ROBOTICS & PERCEPTION GROUP

University of Zurich[UZH]

Fundamentals of Image Processing and Computer Vision

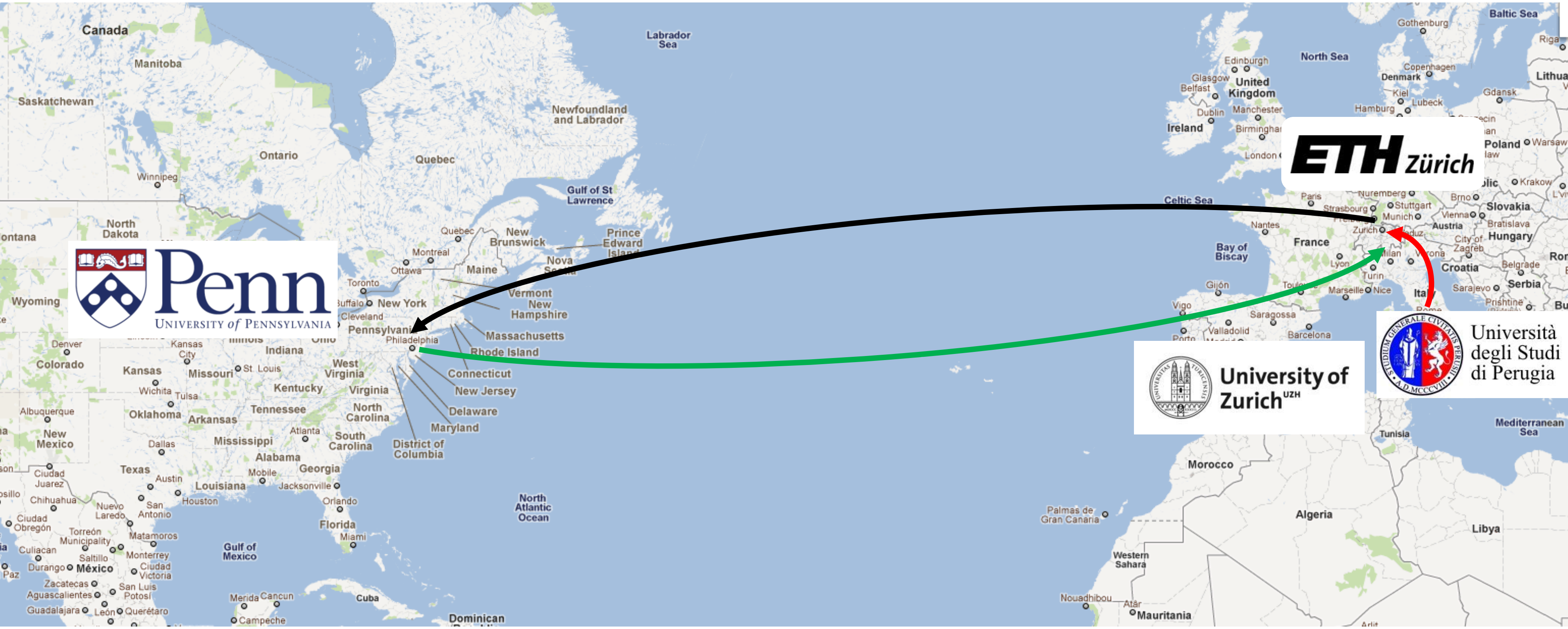
Prof. Dr. Davide Scaramuzza

sdavide@ifi.uzh.ch

Today's Class

- Introductions
- What is Computer Vision?
- Example of Vision Applications
- Specifics of this course
- Image Formation

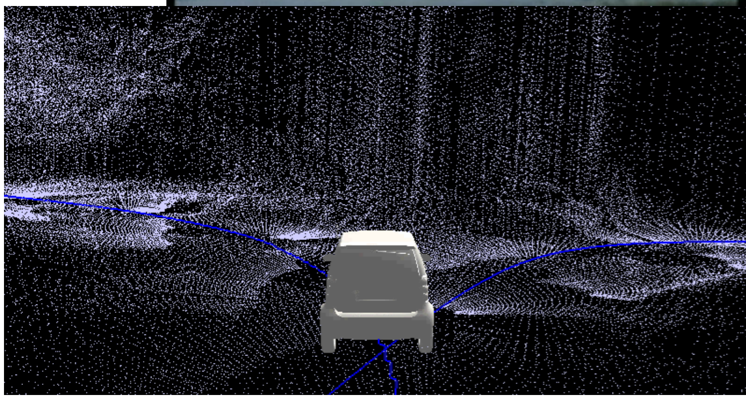
A Bit about Me

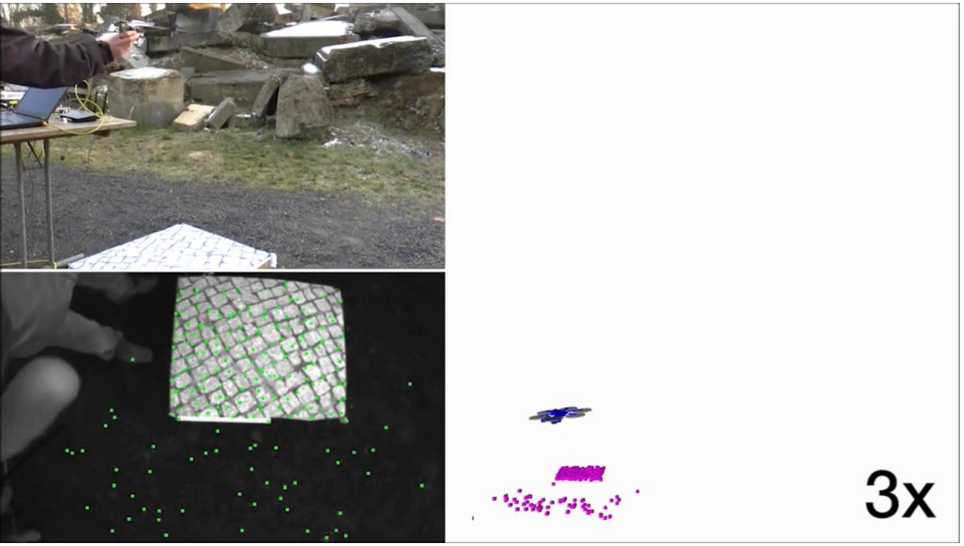


My Research Background

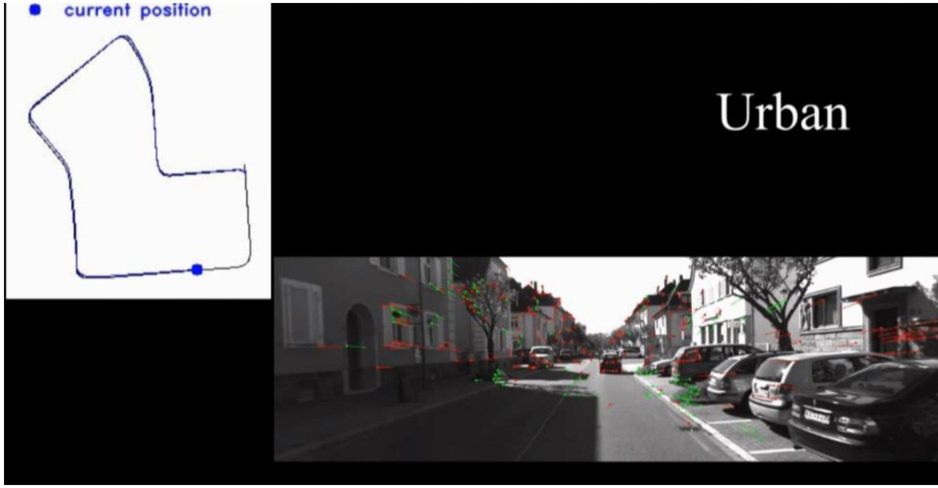
Perception
- ➢ Visual Odometry
- ➢ Camera calibration
- ➢ Sensor fusion

Field and Service Robotics
- ➢ Self driving cars
- ➢ Autonomous micro helicopters





[JFR’10, AURO’11, RAM’14]

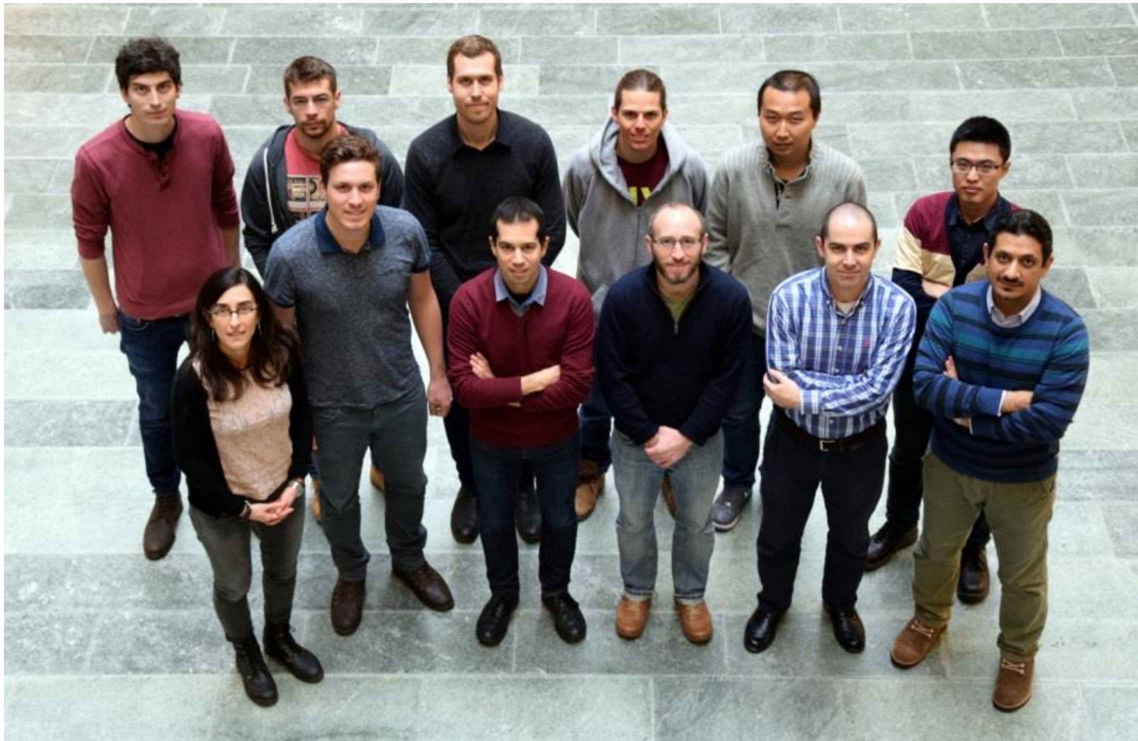


[JFR’11, IJCV’11, PAMI’13, ICRA’14]

My lab

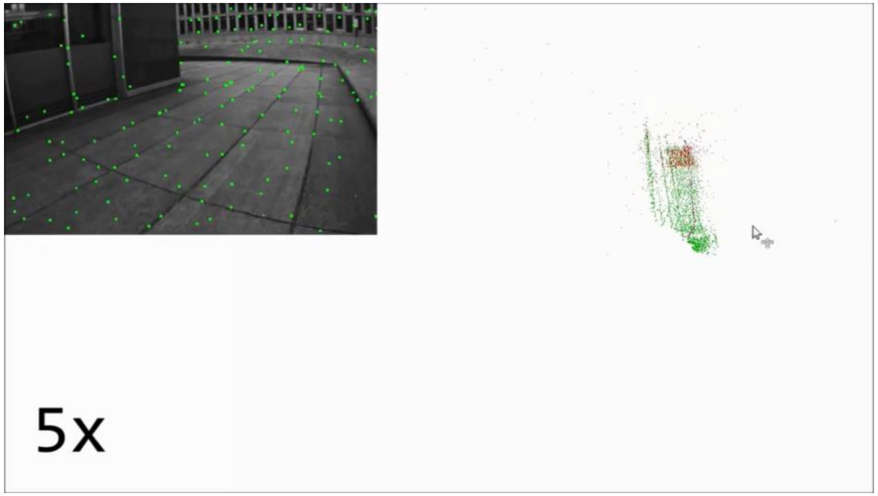
ROBOTICS &
PERCEPTION
GROUP

http://rpg.ifi.uzh.ch
Andreasstrasse 15, 2nd floor

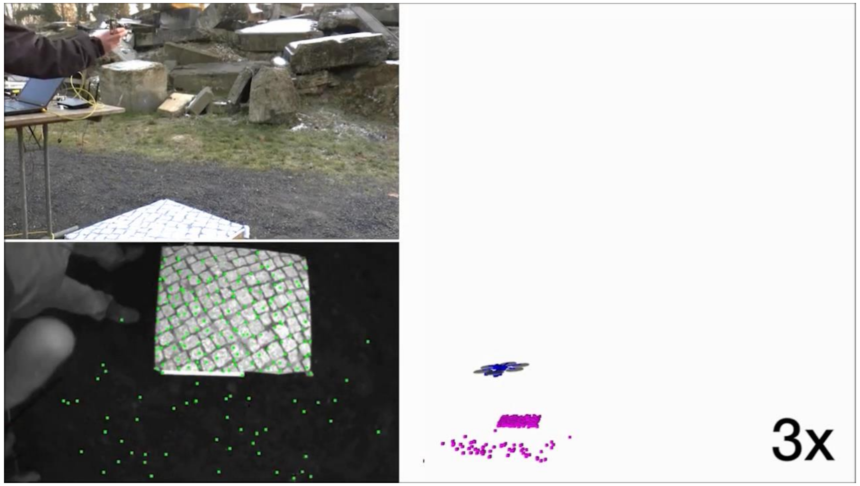


Current Research Activities

Visual-Inertial Odometry

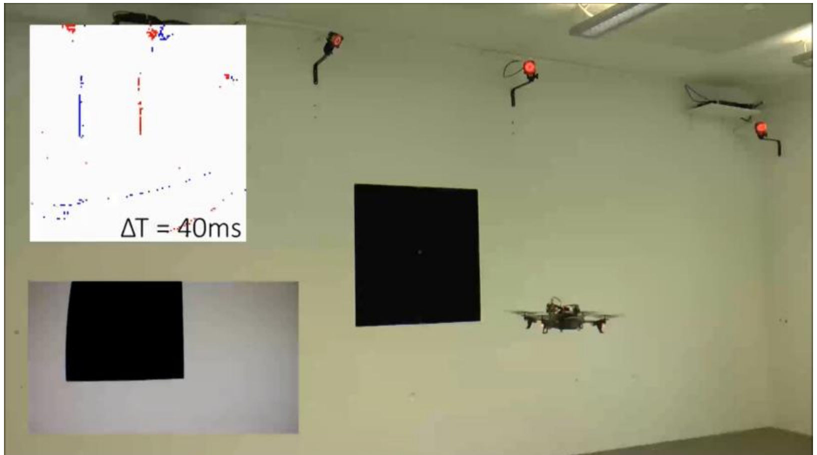


Autonomous Navigation of Flying Robots



Air-ground collaboration

Event-based Vision for Agile Flight



Current Research Activities

Real-time Monocular Dense Reconstruction

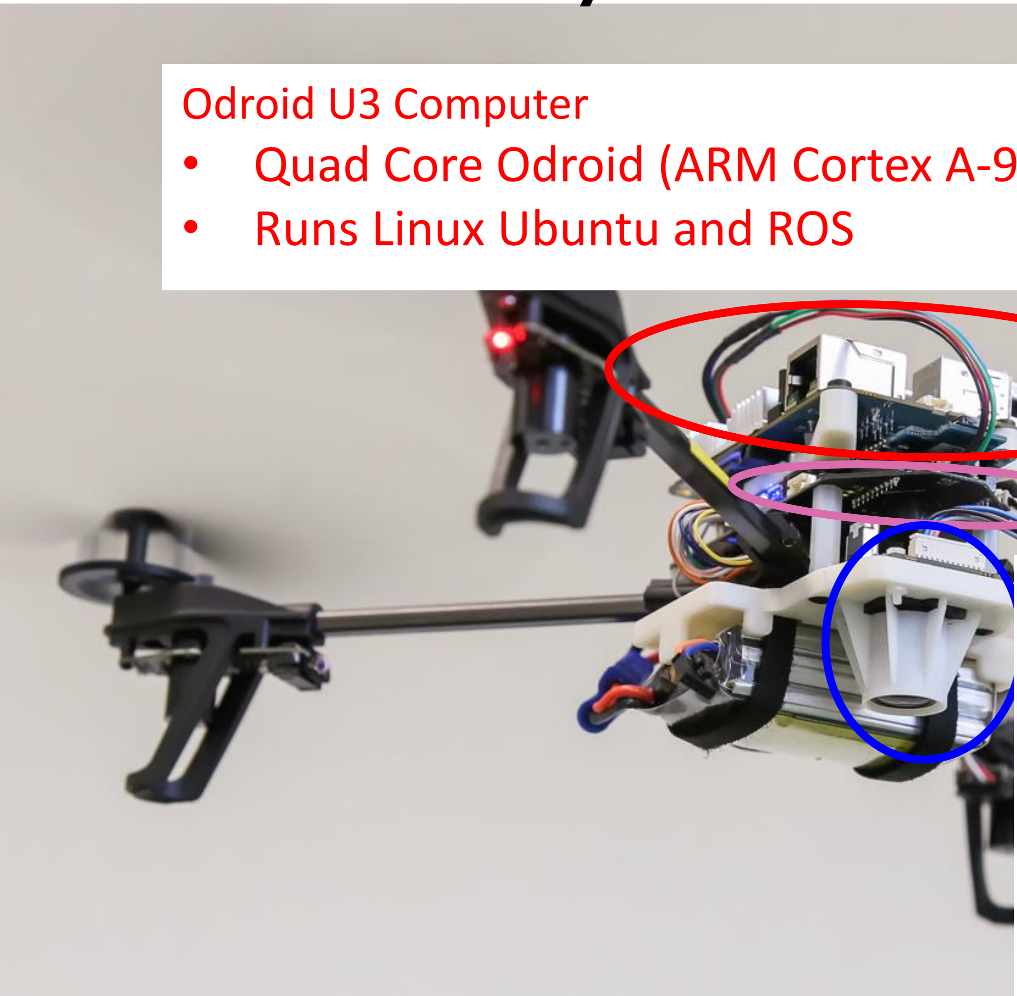
Monocular dense reconstruction
in real-time from a hand-held camera

Stage-set from Gruber et al., "The City of Sights", ISMAR'10.

Quadrotor System

Odroid U3 Computer

- Quad Core Odroid (ARM Cortex A-9) used in Samsung Galaxy S4 phones
- Runs Linux Ubuntu and ROS



450 grams

Flight Results: Hovering

RMS error: 5 mm, height: 1.5 m – Down-looking camera

Faessler, Fontana, Forster, Mueggler, Pizzoli, Scaramuzza, Autonomous, Vision-based Flight and Live Dense 3D Mapping with a Quadrotor Micro Aerial Vehicle, **Journal of Field Robotics, 2015**.

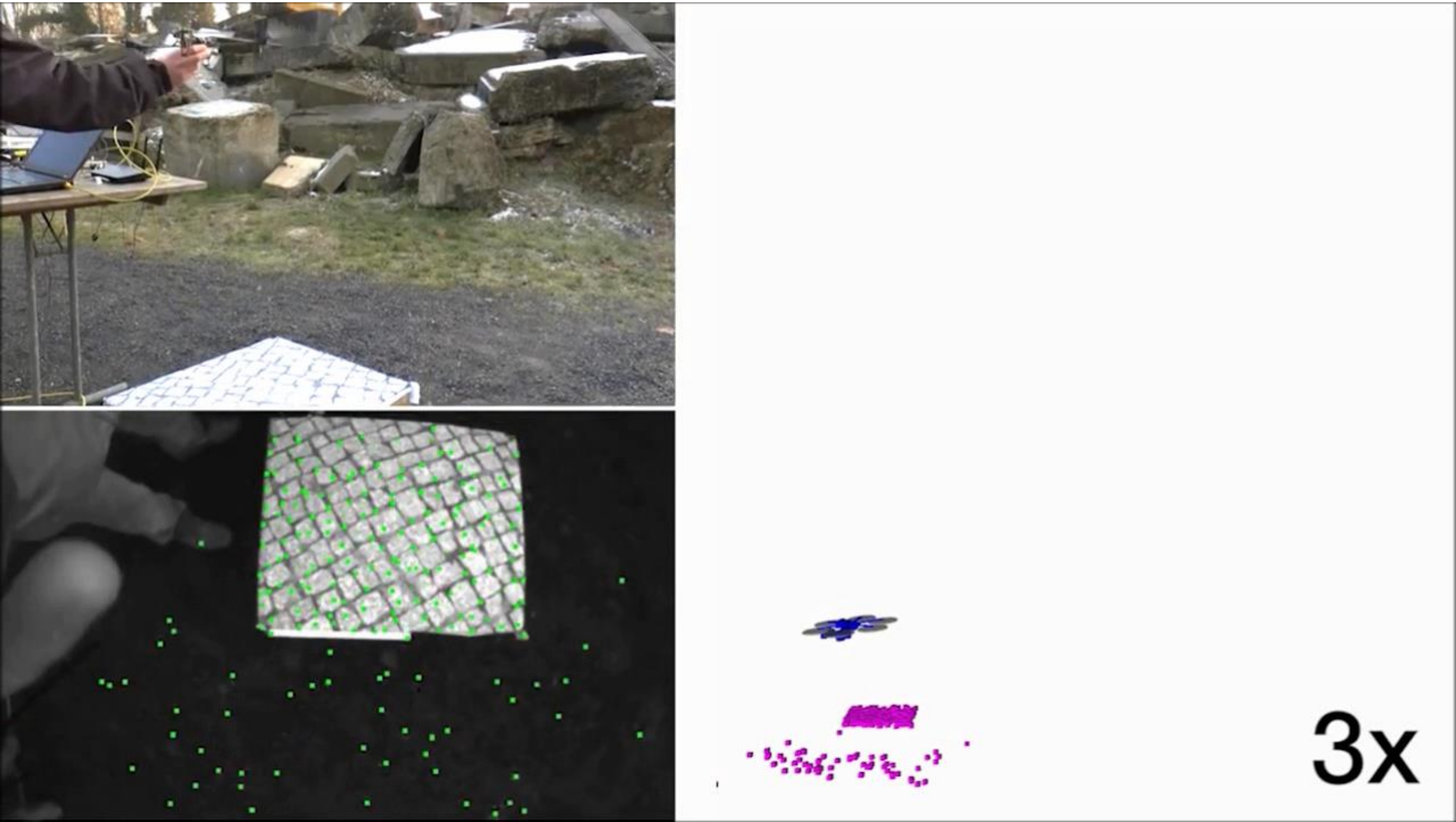
Flight Results: Indoor, aggressive flight

Speed: 4 m/s, height: 1.5 m – Down-looking camera

Faessler, Fontana, Forster, Mueggler, Pizzoli, Scaramuzza, Autonomous, Vision-based Flight and Live Dense 3D Mapping with a Quadrotor Micro Aerial Vehicle, **Journal of Field Robotics, 2015**.

