing points and lines
- Estimating geometry from a single image
- Extensions

Reading:
[HZ] Chapter 2 “Projective Geometry and Transformation in 3D”
[HZ] Chapter 3 “Projective Geometry and Transformation in 3D”
[HZ] Chapter 8 “More Single View Geometry”
[Hoeim & Savarese] Chapter 2

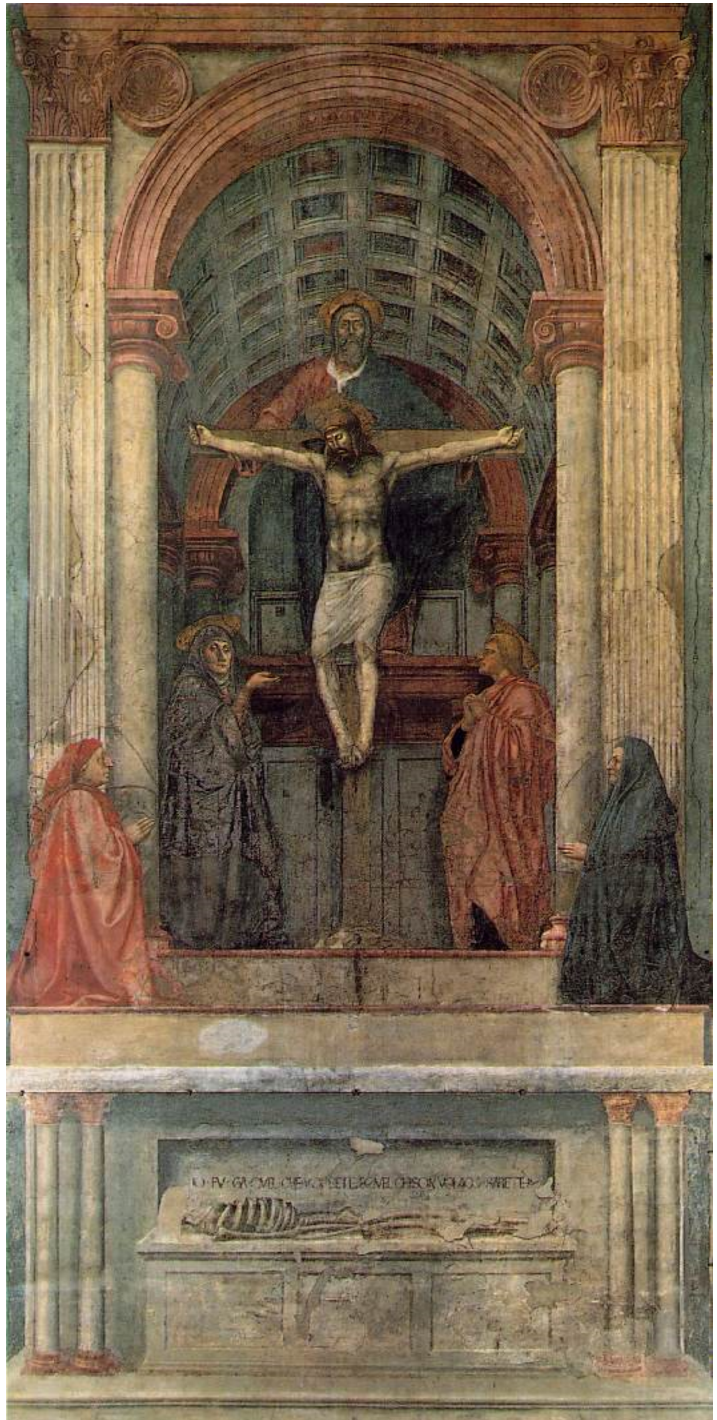
