

EBU7240

Computer Vision

Assignment Project Exam Help

- Camera: Perspective projection -

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Semester 1, 2021

Changjae Oh

2005



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<https://powcoder.com>

Luca Bruno / AP

2013

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Michael Sohn / AP

Announcement of
Pope Benedict XVI (2005),
Pope Francis (2013)

Content

- **The pinhole projection model**
 - Geometric properties
 - Perspective projection matrix
- **Cameras with lenses** Assignment Project Exam Help
 - Depth of focus
 - Field of view
 - Lens aberrations
- **Digital sensors**

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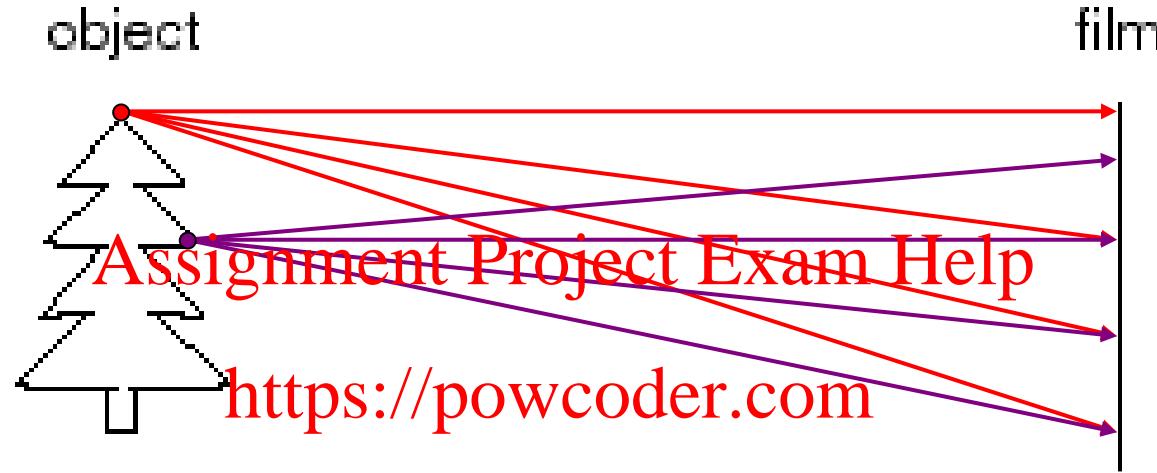
Content

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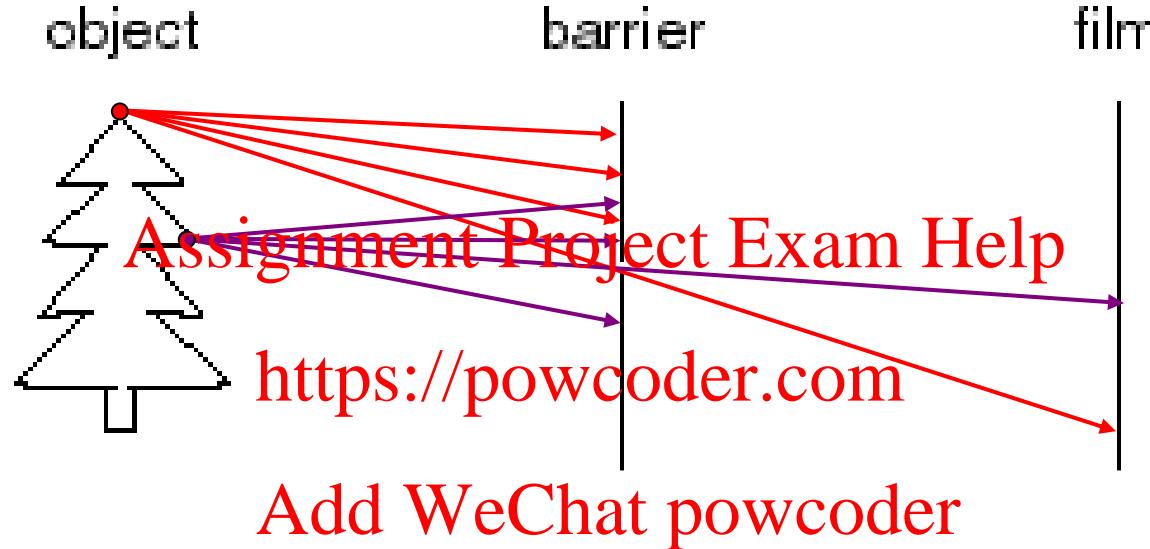
Let's design a camera



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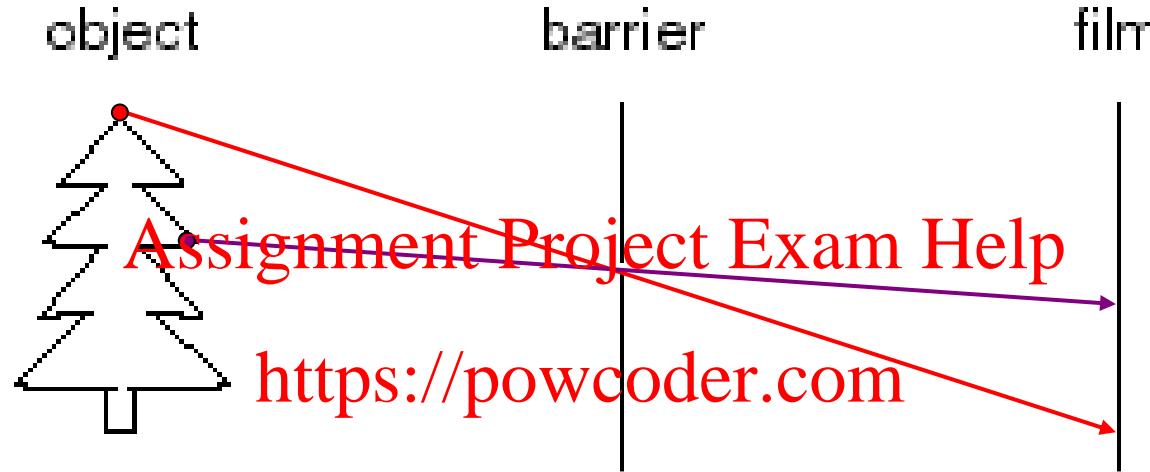
- Idea 1: put a piece of film in front of an object
- Do we get a reasonable image?

Pinhole camera



- Add a barrier to block off most of the rays
 - Tiny aperture without lens
 - Light from a scene passes through the aperture and projects an inverted image on the film

Pinhole camera



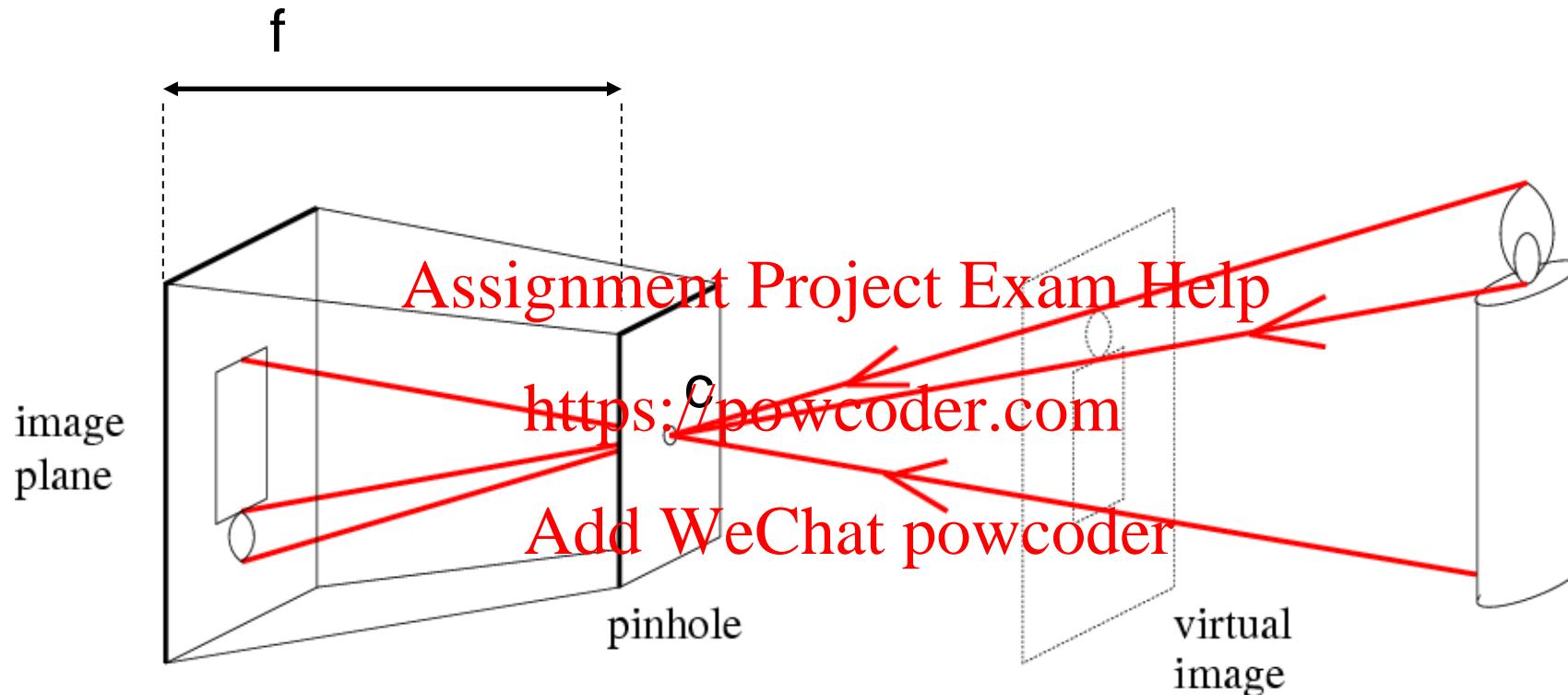
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- **Captures pencil of rays**
 - All rays through a single point: aperture, center of projection, optical center, focal point, camera center
- **The image is formed on the image plane (film)**

Pinhole camera



f = focal length

c = center of the camera

Pinhole cameras are everywhere



Tree shadow during a solar eclipse

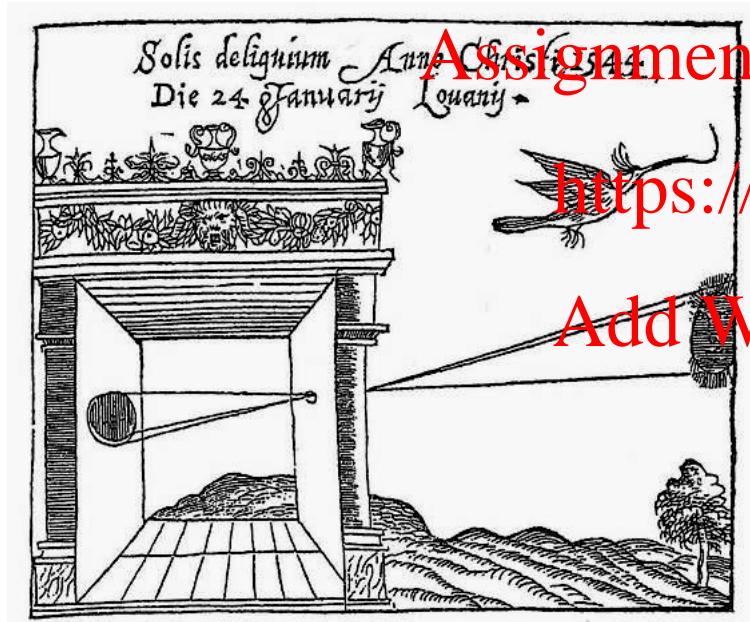
photo credit: Nils van der Burg

<http://www.physicstogo.org/index.cfm>

Credit: Steve Seitz

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)

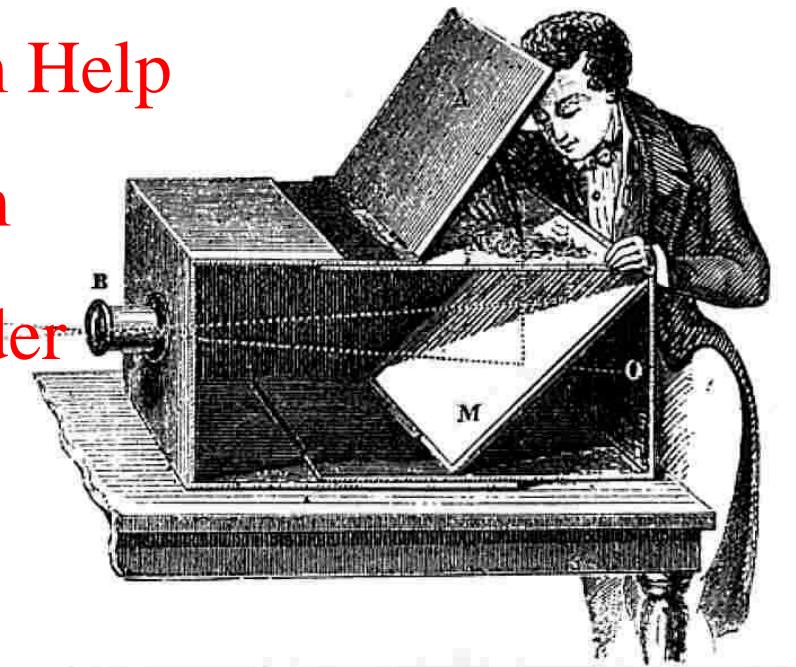


Gemma Frisius, 1558

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[Image source](#)

Turning a room into a camera obscura

My hotel room,
contrast enhanced.



The view from my window



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Accidental pinholes produce images that are unnoticed or misinterpreted as shadows

- A. Torralba and W. Freeman, [Accidental Pinhole and Pinspeck Cameras](#), CVPR 2012

Turning a room into a camera obscura



Accidental Pinhole and Pinspeck Cameras
Revealing the scene outside the picture.
Antonio Torralba, William T. Freeman

Turning a room into a camera obscura



a) Input (occluder present)



b) Reference (occluder absent)



c) Difference image (b-a)



d) Crop upside down



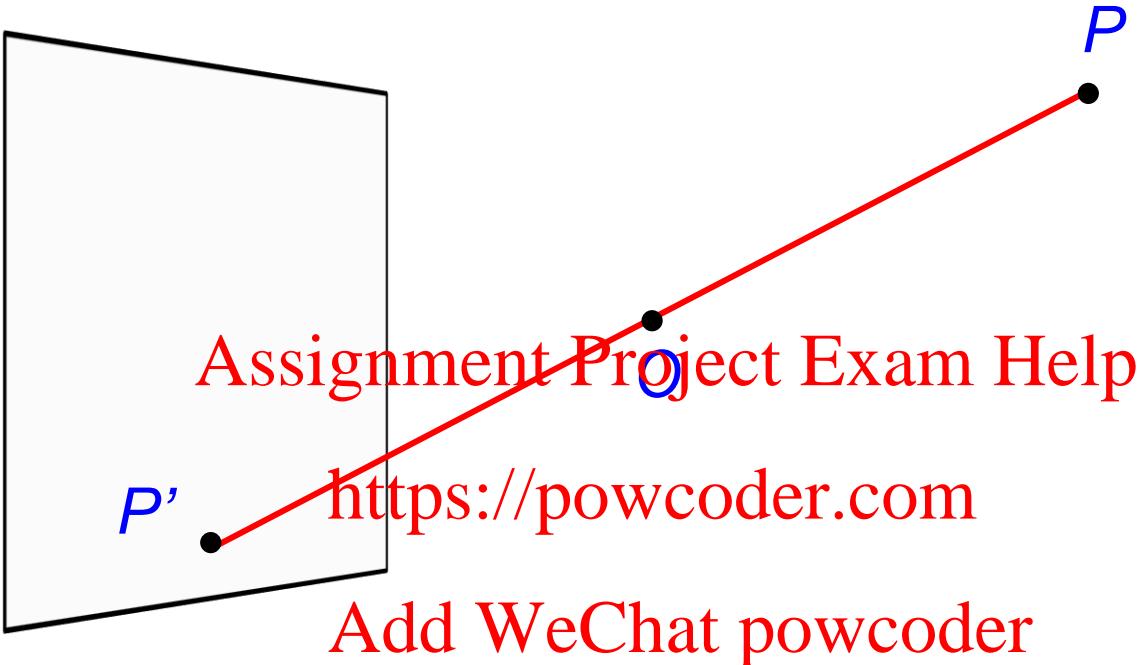
e) True view

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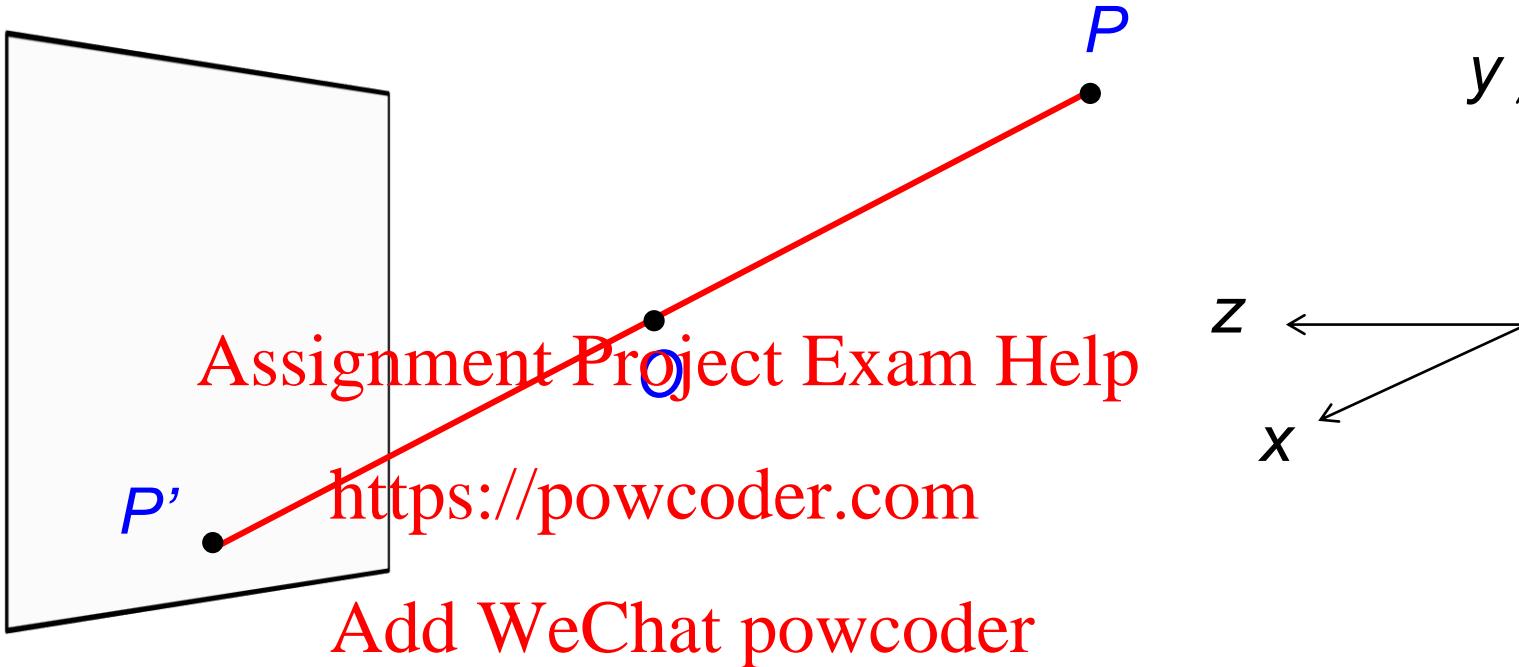
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Pinhole projection model



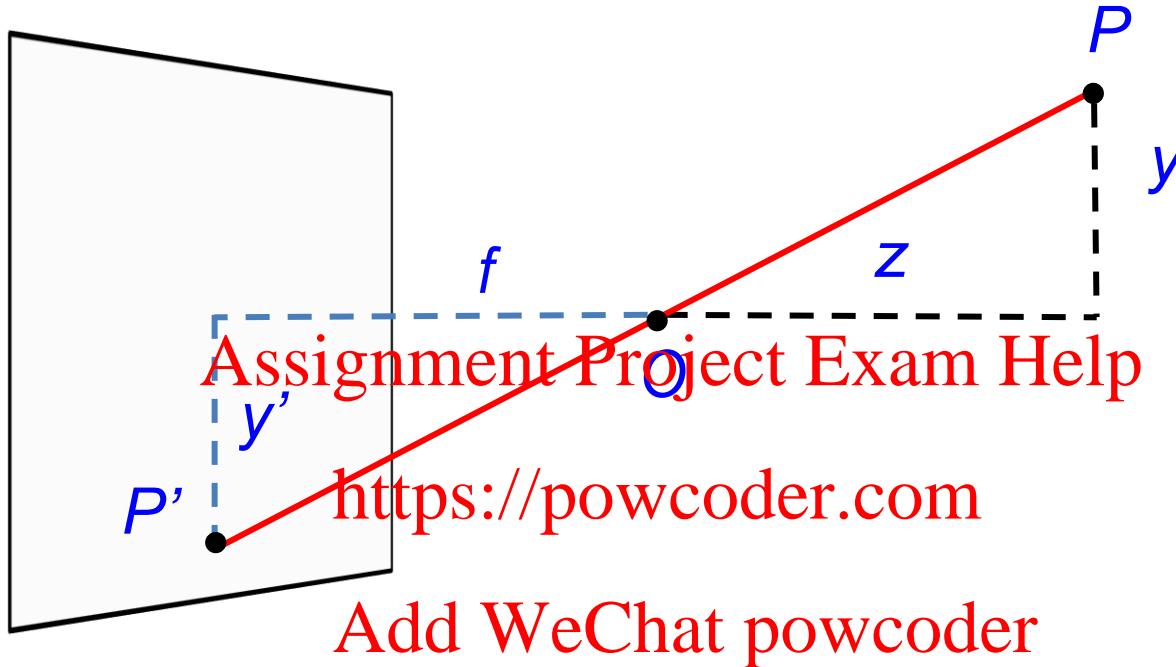
- To compute the projection P' of a scene point P ,
 - Form the visual ray connecting P to the camera center O and find where it intersects the image plane

