Digital Photography Concepts

Reading: Chapters 2 and 3 in "*Photography*" by London *et al.*

Some slides by Perry Kivolowitz (UW), Fredo Durand (MIT), Alexei Efros (CMU), and Steve Seitz (U Washington)

Outline

I. Types of (digital) cameras
II. Controlling exposure
III. Camera shooting modes
IV. Picture modes
V. Controlling the view

Types of Digital Cameras: Point-and-Shoot

- Small – portable and convenient
- Simple – maximize automation, ease-of-use
- Good for:
  - Beginners
  - All-around camera
  - Travel

Photo: Canon web site

Types of Digital Cameras: DSLR

- Maximum flexibility / creative potential
- Interchangeable lenses
- "Raw" shooting mode
- Good for:
  - Advanced users
- Features:
  - Live preview / EVF (Electronic ViewFinder)
  - HD movie recording
  - HDR mode

Photo: dpreview.com

DSLR Viewfinder

- Reflex (R in DSLR) means that we see through the same lens used to take the image

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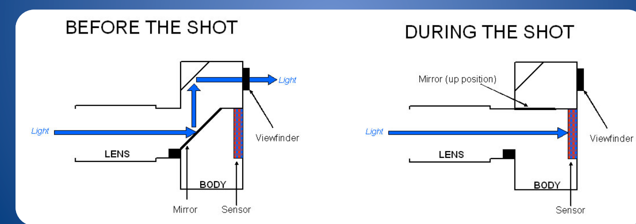
Types of Digital Cameras: DSLR – Single Lens Reflex

- Mirror down – compose shot through actual lens
- Mirror up – take shot



Drawing: techlore.com

Types of Digital Cameras: Smartphones

- By 2003 more phone cameras were sold worldwide than stand-alone digital cameras (replacing point-and-shoot)
- By 2017, an estimated 80% of all photos will be taken by mobile phones
- Include Wi-Fi, GPS, accelerometer, magnetometer, …

Smartphone Camera Characteristics

- Small sensors
  - Area: 25 mm^2 to 43 mm^2
  - Very small pixels: 1 – 2 μm horizontal and vertical
  - Resolution: 5 – 40 megapixels
- Fixed aperture: f/2.0 to f/2.4
- Fixed focal length: 24 – 30 mm (wide-angle lens)
- Auto-focus usually in software (maximize contrast between adjacent pixels)
- Image stabilization

DSLR Camera Characteristics

- Large sensors
  - Area: 300 – 800 mm^2 (about 50 times larger than smartphone cameras)
  - Large pixels: 4 – 8 µm (about 6 times larger than smartphone cameras)
  - Better in low light, less noise, lower crosstalk between pixels
  - High resolution
- Interchangeable lenses (adjustable focal length)
- Adjustable aperture
- Faster, more accurate auto-focus
- Better light metering
- Big, heavy

Outline

I. Types of (digital) cameras
II. Controlling exposure
III. Camera shooting modes
IV. Picture modes
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Controlling Exposure

Exposure: How much light falls on sensor

Too much

Too little

Good exposure is a compromise:
Giving up something to get something else

Controlling Exposure: What are your Tools?

Controlling Exposure: What are your Tools?

I. Shutter speed
   How long sensor is exposed to light
II. Aperture
   How much light can pass thru in any period of time
III. Sensitivity
   How much light needed to cause response in sensor
IV. Lighting
   How much light is illuminating scene

Controlling Exposure: Shutter Speed

- Shutter is a device controlling light's access to the sensor – could be mechanical or electronic
- Fraction of second that shutter is open, expressed in powers of 2
  - 1/4000, 1/2000, 1/1000, 1/500, 1/250, 1/125, 1/60, 1/30, 1/15, 1/8, ¼, ½, 1
- Faster shutter (e.g. 1/500th sec) = less light
- Slower shutter (e.g. 1/30th sec) = more light
- Typical DSLR range: "B" to 1/4000th sec

Controlling Exposure: Shutter Speed

Fast shutter = freeze action

Slow shutter = more light, but blurs motion (object or camera)

Photos: David Hofmann - http://www.pbase.com/david_hofmann/swans_in_motion

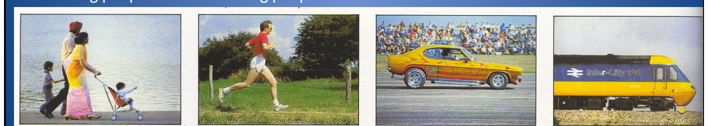
"Fireworks" Photography

- Method: Twist the focus ring on camera during a long (1 -2 sec) exposure!

Effect of Shutter Speed

- Freezing motion

Walking people	Running people	Car	Fast train



1/125	1/250	1/500	1/1000

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Shutter Speed and Focal Length

- Because telephoto lenses “magnify,” they also magnify your hand shaking
- Telephotos therefore require a faster shutter speed
- Rule of thumb:
  - The slowest shutter speed where normal human can hand-hold and get a sharp picture is 1/f
  - E.g., a 500mm lens requires 1/500 sec or higher
- Solution: Image stabilization
  - mechanically compensates for vibration
  - Can gain 2 or 3 shutter speeds (1/125 or 1/60 for a 500mm)

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Your Best Friend

- Use a tripod! It will always enhance sharpness

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Controlling Exposure: Aperture

- Defined as an opening, we’re more concerned with the ***size*** of the opening
- Big opening = more light
- Small opening = less light
- Quantifying the opening size?
  - Called **f-number** or **f-stop**

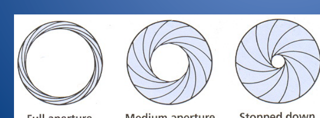


Photo: http://en.wikipedia.org/wiki/File:Aperures.jpg

Controlling Exposure: Aperture – f-number

- Bigger number = smaller opening = less light
- Smaller number = bigger opening = more light
- 1, 1.4, 2, 2.8, 4, 5.6, 8, 11, 16, 22, 32, 45, 64, …
- Values available are *lens dependent*
- Smallest f-number available on a lens indicates its relative "speed"
  - Cheaper lens = larger smallest f-number = slower
  - Pricier lens = smaller smallest f-number = faster
  - eBay: a 2.8 28mm = $160, a 1.4 28mm = $3,995

Controlling Exposure: Aperture – f-number

- Measures the **diameter** of the lens opening
- **f-number** is a ***ratio*** of the lens's *focal length* to its aperture *diameter*
  - f/2.0 on 50mm lens means the aperture diameter is 25mm
  - f/2.0 on a 100mm lens means the aperture is 50mm
- What happens to the ***area*** of the aperture when going from f/2.0 to f/4.0, say when focal length = 50 mm?
  - What is diameter of the aperture in each case?

