# Lecture 9: Camera Optics

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#### CSC 292/572, Fall 2022 **Mobile Visual Computing**



### Logistics

WA1 grades posted.

- The link is on the assignment page
- Can work in groups of 2

#### Project idea document is posted. Feel free to work on your own idea too.

• Submit a one-page proposal describing what you want to work on by Oct. 26, 11:30 AM.



### The Roadmap





### The Roadmap

**Theoretical Preliminaries** 

Human Visual Systems

**Color in Nature, Arts, Tech** (a.k.a., the birth, life, and death of light)

#### **Digital Camera Imaging**

Modeling and Rendering

Applications

#### **Optics in Camera**

Image Sensor Image Signal Processing Image/Video Compression Immersive Content



### **Digital Cameras**

Light –







https://ph.priceprice.com/Google-Pixel-XL-18713/news/Google-Pixel-XL-Repair-1939/



Image Signal Processing



# Why Do Cameras Need Lenses Anyway?



#### Just Expose Sensor to Scene Without Optics







#### Just Expose Sensor to Scene Without Optics





https://www.azosensors.com/article.aspx?ArticleID=1883







#### Just Expose Sensor to Scene Without Optics

Scene









### **Pinhole Camera**

Ideally: Each pixel on the sensor gets light from only one scene point.

Use a very small hole as the aperture.



### **Pinhole Camera**

Ideally: Each pixel on the sensor gets light from only one scene point.

Use a very small hole as the aperture.



#### Pinhole size: 0.45mm Focal length:126mm

https://ondupinhole.com/products/8x10-giant-pinhole-camera



### Long Exposure Time

A small pinhole allows only very small amount of light to enter, requiring very long exposure time; impractical for many scenarios.

影	Sunny	15 to 20 seconds
	Overcast	60 seconds
*	Cloudy	2 minutes
	Indoors	30 minutes to an hour
a	Nightime	A few hours



### Long Exposure Time Common Motion Blur



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https://civilwar150pinholeproject.com/pinhole-cameras/ https://woub.org/2017/10/20/create-your-own-pinhole-camera-at-daco-with-artist-daniel-king/



![](_page_14_Picture_3.jpeg)

![](_page_14_Picture_4.jpeg)

#### Large Pinhole?

![](_page_15_Figure_1.jpeg)

![](_page_15_Picture_2.jpeg)

https://www.flickr.com/photos/dominicspics/4589206921 13

![](_page_15_Picture_4.jpeg)

#### Large Pinhole?

#### Scene

![](_page_16_Figure_3.jpeg)

![](_page_16_Figure_4.jpeg)

![](_page_16_Picture_5.jpeg)

https://www.flickr.com/photos/dominicspics/4589206921 13

![](_page_16_Picture_7.jpeg)

![](_page_17_Figure_2.jpeg)

![](_page_17_Picture_3.jpeg)

https://www.flickr.com/photos/dominicspics/4589206921 13

![](_page_17_Picture_6.jpeg)

## Not All Blurs Are Created Equal

Blur From Large Aperture ("Defocus" Blur)

![](_page_18_Picture_2.jpeg)

https://www.quora.com/Why-do-pinhole-camera-images-lose-image-clarity-when-the-aperture-size-is-increased

#### **Motion Blur**

![](_page_18_Picture_5.jpeg)

![](_page_18_Picture_6.jpeg)

## Imaging With a Convex Lens

A point in the scene emits (or reflects) rays in all directions.

• A pinhole camera captures just one ray from the point.

A convex lens captures/focuses a lot of rays from the same point and sends them to the same pixel on the sensor.

![](_page_19_Figure_4.jpeg)

15

If in focus, the captured image is the geometrically the same as the one captured by a pinhole camera, but brighter given the same exposure time.

• ... under the thin lens and paraxial approximations (later)

![](_page_20_Figure_3.jpeg)

![](_page_20_Picture_4.jpeg)

![](_page_20_Picture_5.jpeg)

If in focus, the captured image is the geometrically the same as the one captured by a pinhole camera, but brighter given the same exposure time.