Pinhole projection model



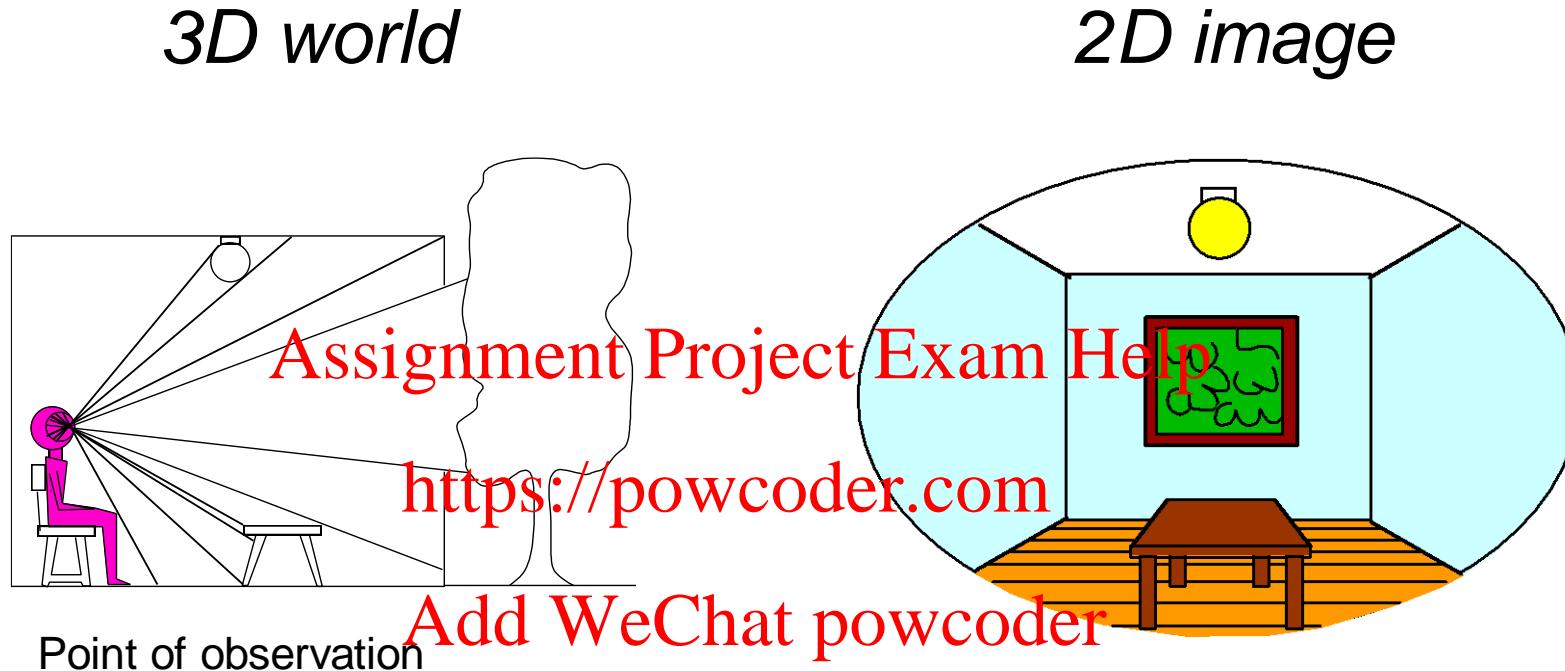
- The coordinate system
 - The optical center (O) is at the origin
 - The image plane is parallel to xy-plane or perpendicular to the z-axis, which is the *optical axis*

Pinhole projection model



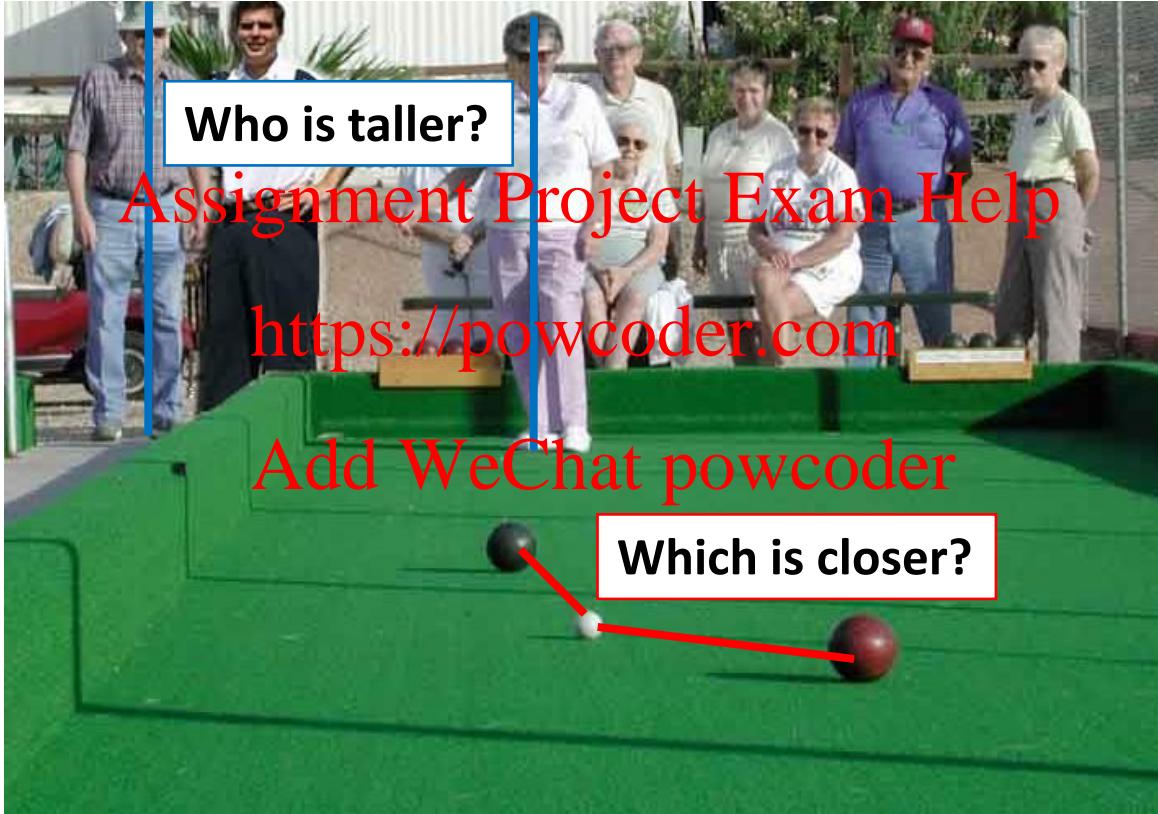
- Projection equations
 - Derived using similar triangles $(x, y, z) \rightarrow (f \frac{x}{z}, f \frac{y}{z})$

Dimensionality reduction: from 3D to 2D

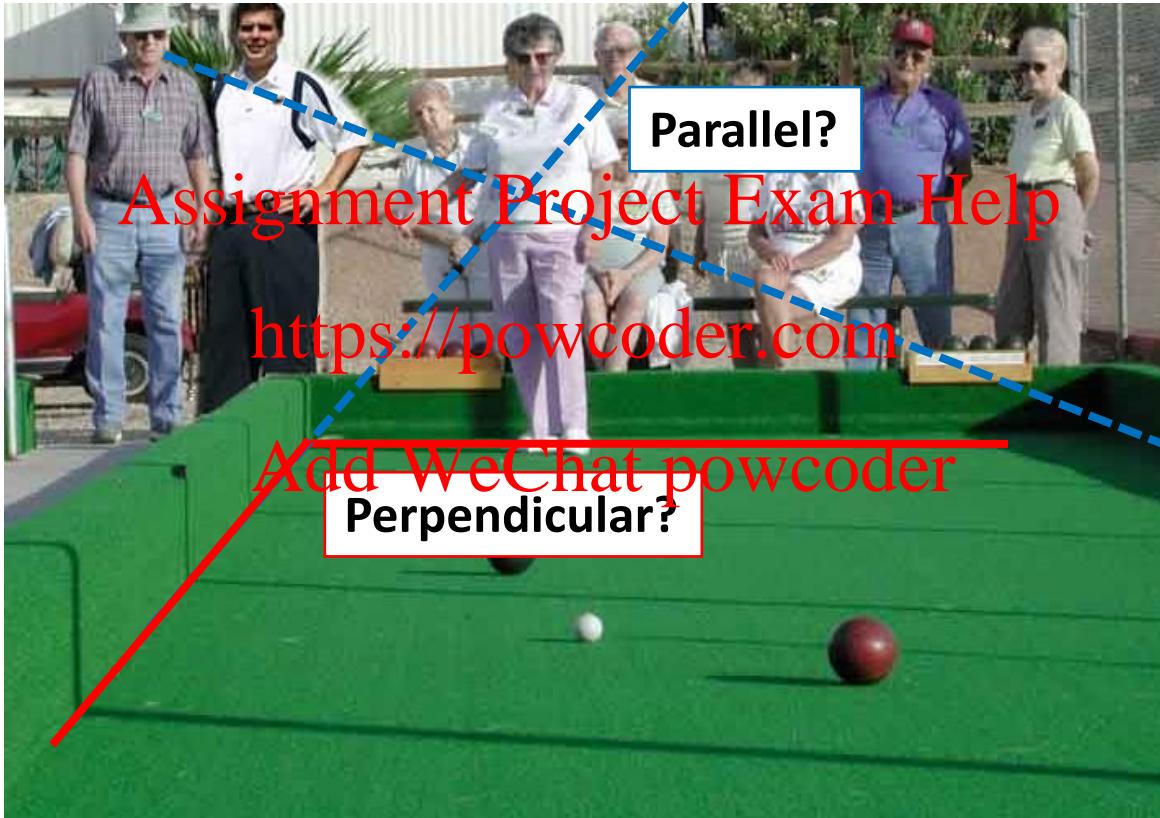


- What properties of the world are preserved?
 - Straight lines, incidence
- What properties are not preserved?
 - Angles, lengths

Properties of projection



Properties of projection



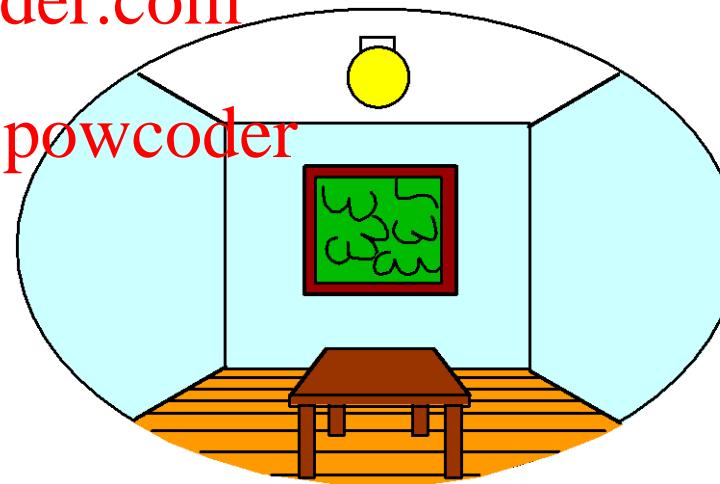
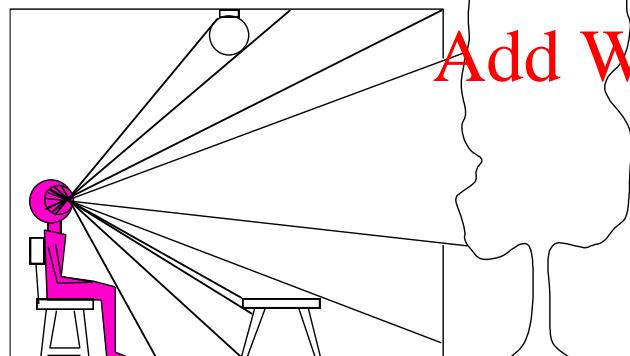
Fronto-parallel planes

- What happens to the projection of a pattern on a plane parallel to the image plane?
 - All points on that plane are at a fixed depth z
 - The pattern gets scaled by a factor of f/z , but angles and ratios of lengths/areas are preserved

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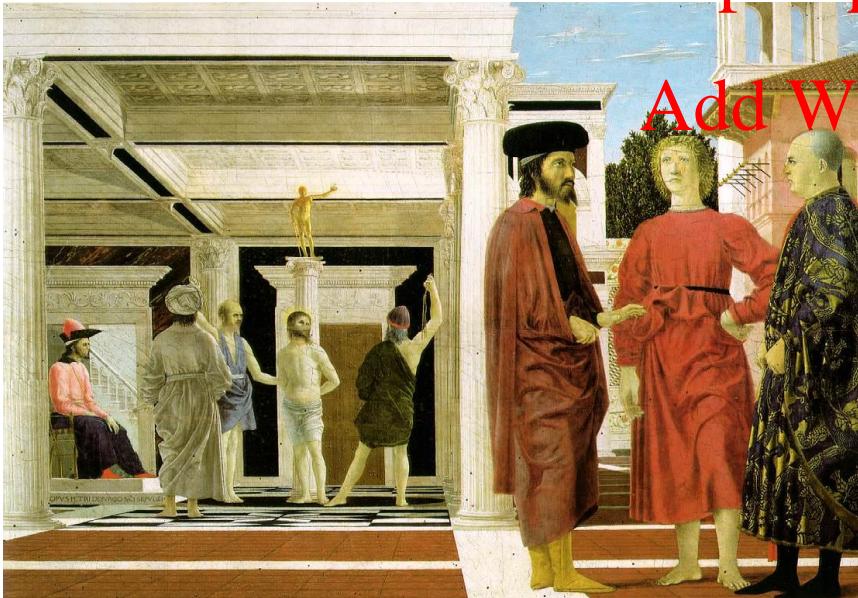
$$(x, y, z) \rightarrow \left(f \frac{x}{z}, f \frac{y}{z} \right)$$

Fronto-parallel planes

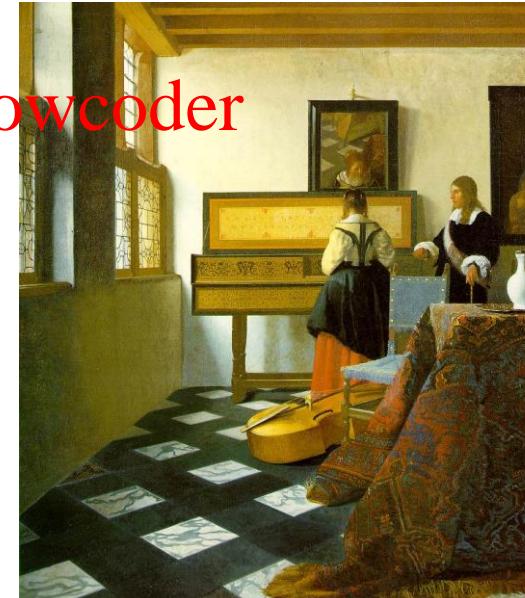
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Piero della Francesca, *Flagellation of Christ*, 1455-1460



Jan Vermeer, *The Music Lesson*, 1662-1665

Slide from S. Lazebnik

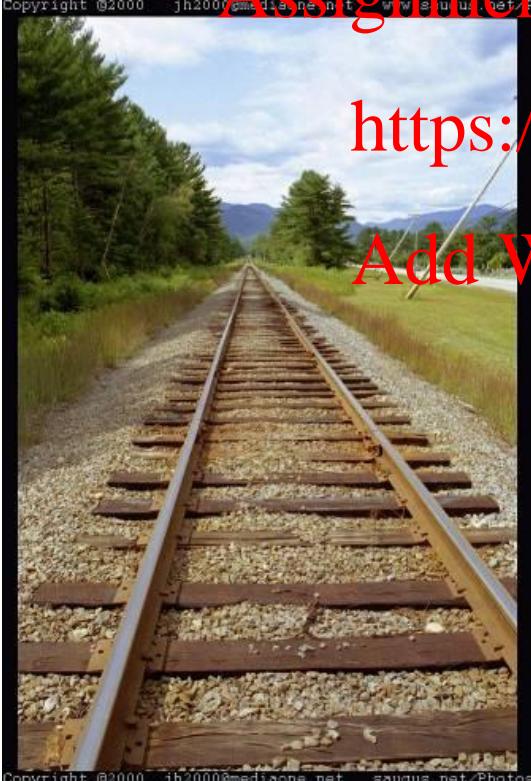
Vanishing points

- All parallel lines converge to a vanishing point
 - Each direction in space is associated with its own vanishing point
 - Exception: directions parallel to the image plane

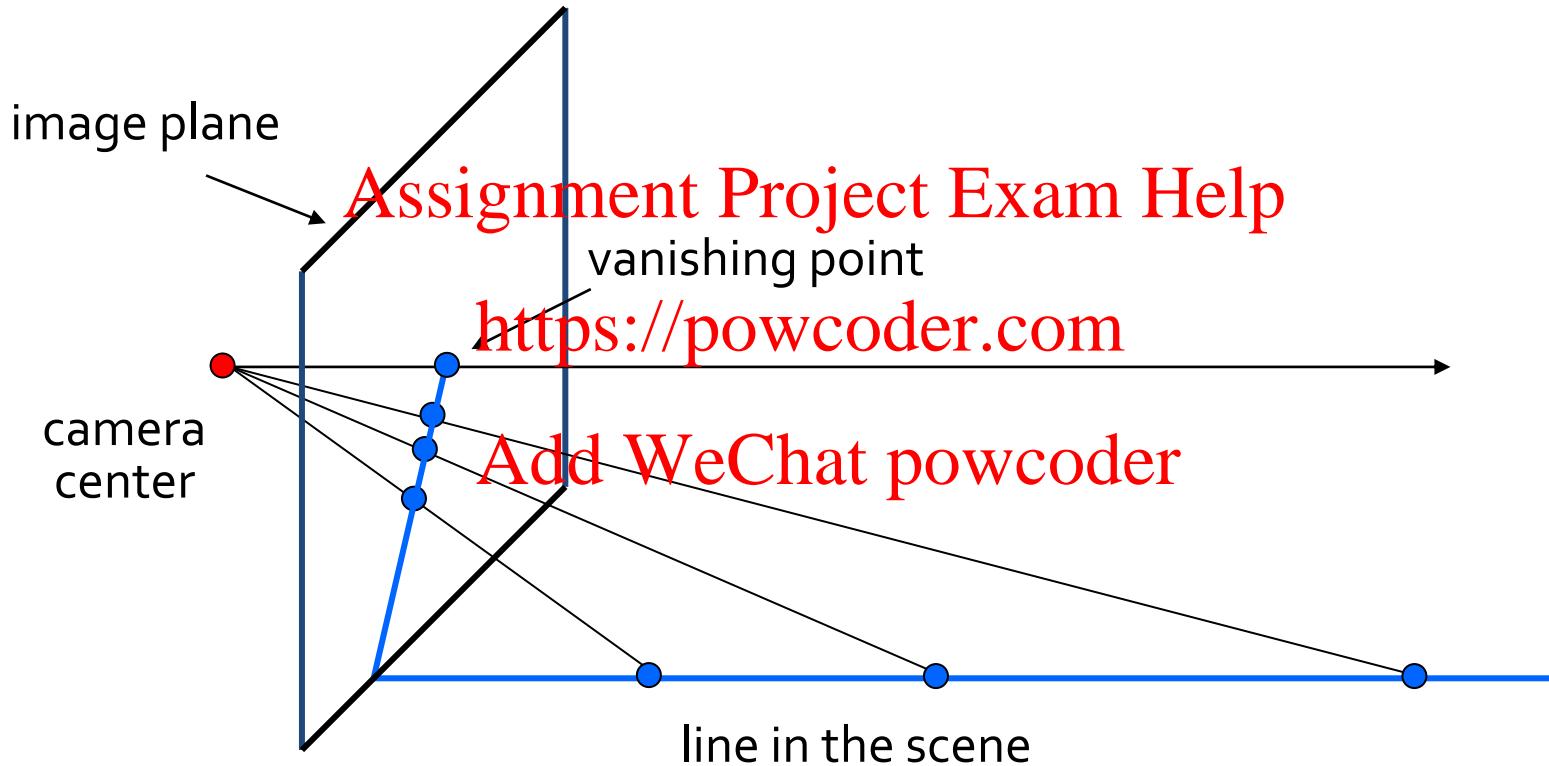
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Constructing the vanishing point of a line



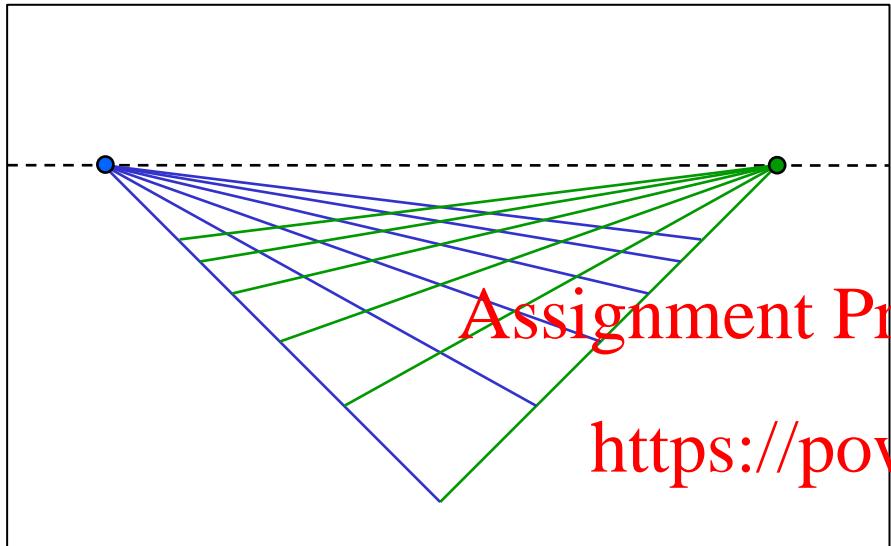
Vanishing lines of planes



How do we construct the vanishing line of a plane?

