BBM 413 Fundamentals of Image Processing

Erkut Erdem
Dept. of Computer Engineering
Hacettepe University

Introduction

Today

- What is image processing?
- Image formation
- Digital images

Today

- But, first logistics..
  - About the class
  - Organization of this course

About this course

- This course is an advanced level undergraduate course about the fundamentals of image processing.
- **Requirements**
  - Programming skills
  - Good math background (Calculus, Linear Algebra, Statistical Methods)
  - Little or no prior knowledge of image processing techniques
- **BBM 415 Introduction to Programming Practicum**
  - The students will gain hand-on experience via a set of programming assignments.

About this course (cont'd.)

- **Goals of the course:**
  - to provide an introduction to students who wish to specialize in interrelated disciplines like image processing, computer vision and computational photography
- **Skills to develop:**
  - a foundational understanding and knowledge of concepts that underlie image processing
- **What is image processing?**
  - What does image processing deal with?
  - Computational analysis of low and mid-level vision

BBM 413-415 Team

Instructor

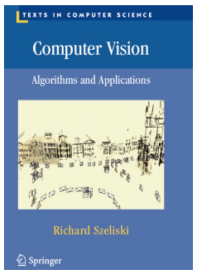
Erkut ERDEM
erkut@cs.hacettepe.edu.tr

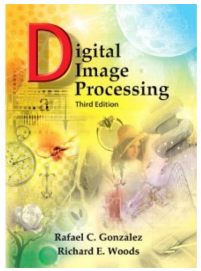
TA

Özge Yalcinkaya
ozge@cs.hacettepe.edu.tr

Textbooks and Reference Material

- Computer Vision: Algorithms and Applications, Richard Szeliski, Springer, 2010
- Digital Image Processing, R. C. Gonzalez, R. E. Woods, 3rd Edition, Prentice Hall, 2008





- Lecture notes and handouts
- Papers and journal articles

Communication

- The course webpage will be updated regularly throughout the semester with lecture notes, programming and reading assignments and important deadlines.

  http://web.cs.hacettepe.edu.tr/~erkut/bbm413.f18

Getting Help

- **Office hours**
  - Wednesdays, 4-6 pm
- **BBM 415 Image Processing Practicum**
  - Course related recitations, practice with example codes, etc.
- **Communication**
  - Announcements and course related discussions through piazza

https://piazza.com/hacettepe.edu.tr/fall2018/bbm413

BBM 415 Image Processing Practicum

- **Programming assignments (PAs) - 20% each**
  - Four programming assignments throughout the semester.
  - Each assignment has a well-defined goal such as solving a specific problem.
  - You must work alone on all assignments stated unless otherwise.
- **A set of quizzes – 20%**
  - Lowest 2 quiz grades will be dropped
- **Important Dates *(Tentative)***
  - PA 1 due: November 2nd
  - PA 2 due: November 23rd
  - PA 3 due: December 14th
  - PA 4 due: December 28th

Policies

- **Work groups**
  - You must work alone on all assignments stated unless otherwise
- **Submission**
  - Assignments due at 23:59 on Friday evenings
  - Electronic submissions (no exceptions!)
  - Submission details will be announced soon.
- **Lateness penalties**
  - Get penalized **10% per day**
  - No late submission later than **3 days after due date**

Course work and grading

- **Course project (25%)**
  - done in groups of 2-3 students
  - https://web.cs.hacettepe.edu.tr/~erkut/bbm413.f18/project/project.html
- **Midterm exam (30%)**
  - Closed book and notes including reading assignments
  - In class on December 4th
- **Final exam (40%)**
  - Closed book and notes
  - To be scheduled by Registrar
- **Class participation (5%)**

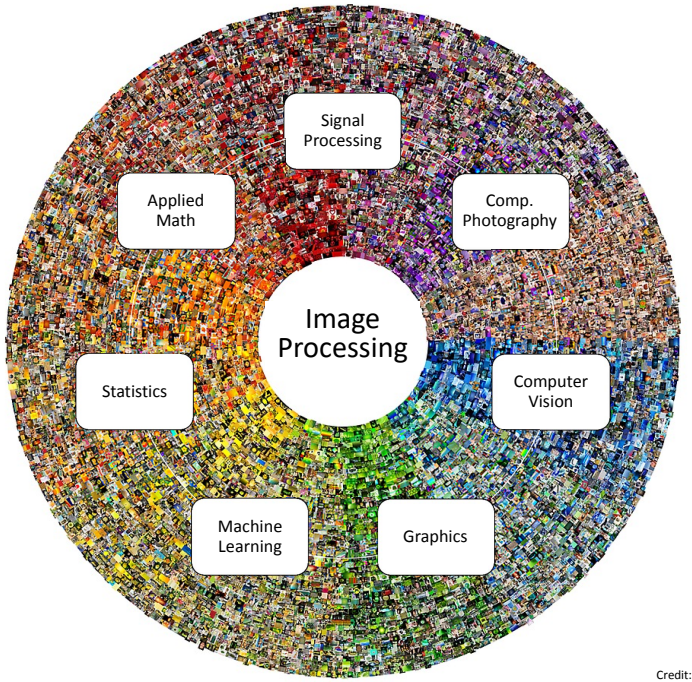
Course Overview

- Introduction, and Image formation *(1 week)*
- Color and Point operations *(1 week)*
- Spatial filtering *(1 week)*
- Frequency Domain Techniques *(2 weeks)*
- Image pyramids and wavelets *(1 week)*
- Gradients, edges, contours *(1 week)*
- Image smoothing *(1 week)*
- Image segmentation *(1 week)*
- Deep learning basics *(1 week)*
- Convolutional neural networks and their applications *(1 week)*

Midterm exam

Today

- What is image processing?
  - What does it mean, to see?
  - Vision as a computational problem
  - Sample image processing problems
- Image formation
- Digital images

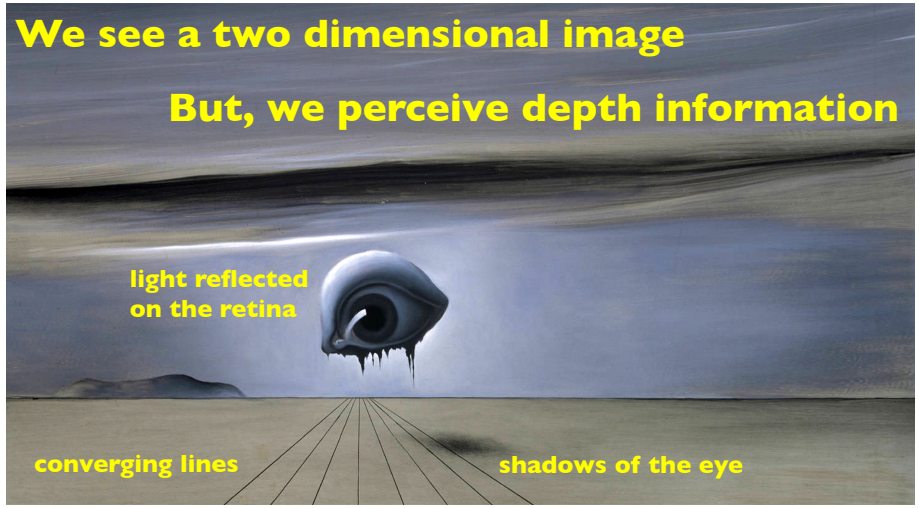


Credit: P. Milanfar

What does it mean, to see?

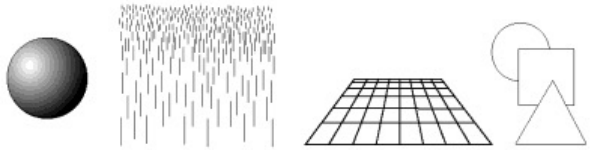
- *"The plain man's answer (and Aristotle's, too) would be, to know what is where by looking. In other words, vision is the process of discovering from images what is present in the world, and where it is."* David Marr, Vision, 1982
- Our brain is able to use an image as an input, and interpret it in terms of objects and scene structures.

What does Salvador Dali's *Study for the Dream Sequence in Spellbound (1945)* say about our visual perception?



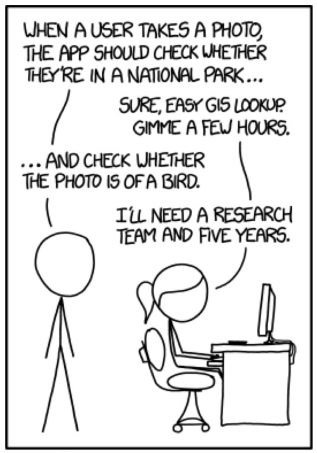
Why does vision appear easy to humans?

- Our brains are specialized to do vision.
- Nearly half of the cortex in a human brain is devoted to doing vision (cf. motor control ~20-30%, language ~10-20%)
- *"Vision has evolved to convert the ill-posed problems into solvable ones by adding premises: assumptions about how the world we evolved in is, on average, put together"*
  Steven Pinker, How the Mind Works, 1997
- Gestalt Theory (Laws of Visual Perception), Max Wertheimer, 1912



Figures: Steven Pinker, How the Mind Works, 1997

Why does vision appear easy to humans?



http://xkcd.com/1425/

Computer Vision

- "Vision is a process that produces from images of the external world a description that is useful to the viewer and not cluttered with irrelevant information" ~David Marr
- The goal of Computer Vision:
  To develop artificial machine vision systems that make inferences related to the scene being viewed through the images acquired with digital cameras.

Things that are easy for us are difficult for computers and viceversa ~ *Marvin Minsky*

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
PROJECT MAC

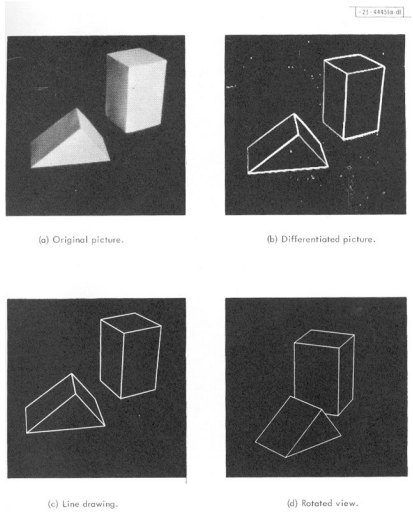
Artificial Intelligence Group July 7, 1966
Vision Memo. No. 100.

THE SUMMER VISION PROJECT

Seymour Papert

The summer vision project is an attempt to use our summer workers effectively in the construction of a significant part of a visual system. The particular task was chosen partly because it can be segmented into sub-problems which will allow individuals to work independently and yet participate in the construction of a system complex enough to be a real landmark in the development of "pattern recognition".

Origins of computer vision



(a) Original picture. (b) Differentiated picture. (c) Line drawing. (d) Rotated view.

L. G. Roberts, *Machine Perception of Three Dimensional Solids,* Ph.D. thesis, MIT Department of Electrical Engineering, 1963.

