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

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: Canon web site
**DSLR Viewfinder**

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

**Types of Digital Cameras: DSLR – Single Lens Reflex**

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

**Types of Digital Cameras: Smartphones**

- By 2003 more phone cameras were sold worldwide than standalone 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 mm² to 43 mm²
  - 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 mm² (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
V. Controlling the view

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  
  - $1/4000$, $1/2000$, $1/1000$, $1/500$, $1/250$, $1/125$, $1/60$, $1/30$, $1/15$, $1/8$, $1/4$, $1$
- Faster shutter (e.g. $1/500^{th}$ sec) = less light
- Slower shutter (e.g. $1/30^{th}$ sec) = more light
- Typical DSLR range: “B” to $1/4000^{th}$ sec

Controlling Exposure:
Shutter Speed

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

“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

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)

Your Best Friend

- Use a tripod! It will always enhance sharpness

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

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

- Example: 50 mm lens (i.e., focal length = 50 mm)
  - f/2.0 \(\Rightarrow\) diam = 50/2 = 25; area = \((\pi/4)(25)^2\) \(\approx\) 490 mm²
  - f/2.8 \(\Rightarrow\) diam = 50/2.8 = 17.9; area = 250 mm²
  - f/4 \(\Rightarrow\) diam = 50/4 = 12.5; area \(\approx\) 123 mm²
  - Each f-stop halves/doubles the area of aperture
  - So, a change of 2 stops results in \(2^2 = 4\) x 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
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

\[ \log_2 N^2 \approx \log_2 t \approx \log_2 t \]

Each increment in speed or aperture is called a “stop”

Similarly, doubling the ISO value means it is twice as sensitive, so $1/125 \@ \text{ISO 400} = 1/250 \@ \text{ISO 800}$
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

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

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
NoVce: More “grainy” noise in high ISO photo

Source: Josh Dunlop
### Digital Image Sensor

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

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### Setting Exposure

<table>
<thead>
<tr>
<th>f/stop</th>
<th>1.4</th>
<th>2</th>
<th>2.8</th>
<th>4</th>
<th>5.6</th>
<th>8</th>
<th>11</th>
<th>16</th>
<th>22</th>
<th>32</th>
<th>45</th>
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<td>t (sec)</td>
<td>1/3.2</td>
<td>1/2</td>
<td>1/2.7</td>
<td>1/3.3</td>
<td>1/3.9</td>
<td>1/6</td>
<td>1/10</td>
<td>1/15</td>
<td>1/20</td>
<td>1/30</td>
<td>1/60</td>
</tr>
</tbody>
</table>

- Illumination increases by factor of 2
- Less light captured but increasing depth of field

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### 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

Outline

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

Depth of Field Control

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?
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 Obscrua
Camera Obscrua, Gemma Frisius, 1558

- The first “camera”
  - Depth of the room is the focal length

Alberti’s “Grid”

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

Dimensionality Reduction Machine (3D to 2D)

3D world

2D image

What have we lost?
• Angles
• Distances (lengths)

Funny Things Happen
**Focal Length: Pinhole Optics**

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

**Focal Length: Pinhole Optics**

- **What happens when the focal length is doubled?** \( q = \frac{2f}{d} p \)
- **What happens when the scene is twice as far away?** \( q = \frac{f}{2d} p \)
- **How do we get the same object size when the focal length is doubled?**
  - \( q = \frac{2f}{2d} p \)
  - Is it equivalent to get closer and to shorten focal length?
Focal Length and Field of View (FOV)

<table>
<thead>
<tr>
<th>Focal Length</th>
<th>FOV</th>
</tr>
</thead>
<tbody>
<tr>
<td>24mm</td>
<td>50°</td>
</tr>
<tr>
<td>50mm</td>
<td>24°</td>
</tr>
<tr>
<td>135mm</td>
<td>10°</td>
</tr>
</tbody>
</table>

Volume of view depends on focal length and sensor size.

Larger Focal Length \( \Rightarrow \) Smaller FOV

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)

Wide angle | Standard | Telephoto

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

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

FOV vs. Viewpoint
- Hitchcock's "Vertigo" and Martin Scorsese's "Goodfellas"
- Move camera viewpoint as you zoom in/out
- Known as a "dolly zoom" or the "Vertigo effect"
- Vertigo (1958): https://youtu.be/GnpZN2HQ3Qq?t=1m56s
- Goodfellas (1990): https://youtu.be/H4Utlw0X0HU
- http://www.youtube.com/watch?v=61Gglbn3kWw

Vertigo Effect

Pinhole Optics
The pinhole allows 1:1 ray mapping
But the image is dark

Pinhole Optics
The pinhole allows 1:1 ray mapping
Pinhole Optics
Solution: Increase the size of the pinhole

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

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

Pinhole Size?

From Photography, London et al.

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

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

Slide by Steve Seitz
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
- 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

\[
\frac{y'}{y} = \frac{D'}{D}
\]
Thin Lens Formula

Similar triangles everywhere!

\[ \frac{y'}{y} = \frac{D'}{D} \]
\[ \frac{y'}{y} = \frac{(D' - f)}{D} \]

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

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, $i = \frac{50}{4} = 12.5$ cm

• Magnification = $\frac{12.5}{50} = \frac{1}{4}$

• 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!

![Diagram of Minimum Focusing Distance](slide_image)

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
Defocus blur depends on distance from plane of focus. Rays from point in focus converge to single pixel.

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)

Defocus Blur and Aperture:
Amount of defocus blur depends on aperture size.
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

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 photography, 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)

Aperture Controls Depth of Field

- For example:

<table>
<thead>
<tr>
<th>Focus Distance</th>
<th>Aperture</th>
<th>Near</th>
<th>Far</th>
<th>Aperture</th>
<th>Near</th>
<th>Far</th>
</tr>
</thead>
<tbody>
<tr>
<td>1′</td>
<td>f/1.4</td>
<td>11.9″</td>
<td>1′ 0.1″</td>
<td>f/16</td>
<td>10.9″</td>
<td>1′ 13″</td>
</tr>
<tr>
<td>10′</td>
<td>f/1.4</td>
<td>5′ 1.6″</td>
<td>11′ 1″</td>
<td>f/16</td>
<td>4′ 9.9″</td>
<td>∞</td>
</tr>
<tr>
<td>50′</td>
<td>f/1.4</td>
<td>33′ 10″</td>
<td>96′</td>
<td>f/16</td>
<td>7′ 9.6″</td>
<td>∞</td>
</tr>
</tbody>
</table>

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(λ)

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

Radial Distortion

- 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

<table>
<thead>
<tr>
<th>Shutter Speed</th>
<th>Aperture</th>
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<tbody>
<tr>
<td>1/8</td>
<td>f/16</td>
</tr>
<tr>
<td>1/125</td>
<td>f/4</td>
</tr>
<tr>
<td>1/500</td>
<td>f/2</td>
</tr>
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</table>

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, lens, and color – video – slides
3. Basic theory of optical imaging systems – video – slides
4. Resolution, contrast, flare, noise, etc. – video – slides
5. Sensors, image sensors – video – slides
6. Image processing pipelines – video – slides
7. Lens image composition, part 1 – video – slides
8. Diffraction and spectroscopy – video – slides
9. Aerial photography – video – slides
10. Image compression, part 1 – video – slides
11. Document image analysis – video – slides
12. High dynamic range imaging – video – slides
13. Light field photography/photography – no video yet – no slides yet
15. The Gigapixel Project – no video yet – no slides yet
17. Color Management – no video yet – no slides yet