Criminisi & Zisserman, 99

http://www.robots.ox.ac.uk/~vgg/projects/SingleView/models/merton/merton.wrl

Criminisi & Zisserman, 99



http://www.robots.ox.ac.uk/~vgg/projects/SingleView/models/merton/merton.wrl

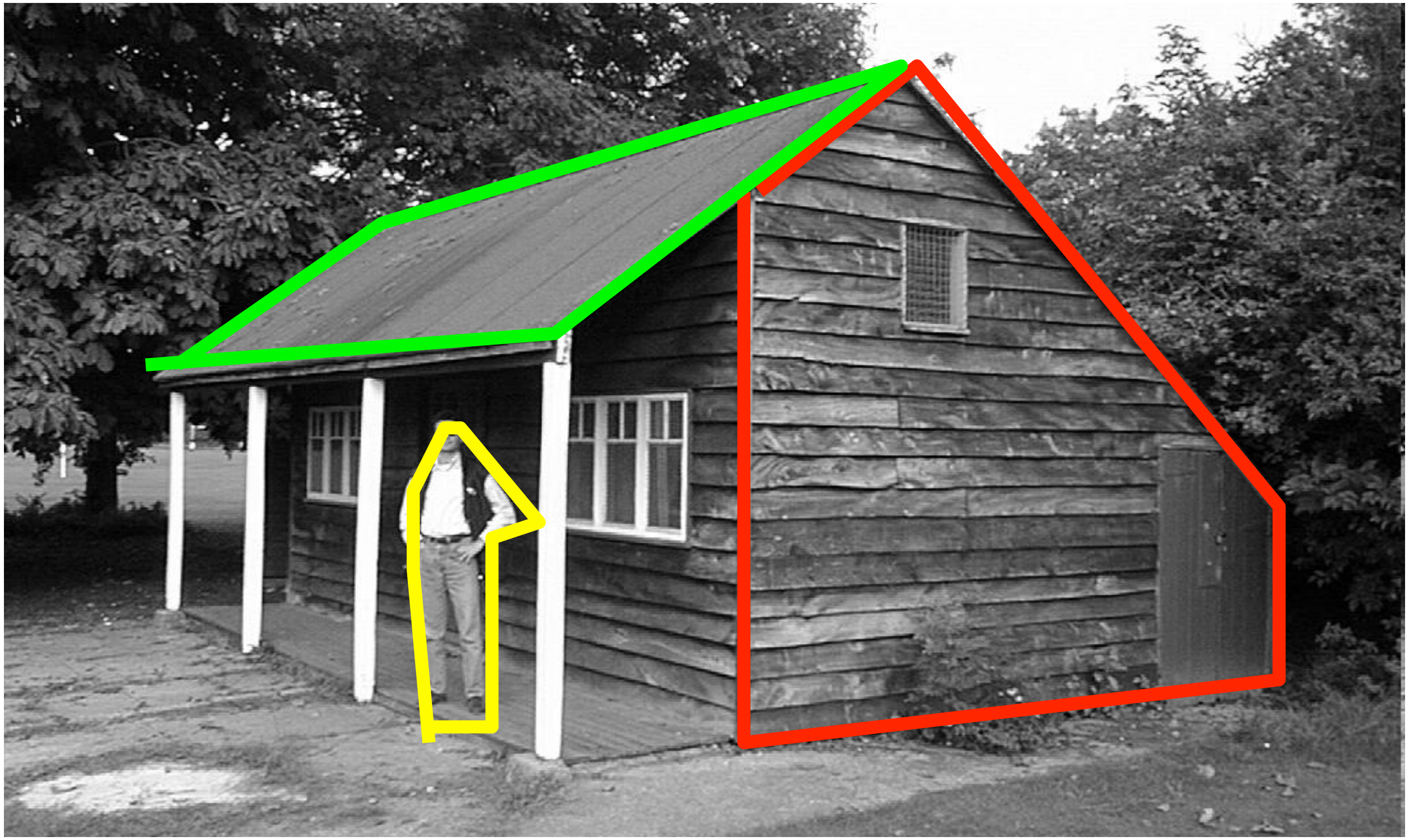


La Trinita' (1426)
Firenze, Santa Maria
Novella; by Masaccio
(1401-1428)

