Computational Photography

Prof. Rob Fergus
Spring 2008

Overview of Today

- Introduction to Computational Photography
- Course Administration
- Syllabus
- History
- Image formation

What is Computational Photography

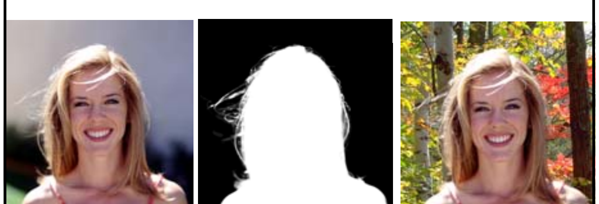
- Convergence of image processing, computer vision, computer graphics and photography
- Digital photography:
  - Simply replaces traditional sensors and recording by digital technology
  - Involves only simple image processing
- Computational photography
  - More elaborate image manipulation, more computation
  - New types of media (panorama, 3D, etc.)
  - Camera design that take computation into account

Spot the difference

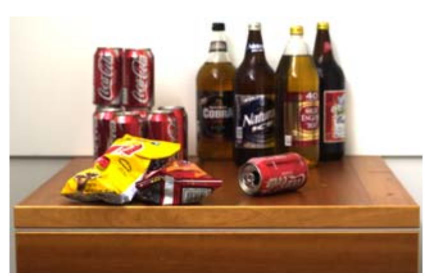
Film c ... camera

Example 1: Matting

- Object cut'n'paste
- Non-binary mask



Example 2: Coded Aperture Imaging

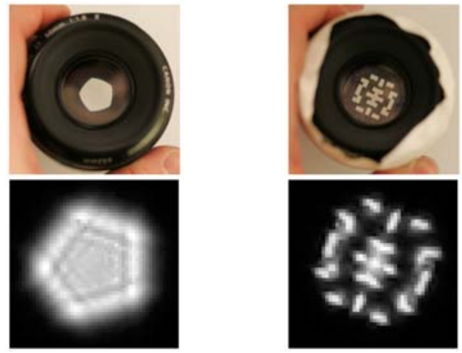


Depth and image from a single image

Output:

Conventional aperture

Coded aperture

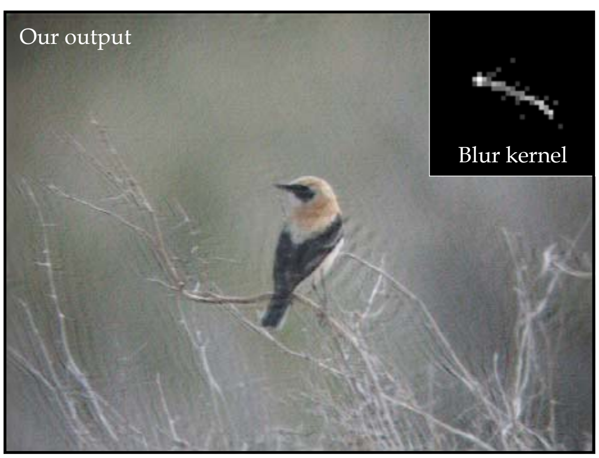


Example 3: Tone mapping

- One of your assignments!

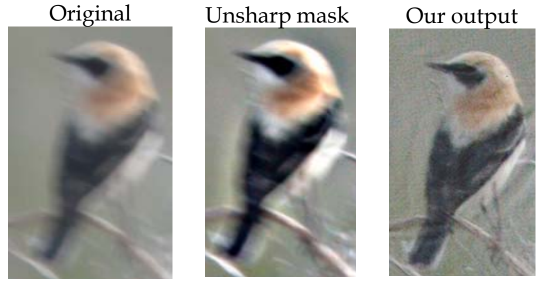
Example 4: Deblurring

Original photograph



Example 4: Deblurring

Original | Unsharp mask | Our output



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People

- Instructor
  - Rob Fergus (fergus@cs.nyu.edu)
  - Office: Room 1226, 719 Broadway
  - Office hours: 8-9pm Wednesday
- Teaching Assistant
  - Dennis Kovacs (kovacs@cs.nyu.edu)
- Course web page:
  http://cs.nyu.edu/~fergus/teaching/comp_photo.html

Grading

- 50% coursework
  - Proposal due with 1st homework
  - See webpage for options
  - Due at end of course
  - Can pair up with another person
- 50% home work assignments
  - 3 assignments throughout course
  - Turn in code and results

Programming Language

- Matlab
  - Assume some familiarity with it
  - Is installed on Courant machines
  - Tutorial available on course webpage
- Can use what ever you want for projects

Equipment

- Machine with Matlab on
- May need digital camera for some projects
  - Can borrow from me
- Won't need Adobe Photoshop

Textbook

- No course textbook
- Siggraph course notes
  - http://www.merl.com/people/raskar/photo
  - Levoy's notes too
- Lots of web resources
  - See links on course webpage

Introductions

- Who are you?
  - Fill in sheet, so I have your details
- What are your interests?
- How much math do you have?