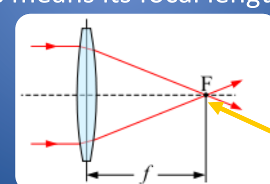
Drawing: http://upload.wikimedia.org/wikipedia/commons/8/8b/Focal-length.svg

Controlling Exposure – Aperture

- Example: 50 mm lens (i.e., focal length = 50 mm)
- f/2.0 ➔ diam = 50/2 = 25; area = $(\pi/4)(25)^2 \approx 490$ mm²
- f/2.8 ➔ diam = 50/2.8 = 17.9; area ≈ 250 mm^2
- f/4 ➔ diam = 50/4 = 12.5; area ≈ 123 mm^2
- **Each f-stop halves/doubles the *area* of aperture**
- So, a change of 2 stops results in 2^2 = 4x increase in *area* of the aperture
- Zoom lenses usually have a *variable* maximum aperture size

Focal Length

- The **focal length** of a lens is a measure of how strongly the lens converges light (in air)
- Distance (in mm) over which parallel rays of light are brought to a focus
- A 50 mm lens means its focal length is 50 mm



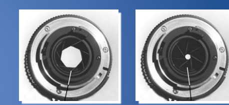
Focal point of the lens

Exposure — Reciprocity

- Two main parameters / settings:
  - Aperture (f-number)
  - Shutter speed (fraction of a second)
- **Reciprocity**
  - **The same exposure is obtained with an exposure twice as long and an aperture *area* half as big**
  - Hence square root of 2 progression of f-stops vs. power of 2 progression of shutter speed
  - N.B. Reciprocity may *not* be accurate for very long exposures

Ways to Vary Exposure

- Shutter speed
- F-stop (aperture)
- Neutral Density (ND) filters
- ISO



Exposure $X = E\,t$, *where E is irradiance and t is shutter speed*

➔ Halving *E* and doubling *t* will *not* change exposure: *reciprocity* **property**

Exposure Value (EV)

- Combinations of shutter speeds and apertures that give the *same exposure* (= irradiance × time) (reciprocity property)

EV = $\log_2 \frac{N^2}{t}$ where *N* = f-number, *t* = shutter speed

1/1000	@	f/1.4
1/500	@	f/2
1/250	@	f/2.8
1/125	@	f/4
1/60	@	f/5.6
1/30	@	f/8
1/15	@	f/11
1/8	@	f/16
1/4	@	f/22

- Each increment in speed or aperture is called a “stop”
- Similarly, doubling the ISO value means it is twice as sensitive, so 1/125 @ ISO 400 = 1/250 @ ISO 800

Many Ways to get the Same Exposure

EV	f-number												
	1.0	1.4	2.0	2.8	4.0	5.6	8.0	11	16	22	32	45	64
−6	60	2 m	4 m	8 m	16 m	32 m	64 m	128 m	256 m	512 m	1024 m	2048 m	4096 m
−5	30	60	2 m	4 m	8 m	16 m	32 m	64 m	128 m	256 m	512 m	1024 m	2048 m
−4	15	30	60	2 m	4 m	8 m	16 m	32 m	64 m	128 m	256 m	512 m	1024 m
−3	8	15	30	60	2 m	4 m	8 m	16 m	32 m	64 m	128 m	256 m	512 m
−2	4	8	15	30	60	2 m	4 m	8 m	16 m	32 m	64 m	128 m	256 m
−1	2	4	8	15	30	60	2 m	4 m	8 m	16 m	32 m	64 m	128 m
0	1	2	4	8	15	30	60	2 m	4 m	8 m	16 m	32 m	64 m
1	1/2	1	2	4	8	15	30	60	2 m	4 m	8 m	16 m	32 m
2	1/4	1/2	1	2	4	8	15	30	60	2 m	4 m	8 m	16 m
3	1/8	1/4	1/2	1	2	4	8	15	30	60	2 m	4 m	8 m
4	1/15	1/8	1/4	1/2	1	2	4	8	15	30	60	2 m	4 m
5	1/30	1/15	1/8	1/4	1/2	1	2	4	8	15	30	60	2 m
6	1/60	1/30	1/15	1/8	1/4	1/2	1	2	4	8	15	30	60
7	1/125	1/60	1/30	1/15	1/8	1/4	1/2	1	2	4	8	15	30
8	1/250	1/125	1/60	1/30	1/15	1/8	1/4	1/2	1	2	4	8	15
9	1/500	1/250	1/125	1/60	1/30	1/15	1/8	1/4	1/2	1	2	4	8
10	1/1000	1/500	1/250	1/125	1/60	1/30	1/15	1/8	1/4	1/2	1	2	4
11	1/2000	1/1000	1/500	1/250	1/125	1/60	1/30	1/15	1/8	1/4	1/2	1	2
12	1/4000	1/2000	1/1000	1/500	1/250	1/125	1/60	1/30	1/15	1/8	1/4	1/2	1
13	1/8000	1/4000	1/2000	1/1000	1/500	1/250	1/125	1/60	1/30	1/15	1/8	1/4	1/2
14		1/8000	1/4000	1/2000	1/1000	1/500	1/250	1/125	1/60	1/30	1/15	1/8	1/4
15			1/8000	1/4000	1/2000	1/1000	1/500	1/250	1/125	1/60	1/30	1/15	1/8
16				1/8000	1/4000	1/2000	1/1000	1/500	1/250	1/125	1/60	1/30	1/15

Exposure and Metering

- Photosensitive sensors measure scene luminance
- The camera metering system measures how bright the scene is (scene "luminance")
- Most cameras then use a center-weighted average
  - Can fail if scenes are very light or very dark

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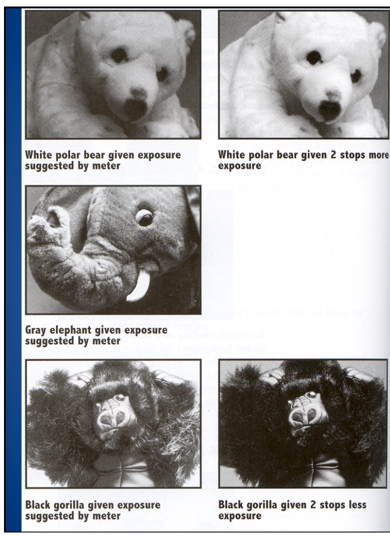
Metering

- Photosensitive sensors measure scene luminance
- Usually TTL (Through The Lens)
- Simple version: center-weighted average

- Assumption? Failure cases?
  - Usually assumes that a scene is 18% gray
  - Problem with dark and bright scenes



White polar bear given exposure suggested by meter

White polar bear given 2 stops more exposure

Gray elephant given exposure suggested by meter

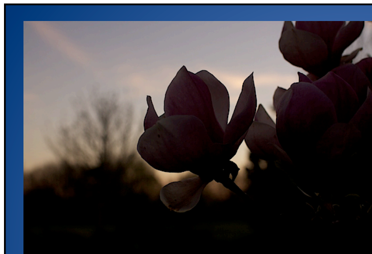
Black gorilla given exposure suggested by meter

Black gorilla given 2 stops less exposure

From *Photography*, London et al.

Controlling Exposure: Sensitivity

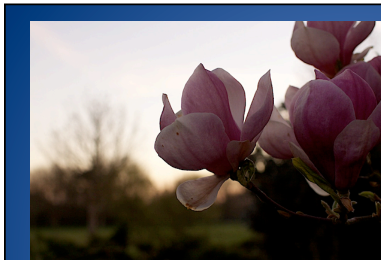
- Sensor is a grid of photosites (pixels), each one a photodiode that absorbs photons and releases electrons; electrons are accumulated and quantized into pixel intensity values
- ISO is a measure of the "film/sensor speed," i.e., sensor's sensitivity to light (in digital cameras it sets the signal ***gain*** of the sensor)
- 100, 200, 400, 800, 1600, 3200, …
- Higher the ISO number, the less light is required to produce an image ➔ High ISO is good for indoor / low light
- ***Linear effect – Doubling ISO, doubles exposure***
  - But doubles the digital noise in the image
- Lower number = Lower sensitivity = Finer quality photos
  - High ISO produces images that are "grainy" and have less detail