 ...under the thin lens and paraxial approximations (later)

![](_page_21_Figure_3.jpeg)

![](_page_21_Picture_4.jpeg)

If in focus, the captured image is the geometrically the same as the one captured by a pinhole camera, but brighter given the same exposure time.

- ...under the thin lens and paraxial approximations (later)
- Both are **perspective projection**

![](_page_22_Figure_4.jpeg)

![](_page_22_Picture_5.jpeg)

If in focus, the captured image is the geometrically the same as the one captured by a pinhole camera, but brighter given the same exposure time.

- ... under the thin lens and paraxial approximations (later)
- Both are **perspective projection**

This's why we can **approximate** image formation process of a lens-based camera using a pinhole camera model.

![](_page_23_Figure_5.jpeg)

![](_page_23_Picture_8.jpeg)

## Making Convex Lens

![](_page_24_Picture_2.jpeg)

#### The simplest way: combining two spherical lenses, which are easy to make.

![](_page_24_Picture_4.jpeg)

https://en.wikipedia.org/wiki/Lens Optics, Hecht, 5ed 17

![](_page_24_Picture_6.jpeg)

#### Aperture

Aperture limits the amount of light that pass through the lens.

Amount of photons allowed through is proportional to the aperture area (radius<sup>2</sup>)

Aperture size has implications on exposure time, motion blur, and depth of field (more on this later).

![](_page_25_Figure_4.jpeg)

![](_page_25_Picture_6.jpeg)

### Shutter

Shutter controls how sensor is exposed to light Mechanical shutter:

- Sensor is *unexposed* to light normally
- Shutter mechanically opens to expose sensor to light
- Shutter open size dictates exposure time
- Focal plane shutter is common these days; inherently a rolling shutter

Electronic shutter (next lecture):

- Sensor is always **exposed** to light
- The pixel circuit resets/drains a pixel's charges to prepare for a capture
- Can be either rolling or global shutter

![](_page_26_Picture_12.jpeg)

### **Mechanical Shutter**

Leaf shutter (usually at the aperture plane)

![](_page_27_Picture_2.jpeg)

https://newatlas.com/aperture-camera-photography-guide/47388/ https://www.juzaphoto.com/article.php?l=it&t=mechanical\_and\_electronic\_shutter 20

#### Focal plane shutter (at the focal plane)

![](_page_27_Picture_5.jpeg)

![](_page_27_Picture_6.jpeg)

#### Focal Plane Shutter (Fast Exposures)

![](_page_28_Picture_1.jpeg)

The Slow Mo Guys, <a href="https://youtu.be/CmjeCchGRQo">https://youtu.be/CmjeCchGRQo</a>

CS184/284A

Inherently a rolling shutter

Exposure time is dictated by the shutter open size

Kanazawa & Ng

![](_page_28_Picture_7.jpeg)

![](_page_28_Picture_8.jpeg)

![](_page_28_Picture_9.jpeg)

# Modeling Lens Behaviors

![](_page_29_Picture_1.jpeg)

### Why Does Convex Lens Focus Light?

Lenses don't magically bend lights.

Lights change direction going through media of different refractive indices.

- Air to glass and glass to air again here.
- Again, lights changing direction at medium interface is macroscopic behavior of particles scattering photons with interference.

![](_page_30_Picture_8.jpeg)

https://en.wikipedia.org/wiki/Lens 23

![](_page_30_Picture_10.jpeg)

#### Snell's Law

#### $n_1 \sin \theta_1 = n_2 \sin \theta_2$

Nair ~ 1 interface

Ρ

n<sub>glass</sub> > 1

![](_page_31_Figure_4.jpeg)

![](_page_31_Picture_5.jpeg)

"Snel has his name mis-spelled for a couple hundred years now."

https://en.wikipedia.org/wiki/Snell%27s\_law 24

![](_page_31_Picture_8.jpeg)

### **Snell's Law in Action**

#### First Interface Second Interface

![](_page_32_Picture_2.jpeg)

Optics, Hecht, 5ed 25

![](_page_32_Picture_4.jpeg)

![](_page_32_Picture_5.jpeg)

### Waveguide

no refraction, and we get "total internal reflection."

~how optical fibers work.