Math show-of-hands

- Principal Components Analysis (PCA)
- Fourier transform
- Matrix pseudo-inverse
- Conjugate gradient descent
- Maximum a-posteriori (MAP)
- Markov Random Field
- Laplace approximation

What the course is NOT about

- Artistic side of photography
- How to use a camera
- Adobe Photoshop
  - But will explain how its coolest tools work
- Optics
- Little on EE hardware (Sensors, A/D)
- Not directly about Computer Vision or Graphics

What the course is about

- Basic image processing
  - Linear & Non-linear, Statistical, Color
- Software tools of Computational Photography
- Little bit on hardware aspects
  - Lenses, funky new camera designs
- Cool applications

Skills you will acquire

- Implement:
  - Panorama stiching
  - Matting
  - Gradient reconstruction
  - Color demosaicing
  - Etc.
- What important problems in area
  - Suitable research topics
- Many of the techniques are widely applicable to vision, graphics and beyond

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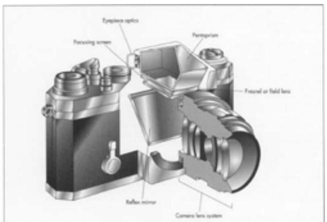
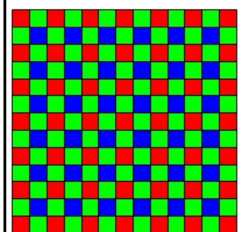
Syllabus

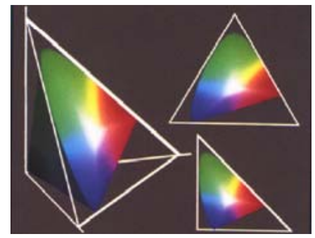
- Image formation
  - How cameras take a picture



Color

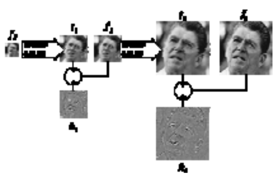
- Demosaicing
- Color spaces, color perception





Wavelet / Frequency domain

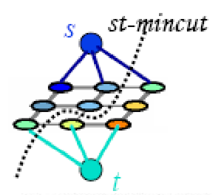
- Gaussian/Laplacian image pyramids



- Frequency domain representation
- Image priors
- Aliasing

Fundamental math/tools

- Graph cuts
- MRF



- Natural image statistics
- Sparse image priors

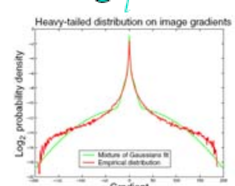


Image processing

- Denoising
- Bilateral filtering

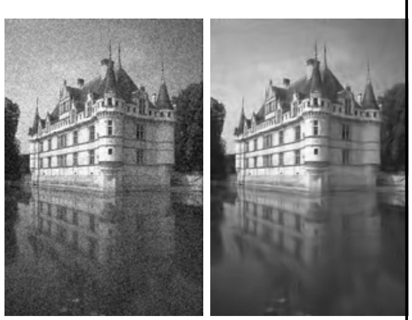


Image blending & compositing

- Gradient domain image manipulation

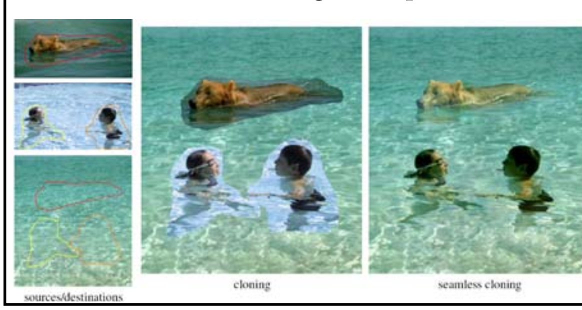
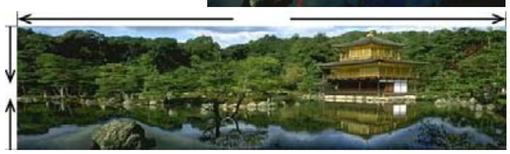


Image warping

- Scene carving



Non-parametric methods

- Image analogies
- Synthesis

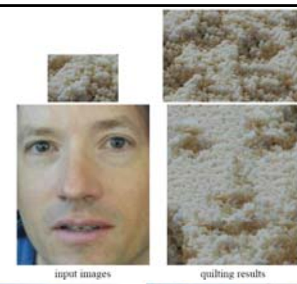
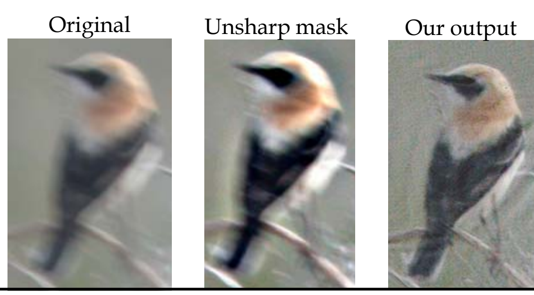


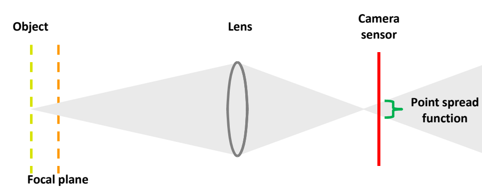
Figure 1 An image analogy. Our problem is to compute a new "analogous" image B' that relates to B in "the same way" as A' relates to A. Here, A, A', and B are inputs to our algorithm, and B' is the output. The full-size images are shown in Figures 10 and 11.

Deblurring

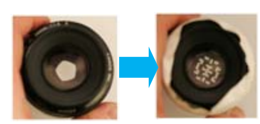
- Non-blind
- Blind



Depth from Defocus



- Coded aperture



Matting

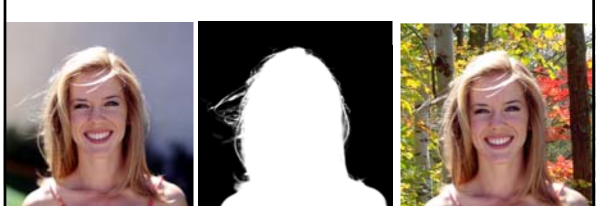
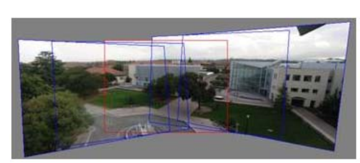