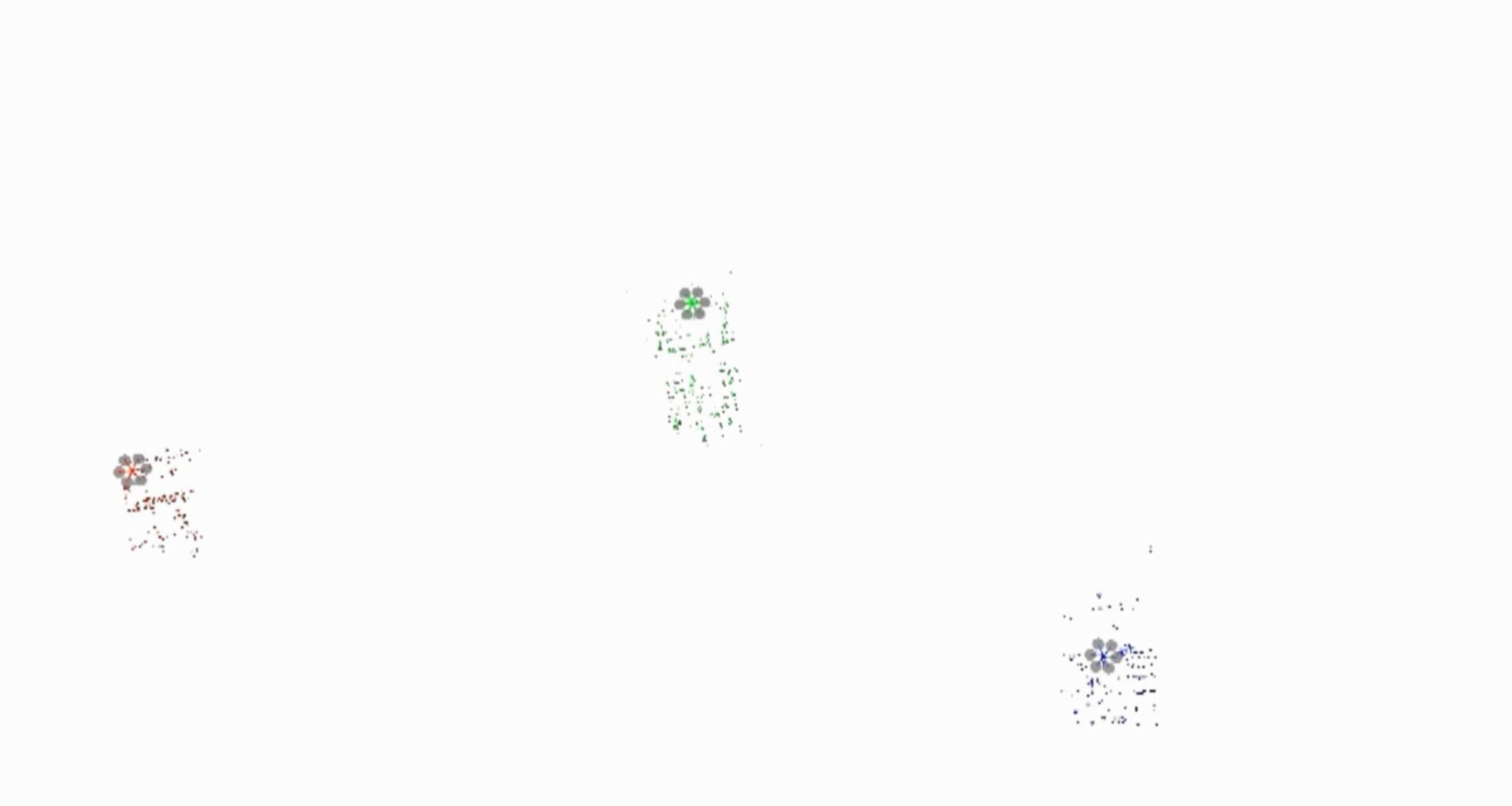
Current Research Activities

Vision-controlled Micro Aerial Vehicles



Current Research Activities

Multi-robot collaboration



Current Research Activities

Air-ground collaboration

Now it’s your turn!

- What’s your name?
- What are you studying?
- Why are you interested in computer vision?

Today's Class

- Introductions
- What is Computer Vision?
- Example of Vision Applications
- Specifics of this course
- Image Formation

What is computer vision?

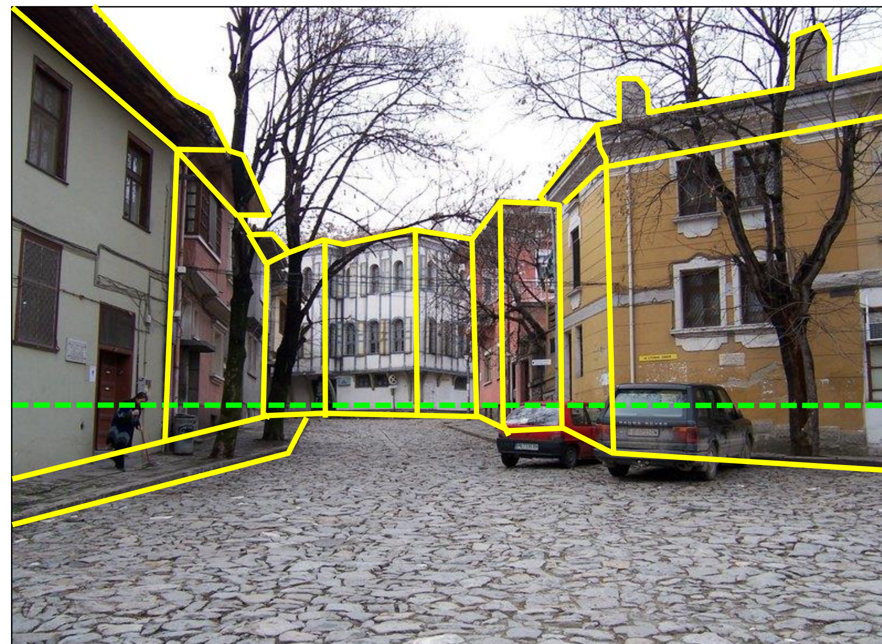
Done?

What is computer vision?

- Automatic extraction of “meaningful” information from images and videos

What kind of information can be extracted from an image?

Semantic information



Geometric information

Vision Demo?

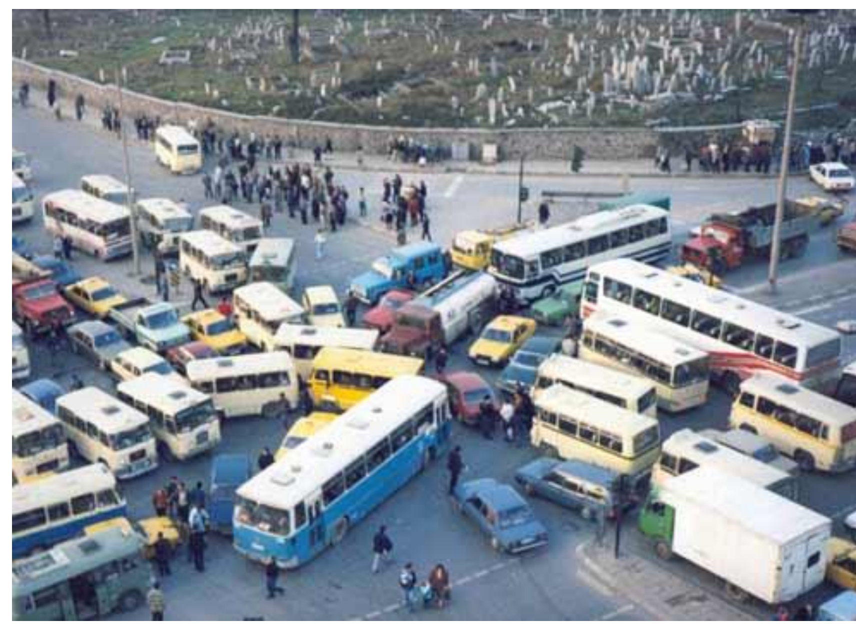
Terminator 2

we're not quite there yet….

Can computers match (or beat) human vision?

Yes and no (but mostly no!)

- humans are much better at “hard” things



- computers can be better at “easy” things

Human perception has its shortcomings…

For example, how do we recognize a face? From its features (mouth, nose, eyes) or from the head as a whole?

[Sinha and Poggio, *Nature*, 1996]

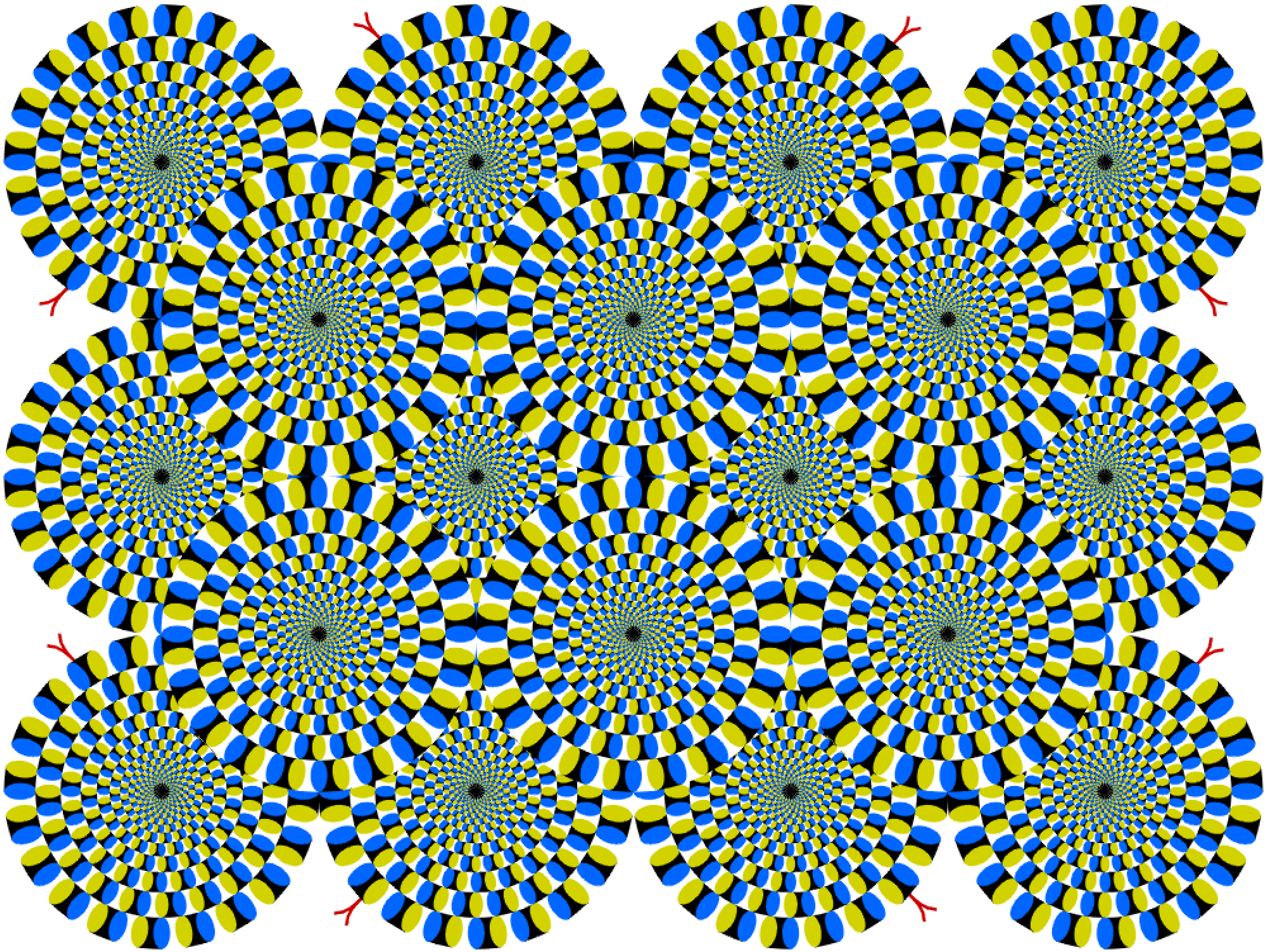
Human perception has its shortcomings…

For example, how do we recognize a face? From its features (mouth, nose, eyes) or from the head as a whole?

Computers are better at recognizing faces!

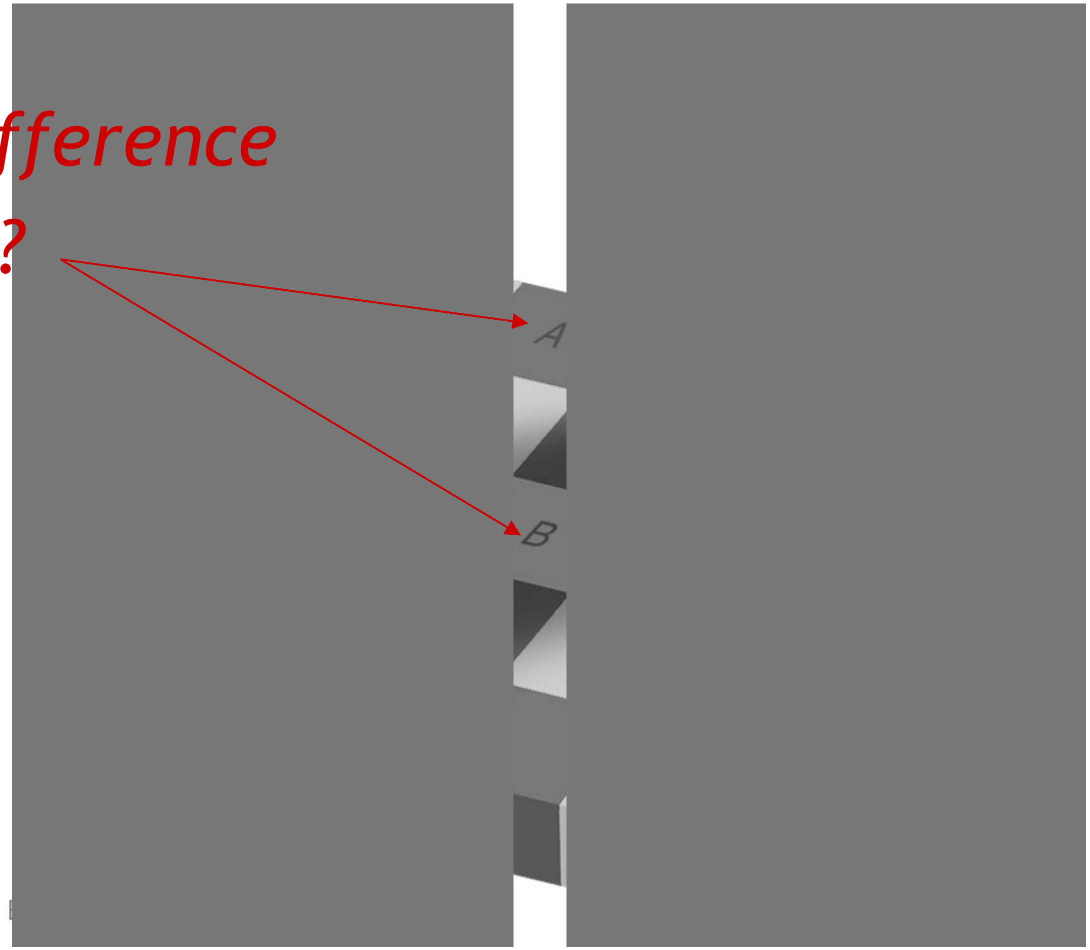
[Sinha and Poggio, *Nature*, 1996]

Human perception has its shortcomings…



Human perception has its shortcomings…

What is the difference in brightness?



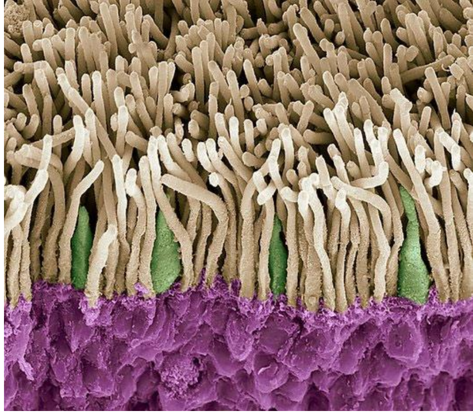
Courtesy E. Adelson

http://web.mit.edu/persci/people/adelson/checkershadow_downloads.html

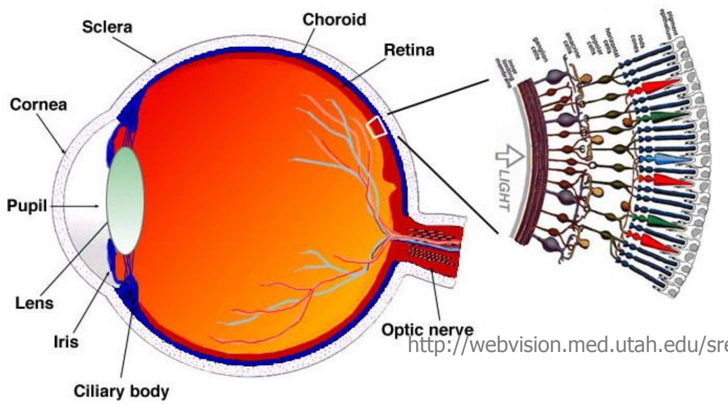
Why study computer vision?

- Relieve humans of boring, easy tasks
- Enhance human abilities: human-computer interaction, visualization
- Perception for robotics / autonomous agents
- Organize and give access to visual content
- Vision is difficult
  - Half of primate cerebral cortex is devoted to visual processing

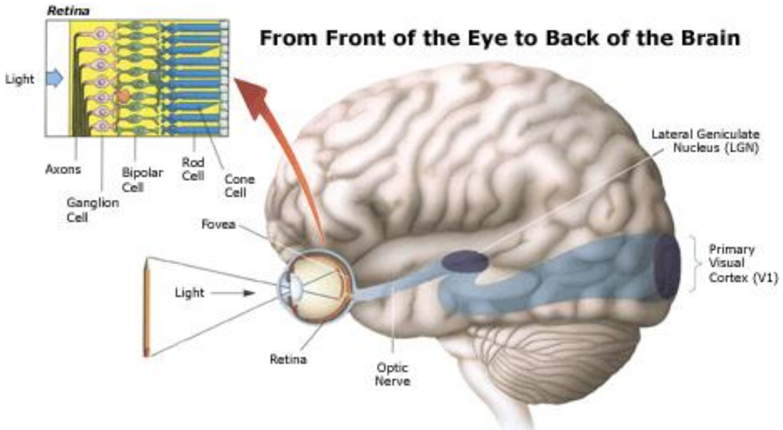
Vision in humans



- **Vision** is our most powerful sense in aiding our perception of the 3D world around us.
- Retina is ~1000mm^2. Contains millions of **photoreceptors**
  (120 mil. rods and 7 mil. Cones for color sampling)
- Provides **enormous** amount of information: data-rate of **~3GBytes/s**
  ⇨ a large proportion of our brain power is dedicated to processing the signals from our eyes
- How many Megapixels does the human eye have?
  > 500Megapixels!

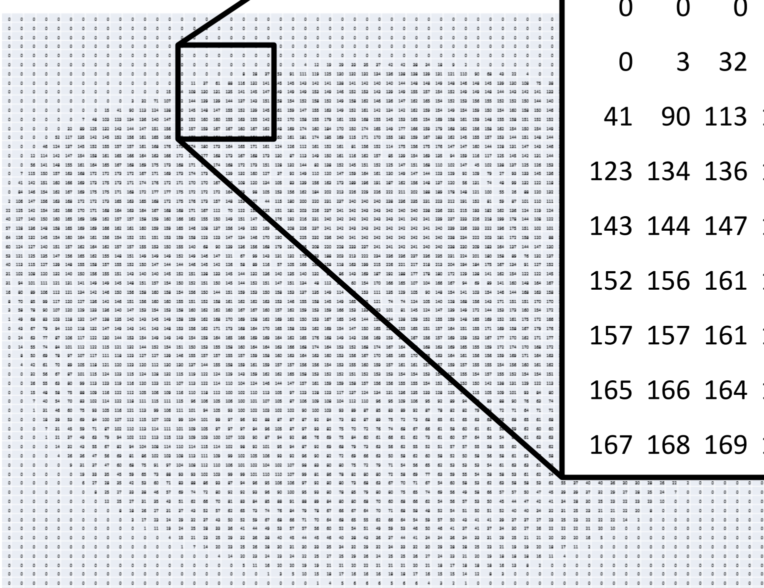


http://webvision.med.utah.edu/sretina.html



Why is vision hard?

- How do we go from an array of number to recognizing a fruit?



0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	8	28
0	0	0	0	0	0	11	37	61	88	116	132
0	0	0	0	15	64	108	130	131	135	141	145
0	3	32	71	107	132	144	139	139	144	137	143
41	90	113	124	138	140	145	148	147	155	152	139
123	134	136	140	147	149	152	160	160	155	163	155
143	144	147	151	156	160	157	159	167	167	160	167
152	156	161	165	166	169	170	170	164	169	173	164
157	157	161	168	176	175	174	180	173	164	165	171
165	166	164	163	166	172	179	177	168	173	167	168
167	168	169	175	173	168	171	177	174	168	172	173

What a computer sees

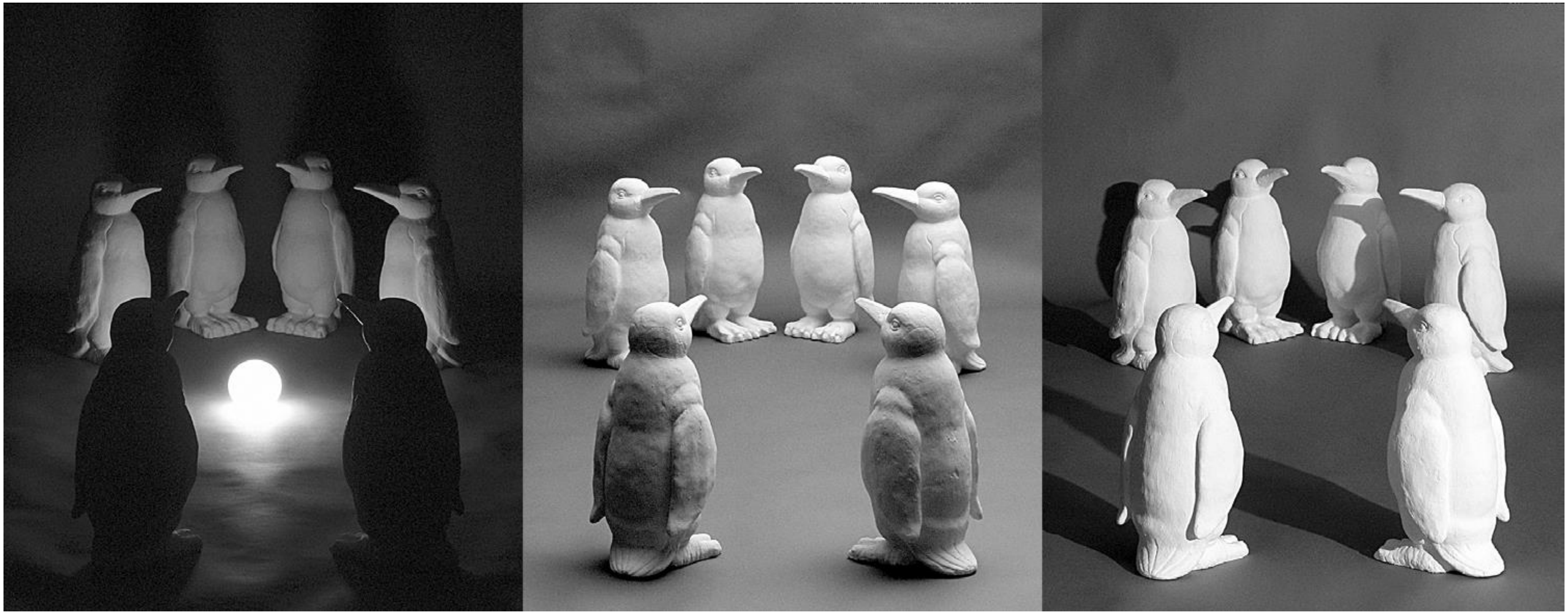
What we see

Why is vision hard?