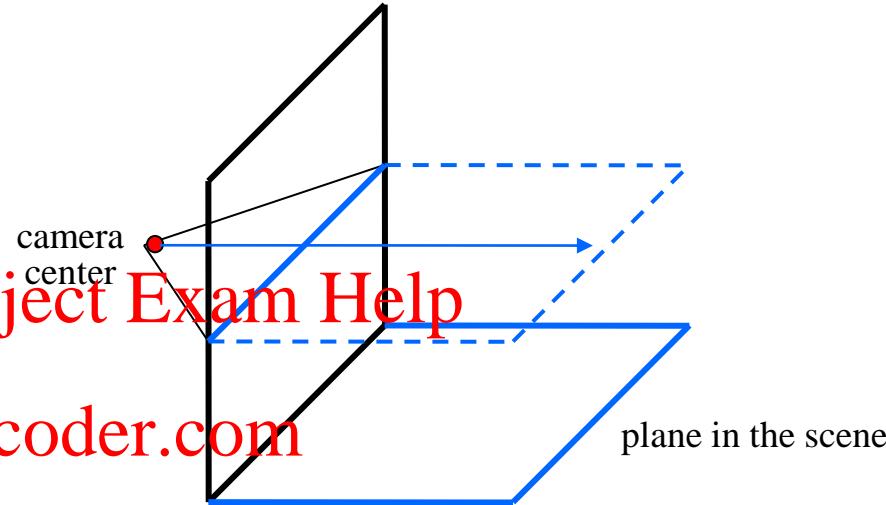
[Image source](#)

Vanishing lines of planes

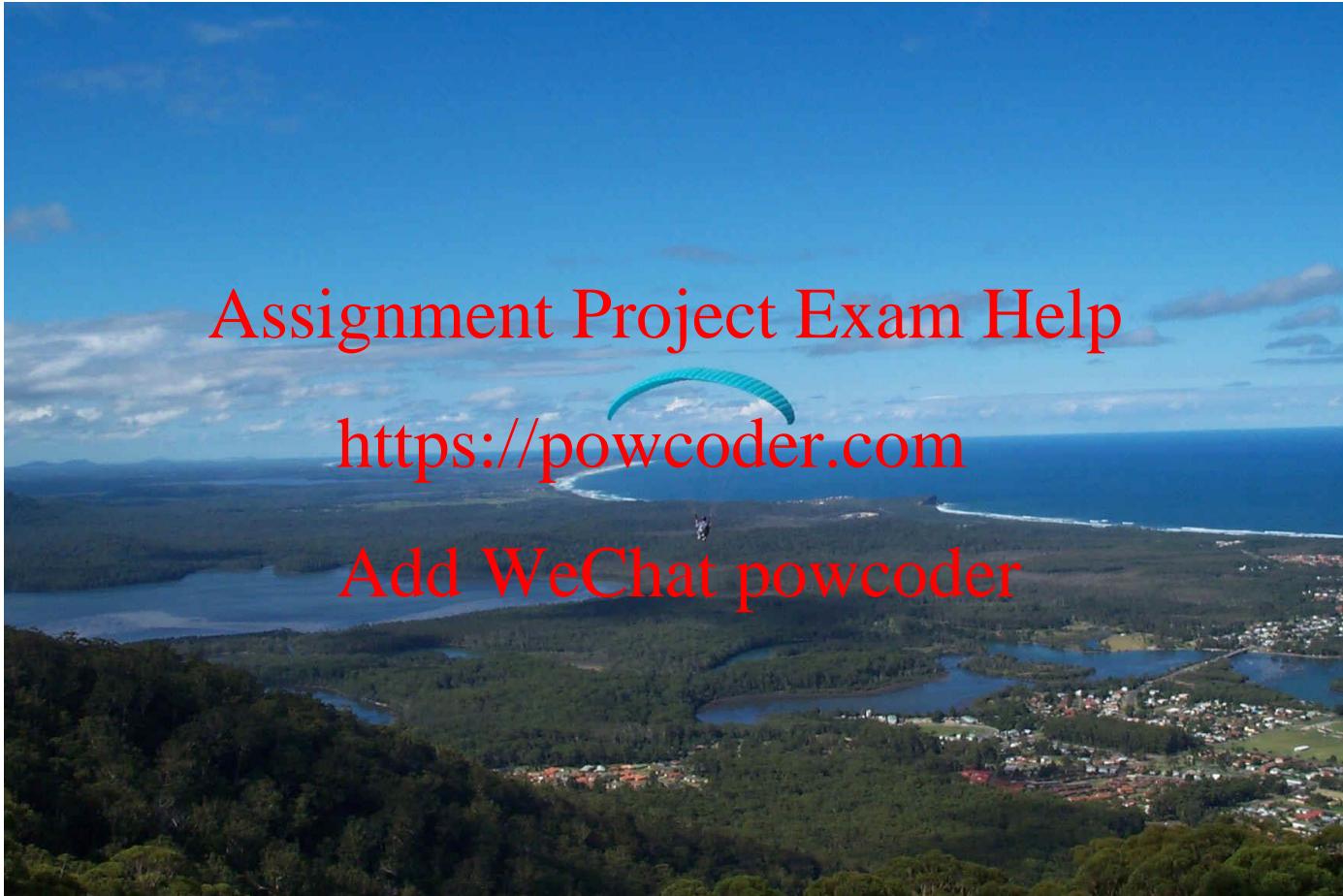


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- *Horizon*: vanishing line of the ground plane
 - All points at the same height as the camera project to the horizon
 - Points higher (resp. lower) than the camera project above (resp. below) the horizon
 - Provides way of comparing height of objects



Vanishing lines of planes



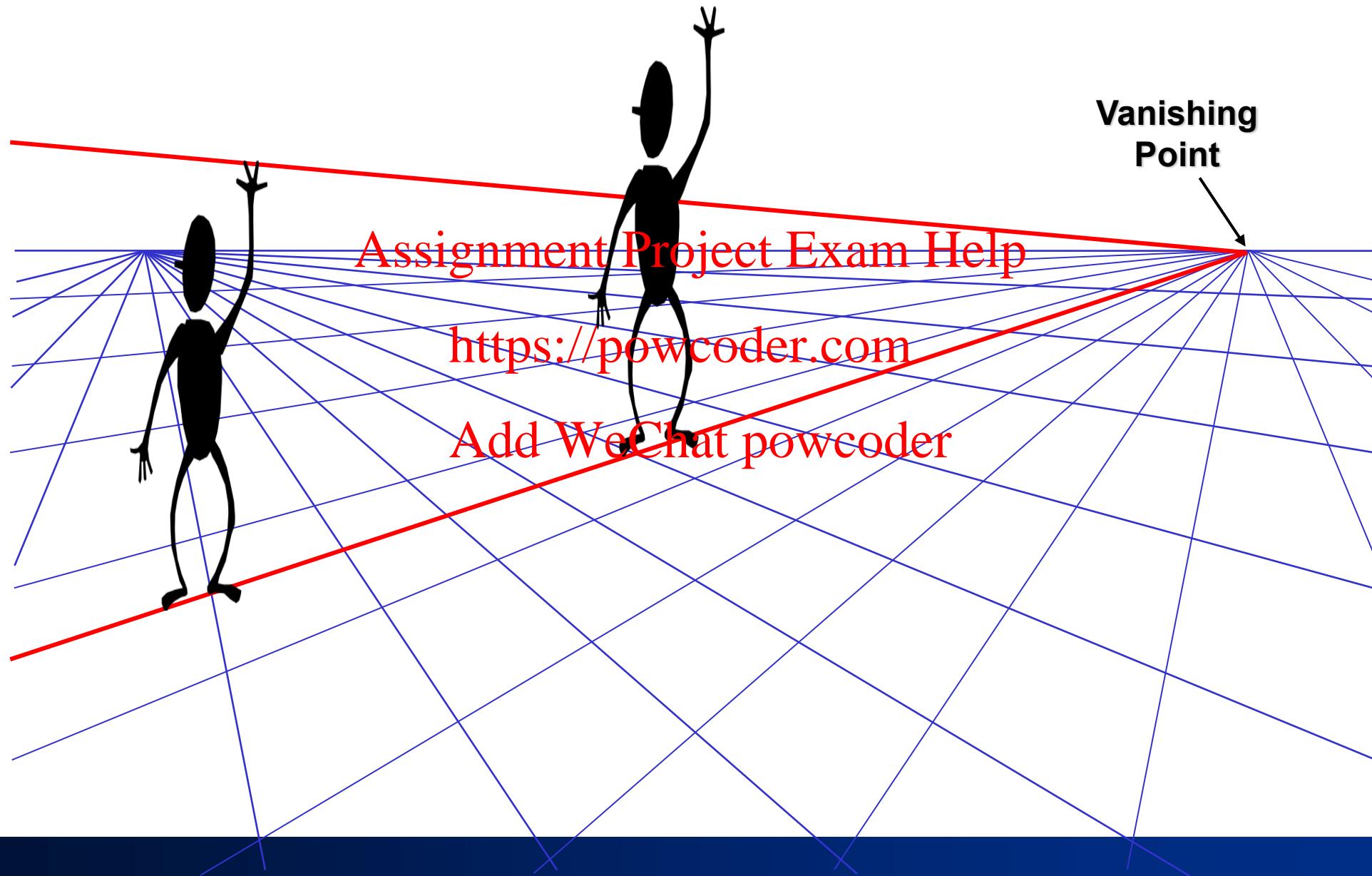
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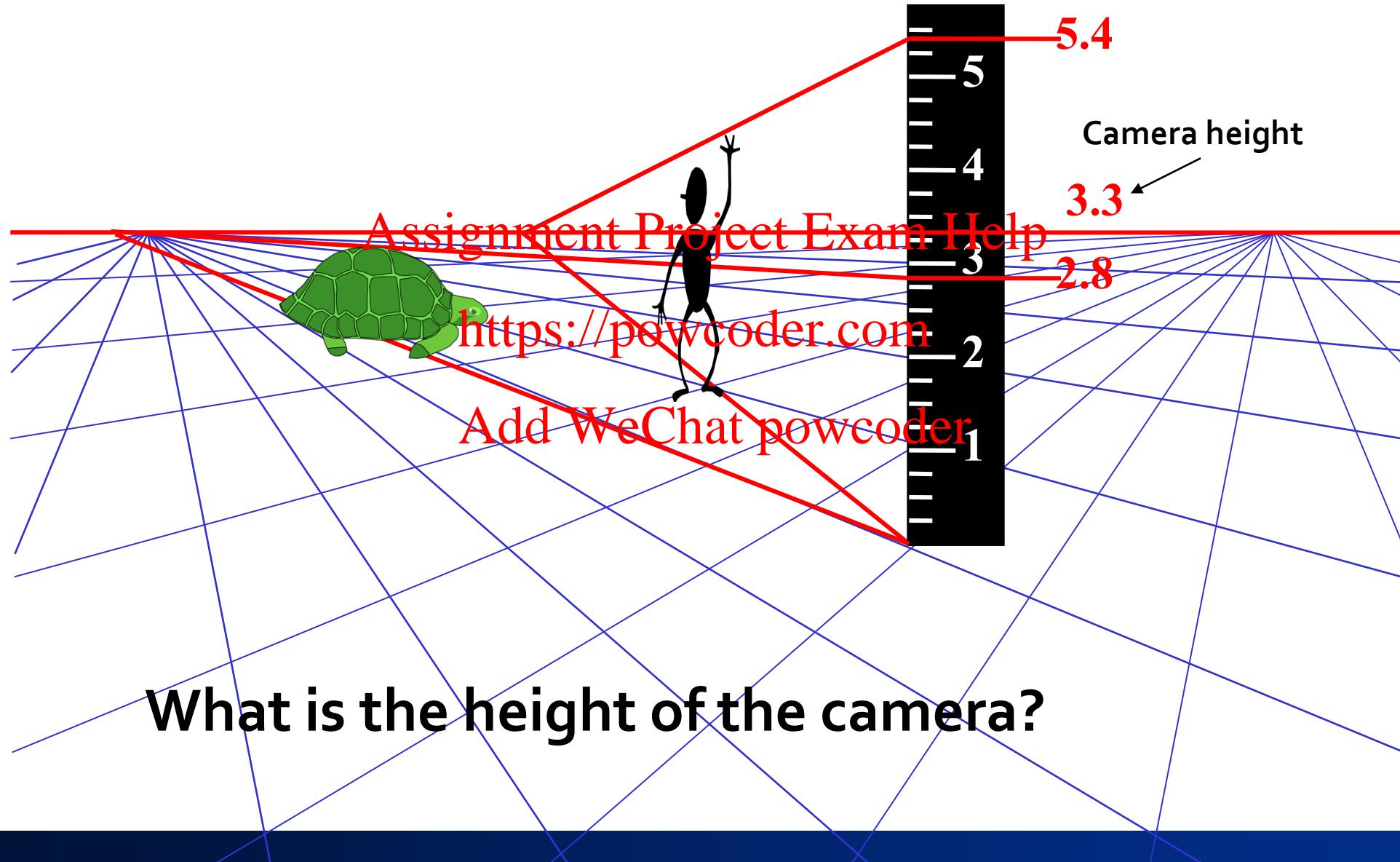
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Is the parachutist above or below the camera?

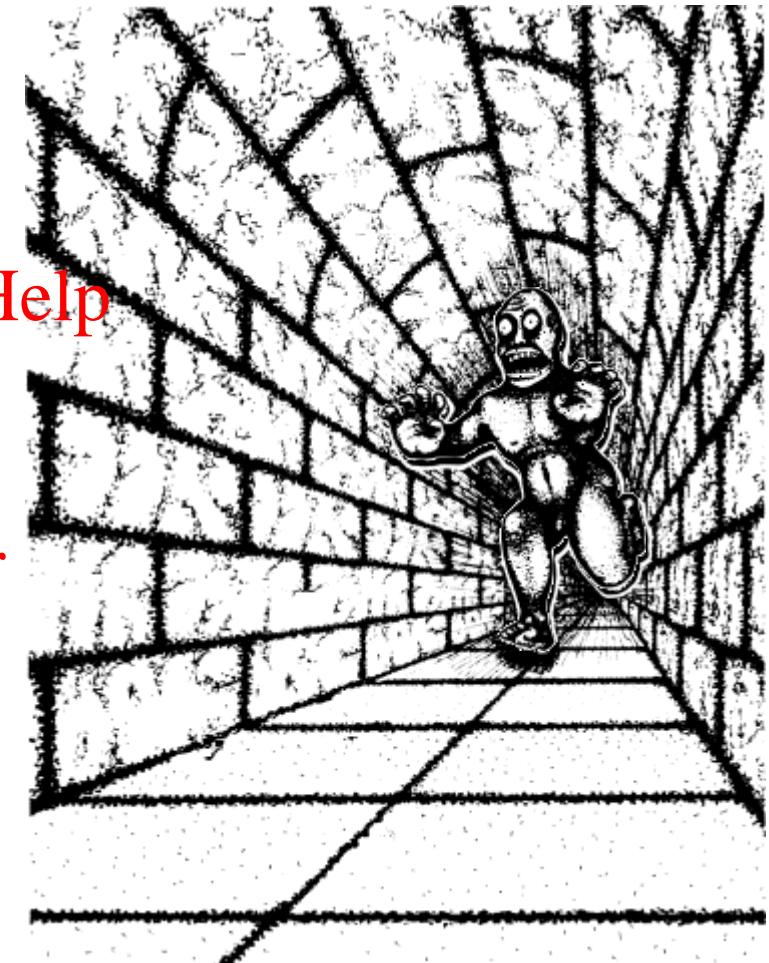
Comparing heights



Measuring height

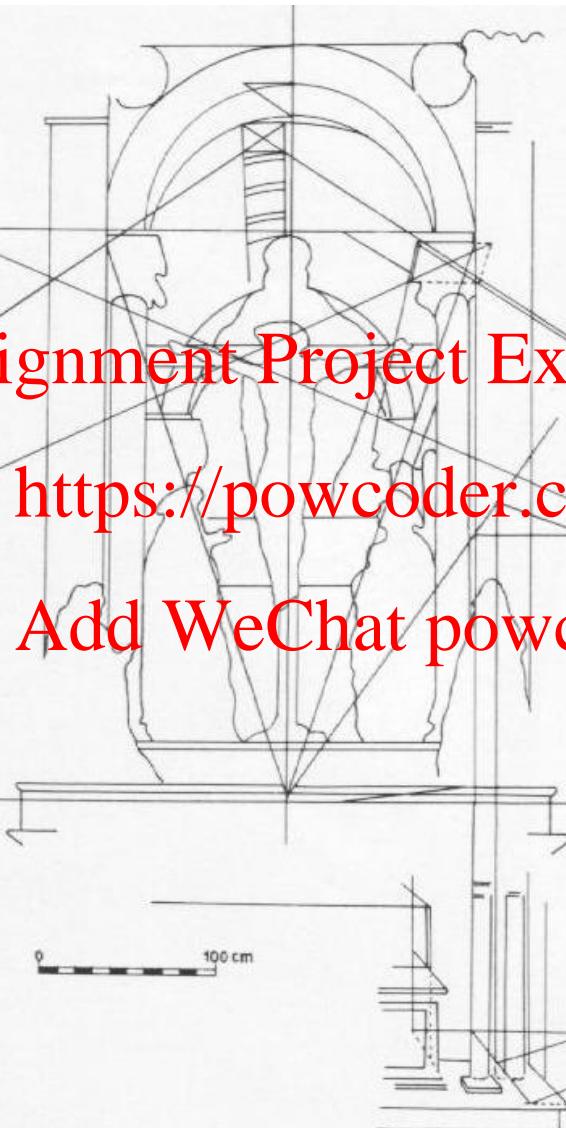
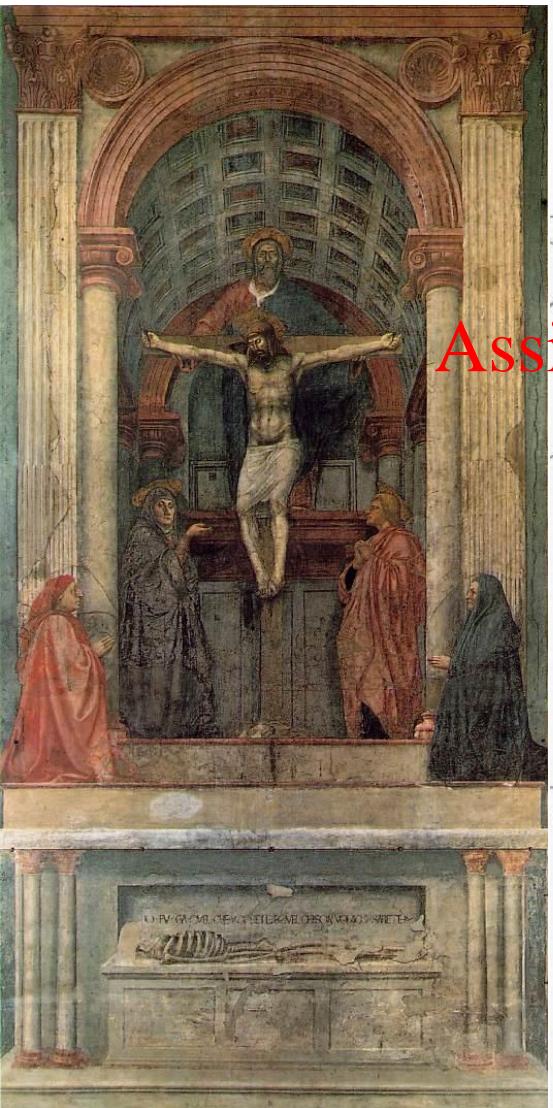


Perspective geometry



Illusion Credit: RN Shepard, Mind Sights: Original Visual Illusions, Ambiguities, and other Anomalies

Perspective cues in art



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- Masaccio, *Trinity*, Santa Maria Novella, Florence, 1425-28
- One of the first consistent uses of perspective in Western art

Perspective distortion

- What is the shape of the projection of a sphere?



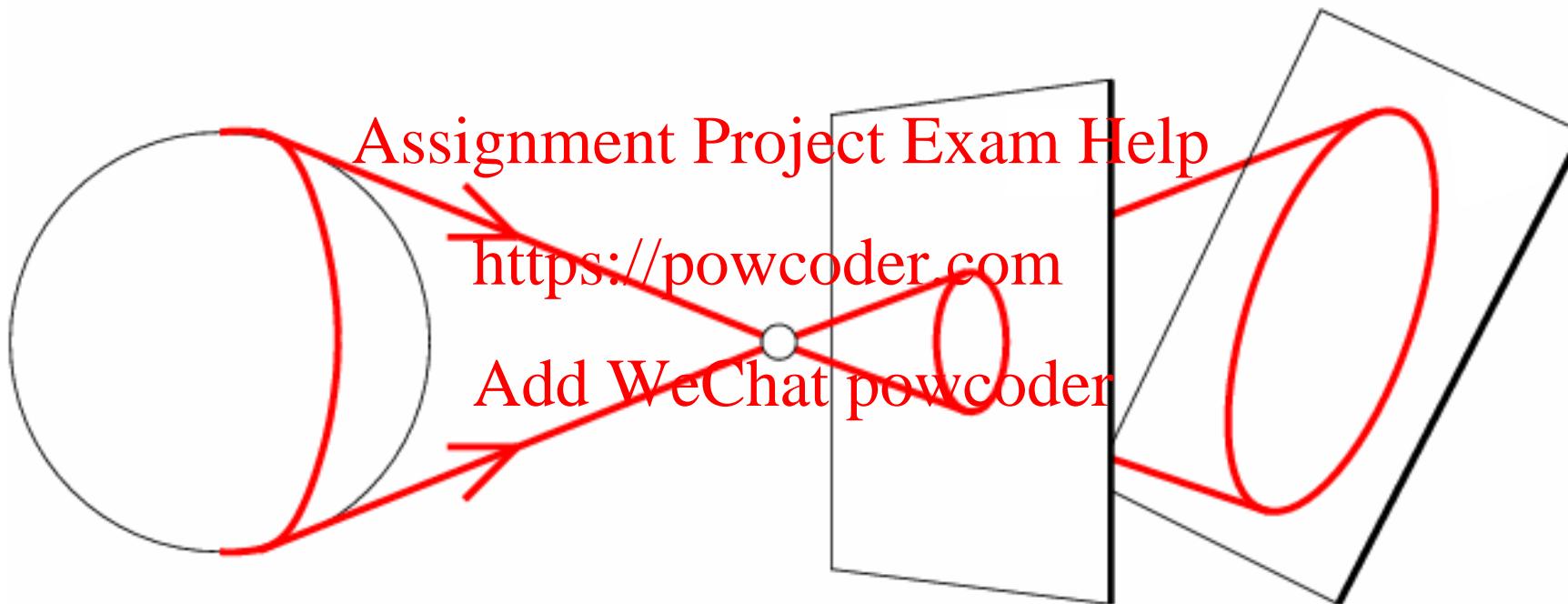
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Perspective distortion

- What is the shape of the projection of a sphere?

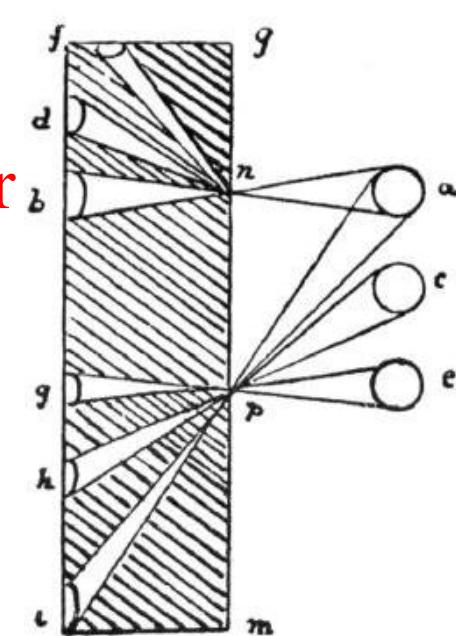


Perspective distortion

- Are the widths of the projected columns equal?