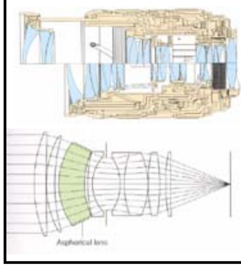
Image registration

- Panoramas
- RANSAC



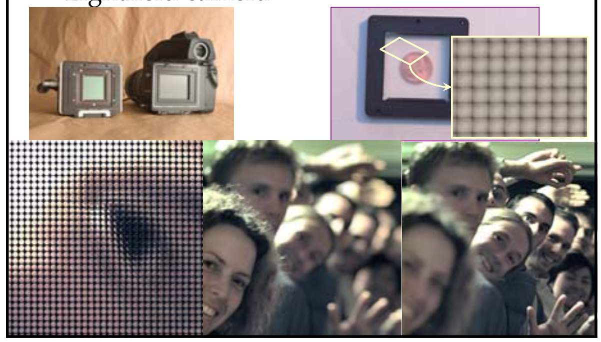
Flash/no-flash

- Active flash methods
- Lens design



Novel Camera Designs

- Lightfield camera



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History

- Courtesy of Fredo Durand (MIT)
- Quick overview of cameras from their invention to the present day
- Electronics only feature fairly recently

Quiz

- **When was photography invented? 1826**
- **By whom? Niepce**
  - Exposure time? 8 hours

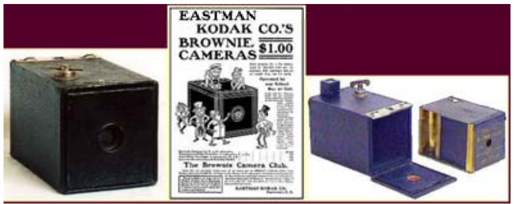
- **William Henry Fox Talbot invents the *calotype* in 1834 which pretty much invents the negative**

First production camera?

- **1839. Daguerrotype**

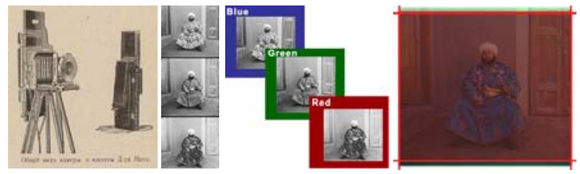
Beginning of hobby photography?

- 1900 Kodak Brownie



Quiz

- Who did the first color photography?
  - Maxwell
    (yes, the same from the EM equations)
- When? 1861
- Oldest color photos still preserved: Prokudin-Gorskii http://www.loc.gov/exhibits/empire/

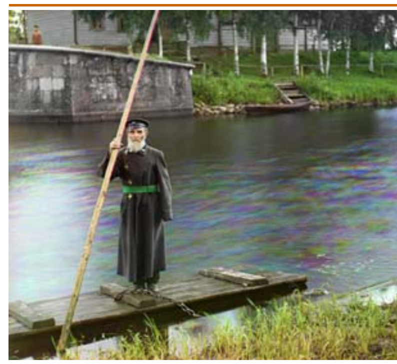


Prokudin-Gorskii

- Digital restoration

http://www.loc.gov/exhibits/empire/

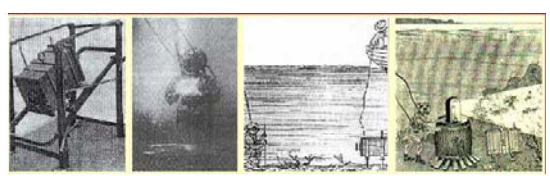
Prokudin-Gorskii



Prokudin-Gorskii

Flash bulb?

- As opposed to podwer systems
- Boutan-Chauffour - 1893
- For underwater photography



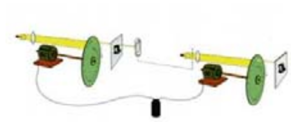
Instant photography?

- 1947, Edwin Land (Polaroid founder)

First TV?

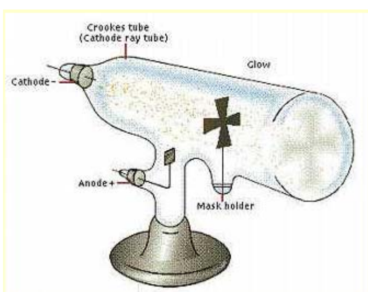
Transmission of moving images

- 1884 - Paul Nipkow
  - Using rotating disk with raster spiral
  - But amplification problems



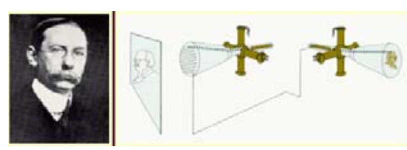
CRT?

- 1897
- Karl Braun



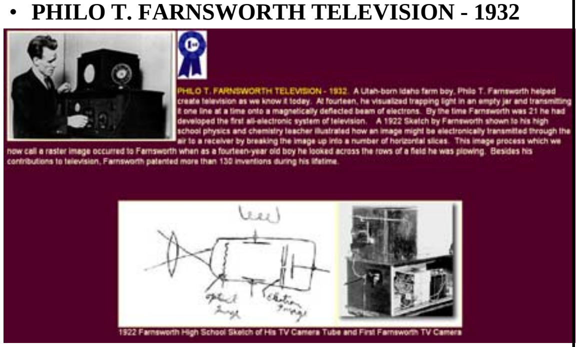
Electronic photography?

- A. A. CAMPBELL SWINTON AND ELECTRONIC PHOTOGRAPHY - 1908
- 25 images per second



Television (II)

- PHILO T. FARNSWORTH TELEVISION - 1932



Color TV

- First broadcast in 1951, CBS

Transistor?

- 1947, Bell Labs (Nobel in 1956)
- William Shockley, John Bardeen and Walter Brattain

Integrated circuit?

- 1959 Bob Noyce of Fairchild Semiconductor (co-founded Intel Corporation in 1968)
  - One transistor, one capacitor
- Also Jack Kilby of Texas Instruments
  - Also inventor of portable calculator

Intel gang

http://www.pbs.org/transistor/background1/events/icinv.html

Autofocus

- 1978, Konica

- 1981 Pentax ME-F.