- Challenges: Viewpoint variations

Why is vision hard?

- Challenges: Illumination



Why is vision hard?

- Challenges: Motion

Why is vision hard?

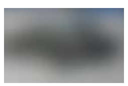
- Challenges: object intra-class variations

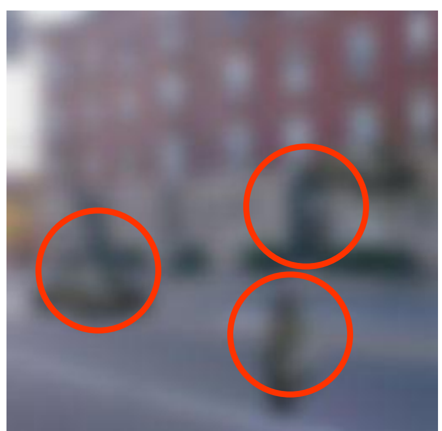





Why is vision difficult?

- Challenges: ambiguities

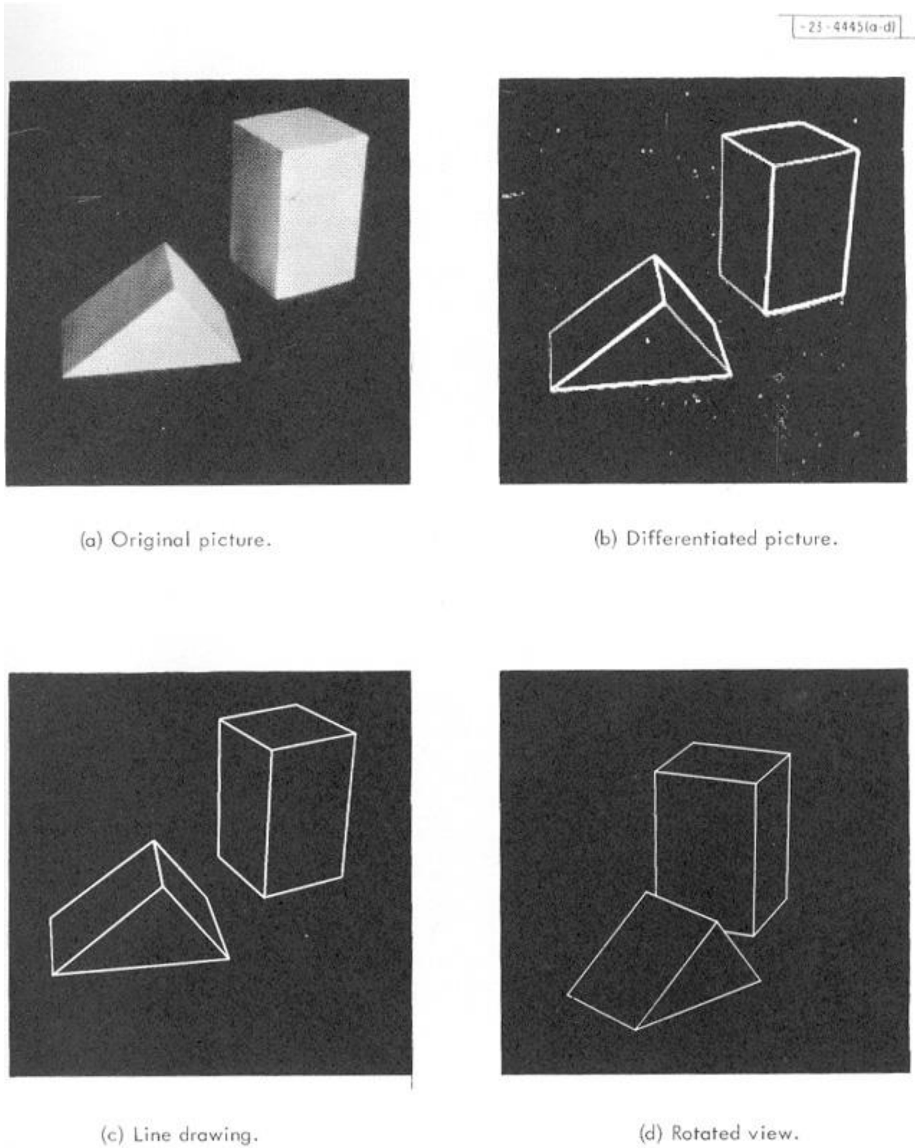




Why is vision difficult?

- Challenges: inherent ambiguities. Many different 3D scenes could give rise to a particular 2D picture

Origins of computer vision

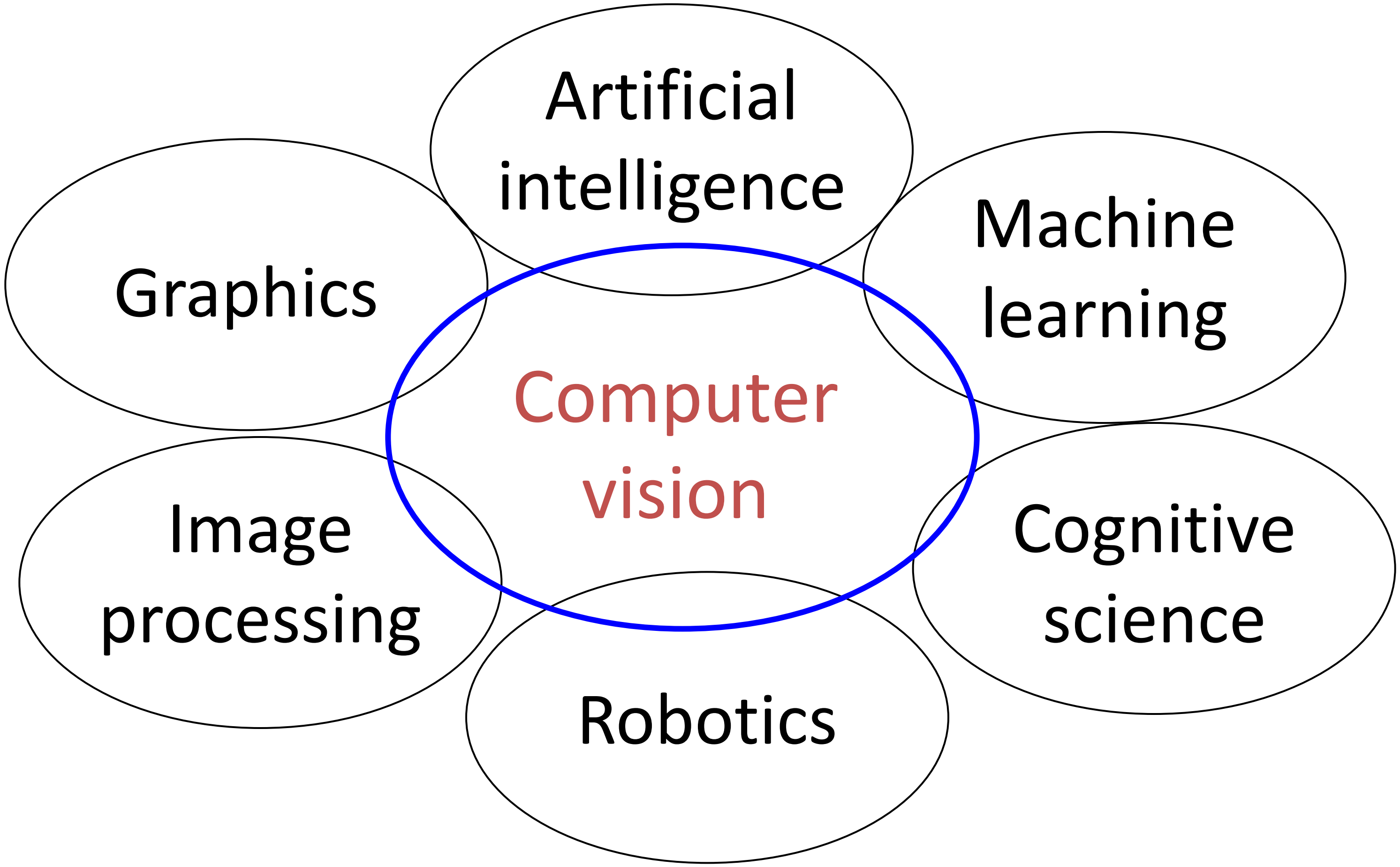


(a) Original picture. (b) Differentiated picture. (c) Line drawing. (d) Rotated view.

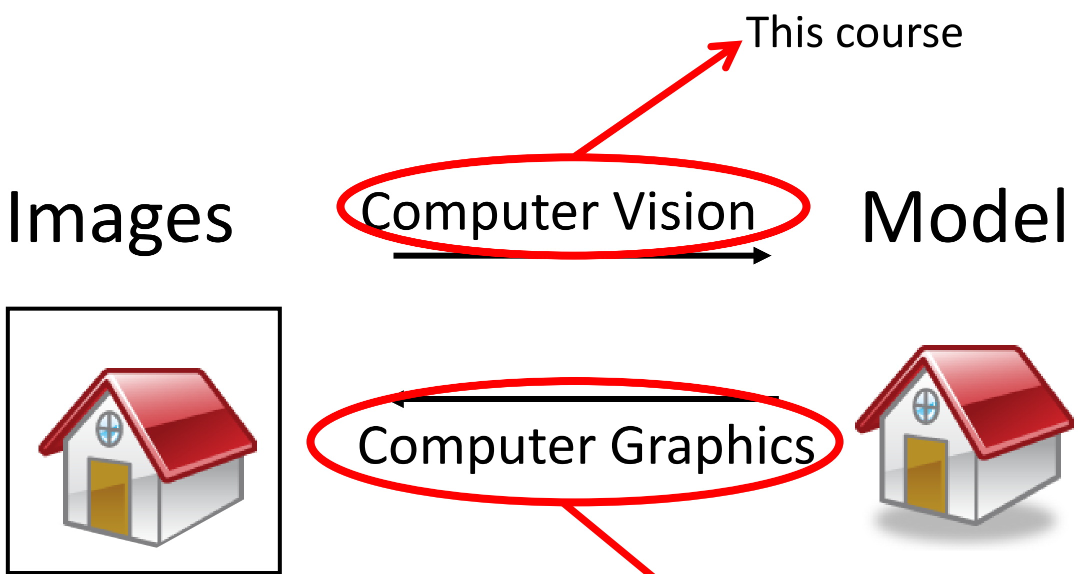
L. G. Roberts, *Machine Perception of Three Dimensional Solids*, Ph.D. thesis, MIT Department of Electrical Engineering, 1963.

He is the **inventor of ARPANET, the current Internet**

Related disciplines



Computer Vision vs Computer Graphics



Prof. Dr. Renato Pajarola
Computer Graphics

Inverse problems: analysis … nthesis.

Today's Class

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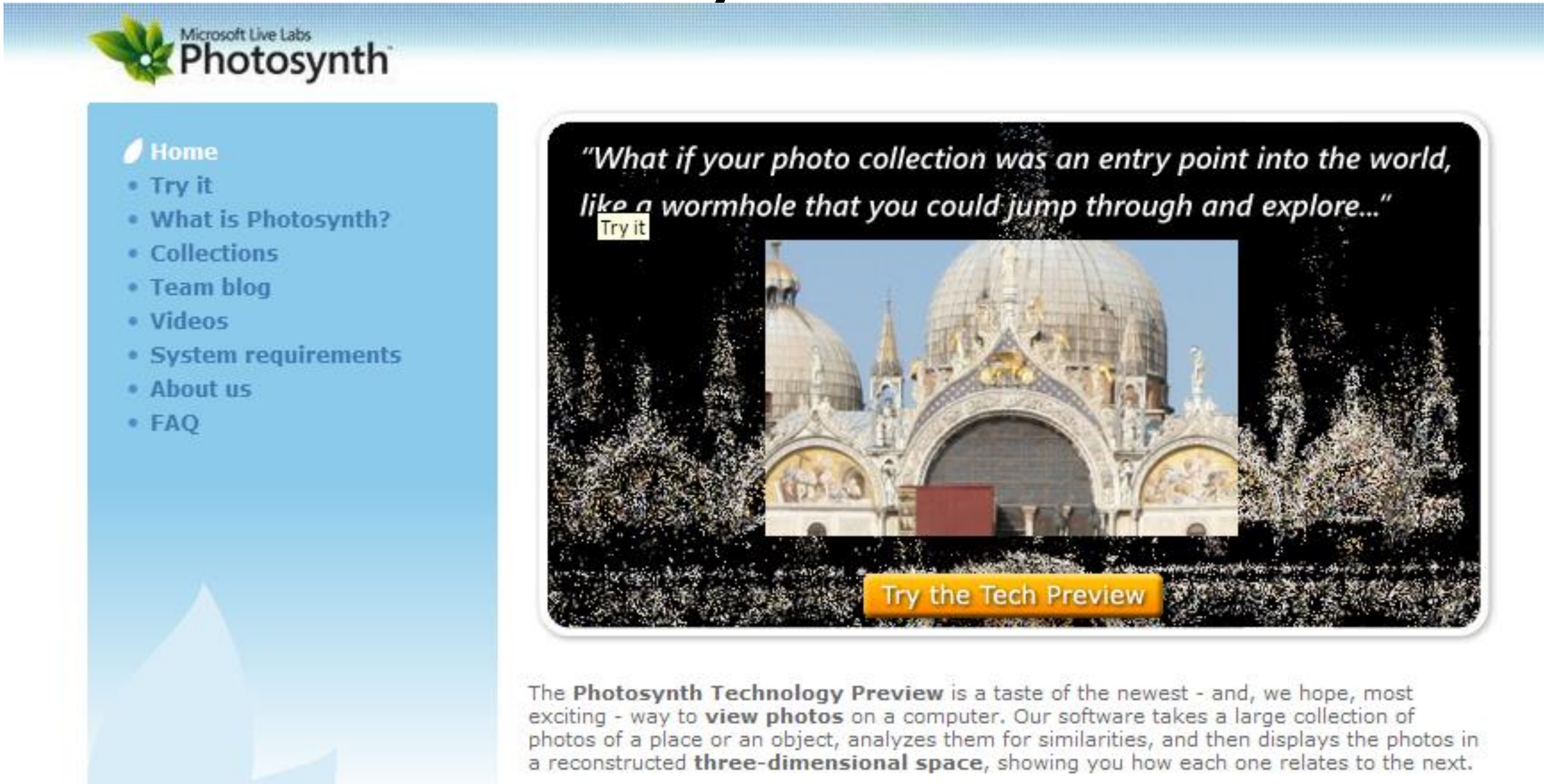
- Example of Vision Applications
- Specifics of this course
- Image Formation
- RPG Research Activities

Microsoft Photosynth



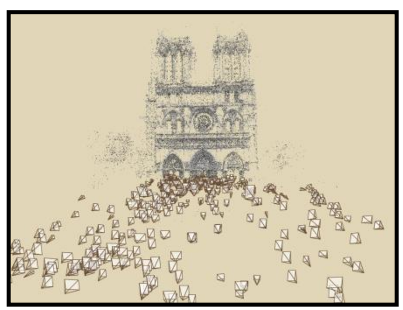
http://labs.live.com/photosynth/

Based on Photo Tourism technology developed by Noah Snavely, Steve Seitz, and Rick Szeliski

Photo Tourism overview

Input photographs

Scene reconstruction



Relative camera positions and orientations

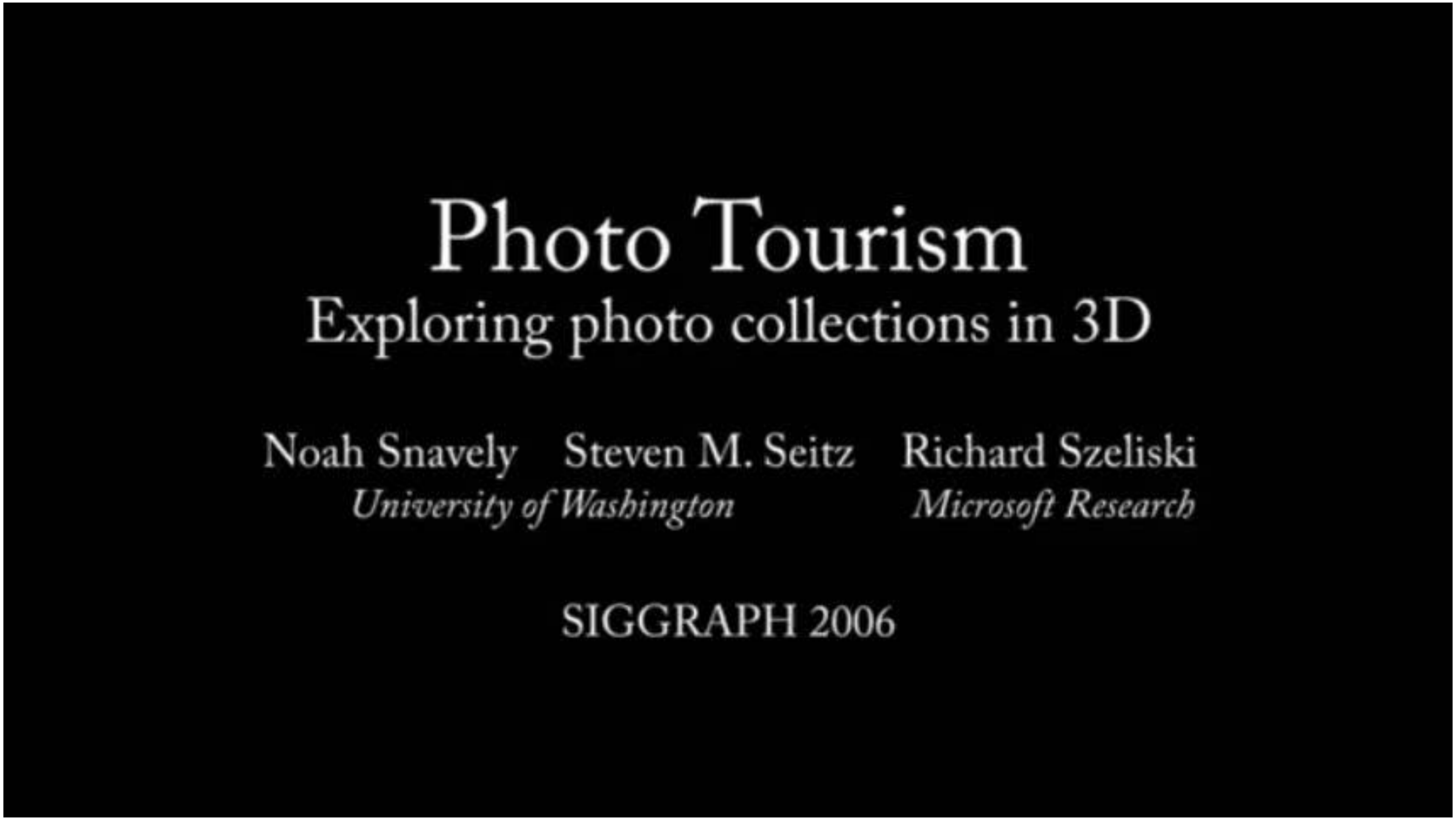
Point cloud

Sparse correspondence

Photo Explorer

System for interactive browsing and exploring large collections of photos of a scene. Computes viewpoint of each photo as well as a sparse 3d model of the scene.

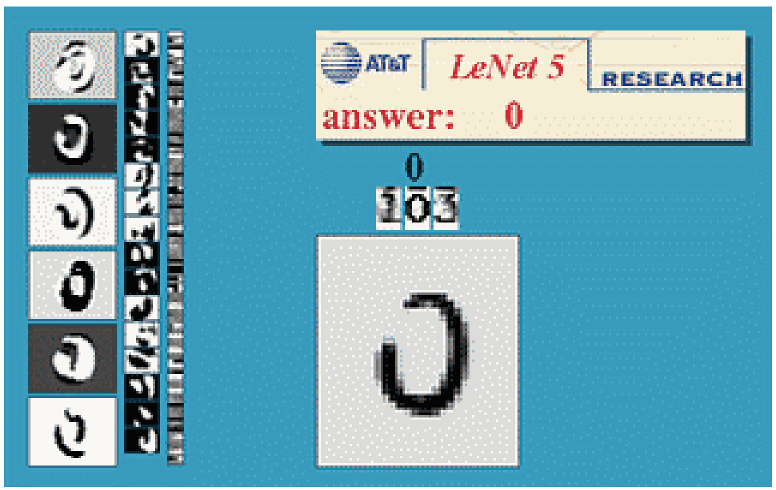
Photo Tourism overview



Optical character recognition (OCR)

Technology to convert scanned docs to text

- If you have a scanner, it probably came with OCR software



Digit recognition, AT&T labs
http://www.research.att.com/~yann/

License plate readers
http://en.wikipedia.org/wiki/Automatic_number_plate_recognition

Face detection

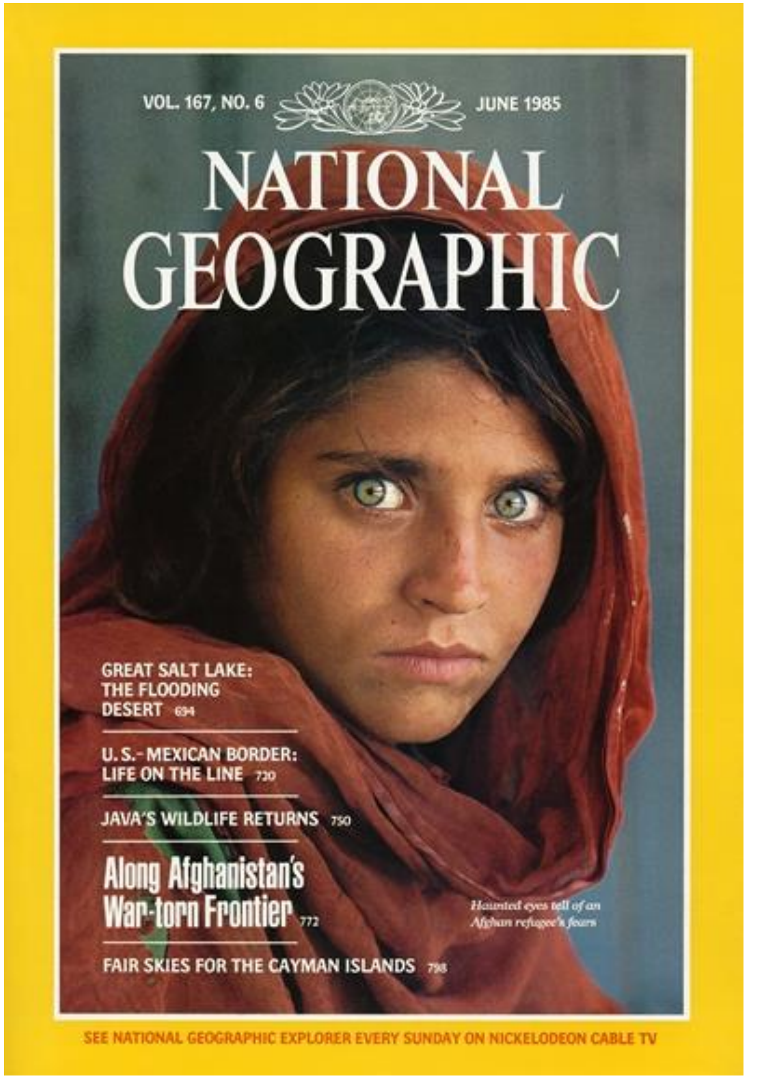
- Most new digital cameras and phones now detect faces
  - Nikon, Canon, Sony, Fuji, …

Object recognition (in supermarkets)

[LaneHawk by EvolutionRobotics]

"A smart camera is flush-mounted in the checkout lane, continuously watching for items. When an item is detected and recognized, the cashier verifies the quantity of items that were found under the basket, and continues to close the transaction. The item can remain under the basket, and with LaneHawk,you are assured to get paid for it… "

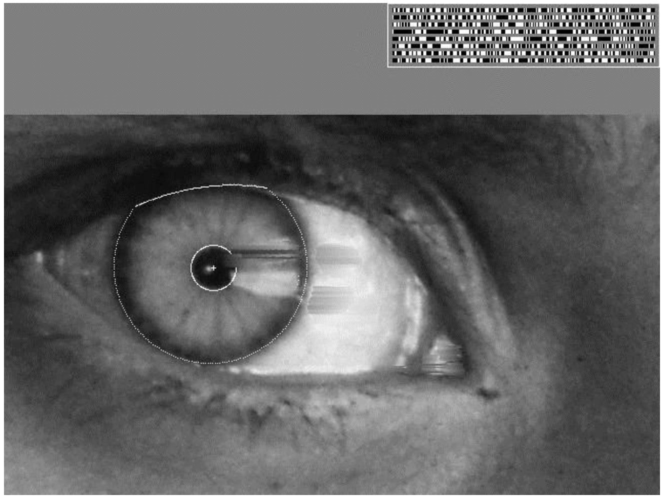
Vision-based biometrics

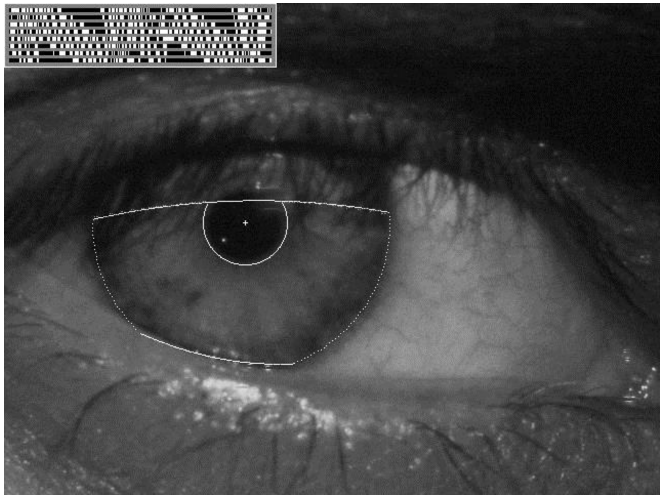


Who is she?