La Trinita' (1426)
Firenze, Santa Maria
Novella; by Masaccio
(1401-1428)

http://www.robots.ox.ac.uk/~vgg/projects/SingleView/models/hut/hutme.wrl

Single view reconstruction - drawbacks

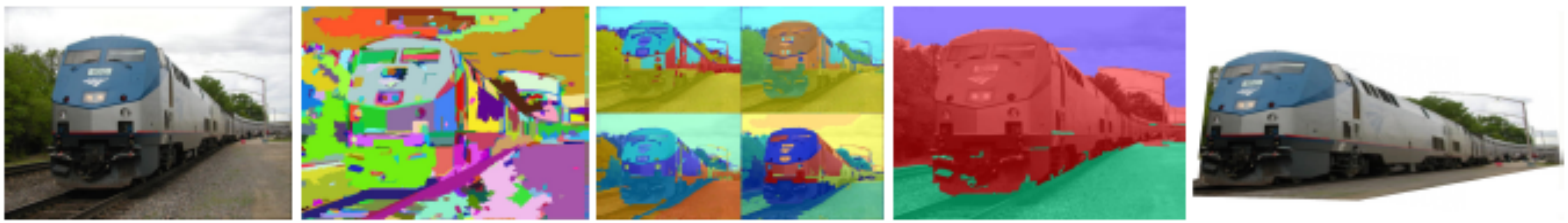


Manually select:

• Vanishing points and lines;
• Planar surfaces;
• Occluding boundaries;
• Etc..

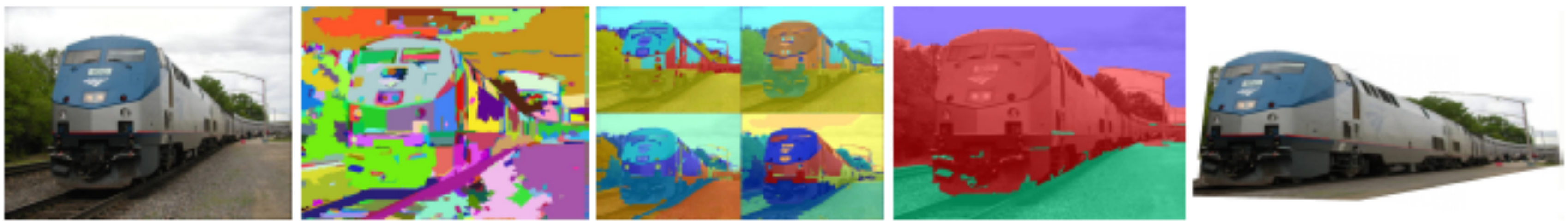
Automatic Photo Pop-up

Hoiem et al, 05



Automatic Photo Pop-up

Hoiem et al, 05…



Automatic Photo Pop-up

Hoiem et al, 05…

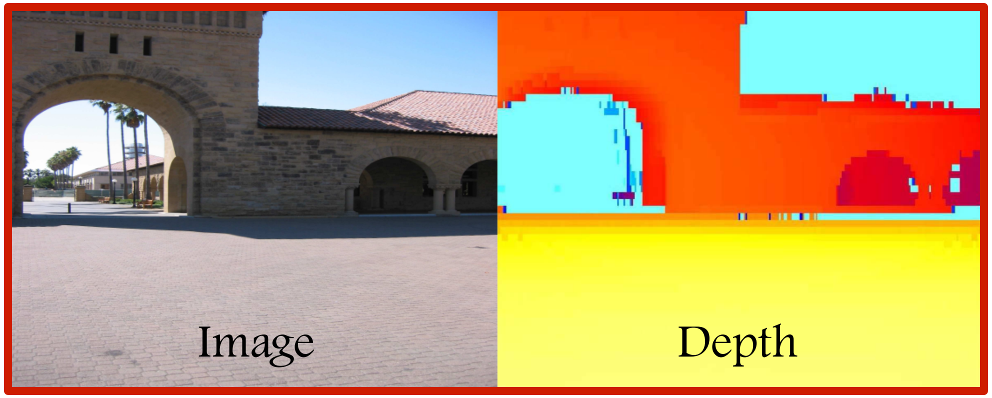
Software:

http://www.cs.uiuc.edu/homes/dhoiem/projects/software.html

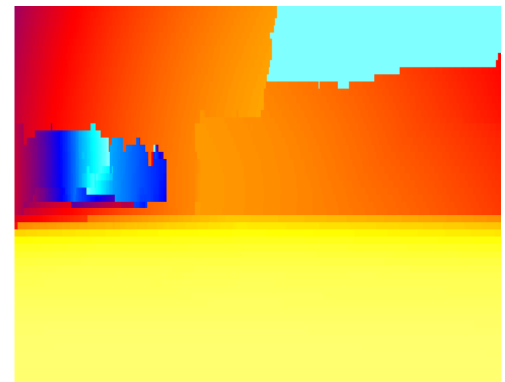
Make3D

Saxena, Sun, Ng, 05…

Training

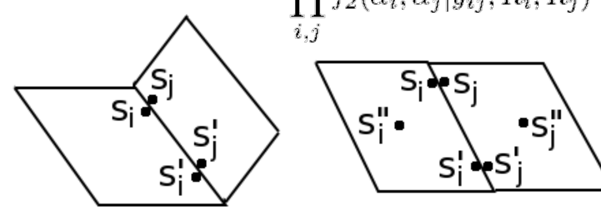


Prediction



Plane Parameter MRF

$$P(\alpha|X,\nu,y,R;\theta) = \frac{1}{Z}\prod_i f_1(\alpha_i|X_i,\nu_i,R_i;\theta) \prod_{i,j} f_2(\alpha_i,\alpha_j|y_{ij},R_i,R_j)$$



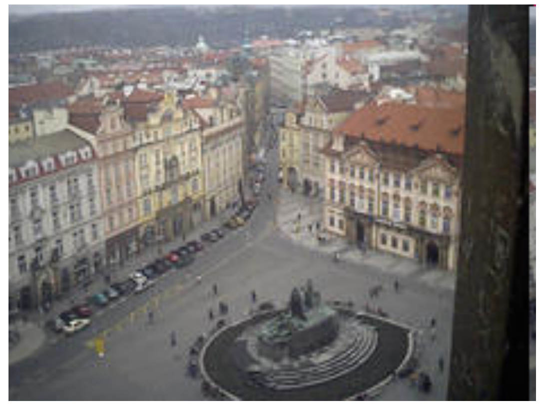
(a) Connectivity

(b) Co-Planarity

youtube

Make3D

Saxena, Sun, Ng, 05…



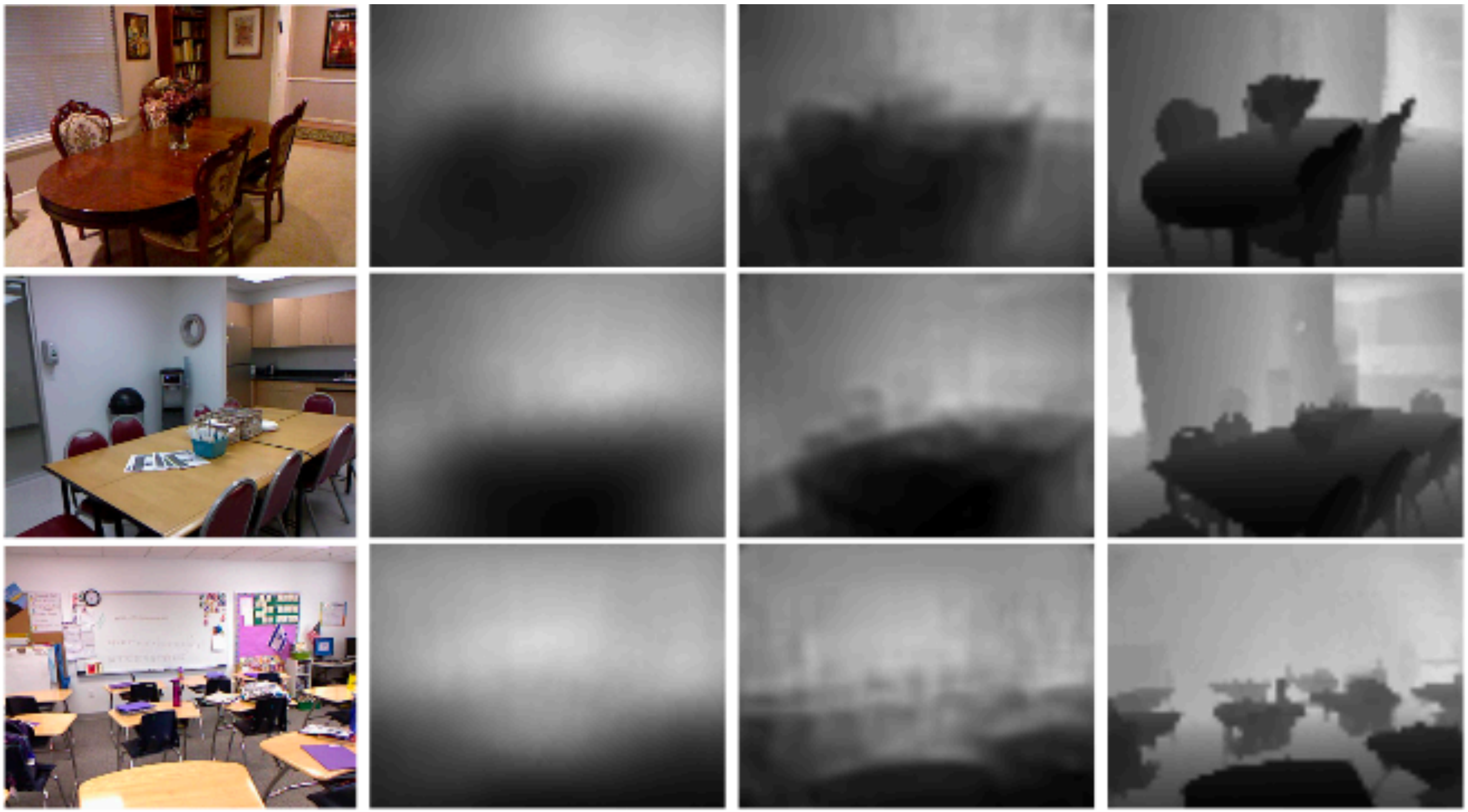
A software: **Make3D**
"Convert your image into 3d model"