- Canon T80 1985
  - Canon AL1 had focus assist but no actuator
- Minolta Maxxum 1985 (AF in body)

First microprocessor in a camera

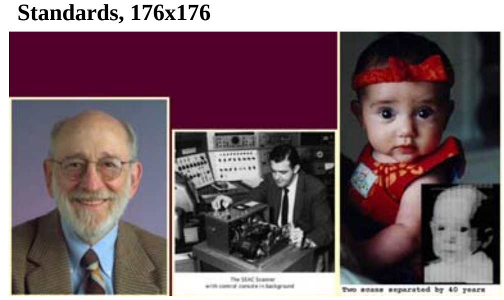
- Canon AE-1976

Japanese take over camera market?

- 1959 Nikon F
  - First motorized SLR
  - First 100% viewfinder
  - Mirror lockup
- Lots of pros switched from Leica to Nikon

First scanned photo?

- 1957, Russell A. Kirsch of the National Bureau of Standards, 176x176



CCD technology?

- 1969, Willard S. Boyle and George E. Smith, Bell Laboratories

CCD in astronomy

- 1979, 1-meter telescope at Kitt Peak National Observatory, 320x512, great for dim light
- Nitrogen cooled

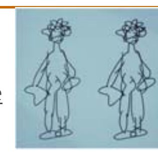
Computer Graphics?

Computers to create image

- Sketchpad, 1961, Ivan Sutherland's MIT PhD thesis

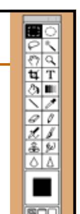
Paint program

- Dick Shoup: SuperPaint [1972-73]
  - 8 bits
  - http://www.rgshoup.com/prof/SuperPaint/
- Alvy Ray Smith (Pixar co-founder): Paint [1975-77]
  - 8 bits then 24 bits
  - http://www.alvyray.com/Awards/AwardsMain.htm
  - http://www.alvyray.com/Bio/BioMain.htm
- Tom Porter: Paint



Photoshop

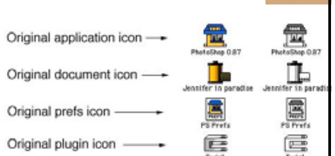
- Thomas Knoll and John Knoll began development in 1987
- Version 1.0 on Mac: 1990
- http://en.wikipedia.org/wiki/Photoshop#Development
- http://www.storyphoto.com/multimedia/multimedia_photoshop.html



Photoshop toolbar from version 1.07

John Knoll. Photo by Jeff Schewe.

Thomas Knoll. Photo by Jeff Schewe.



The original application icons designed by John Knoll.

Internet photo browsing

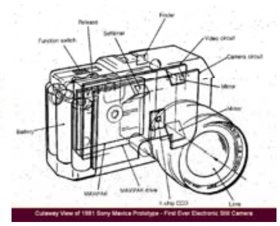
- (Web browser that can display photos)
- Mosaics, NCSA, Urbana Champaign, 1992

First digital camera?

- 1975, Steve Sasson, Kodak
- Uses ccd from Fairchild semiconductor, A/D from Motorola, .01 megapixels, 23 second exposure, recorded on digital cassette

Still video camera

- Sony Mavica 1981
  - Electronic but analog



Completely Digital Commercial camera

- 1991 first completely digital Logitech Dycam 376x240

http://www.g4tv.com/l

Digital

- 1994 Apple quicktake, first mass-market color digital camera, 640 x 480 (commercial failure)

http://www-users.mat.uni.torun.pl/~olka/l

First megapixel sensor

- Of reasonable size?
- (Kodak) Videk 1987, 1.4MPixels

Digital SLR?

- 1992 Kodak DCS 200, 1.5 Mpixels, based on Nikon body

Pros adopt digital?

- Nikon D1 1999, 2.7MPixels

Consumer digital SLR?

- Canon D30, 2000 3MPixels

Current cameras

Canon 40D: 12 MP

Canon 950IS: 8MP

Hasselblad H3D: 39 MP

Break !!!

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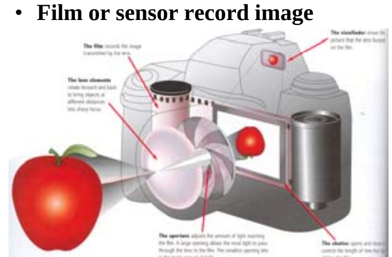
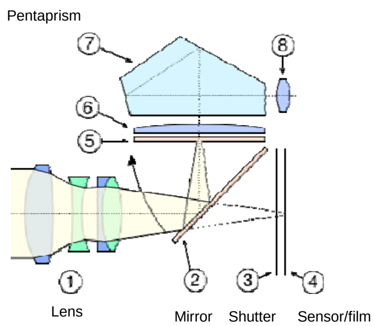
Overview

- Lens and viewpoint determine perspective
- Aperture and shutter speed determine exposure
- Aperture and other effects determine depth of field
- Film or sensor record image

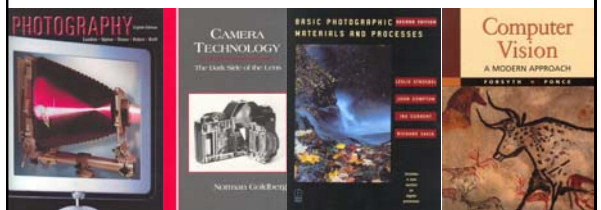


SLR Design



Reference

http://en.wikipedia.org/wiki/Lens_(optics)

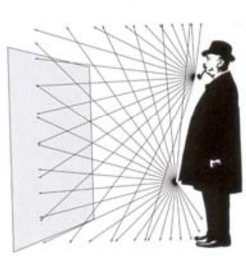


- The slides use illustrations from these books

Overview

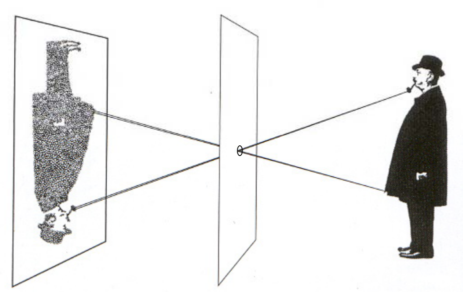
- Pinhole camera
- Lenses
- Exposure
- Sensor

It receives light from all directions



From Photography, London et al.