Slide credit: S. Lazebnik

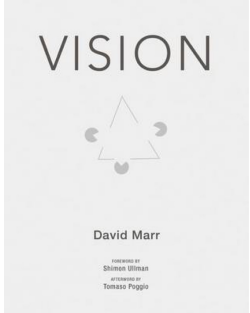
Vision: a very difficult computational problem, at several levels of understanding

- Vision as an information processing task [David Marr, 1982]
- Three levels of understanding:

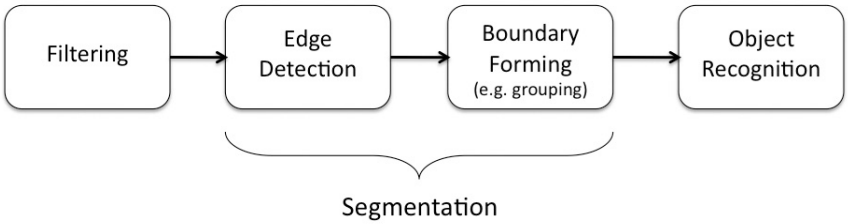
1. Computational theory
   - What is computed? Why it is computed?
2. Representation and Algorithm
   - How it is computed?
   - Input, Output, Transformation
3. Physical Realization
   - Hardware

Reading Assignment #1

- D. Marr (1982). Vision: A Computational Investigation into the Human Representation and Processing of Visual Information. Chapter 1.

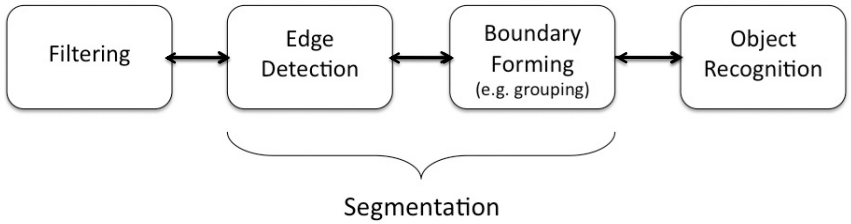


Visual Modules and the Information Flow



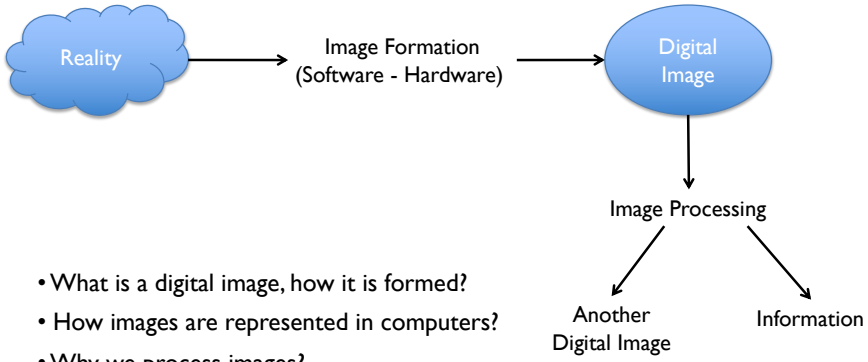
- Visual perception as a data-driven, bottom-up process (traditional view since D. Marr)
- Unidirectional information flow
- Simple low-level cues >> Complex abstract perceptual units

Visual Modules and the Information Flow



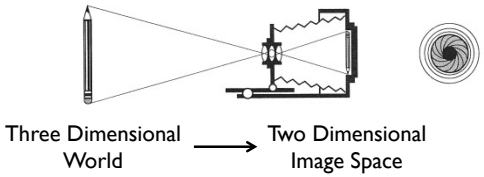
- Vision modules can be categorized into three groups according to their functionality:
  - Low-level vision: filtering out irrelevant image data
  - Mid-level vision: grouping pixels or boundary fragments together
  - High-level vision: complex cognitive processes

Fundamentals of Image Processing



- What is a digital image, how it is formed?
- How images are represented in computers?
- Why we process images?
- How we process images?

Image Formation

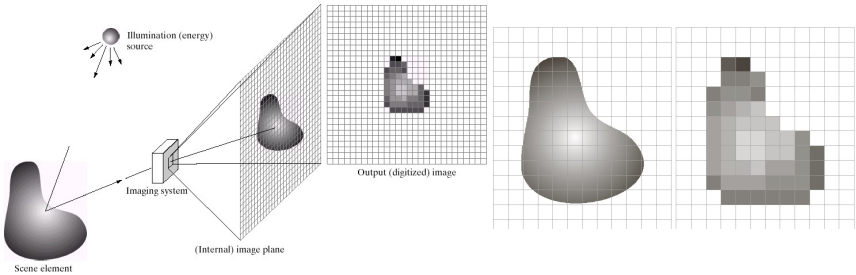


- What is measured in an image location?
  - brightness
  - color

<< viewpoint, illumination conditions, local geometry, local material properties

Figures: Francis Crick, The Astonishing Hypothesis, 1995

Image Formation



- Discretization
  - in image space - sampling
  - In image brightness - quantization

Figures: Gonzalez and Woods, Digital Image Processing, 3rd Edition, 2008

Image Representation

- **Digital image:** 2D discrete function f
- **Pixel**: Smallest element of an image f(x,y)

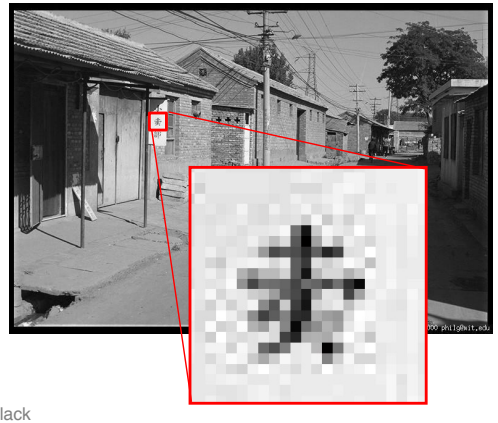
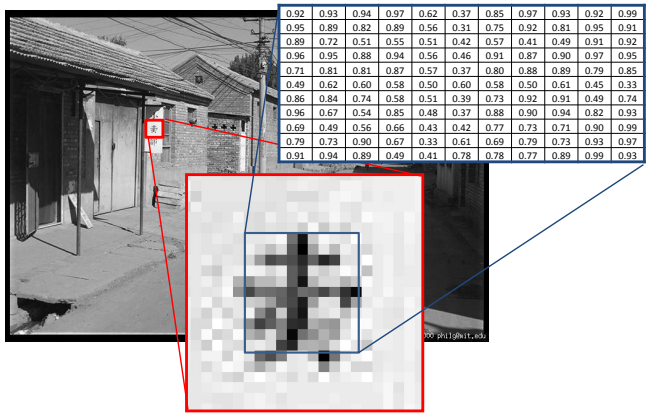


Figure: M. J. Black

Image Representation

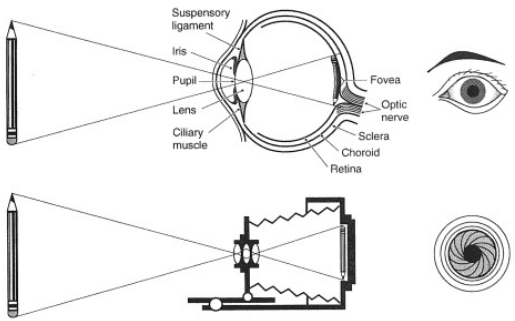
- **Digital image:** 2D discrete function f
- **Pixel**: Smallest element of an image f(x,y)



0.92	0.93	0.94	0.97	0.62	0.37	0.85	0.97	0.93	0.92	0.99
0.95	0.89	0.82	0.89	0.56	0.31	0.75	0.92	0.81	0.95	0.91
0.89	0.72	0.51	0.55	0.51	0.42	0.57	0.41	0.49	0.91	0.92
0.96	0.95	0.88	0.94	0.56	0.46	0.91	0.87	0.90	0.97	0.95
0.71	0.81	0.81	0.87	0.57	0.37	0.80	0.88	0.89	0.79	0.85
0.49	0.62	0.60	0.58	0.50	0.60	0.58	0.50	0.61	0.45	0.33
0.86	0.84	0.74	0.58	0.51	0.39	0.73	0.92	0.91	0.49	0.74
0.96	0.67	0.54	0.85	0.48	0.37	0.88	0.90	0.94	0.82	0.93
0.69	0.49	0.56	0.66	0.43	0.42	0.77	0.73	0.71	0.90	0.99
0.79	0.73	0.90	0.67	0.33	0.61	0.69	0.79	0.73	0.93	0.97
0.91	0.94	0.89	0.49	0.41	0.78	0.78	0.77	0.89	0.99	0.93

Figure: M. J. Black

Human Eye

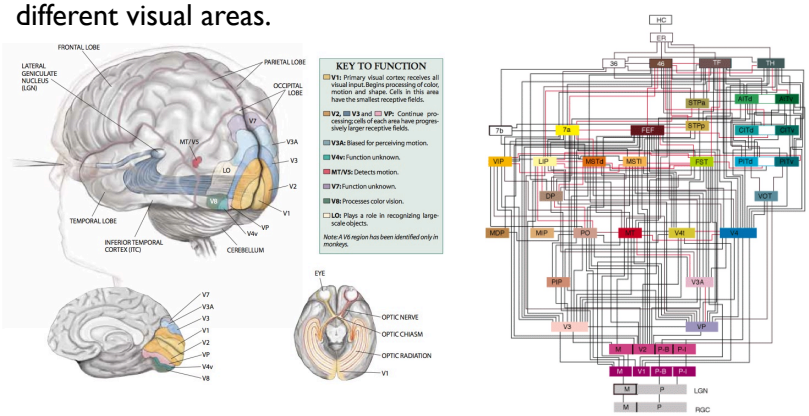


- Two types of receptor cells in retina:
  - Cone Receptor cells: 6-7 million → function in bright light, color sensitive, fine detail
  - Rod receptor cells: 75-150 million → function in dim light, color insensitive, coarse detail

Figure: Francis Crick, The Astonishing Hypothesis, 1995

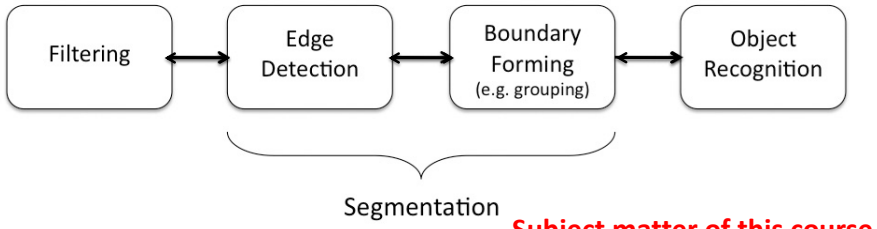
Hierarchy of Visual Areas

- There are many different neural connections between different visual areas.