![](_page_33_Figure_3.jpeg)

https://www.researchgate.net/figure/Light-propagation-in-a-waveguide-due-to-total-internal-reflection\_fig14\_274666441 https://www.tutorialspoint.com/principles\_of\_communication/principles\_of\_optical\_fiber\_communications.htm

# When lights goes from glass to air and when $\theta_1$ is large enough, there will be

![](_page_33_Picture_7.jpeg)

#### Aside: Gravitational Lens

![](_page_34_Figure_1.jpeg)

https://en.wikipedia.org/wiki/Gravitational\_lens 27

![](_page_34_Picture_3.jpeg)

![](_page_34_Picture_4.jpeg)

#### Aside: Gravitational Lens

![](_page_35_Picture_1.jpeg)

## -GALAX-Y-CLUSTER

https://newatlas.com/space/james-webb-space-telescope-gravitational-lensing/ 28

![](_page_35_Picture_4.jpeg)


https://newatlas.com/space/james-webb-space-telescope-gravitational-lensing/



https://hubblesite.org/contents/articles/gravitational-lensing











$$n_1 \sin \alpha = n_2 \sin \beta$$
  

$$\alpha = \theta_1 + \mu_1 \quad \beta = \mu_1 - \phi$$
  

$$\sin \mu_1 = \frac{h_1}{R_1} \quad \tan \theta_1 = \frac{h_1}{u}$$

$$\phi$$
 (





$$n_{1} \sin \alpha = n_{2} \sin \beta$$

$$\alpha = \theta_{1} + \mu_{1} \quad \beta = \mu_{1} - \phi$$

$$\sin \mu_{1} = \frac{h_{1}}{R_{1}} \quad \tan \theta_{1} = \frac{h_{1}}{u}$$

$$\phi$$
 (

$$n_{2} \sin \delta = n_{1} \sin \gamma$$
  

$$\delta = \mu_{2} + \phi \quad \gamma = \mu_{2} + \theta_{2}$$
  

$$\sin \mu_{2} = \frac{h_{2}}{R_{2}} \quad \tan \theta_{2} = \frac{h_{2}}{v}$$



### **Assumption 1: Thin Lens Assumption**



$$n_{1} \sin \alpha = n_{2} \sin \beta$$

$$\alpha = \theta_{1} + \mu_{1} \quad \beta = \mu_{1} - \phi$$

$$\sin \mu_{1} = \frac{h_{1}}{R_{1}} \quad \tan \theta_{1} = \frac{h_{1}}{u}$$

$$\phi$$
 (

$$R_1 \Rightarrow h_1 \approx h_2$$

$$n_2 \sin \delta = n_1 \sin \gamma$$
  

$$\delta = \mu_2 + \phi \quad \gamma = \mu_2 + \theta_2$$
  

$$\sin \mu_2 = \frac{h_2}{R_2} \quad \tan \theta_2 = \frac{h_2}{v}$$



# **Assumption 2: Paraxial Assumption**

Consider only rays staying close to the optical axis.



$$n_{1} \sin \alpha = n_{2} \sin \beta$$

$$\alpha = \theta_{1} + \mu_{1} \quad \beta = \mu_{1} - \phi$$

$$\sin \mu_{1} = \frac{h_{1}}{R_{1}} \quad \tan \theta_{1} = \frac{h_{1}}{u}$$

gles.  
os(
$$\alpha$$
) ~= 1.

$$n_2 \sin \delta = n_1 \sin \gamma$$
  

$$\delta = \mu_2 + \phi \quad \gamma = \mu_2 + \theta_2$$
  

$$\sin \mu_2 = \frac{h_2}{R_2} \quad \tan \theta_2 = \frac{h_2}{v}$$





$$\frac{n_2 - n_1}{n_1} \left(\frac{1}{R_1} + \frac{1}{R_2}\right) = \left(\frac{1}{u} + \frac{1}{v}\right)$$

 $\phi$ 

Observe that v depends only on u regardless of the path the ray takes (for a given camera)







$$\frac{n_2 - n_1}{n_1} \left(\frac{1}{R_1} + \frac{1}{R_2}\right) = \left(\frac{1}{u} + \frac{1}{v}\right)$$

 $\phi$ 

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 $\phi$ 

Observe that v depends only on u regardless of the path the ray takes (for a given camera)