http://make3d.stanford.edu/

http://make3d.cs.cornell.edu/

Depth map reconstruction using deep learning

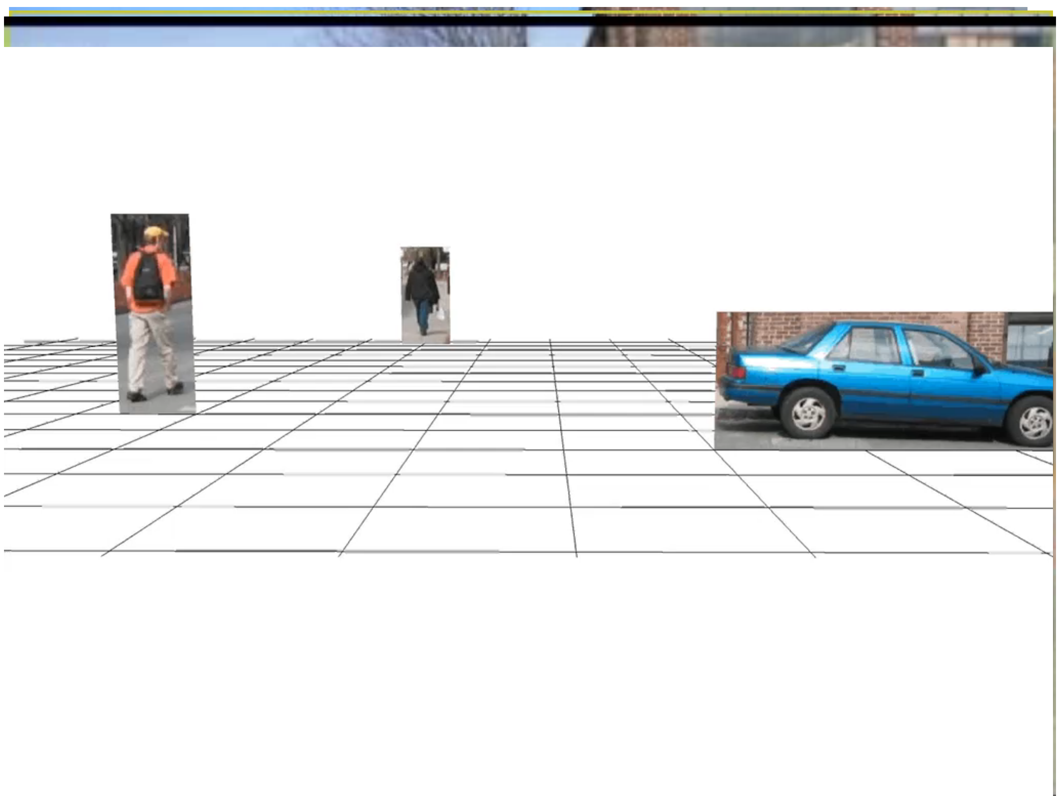
Eigen et al., 2014



Depth Map Prediction from a Single Image using a Multi-Scale Deep Network,
Eigen, D., Puhrsch, C. and Fergus, R. Proc. Neural Information Processing Systems 2014,