- The exterior columns are wider
- This is not an optical illusion, and is not due to lens flaws
- Phenomenon pointed out by Da Vinci

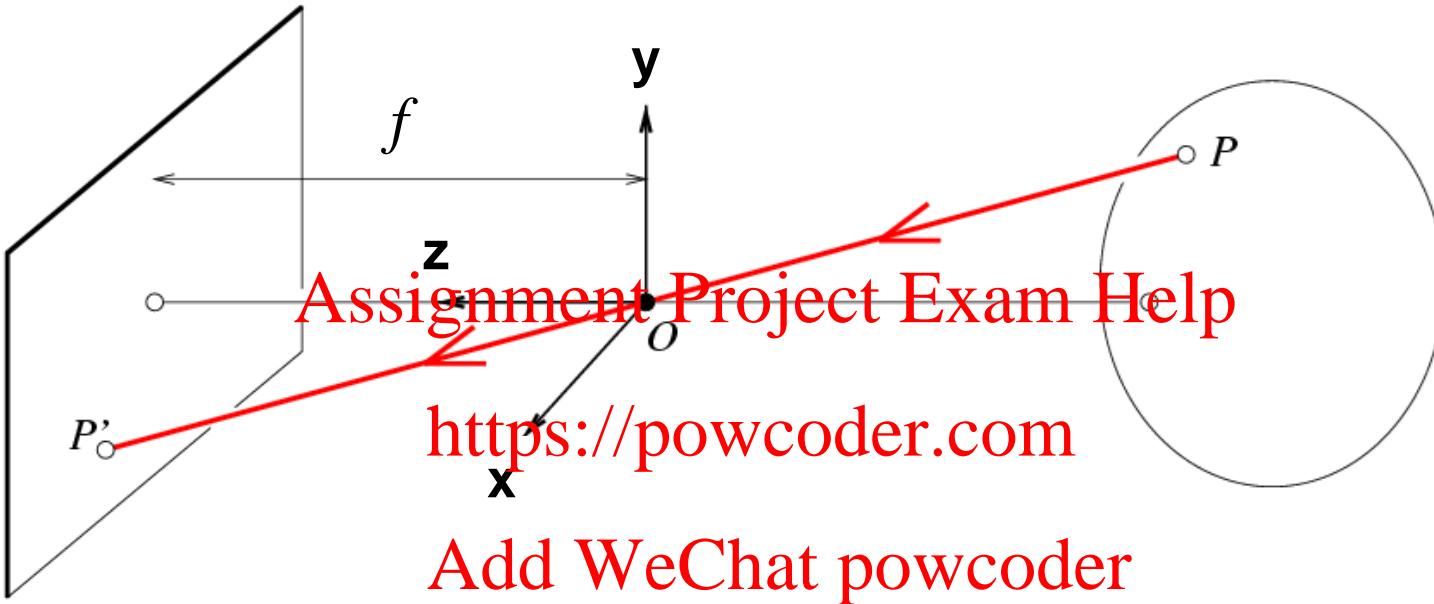
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Perspective distortion: People



Modelling projection: world to image



- **Projection equation:** $(x, y, z) \rightarrow (f \frac{x}{z}, f \frac{y}{z})$

Note: 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**.

Homogeneous coordinate

- Nonlinearity in the projection equation

$$(x, y, z) \rightarrow (f \frac{x}{z}, f \frac{y}{z}) \quad : \text{division by } z \text{ is nonlinear}$$

- Add one more coordinate for linear transformation

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

homogeneous image coordinates

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homogeneous scene coordinates

Converting from homogeneous coordinates

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

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

Homogeneous coordinate

- Why does this matter?
 - Homogeneous coordinates can handle general cases
 - Invariant to scaling
 - Point in Cartesian is ray in Homogeneous.

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$$k \begin{bmatrix} x \\ y \\ w \end{bmatrix} = \begin{bmatrix} kx \\ ky \\ kw \end{bmatrix} \Rightarrow \begin{bmatrix} \frac{kx}{kw} \\ \frac{ky}{kw} \end{bmatrix} = \begin{bmatrix} \frac{x}{w} \\ \frac{y}{w} \end{bmatrix}$$

Homogeneous Coordinates Cartesian Coordinates

Photo Tourism

Exploring photo collections in 3D

<https://powcoder.com>

Noah Snavely Steven M. Seitz Richard Szeliski
University of Washington *Microsoft Research*

SIGGRAPH 2006

Homogeneous coordinate

- EBU6230 Image and Video Processing
 - Week 2 day 1: image_transformations
- <https://pages.mtu.edu/~shene/COURSES/cs3621/NOTES/geometry/homo-coor.html>

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Perspective projection matrix

- Projection:
 - a matrix multiplication with homogeneous coordinates

$$\begin{bmatrix} f & 0 & 0 & 0 \\ 0 & f & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} = \begin{bmatrix} fx \\ fy \\ z \end{bmatrix} \Rightarrow \left(f \frac{x}{z}, f \frac{y}{z} \right)$$

divide by the third coordinate

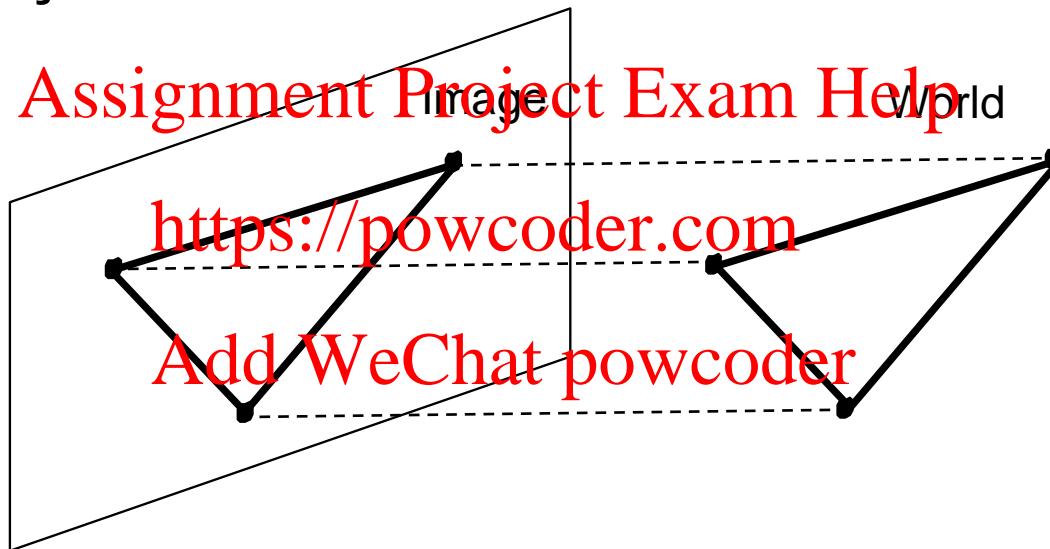
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In practice: lots of coordinate transformations...

$$\begin{bmatrix} 2D \\ point \\ (3 \times 1) \end{bmatrix} = \begin{bmatrix} Camera \\ to \\ pixel \\ coord. \\ trans. \\ matrix \\ (3 \times 3) \end{bmatrix} \begin{bmatrix} Perspective \\ projection \\ matrix \\ (3 \times 4) \end{bmatrix} \begin{bmatrix} World \\ to \\ camera \\ coord. \\ trans. \\ matrix \\ (4 \times 4) \end{bmatrix} \begin{bmatrix} 3D \\ point \\ (4 \times 1) \end{bmatrix}$$

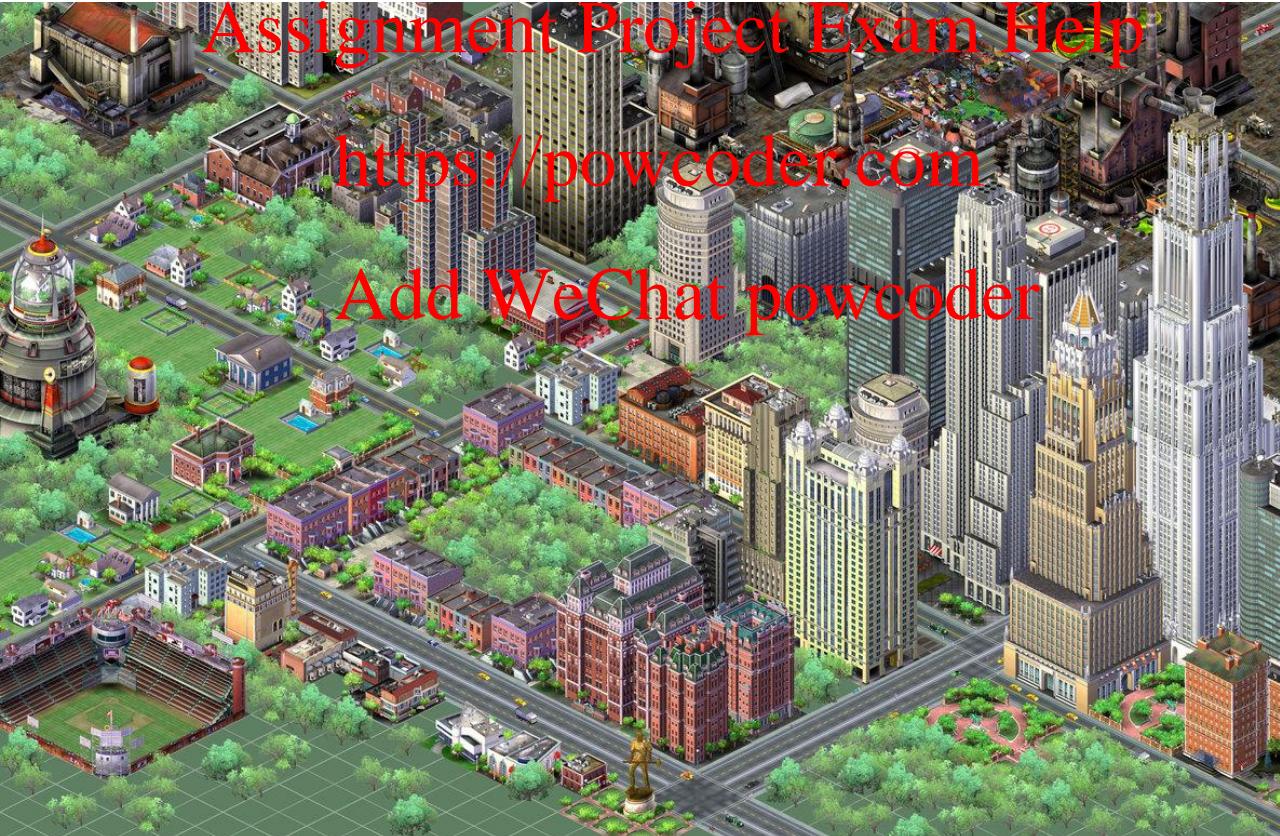
Orthographic Projection

- **Special case of perspective projection**
 - Distance from center of projection to image plane is infinite
 - Also called “parallel projection”



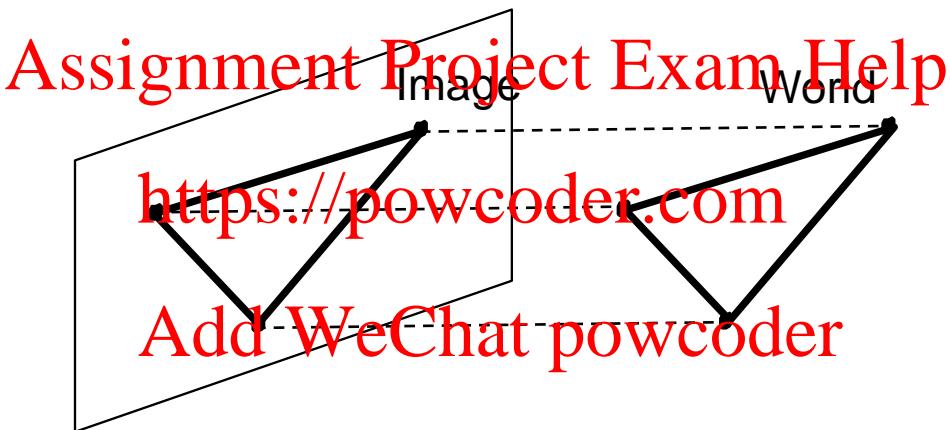
Orthographic Projection

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Orthographic Projection

- **Special case of perspective projection**
 - Distance from center of projection to image plane is infinite
 - Also called “parallel projection”



- What's the projection matrix?

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} = \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} \Rightarrow (x, y)$$

Quiz-01) 3D-to-2D

- When the 3D world dimension reduces to 2D, what properties are preserved?
 - Straight lines
 - Incidence
 - Angles
 - Lengths

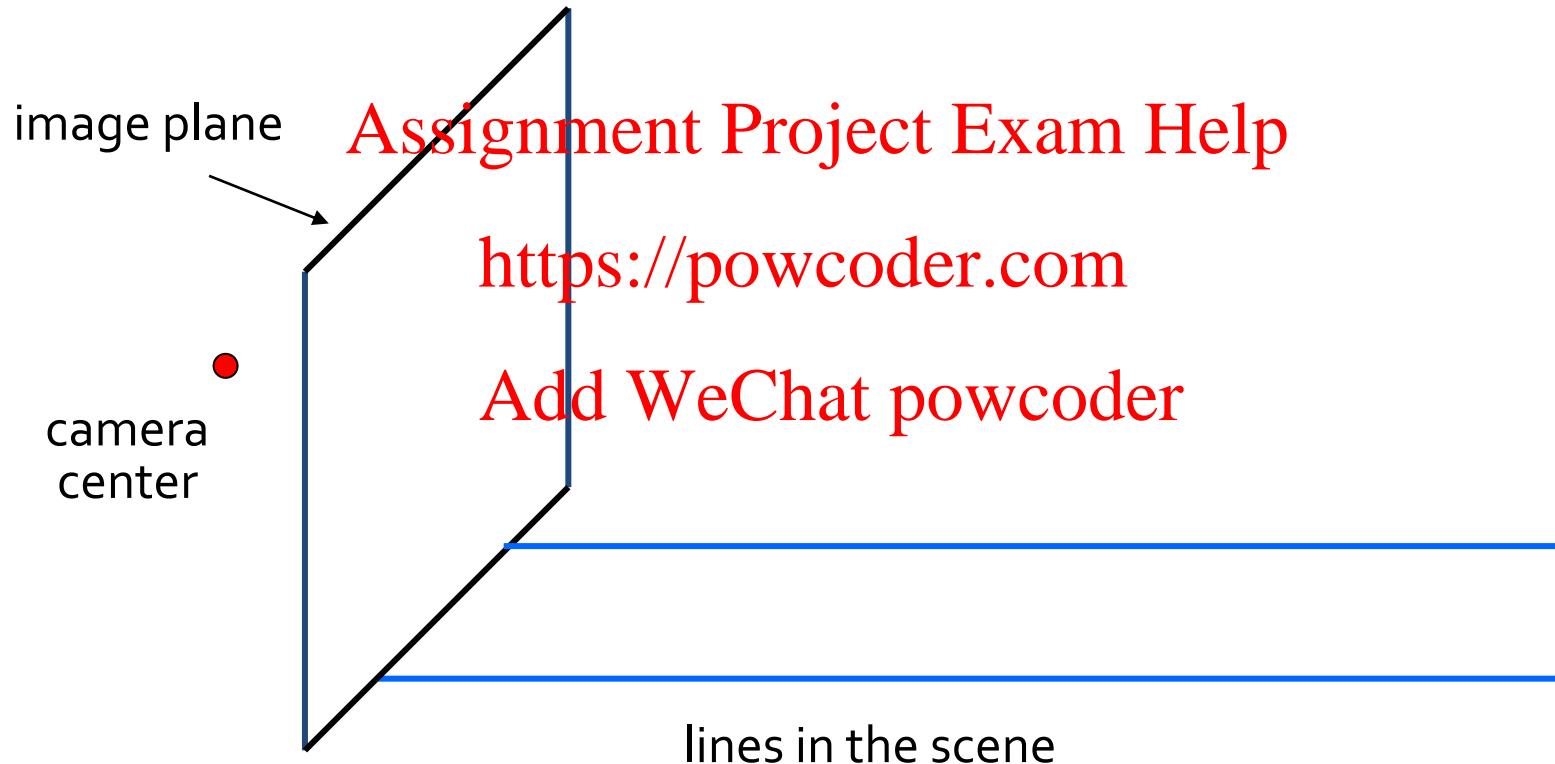
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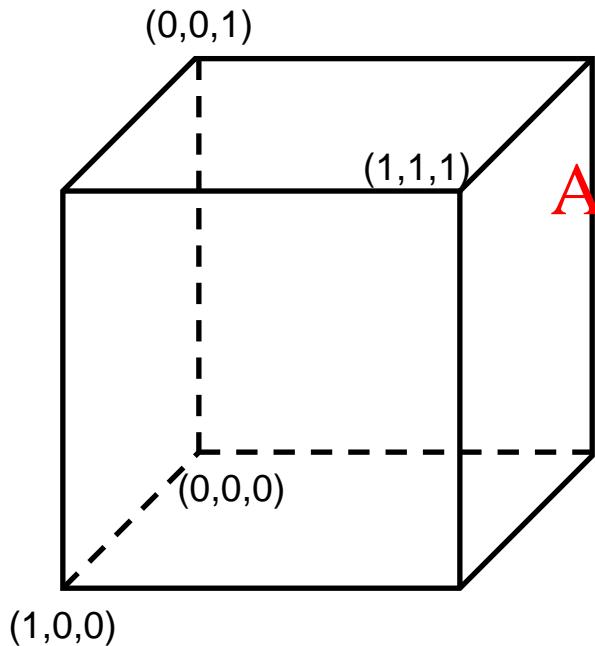
Quiz-02) Constructing the vanishing point of a line

- In the figure below, there are two blue parallel lines, perpendicular to the image plane. Draw how the lines look like in the image plan and discuss the result



Quiz-03) Orthographic projection

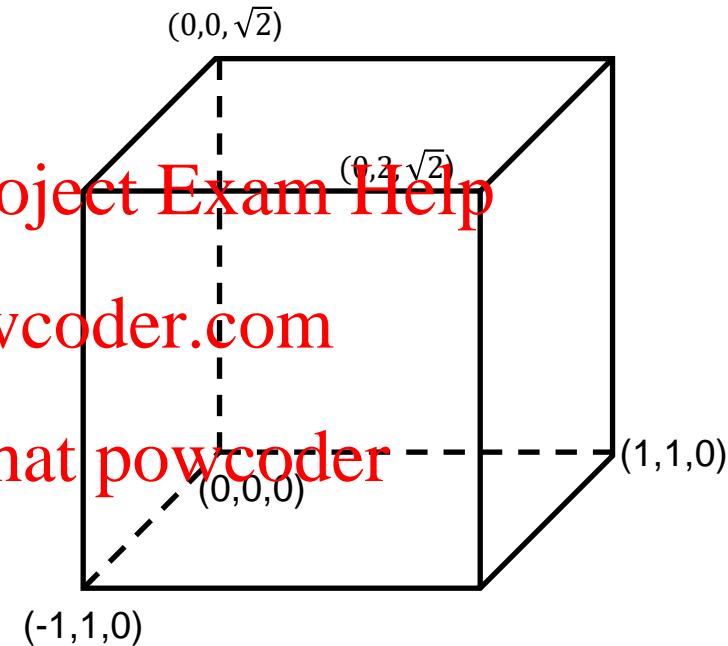
- Perform Orthographic projection to each 3D cube in 3D below and show the result in 2D



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Quiz-04) Projection matrix (2D-to-2D)

- Given two point sets:
 - $\mathbf{x} = \{x_1, \dots, x_4\} = \{(u_1, v_1), \dots, (u_4, v_4)\} = \{(0,260), (640,260), (0,400), (640,400)\}$
 - $\mathbf{x}' = \{x'_1, \dots, x'_4\} = \{(u'_1, v'_1), \dots, (u'_4, v'_4)\} = \{(0,0), (400,0), (0,640), (400,640)\}$

Find the perspective projection matrix \mathbf{P} such that $\mathbf{x}' = \mathbf{P}\mathbf{x}$

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EBU7240

Computer Vision

- Camera: lenses & digital sensors -

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Semester 1, 2021

Changjae Oh

Content

- The pinhole projection model
 - Geometric properties
 - Perspective projection matrix
- **Cameras with lenses**
[Assignment Project Exam Help](https://powcoder.com)
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 - Field of view
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Building a Real Camera



Home-made pinhole camera



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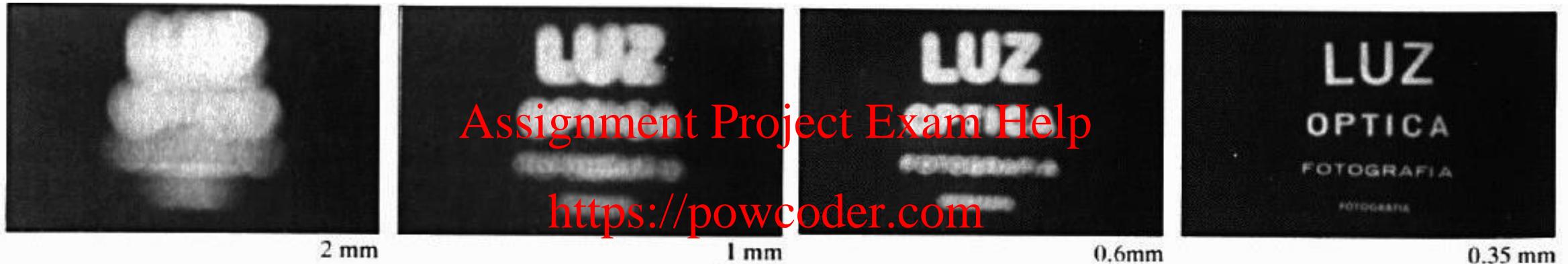
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<http://www.debevec.org/Pinhole/>

Shrinking the aperture

- Images with varying the aperture size

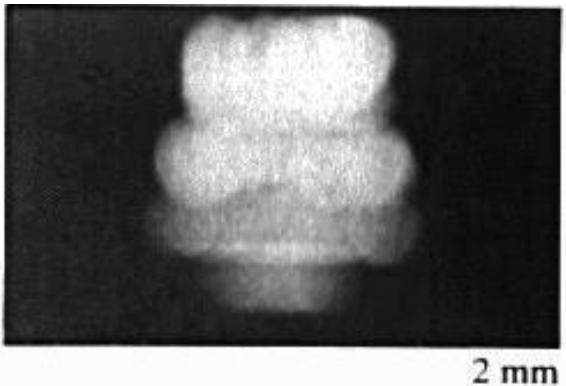


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- Why not make the aperture as small as possible?
 - Less light gets through
 - Diffraction effects...