• So all rays from an on-axis point focus at the same point







$$\frac{n_2 - n_1}{n_1} \left(\frac{1}{R_1} + \frac{1}{R_2}\right) = \left(\frac{1}{u} + \frac{1}{v}\right)$$

Observe that v depends only on u regardless of the path the ray takes (for a given camera)

- So all rays from an on-axis point focus at the same point
- In reality, only paraxial rays follow this (more later)









$$\frac{n_2 - n_1}{n_1} \left(\frac{1}{R_1} + \frac{1}{R_2}\right) = \left(\frac{1}{u} + \frac{1}{v}\right)$$
$$\int u \to \infty$$



### Gauss' Lens Equation



That is, incident rays parallel to optical axis converge at the same point



Where parallel rays converge is **defined** as the focal point



### **Gauss' Lens Equation**







Under thin lens and paraxial ray approximations:





Under thin lens and paraxial ray approximations:



• Rays parallel to the optical axis always pass through the focal point on the other side.



Under thin lens and paraxial ray approximations:

- Rays passing through the focal point will be parallel on the other side.



• Rays parallel to the optical axis always pass through the focal point on the other side.



Under thin lens and paraxial ray approximations:

- Rays passing through the focal point will be parallel on the other side.



• Rays parallel to the optical axis always pass through the focal point on the other side.

• Rays passing through the optical center won't change direction if the lens is symmetric.



# Ideal Lens

Move the sensor plane to focus on scene points at different distances.

- This is how camera auto-focus works (later)
- Or equivalently move the lens



Optics, Hecht, 5ed



# Ideal Lens

Move the sensor plane to focus on scene points at different distances.

- This is how camera auto-focus works (later)
- Or equivalently move the lens

The greater the curvature, the shorter the focal length and the more "optical power".

• Need higher optical power to focus on closer objects.







# **Optics in Human Eyes**



1.  $n_1 = 1.009$  (air) 2.  $n_2 = 1.376$  (cornea) 3.  $n_3 = 1.336$  (aqueous fluid) 4.  $n_4 = 1.413$  (lens) 5.  $n_5 = 1.337$  (vitreous fluid)

Figure 4.25: A ray of light travels through five media before hitting the retina. The indices of refraction are indicated. Considering Snell's law, the greatest bending occurs due to the transition from air to the cornea. Note that once the ray enters the eye, it passes through only liquid or solid materials.



Eye lenses "accommodate" to focus on objects of different distances









# When Object is Closer Than f



glass. The object is less than one focal length from the lens.





https://activeforlife.com/play-centres/ 44



# Virtual Reality Display







### Lenses in Virtual Reality Display



### https://www.youtube.com/watch?v=4VdQr4T5wN8

https://www.tomshardware.com/news/virtual-reality-lens-basics-vr,36182.html 46



### Lenses in Virtual Reality Display



https://www.tomshardware.com/news/virtual-reality-lens-basics-vr,36182.html 46 https://www.youtube.com/watch?v=4VdQr4T5wN8







# Lens in Virtual Reality Display







### Magnification













### Magnification





### Increasing Focal Length





### **Increasing Focal Length Reduces Field of View**







# Focal Length vs. Field of View vs. Magnification



https://infocusfilmschool.com/how-to-use-lenses-in-film/focal-length-and-angle-of-view-guide/



# Focal Length vs. Field of View



15mm (fisheye)









14mm 🦳





Canon - EF Lens Work III-The Eye of EOS, 8e 55





# Focal Length vs. Field of View











135mm









Canon - EF Lens Work III-The Eye of EOS, 8e 56




### **Telephoto Cameras**



Real Lenses



## **Real Lenses are Very Complex**





### Cross section of the EF 24-70 mm f/2.8

Canon - EF Lens Work III-The Eye of EOS, 8e https://www.scribd.com/article/372092140/Anatomy-Of-Alens 59



## Real Lenses are Very Complex



https://wccftech.com/samsung-developed-5x-periscope-zoom-camera-module/ 60



### **Real Lenses**

So far we've assumed thin lens and paraxial approximations.