Figures: Nikos K. Logothetis, Vision: A Window on Consciousness, SciAm, Nov 1999F (on the left)
Felleman & van Essen, 1991 (on the right)

Visual Modules and the Information Flow



- Vision modules can be categorized into three groups according to their functionality:
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Image Filtering

- Instagram

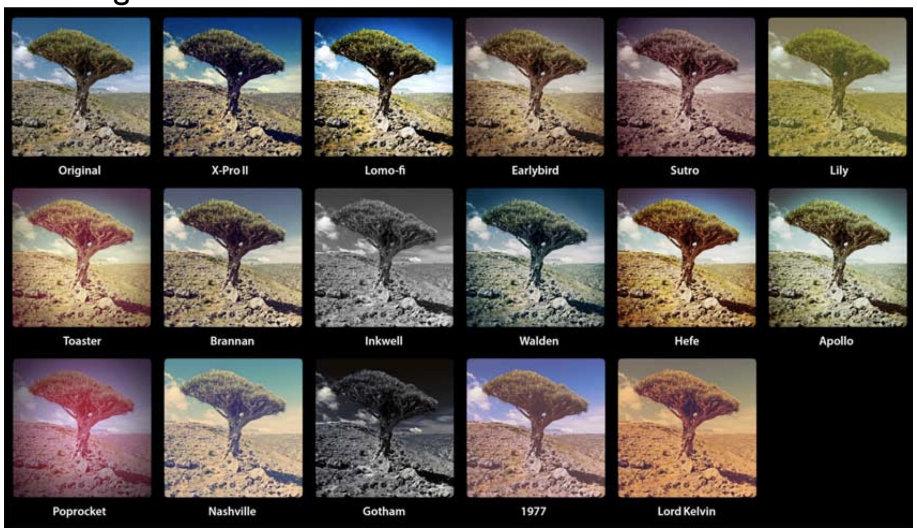


Image Filtering

- Filtering out the irrelevant information

$$f(x) = u(x) + n(x)$$

observed image — desired image — irrelevant data

- Image denoising, image sharpening, image smoothing, image deblurring, etc.
- Edge detection
- Required for many other image image manipulation tasks

Edge Detection

Canny edge detector

- Edges: abrupt changes in the intensity
  - Uniformity of intensity or color
- Edges to object boundaries

Image Filtering

- **<u>Difficulty:</u>** Some of the irrelevant image information have characteristics similar to those of important image features

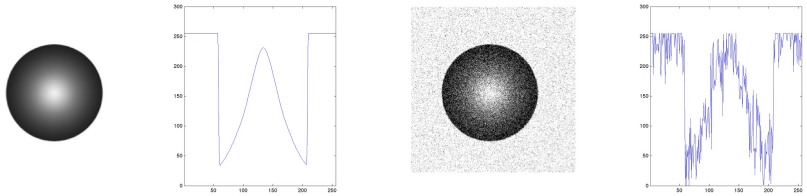


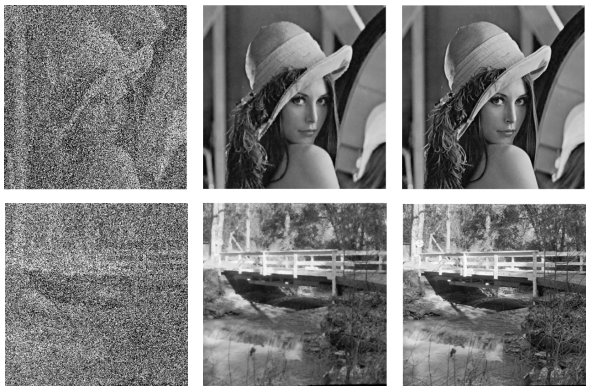
Image Smoothing - A Little Bit of History

- Gaussian Filtering / linear diffusion $\frac{\partial u}{\partial t} = \nabla \cdot (\nabla u) = \nabla^2 u$
  - the most widely used method

- mid 80's – unified formulations
  - methods that combine smoothing and edge detection
  - Geman & Geman'84, Blake & Zisserman'87, Mumford & Shah'89, Perona & Malik'90

Image Denoising

- Images are corrupted with 70% salt-and-pepper noise

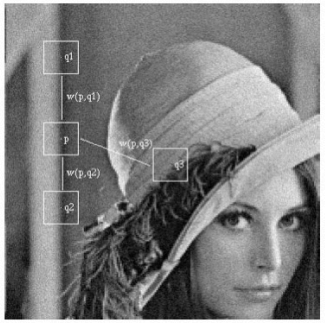


Noisy input Recovered image Original image

What do these examples demonstrate?

R. H. Chan, C.-W. Ho, and M. Nikolova, Salt-and-Pepper Noise Removal by Median-Type Noise Detectors and Detail-Preserving Regularization. IEEE TIP 2005

Non-local Means Denoising



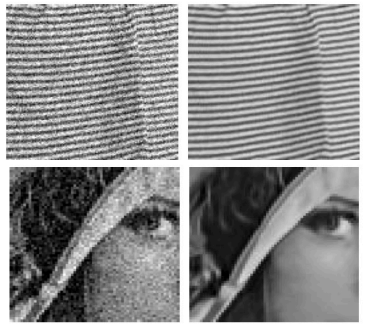


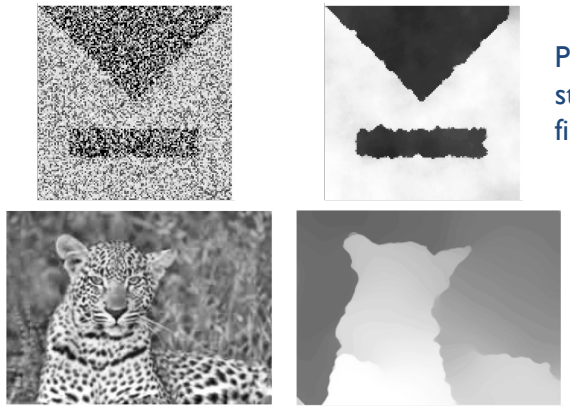
Figure 1. Scheme of NL-means strategy. Similar pixel neighborhoods give a large weight, w(p,q1) and w(p,q2), while much different neighborhoods give a small weight w(p,q3).

Preserve fine image details and texture during denoising

A. Buades, B. Coll, J. M. Morel, A non-local algorithm for image denoising, CVPR, 2005

Context-Guided Smoothing

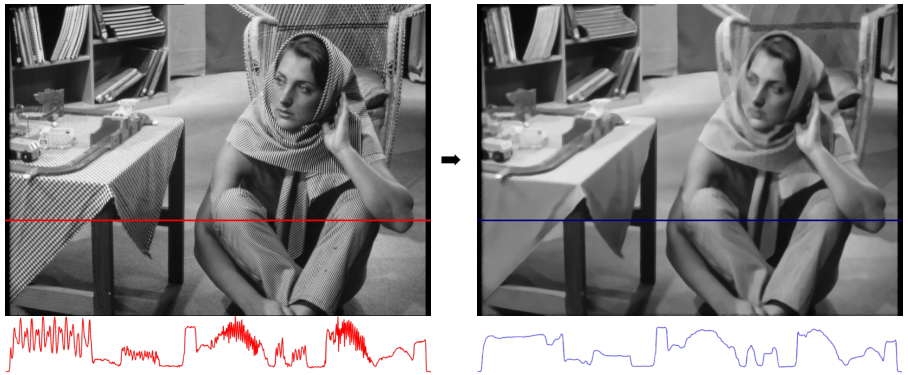
- Use local image context to steer filtering



Preserve main image structures during filtering

E. Erdem and S. Tari, Mumford-Shah Regularizer with Contextual Feedback, JMIV, 2009

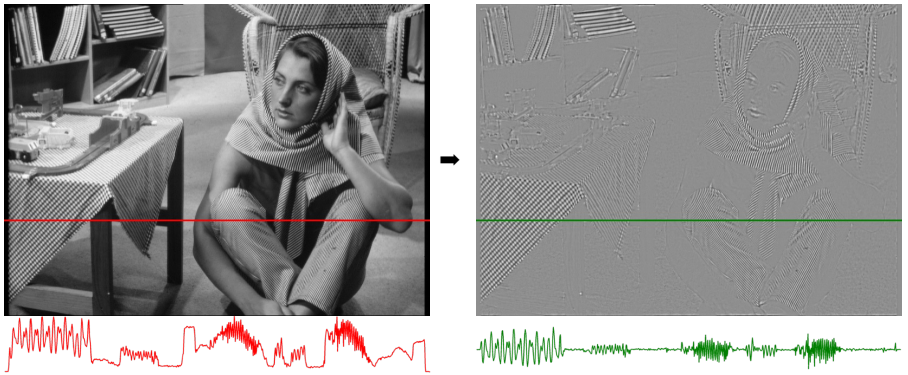
Structure-Preserving Smoothing



input structure

L. Karacan, E. Erdem and A. Erdem, Structure Preserving Image Smoothing via Region Covariances, TOG, 2013

Structure-Preserving Smoothing



input texture

L. Karacan, E. Erdem and A. Erdem, Structure Preserving Image Smoothing via Region Covariances, TOG, 2013

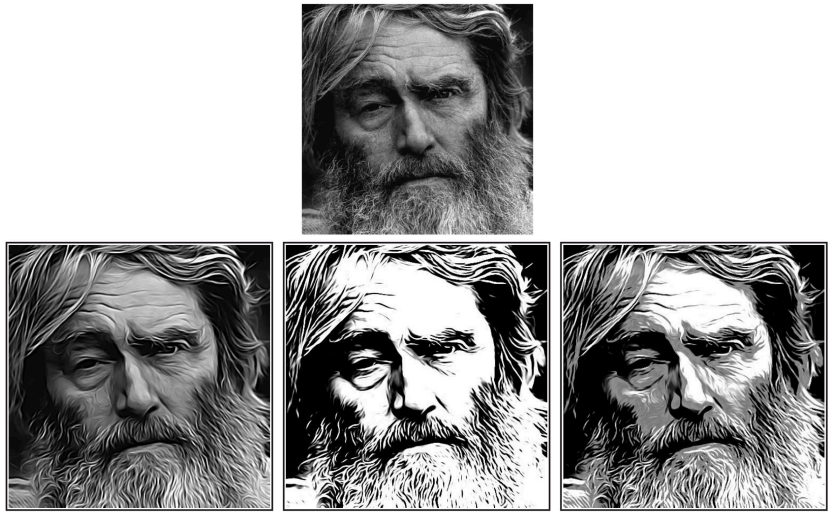
Image Abstraction

L. Karacan, E. Erdem and A. Erdem, Structure Preserving Image Smoothing via Region Covariances, TOG, 2013

Detail Enhancement

L. Karacan, E. Erdem and A. Erdem, Structure Preserving Image Smoothing via Region Covariances, TOG, 2013

Artistic Stylizations

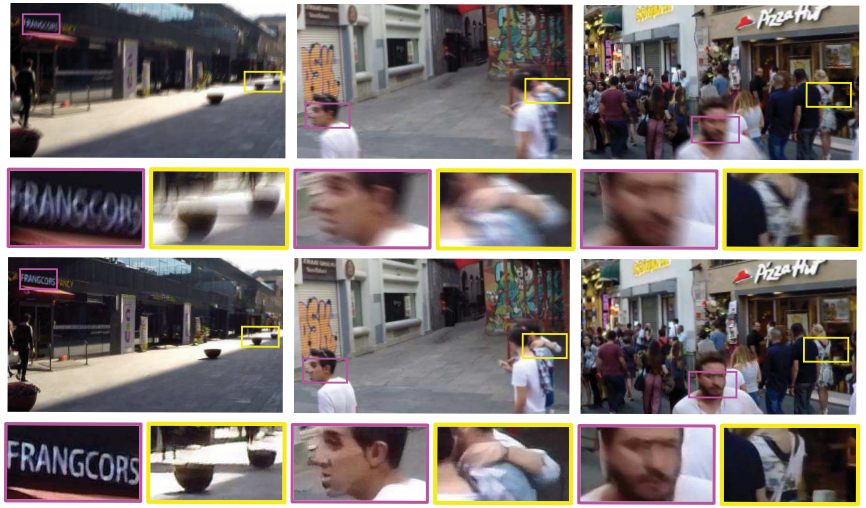


H. Winnemöller, J. E. Kyprianidis and S. C. Olsen, XDoG: An eXtended difference-of-Gaussians compendium including advanced image stylization, Computers & Graphics, 2012