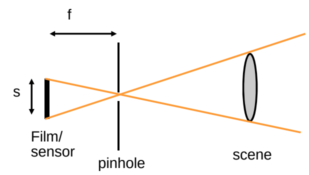
Pinhole



From Photography, London et al.

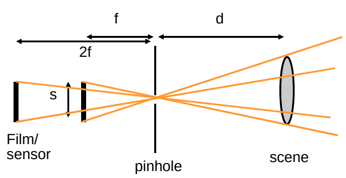
Pinhole demo

Focal length

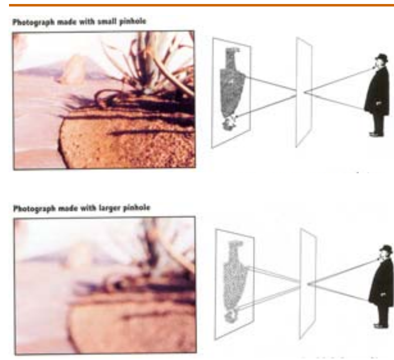


Focal length: pinhole optics

- **What happens when the focal length is doubled?**
  - Projected object size is doubled
  - Amount of light gathered is divided by 4



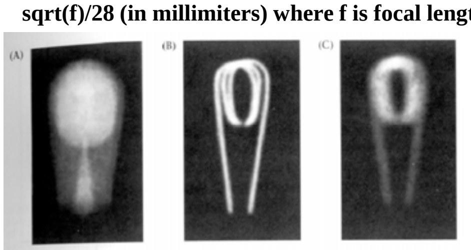
Pinhole size?



From Photography, London et al.

Diffraction limit

- **Optimal size for visible light: sqrt(f)/28 (in millimiters) where f is focal length**



2.18 DIFFRACTION LIMITS THE QUALITY OF PINHOLE OPTICS. These three images of a bulb filament were made using pinholes with decreasing size. (A) When the pinhole is relatively large, the image rays are not properly converged, and the image is blurred. (B) Reducing the size of the pinhole improves the focus. (C) Reducing the size of the pinhole further worsens the focus, due to diffraction. From Ruechardt, 1958.

From Wandell

Solution: refraction!

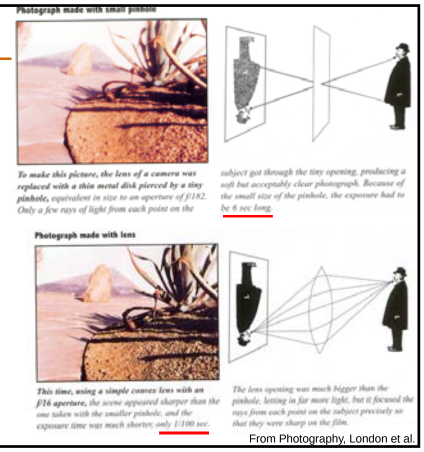
From Photography, London et al.

Overview

- Pinhole camera
- Lenses
- Exposure
- Sensor

Lenses

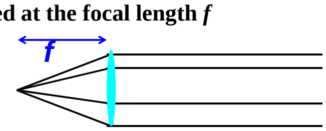
- gather more light!
- But need to be focused



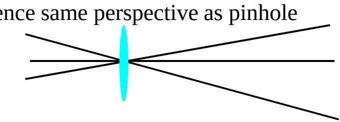
Lens demo

Thin lens optics

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

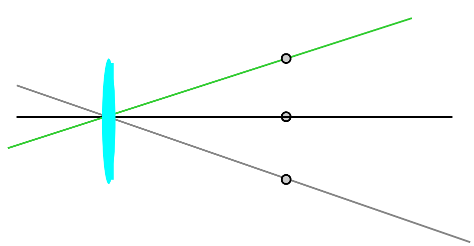


- All rays going through the center are not deviated
  - Hence same perspective as pinhole



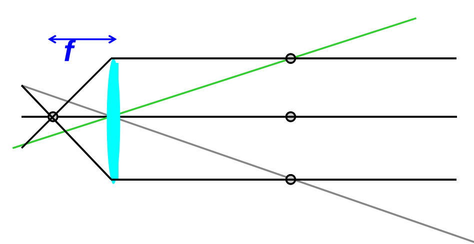
How to trace rays

- Start by rays through the center



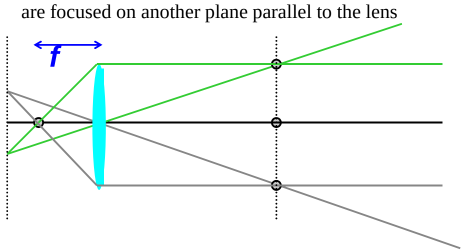
How to trace rays

- Start by rays through the center
- Choose focal length, trace parallels



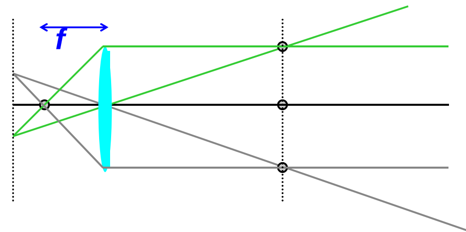
How to trace rays

- **Start by rays through the center**
- **Choose focal length, trace parallels**
- **You get the focus 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