Shrinking the aperture

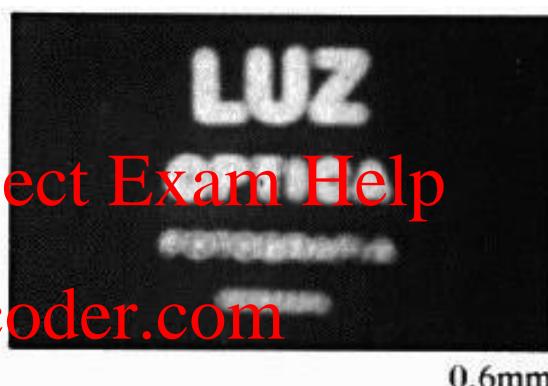
- Images with varying the aperture size



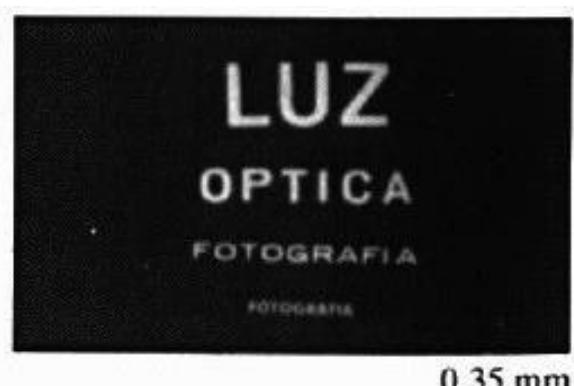
2 mm



1 mm



0.6mm

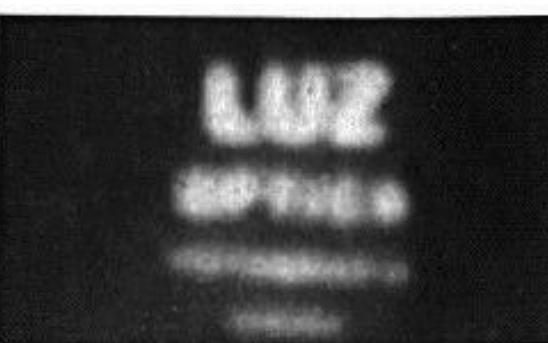


0.35 mm

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0.15 mm

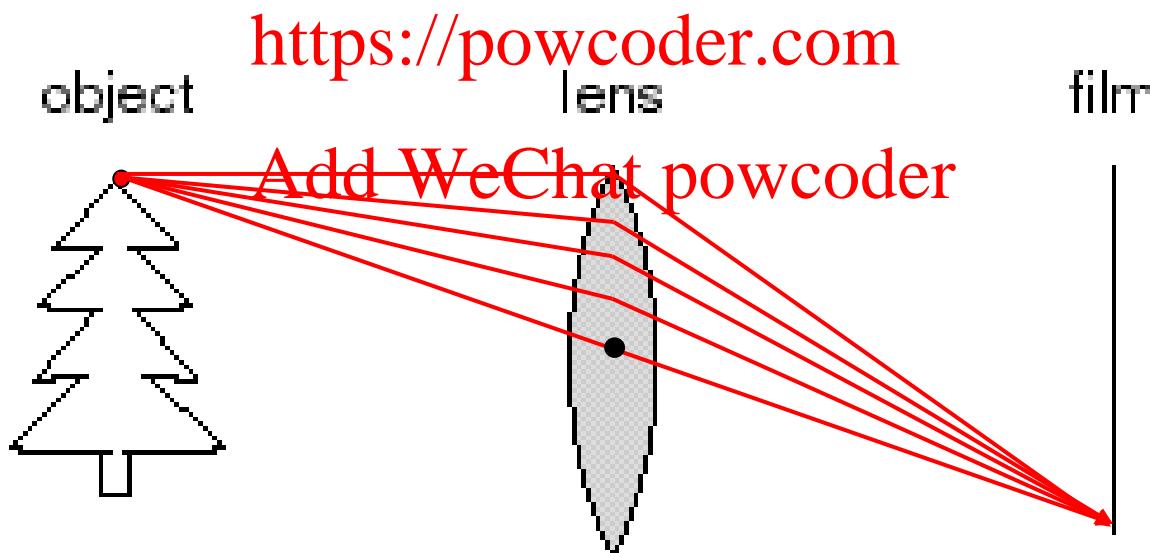


0.07 mm

Adding a lens

- A lens focuses light onto the film
 - Thin lens model:
 - Rays passing through the center are not deviated (pinhole projection model still holds)

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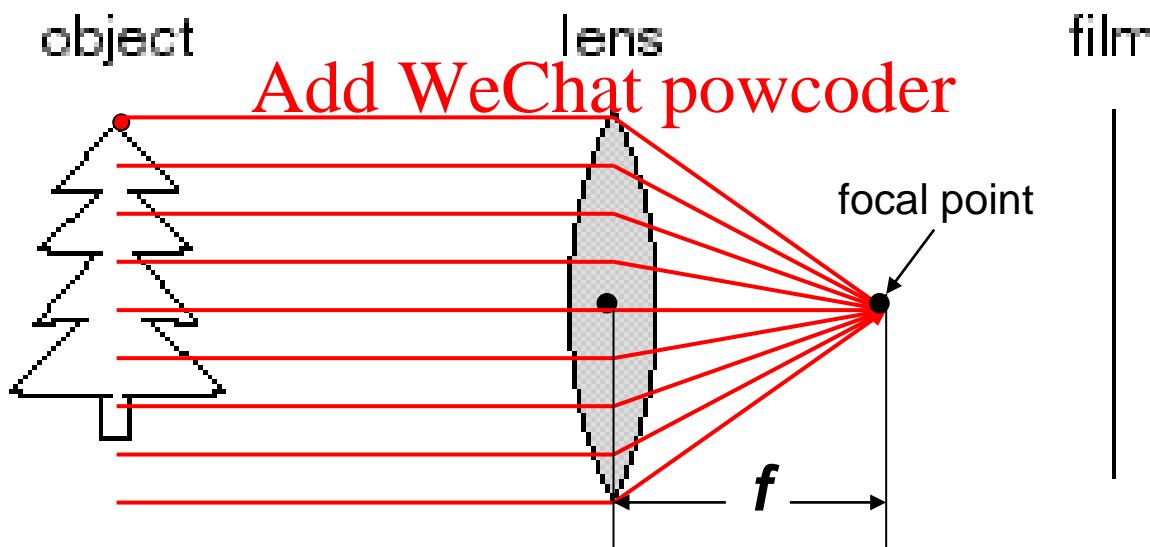


Adding a lens

- A lens focuses light onto the film
 - Thin lens model:
 - Rays passing through the center are not deviated (pinhole projection model still holds)
 - All rays parallel to the optical axis pass through the *focal point*
 - All parallel rays converge to points on the *focal plane*

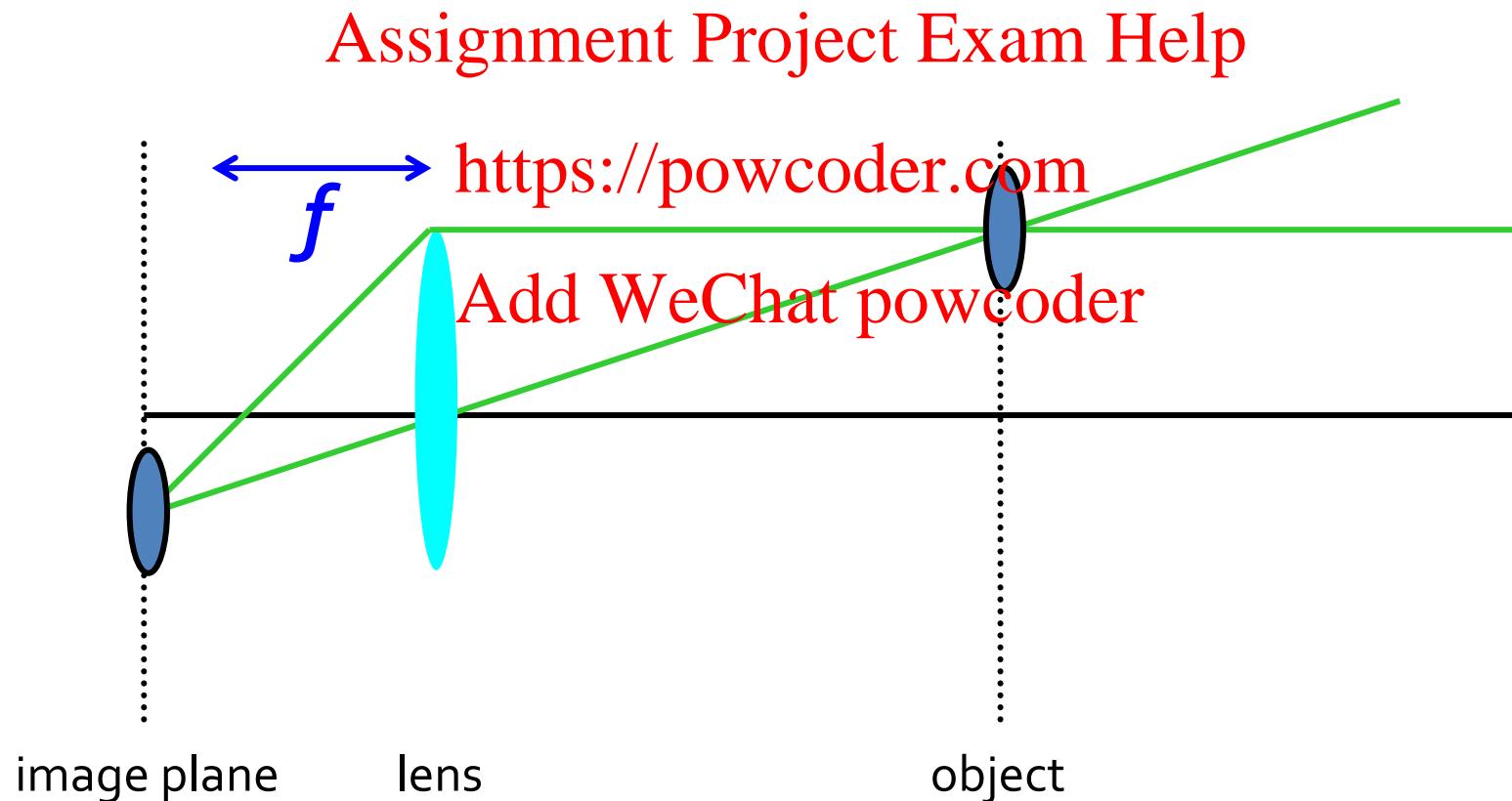
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<https://powcoder.com>



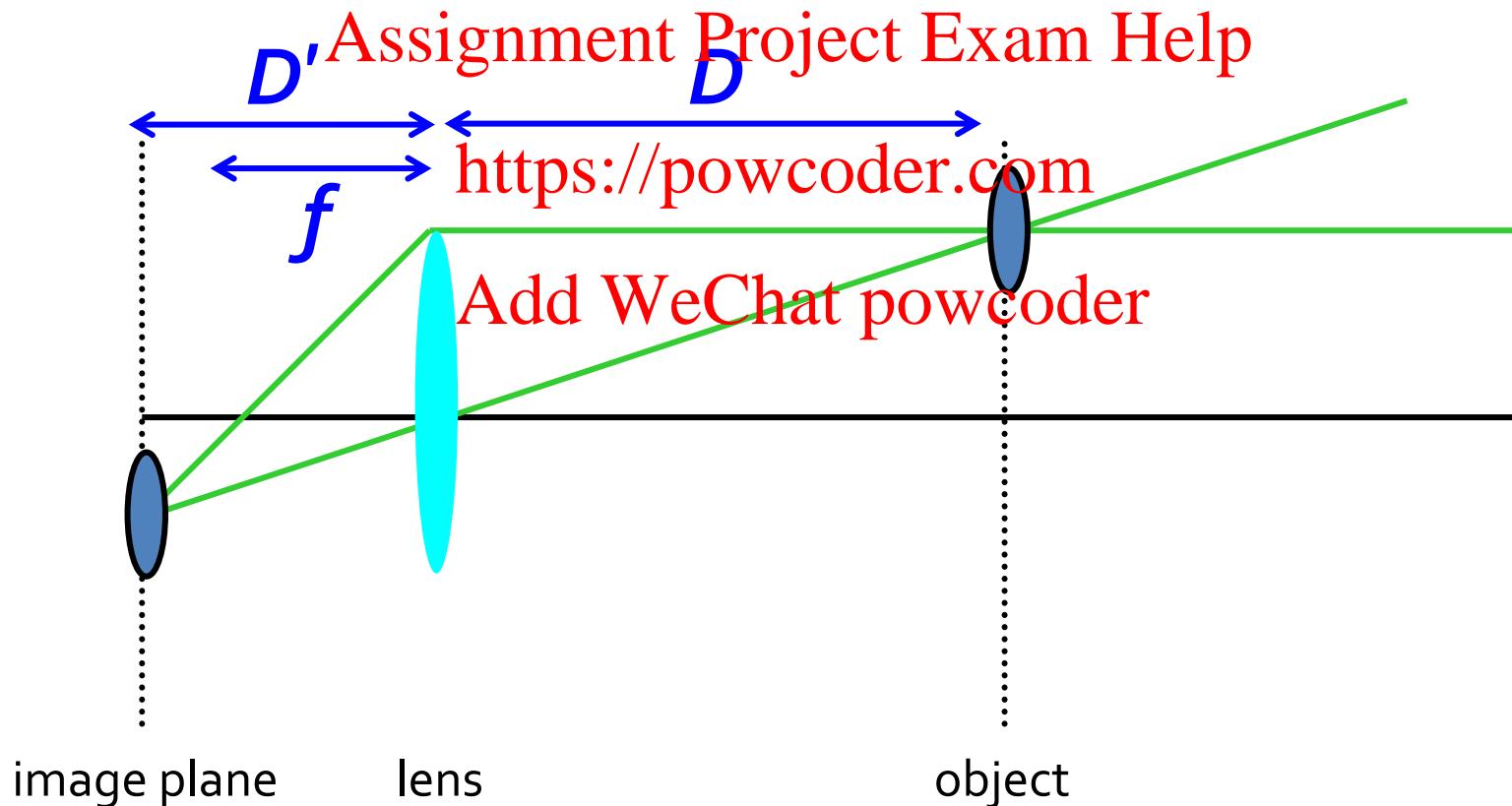
Thin lens formula

- Where does the lens focus the rays coming from a given point in the scene?



Thin lens formula

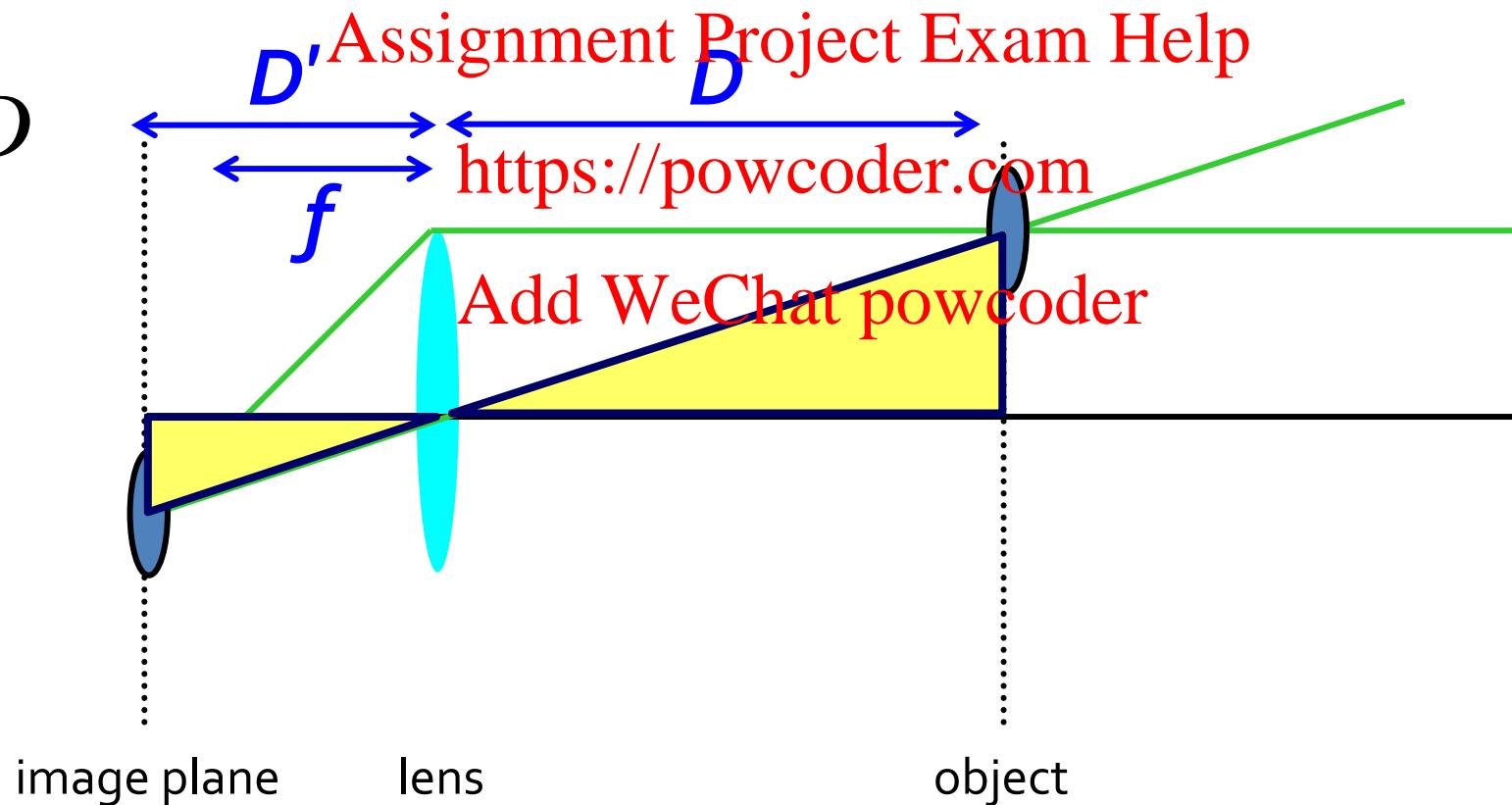
- What is the relation between the focal length (f), the distance of the object from the optical center (D), and the distance at which the object will be in focus (D')?



Thin lens formula

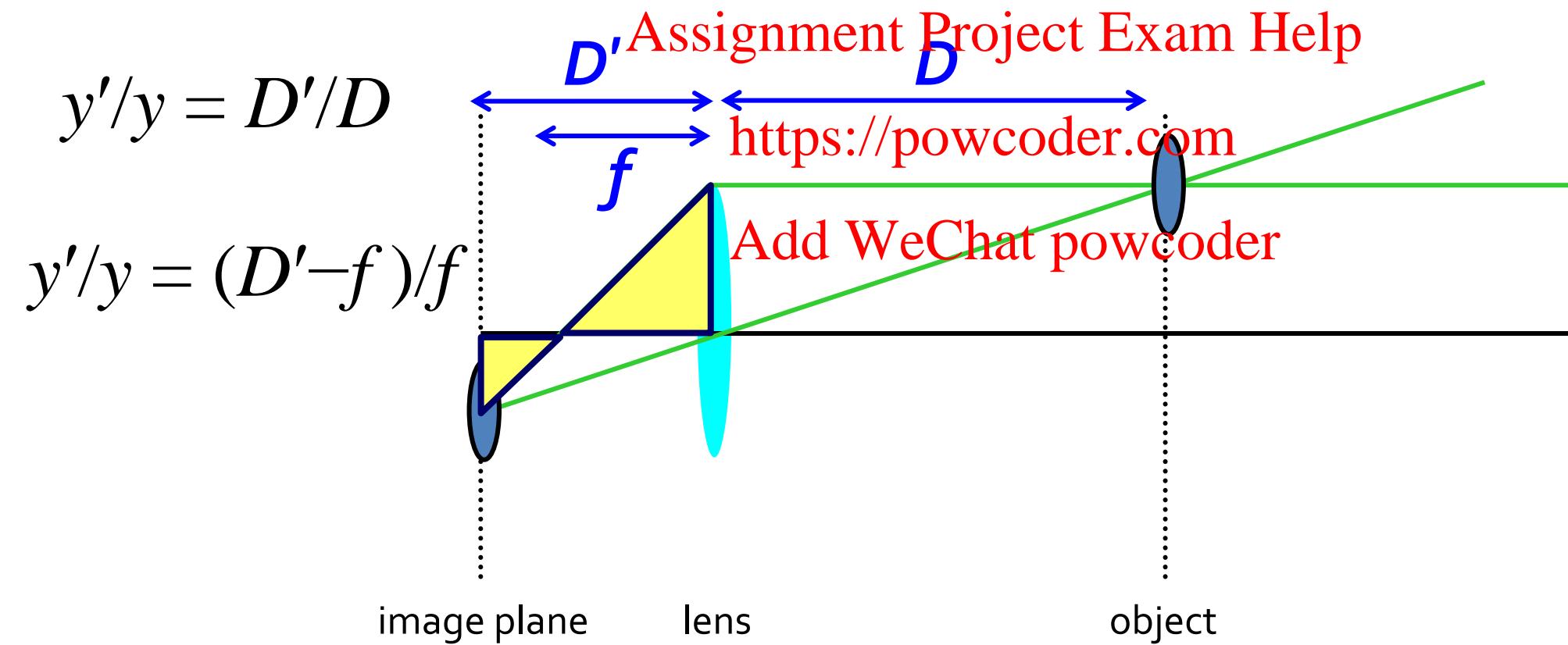
- Similar triangles everywhere!

$$y'/y = D'/D$$



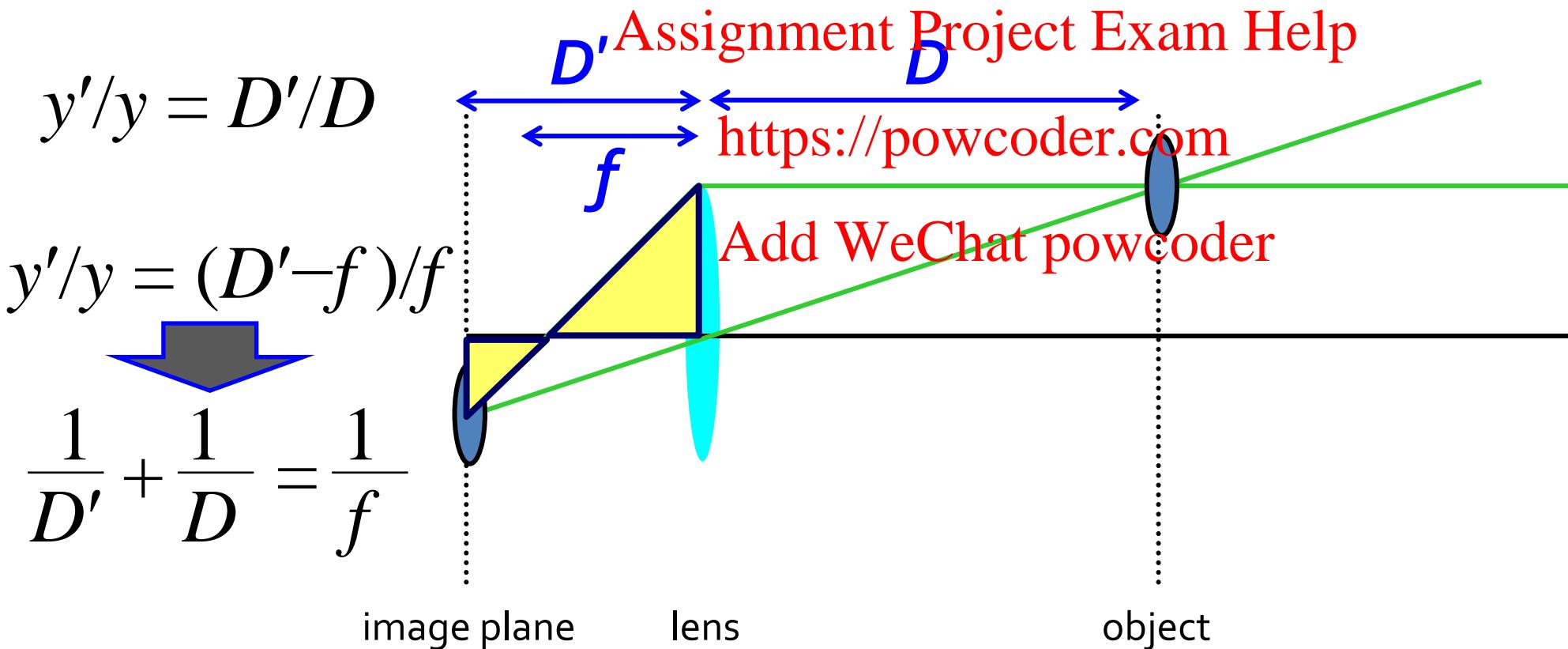
Thin lens formula

- Similar triangles everywhere!