Image deblurring

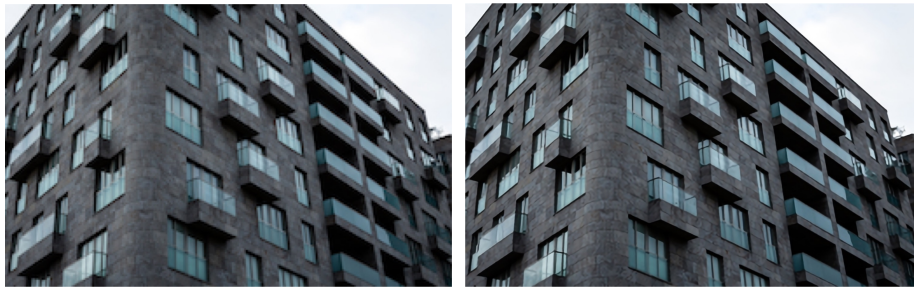
S. Cho and S. Lee. Fast Motion Deblurring. ACM Transactions on Graphics, 2009

Image deblurring



S. Nah, T. H. Kim and K. M. Lee. Deep Multi-scale Convolutional Neural Network for Dynamic Scene Deblurring. CVPR 2017

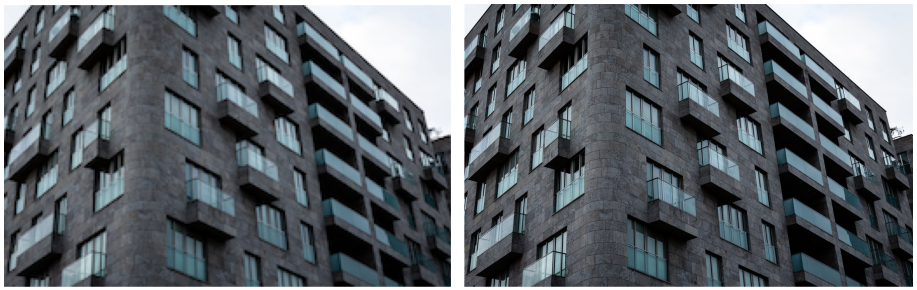
Image superresolution



input 4x output

W.-S. Lai, J.-B. Huang, N. Ahuja and M.-H. Yang,
Deep Laplacian Pyramid Networks for Fast and Accurate Super-Resolution, CVPR 2017

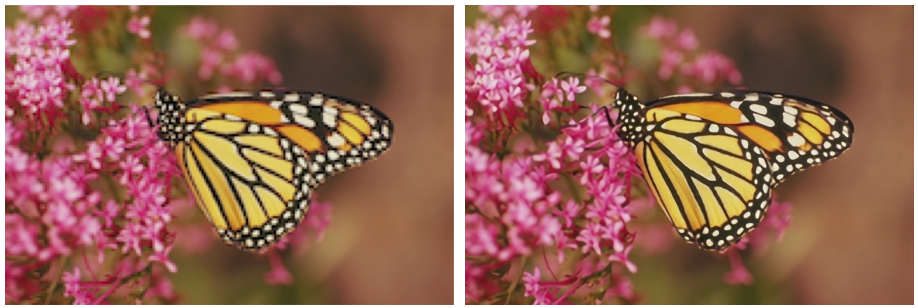
Image superresolution



input 4x original

W.-S. Lai, J.-B. Huang, N. Ahuja and M.-H. Yang,
Deep Laplacian Pyramid Networks for Fast and Accurate Super-Resolution, CVPR 2017

Image superresolution



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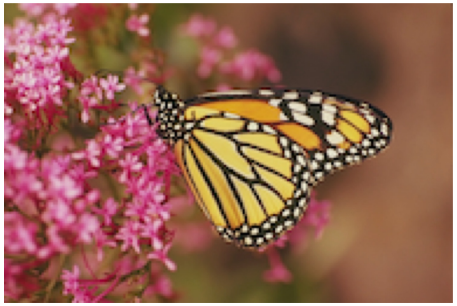


input

4x original

W.-S. Lai, J.-B. Huang, N. Ahuja and M.-H. Yang,
Deep Laplacian Pyramid Networks for Fast and Accurate Super-Resolution, CVPR 2017

Image Segmentation

- Partition an image into meaningful regions that are likely to correspond to objects exist in the image

Grouping of pixels

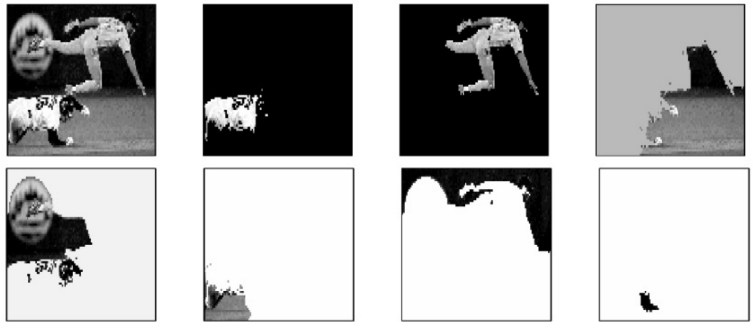
according to what criteria?

high-level object specific knowledge matters!

Figures: A. Erdem

Normalized Cuts

- A graph-theoretic formulation for segmentation



J. Shi and J. Malik, Normalized Cuts and Image Segmentation, IEEE Trans. Pattern Anal. Mach. Intel.

Normalized Cuts

Slide credit S. Lazebnik

From contours to regions

- State-of-the-art: gPb-owt-ucm segmentation algorithm

P. Arbelaez, M. Maire, C. Fowlkes and J. Malik, Contour Detection and Hierarchical Image Segmentation, IEEE Trans Pattern Anal. Mach. Intell. 33(5):898-916, 2011

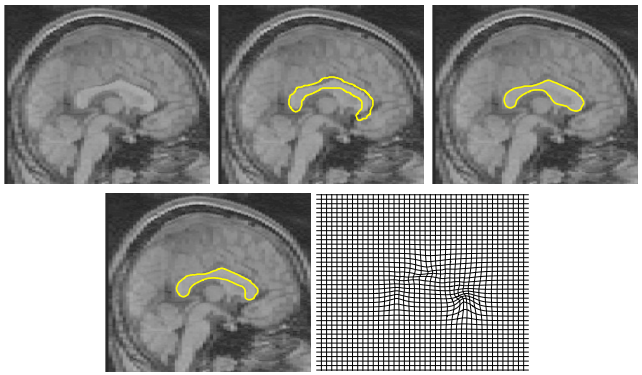
From contours to regions

- State-of-the-art: gPb-owt-ucm segmentation algorithm

P. Arbelaez, M. Maire, C. Fowlkes and J. Malik, Contour Detection and Hierarchical Image Segmentation, IEEE Trans Pattern Anal. Mach. Intell. 33(5):898-916, 2011

Prior-Shape Guided Segmentation

- Incorporate prior shape information into the segmentation process



Our result Deformation map

E. Erdem, S. Tari, and L. Vese, Segmentation Using The Edge Strength Function as a Shape Prior within a Local Deformation Model, ICIP 2009

Image Inpainting

- Reconstructing lost or deteriorated parts of images

What do these examples demonstrate?

M. Bertalmio, G. Sapiro, V. Caselles and C. Ballester, Image Inpainting, SIGGRAPH, 2000

Image Resizing

- Resize an image to arbitrary aspect ratios

Image Retargetting

- automatically resize an image to arbitrary aspect ratios while preserving important image features

How we define the importance?

S. Avidan and A. Shamir, Seam Carving for Content-Aware Image Resizing, SIGGRAPH, 2007

Image Retargeting

S. Avidan and A. Shamir, Seam Carving for Content-Aware Image Resizing, SIGGRAPH, 2007

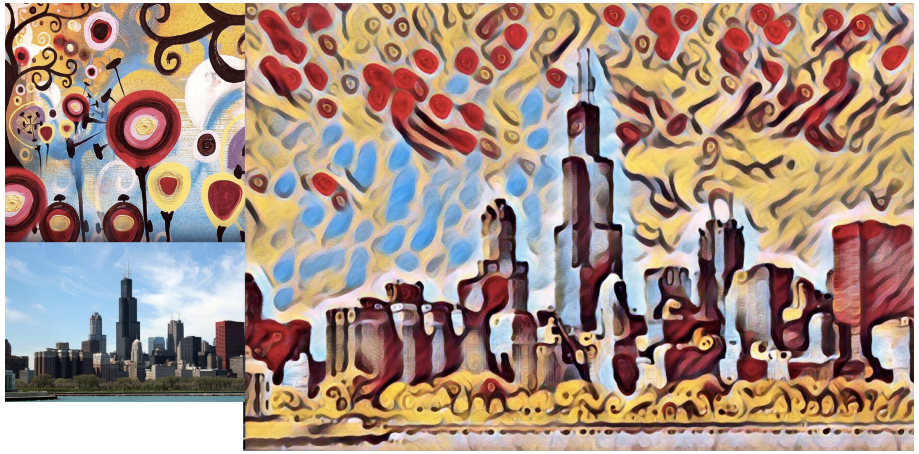
Image Retargeting

L. Karacan, E. Erdem and A. Erdem, Structure Preserving Image Smoothing via Region Covariances, TOG, 2013

Style Transfer

J. Johnson, A. Alahi and L. Fei Fei, Perceptual losses for real-time style transfer and super-resolution, ECCV 2016

Style Transfer



J. Johnson, A. Alahi and L. Fei Fei, Perceptual losses for real-time style transfer and super-resolution, ECCV 2016

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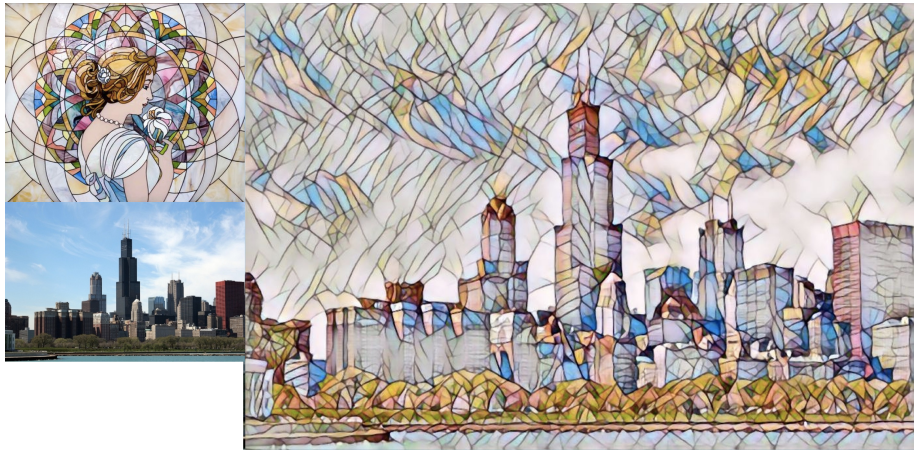