Real lenses are neither thin nor can we ignore non-paraxial rays.

optics principles still apply.

A typical strategy to correct deviations from ideal lenses is to cascade a sequence of lenses, i.e., compound lens.

- So real lens behaviors deviate away from ideal lens, but the same geometrical



61

## **Thick Lens Geometry**

Simplifications made for thin lenses won't apply.



# The same geometric principles still apply; need to consider more parameters.

Optics, Hecht, 5ed



### Lens Aberrations

Recall paraxial rays are rays that stay close to optical axis throughout the system. These rays:

- are originated from objects close to/on optical axis **AND**
- have a small incident angle when approaching the lens

(Monochromatic) aberrations refer to deviations from ideal lens when considering non-paraxial rays, i.e.,:

- Rays that are not originated from from objects close to/on optical axis **OR**
- Have oblique incident angles



### Lens Aberrations

considering only the first term), five forms of aberrations show up:

- spherical aberration, coma, astigmatism, field curvature, distortion
- This is called third-order theory, c.f. paraxial approximation (which is called first-order theory or Gaussian Optics).

Higher-order aberrations show up when considering additional terms.

### **Chromatic** aberrations:

• arise from the fact that refractive index is actually a function of frequency.

$$\sin \phi = \phi \left[ -\frac{\phi^3}{3!} + \frac{\phi^5}{5!} - \frac{\phi^7}{7!} + \cdots \right]$$

When considering the second term of Taylor series expansion (compared to



## **Spherical Aberration**

Spherical aberration: aberration induced by spherical lens.

- For a point on the optical axis, not all its rays focus at the same point.
- By extension, not all parallel rays focus at the same point.



Color Imaging-Fundamentals and Applications, Reinhard https://en.wikipedia.org/wiki/Spherical\_aberration







## **Spherical Aberration**

Spherical aberration: aberration induced by spherical lens.

- For a point on the optical axis, not all its rays focus at the same point.
- By extension, not rays parallel to the optical axis focus at the same point.

### Fixing spherical aberrations:

- Using a combination of convex and concave lens
- Using aspherical/hyperbolic lens





Hyperbolic lens



### Aspherical lens



https://en.wikipedia.org/wiki/Spherical\_aberration https://photographylife.com/what-is-spherical-aberration





### **Spherical Aberration**



### Hubble Space Telescope images of the M-100 galaxy with (before repair) and without (after repair) spherical aberration.



https://hubblesite.org/image/4272/news/37-spiral-galaxies 67







## **Spherical Aberration in Mirrors**

### **Spherical Mirror**



https://www.telescope-optics.net/spherical1\_files/spherical1.htm http://www.vikdhillon.staff.shef.ac.uk/teaching/phy217/telescopes/phy217\_tel\_reflectors.html 68









### **Could It Have Been Possible?**



https://www.livescience.com/8383-study-archimedes-set-roman-ships-afire-cannons.html



### **Could It Have Been Possible?**



https://www.livescience.com/8383-study-archimedes-set-roman-ships-afire-cannons.html



### Coma

### Rays from an off-axis point focus on different points. By extension, parallel rays that are not parallel to the optical axis don't focus on the same point.







### Astigmatism



https://en.wikipedia.org/wiki/Astigmatism https://www.edmundoptics.com/knowledge-center/application-notes/imaging/how-aberrations-affect-machine-vision-lenses/





## Astigmatism





https://en.wikipedia.org/wiki/Astigmatism https://www.edmundoptics.com/knowledge-center/application-notes/imaging/how-aberrations-affect-machine-vision-lenses/





### **Field Curvature**



### If a lens is free from all previous aberrations, a scene point is sharply imaged on a point on the sensor; but the image "plane" is actually a curved surface.



The image-sensor array of the Kepler space observatory is curved to compensate for the field curvature.

https://www.edmundoptics.com/knowledge-center/application-notes/imaging/how-aberrations-affect-machine-vision-lenses/





### Distortion

Pinhole cameras and ideal lens perform perspective projections, where straight lines remain straight in images.

Distortion is deviation from perspective projection. It is more significant at the extremities of the lens.

Fisheye lens is an extreme example.