Vision-based biometrics

"*How the Afghan Girl was Identified by Her Iris Patterns*" Read the story

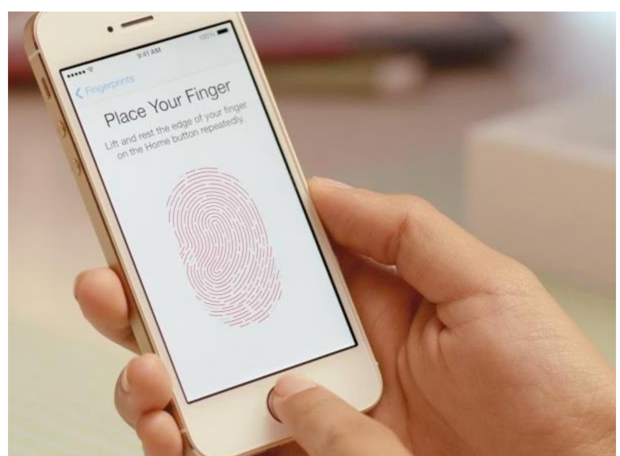




Login without a password…

Fingerprint scanners on
many new laptops,
other devices

Face recognition systems now
beginning to appear more widely
http://www.sensiblevision.com/



Fingerprint scanner in
iPhone 5S

Object recognition (in mobile phones)

- This is becoming real:
  - Lincoln Microsoft Research
  - Point & Find, Nokia
  - SnapTell.com (Amazon)
  - Google Goggles

Special effects: shape and motion capture

Sports

- Augmented Reality

2013 America's Cup
For football event, see also (Libero Vision) (Swiss company) http://www.vizrt.com/products/viz_libero/

3D Reconstruction by Multi-View Stereo

[YouTube Video]

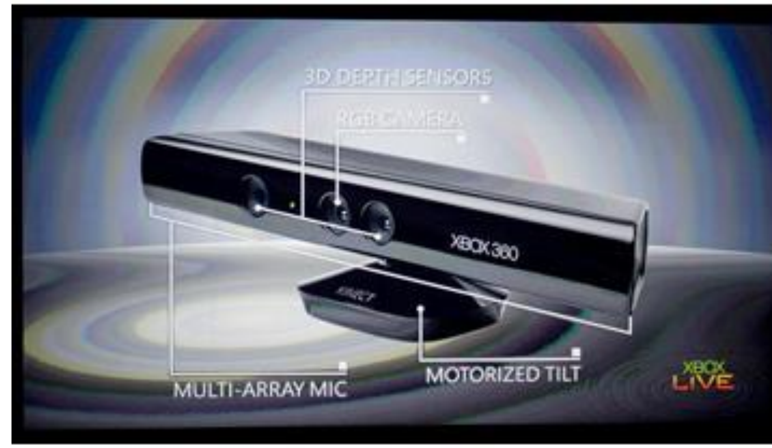
3D Reconstruction: Multi-View Stereo

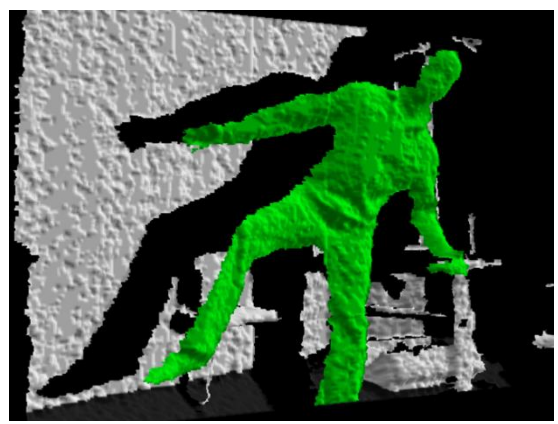
[YouTube Video]

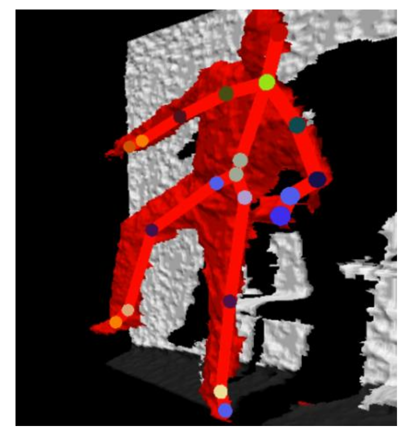
Automotive safety

- Mobileye: Vision systems in high-end BMW, GM, Volvo models
  - Pedestrian collision warning
  - Forward collision warning
  - Lane departure warning
  - Headway monitoring and warning

Vision-based interaction: Xbox Kinect







3D Reconstruction: Kinect Fusion

[YouTube Video]

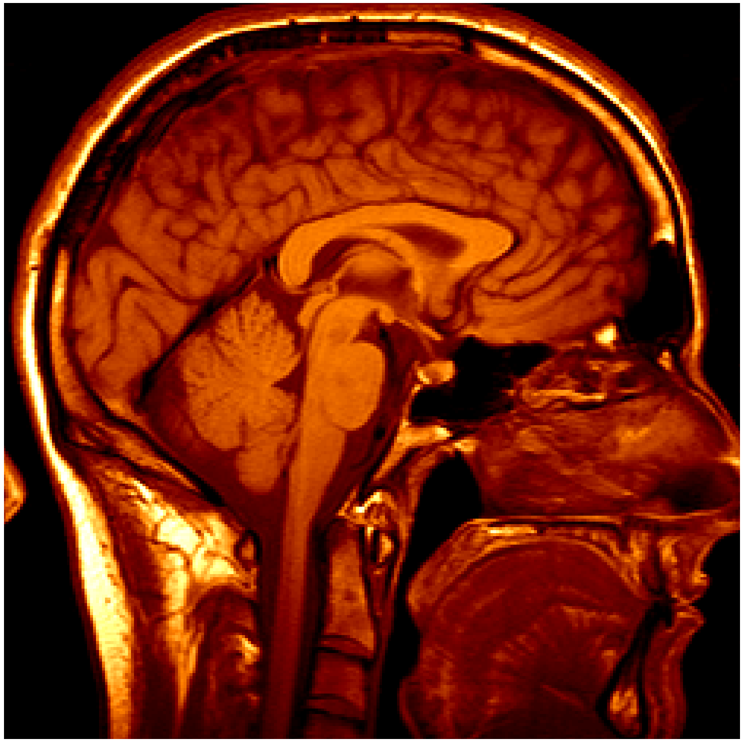
Vision in space

NASA'S Mars Exploration Rover Spirit captured this westward view from atop a low plateau where Spirit spent the closing months of 2007.

Vision systems (JPL) used for several tasks

- Panorama stitching
- 3D terrain modeling
- Obstacle detection, position tracking
- For more, read "Computer Vision on Mars" by Matthies et al.

Medical imaging



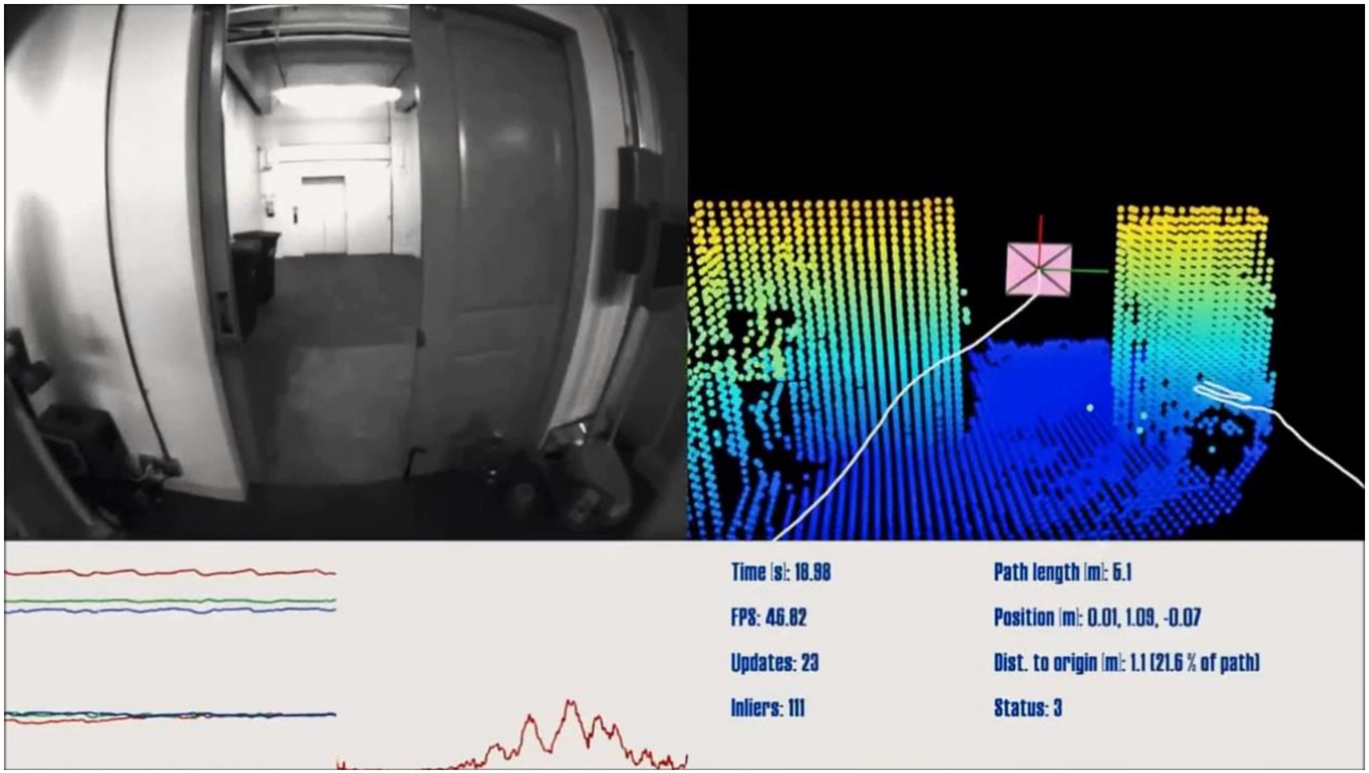
3D imaging
MRI, CT

Image guided surgery
Grimson et al., MIT

Dacuda's mouse scanner

- Technical Consultant for *Dacuda AG* inventor of the world's first mouse scanner, currently distributed by LG: *SmartScan LG LSM100*

Google Tango Phone



Project Tango

Google Tango Demo

Current state of the art

- You just saw examples of current systems.
  - Many of these are less than 5 years old
- This is a very active research area, and rapidly changing
  - Many new apps in the next 5 years
- To learn more about vision applications and companies
  - David Lowe maintains an excellent overview of vision companies
    - http://www.cs.ubc.ca/spider/lowe/vision.html

Today's Class

- Introductions
- What is Computer Vision?
- Example of Vision Applications
- Specifics of this course
- Image Formation

Organization of this Course

- **Lectures**:
  - 10:15 to 12:00 every week; **Except for next week (8:15 to 10): does it work?**
  - Room: BIN-2-A.01 - Binzmuhlestrasse 14

- **Exercises:**
  - 14:15 to 15:45 roughly every 2 weeks (please bring your laptop)

- **Course website: http://rpg.ifi.uzh.ch/teaching.html**
  - Check it out for the PDFs of the lecture slides and updates

Course Schedule

For updates, slides, and additional material: http://rpg.ifi.uzh.ch/teaching.html

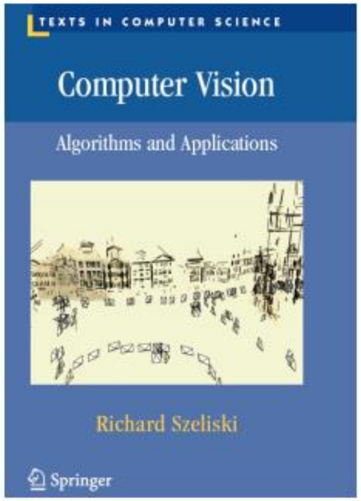
Lecture number	Date	Time	Description of the lecture/exercise	Lecturer
01	17.09.2015	10:15 - 12:00	**Introduction**	Scaramuzza
02	24.09.2015	08:15 - 10:00	**Image Formation**	Scaramuzza
03	01.10.2015	10:15 - 12:00	**Filtering**	Scaramuzza
		14:15 – 15:45	Exercise: Matlab intro + filtering exercise	Elias Mueggler/Zichao Zhang
04	08.10.2015	10:15 - 12:00	**Edge detection & Line Detection**	Scaramuzza
05	15.10.2015	10:15 - 12:00	**Point Feature Detectors**	Scaramuzza
		14:15 – 15:45	Exercise: Harris detector	Elias Mueggler/Zichao Zhang
06	22.10.2015	10:15 - 12:00	**Multiple-view geometry 1 (Epipolar geometry and stereo)**	Scaramuzza
07	29.10.2015	10:15 - 12:00	**Multiple-view geometry 2 (Two-view Structure from Motion and RANSAC)**	Scaramuzza
		14:15 – 15:45	Exercise: 8-point algorithm and RANSAC	Elias Mueggler/Zichao Zhang
08	05.11.2015	10:15 - 12:00	**Multiple-view geometry 3 (n-view Structure-from-Motion and Bundle Adjustment)**	Scaramuzza
09	12.11.2015	10:15 - 12:00	**3D Reconstruction (Multi-view Stereo)**	Scaramuzza
10	19.11.2015	10:15 - 12:00	**Shape from X, Photometric Stereo, Multi-view Photometric Stereo**	Scaramuzza
		14:15 – 15:45	Exercise Photometric stereo	Elias Mueggler/Zichao Zhang
11	26.11.2015	10:15 - 12:00	**Optical Flow and Tracking (Lucas-Kanade)**	Scaramuzza
		14:15 – 15:45	Exercise: Lucas-Kanade tracker	Elias Mueggler/Zichao Zhang
12	03.12.2015	10:15 - 12:00	**Image Retrieval**	Scaramuzza
		14:15 – 15:45	Exercise: Recognition with Bag of Words	Elias Mueggler/Zichao Zhang
13	10.12.2015	10:15 - 12:00	**Paper presentations**	ALL
14	17.12.2015	10:15 - 12:00	**Paper presentations + Lab visit with live demonstrations**	ALL
15	14.01.2015	08:00 – 18:00	**Oral exams**	ALL

Exercises

- Every two weeks
- Bring **your own laptop**
- Have **Matlab** pre-installed
  - You can download it from the UZH website: http://www.id.uzh.ch/dl/sw/angebote_4.html
  - You will need to install all the toolboxes included in the license.
  - Info on how to setup the license can be found here: http://www.s3it.uzh.ch/software/matlab/

Have you used Matlab before?

Recommended Textbook



- Computer Vision: Algorithms and Applications, R. Szeliski, 2009.

- Can be freely downloaded from http://szeliski.org/Book/

- Other books:
  - *An Invitation to 3D Vision*: Y. Ma, S. Soatto, J. Kosecka, S.S. Sastry
  - *Multiple view Geometry*: R. Hartley and A. Zisserman
  - *Autonomous Mobile Robots*: R. Siegwart, I.R. Nourbakhsh, D. Scaramuzza -> Chapter 4

Instructors

- Lectures
  - Davide Scaramuzza: sdavide (at) ifi (dot) uzh (dot) ch

- Exercises
  - Elias Mueggler: mueggler (at) ifi (dot) uzh (dot) ch
  - Zichao Zhang: zhangzichao17 (at) gmail (dot) com

Office receiving times

- Tuesdays and Thursdays from 2 to 4pm
  AND 2.26 (preferred: announce by email)

Prerequisites

- Linear algebra
- Matrix calculus
- No prior knowledge of computer vision, image processing, or graphics is required

Grading and Exam

- 40%: You can choose one of these two options
  - Option 1: presentation of one paper in front of the class (last two lectures: Dec. 10th and 17th)
  - Option 2: mini project (list will be out on Sep. 24th)

- 60%: oral exam (30 minutes) – Date: Jan 14, 2016

- In addition, strong class and exercise participation can offset negative performance in any one of the above components.

Class Participation

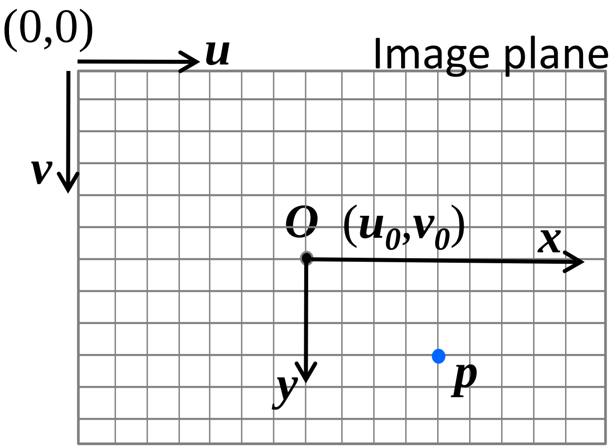
- Class participation includes
  - showing up
  - being able to articulate key points from last lecture

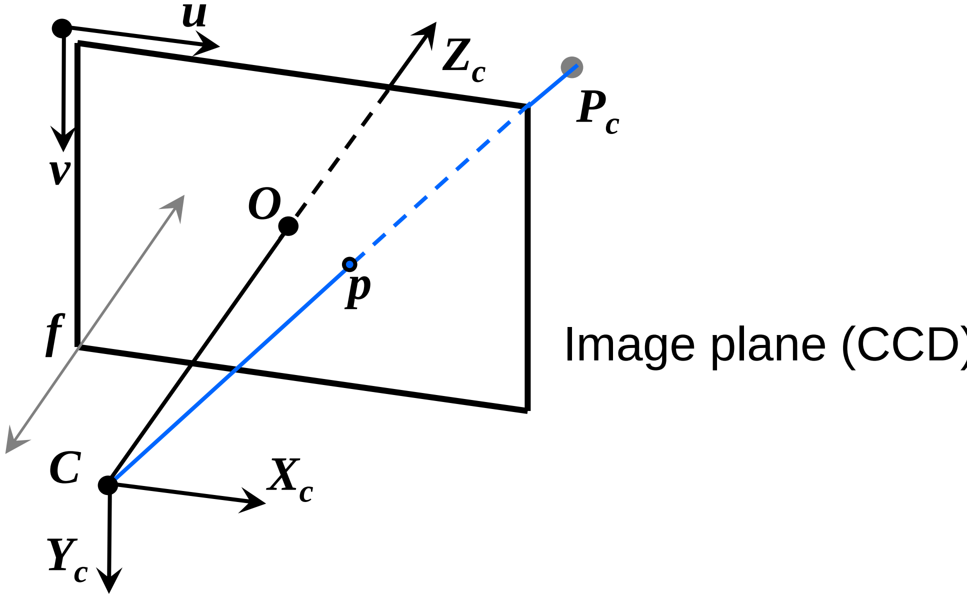
Course Topics

- Principles of image formation
- Image filtering
- Feature detection
- Multi-view geometry
- Structure from motion
- Visual recognition

Course Topics

- Principles of image formation
  - Perspective projection
  - Camera calibration





