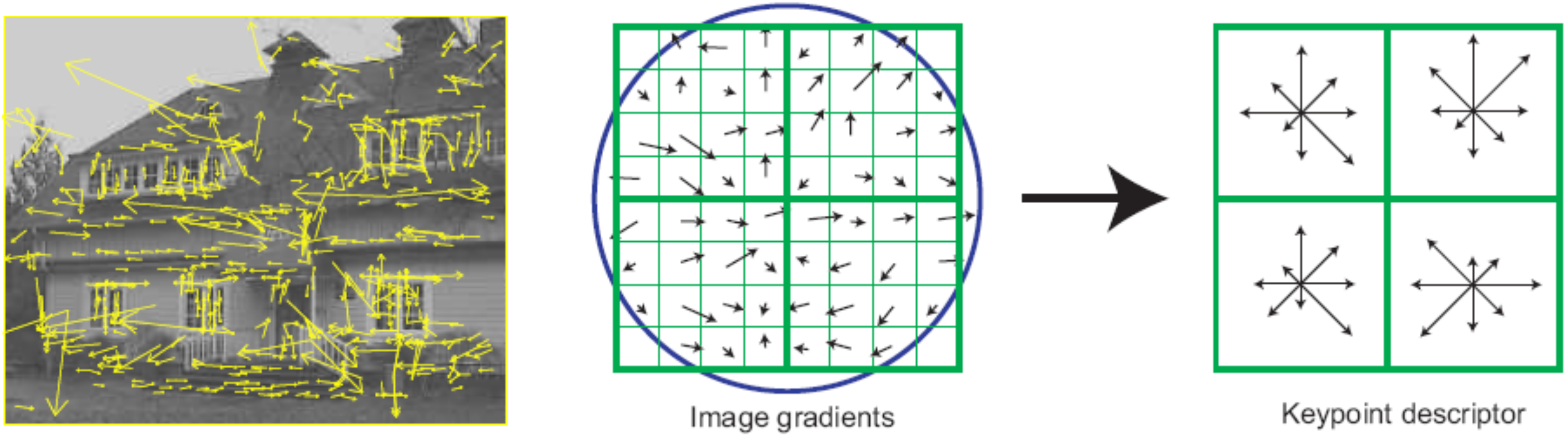
Feature descriptors and matching

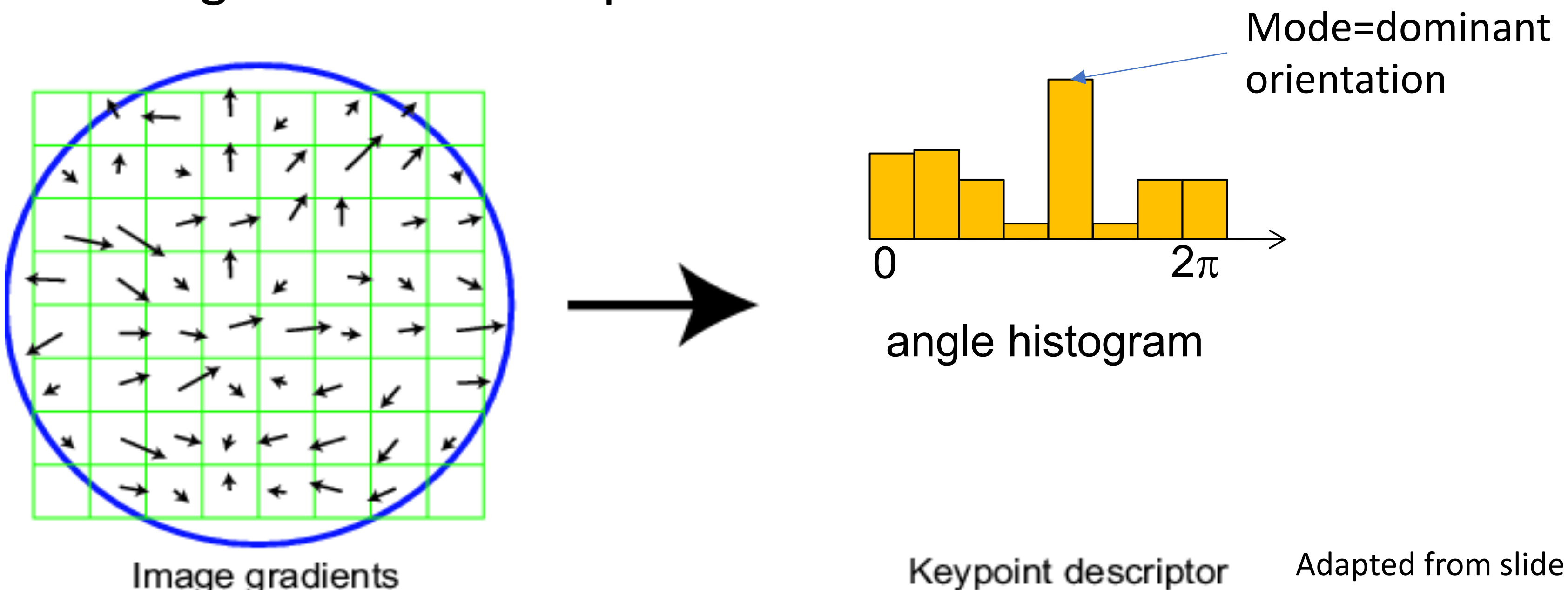
The SIFT descriptor



SIFT – Lowe IJCV 2004

Scale Invariant Feature Transform

- DoG for scale-space feature detection
- Take 16x16 square window around detected feature at appropriate scale
  - Compute gradient orientation for each pixel
  - Throw out weak edges (threshold gradient magnitude)
  - Create histogram of surviving edge orientations: note: each pixel contributes vote proportional to gradient magnitude
  - Find mode of histogram and rotate patch so that mode is 0

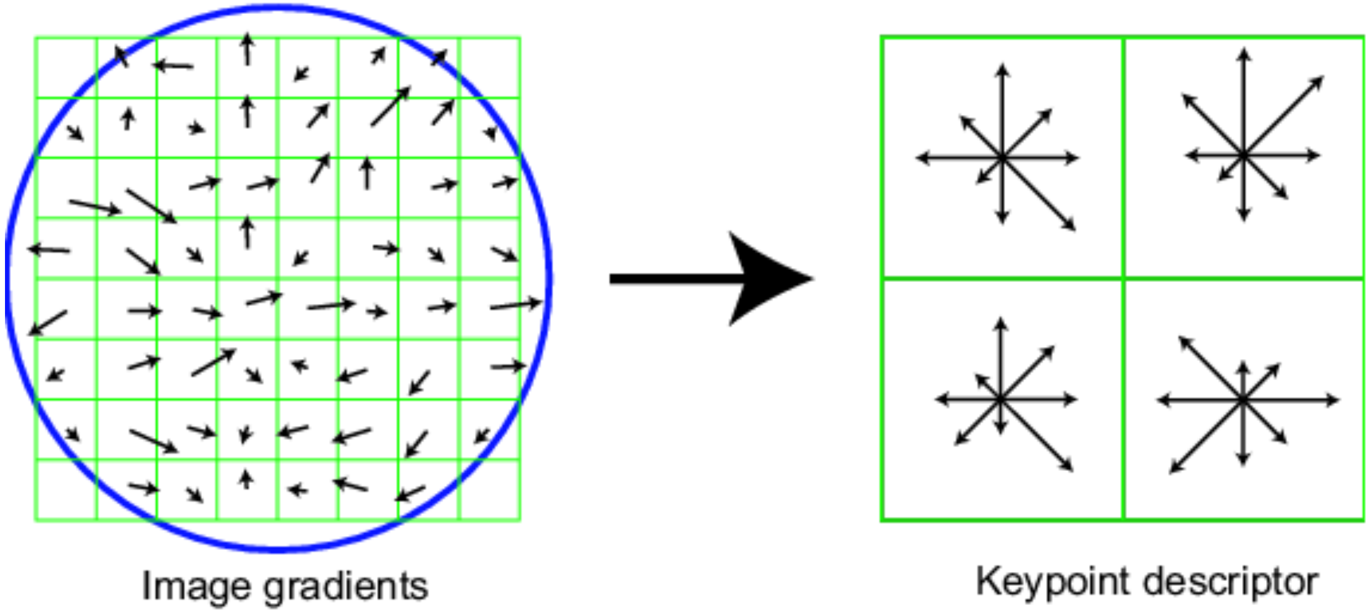


Adapted from slide by David Lowe

SIFT descriptor

Create histogram

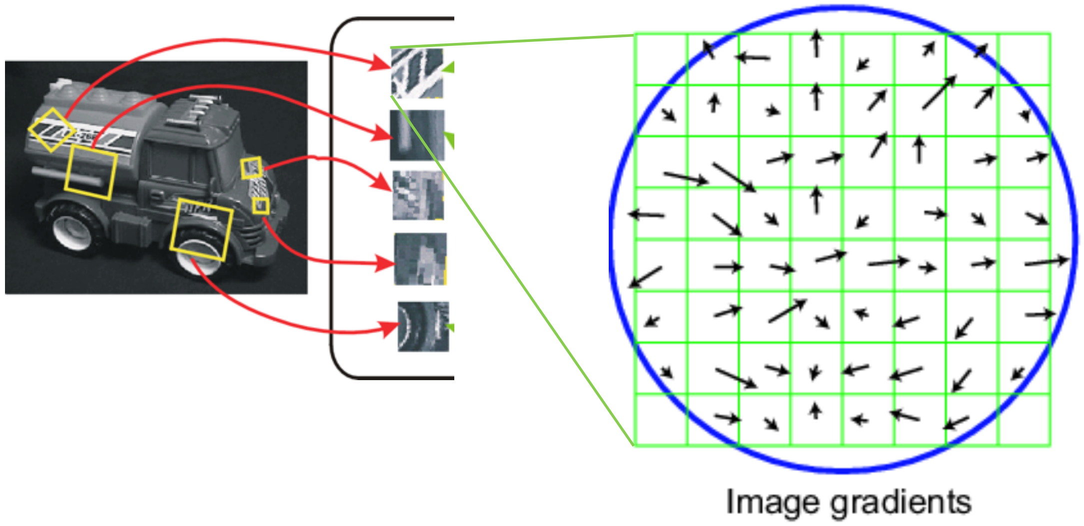
- Divide the 16x16 window into a 4x4 grid of cells (2x2 case shown below)
- Compute an orientation histogram for each cell
- 16 cells * 8 orientations = 128 dimensional descriptor