Coherent object detection and scene layout estimation from a single image

Y. Bao, M. Sun, S. Savarese, CVPR 2010, BMVC 2010



Next lecture:

Multi-view geometry (epipolar geometry)

Appendix

Vanishing points - example

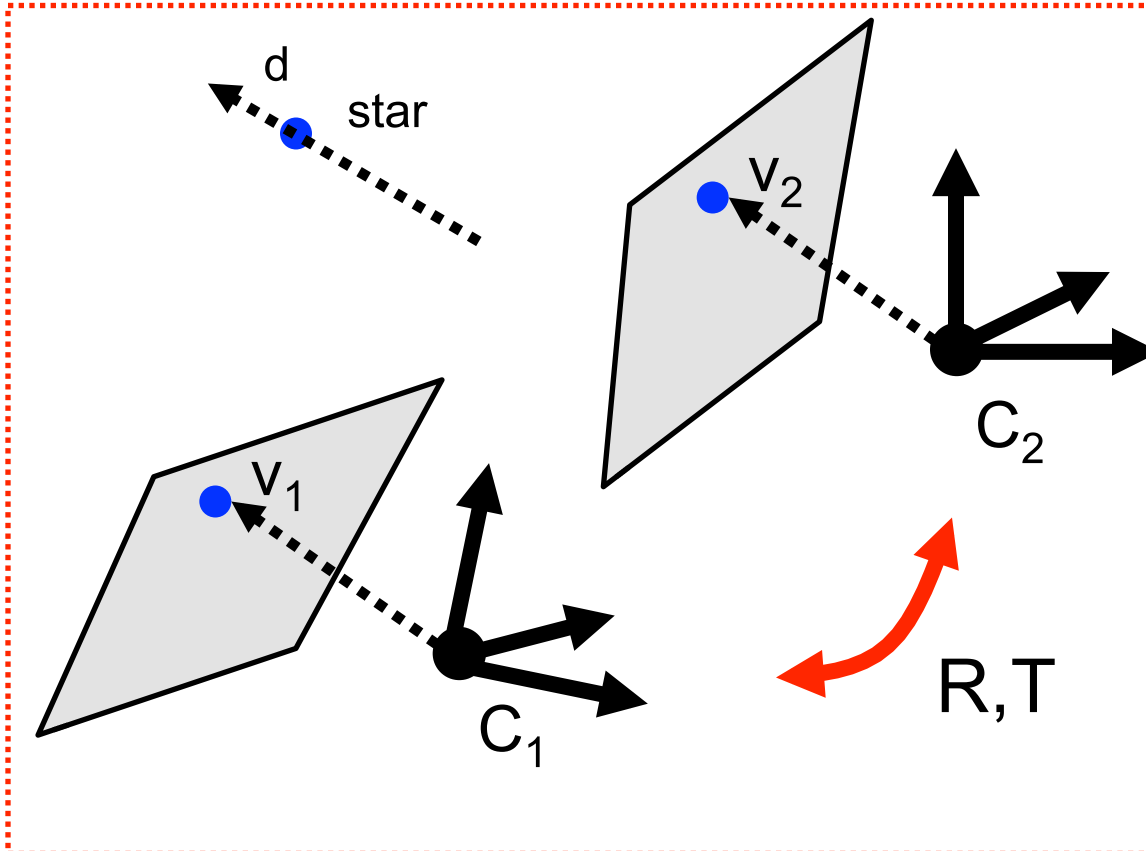
v1, v2: measurements
K = known and constant