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Style Transfer

F. Luan, S. Paris, E. Shechtman and K. Bala, Deep Photo Style Transfer, CVPR 2017

Style Transfer

F. Luan, S. Paris, E. Shechtman and K. Bala, Deep Photo Style Transfer, CVPR 2017

Style Transfer

F. Luan, S. Paris, E. Shechtman and K. Bala, Deep Photo Style Transfer, CVPR 2017

Today

- What is image processing?
- Image formation
- Digital images

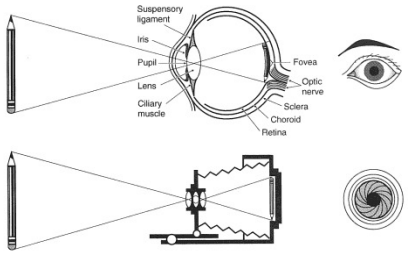
An image is:

- A 2D distribution of intensity or color
- A function defined on a two-dimensional plane

$$I : \mathbb{R}^2 \rightarrow \ldots$$

- Note: no mention of pixels yet
- To process images, must:
  - obtain images—capture the scenes via hardware
  - represent images—encode them numerically

Image Formation



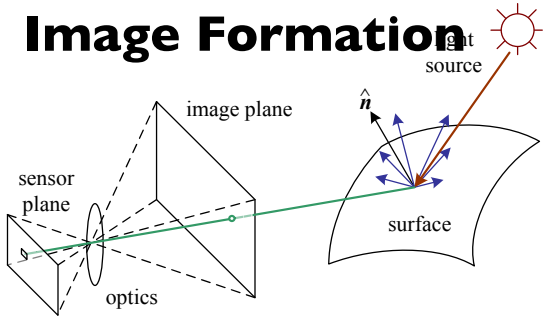
Three Dimensional World → Two Dimensional Image Space

- What is measured in an image location?
  - brightness
  - color

<< viewpoint
illumination conditions
local geometry
local material properties

Figures: Francis Crick, The Astonishing Hypothesis,

Image Formation



Three Dimensional World → Two Dimensional Image Space

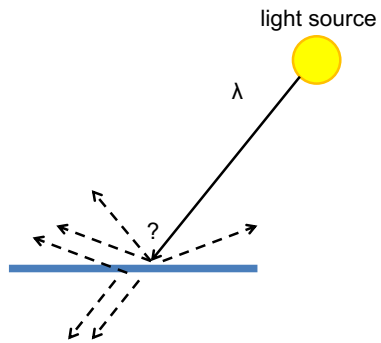
- What is measured in an image location?
  - brightness
  - color

<< viewpoint
illumination conditions
surface properties
(local geometry and local material properties)

Figures: Francis Crick, The Astonishing Hypothesis,

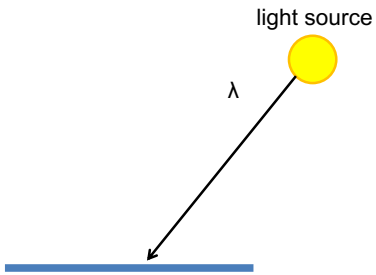
A photon's life choices

- Absorption
- Diffusion
- Reflection
- Transparency
- Refraction
- Fluorescence
- Subsurface scattering
- Phosphorescence
- Interreflection



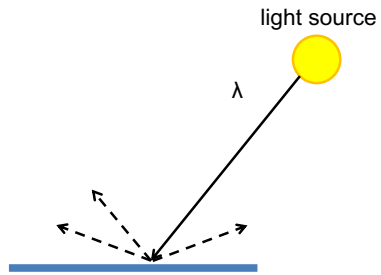
A photon's life choices

- **Absorption**
- Diffusion
- Reflection
- Transparency
- Refraction
- Fluorescence
- Subsurface scattering
- Phosphorescence
- Interreflection



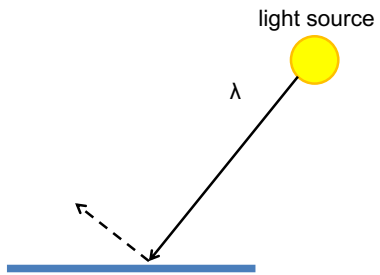
A photon's life choices

- Absorption
- **Diffuse Reflection**
- Reflection
- Transparency
- Refraction
- Fluorescence
- Subsurface scattering
- Phosphorescence
- Interreflection



A photon's life choices

- Absorption
- Diffusion
- **Specular Reflection**
- Transparency
- Refraction
- Fluorescence
- Subsurface scattering
- Phosphorescence
- Interreflection



A photon's life choices

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- Diffusion
- Reflection
- **Transparency**
- Refraction
- Fluorescence
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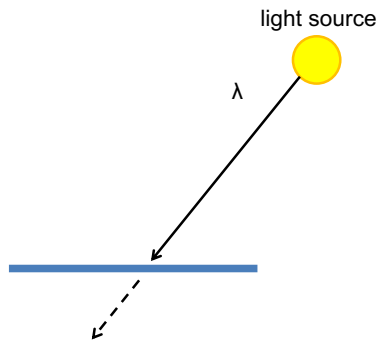
- Phosphorescence
- Interreflection



A photon's life choices

- Absorption
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- Transparency
- **Refraction**
- Fluorescence
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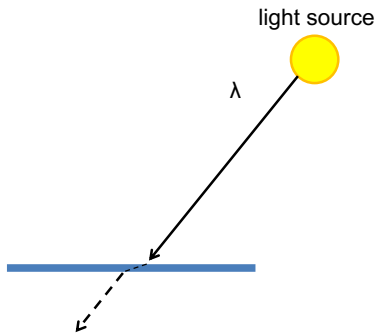

A photon's life choices

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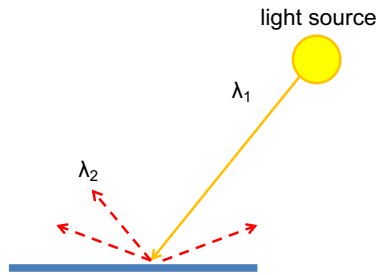

A photon's life choices

- Absorption
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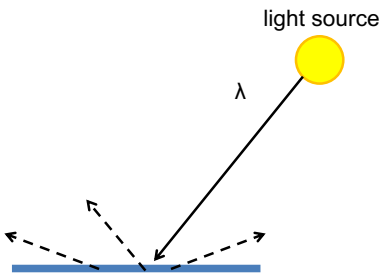
- Fluorescence
- **Subsurface scattering**
- Phosphorescence
- Interreflection



A photon's life choices

- Absorption
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- Fluorescence
- Subsurface scattering
- **Phosphorescence**
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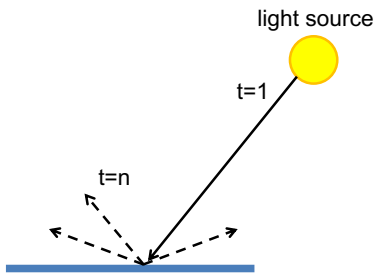
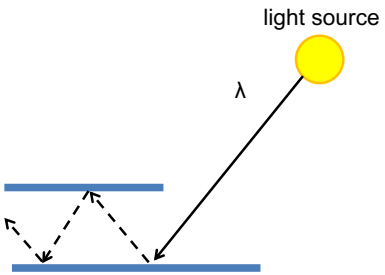


A photon's life choices

- Absorption
- Diffusion
- Reflection
- Transparency
- Refraction
- Fluorescence
- Subsurface scattering
- Phosphorescence
- **Interreflection**



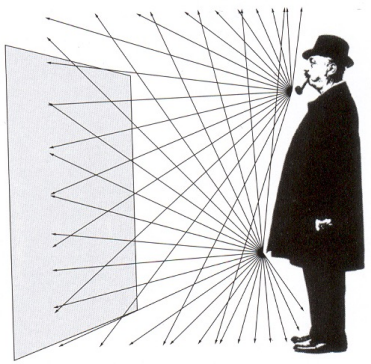
(Specular Interreflection)

Image Formation

Images cannot exist without light!

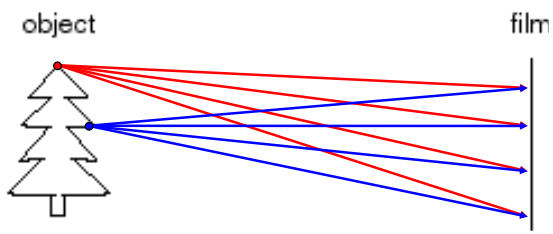
Why is there no image on a white piece of paper?

It receives light from all directions



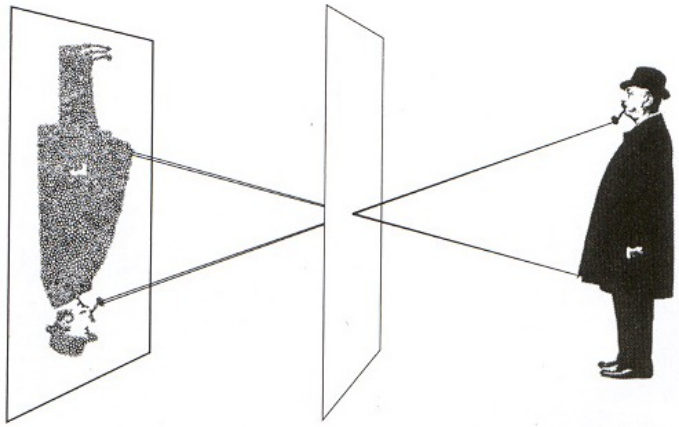
From Photography, London et al.

Image Formation



- Let's design a camera
  - Idea 1: put a piece of film in front of an object
  - Do we get a reasonable image?

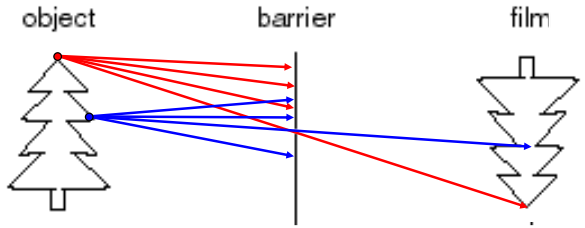
Pinhole camera



A pinhole projects all rays through a common center of projection.