Course Topics

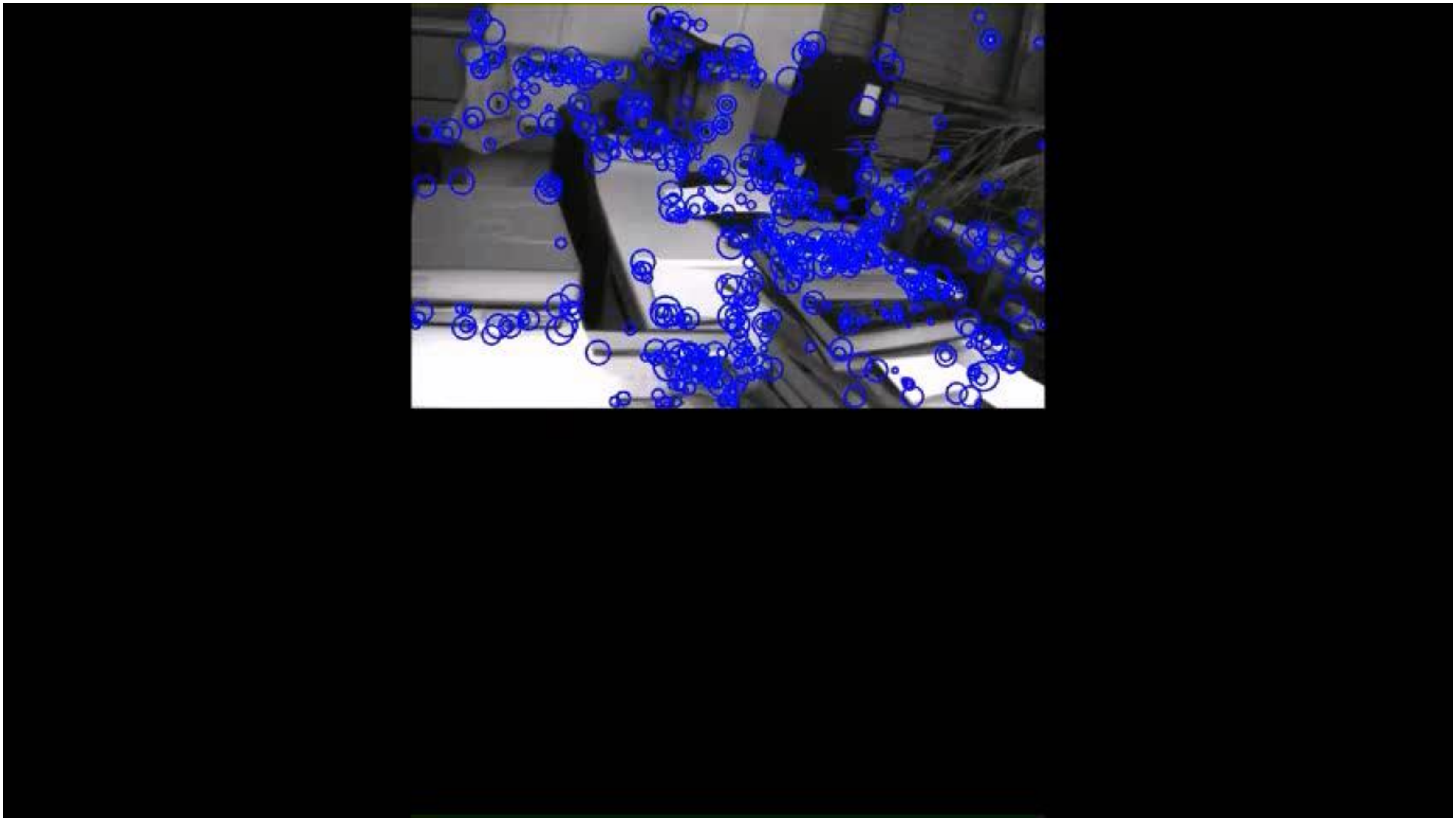
- Image filtering

Low-pass filtered image

High-pass filtered image

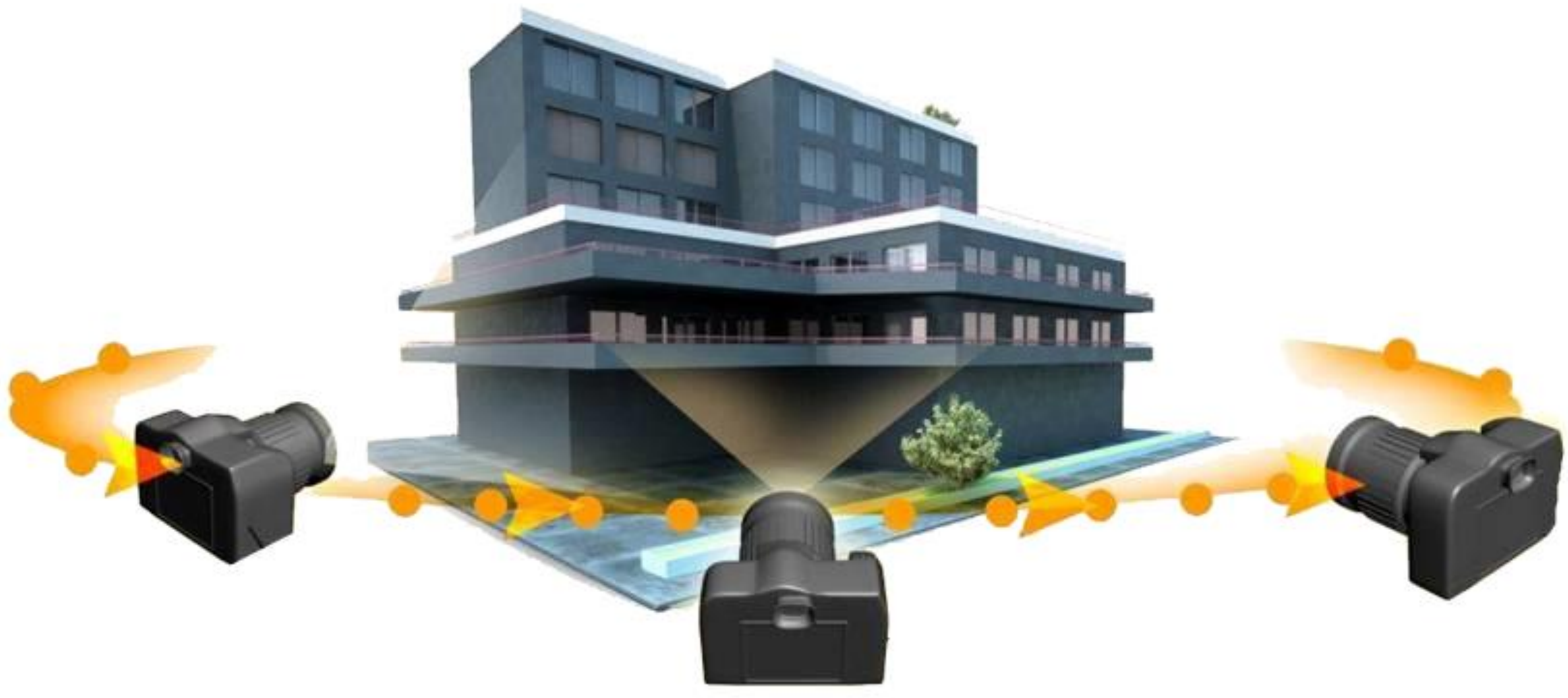
Course Topics

- Feature detection and matching



Course Topics

- Multi-view geometry and 3D reconstruction



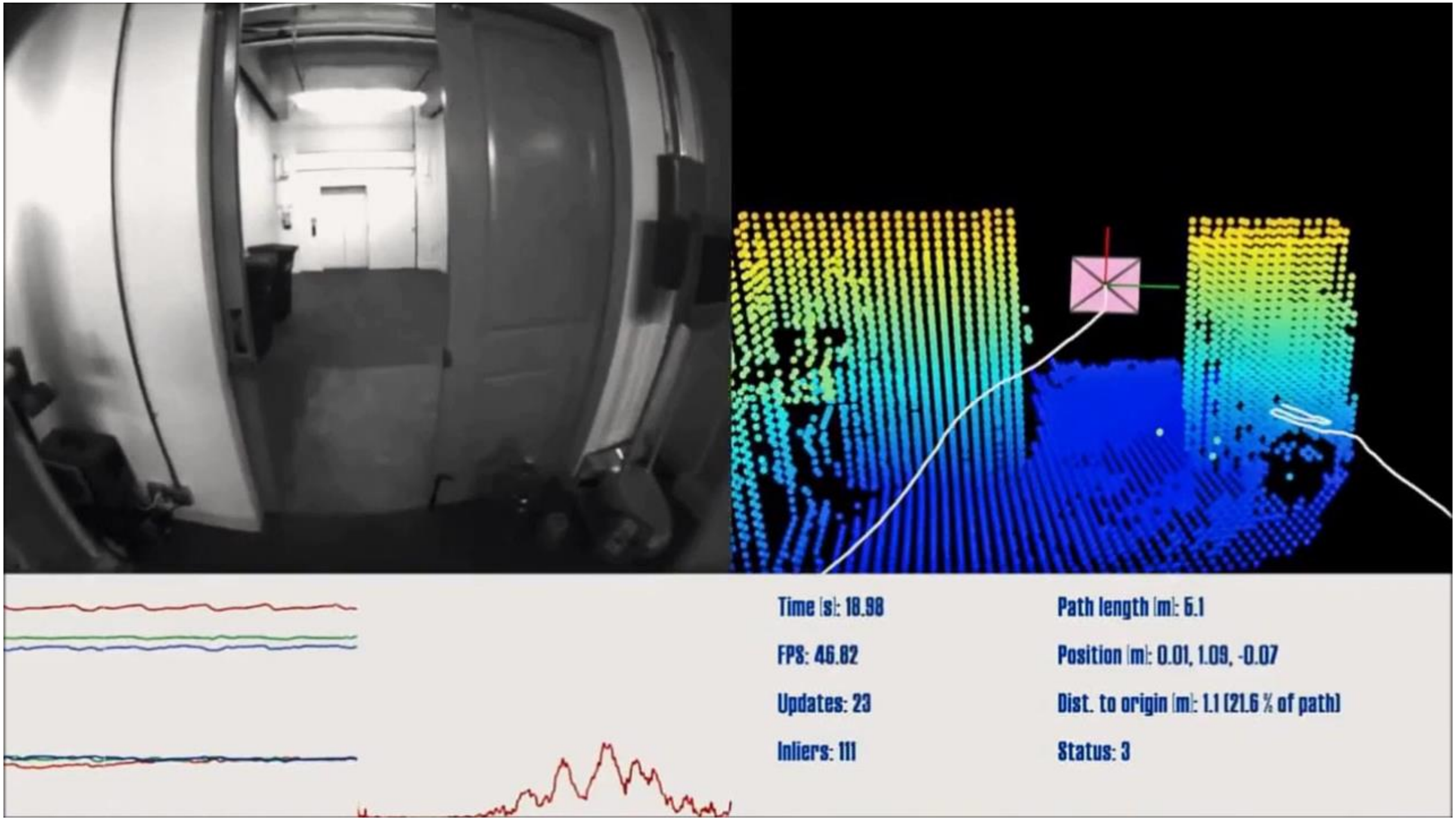
Course Topics

- Multi-view geometry and 3D reconstruction

San Marco square, Venice
14,079 images, 4,515,157 points

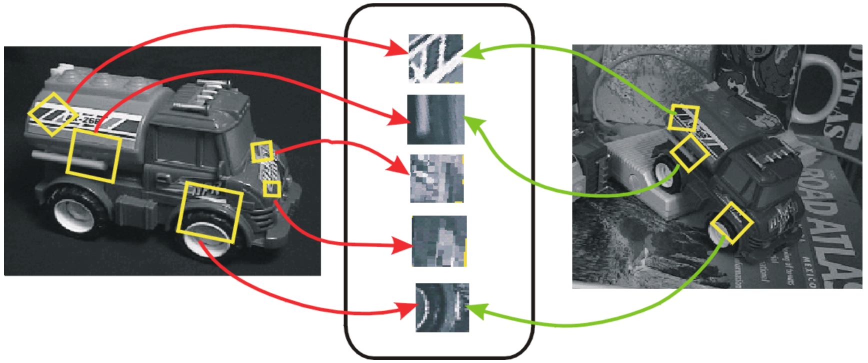
Course Topics

- Visual odometry

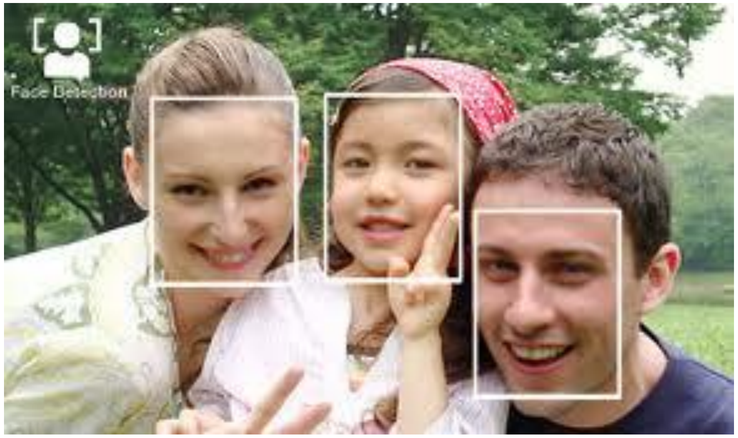


Course Topics

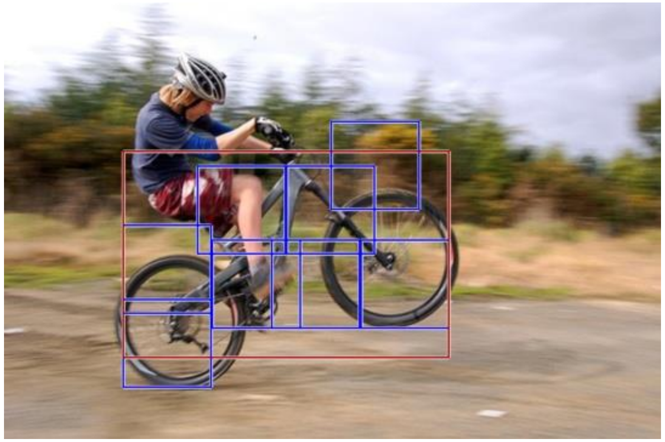
- Visual recognition



Instance recognition, large-scale alignment



Sliding window detection



Part-based models

Today's Class

- Introductions
- What is Computer Vision?
- Example of Vision Applications
- Specifics of this course
- Image Formation

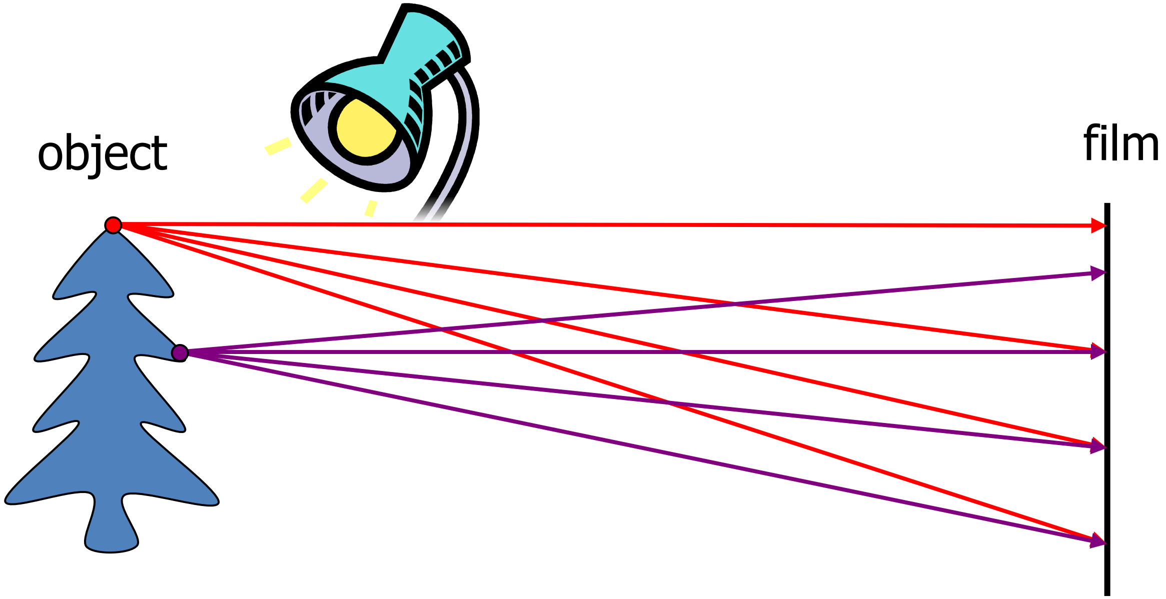
Let’s get started: Image formation

- How are objects in the world captured in an image?

The camera

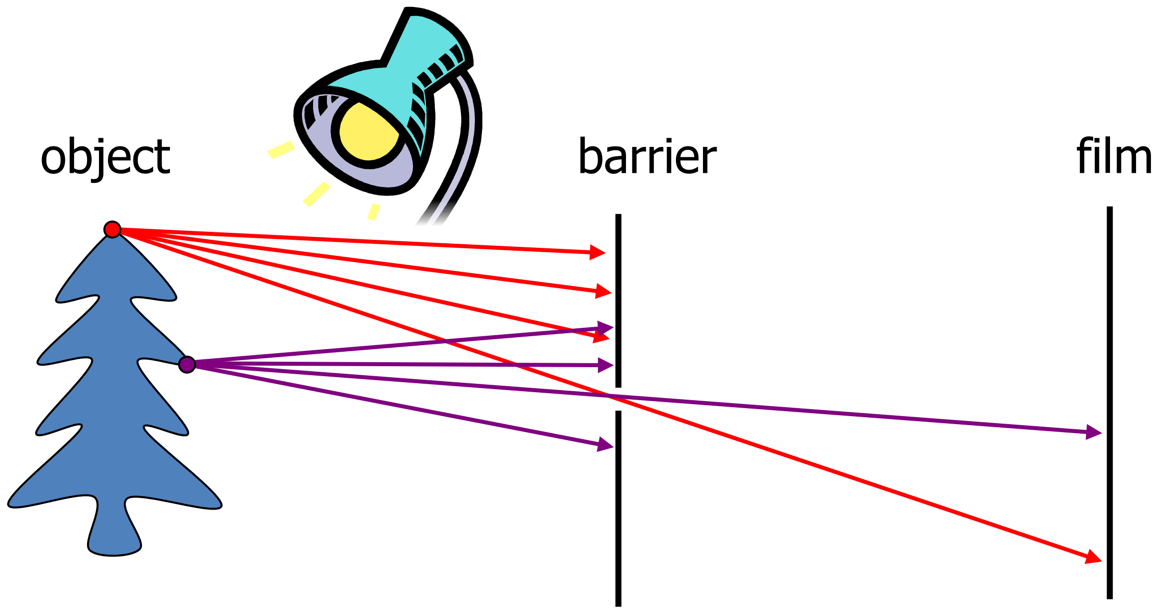
Sony Cybershot WX1

How to form an image



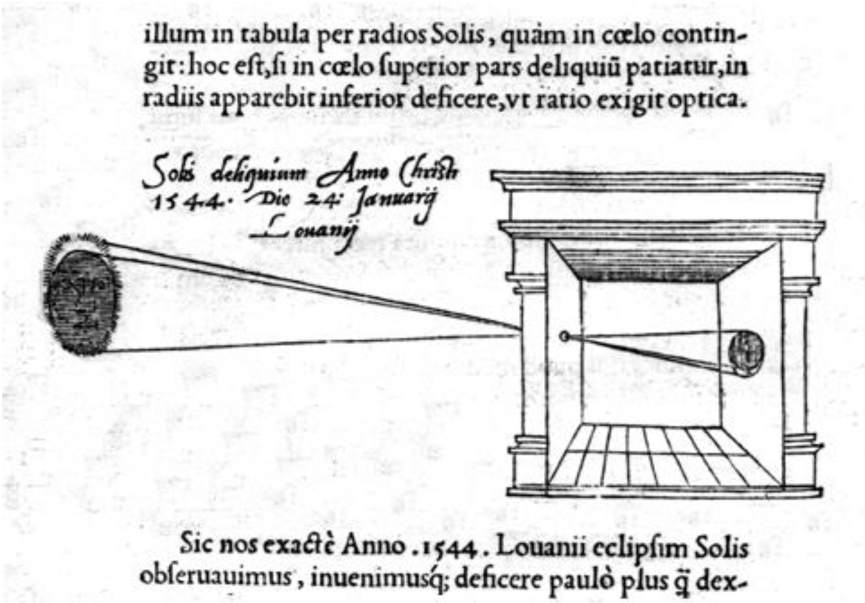
- Place a piece of film in front of an object
  ⇨ Do we get a reasonable image?

Pinhole camera



- Add a barrier to block off most of the rays
  - This reduces blurring
  - The opening is known as the **aperture**

Camera obscura

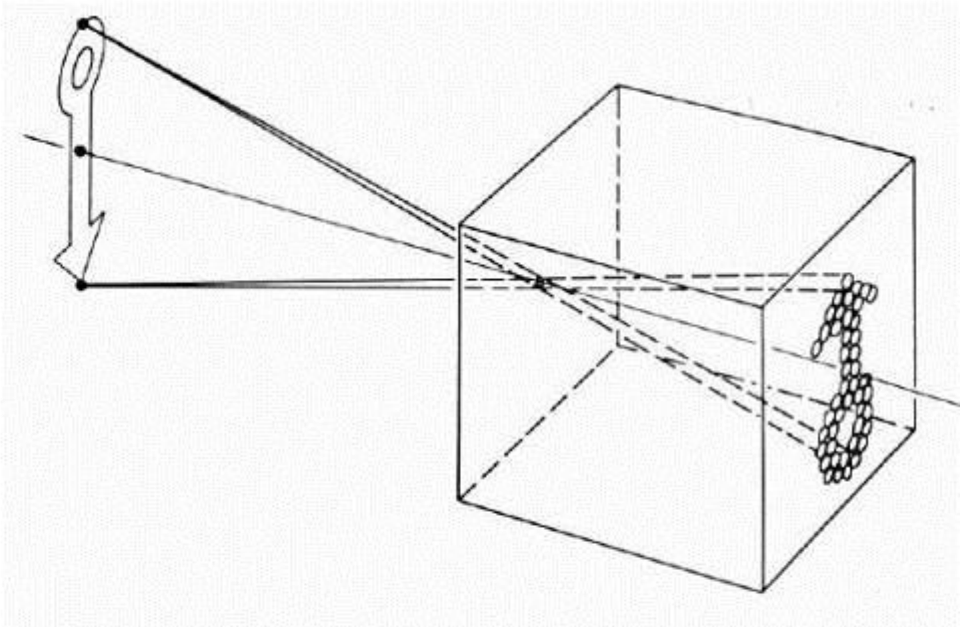


In Latin, means ‘dark room’

- Basic principle known to Mozi (470-390 BC), Aristotle (384-322 BC)
- Drawing aid for artists: described by Leonardo da Vinci (1452-1519)
- Image is inverted
- Depth of the room (box) is the effective focal length

"**Reinerus Gemma-Frisius**, observed an eclipse of the sun at Louvain on January 24, 1544, and later he used this illustration of the event in his book De Radio Astronomica et Geometrica, 1545. It is thought to be the first published illustration of a camera obscura..." Hammond, John H., The Camera Obscura, A Chronicle

Pinhole camera model



- Pinhole model:
  - Captures **beam of rays** – all rays through a single point
  - The point is called **Center of Projection** or **Optical Center**
  - The image is formed on the **Image Plane**

- We will use the pinhole camera model to describe how the image is formed

Camera obscura at home

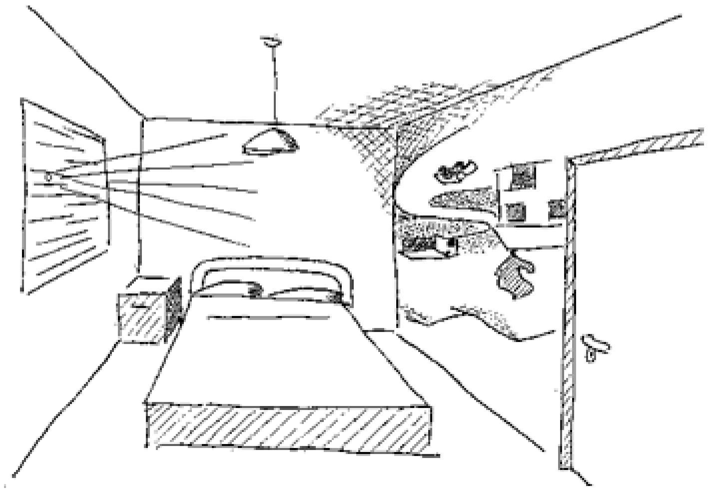


Figure 1 - A lens on the window creates the image of the external world on the opposite wall and you can see it every morning, when you wake up.