ISO 100

ISO 200

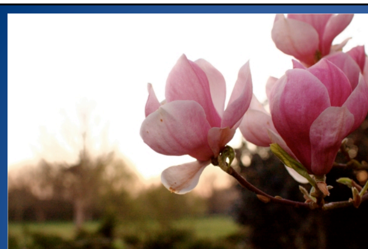
Source: Josh Dunlop



ISO 400

ISO 800

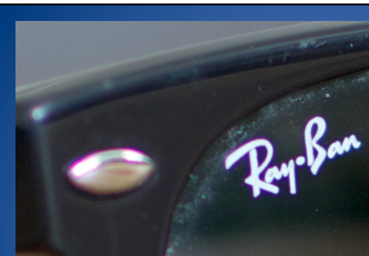
Source: Josh Dunlop



ISO 1600

ISO 3200

Source: Josh Dunlop



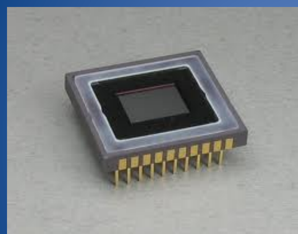
ISO 100

Notice: More "grainy" noise in high ISO photo

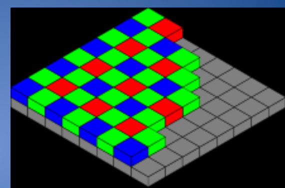
ISO 3200

Source: Josh Dunlop

Digital Image Sensor

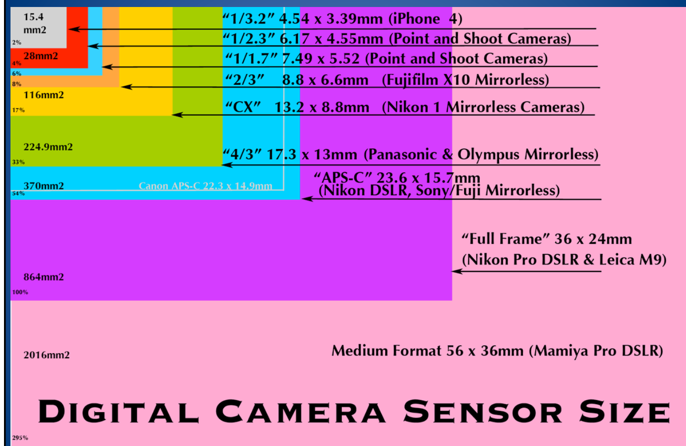


CCD or CMOS sensor array



Bayer sensor (color filter array)

- Sensor parameters include dynamic range, low-light sensitivity, and signal-to-noise ratio



Setting Exposure

f/1 1.4 2 2.8 4 5.6 8 11 16 22 32 45 …

← Illumination increases by factor of 2

→ Less light captured but increasing depth of field

t = 1 ½ ¼ 1/8 1/15 1/30 1/60 1/125 1/250 …

← Illumination increases by factor of 2

→ Less light captured but less motion blur

Question: When creating an HDR image, why did we vary the shutter speed and *not* the aperture?

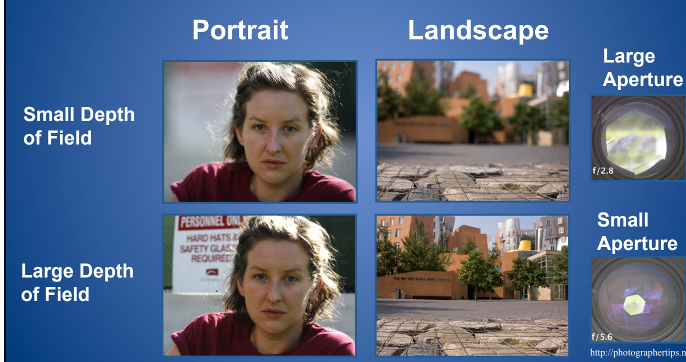
Controlling Exposure: Aperture: Depth of Field

- Aperture also controls "depth of field" (DOF)
- If you focus at *d* feet, DOF is a range in front and behind that is also "acceptably" focused
- Bigger f-number = larger DOF

f/32 f/5.6

Photo: http://en.wikipedia.org/wiki/Depth_of_field

Depth of Field Control



Outline

I. Types of (digital) cameras
II. Controlling exposure
III. Camera shooting modes
IV. Picture modes
V. Controlling the view

Camera Shooting Modes

- Many ways to achieve a "correct" exposure
- Basic shooting modes favor one aspect over another

Camera Shooting Modes: Shutter Priority (S)

- You pick the shutter speed
- Camera picks the aperture
- Utilizes reciprocity property
- You control how much motion blur – choosing between freezing action or blurring it
- Can require an impossible aperture since aperture is more restricted

Camera Shooting Modes: Aperture Priority (A)

- You choose aperture
- Camera chooses shutter speed
- You control the depth of field – choosing between isolating foreground or including background
- Can require an impossible shutter speed
- Often the preferred mode for professional photographers

Camera Shooting Modes: Automatic

- Camera chooses everything

Camera Shooting Modes: Manual

- Full control, but takes time and thought

Camera Shooting Modes: Some Fancier Modes

- Portrait mode
  - Chooses small aperture and adjusts shutter speed
- Sports mode
  - Chooses fast shutter speed and adjusts aperture
- Sunset mode
  - Chooses both then under-exposes
- Night mode
  - Fires flash, then exposes for background

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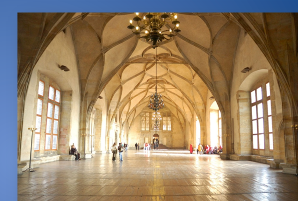
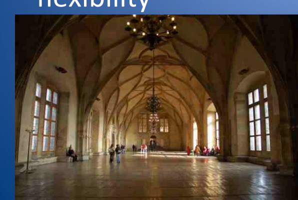
Picture Modes: JPEG

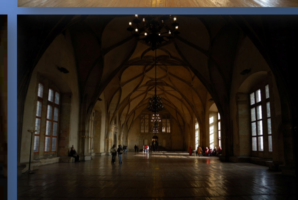
- A lossy compression method
- Usually 8 bits per color, 24 bits per pixel
- More loss = smaller file
- Shoot on "fine" – storage is cheap

Picture Modes: Raw

- A digital "negative"
- Usually loseless
- Large files
- MUCH greater flexibility







Many Other Image File Formats

- GIF
  – Only 8 bits per pixel (“256 colors”)
- PNG
  – Open source successor to GIF
- BMP
- TIFF
- PPM, PGM, PBM, PNM
- etc.

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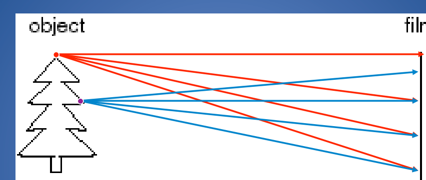
Controlling What we Image

- What set of rays of light do we capture in a single image?
- Determined by
  – **Viewpoint**: position and orientation of the camera in world, time when taken (often stored in image metadata from internal clock and GPS)
  – **View volume**: lens and camera projection determine how light rays project to pixels on sensor

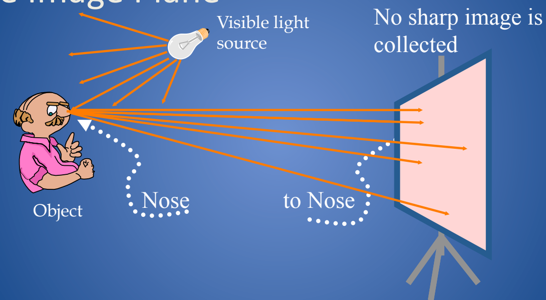
How do we See the World?



- Let’s design a camera
  – Idea 1: put a sensor in front of an object
  – Why don’t we get a good image?