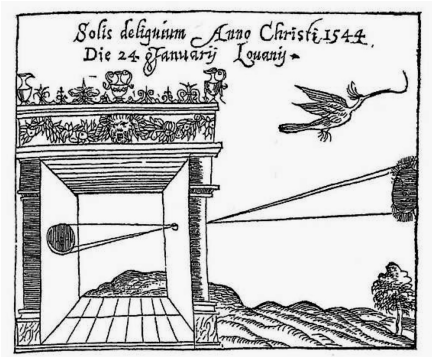
From Photography, London et al.

Pinhole camera



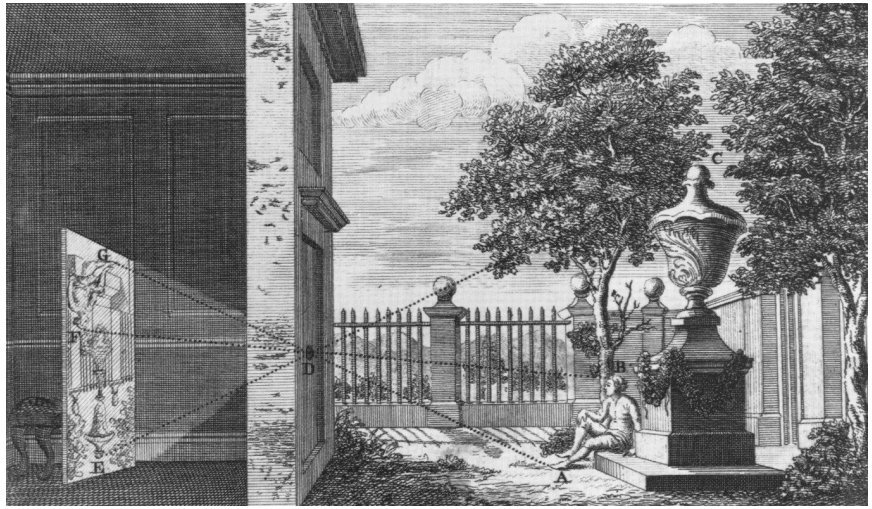
- Add a barrier to block off most of the rays
  - This reduces blurring
  - The opening is known as the **aperture**
  - How does this transform the image?

Camera Obscura

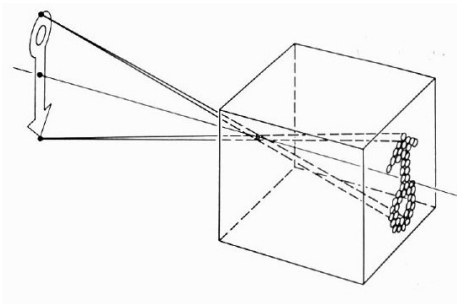


- Basic principle known to Mozi (470-390 BC), Aristotle (384-322 BC)
- Drawing aid for artists: described by Leonardo da Vinci (1452-1519)

Camera Obscura



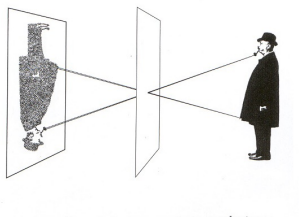
Camera Obscura



- The first camera
  - How does the aperture size affect the image?

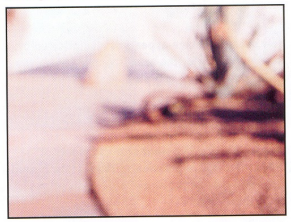
Pinhole Size?

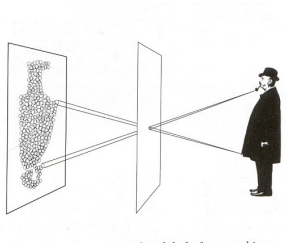
Photograph made with small pinhole



Small pinhole-
sharp but hard to
collect enough light

Photograph made with larger pinhole

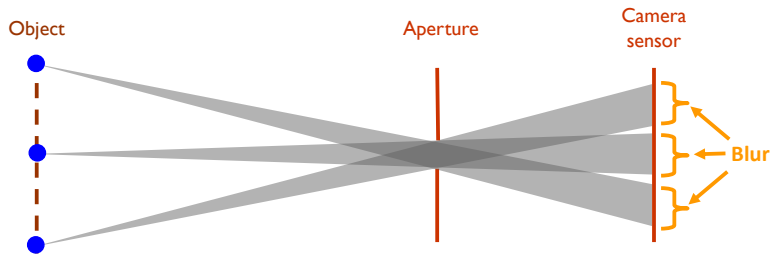




Larger pinhole-
Blur

From Photography, London et al.

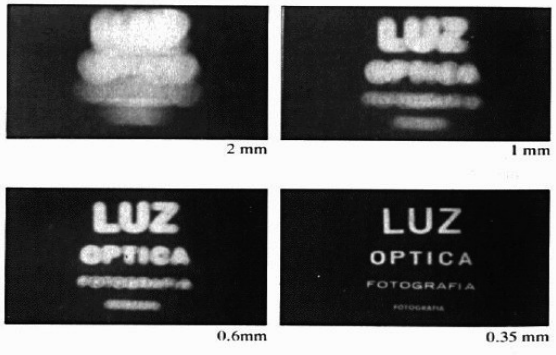
Pinhole Size



small hole => sharp, but doesn't collect enough light (noise)

larger hole => easy to collect enough light, but blur occurs

Pinhole Size



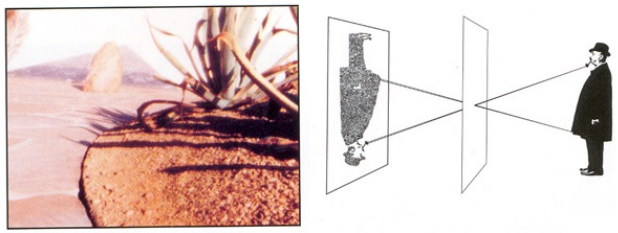
- Why not make the aperture as small as possible?
  - Less light gets through
  - Diffraction effects...

Solution: light refraction!

From Photography, London et al.

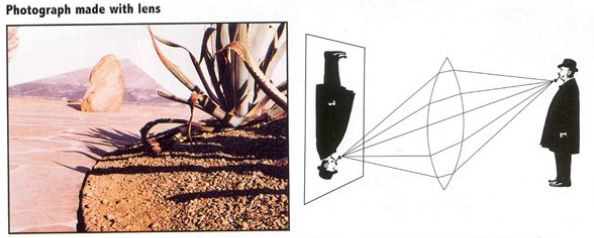
- gather more light!
- But need to be focused

Photograph made with small pinhole



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

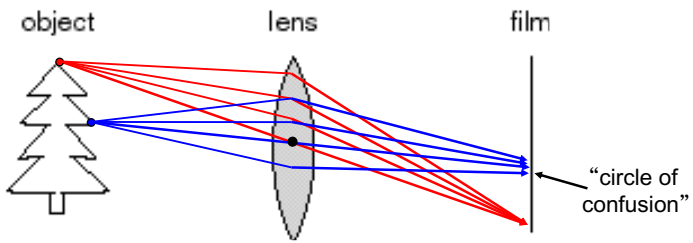
Photograph made with lens



This time, using a simple convex lens with an f/16 aperture, *the scene appeared sharper than the one taken with the smaller pinhole, and the exposure time was much shorter, only 1/100 sec. The lens opening was much bigger than the pinhole, letting in far more light, but it focused the rays from each point on the subject precisely so that they were sharp on the film.*

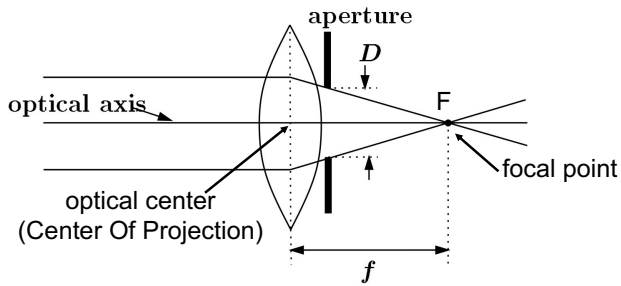
From Photography, London et al.

Adding a lens



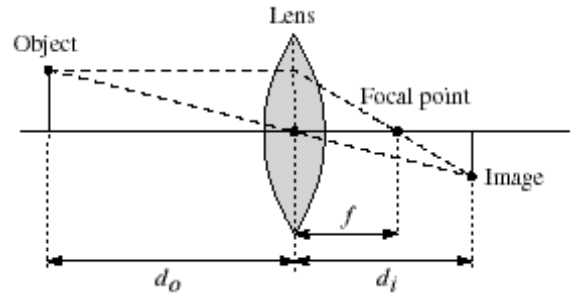
- A lens focuses light onto the film
  - There is a specific distance at which objects are "in focus"
    - other points project to a "circle of confusion" in the image
  - Changing the shape of the lens changes this distance

Lenses



- A lens focuses parallel rays onto a single focal point
  - focal point at a distance f beyond the plane of the lens
    - f is a function of the shape and index of refraction of the lens
  - Aperture of diameter D restricts the range of rays
    - aperture may be on either side of the lens
  - Lenses are typically spherical (easier to produce)
  - Real cameras use many lenses together (to correct for aberrations)

Thin lenses



- Thin lens equation: $\frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f}$
  - Any object point satisfying this equation is in focus