(d)

(e)

**Figure 6.34** (*a*) Undistorted object. (*b*) When the magnification on the optical axis is less than the off-axis magnification, pincushion distortion results. (*c*) When it is greater on axis than off, barrel distortion results. (*d*) Pincushion distortion in a single thin lens. (*e*) Barrel distortion in a single thin lens. (*E*.H.)



### **Chromatic Aberration**



### Longer-wavelength lights have lower refractive indices



https://news.smugmug.com/what-is-chromatic-aberration-how-do-i-deal-with-it-26d5a55c0924 74



## **Chromatic Aberration**

The "dispersive power" of the lens material dictates the degree of chromatic aberration



### Longer-wavelength lights have lower refractive indices



https://www.shutterstock.com/video/clip-369937-prism---light-dispersion-seamless-loop-hd1080p





## Fixing Chromatic Aberration: Achromatic doublets











### Filling the frame with unapproachable subjects.

### Excellent for photographing wild animals in the jungle or on the playing field.

The photographer's dream is to get right up close to the driver as his racecar careens around a corner at 200mph and capture the tension on his face, or sneak up on a hungry lion in the jungle and capture his subdued aggressiveness digitally or on film. For better or for worse, these acts are physically dangerous or simply impossible, but with a super telephoto lens, the photograph is not impossible. A 600mm lens lets you capture all those dramatic sports and wildlife moments with the visual impact of physical immediacy. The subtle movements of a subject moving far off in the distance can be brought in to fill the frame, with visual tension enhanced by the perspective compression that only a super telephoto lens can deliver.

Normally, this class of lens requires a tripod, but with the Image Stabilizing mechanism, all you need is a monopod for total mobility.

### EF 600mm f/4L IS USM

This new 600mm super telephoto lens is equipped with an Image Stabilizer system and has a large aperture of f/4, providing the finest image performance in its class. It offers reliable capabilities when used to photograph wild animals or field sports. The optical system includes one fluorite lens element and two UD lens elements that eliminate secondary spectrum, resulting in a level of image quality with high contrast previously impossible to attain. With its improved drive algorithm, its autofocus is the fastest in







### EF 600mm f/4L IS USM

• Focal length and maximum aperture: 600 mm 1:4

- Lens construction: 17 elements in 13 groups (protective glass and drop-in filter included) • Diagonal angle of view: 4° 10'
- Focus adjustment: Ring-type USM, inner focusing system, full-time manual focus
- Closest focusing distance: 5.5 m/ 18 ft., 0.12 x magnification Filter size: 52 mm rear drop in
- Max. diameter x length, weight: ø 168 x 456 mm, 5,360 g/ 6.6" x 18", 11.8 lbs.



EF 600mm f/4L IS USM ·1/80sec. ·f/9

the world\*1. The closest focusing distance has been reduced to 5.5m/18ft. In addition to using a full-time mechanical manual focus and an AF stop function, the focus preset and other features were improved to make it easier to use. The use of a magnesium alloy for its principal parts has reduced its weight, making holding and mobility better than ever. It offers superior dust-proof and drip-proof<sup>\*2</sup> performance for outstanding photography in the field.

- \*1 Bodies: EOS-1V/HS, EOS-3, EOS-1Ds Mark II, EOS-1Ds, EOS-1D Mark II N, EOS-1D Mark II, EOS-1D (all when using rechargeable battery pack) \*2 Dust-proof and drip-proof models: EOS-1V/HS, EOS-1Ds Mark II, EOS-1Ds, EOS-1D Mark II
- N, EOS-1D Mark II, EOS-1D, Extender EF 1.4xII, Extender EF 2xII



With its Image Stabilizer and large diameter, this lens dramatically expands the scope of what can be photographed, as well as how it is expressed. Fleeting moments of natural beauty at dawn, for example, or views of city skylines at night can be beautifully captured with handheld shots. In portrait photography, the large diameter can create a shallow depth of field that sets your subject apart from the background for expressive results that are truly impressive. By freeing you from camera-shake blur and empowering you with a large maximum aperture, this flexible, high-quality standard zoom lens lets you explore infinite photographic possibilities.

