CS559 – Lecture 2
Lights, Cameras, Eyes

These are course notes (not used as slides)
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Adjusted after class – stuff we didn’t get to removed / mistakes fixed

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Light

• Electromagnetic radiation
  – Wavelengths between 380nm – 800nm
  – Wavelength vs. frequency

• Particle model
  – Travels from source to receiver

Path of Light

• From source to viewer

• Not known until around 1000
  – Euclid and Ptolemy PROVED otherwise
• Ibn Al-Haythan (Al-hazen) around 985
  – Triumph of the scientific method
    • Proof by observation – not authority
    • Experiment – stare at sun, burns eyes, …
    • Also figure out light travels in straight lines

Looking at things

• Light leaves source
• Light bounces off object
• Light goes to receiver
  – Eye
  – Camera

• Receiver is 2D, process is 3D
• Mathematics later

• Camera first
  – Flat receiver

Getting light to “imager”

• Light generally bounces off things in all directions
  – See from any direction
  – Not the same! (mirror)
  – Deal with this in detail later

• Generally doesn’t matter if emitter (source) or reflector
  – Same to receiver

Depth and Distance

• Light travels in straight lines
  – Except in weird cases that only occur in theoretical physics

• Doesn’t matter how far away
  – Can’t tell where photon comes from
  – Photons leaving source might not all make it to eye
  – Photons might bounce around on stuff
    • Longer distance, more chance of hitting something
Capturing Images

- Measure light at all places on the “imaging plane”?  
  - Not quite…
  - Potentially all paths between world and imager  
    - Need to be picky about which rays we look at

“Ideal Imaging”

- Each point in world maps to a single point in image  
  - Image appears sharp  
  - Image is “in focus”
- Otherwise image is “blurry”  
  - Image is out of focus

- How to do this?  
  - Pinhole Camera  
    - Infinitesimal hole in blocking surface – just a point  
    - Only 1 path from world point to image  
    - Focal Point

Why is pinhole imaging not so ideal in practice?

- Finite aperture  
  - Always will be some blurriness
- Too selective about light  
  - Lets very little light
- Smaller aperture  
  - Less blurry  
  - Less light
- Want bigger aperture, but keep sharpness

A “virtual pinhole” - Lenses

- Lens bends light
- Convex lenses – take bundles of light and make them converge (pass through a point)
- Parallel rays converge  
  - A virtual pinhole!
- Light rays from “far away” are (effectively) parallel
- What about non-parallel rays?  
  - Infinitesimal aperture = infinite sharpness

“Thin” Lenses

- All points at one distance get to another place
- Different distances map to different distances
- If we fix the distance to the image plane, then only objects at a single distance will be in focus  
  - $1/D + 1/I = 1/F$  
  - Farther objects image closer

Focusing with a lens

- Objects at “focussed distance” – sharp (in focus)
- Objects at other distances are not sharp
- Some blurriness is OK  
  - Circle of Confusion
- Depth of Field  
  - Range of distances that things are “close enough” to being in focus
Controlling the image

- Smaller aperture = less blurry = larger depth of field
  - But less light

- Lens determines
  - What gets to the imaging surface
  - What is in focus

Measuring on the image plane

- Want to measure / record the light that hits the image plane

- At every position on the image plane (in the image) we can measure the amount of light
  - Continuous phenomenon (move a little bit, and it can be different)
  - Can think of an image as a function that given a position \((x, y)\) tells us the “amount” of light at that position
    \[ i = f(x, y) \]
  - For now, simplify “amount” as just a quantity, ignoring that light can be different colors

Measuring on the image plane

- \( i = f(x, y) \)
- Continuous quantities
  - Continuous in space
  - Continuous in value

- Computers (and measuring in general) is difficult with continuous things

- Major issue
  - Limits to how much we can gather
  - Reconstruct continuous thing based on discrete set of observations
  - Manipulate discrete representations

Measuring on the image

- Water/rain analogy
  - Put a set of buckets to catch water
  - Wait over a duration of time
    - Use a shutter to control the amount of time

- Measurement depends on
  - Amount of light
  - Size of aperture (how much of the light we let through)
  - Duration

Types of “buckets”

- Film
  - Silver halide crystals change when exposed to light

- Electronic
  - Old analog ways – vidicon tubes
    - Store the charge on a plate, scan the plate to read
  - New ways: use an MOS transistor as a bucket

- Biological
  - Chemicals (photo-pigments) store the photon and release it as electricity
  - Isn’t really a shutter

Similarities

- Low light levels are hard
  - Need to get enough photons to measure
  - Small counting errors (noise) – are big relative to small measurements

- Tradeoffs on bucket sizes
  - Big buckets are good (lower noise in low light)
  - Lots of buckets are good (sense more places)
  - For a fixed area, there is a tradeoff
    - Especially in digital cameras/videocameras
MOS Transistors

- Metal Oxide Semiconductors
- Semiconductor acts as a "bucket" for electrons
- Metal at top is a "gate" – creates electric field that can connect/disconnect the two sides

CCD sensors

- CCD = Charge Coupled Device
- "Bucket Brigade" of MOS transistors
- Use gates to move charge along
- Read out "at edge"
- Shift register to transfer out images
- Advantage:
  - Cheap / easy to make large numbers of buckets
  - Uniform
  - Blooming

CMOS sensors

- Disadvantage of CCDs
  - Have to shift things out (slow, lose info)
  - Different than computer chips
- CMOS (complimentary Metal Oxide Semiconductor)
  - Just like computer chips
  - Put more circuitry around each sensor transistor
    - Amplify / switch signals as needed
  - Use normal "wires" to carry info to where it needs to go
- Downside: space for circuit means less space for sensors (smaller buckets = more noise), not uniform
- Upside: same "technology curve" as computers, so will get better, faster, cheaper, lower power, …

Digital Camera

- Megapixels = number of buckets
  - 7 or 8 million buckets in a consumer camera

- But...
  - How big are the sensors?
    - Same size / more megapixels = smaller buckets = more noise
    - (unless the sensor technology gets better)
  - How good is the lens?
    - Smaller buckets don’t do you any good if the lens can’t aim it into the right bucket

Eye

- Pupil – hole in the eye
- Lens
- Iris
  - round muscle – size of pupil
- Cornea
  - Clear protective coating
- Fluid filled spaces – acts as lens
  - Aqueous humor
  - Vitreous humor
- Rectus Muscles
  - Change shape of eyeball to focus
- Optic Nerve
  - Carries information away
- Blind Spot
  - Where the optic nerve is
- Central Fovea

Retina – the “image plane” of the eye

- Only place on body to see blood vessels directly
- Has photoreceptors
  - Cells sensitive to light
- Photopigments
  - chemicals that change when exposed to light
  - Different photoreceptors have different pigments
  - Different pigments behave differently
    - Sensitivity, color selectivity, regeneration speed
- Types of photoreceptors
Rods

- **Photopigment: Rhodopsin**
  - Breaks into retinene + protein
  - Must be reassembled before can work again
- **Very sensitive**
  - Bright light means that it breaks down faster than it is regenerated
  - Less useful in bright light
- **Blinded by bright light at night**