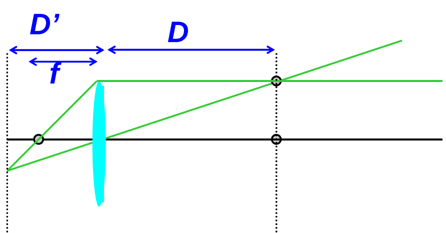


Focusing

- **To focus closer than infinity**
  - Move the sensor/film ***further*** than the focal length

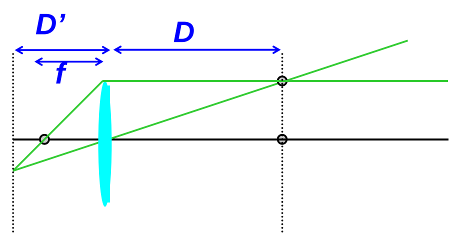


Thin lens formula



Thin lens formula

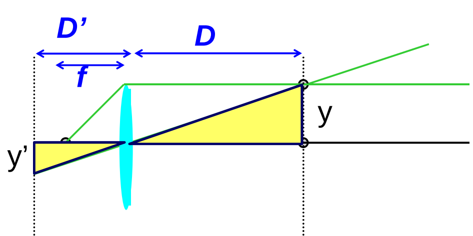
Similar triangles everywhere!



Thin lens formula

Similar triangles everywhere!

y’/y = D’/D

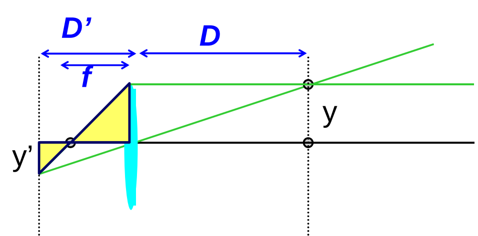


Thin lens formula

Similar triangles everywhere!

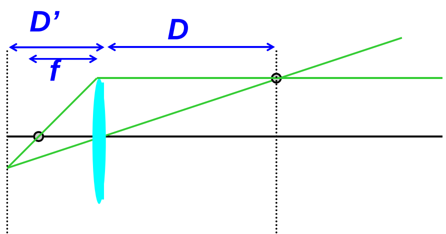
y’/y = D’/D

y’/y = (D’-f)/f



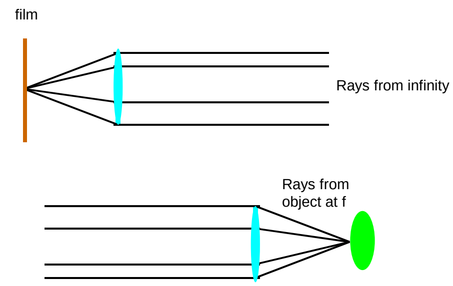
Thin lens formula

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



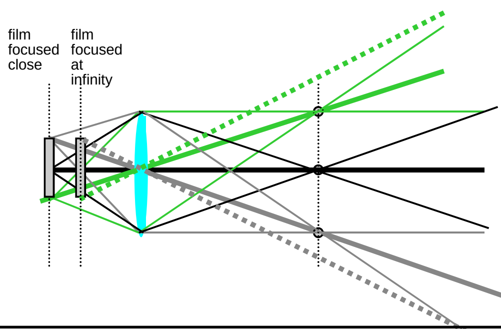
Minimum focusing distance

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

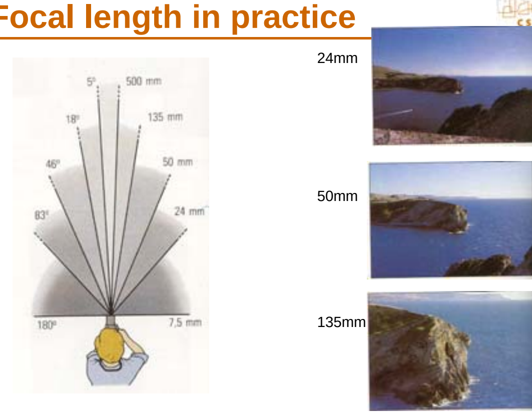


Field of view & focusing

- What happens to the field of view when one focuses closer?
  - It's reduced

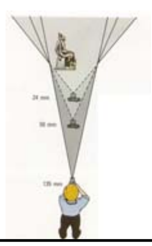


Focal length in practice



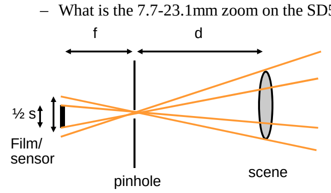
Perspective vs. viewpoint

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



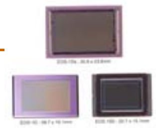
Focal length & sensor

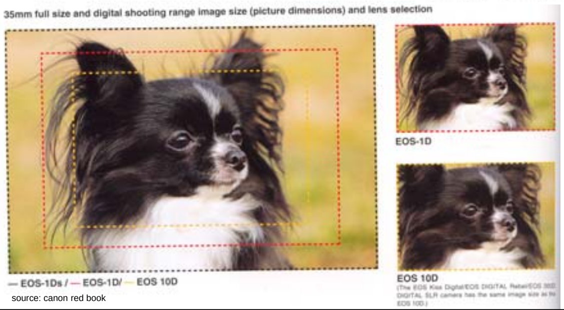
- What happens when the film is half the size?
- Application:
  - Real film is 36x24mm
  - On the 40D, the sensor is 22.5 x 15.0 mm
  - Conversion factor on the 40D?
  - On the SD500, it is 1/1.8 " (7.18 x 5.32 mm)
  - What is the 7.7-23.1mm zoom on the SD500?