Adapted from slide by David Lowe

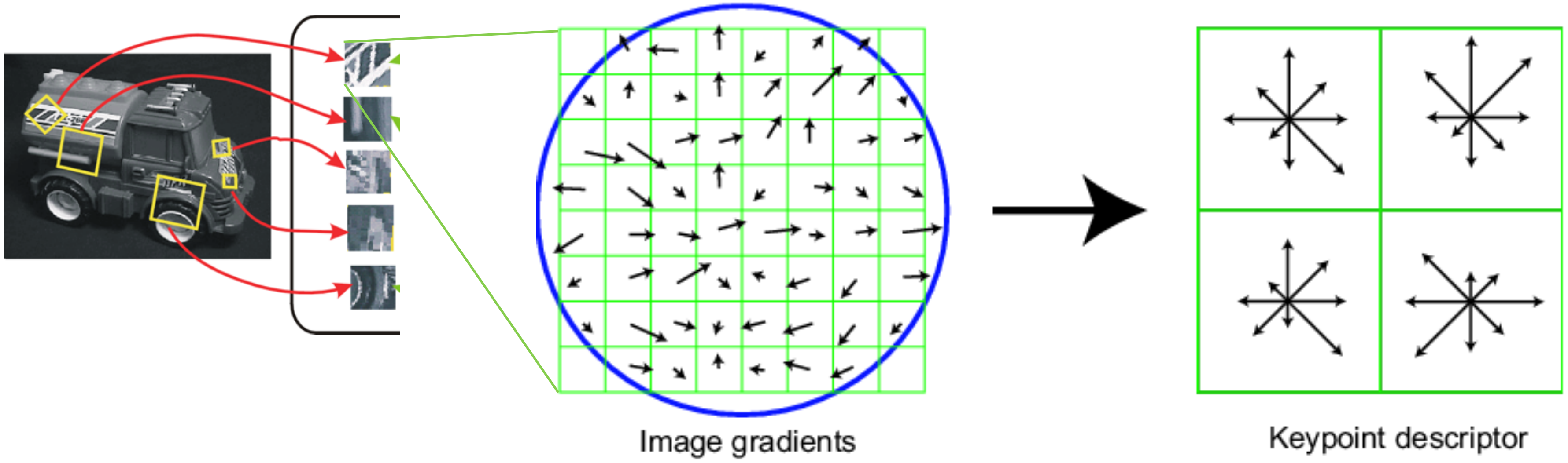
SIFT vector formation

- Computed on rotated and scaled version of window according to computed orientation & scale
  - resample the window



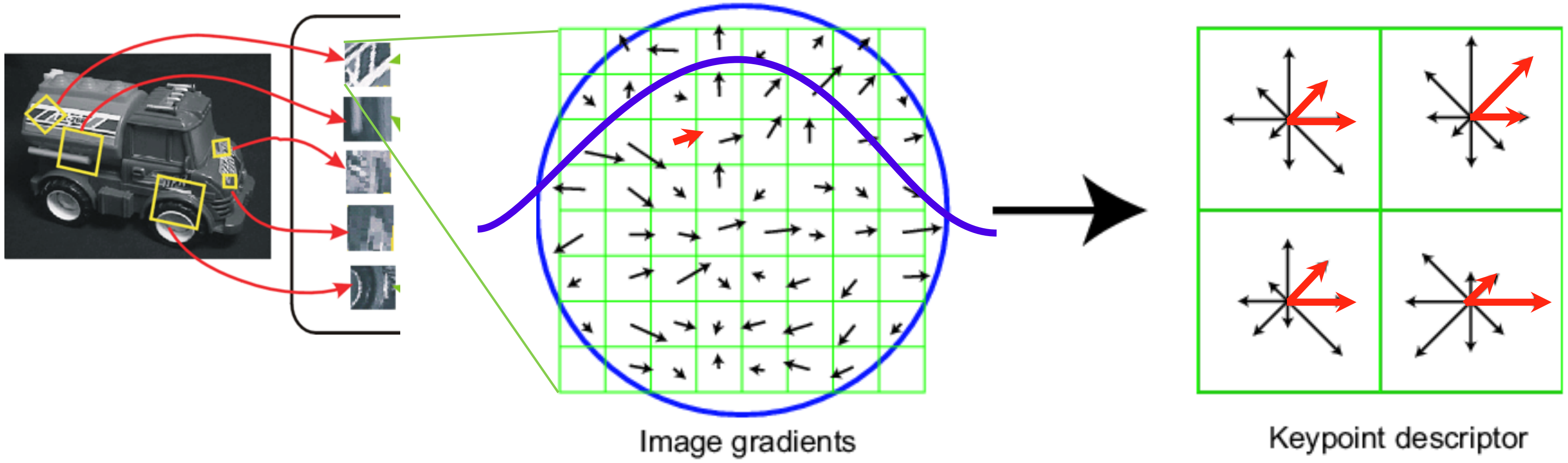
Reduce effect of illumination

- 128-dim vector normalized to 1: invariance to contrast changes
- Threshold gradient magnitudes to avoid excessive influence of high gradients
  - after normalization, clamp gradients >0.2
  - renormalize