Slide by Steve Seitz

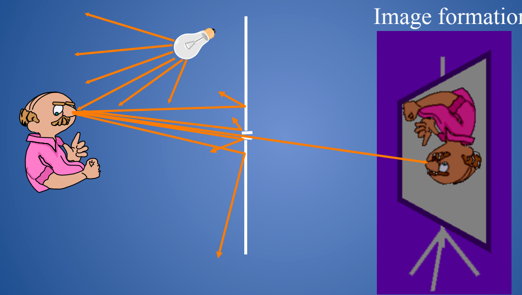
We want to Map each Point on an Object to ***One and Only One*** Point on the Image Plane



However, light from each point on the object ends up at ***ALL*** points on the image plane → complete blurring

Pinhole Optics:

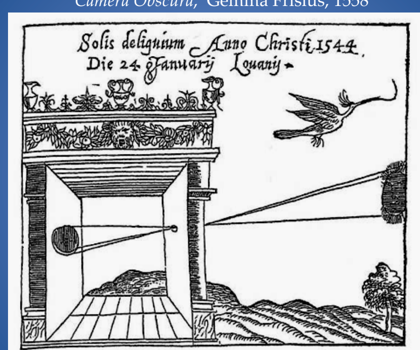
The pinhole allows 1:1 ray mapping



Barrier blocks most of the rays

Camera Obscura

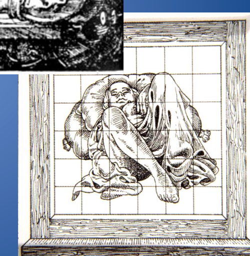
Camera Obscura, Gemma Frisius, 1558



- The first "camera"
  - Depth of the room is the **focal length**

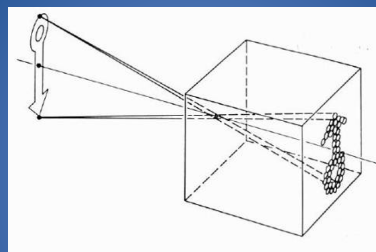
Alberti's "Grid"

Albrect Dürer (c. 1525)
Draughtsman drawing a reclining nude. Woodcut.



View through grid

Pinhole Camera Model

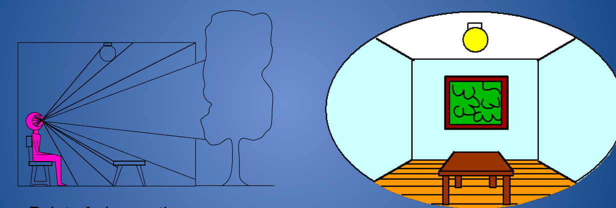


- **Pinhole model**:
  - Captures a **cone of rays** – all rays through a single point
  - The pinhole point is called **Center of Projection (COP)**
  - The image is formed on the **Image Plane**
  - **(Effective) Focal length** ***f*** is distance from COP to Image Plane
  - ***All scene points in perfect focus***

Slide by Steve Seitz

Dimensionality Reduction Machine (3D to 2D)

3D world   2D image



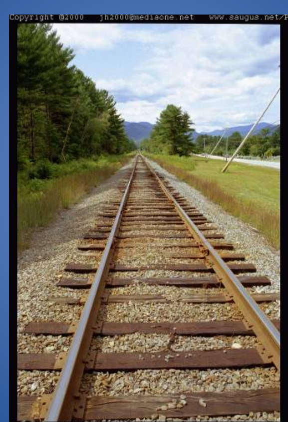
Point of observation

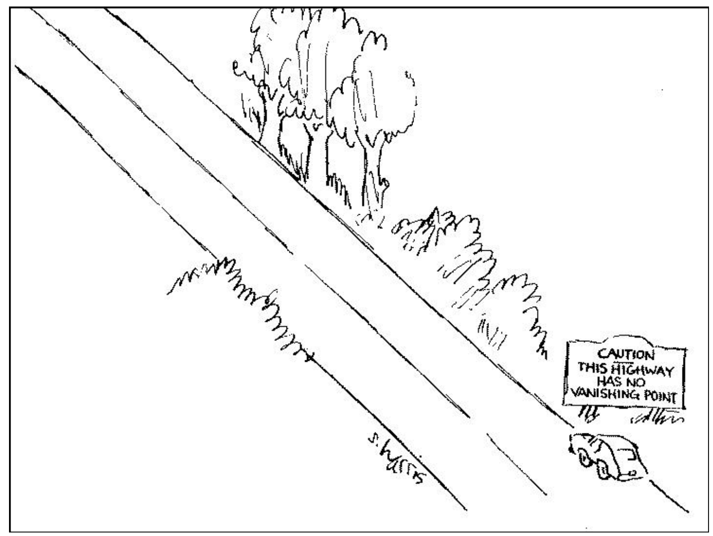
What have we lost?

- Angles
- Distances (lengths)

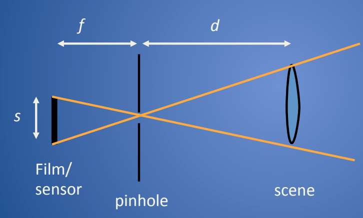
Figures © Stephen E. Palmer, 2002

Funny Things Happen





Focal Length: Pinhole Optics



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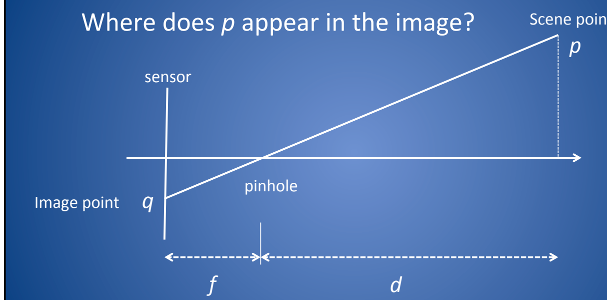
Focal Length: Pinhole Optics

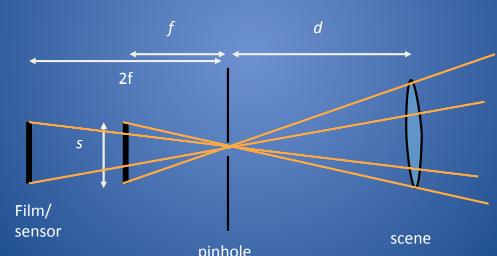
Where does *p* appear in the image?



$$q = (f/d)p$$

Focal Length: Pinhole Optics

- What happens when the focal length is *doubled*?
  - Projected object size doubles: $q = (2f/d)p$



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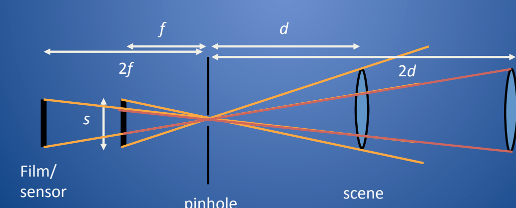
Focal Length: Pinhole Optics

- What happens when the focal length is *doubled*? $q = (2f/d)p$
- What happens when the scene is *twice* as far away? $q = (f/2d)p$
- How do we get the **same object size** when the focal length is doubled? $q = (2f/2d)p$
  - Is it equivalent to get closer and to shorten focal length?