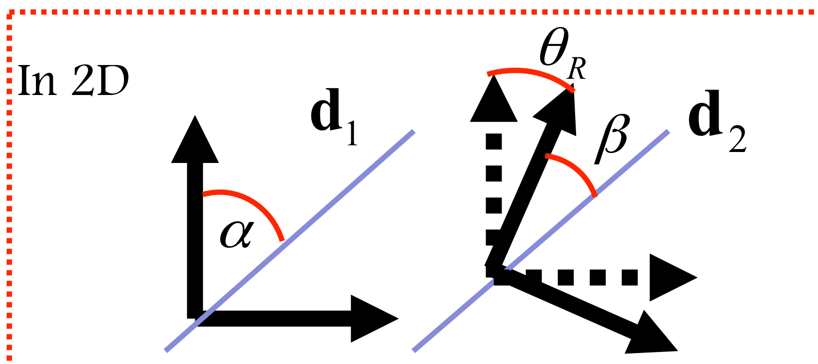
Can I compute R?
No rotation around z

$$\mathbf{d}_1 = \frac{K^{-1}\,\mathbf{v}_1}{\left\|K^{-1}\,\mathbf{v}_1\right\|}$$

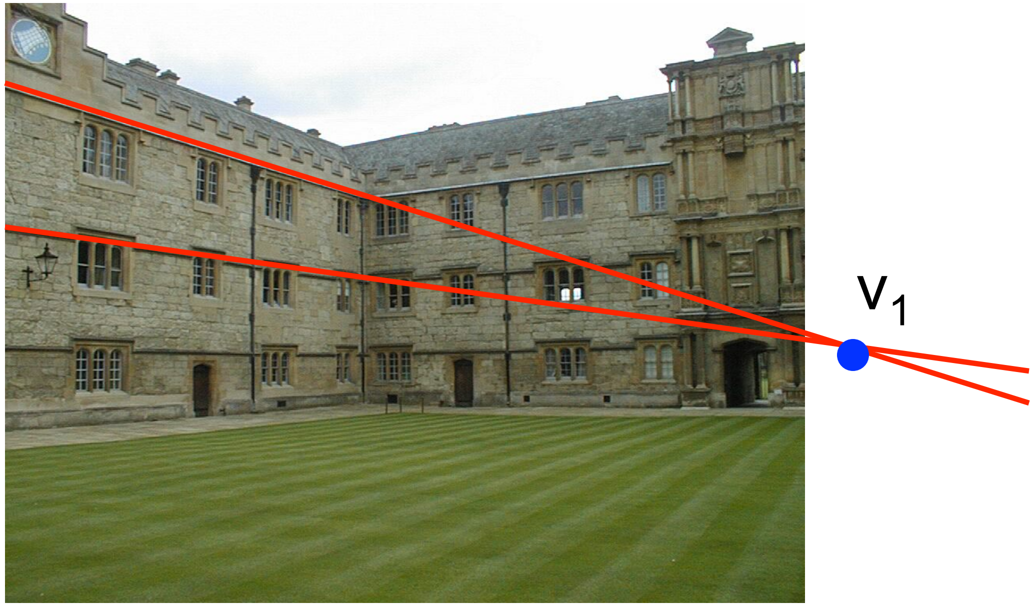
$$\mathbf{d}_2 = \frac{K^{-1}\,\mathbf{v}_2}{\left\|K^{-1}\,\mathbf{v}_2\right\|}$$

$$R\,\mathbf{d}_1 = \mathbf{d}_2 \longrightarrow R$$





$$\theta_R = \alpha - \beta$$



$$\mathbf{d}_1 = \frac{K^{-1}\,\mathbf{v}_1}{\left\| K^{-1}\,\mathbf{v}_1 \right\|}$$

$$\mathbf{d}_2 = \frac{K^{-1}\,\mathbf{v}_2}{\left\| K^{-1}\,\mathbf{v}_2 \right\|}$$

$$\longrightarrow \quad R$$