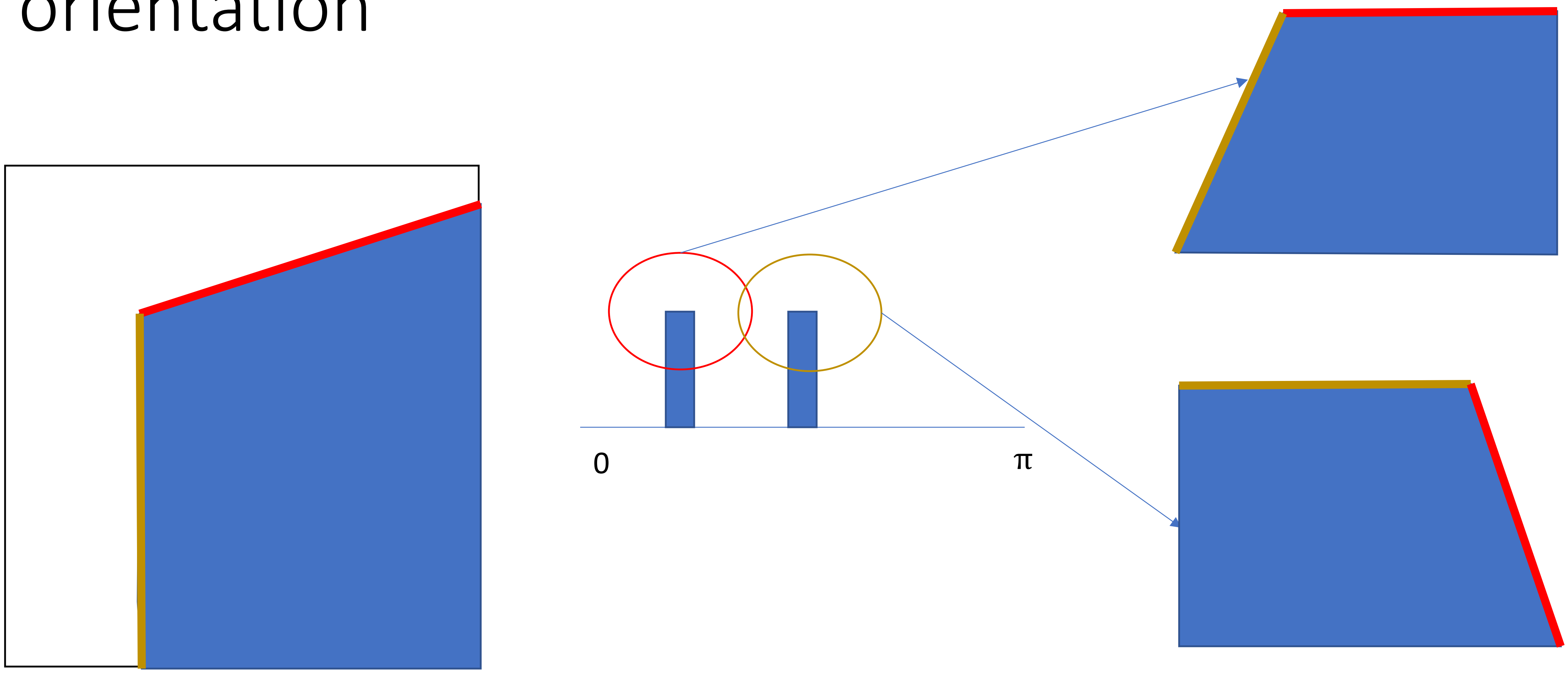


Other tips and tricks

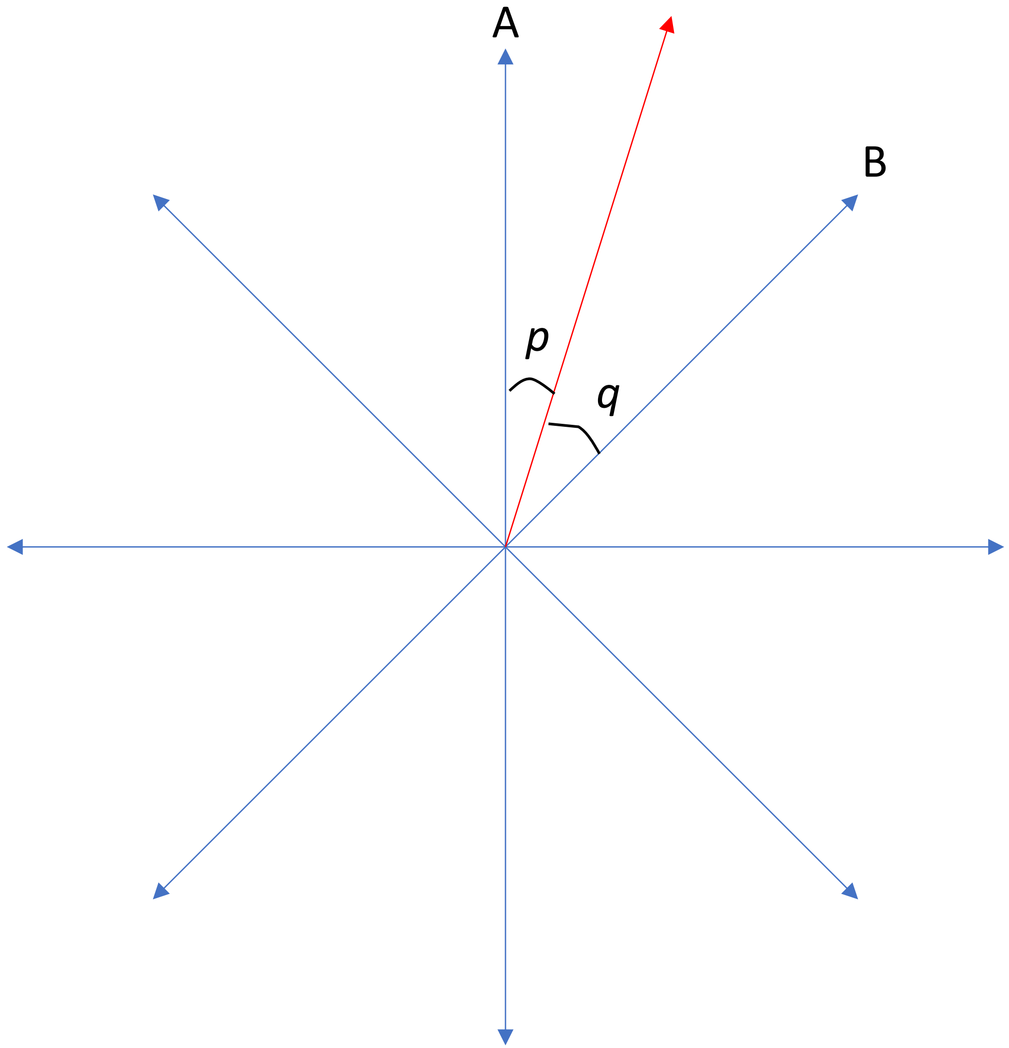
- When identifying dominant orientation, if multiple modes, create multiple keypoints
- Weigh pixels in center of patch more highly (Gaussian weights)
- Trilinear interpolation
  - a given gradient contributes to 8 bins: 4 in space times 2 in orientation



Multiple modes when measuring dominant orientation

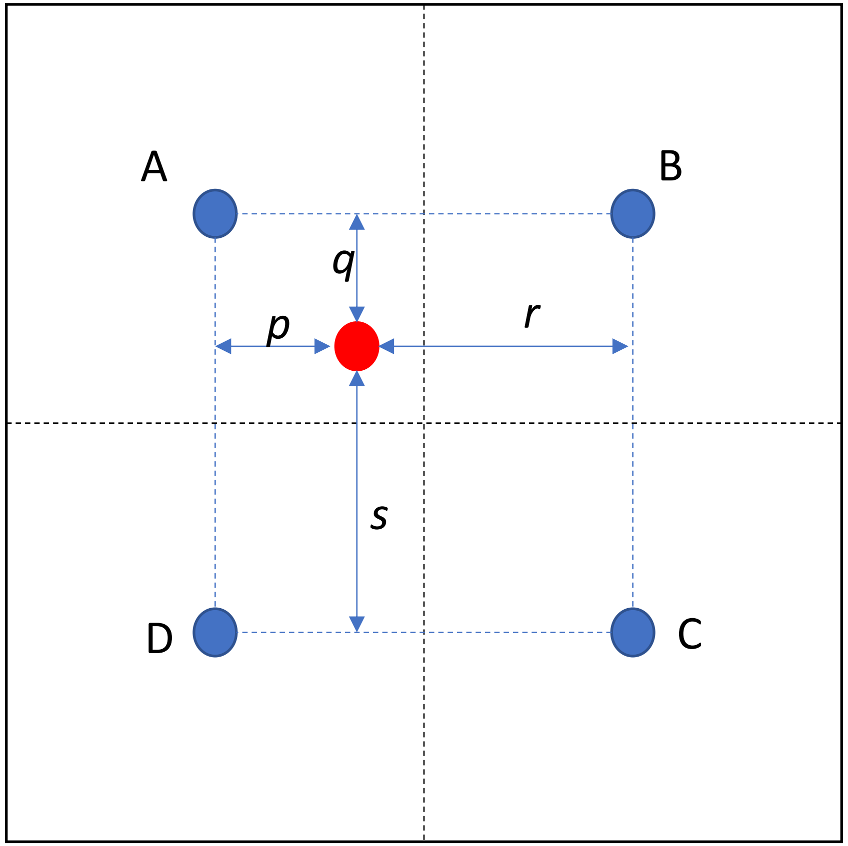


Linear interpolation into orientation grid



- Blue arrows are centers of orientation bin
- Pixel with red orientation contributes to:
  - Histogram A with weight q
  - Histogram B with weight p

Bilinear interpolation into spatial grid cells



- Blue dots are centers of histograms
- Red pixel contributes to:
  - Histogram A with weight proportional to $r \cdot s$
  - Histogram B with weight proportional to $p \cdot s$
  - Histogram A with weight proportional to $p \cdot q$
  - Histogram A with weight proportional to $r \cdot q$

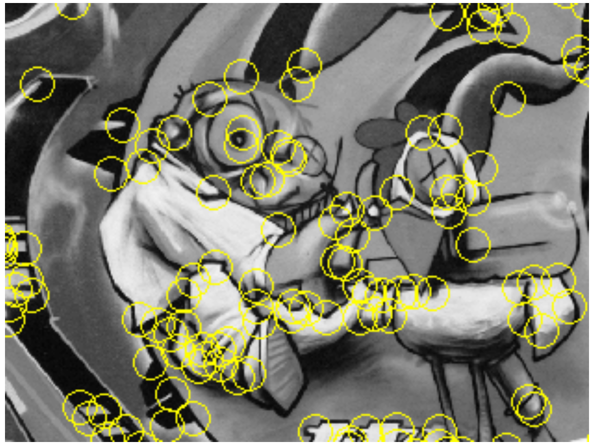
Properties of SIFT

Extraordinarily robust matching technique

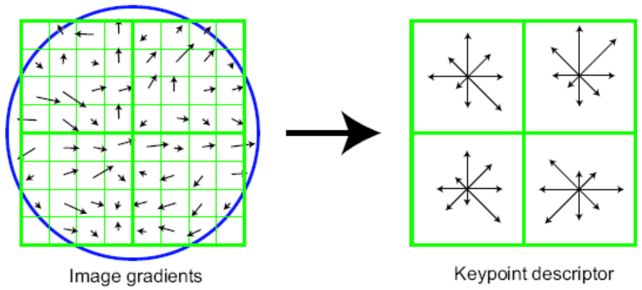
- Can handle changes in viewpoint
  - Up to about 60 degree out of plane rotation
- Can handle significant changes in illumination
  - Sometimes even day vs. night (below)
- Fast and efficient—can run in real time
- Lots of code available: http://people.csail.mit.edu/albert/ladypack/wiki/index.php/Known_implementations_of_SIFT

Summary

- Keypoint detection: repeatable and distinctive
  - Corners, blobs, stable regions
  - Harris, DoG



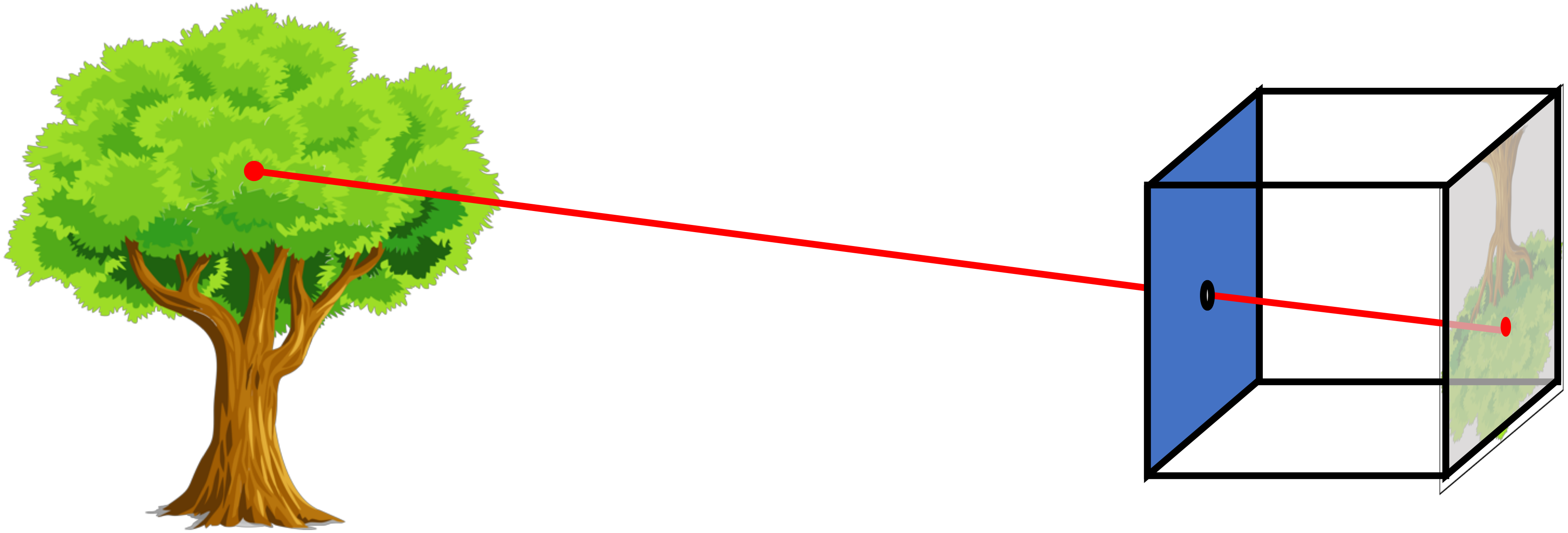
- Descriptors: invariant and discriminative
  - spatial histograms of orientation