Sensor size

- **Similar to cropping**





source: canon red book

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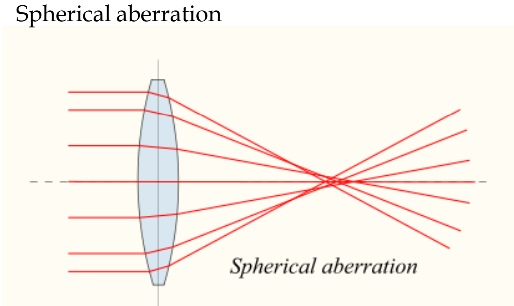
http://www.photozone.de/3Technology/digital_1.htm

Lens imperfections

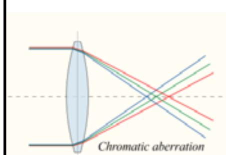
1. Spherical aberration



From Wikipedia

Lens inperfections

2. Chromatic aberration

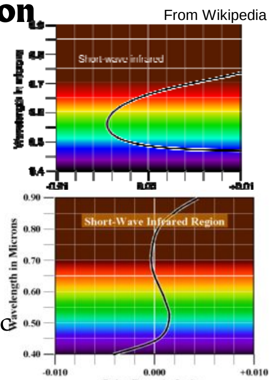


From Wikipedia

Correcting Chromatic Aberration

- Use multiple lens elements
- Green & Blue in focus → acromatic
- Red, Green & Blue in focus → apochromatic

From Wikipedia



Recap

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

Handout lenses

Overview

- Pinhole camera
- Lenses
- Exposure
- Sensor

Exposure

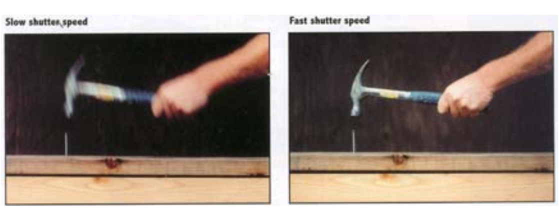
- **Get the right amount of light to sensor/film**
- **Two main parameters:**
  - Shutter speed
  - Aperture (area of lens)

Shutter speed

- **Controls how long the film/sensor is exposed**
- **Pretty much linear effect on exposure**
- **Usually in fraction of a second:**
  - 1/30, 1/60, 1/125, 1/250, 1/500
  - Get the pattern ?
- **On a normal lens, normal humans can hand-hold down to 1/60**
  - In general, the rule of thumb says that the limit is the inverse of focal length, e.g. 1/500 for a 500mm

Main effect of shutter speed

- **Motion blur**



From Photography, London et al.

Effect of shutter speed

- **Freezing motion**

Walking people

1/125

Running people

1/250

Car

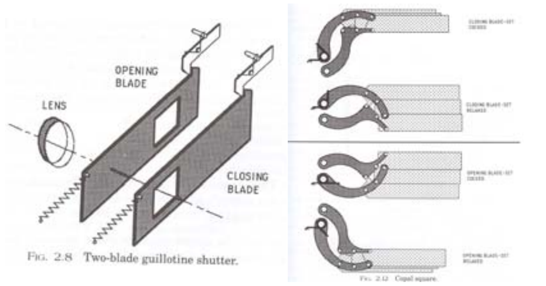
1/500

Fast train

1/1000

Shutter

- **Various technologies**
- **Goal: achieve uniform exposure across image**



From Camera Technology, Goldber

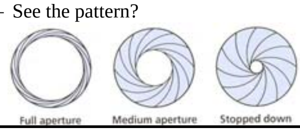
Your best friend

- **Use a tripod! It will always enhance sharpness**
  - Avoid camera shake

  - More about shake & stabilization in lens lecture

Aperture

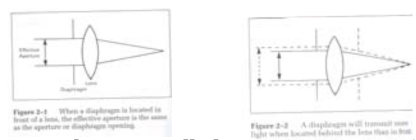
- **Diameter of the lens opening (controlled by diaphragm)**
- **Expressed as a fraction of focal length, in f-number**
  - f/2.0 on a 50mm means that the aperture is 25mm
  - f/2.0 on a 100mm means that the aperture is 50mm
- **Disconcerting: small f number = big aperture**
- **What happens to the area of the aperture when going from f/2.0 to f/4.0?**
- **Typical f numbers are f/2.0, f/2.8, f/4, f/5.6, f/8, f/11, f/16, f/22, f/32**
  - See the pattern?



$$\text{Area} = \pi \left(\frac{f}{2N}\right)^2$$

Aperture & physical lens size

- **On telephoto, the lens size is directly dictated by the max (that is min) f number**
- **Other lenses, not always clear**
- **The aperture can be internal or not**



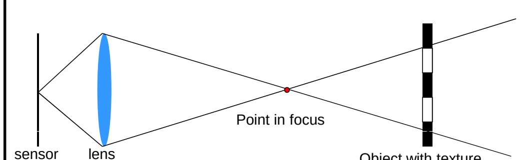
- **Zoom lenses usually have a variable maximal aperture**
  - Why?