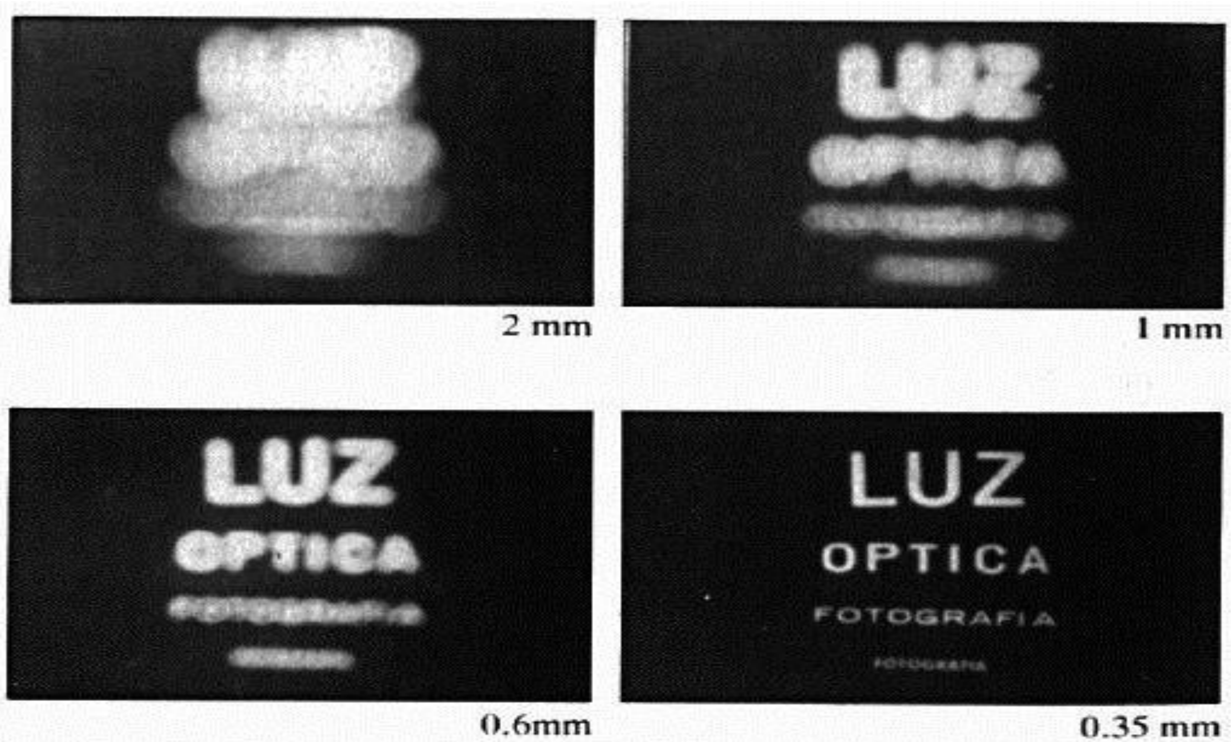
http://www.youtube.com/watch?v=B2aOs8RWntg

Sketch from http://www.funsci.com/fun3_en/sky/sky.htm

Home-made pinhole camera

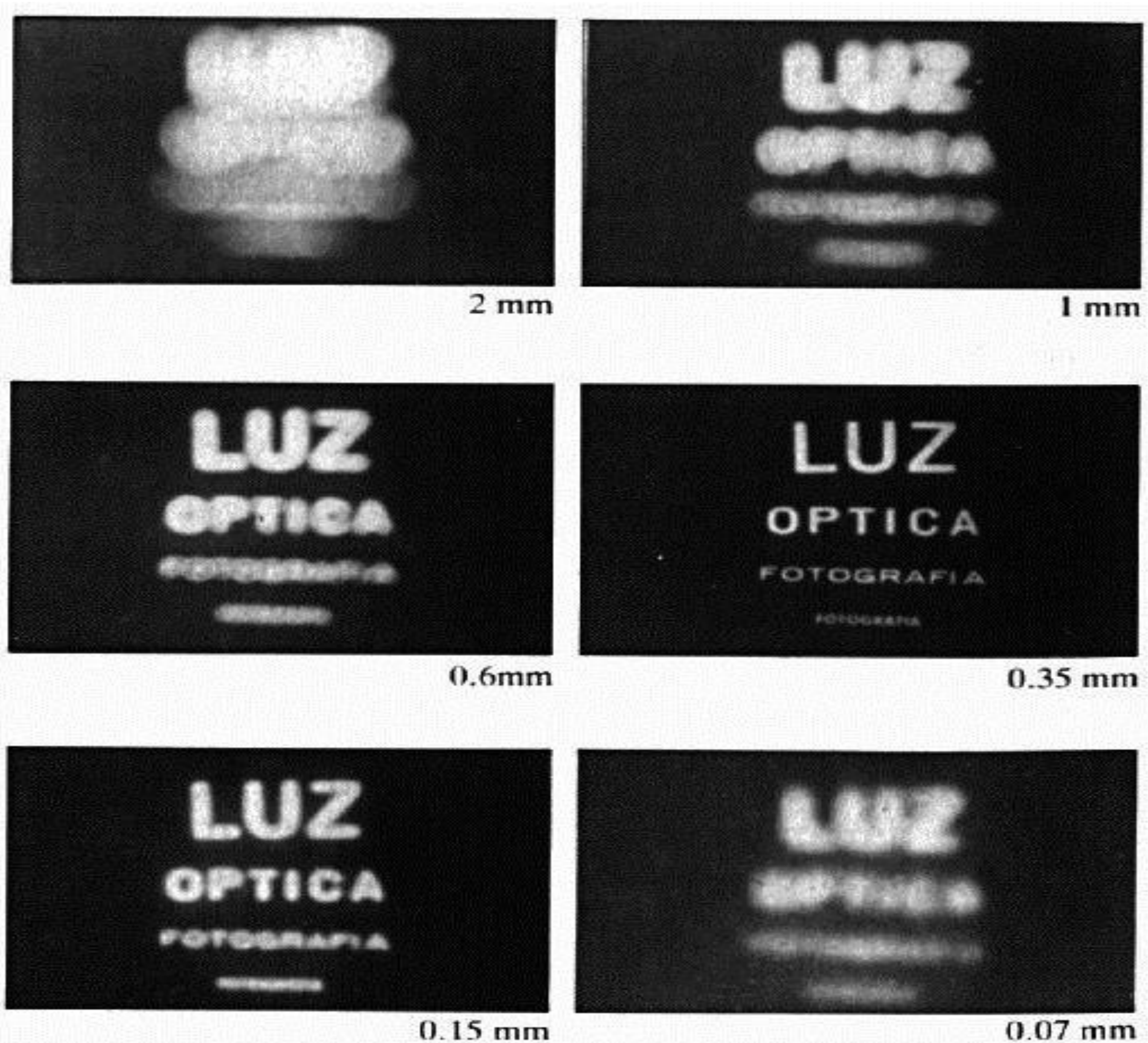
What can we do
to reduce the blur?

Shrinking the aperture



Why not make the aperture as small as possible?

Shrinking the aperture

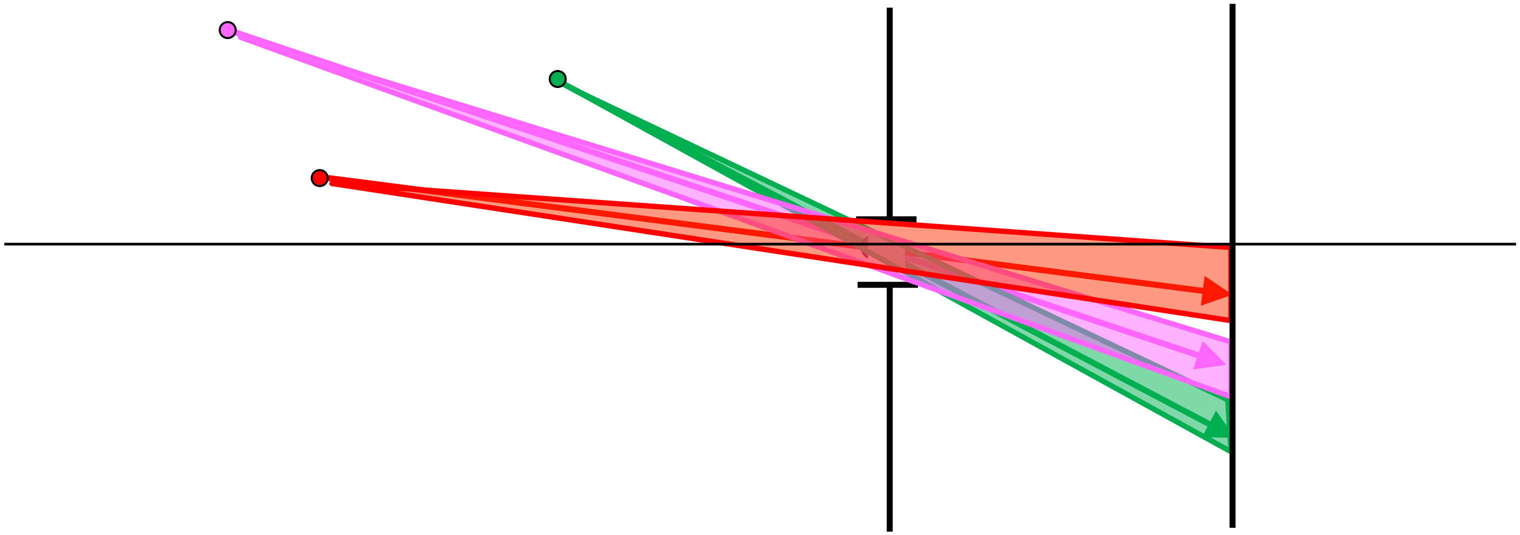


Why not make the aperture as small as possible?

- Less light gets through (must increase the exposure)
- Diffraction effects…

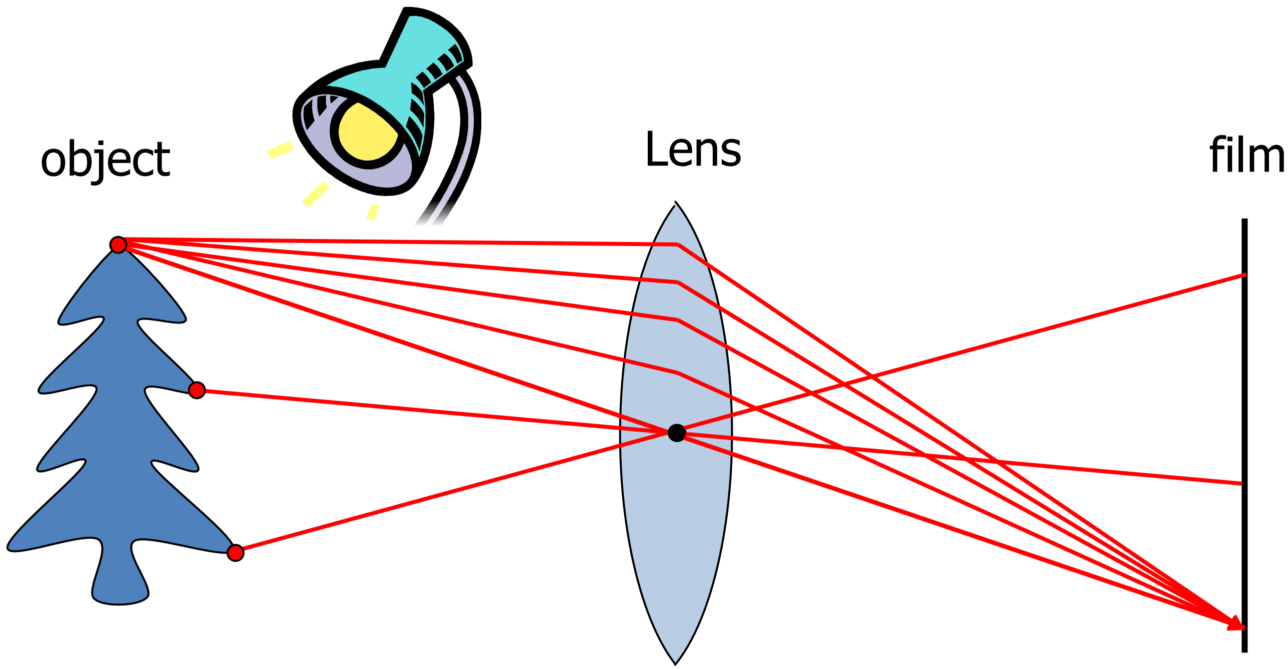
Why use a lens?

- *The ideal pinhole:*
  only one ray of light reaches each point on the film
  ⇨ image can be very dim
- Making the pinhole bigger (i.e. aperture)…



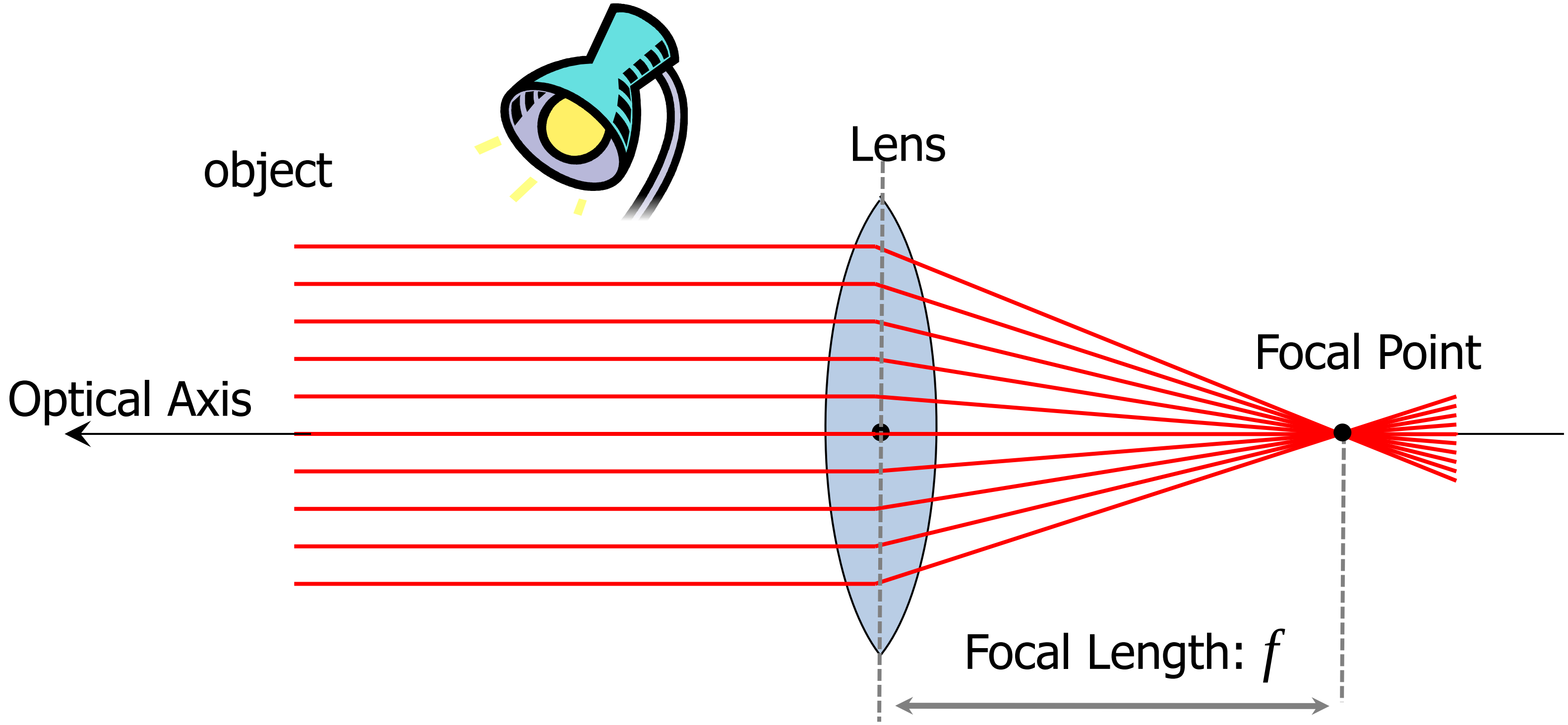
- A lens can focus multiple rays coming from the same point

Image formation using a converging lens



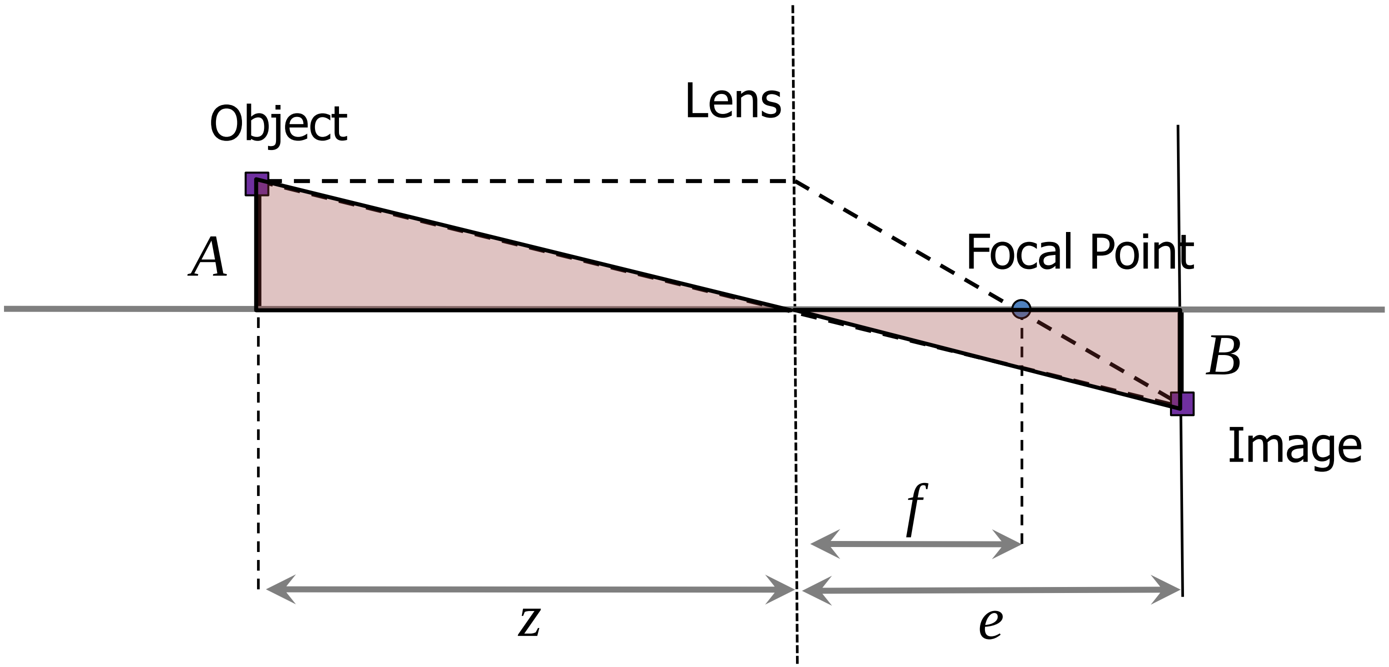
- A lens focuses light onto the film
- Rays passing through the optical center are not deviated

Image formation using a converging lens



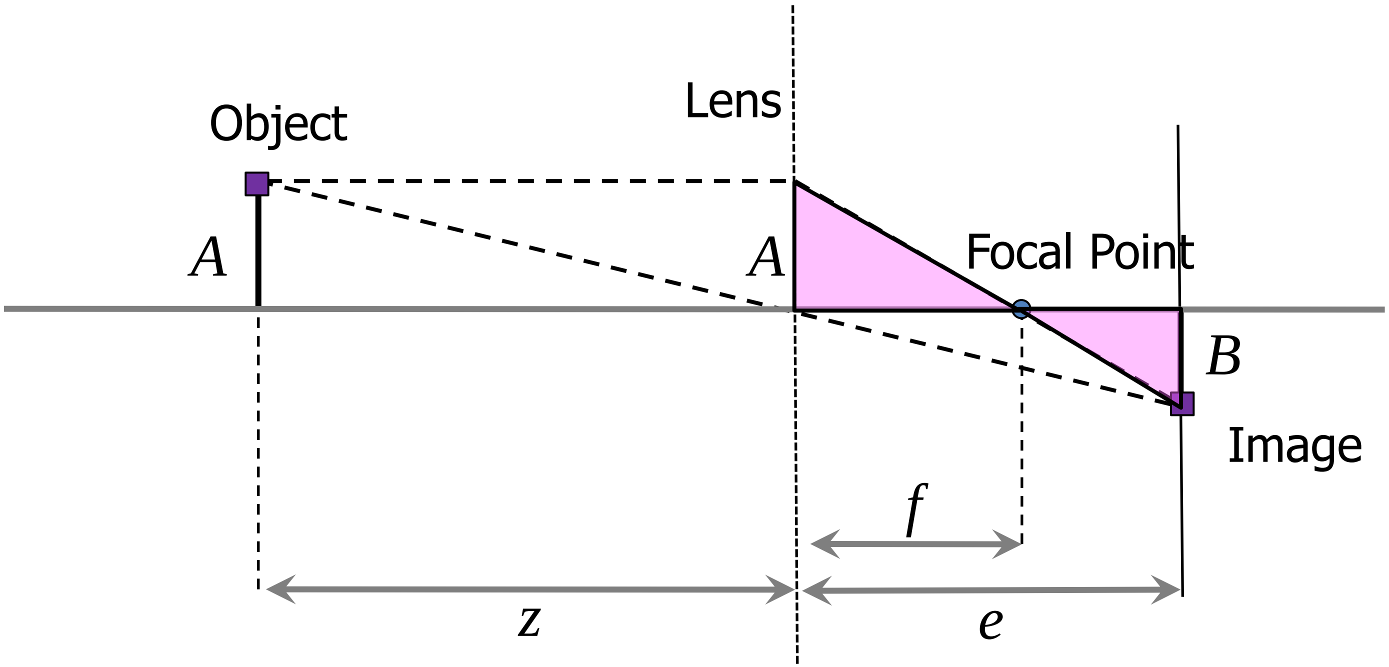
- A lens focuses light onto the film
- Rays passing through the optical center are not deviated
- All rays parallel to the **Optical Axis** converge at the **Focal Point**