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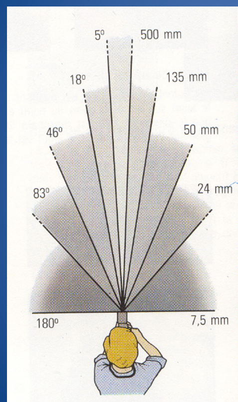
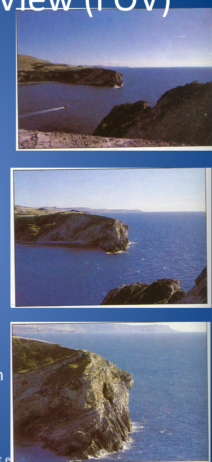
Focal Length and Field of View (FOV)



24mm

50mm

135mm



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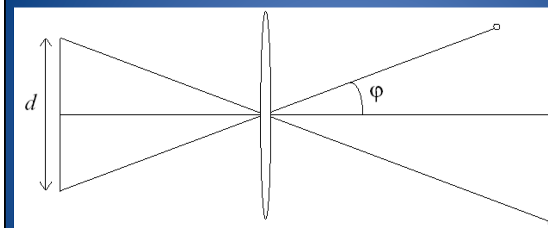
FOV depends on Focal Length *and* Sensor Size



d = sensor diagonal
f = focal length

Size of field of view governed by size of the camera retina:

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

Larger Focal Length ➔ Smaller FOV

Question: To get same field of view, how much bigger must sensor diameter be when the focal length doubles?

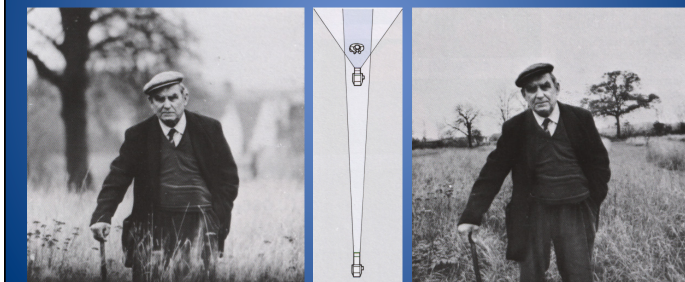
Answer: Double sensor diameter to capture same FOV

Human Eye

- Focal length: 0.017 m
- FOV (monocular): 160° (w) by 175° (h)
- Aperture: Pupil diameter range: 1 – 8 mm

FOV vs. Viewpoint

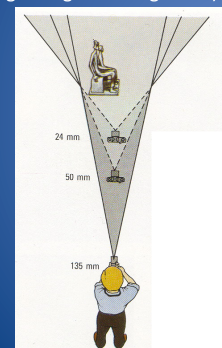
- Focal length NOT ONLY changes subject size
- Same size by moving the viewpoint (i.e., camera position), but different FOV (i.e., background)

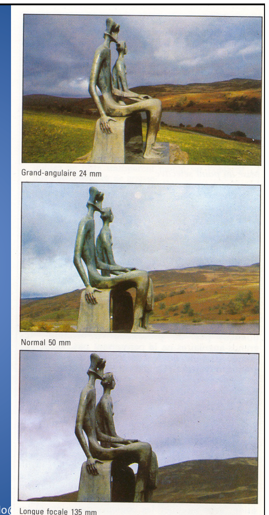


Snapshot-**Perspective**-Speed, aperture-Filter-Lighting-Processing & Print-Make up-Retouching

FOV vs. Viewpoint

- Telephoto makes it easier to select background (a small change in viewpoint is a big change in background)





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FOV vs. Viewpoint

- Portrait: distortion with wide angle lens (i.e., short focal length)
- Why?

Wide angle | Standard | Telephoto

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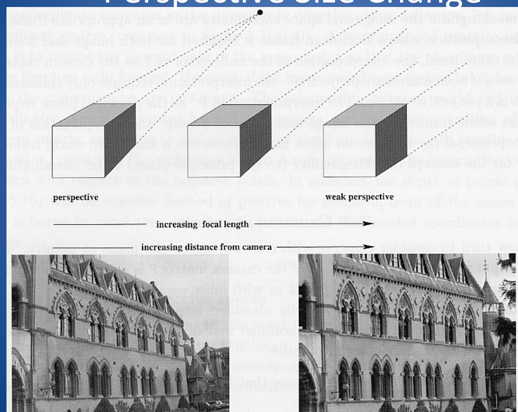
Large Focal Length Compresses Depth

400 mm | 200 mm | 100 mm | 50 mm | 28 mm | 17 mm

© 1995-2005 Michael Reichmann

Large Focal Length Shows Less Perspective Size Change



From Zisserman & Hartley

FOV vs. Viewpoint

- Hitchcock's "Vertigo" and Martin Scorcese's "Goodfellas"
- Move camera viewpoint as you zoom in/out
- Known as a "dolly zoom" or the "Vertigo effect"
- Vertigo (1958): http://youtu.be/GnpZN2HQ3OQ?t=1m56s
- Jaws (1975): http://youtu.be/NB4bikrNzMk
- Goodfellas (1990): http://youtu.be/H4Utlw0XiHU
- http://www.youtube.com/watch?v=61GgIn3kWJw

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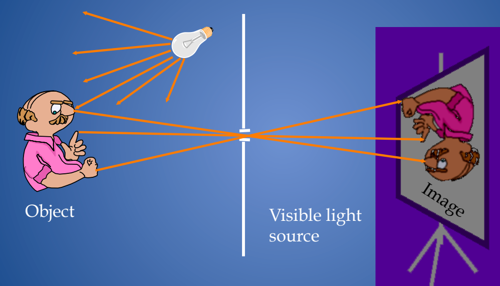
Vertigo Effect

Pinhole Optics

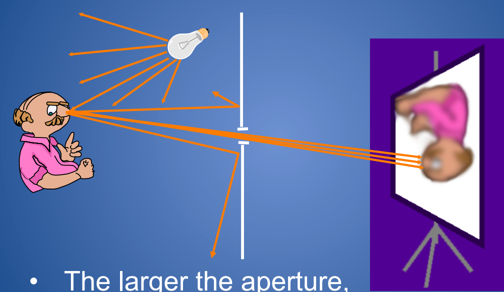
The pinhole allows 1:1 ray mapping



But the image is **dark**

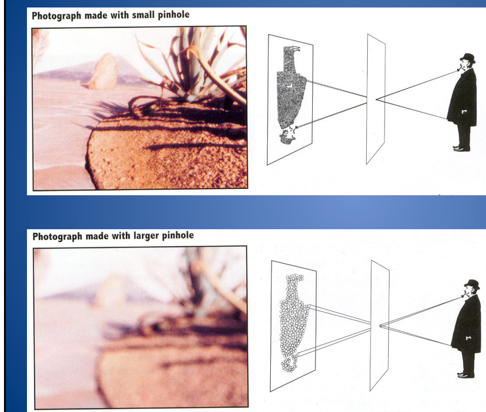
Pinhole Optics

Solution: Increase the size of the pinhole



- The larger the aperture, the brighter the image
- However, it is also ***blurred*** more

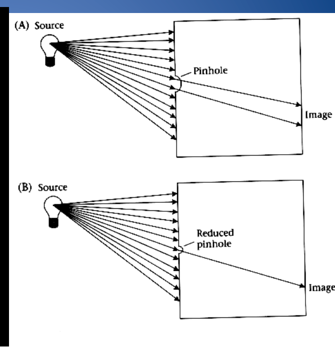
Pinhole Size?



From Photography, London et al.