Thin lens formula

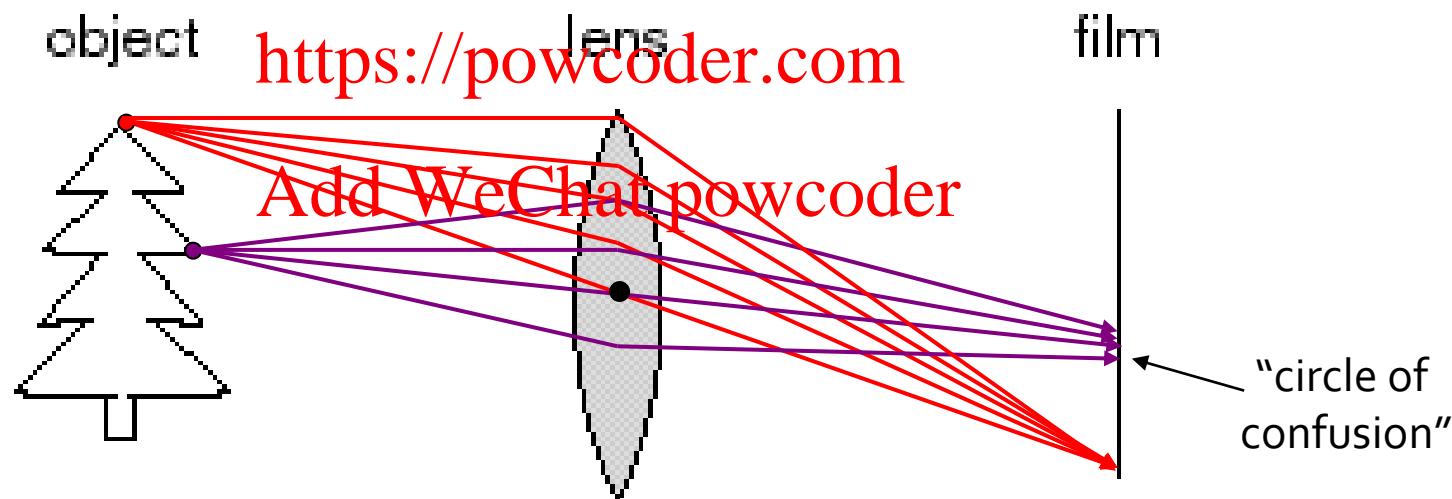
- Any point satisfying the thin lens equation is in focus.
- What happens when D is very large?



Depth of Field

- For a fixed focal length, there is a specific distance at which objects are “in focus”
 - Other points project to a “circle of confusion” in the image

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Depth of Field

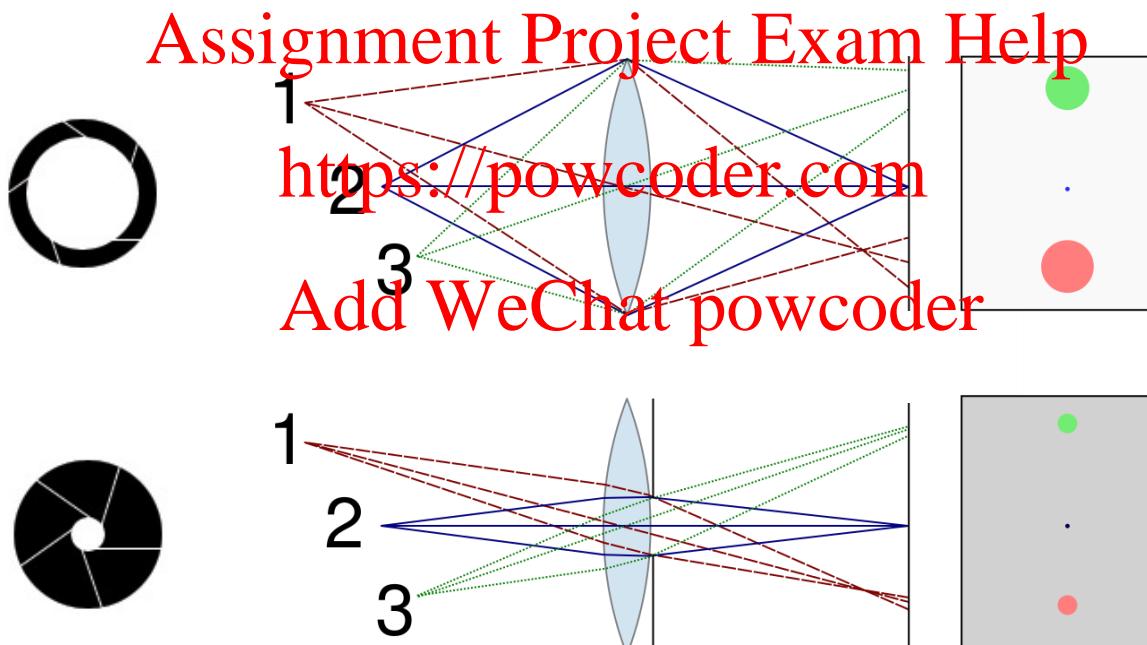


<http://www.cambridgeincolour.com/tutorials/depth-of-field.htm>



Controlling depth of field

- **Changing the aperture size affects depth of field**
 - A smaller *aperture* increases the range in which the object is approximately in focus
 - But small aperture reduces amount of light – need to increase *exposure*



http://en.wikipedia.org/wiki/File:Depth_of_field_illustration.svg

Varying the aperture

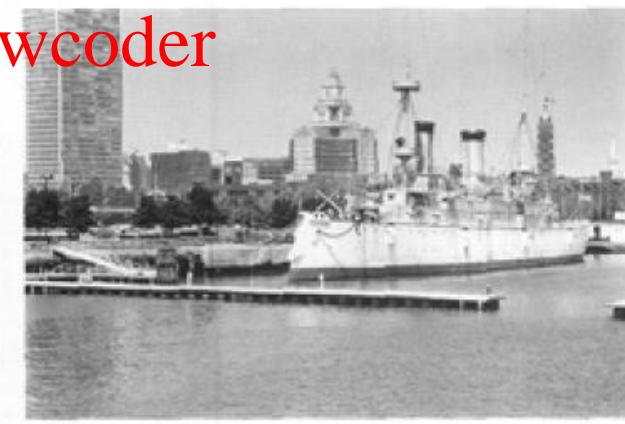
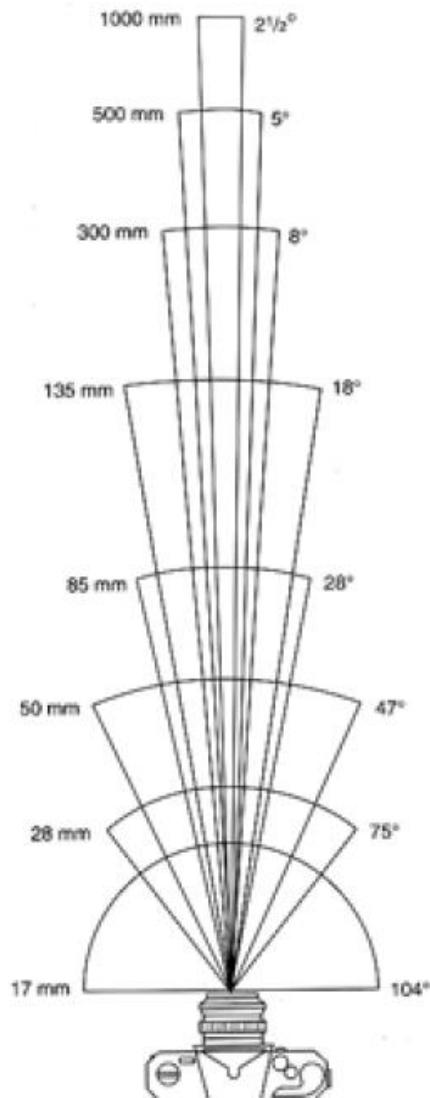


Large aperture = small DOF



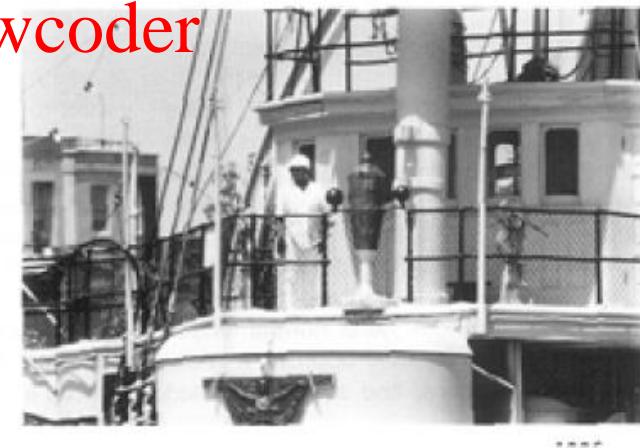
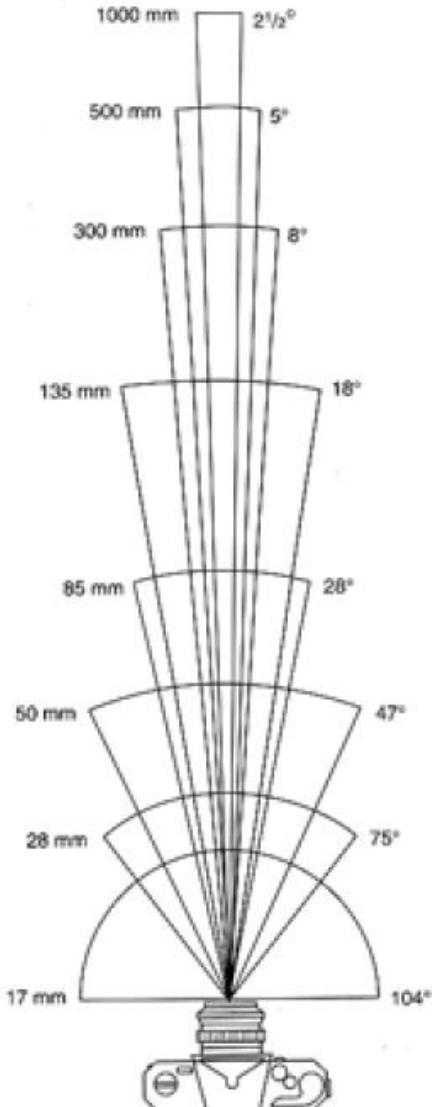
Small aperture = large DOF

Field of View



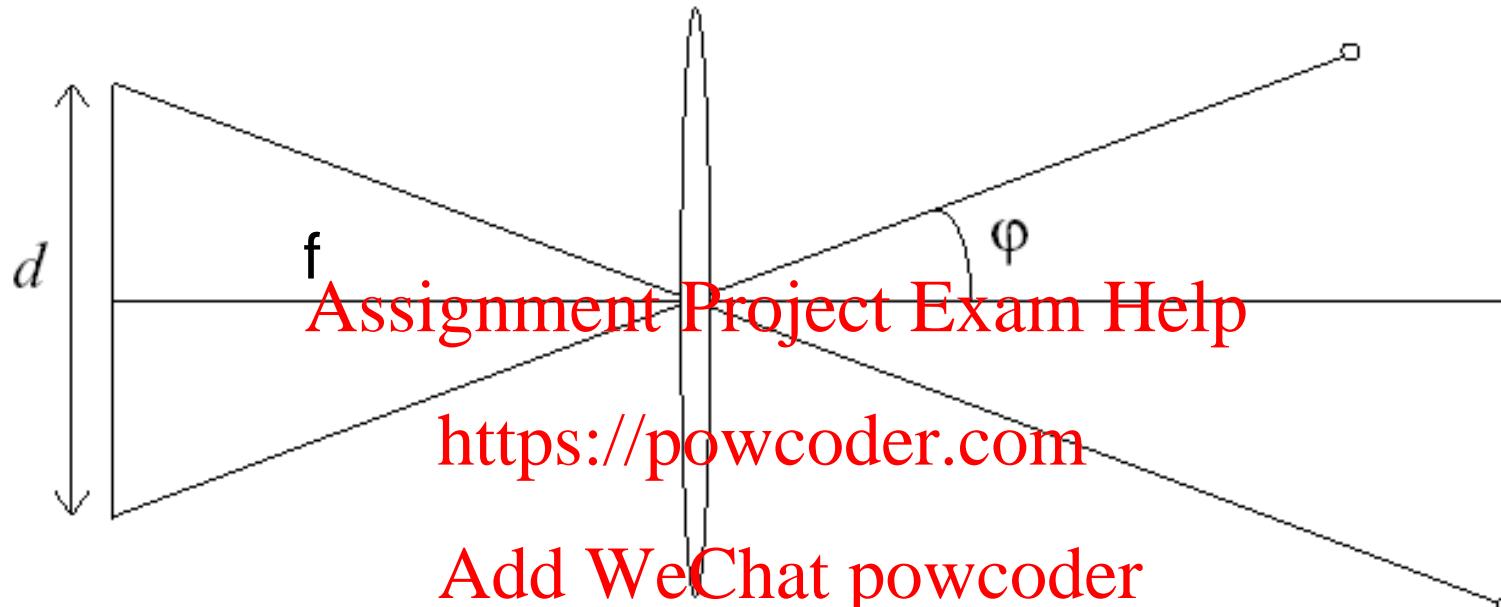
From London and Upton

Field of View



From London and Upton

Field of View

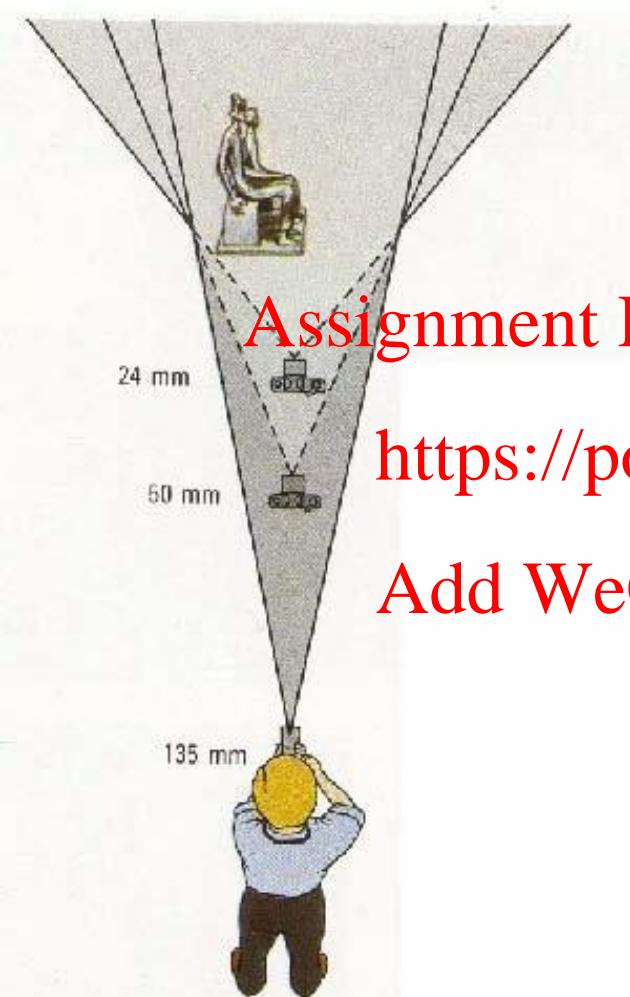


FOV depends on focal length and size of the camera retina

$$\varphi = \tan^{-1}\left(\frac{d}{2f}\right)$$

Larger focal length = smaller FOV

Field of View / Focal Length



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Large FOV, small f
Camera close to car

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Small FOV, large f
Camera far from the car

Sources: A. Efros, F. Durand

Same effect for faces



wide-angle



standard



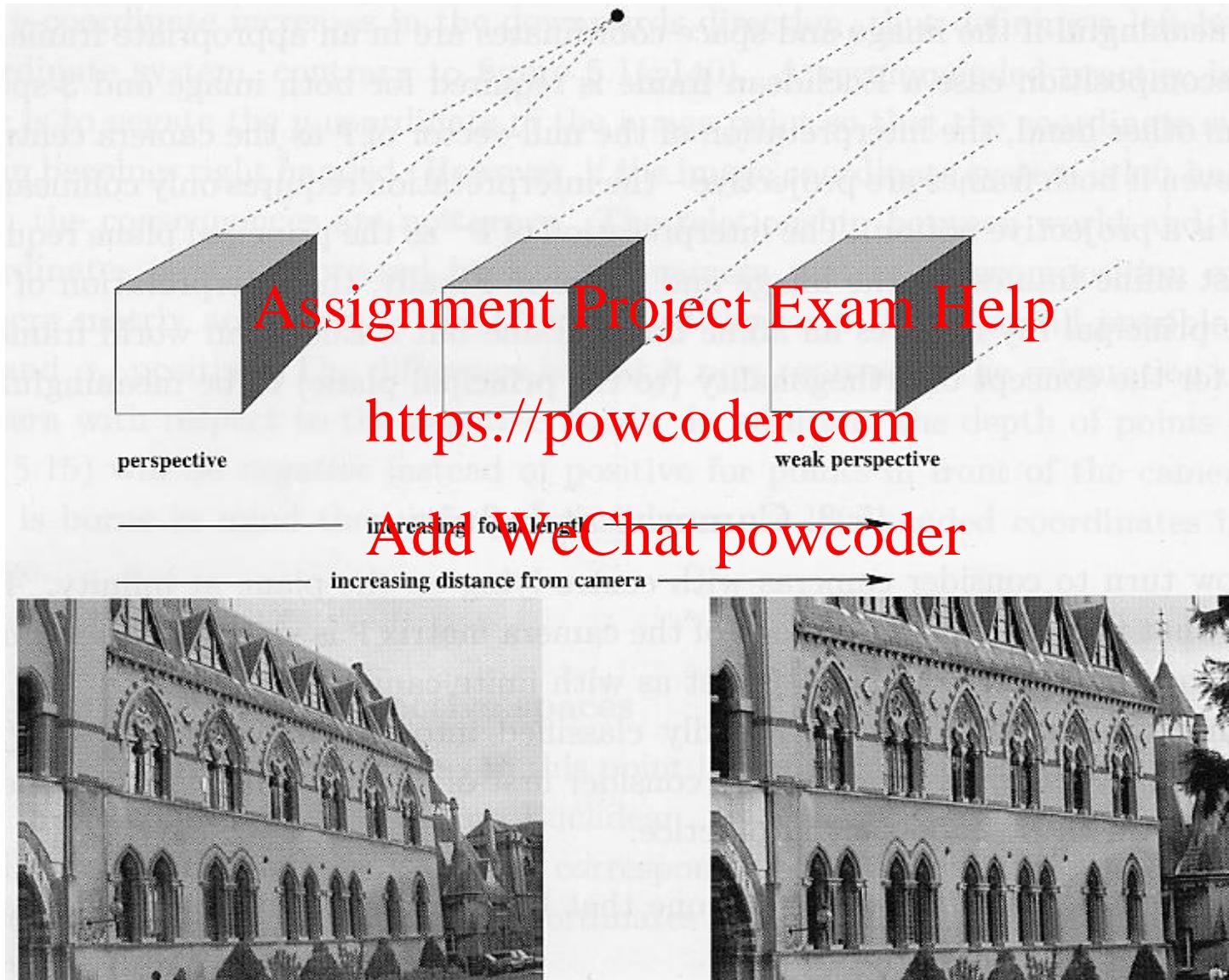
telephoto

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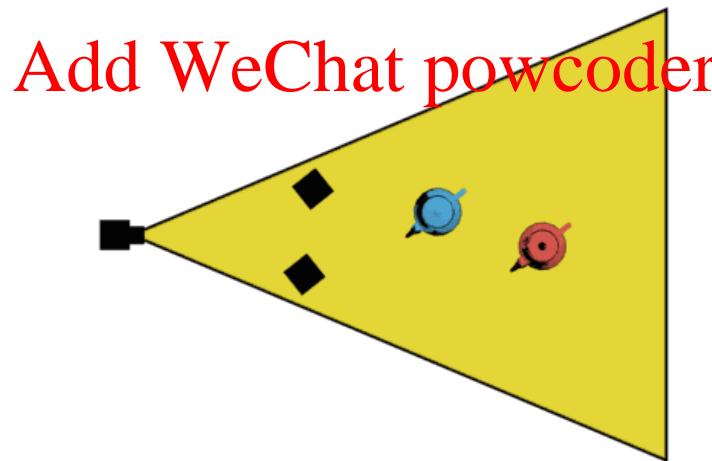
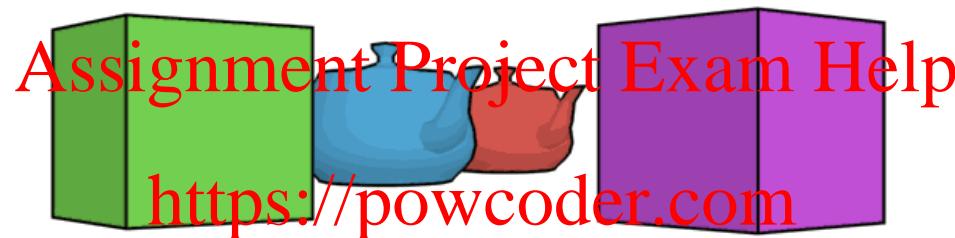
Approximating an orthographic camera



Source: Hartley & Zisserman

The dolly zoom

- Continuously adjusting the focal length while the camera moves away from (or towards) the subject



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

The dolly zoom

- Continuously adjusting the focal length while the camera moves away from (or towards) the subject