Thin lens equation



Find a relationship between f, z and e

Thin lens equation



- Similar Triangles:

$$\frac{B}{A} = \frac{e}{z}$$

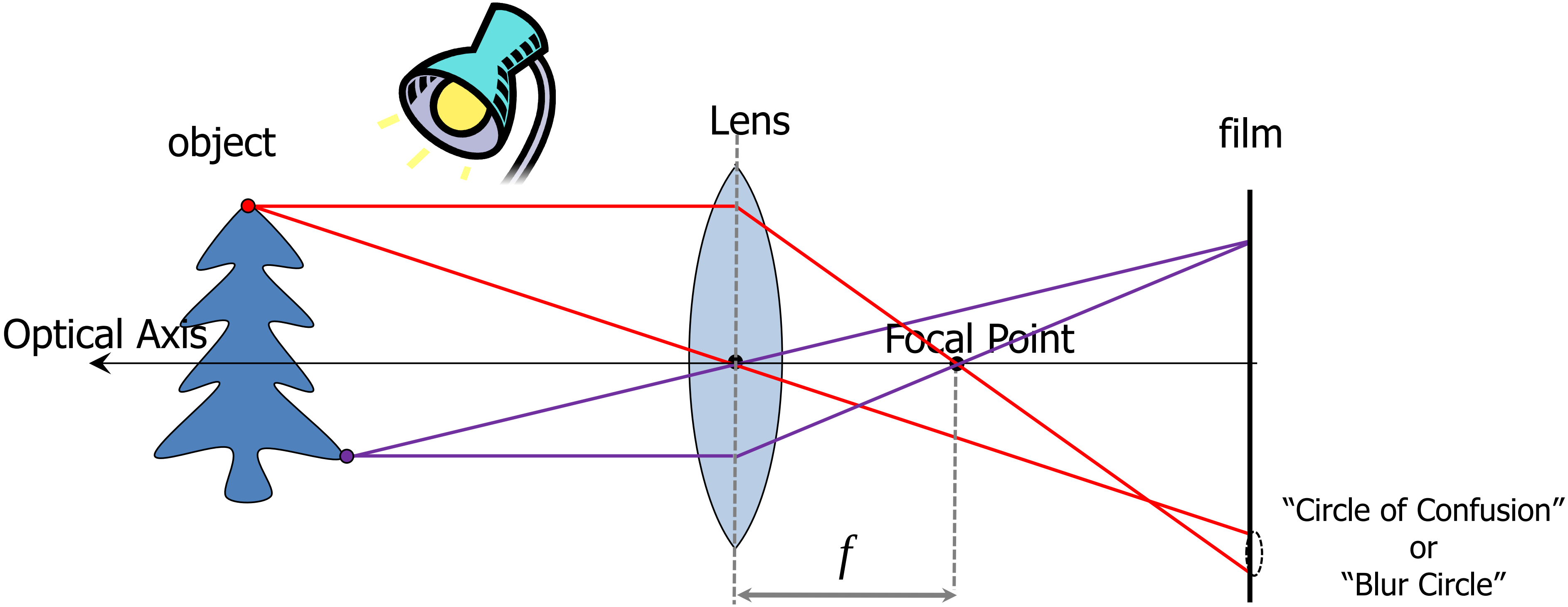
$$\frac{B}{A} = \frac{e-f}{f} = \frac{e}{f} - 1$$

$$\frac{e}{f} - 1 = \frac{e}{z}$$

"Thin lens equation"

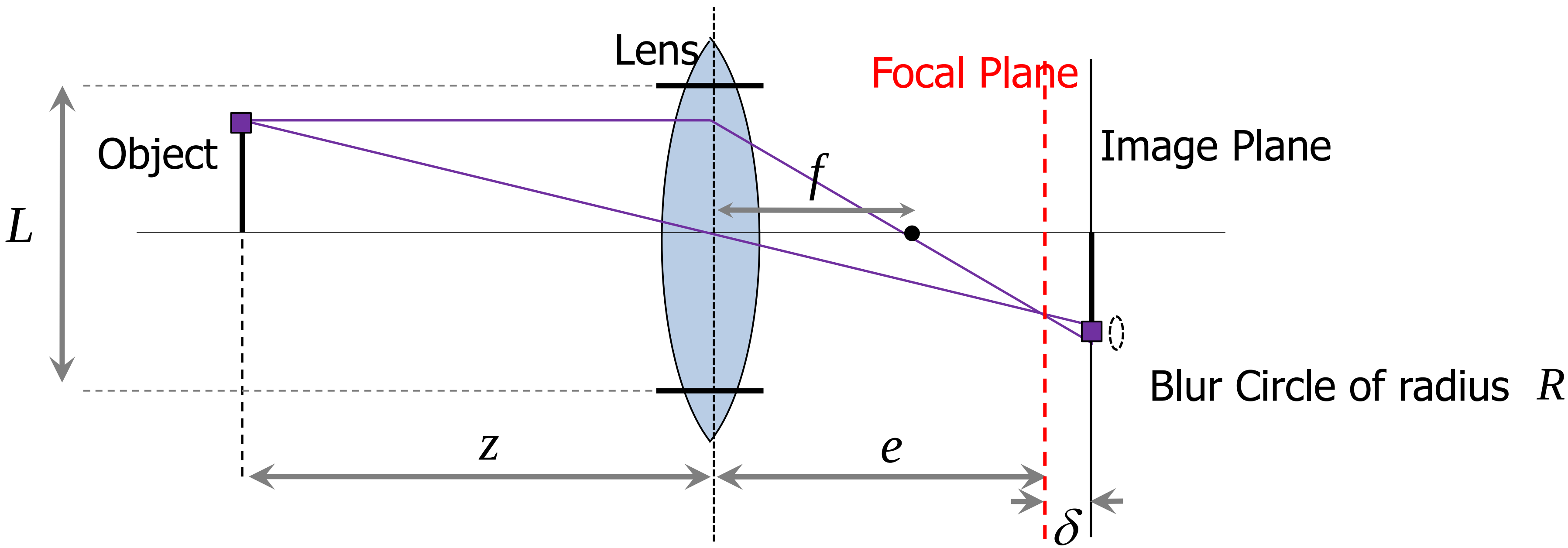
- Any object point satisfying this equation is in focus

“In focus”



- There is a specific distance from the lens, at which world points are “in focus” in the image
- Other points project to a “blur circle” in the image

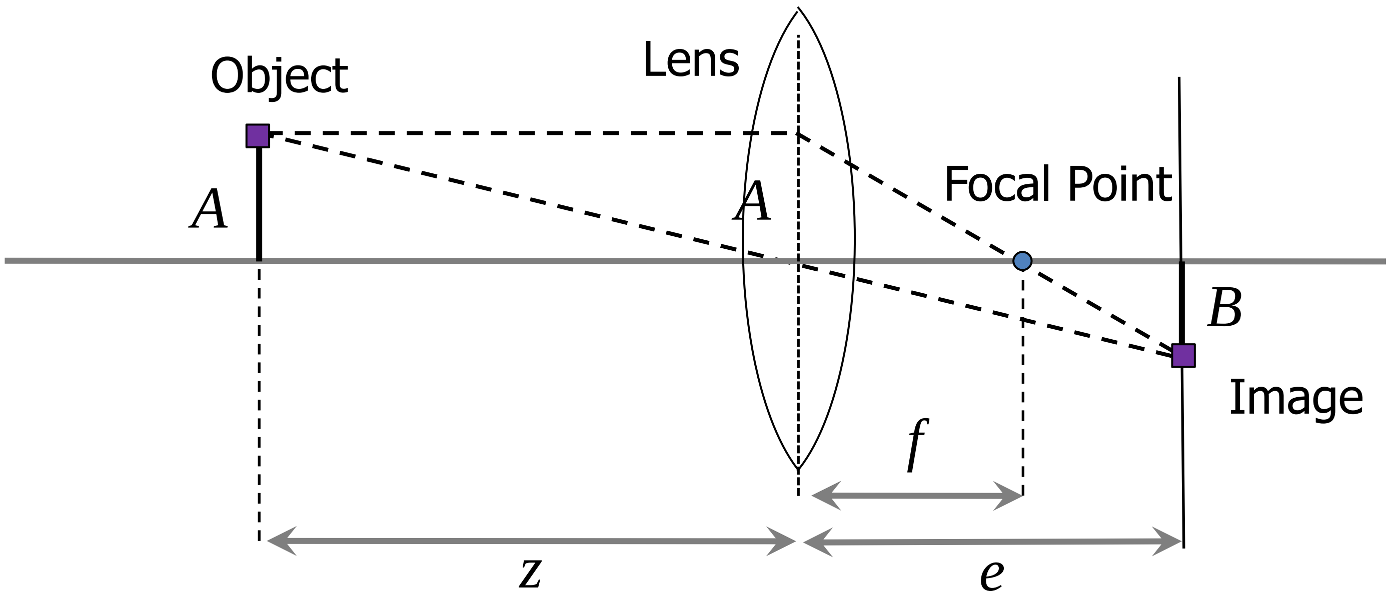
Blur Circle



- Object is out of focus ⇨ Blur Circle has radius: $R = \frac{L\delta}{2e}$
  - A minimal L (pinhole) gives minimal R
  - To capture a 'good' image: adjust camera settings, such that R remains smaller than the image resolution

The Pin-hole approximation

- What happens if $z \gg f$?

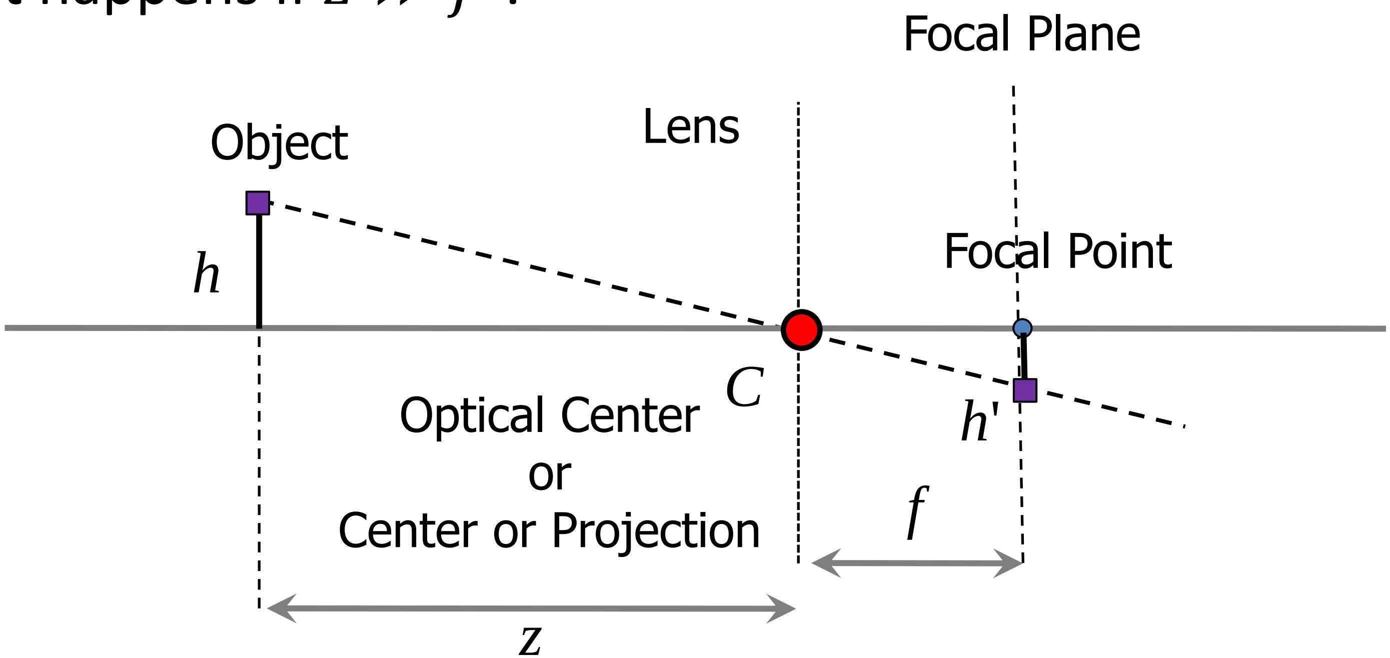


- We need to adjust the image plane such that objects at infinity are in focus

$$\frac{1}{f} = \underbrace{\frac{1}{z}}_{\cong 0} + \frac{1}{e} \Rightarrow \frac{1}{f} \approx \frac{1}{e} \Rightarrow f \approx e$$

The Pin-hole approximation

- What happens if $z \gg f$?

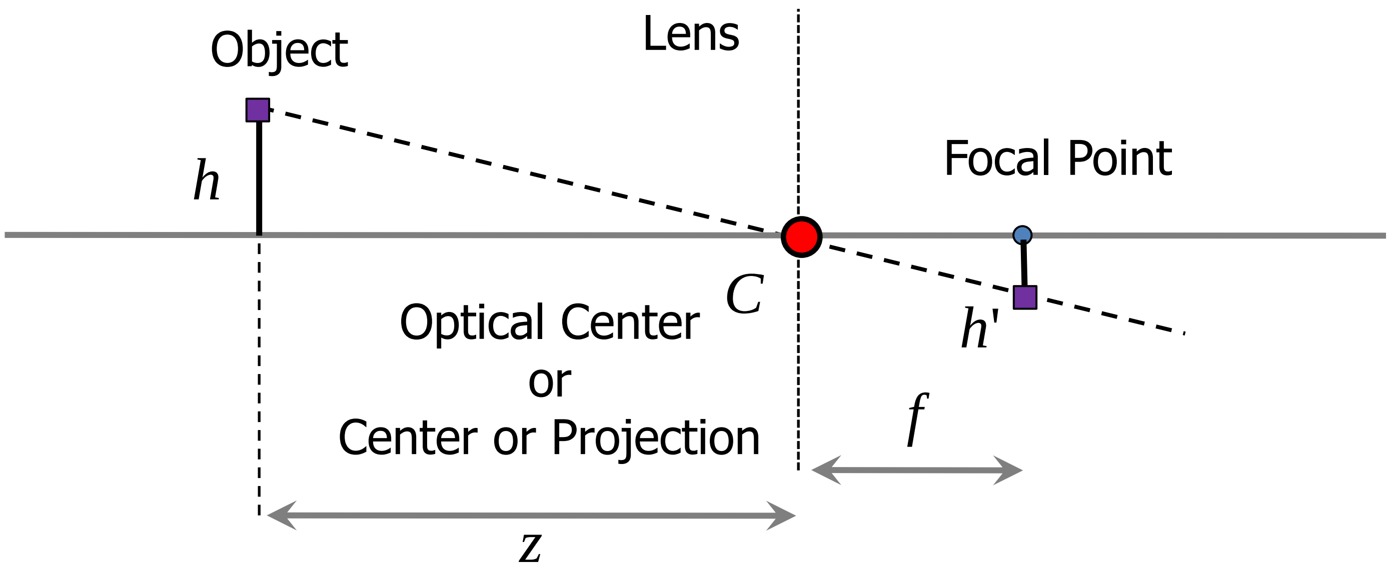


- We need to adjust the image plane such that objects at infinity are in focus

$$\frac{1}{f} = \underbrace{\frac{1}{z}}_{\cong 0} + \frac{1}{e} \Rightarrow \frac{1}{f} \approx \frac{1}{e} \Rightarrow f \approx e$$

The Pin-hole approximation

- What happens if $z \gg f$?



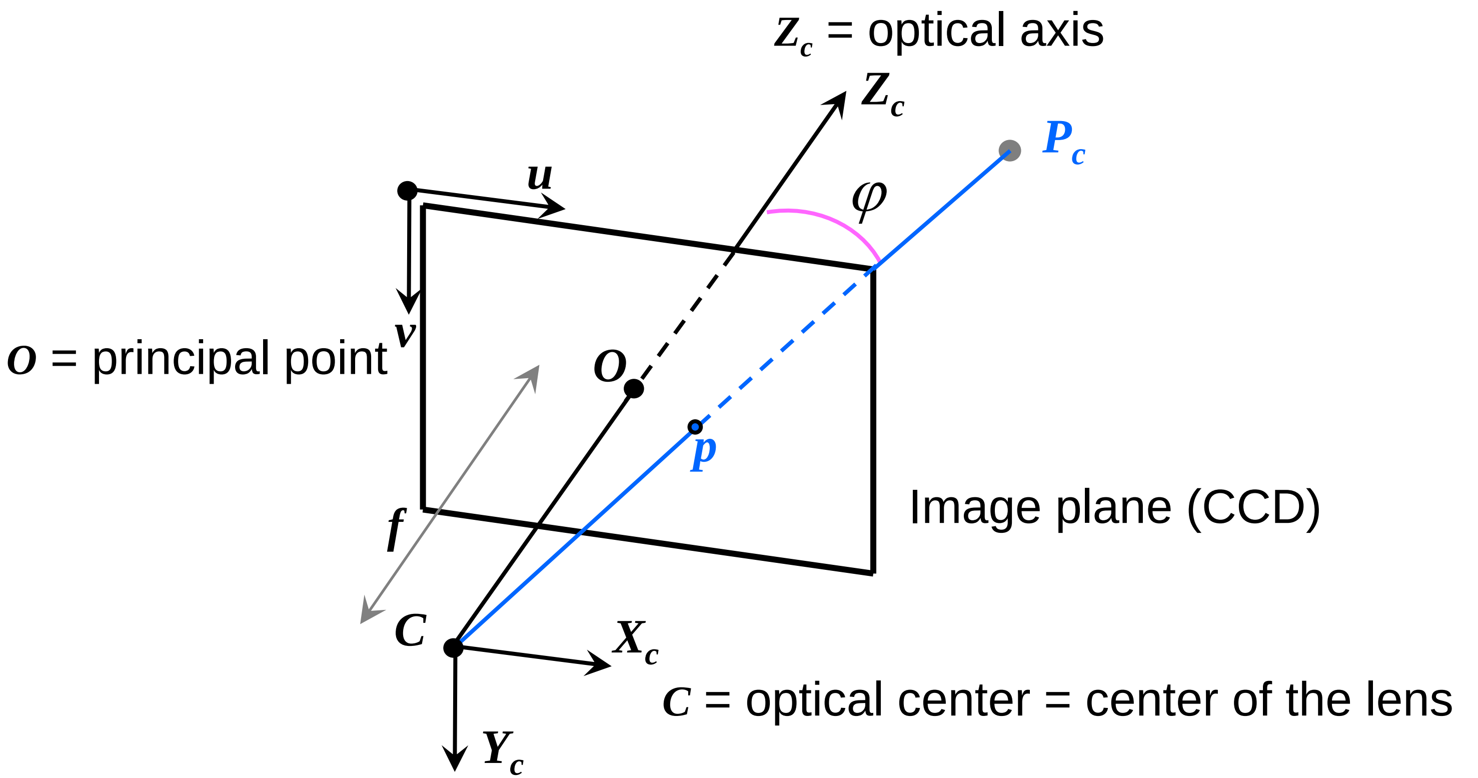
- We need to adjust the image plane such that objects at infinity are in focus

$$\frac{h'}{h} = \frac{f}{z} \Rightarrow h' = \frac{f}{z} h$$

- The dependence of the apparent size of an object on its depth (i.e. distance from the camera) is known as **perspective**

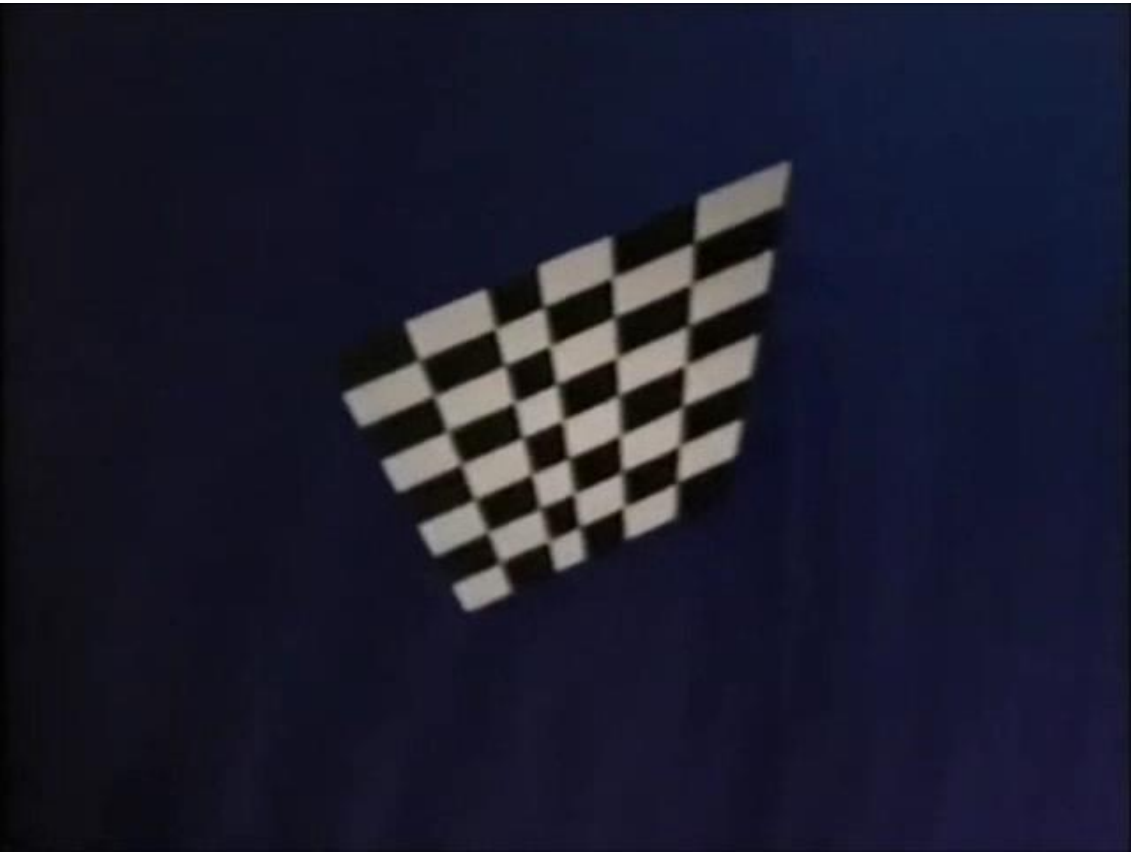
Perspective Projection

- For convenience, the image plane is usually represented in front of C such that the image preserves the same orientation (i.e. not flipped)
- A camera does not measure distances but angles!



Playing with Perspective

- Perspective gives us very strong depth cues
  ⇨ hence we can perceive a 3D scene by viewing its 2D representation (i.e. image)
- An example where perception of 3D scenes is misleading:



"Ames room"

A clip from "The computer that ate Hollywood" documentary. Dr. Vilayanur S. Ramachandran.

Perspective effects

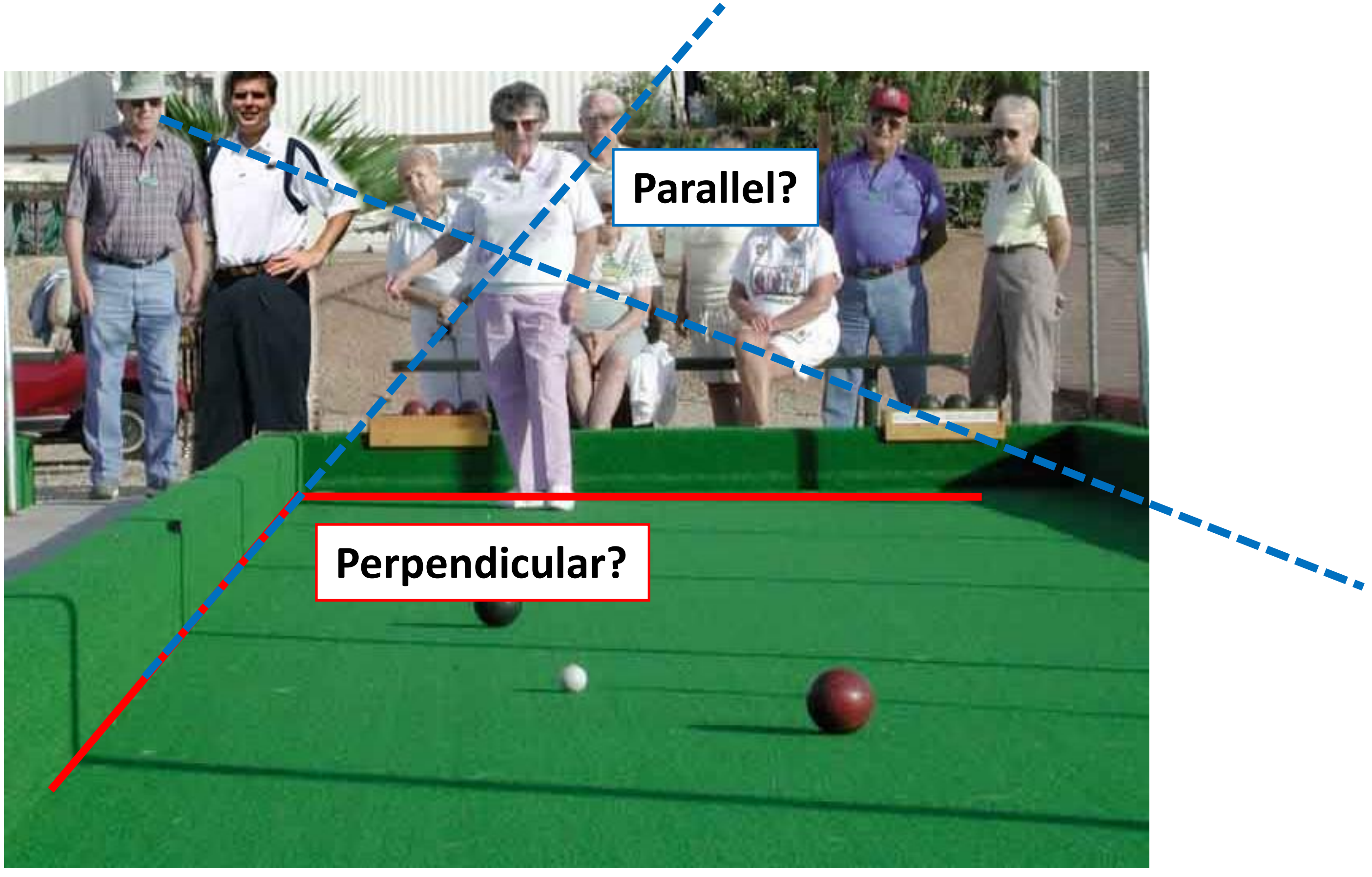
- Far away objects appear smaller

Perspective effects

Projective Geometry

What is lost?