- Next up: using correspondences for reconstruction

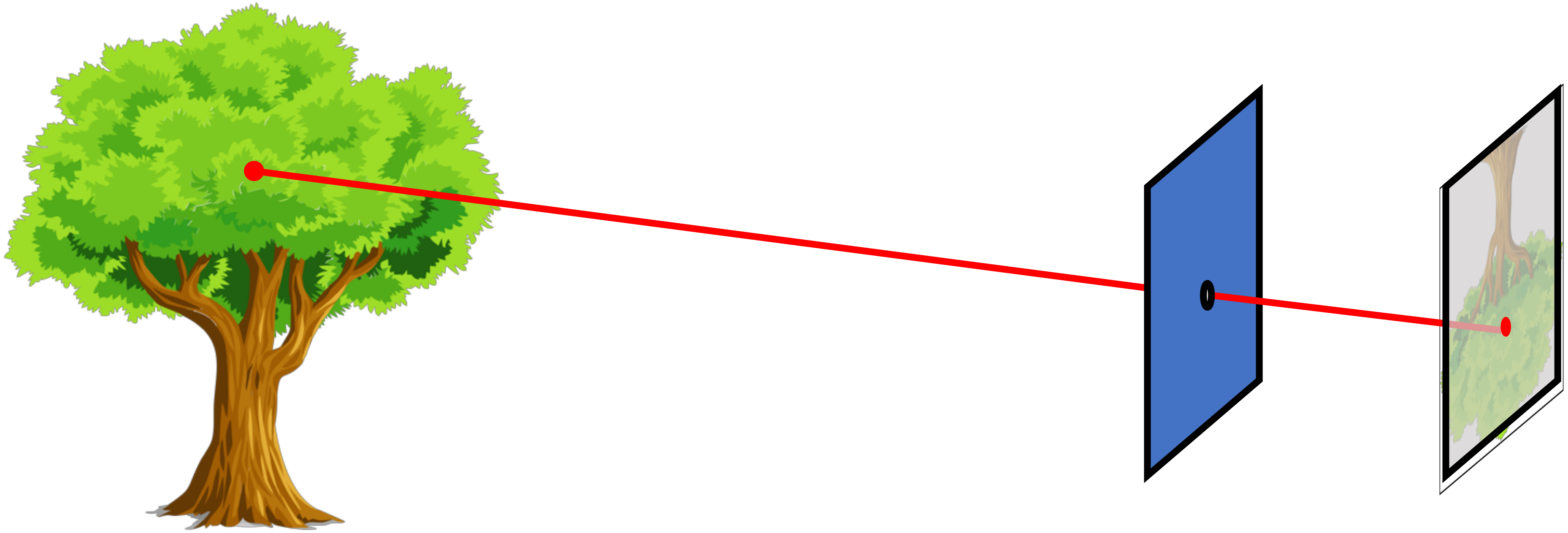
Geometry of Image Formation

The pinhole camera



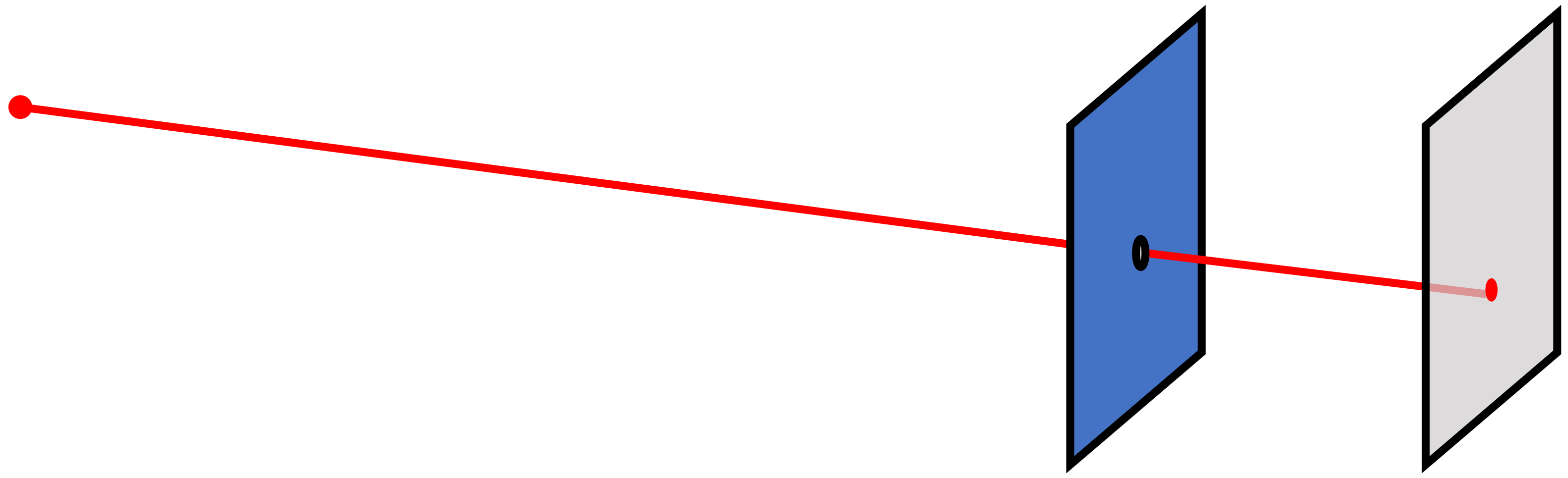
- Let’s abstract out the details

The pinhole camera



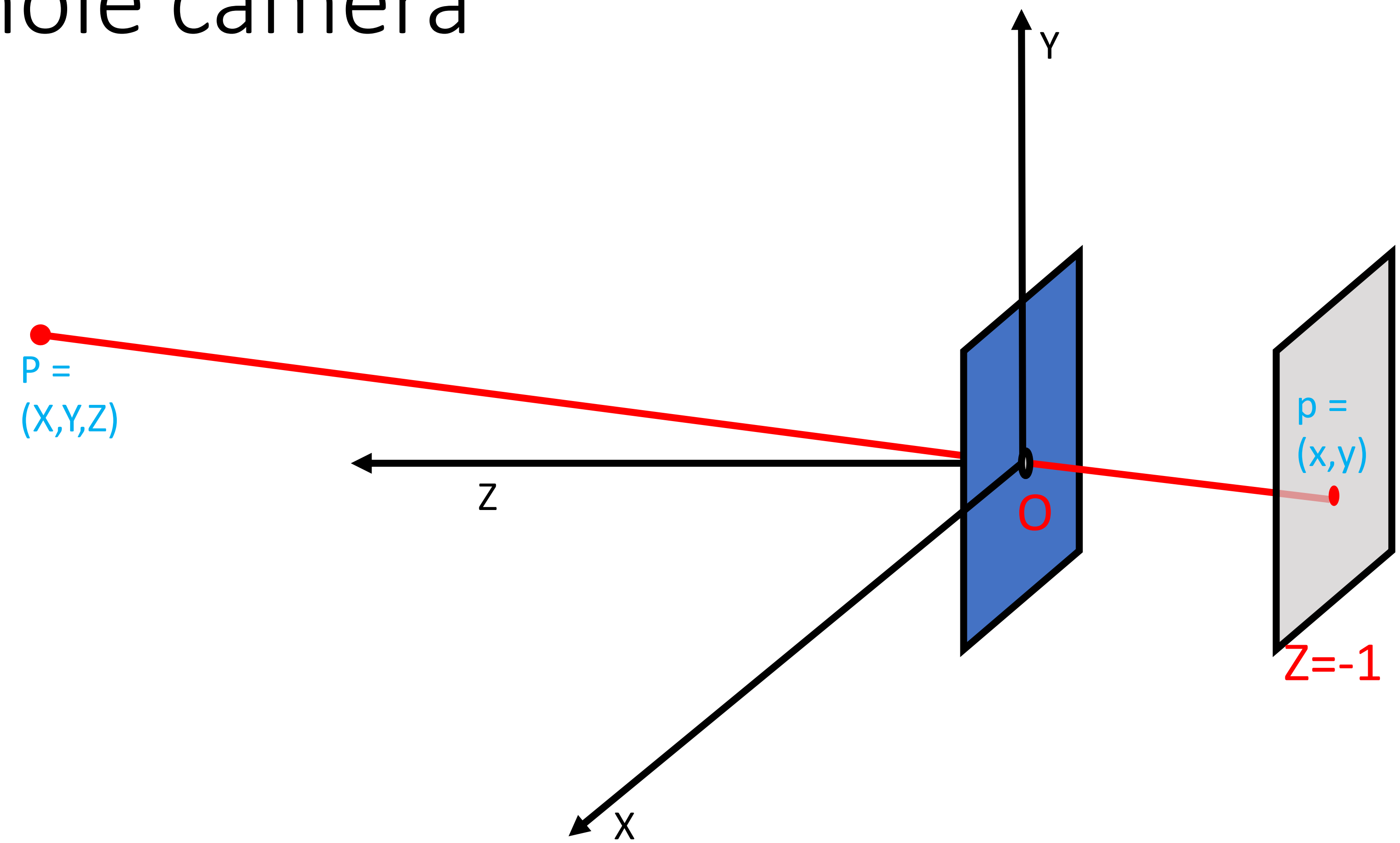
- We don’t care about the other walls of the box, so let’s remove those