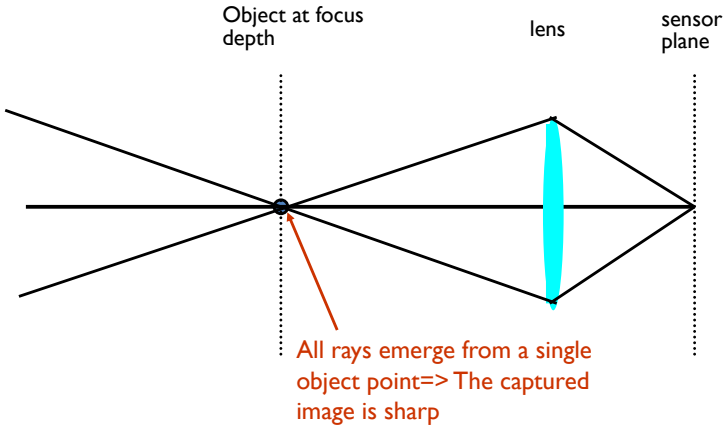
A lens is focused at a single depth

$$\frac{1}{z_o} + \frac{1}{z_i} = \frac{1}{f}$$

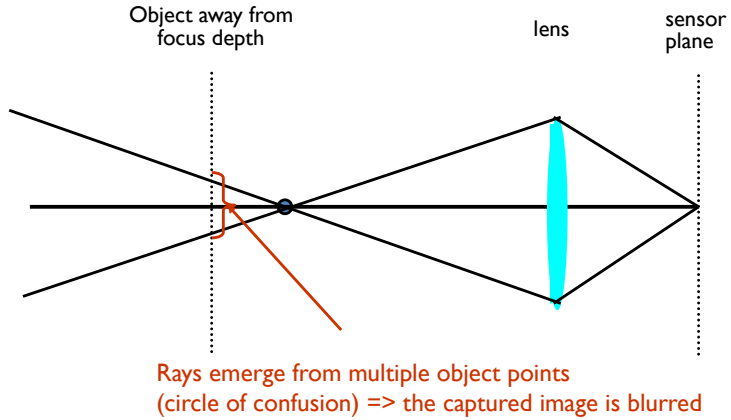
z_0: distance to the (focused) object

z_i: distance behind the lens at which the image is formed

f: focal length



A lens is focused at a single depth

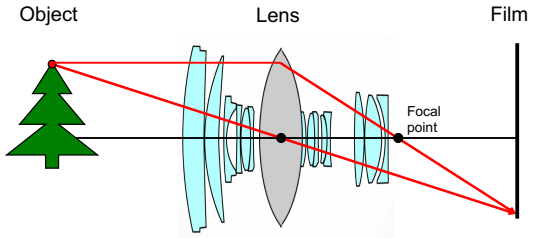


A lens is focused at a single depth

$$\frac{1}{z_o} + \frac{1}{z_i} = \frac{1}{f}$$

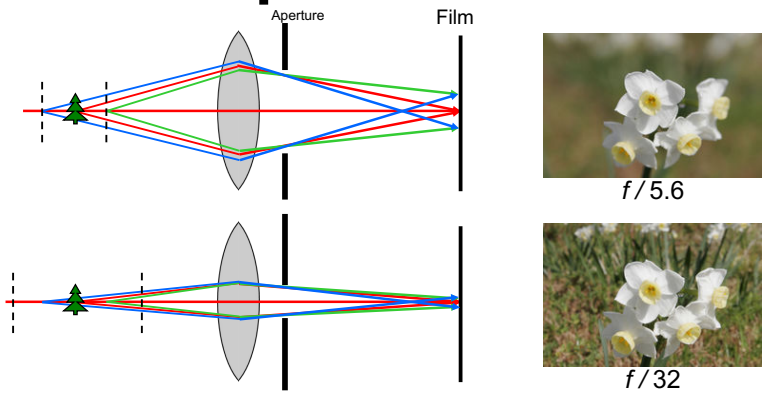
Thin lens assumption

The thin lens assumption assumes the lens has no thickness, but this isn't true…



By adding more elements to the lens, the distance at which a scene is in focus can be made roughly planar.

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

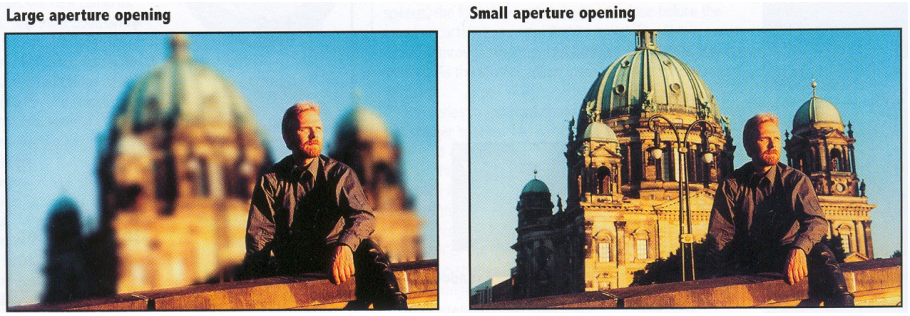
Flower images from Wikipedia http://en.wikipedia.org/wiki/Depth_of_field

Aperture

- Diameter of the lens opening (controlled by diaphragm)
- Controls depth of field
- 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

Main effect of aperture

- **Depth of field:** Allowable depth variation in the scene that limits the circle of confusion to a tolerable number



From Photography, London et al.

Depth of field

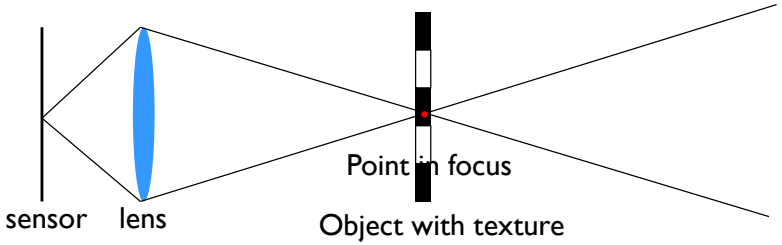


Image of object in focus- sharp (all rays hitting a single sensor point emerge from a single point on the object)

Depth of field

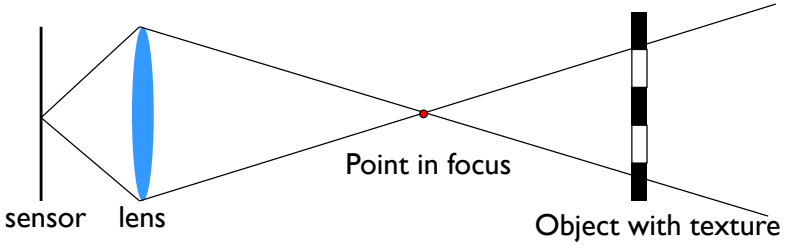
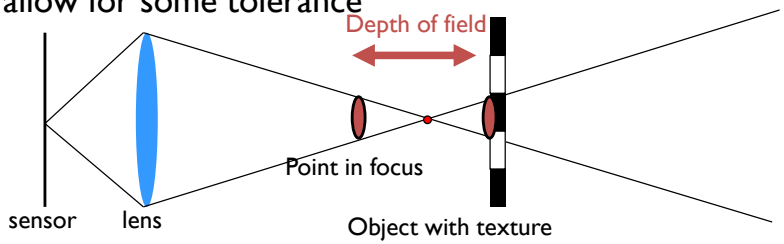


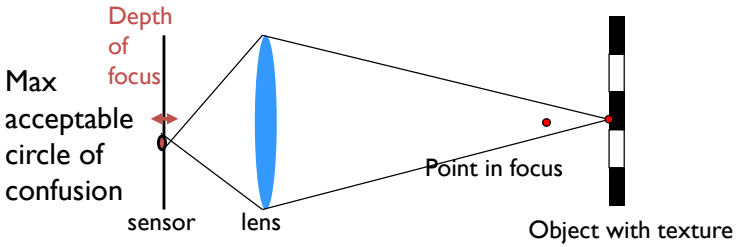
Image of object in focus- sharp (all rays hitting a single sensor point emerge from a single point on the object)

Image of an object away from focus depth- blurred (rays hitting a single sensor point emerge from multiple points on the object)

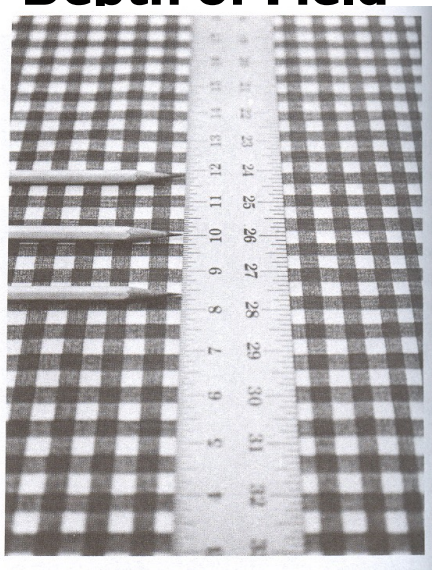
Depth of field

- We allow for some tolerance





Depth of Field



Depth of Field

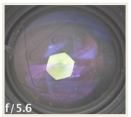
Portrait | Landscape

Shallow Depth of Field

Large Depth of Field

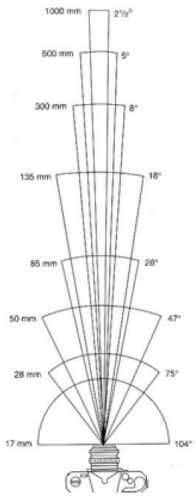
Large Aperture

Small Aperture



http://photographertips.net

Field of View (Zoom, focal length)



From London and Upton

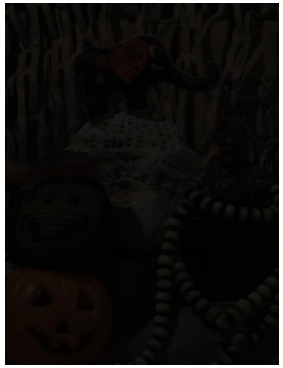
Exposure

- <u>Exposure:</u> How much light falls on sensor
- Get the right amount of light to sensor/film
- Main parameters:
  - Shutter speed: How long sensor is exposed to light
  - Aperture (area of lens): How much light can pass through from the lens
  - Sensitivity: How much light is needed by the sensor
  - Lighting conditions

Shutter speed

- Controls how long the film/sensor is exposed, i.e. the amount of light reaching the sensor
- 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 ?
- Faster shutter (e.g. 1/500th sec) = less light
- Slower shutter (e.g. 1/30th sec) = more light
- 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

Shutter speed



Short exposure- dark

medium exposure

long exposure- saturation

Shutter speed

Short exposure after contrast adjustment- noise

medium exposure

long exposure- saturation

Main effect of slower shutter speed

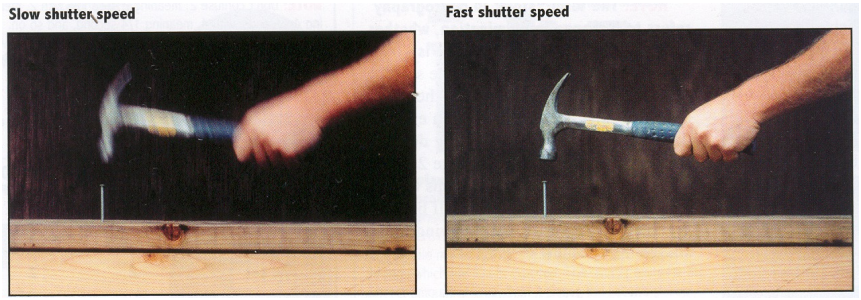
- For dynamic scenes, the shutter speed also determines the amount of *motion blur* in the resulting picture.
- Camera shake

Image taken with a tripod

Image taken with a hand held camera

Main effect of slower shutter speed

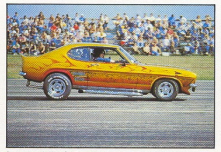
- For dynamic scenes, the shutter speed also determines the amount of *motion blur* in the resulting picture.
- Scene motion



From Photography, London et al.