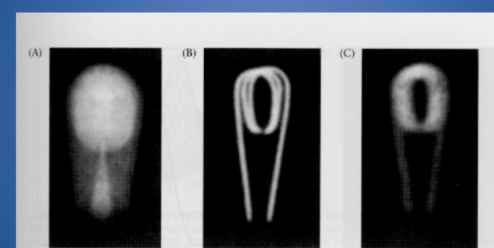
Lensless Imaging Systems: Pinhole Optics

- Pinhole optics focuses images
  - without lens
  - with infinite depth of field
- Smaller the pinhole
  - better the focus
  - less light energy from any single scene point
  - longer exposure time needed



Diffraction and Pinhole Optics

Optimal size for visible light:
$\sqrt{f}/28$ (in millimeters) where *f* is focal length



Pinhole too big ➔ blurring because rays from a single scene point don't converge to a point on image

Pinhole too small ➔ diffraction-based blurring

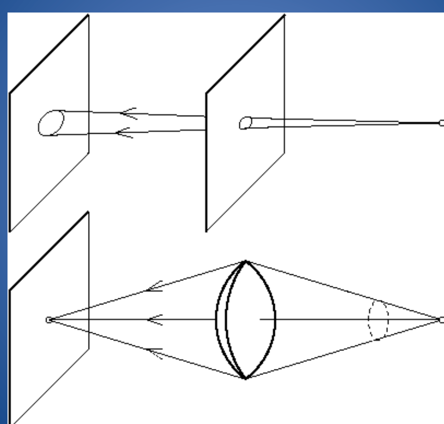
Pinhole Camera Summary

- Advantages (theoretical)
  - Perfect pinhole point ➔ Perfect focus everywhere
- Disadvantages (practical)
  - Pinhole too big ➔ blurry image
  - Pinhole too small ➔ Not enough light, and diffraction limits sharpness

Solution: Refraction using Lenses

From Photography, London et al.

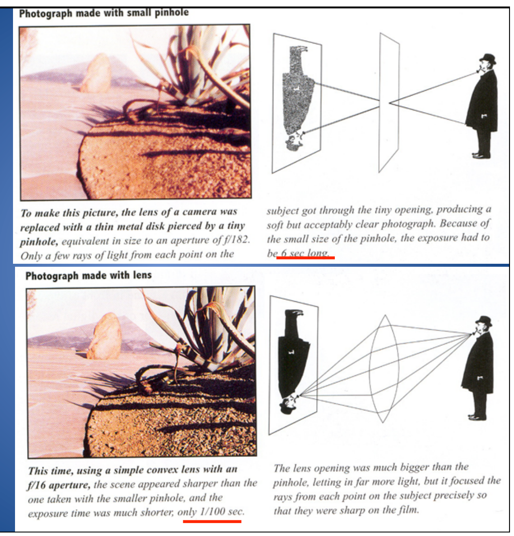
The Reason for Lenses



Slide by Steve Seitz

Goals

- Same projection as pinhole but *more* light
- Focused



Photograph made with small pinhole

To make this picture, the lens of a camera was replaced with a thin metal disk pierced by a tiny pinhole, *equivalent in size to an aperture of f/182. Only a few rays of light from each point on the subject got through the tiny opening, producing a soft but acceptably clear photograph. Because of the small size of the pinhole, the exposure had to be 6 sec long.*

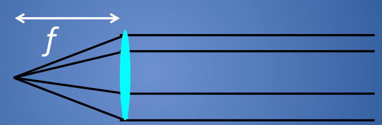
Photograph made with lens

This time, using a simple convex lens with an f/16 aperture, *the scene appeared sharper than the one taken with the smaller pinhole, and the exposure time was much shorter, only 1/100 sec.*

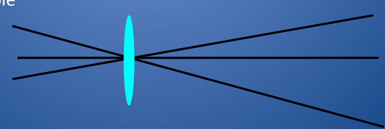
The lens opening was much bigger than the pinhole, letting in far more light, but it focused the rays from each point on the subject precisely so that they were sharp on the film.

Thin Lens Optics for a Converging Lens

- Simplification of **geometrical optics** for well-behaved lenses
- All parallel rays converge to ***one*** point on a plane located at the focal length *f*

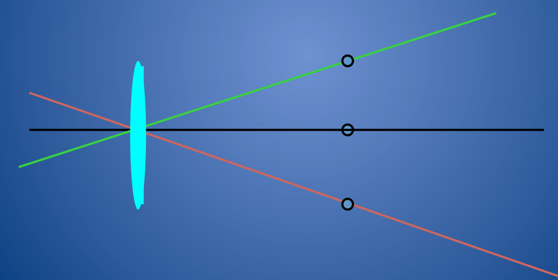


- All rays going through the *center* are not deviated
  - Same as pinhole



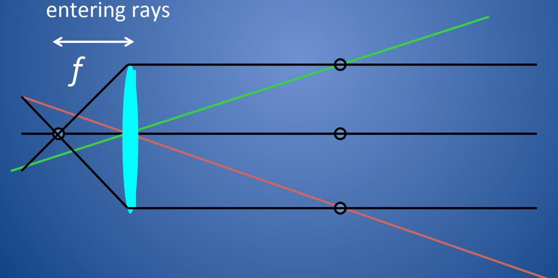
How to Trace Rays

- Start by rays through the center



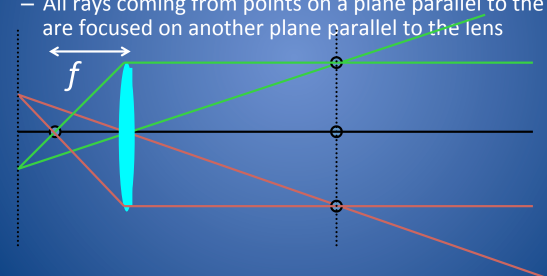
How to Trace Rays

- Start by rays through the center
- Choose lens focal length, trace parallels
  - Lens' focal length defines a constant "deflection angle" for all entering rays



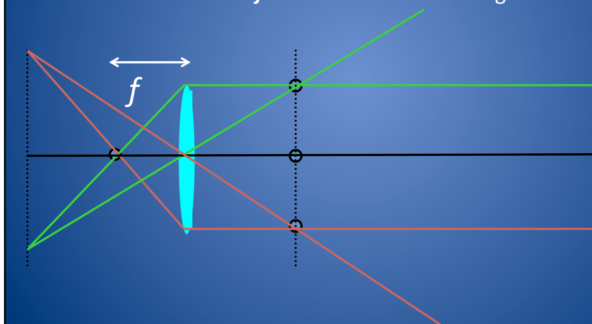
How to Trace Rays

- Start by rays through the center
- Choose focal length, trace parallels
- You get the focus (image) plane for a given scene plane
  - All rays coming from points on a plane parallel to the lens are focused on another plane parallel to the lens

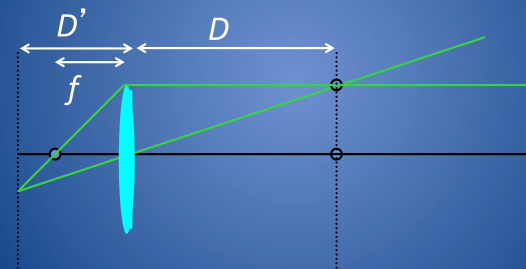


Focusing

- To focus closer than infinity
  - Move the sensor ***farther*** than the focal length

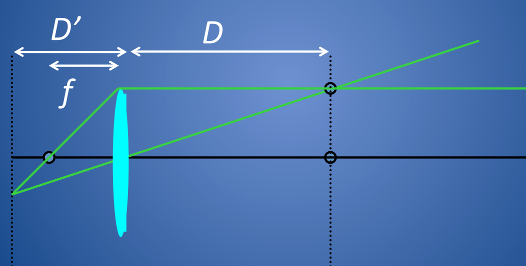


Where to Put the Sensor for an In-Focus Image?: Thin Lens Formula



Thin Lens Formula

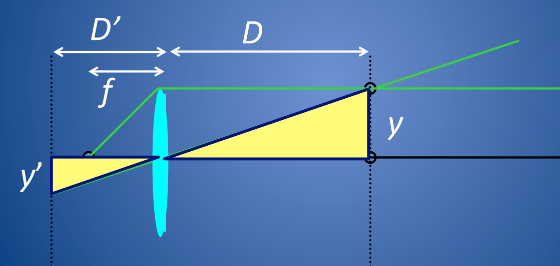
Similar triangles everywhere!