The pinhole camera



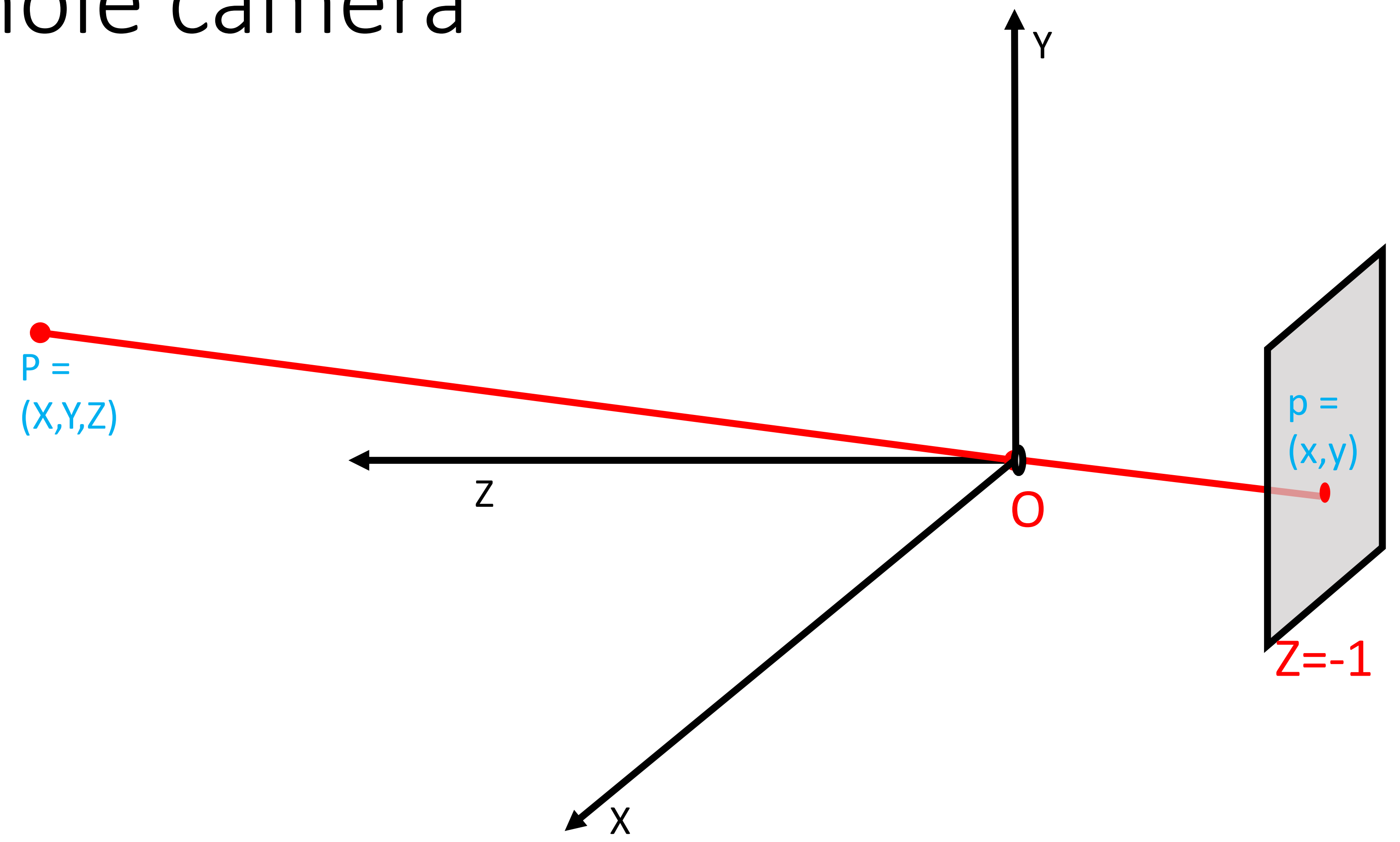
- Let’s look at a individual points in the world and not worry about what they are.

The pinhole camera



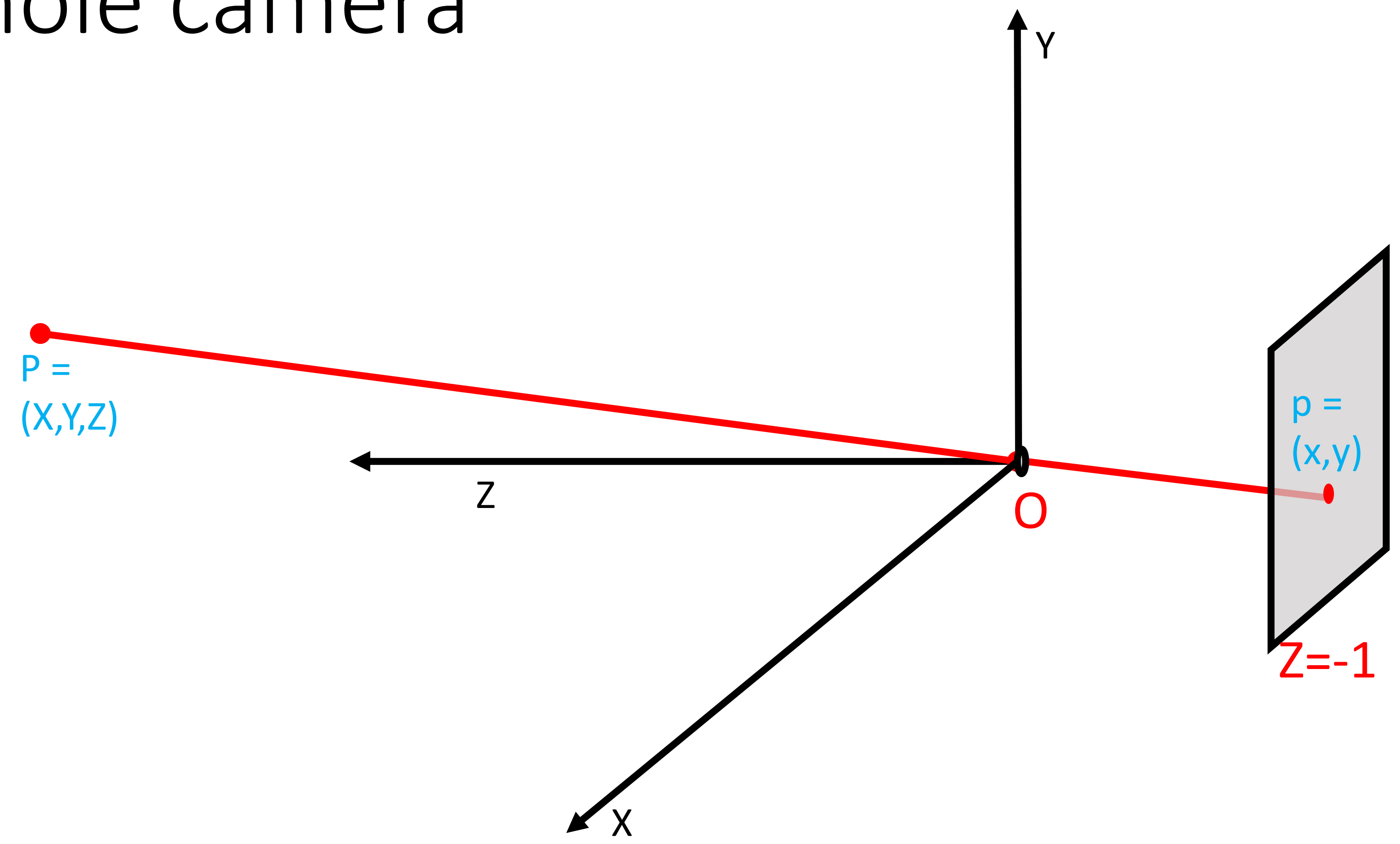
- Let’s place the origin at the pinhole, with Z axis pointing away from the screen (called *camera plane*)

The pinhole camera



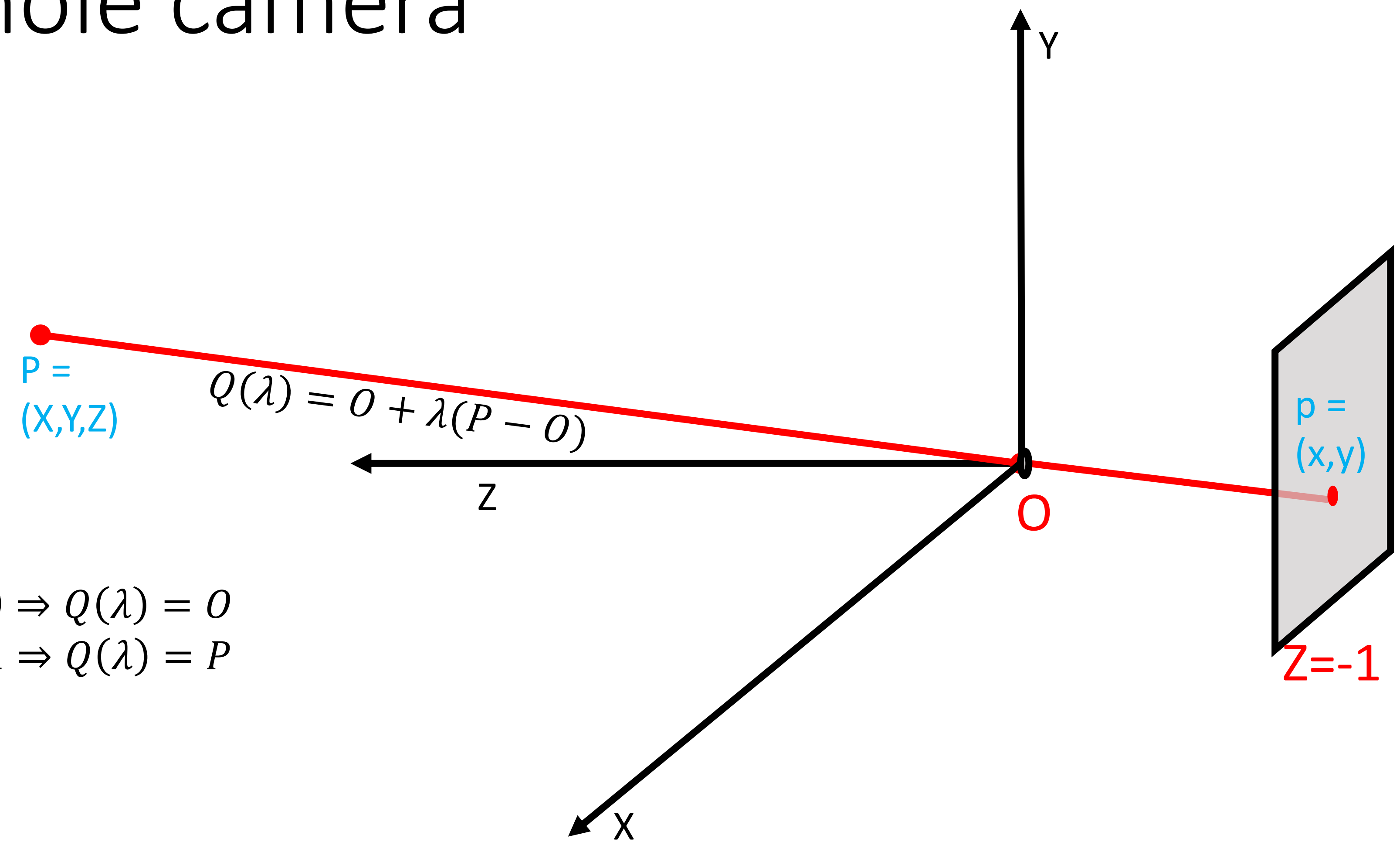
- Let’s remove the wall with the pinhole: all we care about is that all light rays of interest *must pass through the pinhole, i.e., the origin*

The pinhole camera



- Question: Where will we see the "image" of point P on the camera plane?