Main effect of aperture

- **Depth of field**

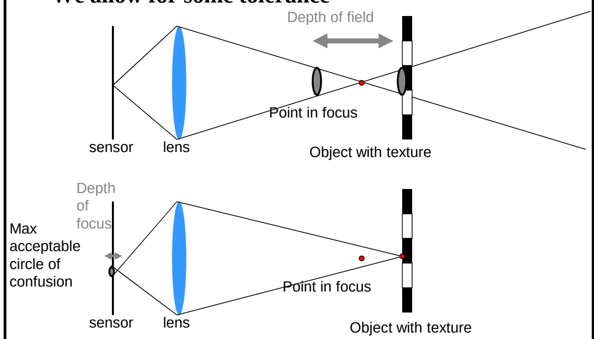
From Photography, London et a

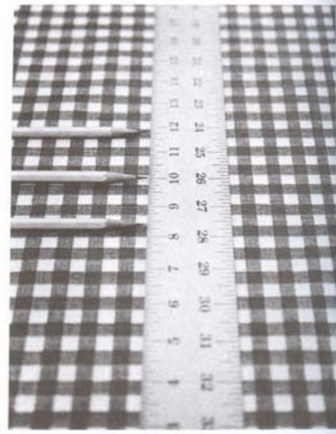
Depth of field



Depth of field

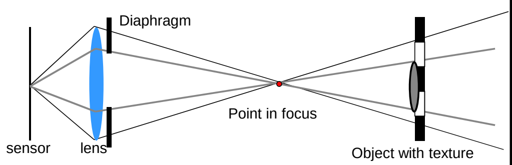
- **We allow for some tolerance**



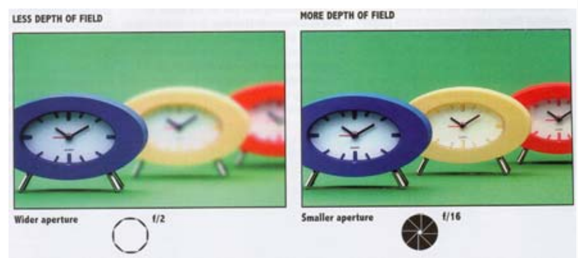


Depth of field

- **What happens when we close the aperture by two stop?**
  - Aperture diameter is divided by two
  - Depth of field is doubled



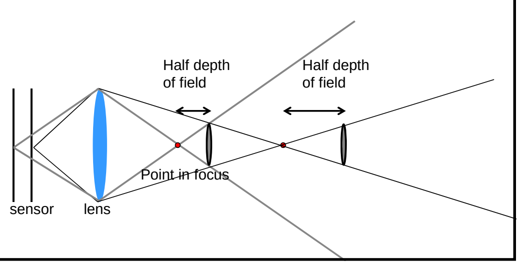
Depth of field



From Photography, London et a

Depth of field & focusing distance

- **What happens when we divide focusing distance by two?**
  - Similar triangles => divided by two as well



Depth of field & focusing distance

- **What happens when we divide focusing distance by two?**
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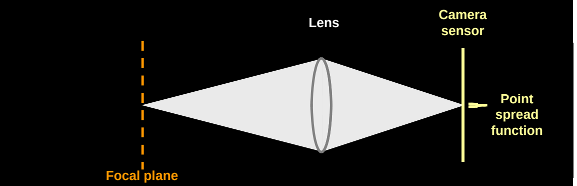
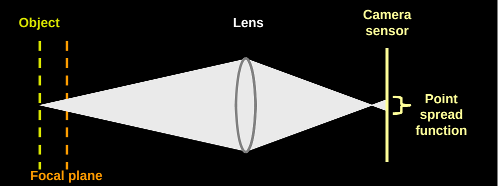
From Photography, London et a

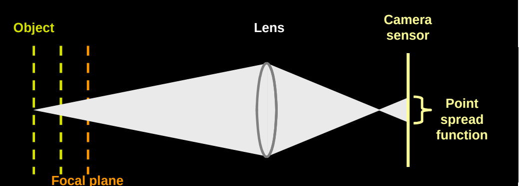
Lens and defocus



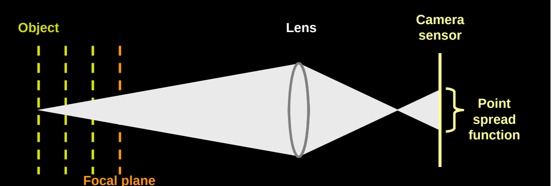
Lens and defocus



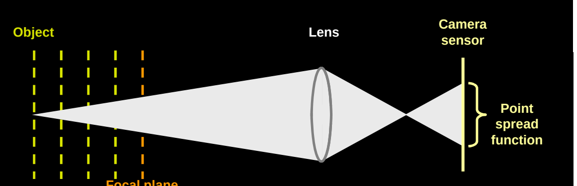
Lens and defocus



Lens and defocus

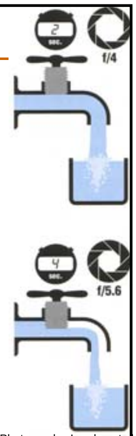


Lens and defocus



Depth and defocus demo

Exposure



- **Two main parameters:**
  - Aperture (in f stop)
  - Shutter speed (in 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 two progression of f stops vs. power of two progression of shutter speed
  - Reciprocity can fail for very long exposures

From Photography, London et a

Reciprocity

- **Assume we know how much light we need**
- **We have the choice of an infinity of shutter speed/aperture pairs**

- **What will guide our choice of a shutter speed?**
  - Freeze motion vs. motion blur, camera shake
- **What will guide our choice of an aperture?**
  - Depth of field, diffraction limit
- **Often we must compromise**
  - Open more to enable faster speed (but shallow DoF)

Small aperture (deep depth of field), slow shutter speed (motion blurred). *In t scene, a small aperture (f/16) produced great depth of field: the nearest pavi stones as well as the farthest trees are sharp. But to admit enough light, a slo shutter speed (1/8 sec) was needed; it was too slow to show moving pigeons sh It also meant that a tripod had to be used to hold the camera steady.*

From Photography, London et a

Medium aperture (moderate depth of field), medium shutter speed (some motion sharp). *A medium aperture (f/4) and shutter speed (1/125 sec) sacrifice some background detail to produce recognizable images of the birds. But the exposure is all too long to show the motion of the birds' wings sharply.*

From Photography, London et a

Large aperture (shallow depth of field), fast shutter speed (motion sharp). *A fa shutter speed (1/500 sec) stops the motion of the pigeons so completely that the flapping wings are frozen. But the wide aperture (f/2) needed gives so little dept of field that the background is now out of focus.*

From Photography, London et a