Thin Lens Formula

Similar triangles everywhere!

$y'/y = D'/D$

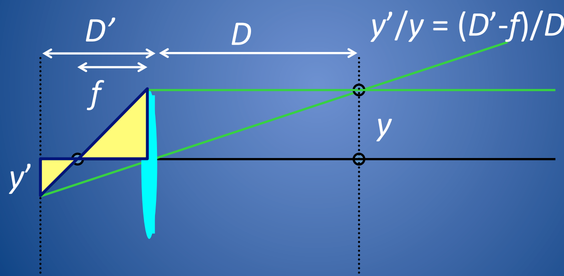


Thin Lens Formula

Similar triangles everywhere!

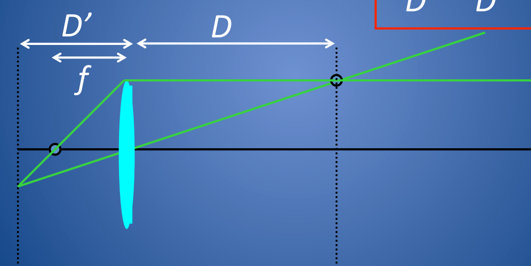
$y'/y = D'/D$

$y'/y = (D'-f)/D$



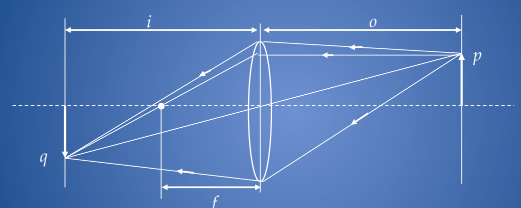
Thin Lens Formula

$$\frac{1}{D'} + \frac{1}{D} = \frac{1}{f}$$



Summary: Image Formation using a Converging Lens

Ideal Lens: Same projection as pinhole but gathers more light



Thin Lens Formula: $\frac{1}{i} + \frac{1}{o} = \frac{1}{f}$ aka **Lensmaker's Equation**

- ***f* is the focal length of the lens** – determines the lens's ability to bend (refract) light
- *f* different from *i*, which is the distance behind the lens where point *p* is in focus

Slide by Shree Nayar

Example 1

- Object at distance 20 cm from lens, and lens focal length = 10 cm

$$\frac{1}{i} = \frac{1}{f} - \frac{1}{o} = \frac{1}{10} - \frac{1}{20} = \frac{1}{20}$$

- So, focused image is at distance 20 cm behind lens
- Magnification = *i*/*o* = 20/20 = 1 so image is same size as the object
- When object is at distance = twice the focal length, the magnification = 1

Example 2

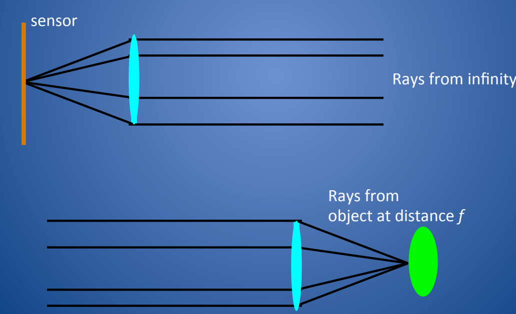
- Let o = 50 cm, f = 10 cm

$$\frac{1}{i} = \frac{1}{10} - \frac{1}{50} = \frac{4}{50}$$

- So, i = 50/4 = 12.5 cm
- Magnification = 12.5/50 = ¼
- As object moves farther away (20 to 50), the image gets closer to the lens (20 to 12.5)
- When object is farther than focal length, image is *upside-down* and *smaller* than object

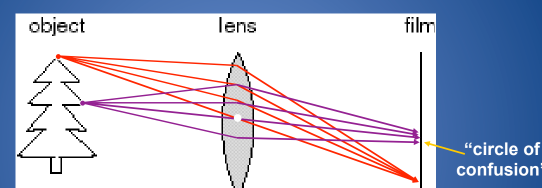
Minimum Focusing Distance

- By symmetry, an object at the focal length requires the film to be at infinity!



Focus

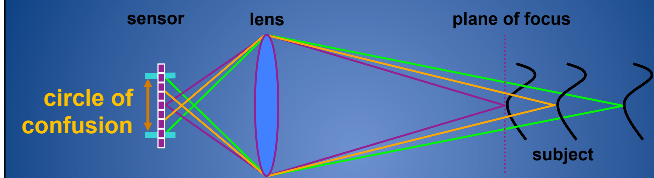
Focus and Defocus



- A lens focuses light onto the sensor
  - There is a specific distance at which objects are "in focus"
  - Change distance between lens and sensor to focus on an object
  - With 50 mm focal length lens, object at 0.5 m means i = 56 mm, while object at infinity means i = 50 mm, so distance lens has to move to focus is small
  - Scene points at other distances project to a "**circle of confusion**" in the image

Slide by Steve Seitz

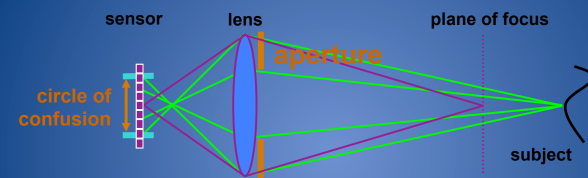
Depth and Defocus Blur



Rays from point in focus converge to single pixel

Defocus blur depends on distance from plane of focus

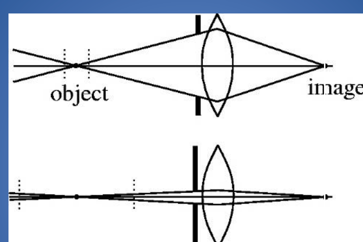
Defocus Blur and Aperture



Amount of defocus blur depends on aperture size

http://photographertips.net

Aperture Controls 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 because the rays that enter the lens are all at small angles from the optical axis, and therefore diverge very slowly behind the lens

Depth Of Field (DOF)

Aperture controls Depth of Field

- If you focus at *d* feet, DOF is a range in front and behind that is also “acceptably” focused
- Bigger f-number (i.e., smaller aperture) = larger DOF

f/32

f/5.6

Photo: http://en.wikipedia.org/wiki/Depth_of_field

Depth of Field

Mark Kauffman, *Princess Margaret Inspecting King’s African Rifles, Mauritius*, 1956

Depth of Field

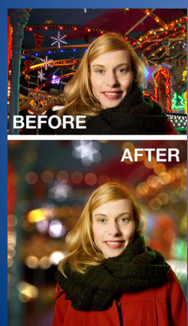
http://www.cambridgeincolour.com/tutorials/depth-of-field.htm

Aperture Size is a Critical Parameter for Photographers

In photograhy, **bokeh** is the blur, or the aesthetic quality of the blur, in out-of-focus areas of an image, or "the way the lens renders out-of-focus points of light"

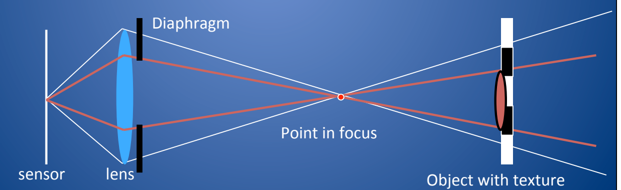
Decreasing DOF and Adding Bokeh

- Tadaa SLR app for iPhone
  - Manual editing of what to keep in focus



Depth of Field

- What happens when we close the aperture by ***two*** stops?
  - Aperture diameter is divided by 2
    - Each f stop halves/doubles the *area* of aperture
  - **Depth of field is doubled**

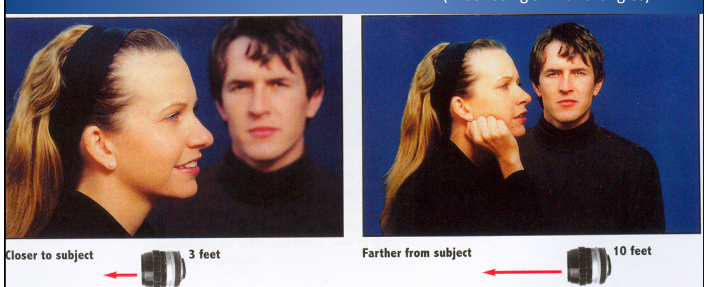


Depth of Field and Focusing Distance

What happens when we divide focusing distance by 2?