This large-aperture EF-S Series standard zoom lens features an optical system consisting of 19 lens elements in 12 groups. Three aspherical lens elements (one glass-molded and two replica surfaces) efficiently compensate for aberration fluctuations over the entire zoom range while enabling a large f/2.8 aperture and high image quality. Two UD lenses also reduce secondary chromatic aberrations to produce high-resolution, high-contrast images without colour bleeding around subject edges. The inner focus and a ring-type USM achieve silent, high-speed autofocusing, while full-time manual focus override offers excellent operability by enabling users to tweak focusing without exiting the autofocusing mode. Now it's easier to determine the ideal focus when shooting portrait and close-up photos with a large aperture setting. A circular aperture diaphragm contributes to beautiful background blur, and the optimised lens configuration and coating reduce the flare and ghost so common with digital cameras. This outstanding optical performance and operability is further enhanced by an Image Stabilizer that reduces the amount of camera-shake blur to roughly that of a 3 f-stop faster shutter speed.\*2 Clearly, this standard zoom lens meets the stringent requirements of professionals. The lens mechanism is designed to ensure that it fits only EOS DIGITAL SLR cameras designed to take EF-S lenses, and it is equipped with a special attachment indicator and protective rubber mount ring to prevent mistaken attempts to attach it to other EOS SLR cameras, and to prevent damage to the camera body.  $(\rightarrow P.128$  Special characteristics of EF-S lenses) \*1 Can be used only with EOS DIGITAL SLR cameras designed to take EF-S lenses. \* Compatible EOS DIGITAL SLR cameras: EOS 30D, EOS 20D, EOS 20Da,

EF-S 17-55mm f/2.8 IS USM ·1/100sec. ·f/4

f/2.8 aperture brightness and IS flexibility. This EF-S large-diameter standard zoom lens satisfies the most demanding professionals.

### EF-S 17-55mm f/2.8 IS USM \*1

EOS 400D DIGITAL, EOS 300D DIGITAL (as of September 2006) \*2 Based on a shutter speed of 1/focal length x 1.6 seconds, which is considered the limit for handheld photography without image stabilization.

### EF-S 17-55mm f/2.8 IS USM

• Focal length and maximum aperture: 17-55mm 1:2.8 • Lens construction: 19 elements in 12 groups • Diagonal angle of view: 78°30'-27°50' • Focus adjustment: Ring-type USM, inner focusing system, full-time manual focus • Closest focusing distance: 0.35 m/1.5 ft., 0.17 x magnification • Zoom system: Rotation type • Filter size: 77 mm • Max. diameter x length, weight: ø 83.5 x 110.6 mm, 645 g/3.3" x 4.4", 1.4 lbs.

This lens can be used only with cameras designed to take EF-S lenses







### Lens Design



Photo-1 CAD-facilitated lens design





# Depth of Field



If CoC is greater than a threshold, the point appears blur.

- Multiple pixels get some rays from that point
- Blur from defocus; c.f. motion blur





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### Bokeh

Bokeh is the size of an out-of-focus/defocused point.

Shape of bokeh is ~shape of the aperture.







https://en.wikipedia.org/wiki/Bokeh 83













## **Depth of Field**

and farthest scene points that will be in focus?



# Given that the sensor is focused on objects at distance T, what are the nearest



### **Depth of Field**



\* Note: you can infer T from f and the lens-sensor distance given a camera, but from f alone we can't infer T.

# N: F-number (f/A)




### **F-Number**



https://photobizblog.files.wordpress.com/2013/02/aperture.jpg http://sonyaddict.com/2019/09/02/7artisans-35mm-f-1-4-now-available/

### focal length A





# Why F-Number is So-Defined?



# focal length \_ aperture size

The irradiance of a pixel (photons per area) is proportional to:

• 1. square of aperture size A (the amount of photons that are allowed through)

• 2. inverse square of the focal length (remember irradiance falls off quadratically with distance)

• So pixel irradiance  $\sim = 1/N^2$ 







### How to Increase DOF?



1. Focus on farther away (e.g., landscape)

# T: distance to object in focus f: focal length C: CoC threshold N: F-number (f/A)





# A large T

https://markdenneyphotography.com/blog

CALLER BERTHERE







### How to Increase DOF?



- 1. Increase T: focus on farther away (e.g., landscape)
- 2. Reduce A: use a large F-number (smaller aperture)