The pinhole camera



$$\lambda = 0 \Rightarrow Q(\lambda) = O$$
$$\lambda = 1 \Rightarrow Q(\lambda) = P$$

$$Q(\lambda) = \big(0 + \lambda(X - 0), 0 + \lambda(Y - 0), 0 + \lambda(Z - 0)\big) = (\lambda X, \lambda Y, \lambda Z)$$

The pinhole camera

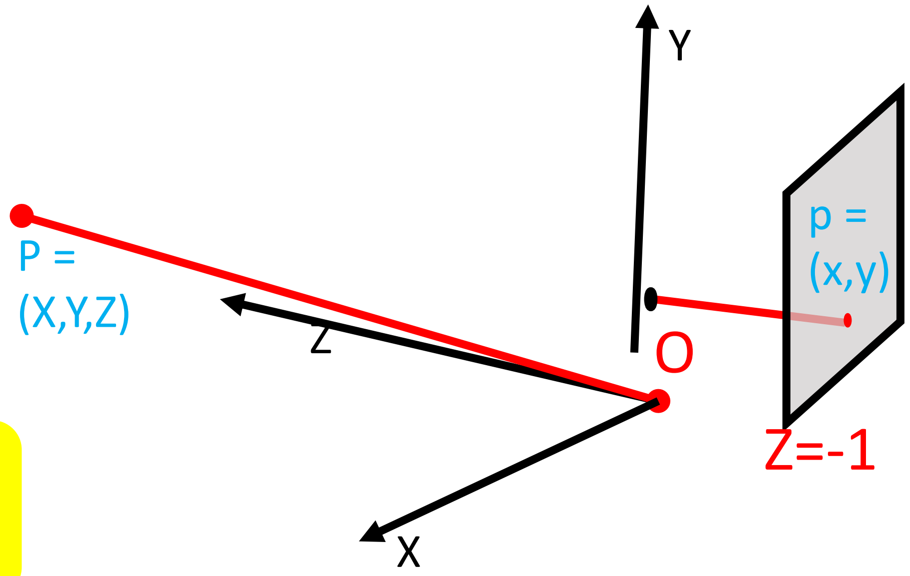
- Pinhole camera collapses *ray OP to point p*
- Any point on ray OP = $O + \lambda(P - O) = (\lambda X, \lambda Y, \lambda Z)$
- For this point to lie on Z=-1 plane:

$$\lambda^* Z = -1$$

$$\Rightarrow \lambda^* = \frac{-1}{Z}$$

- Coordinates of point p:

$$(\lambda^* X, \lambda^* Y, \lambda^* Z) = (\frac{-X}{Z}, \frac{-Y}{Z}, -1)$$



The projection equation

- A point P = (X, Y, Z) in 3D projects to a point p = (x,y) in the image

$$x = \frac{-X}{Z}$$

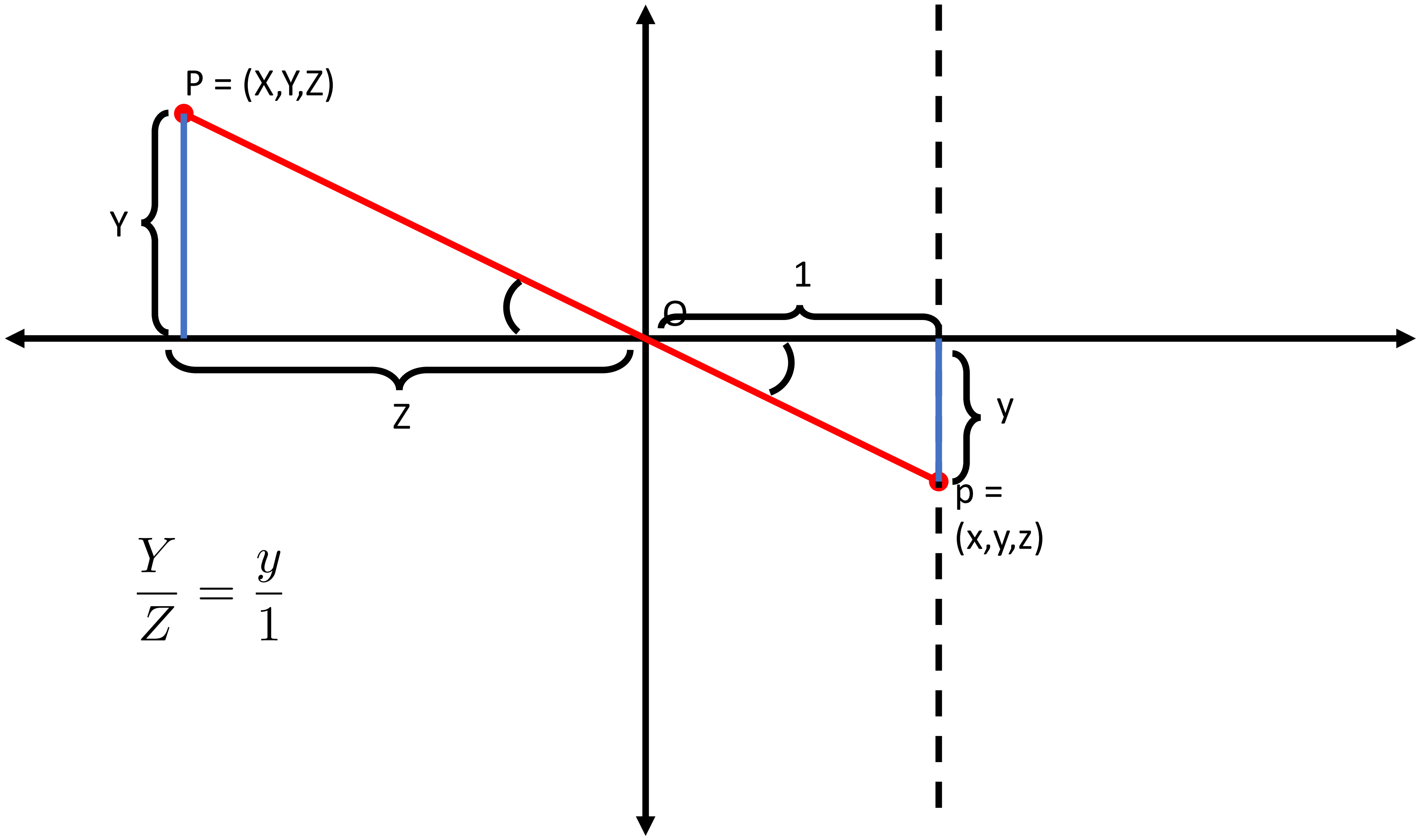
$$y = \frac{-Y}{Z}$$

- But pinhole camera's image is inverted, invert it back!

$$x = \frac{X}{Z}$$

$$y = \frac{Y}{Z}$$

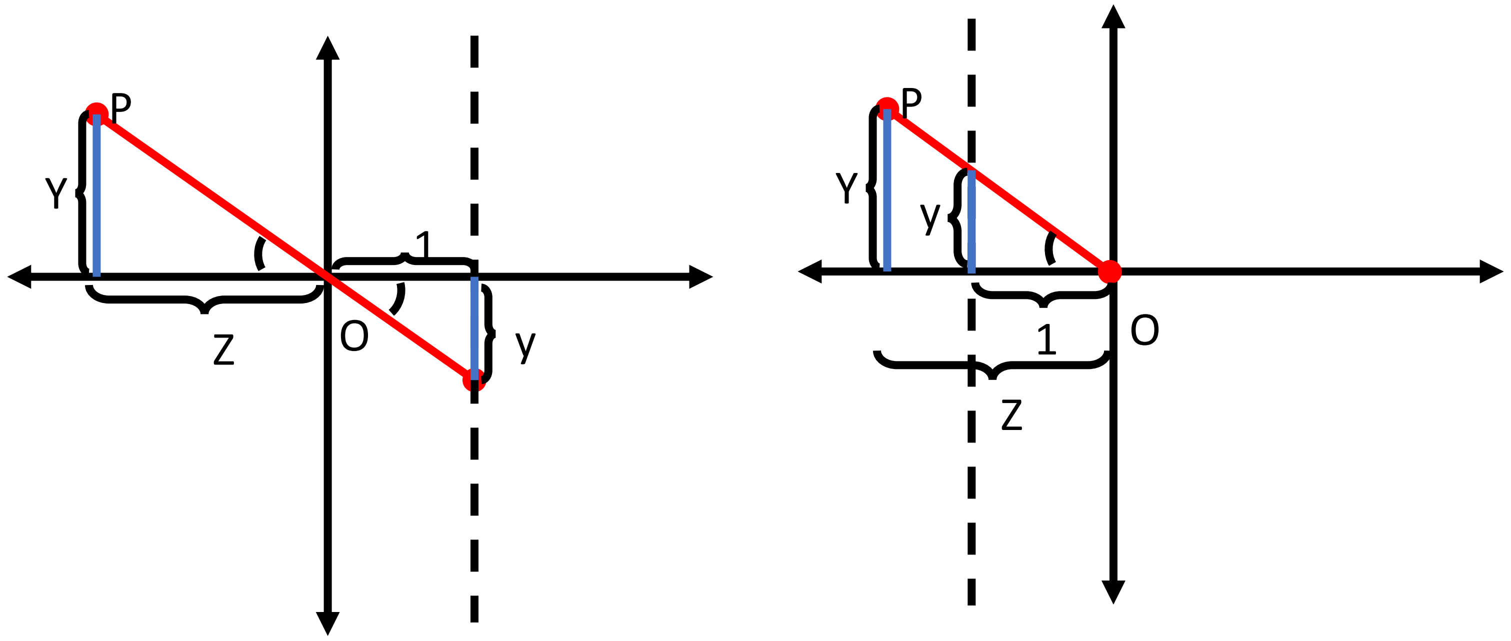
Another derivation



$$\frac{Y}{Z} = \frac{y}{1}$$

A virtual image plane

- A pinhole camera produces an inverted image
- Imagine a ”virtual image plane” in the front of the camera