Similar triangles ➔ **DOF divided by 2 as well**

(Proof using similar triangles)



From Photography, London et al.

Aperture Controls Depth of Field

- For example:

Focus Distance	Aperture	Near	Far	Aperture	Near	Far
1'	f/1.4	11.9"	1' 0.1"	f/16	10.9"	1' 13"
10'	f/1.4	9' 1.6"	11' 1"	f/16	4' 9.9"	∞
50'	f/1.4	33' 10"	96'	f/16	7' 9.6"	∞

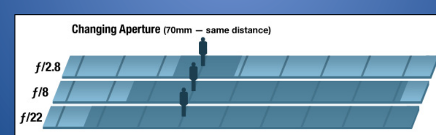
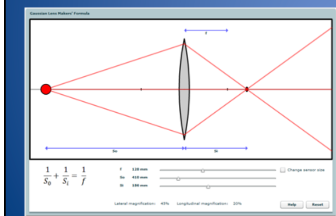


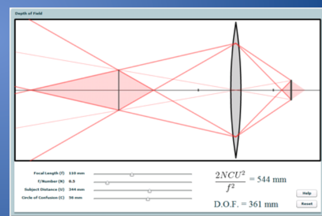
Image: http://www.tutorial9.net/photography/depth-of-field-in-photography/

Flash Applets on Photography

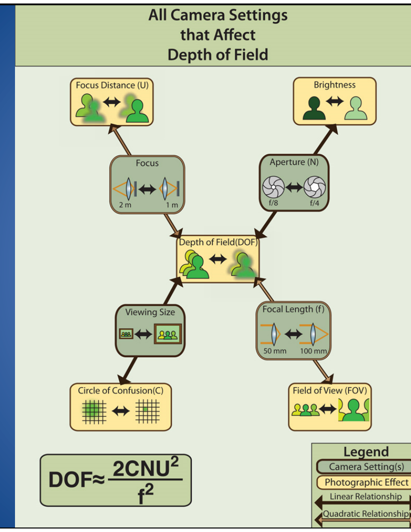
http://graphics.stanford.edu/courses/cs178-10/applets/applets.html



Focus

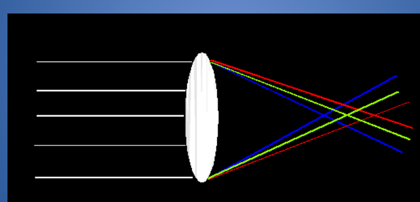


Depth of field



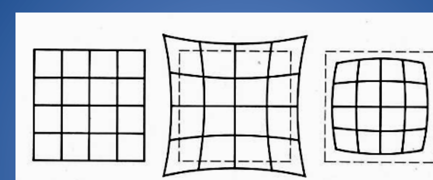
Lens Flaws: Chromatic Aberration

- Dispersion: wavelength-dependent refractive index
  - (enables prism to spread white light beam into rainbow)
- Modifies ray-bending and lens focal length: $f(\lambda)$



- color fringes near edges of image
- Corrections: add 'doublet' lens of flint glass, etc.

Radial Distortion



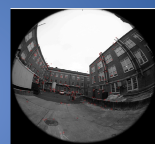
No distortion Pin cushion Barrel

- Radial distortion of the image
  - Caused by imperfect lenses
  - Deviations are most noticeable for rays that pass through the edge of the lens

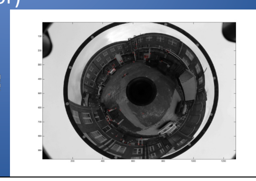
Ultra Wide-Angle Optics

- Sometimes distortion *is* what you want

Fisheye lens

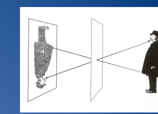
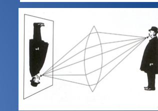
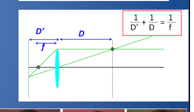



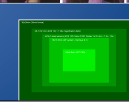
Catadioptric system (lens + mirror)

Recap

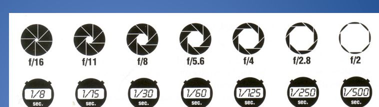
- Pinhole is the simplest model of image formation
- Lenses gather more light
  - But get only one plane focused
  - Focus by moving sensor
  - Cannot focus arbitrarily close
- Focal length determines field of view
  - From wide angle to telephoto
  - Also depends on sensor size



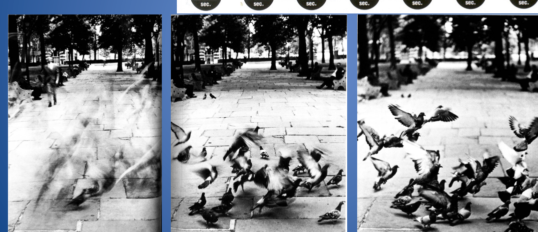
Recap

- Exposure
  - reciprocity



aperture

shutter speed



Shutter Speed 1/8	Shutter Speed 1/125	Shutter Speed 1/500
Aperture f/16	Aperture f/4	Aperture f/2

Recap

- Many parameters with many tradeoffs:

Focal length, aperture, shutter speed, ISO, focus, depth of field, field of view, viewpoint (camera pose), filters, lighting, light metering, scene characteristics (composition, motion), sensor characteristics (sensor size, pixel size, resolution, white balance, gain), etc.

A Photographer's Wish List

- Temporal Photography
  - Camcorder
- 3D Photography
  - Stereo cameras and camcorders
- Superpower Photography
  - Seeing around corners
  - X-ray vision
  - Telepresence / Tele-vision

Marc Levoy's Applets

http://graphics.stanford.edu/courses/cs178-10/applets/applets.html

Dick Lyon's Lectures on Photography
http://www.dicklyon.com/phototech/

PhotoTechEDU – A Photographic Technology Lecture Series

Videos and Slides

Search on Google video for photographic technology (which misses a few in the series) or PhotoTechEDU, (which misses some different ones).

List of lectures, with links to Google video and PDF files of slides:

1. Overview: ideal camera, exposure controls, optics, etc. – video – slides
2. Camera, eye, and color – video – slides
3. Ray tracing for optical imaging systems – video – slides
4. Resolution, contrast, flare, noise, etc. – video – slides
5. Silicon image sensors – video – slides
6. Image processing pipelines – video – slides
7. Lossy image compression, part 1 – video – slides
8. Diffraction and spectroscopy – video – slides
9. Astrophotography – video – slides
10. Image compression, part 2 – video – slides
11. Document image analysis – video – slides
12. High-dynamic-range imaging – video – slides
13. Light field (plenoptic) photography – no video yet – no slides yet
14. Image Forensics – video –
15. The Gigapxl Project – no video yet – no slides yet
16. Multi-viewpoint Mosaics – video – slides
17. Color Management – no video yet – no slides yet