Effect of Shutter Speed

- Freezing motion

Walking people	Running people	Car	Fast train
			
1/125	1/250	1/500	1/1000

Frédo Durand

Today

- What is image processing?
- Image formation
- Digital images

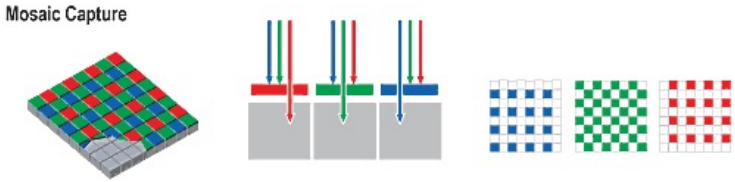
Digital camera

- A digital camera replaces film with a sensor array
  - Each cell in the array is light-sensitive diode that converts photons to electrons
  - Two common types
    - Charge Coupled Device (CCD)
    - CMOS
  - http://electronics.howstuffworks.com/digital-camera.htm

Slide by Steve Seitz

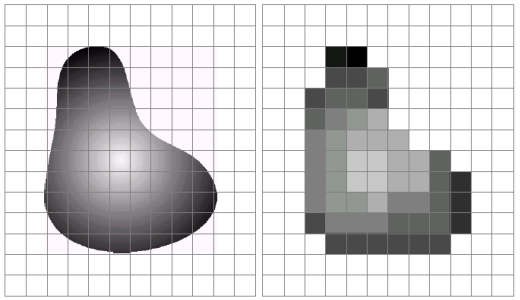
Digital camera

- Color typically captured using color mosaic
- Demosaicing



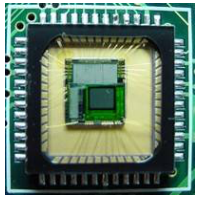
[Foveon]

Sensor Array



a b

FIGURE 2.17 (a) Continuos image projected onto a sensor array. (b) Result of image sampling and quantization.



CMOS sensor

Issues with digital cameras

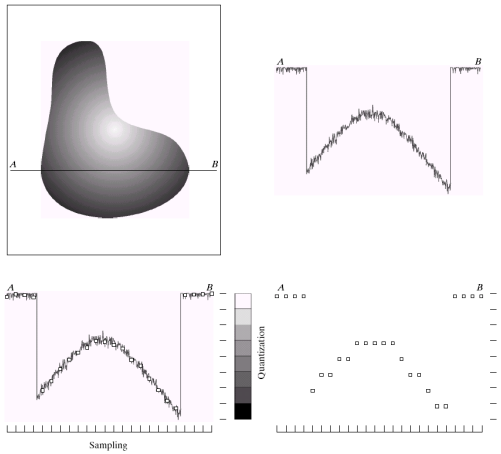
- Noise
  - big difference between consumer vs. SLR-style cameras
  - low light is where you most notice noise
- Compression
  - creates artifacts except in uncompressed formats (tiff, raw)
- Color
  - color fringing artifacts from Bayer patterns
- Blooming
  - charge overflowing into neighboring pixels
- In-camera processing
  - oversharpening can produce halos
- Interlaced vs. progressive scan video
  - even/odd rows from different exposures
- Are more megapixels better?
  - requires higher quality lens
  - noise issues
- Stabilization
  - compensate for camera shake (mechanical vs. electronic)

More info online, e.g.,

http://electronics.howstuffworks.com/digital-camera.htm

http://www.dpreview.com/

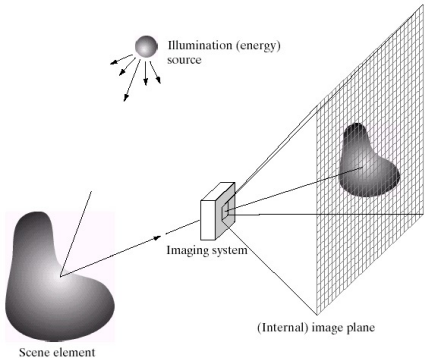
Sampling and Quantization

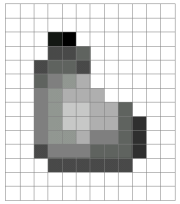


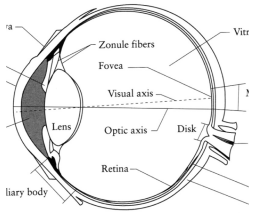
a b
c d

FIGURE 2.16 Generating a digital image. (a) Continuous image. (b) A scan line from *A* to *B* in the continuous image, used to illustrate the concepts of sampling and quantization. (c) Sampling and quantization. (d) Digital scan line.

Image Representation







- Discretization
  - in image space - sampling
  - In image brightness - quantization

Figures: Gonzalez and Woods, Digital Image Processing, 3rd Edition, 2008

Image Representation

- **Digital image:** 2D discrete function f
- **Pixel**: Smallest element of an image f(x,y)

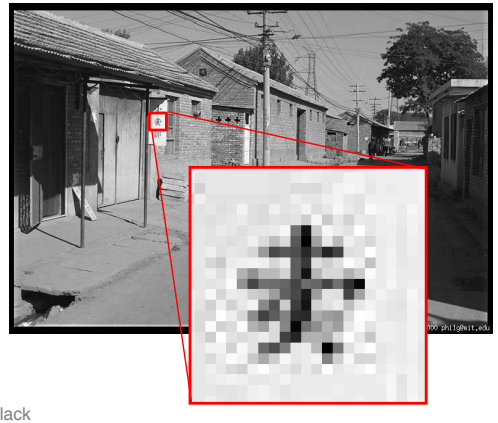
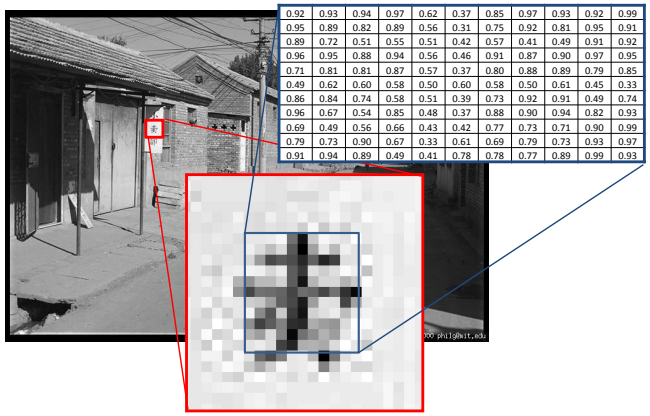


Figure: M. J. Black

Image Representation

- **Digital image:** 2D discrete function f
- **Pixel**: Smallest element of an image f(x,y)



0.92	0.93	0.94	0.97	0.62	0.37	0.85	0.97	0.93	0.92	0.99
0.95	0.89	0.82	0.89	0.56	0.31	0.75	0.92	0.81	0.95	0.91
0.89	0.72	0.51	0.55	0.51	0.42	0.57	0.41	0.49	0.91	0.92
0.96	0.95	0.88	0.94	0.56	0.46	0.91	0.87	0.90	0.97	0.95
0.71	0.81	0.81	0.87	0.57	0.37	0.80	0.88	0.89	0.79	0.85
0.49	0.62	0.60	0.58	0.50	0.60	0.58	0.50	0.61	0.45	0.33
0.86	0.84	0.74	0.58	0.51	0.39	0.73	0.92	0.91	0.49	0.74
0.96	0.67	0.54	0.85	0.48	0.37	0.88	0.90	0.94	0.82	0.93
0.69	0.49	0.56	0.66	0.43	0.42	0.77	0.73	0.71	0.90	0.99
0.79	0.73	0.90	0.67	0.33	0.61	0.69	0.79	0.73	0.93	0.97
0.91	0.94	0.89	0.49	0.41	0.78	0.78	0.77	0.89	0.99	0.93

Figure: M. J. Black

Datatypes for raster images

- Bitmaps: `boolean` per pixel (1 bpp): $I : \mathbb{R}^2 \rightarrow \{0, 1\}$
  - interp. = black and white; e.g. fax
- Grayscale: integer per pixel: $I : \mathbb{R}^2 \rightarrow [0, 1]$
  - interp. = shades of gray; e.g. black-and-white print
  - precision: usually `byte` (8 bpp); sometimes 10, 12, or 16 bpp
- Color: 3 integers per pixel: $I : \mathbb{R}^2 \rightarrow [0, 1]^3$
  - interp. = full range of displayable color; e.g. color print
  - precision: usually `byte[3]` (24 bpp)
  - sometimes 16 (5+6+5) or 30 or 36 or 48 bpp
  - indexed color: a fading idea

Datatypes for raster images

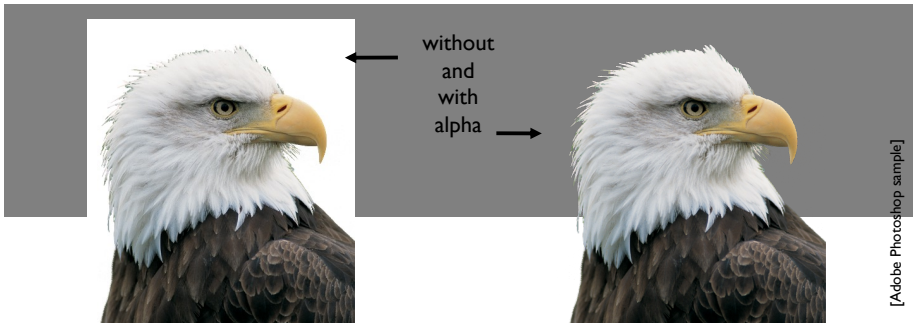
- Floating point: $I : \mathbb{R}^2 \rightarrow \mathbb{R}_+$ or $I : \mathbb{R}^2 \rightarrow \mathbb{R}^3_+$
  - more abstract, because no output device has infinite range
  - provides *high dynamic range* (HDR)
  - represent real scenes independent of display
  - becoming the standard intermediate format in graphics processors
- Clipping and white point
  - common to compute FP, then convert to integer
  - full range of values may not "fit" in display's output range
  - simplest solution: choose a maximum value, scale so that value becomes full intensity (2^n–1 in an *n*-bit integer image)

Intensity encoding in images

- What do the numbers in images (pixel values) mean?
  - they determine how bright that pixel is
  - bigger numbers are (usually) brighter

Datatypes for raster images

- For color or grayscale, sometimes add *alpha* channel
  - describes transparency of images



[Adobe Photoshop sample]

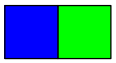
Storage requirements for images

- 1024x1024 image (1 megapixel)
  - bitmap: 128KB
  - grayscale 8bpp: 1MB
  - grayscale 16bpp: 2MB
  - color 24bpp: 3MB
  - floating-point HDR color: 12MB

Converting pixel formats

- Color to gray
  - could take one channel (blue, say)
    - leads to odd choices of gray value
  - combination of channels is better
    - but different colors contribute differently to lightness
    - which is lighter, full blue or full green?
    - good choice: gray = 0.2 R + 0.7 G + 0.1 B
    - more on this in color, later on

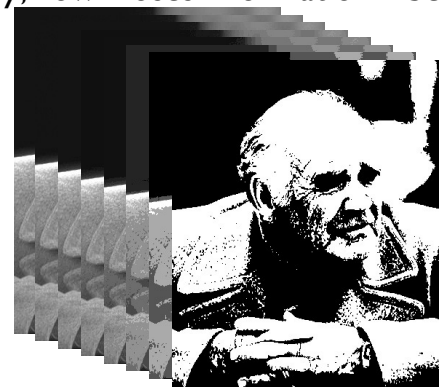
Same pixel values.



Same luminance?

Converting pixel precision

- Up is easy; down loses information—be careful



1 bpp (2 grays)

[photo: Philip Greenspun]

Next week

- Color
- Point operations