# T: distance to object in focus f: focal length C: CoC threshold N: F-number (f/A)





# Small Aperture Increases DOF

#### $A \downarrow$ ; F-Number 1; DOF 1



#### f/4.0; DOF = 2.2 cm

#### f/22; DOF = 12.4 cm

https://en.wikipedia.org/wiki/Depth\_of\_field







f/16



f/4

f/1.4





# **Motion Blur vs. DOF Trade-off**

A small aperture increases the exposure time and motion blur.



f / 4 1/125 sec



f / 11 1/15 sec

f / 32 1/2 sec







# Large Apertures for Small DOFs

Large DOF is not always desirable

• Portrait photography needs a small (shallow) DOF, which requires a large aperture.

Smartphone cameras can't have a large aperture. Computational photography to the rescue

• "synthesis depth of field"



https://ai.googleblog.com/2017/10/portrait-mode-on-pixel-2-and-pixel-2-xl.html 96





# Synthetic Depth of Field

Shot an all-in-focus photo



#### Estimate pixel depths

#### Blur background pixels



# **DOF of a Pinhole Camera**

- A pinhole camera effectively has an infinite depth of field.
  - Ideal pinhole camera is a special camera with an infinitesimal aperture.
  - pinhole size is large.

$$DOF = \frac{2CT^2N}{f^2}$$
$$N = \frac{f}{A}$$



• Everything is in-focus; each point has only one ray reaching the sensor — unless the



### How to Increase DOF?



- 1. Increase T: focus on farther away (e.g., landscape)
- 2. Reduce A: use a large F-number (smaller aperture)
  - Affects exposure time (motion blur)
- 3. Decrease f: shorter focal length
  - Just remember that f affects magnification and field of view too.

#### **T**: distance to object in focus f: focal length N: F-number (f/A)





Making Use of Blur



# **Motion Blur vs. Defocused Blur**



https://pixabay.com/id/photos/kabur-mengaburkan-kedalaman-lapangan-193817/ https://www.formula1.com/en/latest/article.were-better-than-10th-says-frustrated-ricciardo-as-he-vows-to-make-it-happen.5BsABn0Xuu0nwH4BPIaP4H.html **101** 



# **Infer Speed from Motion Blur**



1. Translate # of pixels to distance on the sensor using pixel size.

2. Translate the distance on sensor to the distance in the scene (depends on the scene depth).

3. Use exposure time to estimate the object speed.



# Motion from Blur Challenges





#### Non-linear motion

https://www.formula1.com/en/latest/article.were-better-than-10th-says-frustrated-ricciardo-as-he-vows-to-make-it-happen.5BsABn0Xuu0nwH4BPlaP4H.html **103** 





## Depth From Defocused Blur



Scene depth is proportional to the CoC size.





https://www.formula1.com/en/latest/article.were-better-than-10th-says-frustrated-ricciardo-as-he-vows-to-make-it-happen.5BsABn0Xuu0nwH4BPlaP4H.html **104** 





# **Depth From Defocus Challenges**

CoCs of Point 1 and Point 3 are the same, but they have different depth.







#### Defocus of general lens

#### Far out of focus

#### In focus Near out of focus

Far



× Identical PSF at both sides of the focal plane. × Impossible to tell the depth based on the blur size.

trentwoodsphoto.com









#### Independent-crafted designs

Veeraraghavan et al., 2007





× The difference in PSFs across depth is only in scale.

Slide credit: Vivek Boominathan

#### Levin *et al.*, 2007 (previously discussed)











### PhaseCam3D sensor – Three upgrades





Yicheng Wu, Vivek Boominathan, et. al. "PhaseCam3D - Learning Phase Masks For Passive Single-view Depth Estimation"

Slide credit: Vivek Boominathan

More light. More control in PSFs. Better for reconstruction. → Joint learning.



#### Fabricate the learned phase mask



Yicheng Wu, Vivek Boominathan, et. al. "PhaseCam3D - Learning Phase Masks For Passive Single-view Depth Estimation"

#### **Slides from Vivek Boominathan**

#### Fabricated phase mask