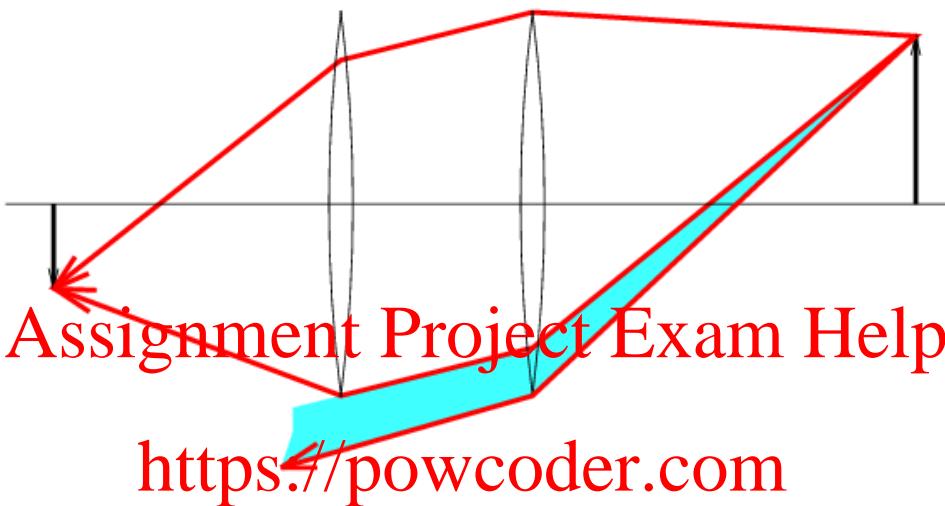
[Example of dolly zoom from Goodfellas \(YouTube\)](#)

Real lenses



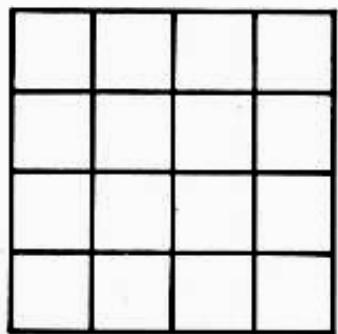
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Lens flaws: Vignetting

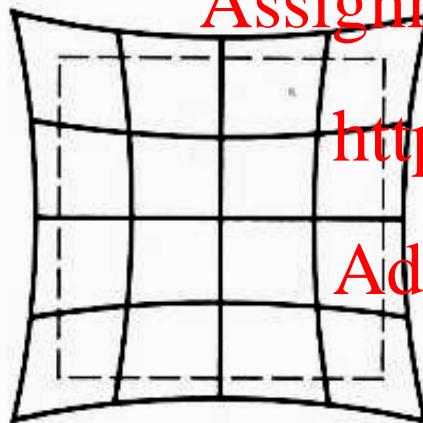


Radial Distortion

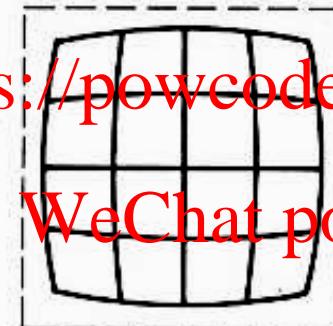
- Caused by imperfect lenses
- Deviations are most noticeable near the edge of the lens



No distortion



Pin cushion



Barrel

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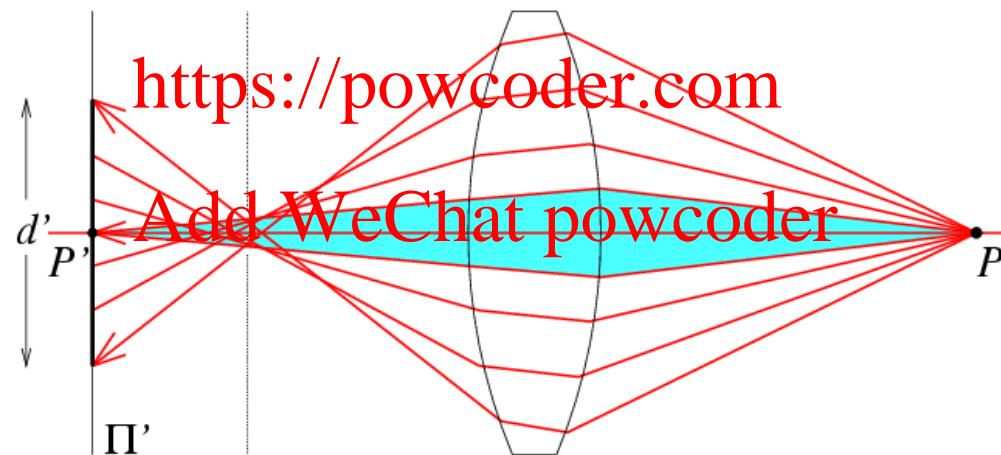
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Lens flaws: Spherical aberration

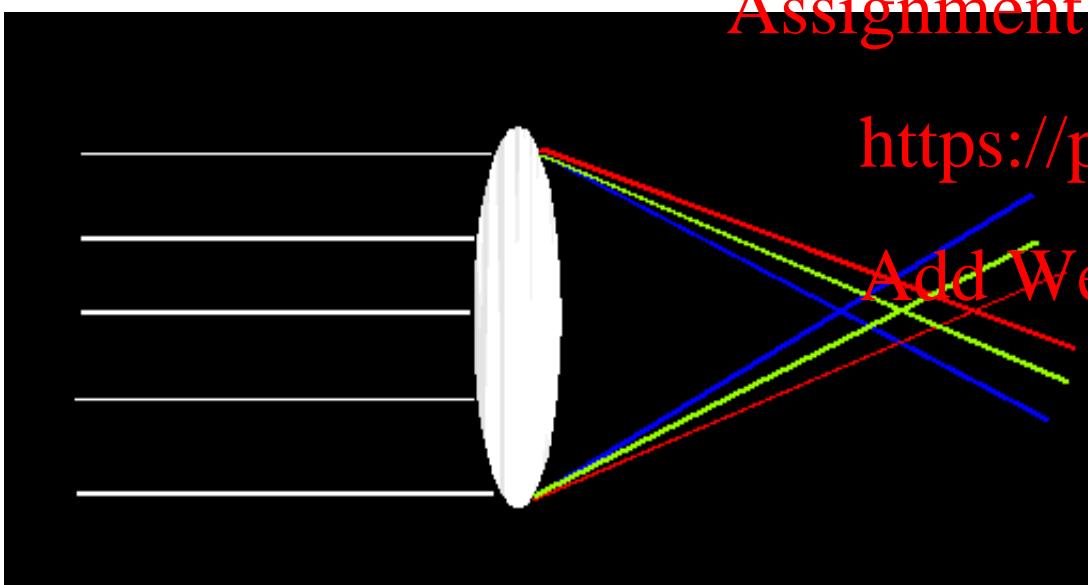
- Spherical lenses don't focus light perfectly
- Rays farther from the optical axis focus closer

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Lens flaws: Chromatic Aberration

- Lens has different refractive indices for different wavelengths: causes color fringing



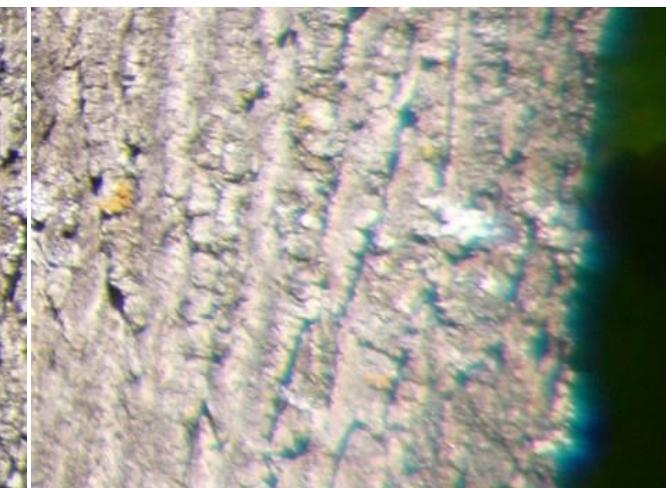
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Near Lens Center

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Near Lens Outer Edge



Content

- The pinhole projection model
 - Geometric properties
 - Perspective projection matrix
- Cameras with lenses
 - Depth of focus
 - Field of view
 - Lens aberrations
- Digital sensors

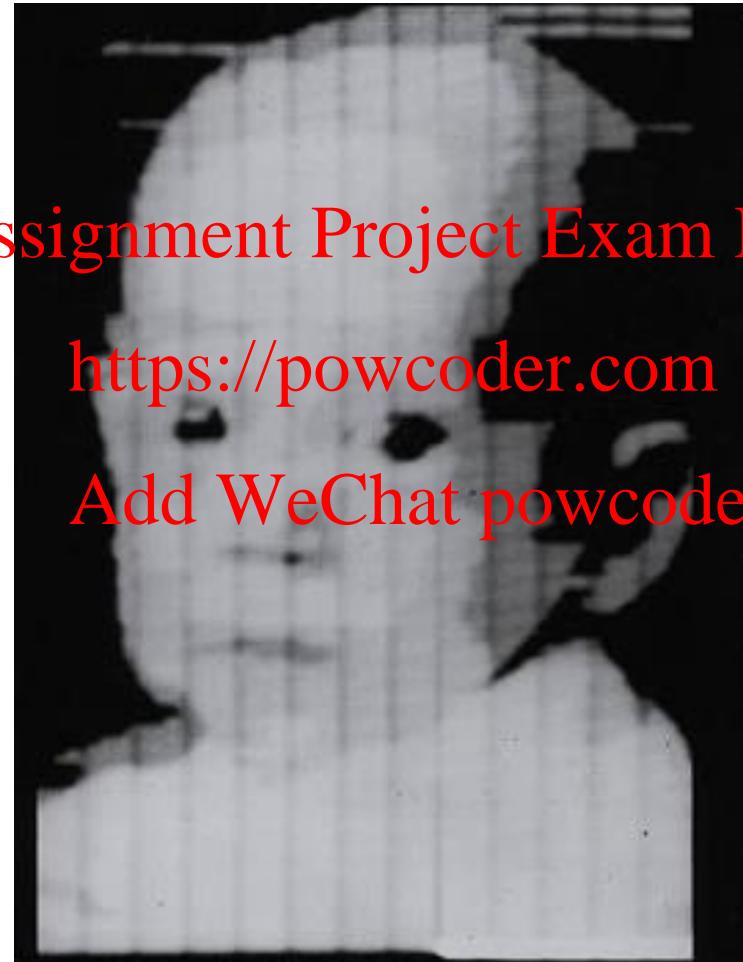
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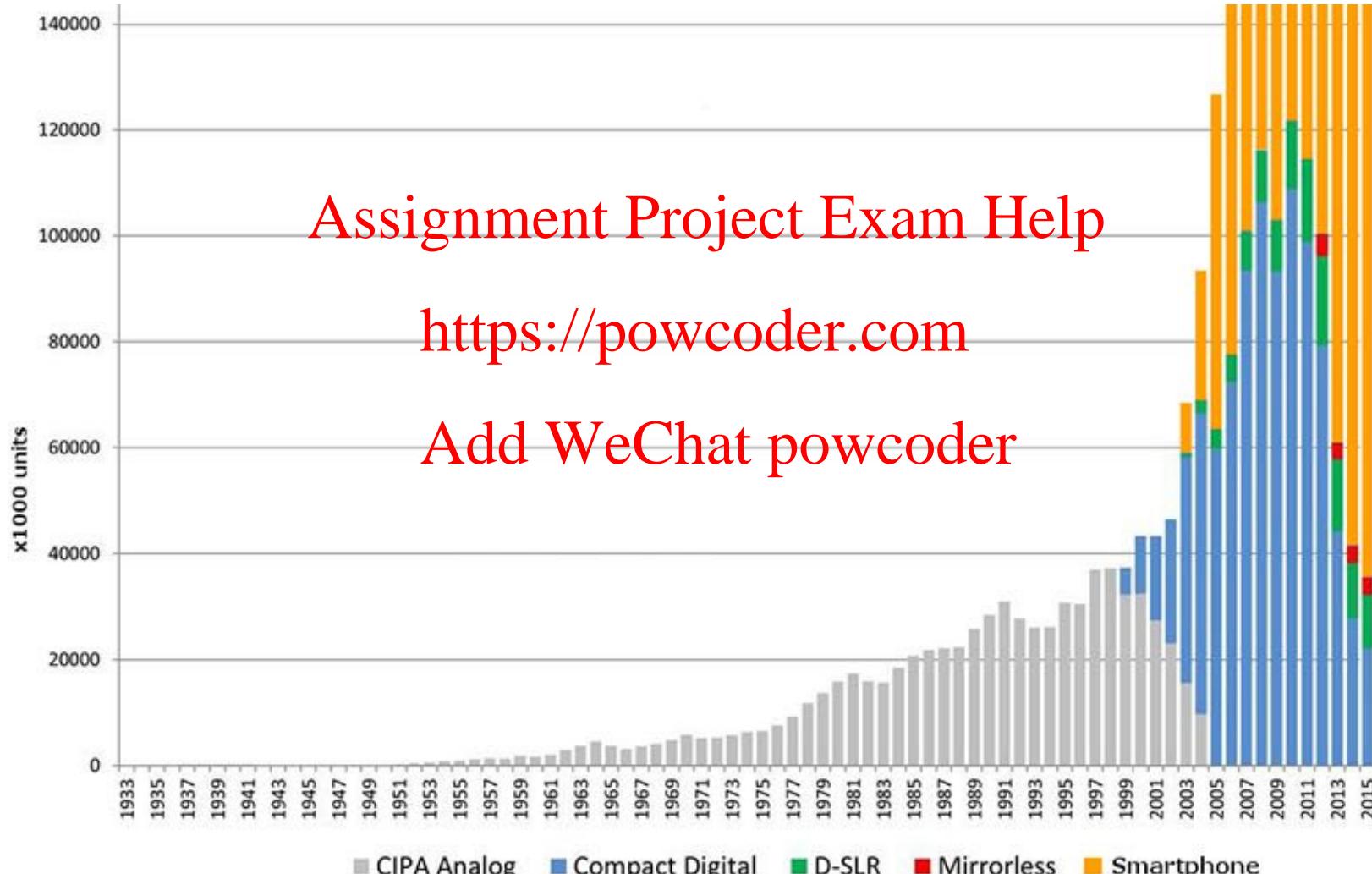
First digitally scanned photograph

- 1957, 176x176 pixels



<http://listverse.com/history/top-10-incredible-early-firsts-in-photography/>

Camera sales over time



Camera sales over time

- The full chart...



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Digital cameras

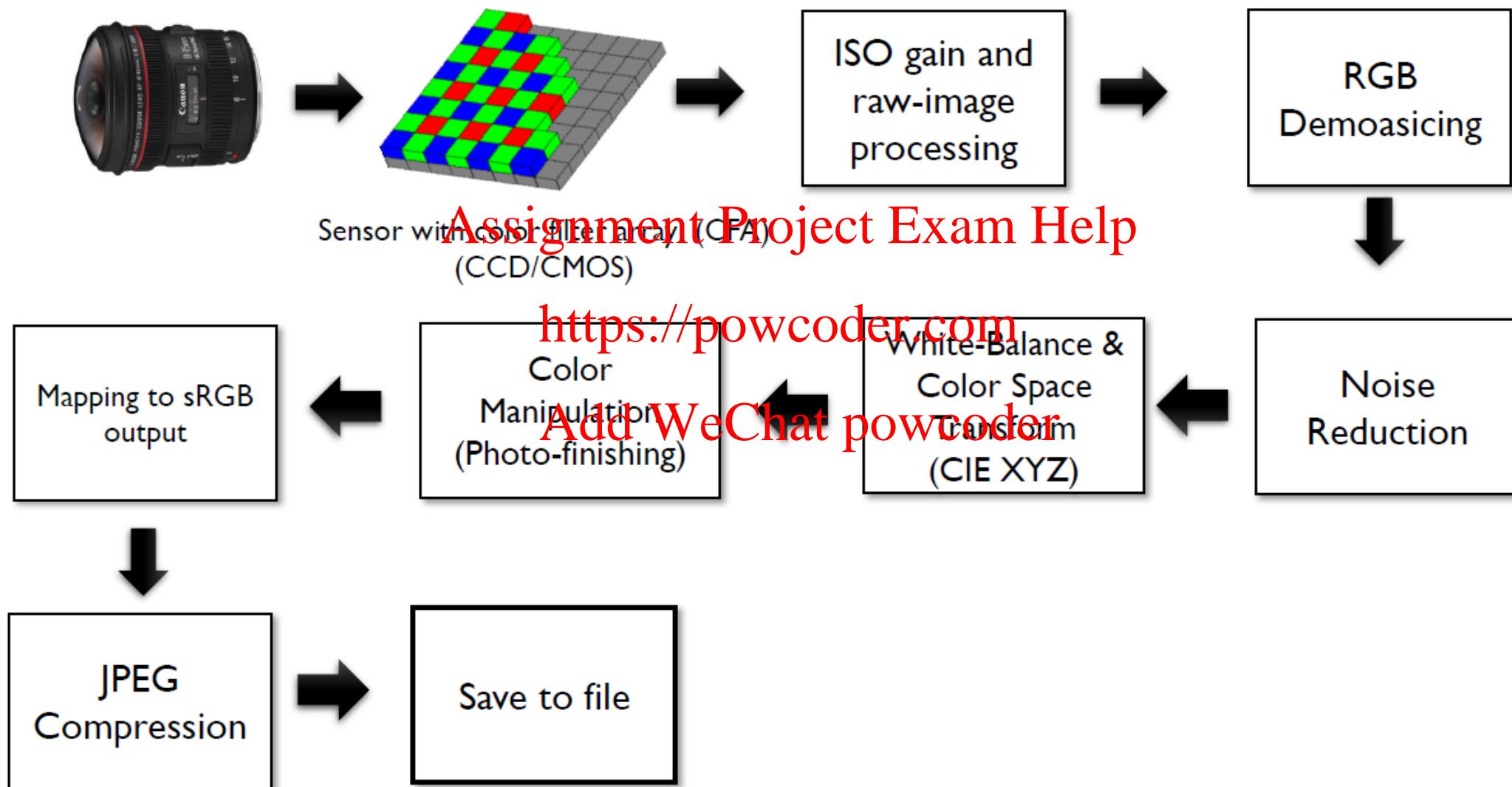
- Digital cameras are not designed to be light measuring devices
- They are designed to produce visually pleasing photographs
- There is a great deal of processing (photo finishing) applied in the camera hardware

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Modern photography pipeline



Source: M. Brown

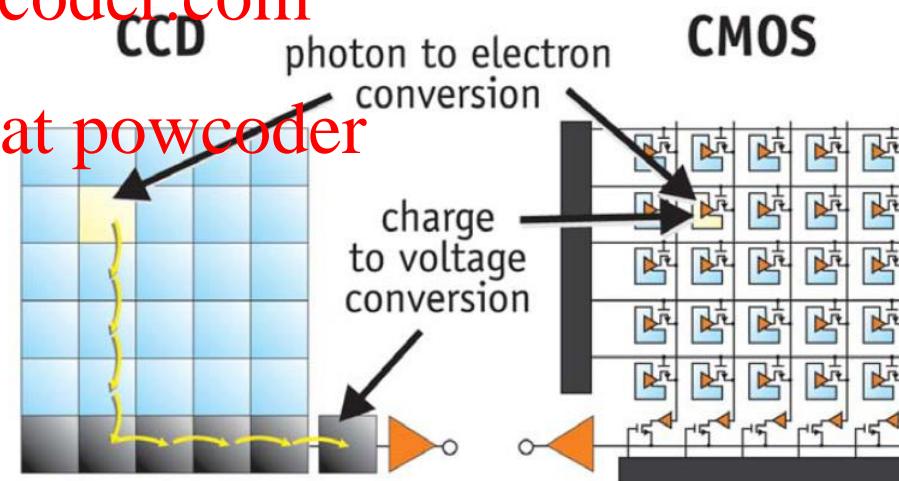
Digital camera sensors

- Each cell in a sensor array is a light-sensitive diode that converts photons to electrons
 - Dominant in the past: Charge Coupled Device (CCD)
 - Dominant now: Complementary Metal Oxide Semiconductor (CMOS)
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<https://powcoder.com>

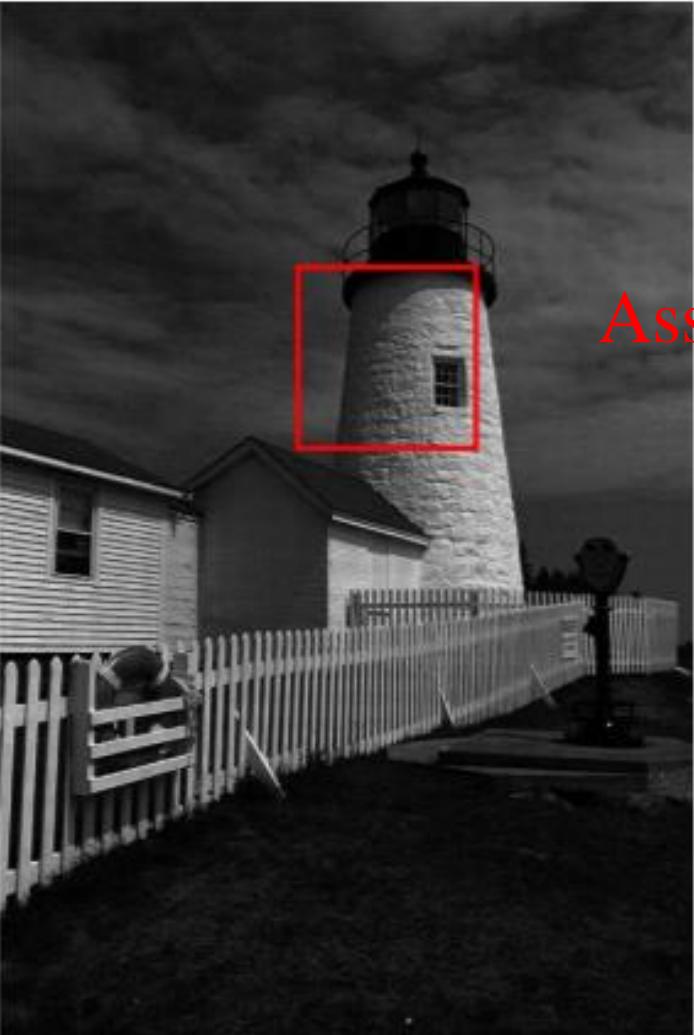
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CCDs move photogenerated charge from pixel to pixel and convert it to voltage at an output node. CMOS imagers convert charge to voltage inside each pixel.

<http://electronics360.globalspec.com/article/9464/ccd-vs-cmos-the-shift-in-image-sensor-technology>

What does a raw image look like?