The projection equation

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

Consequence 1: Farther away objects are smaller

Image of foot: $(\frac{X}{Z}, \frac{Y}{Z})$

Image of head: $(\frac{X}{Z}, \frac{Y+h}{Z})$

$$\frac{Y+h}{Z} - \frac{Y}{Z} = \frac{h}{Z}$$

Consequence 2: Parallel lines converge at a point

- Point on a line passing through point A with direction D:
$$Q(\lambda) = A + \lambda D$$
- Parallel lines have the same direction but pass through different points
$$Q(\lambda) = A + \lambda D$$
$$R(\lambda) = B + \lambda D$$
-

Consequence 2: Parallel lines converge at a point

- Parallel lines have the same direction but pass through different points

$$Q(\lambda) = A + \lambda D$$
$$R(\lambda) = B + \lambda D$$

- $A = (A_X, A_Y, A_Z)$
- $B = (B_X, B_Y, B_Z)$
- $D = (D_X, D_Y, D_Z)$

Consequence 2: Parallel lines converge at a point

- $Q(\lambda) = (A_X + \lambda D_X, A_Y + \lambda D_Y, A_Z + \lambda D_Z)$
- $R(\lambda) = (B_X + \lambda D_X, B_Y + \lambda D_Y, B_Z + \lambda D_Z)$
- $q(\lambda) = \left(\frac{A_X + \lambda D_X}{A_Z + \lambda D_Z}, \frac{A_Y + \lambda D_Y}{A_Z + \lambda D_Z}\right)$
- $r(\lambda) = \left(\frac{B_X + \lambda D_X}{B_Z + \lambda D_Z}, \frac{B_Y + \lambda D_Y}{B_Z + \lambda D_Z}\right)$
- Need to look at these points as Z goes to infinity
- Same as $\lambda \to \infty$

Consequence 2: Parallel lines converge at a point

- $q(\lambda) = \left(\frac{A_X+\lambda D_X}{A_Z+\lambda D_Z}, \frac{A_Y+\lambda D_Y}{A_Z+\lambda D_Z}\right)$
- $r(\lambda) = \left(\frac{B_X+\lambda D_X}{B_Z+\lambda D_Z}, \frac{B_Y+\lambda D_Y}{B_Z+\lambda D_Z}\right)$

$$\lim_{\lambda \to \infty} \frac{A_X + \lambda D_X}{A_Z + \lambda D_Z} = \lim_{\lambda \to \infty} \frac{\frac{A_X}{\lambda} + D_X}{\frac{A_Z}{\lambda} + D_Z} = \frac{D_X}{D_Z}$$

$$\lim_{\lambda \to \infty} q(\lambda) = (\frac{D_X}{D_Z}, \frac{D_Y}{D_Z})$$

$$\lim_{\lambda \to \infty} r(\lambda) = (\frac{D_X}{D_Z}, \frac{D_Y}{D_Z})$$

Consequence 2: Parallel lines converge at a point

- Parallel lines have the same direction but pass through different points

$$Q(\lambda) = A + \lambda D$$
$$R(\lambda) = B + \lambda D$$

- Parallel lines converge at the same point $(\frac{D_X}{D_Z}, \frac{D_Y}{D_Z})$
- This point of convergence is called the *vanishing point*
- What happens if $D_Z = 0$?

Consequence 2: Parallel lines converge at a point

What about planes?

$$N_X X + N_Y Y + N_Z Z = d$$

$$\Rightarrow N_X \frac{X}{Z} + N_Y \frac{Y}{Z} + N_Z = \frac{d}{Z}$$

$$\Rightarrow N_X x + N_Y y + N_Z = \frac{d}{Z}$$

Take the limit as Z approaches infinity

$$N_X x + N_Y y + N_Z = 0$$

Vanishing line of a plane

What about planes?

$$N_X X + N_Y Y + N_Z Z = d$$

Normal: (N_X, N_Y, N_Z)

What do parallel planes look like?

$$N_X X + N_Y Y + N_Z Z = d$$

$$N_X x + N_Y y + N_Z = 0$$

$$N_X X + N_Y Y + N_Z Z = c$$

$$N_X x + N_Y y + N_Z = 0$$

Vanishing lines

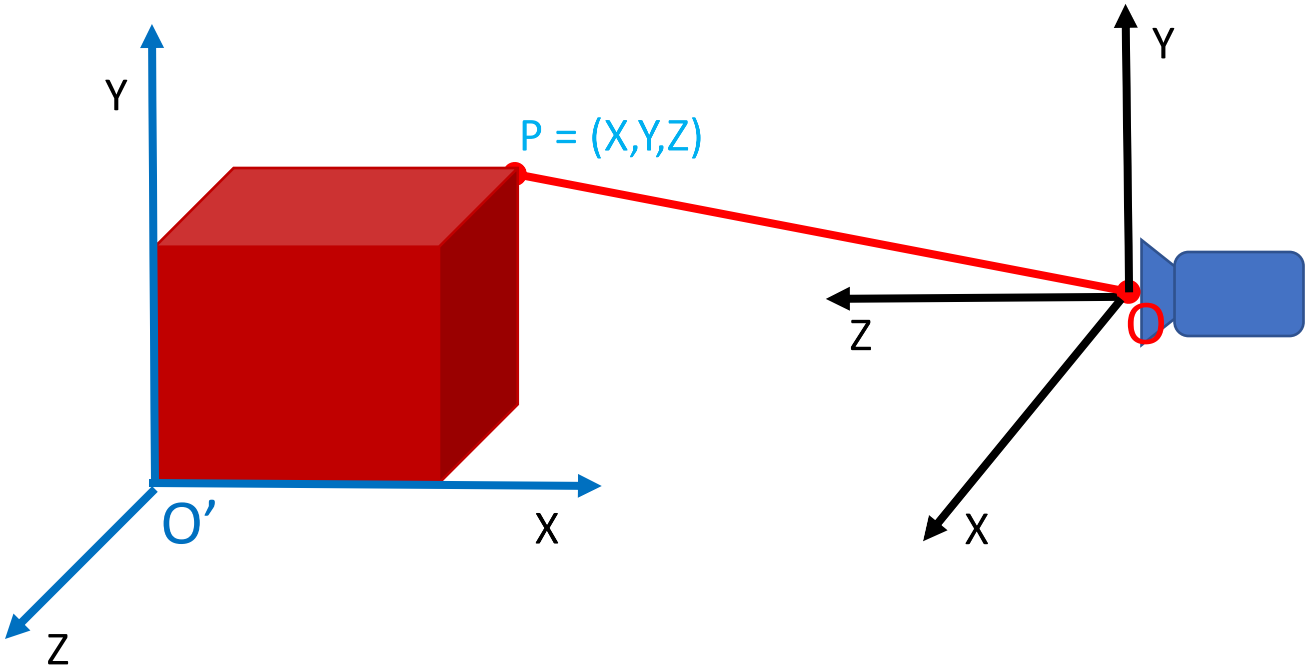
Parallel planes converge!

Vanishing line

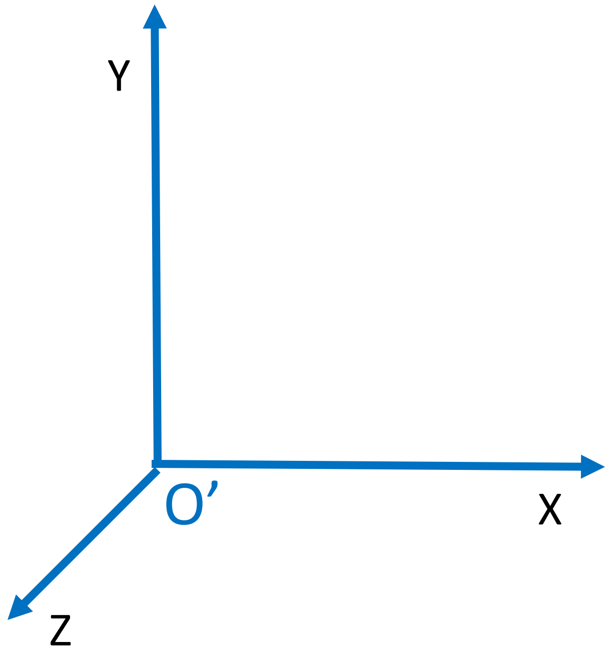
$$N_X X + N_Y Y + N_Z Z = d$$

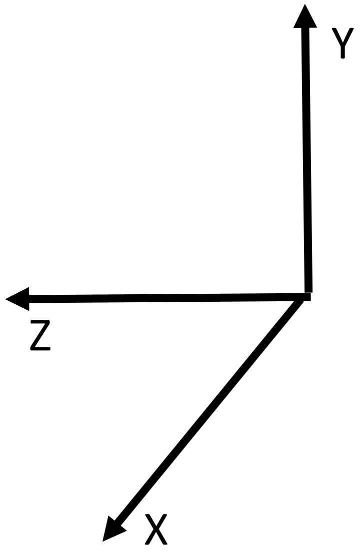
- What happens if $N_X = N_Y = 0$?
- Equation of the plane: $Z = c$
- Vanishing line?

Changing coordinate systems



Changing coordinate systems





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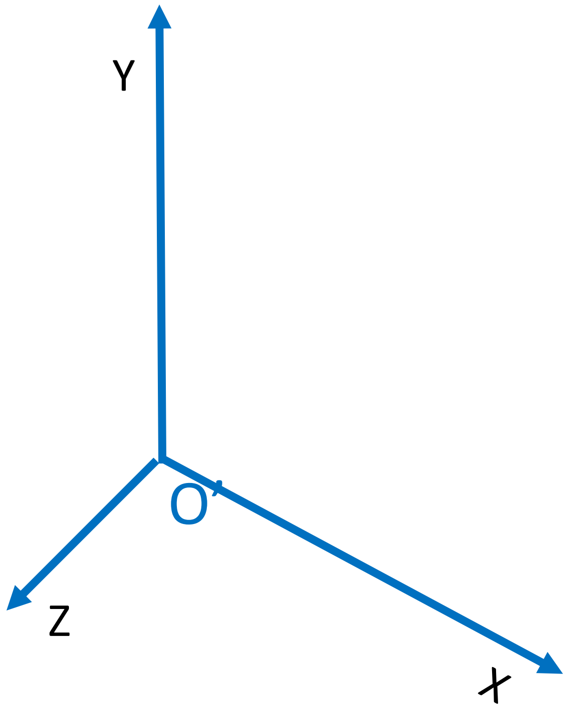

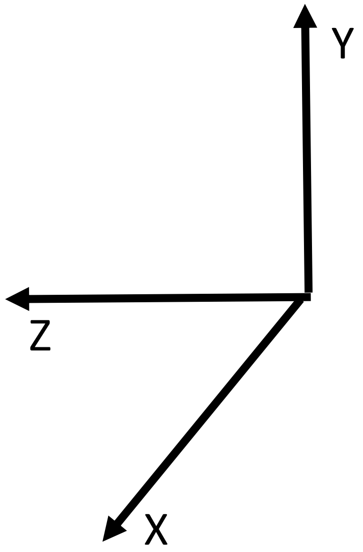

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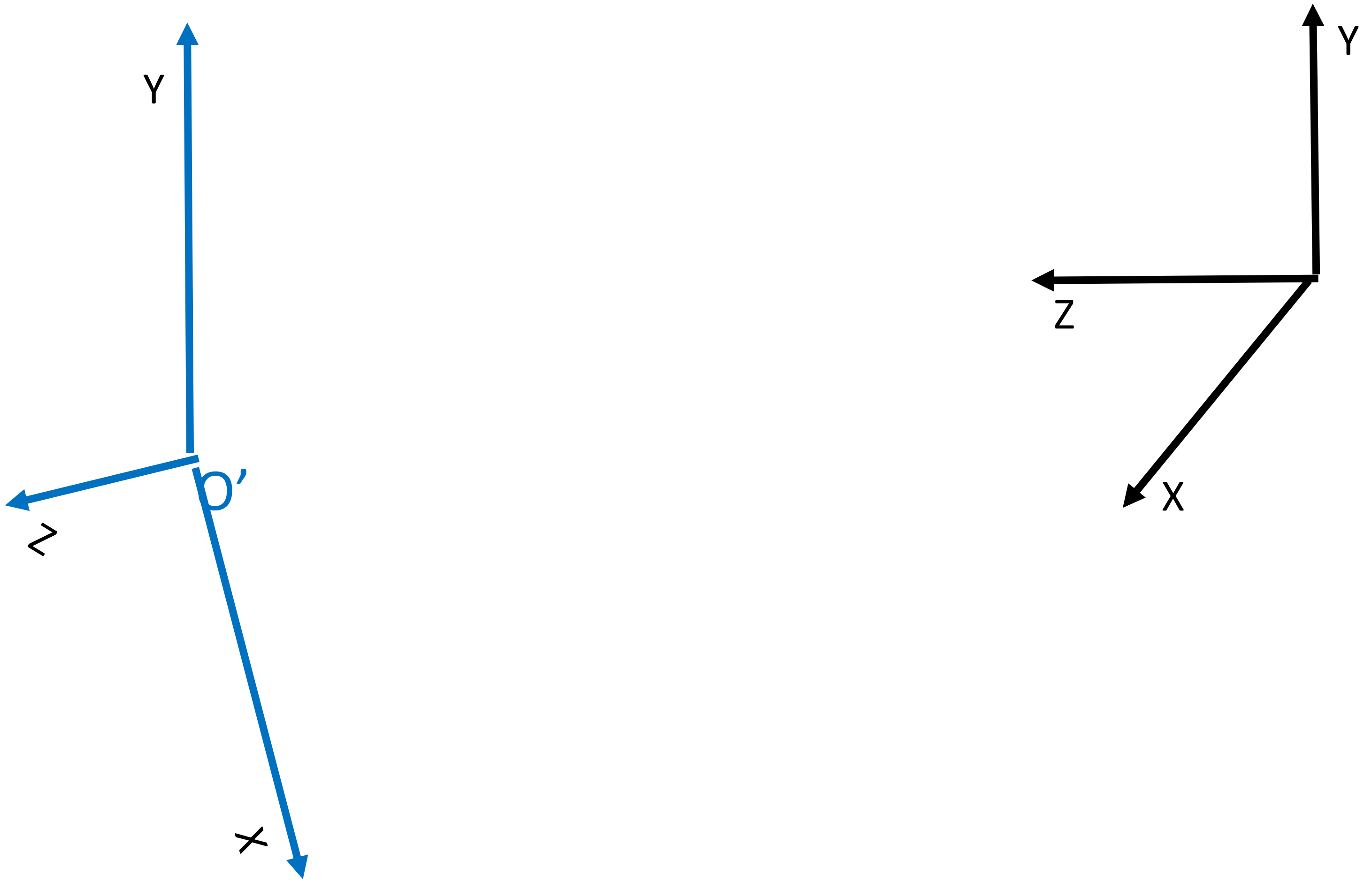

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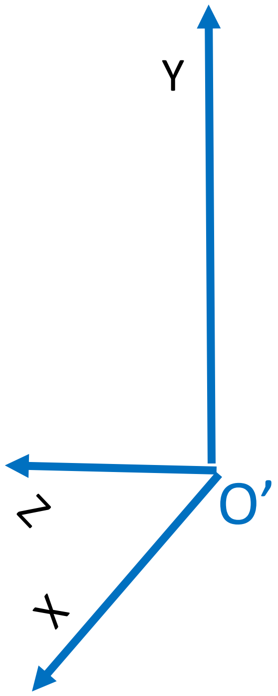

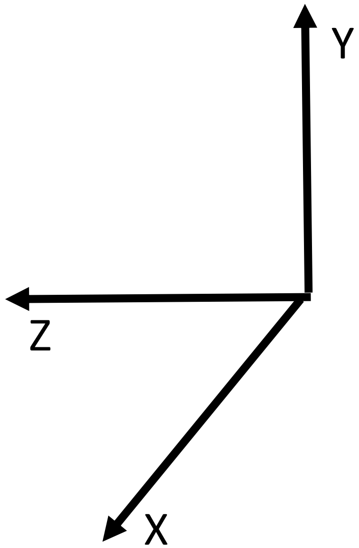

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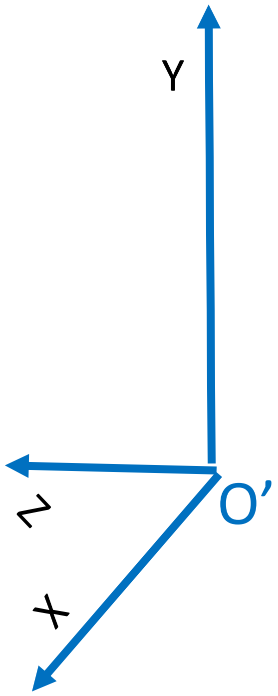
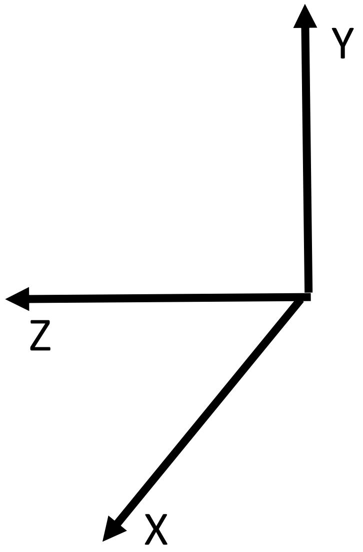




Rotations and translations

- How do you represent a rotation?
- A point in 3D: (X,Y,Z)
- Rotations can be represented as a matrix multiplication

$$\mathbf{v}' = R\mathbf{v}$$

- What are the properties of rotation matrices?

Properties of rotation matrices

- Rotation does not change the length of vectors

$$\mathbf{v}' = R\mathbf{v}$$

$$\|\mathbf{v}'\|^2 = \mathbf{v}'^T\mathbf{v}'$$

$$= \mathbf{v}^T R^T R\mathbf{v}$$

$$\|\mathbf{v}\|^2 = \mathbf{v}^T\mathbf{v}$$

$$\Rightarrow R^T R = I$$

Properties of rotation matrices

$$\Rightarrow R^T R = I$$

$$\Rightarrow det(R)^2 = 1$$

$$\Rightarrow det(R) = \pm 1$$

$$det(R) = 1$$

Rotation

$$det(R) = -1$$

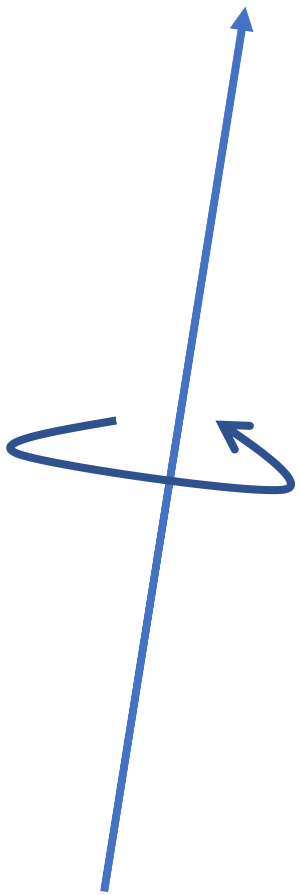
Reflection

Rotation matrices

- Rotations in 3D have an axis and an angle
- Axis: vector that does not change when rotated

$$R\mathbf{v} = \mathbf{v}$$

- Rotation matrix has eigenvector that has eigenvalue 1



Rotation matrices from axis and angle

- Rotation matrix for rotation about axis $\boldsymbol{v}$ and θ
- First define the following matrix

$$[\mathbf{v}]_\times = \begin{bmatrix} 0 & -v_z & v_y \\ v_z & 0 & -v_x \\ -v_y & v_x & 0 \end{bmatrix}$$

- Interesting fact: this matrix represents cross product

$$[\mathbf{v}]_\times \mathbf{x} = \mathbf{v} \times \mathbf{x}$$

Rotation matrices from axis and angle

- Rotation matrix for rotation about axis $\boldsymbol{v}$ and θ
- Rodrigues' formula for rotation matrices

$$R = I + (\sin\theta)[\mathbf{v}]_\times + (1 - \cos\theta)[\mathbf{v}]_\times^2$$

Translations

$$\mathbf{x}' = \mathbf{x} + \mathbf{t}$$

- Can this be written as a matrix multiplication?

Putting everything together

- Change coordinate system so that center of the coordinate system is at pinhole and Z axis is along viewing direction

$$\mathbf{x}'_w = R\mathbf{x}_w + \mathbf{t}$$

- Perspective projection

$$\mathbf{x}'_w \equiv (X, Y, Z)$$
$$\mathbf{x}'_{img} \equiv (x, y)$$

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