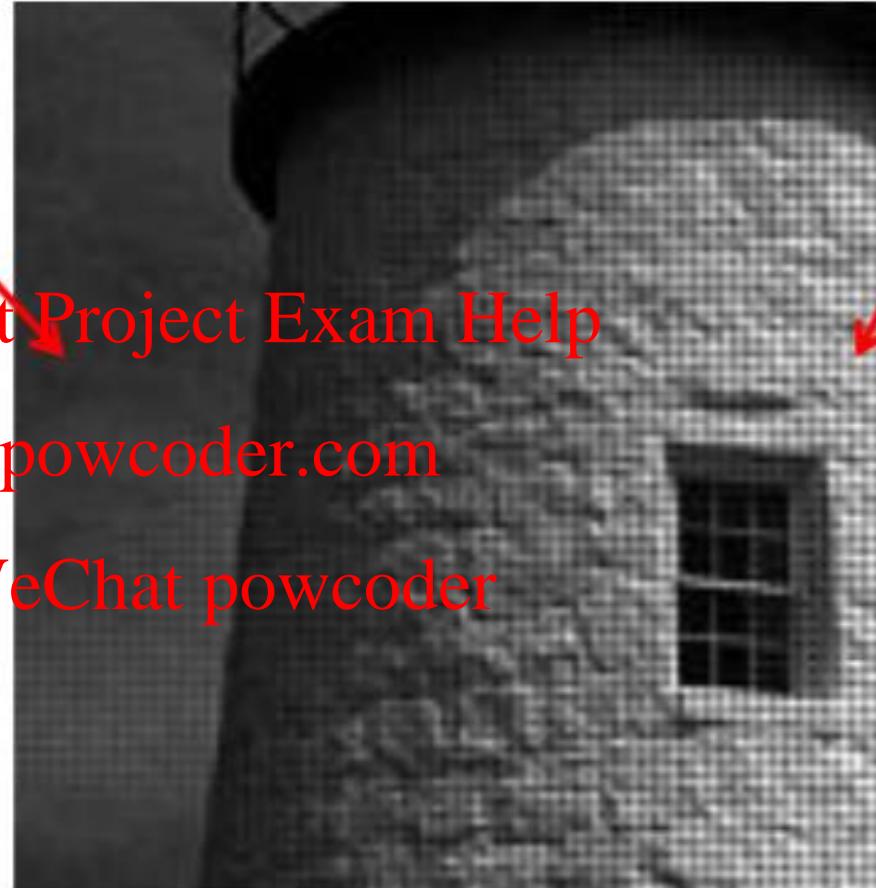


lots of
noise

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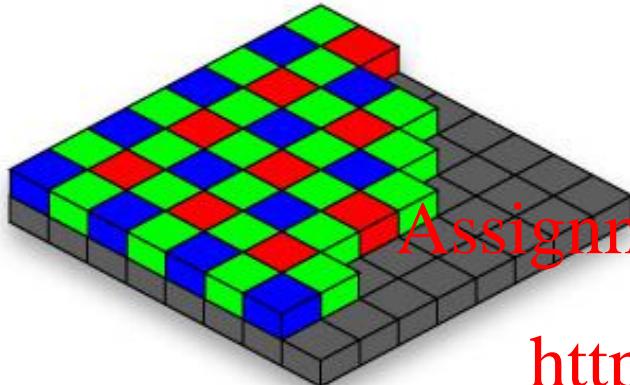


mosaicking
artifacts

- Kind of disappointing.
- We call this the *RAW* image.

Color filter arrays

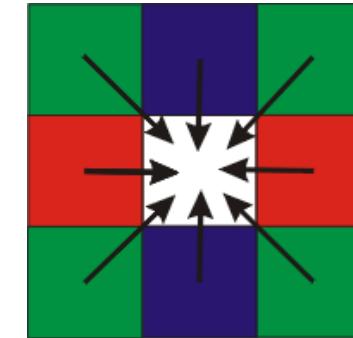
Bayer grid



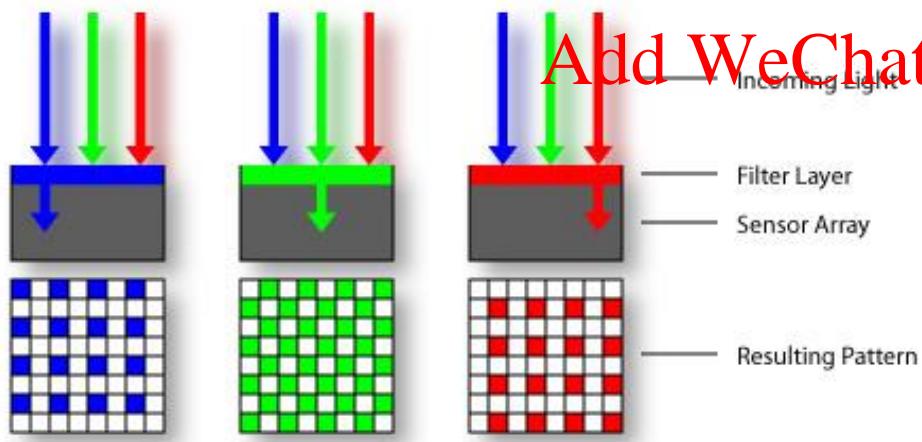
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Demosaicing:

Estimation of missing components from nei
ghbor values

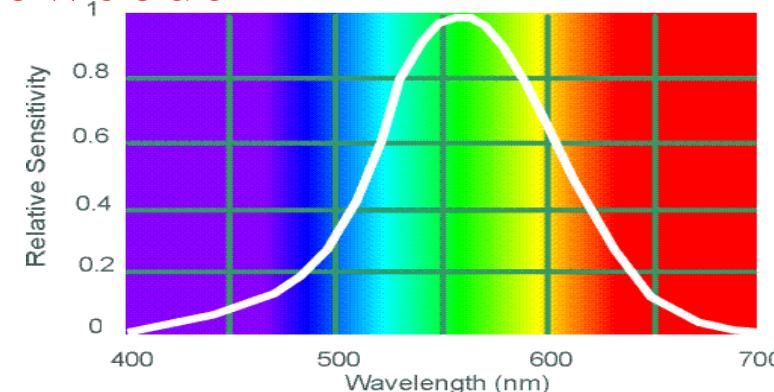


<https://powcoder.com>



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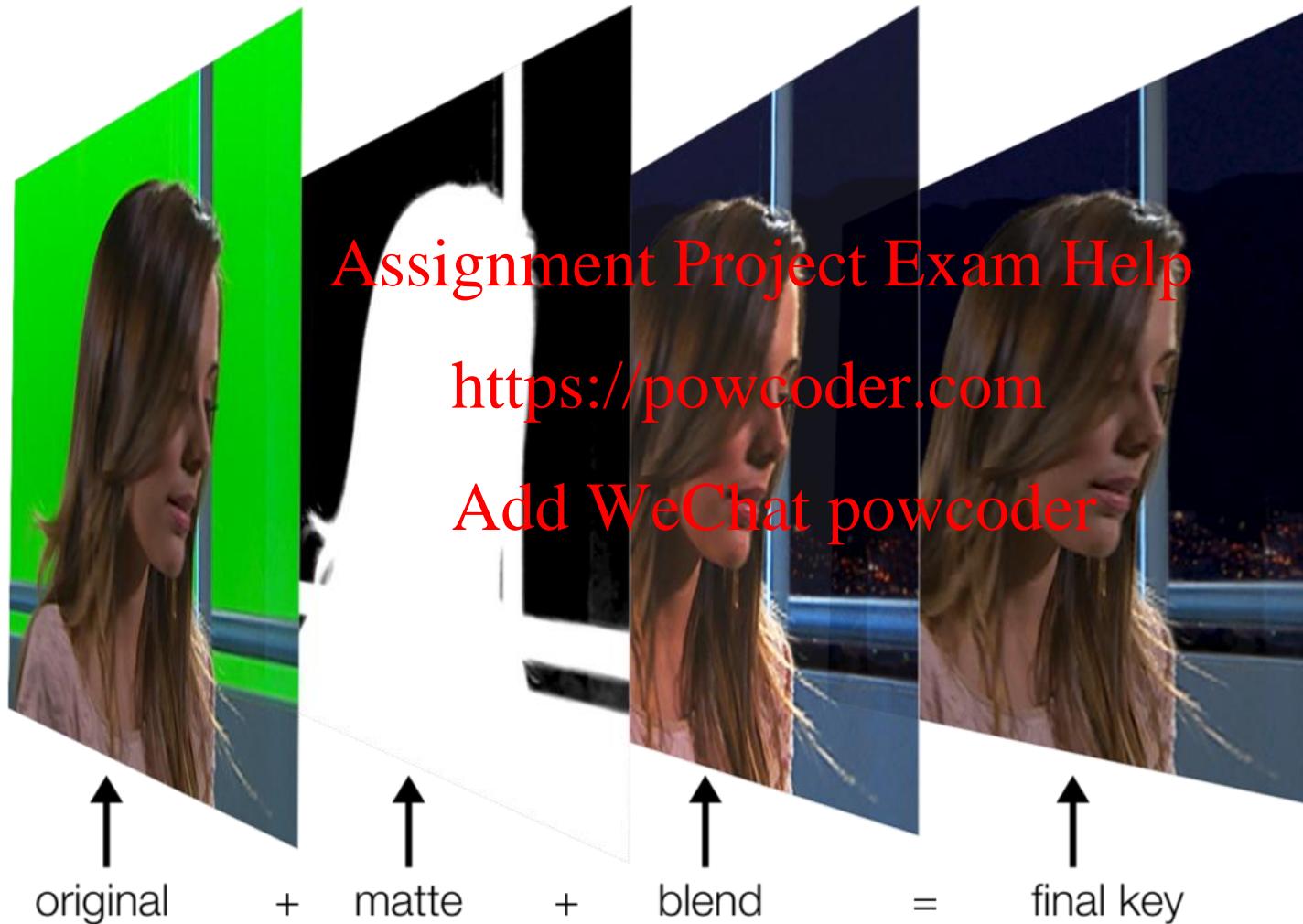
Why more green?



Human Luminance Sensitivity Function

Source: Steve Seitz

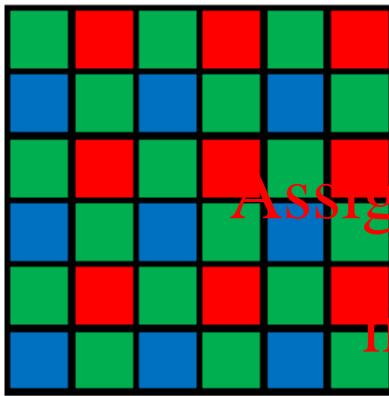
Virtual Background



<https://infocusfilmschool.com/filming-green-screen-guide/>

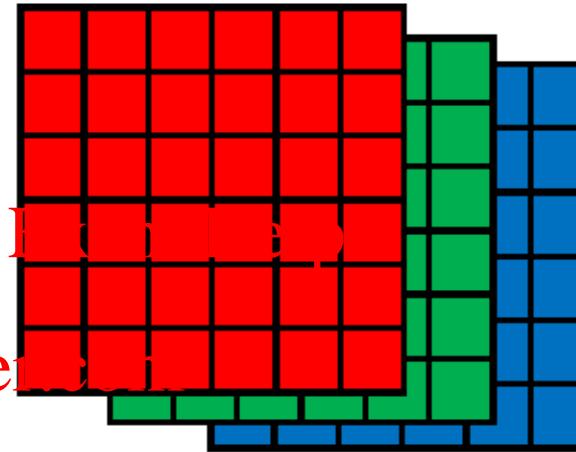
Demosaicing

- Producing full RGB image from mosaiced sensor output



Assignment Project I: Demosaicing

<https://powcoder.com>

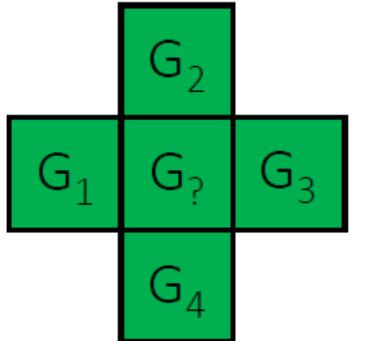


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- Interpolate from neighbors:
 - Bilinear interpolation (needs 4 neighbors).
 - Bicubic interpolation (needs more neighbors, may overblur).
 - Edge-aware interpolation.
 - Large area of research.

Demosaicing

- Bilinear interpolation: Simply average your 4 neighbors.

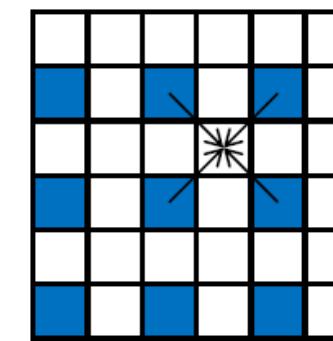
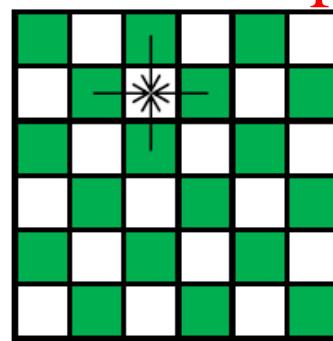
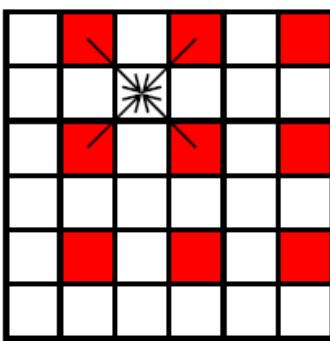


$$G_? = \frac{G_1 + G_2 + G_3 + G_4}{4}$$

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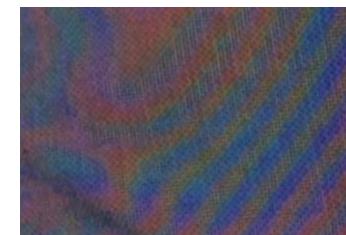
<https://powcoder.com>

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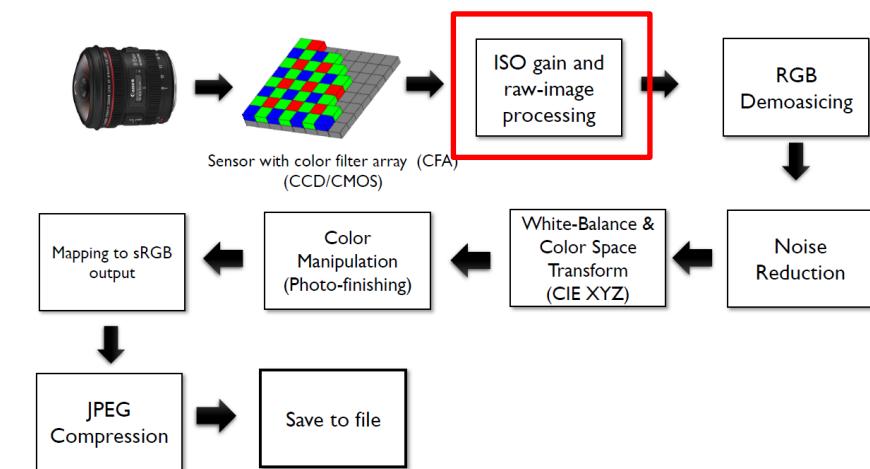


Digital camera artifacts

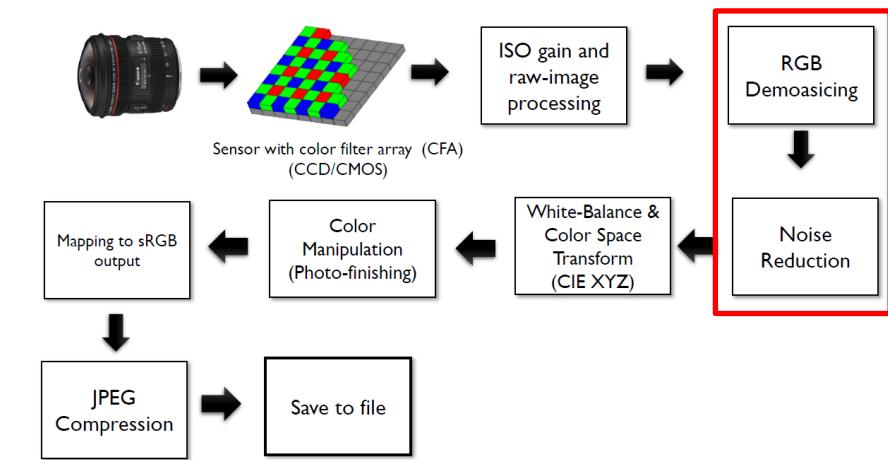
- **Noise**
 - low light is where you most notice noise
 - light sensitivity (ISO) / noise tradeoff
 - stuck pixels
- **In-camera processing** [Assignment](#) [Project](#) [Exam](#) [Help](#)
<https://powcoder.com>
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- **Compression**
 - JPEG artifacts, blocking
- **Blooming**
 - CCD charge overflowing into neighboring pixels
- **Color artifacts**
 - Color moire
 - Purple fringing from microlenses



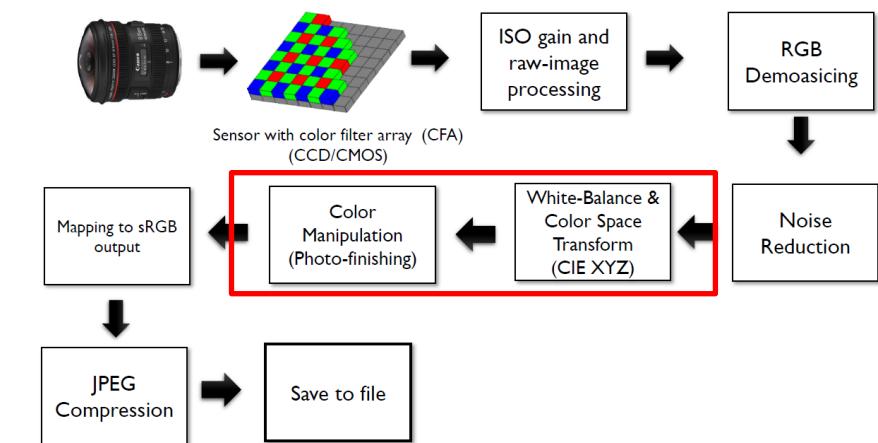
Walking through the pipeline



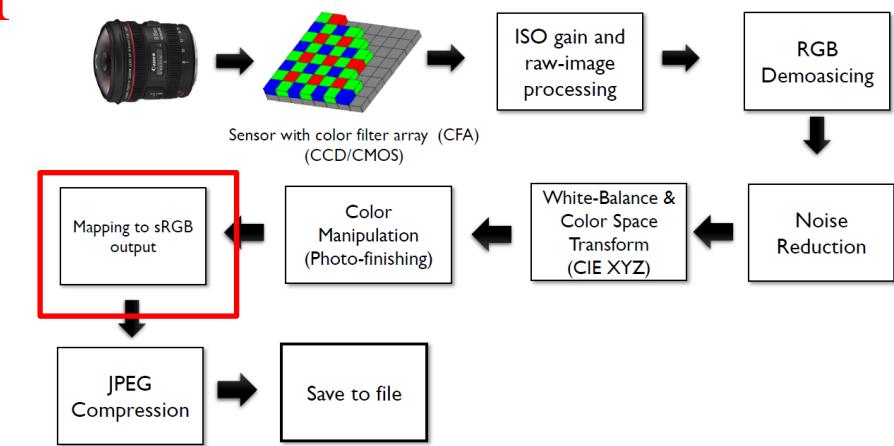
Walking through the pipeline



Walking through the pipeline



Walking through the pipeline

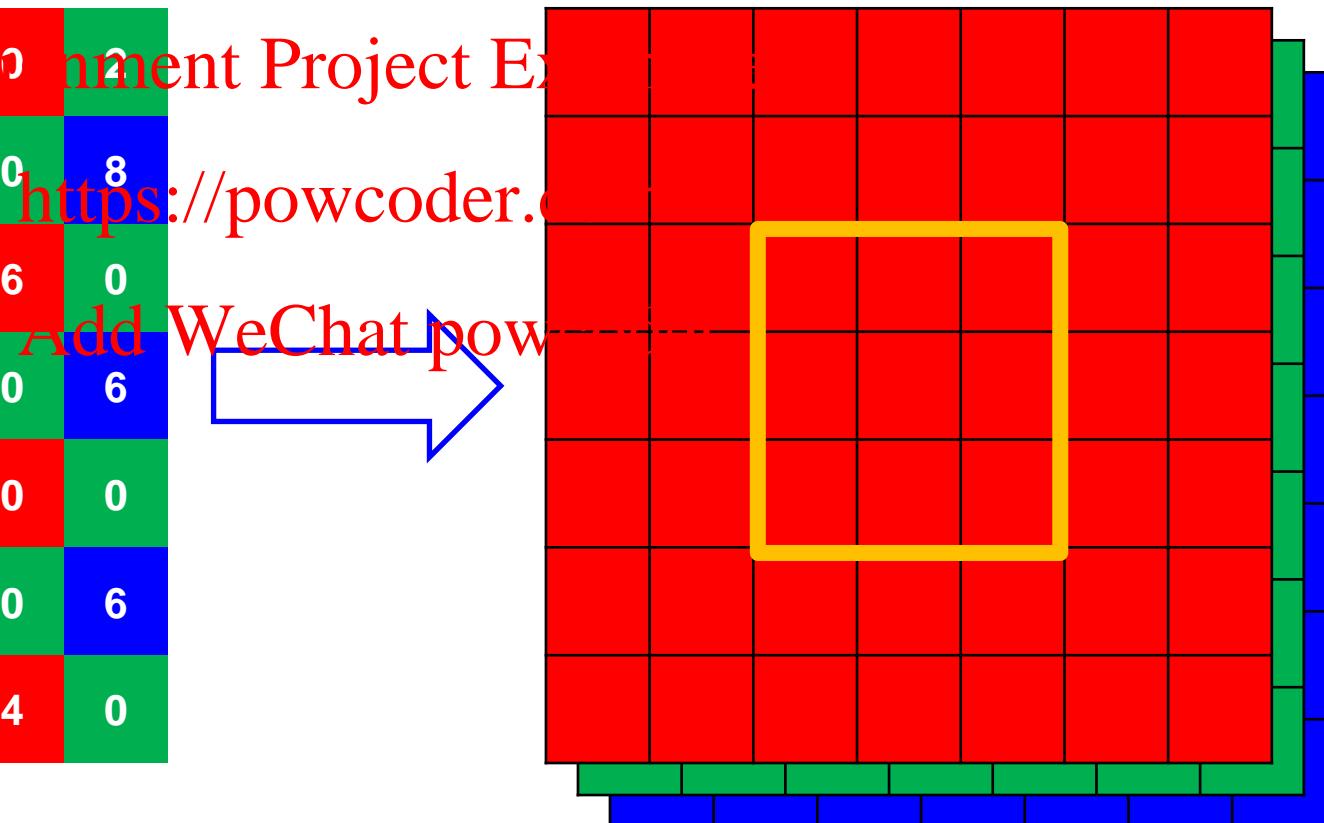


Quiz

- A Bayer filter mosaic is a color filter array (CFA) for arranging RGB color filters on a square grid of photo sensors. Figure 1 shows a raw image obtained by the Bayer pattern CFA where each pixel includes the R or G or B value. Perform image demosaicing to the image region in orange box using bilinear interpolation and provide each pixel's RGB value, (R, G, B) of the 3×3 image.

4	2	8	10	As	0	7	1	1
8	8	8	2	6	0	8	1	1
0	2	2	4	2	6	0	1	1
8	0	8	10	8	0	6	1	1
0	2	0	2	0	0	0	1	1
10	0	8	0	8	0	6	1	1
0	2	0	2	0	4	0	1	1

Figure 1



Next topic

- **How can we remove artifacts in images?**
 - Prerequisite
 - Review EBU6230 Image/Video Processing - Week2: Image Filtering

Assignment Project Exam Help

<https://powcoder.com>

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