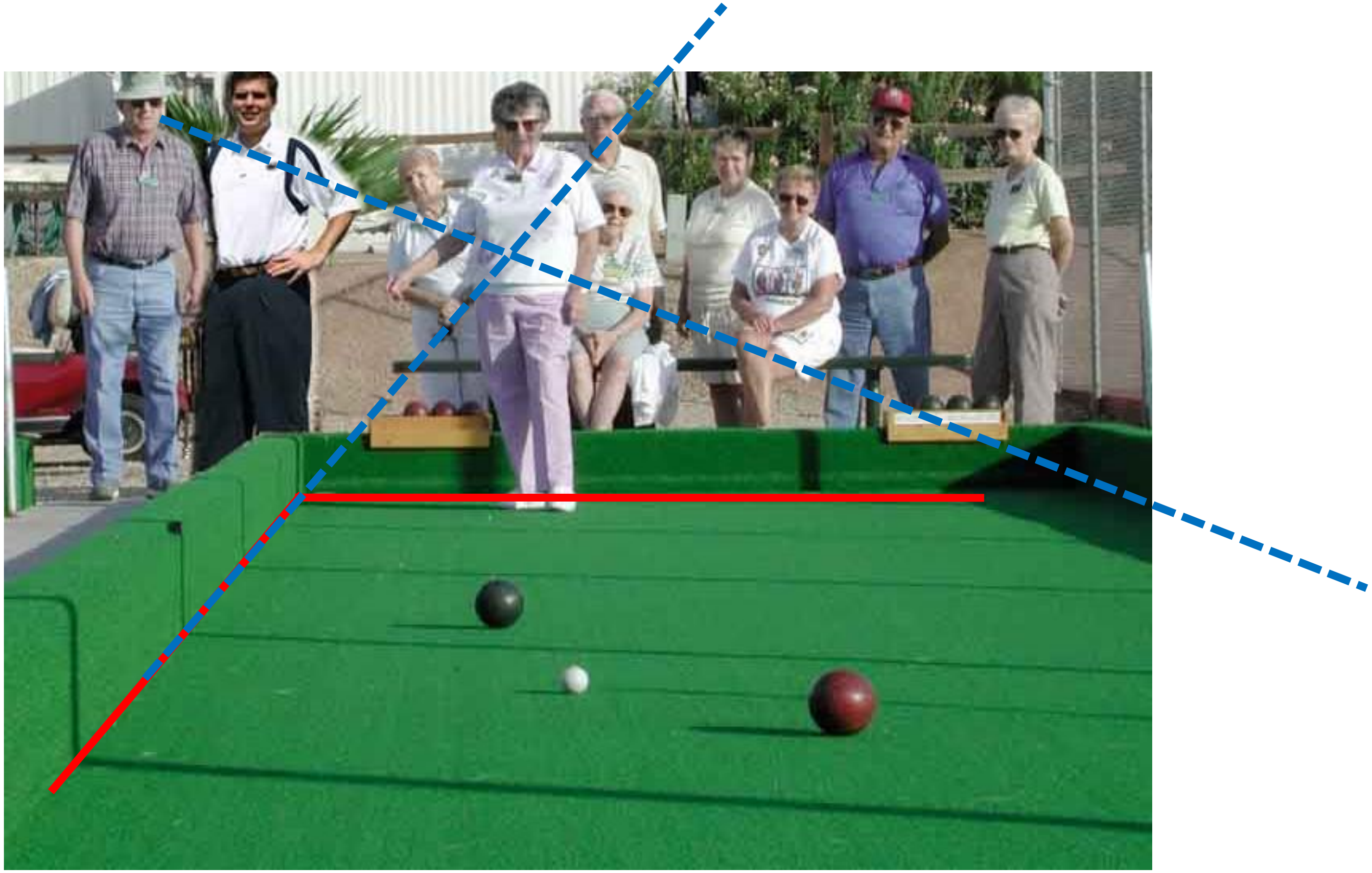
- Length
- Angles



Projective Geometry

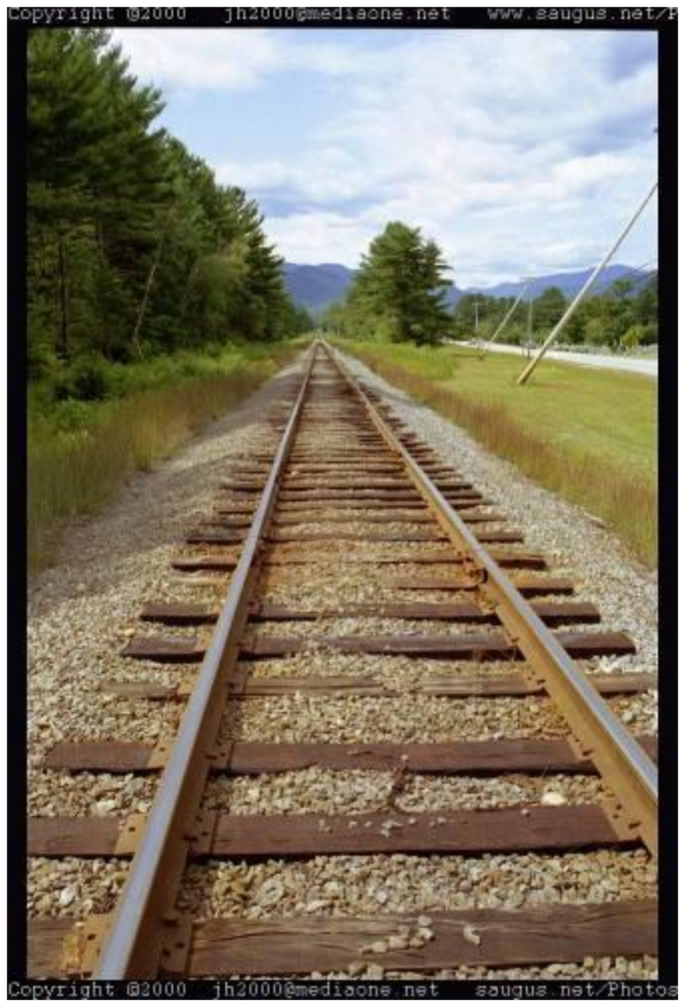
What is preserved?

- Straight lines are still straight



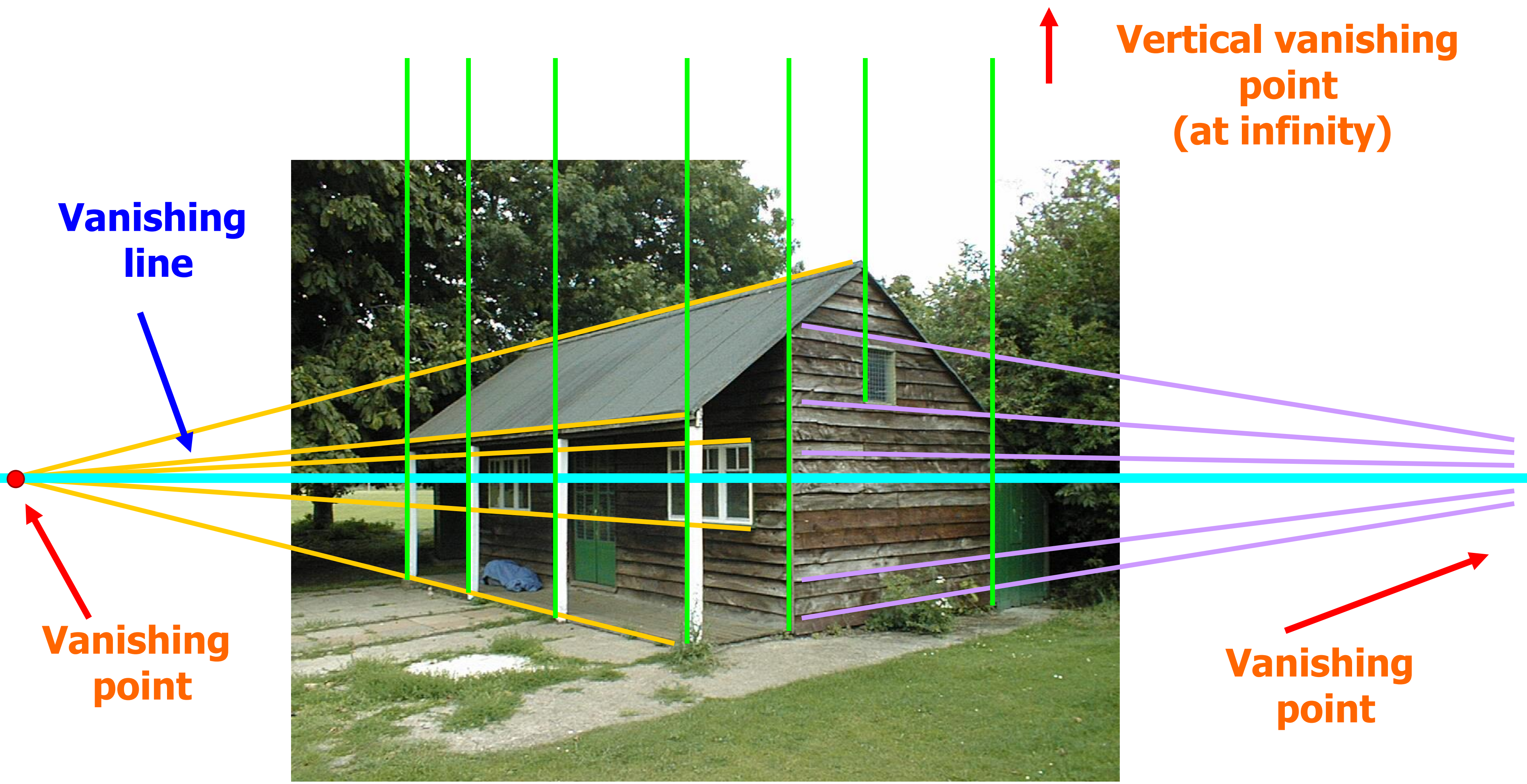
Vanishing points and lines

Parallel lines in the world intersect in the image at a “vanishing point”



Vanishing points and lines

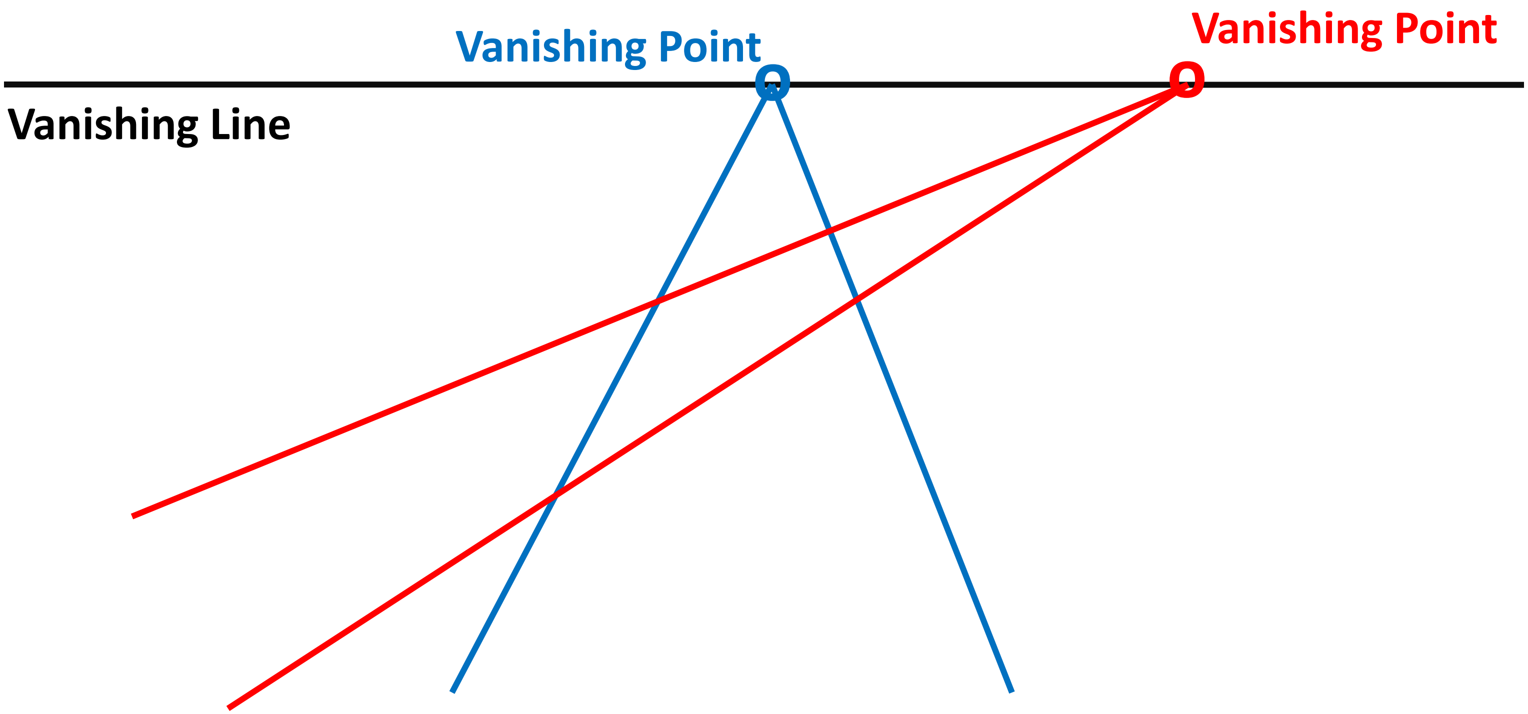
Parallel lines in the world intersect in the image at a “vanishing point”



Slide from Efros, Photo from Criminisi

Vanishing points and lines

Parallel **planes** in the world intersect in the image at a "vanishing line"



Today's Class

- Introductions
- What is Computer Vision?
- Example of Vision Applications
- Specifics of this course
- Image Formation 1
- Other camera parameters

Pinhole size / aperture

How does the size of the aperture affect the image we'd get?

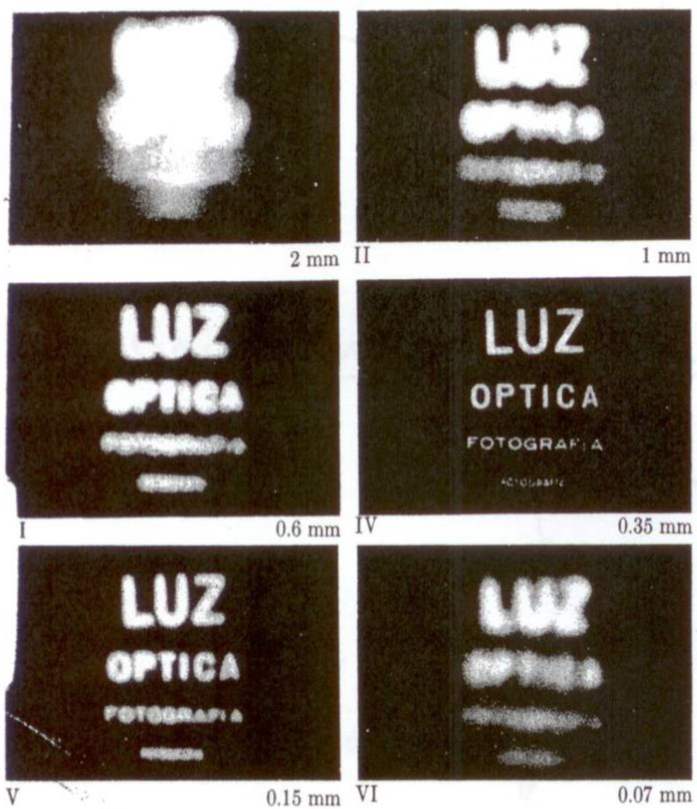
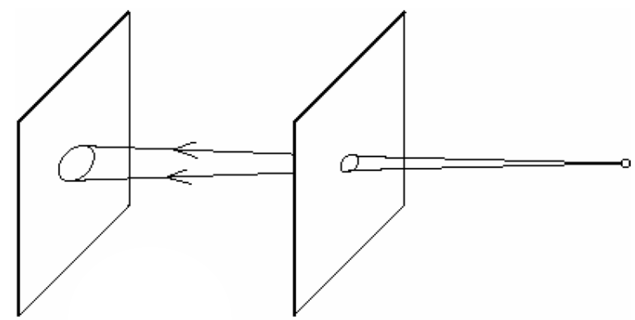


Fig. 5.96 The pinhole camera. Note the variation in image clarity as the hole diameter decreases. [Photos courtesy Dr. N. Joel, UNESCO.]

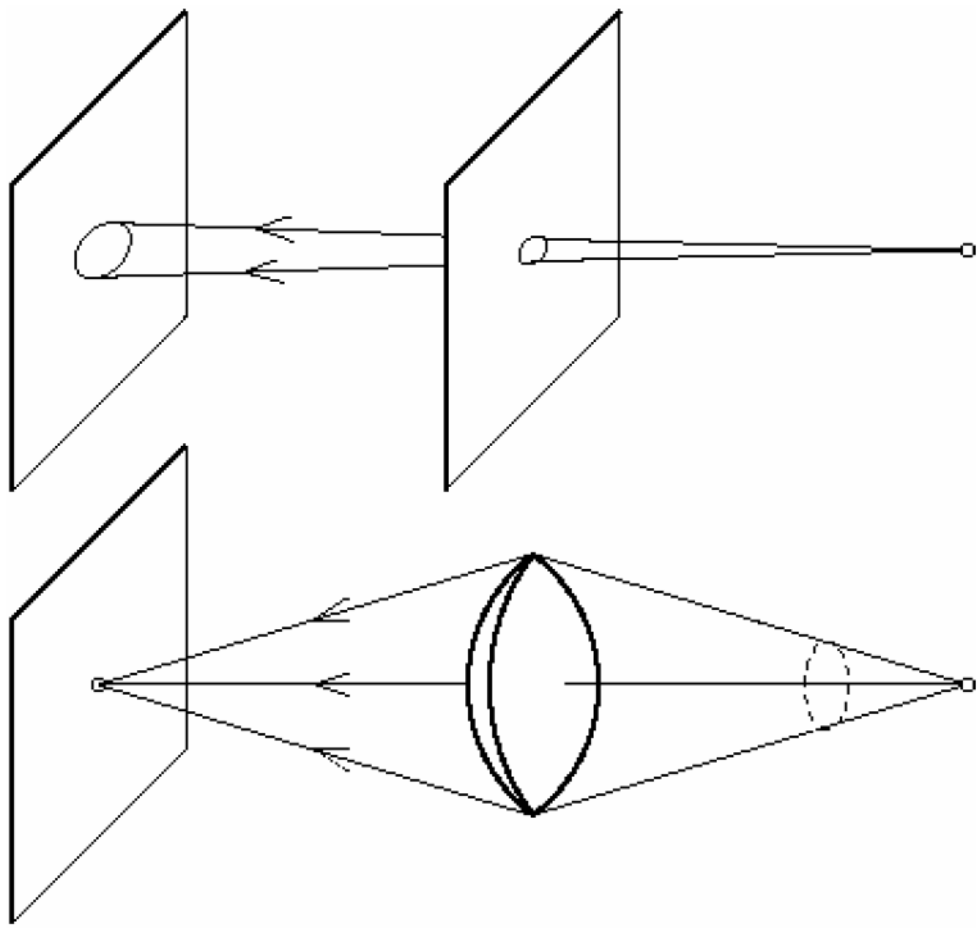
Larger

↓

Smaller

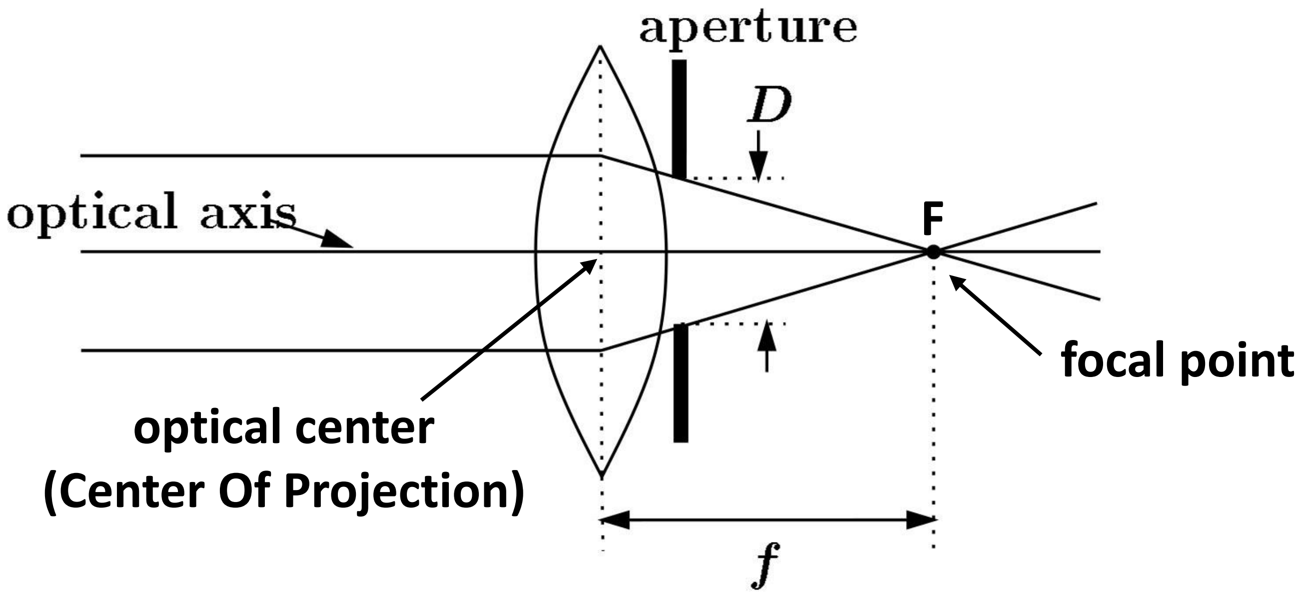


Pinhole vs. lens



- A lens focuses light onto the film

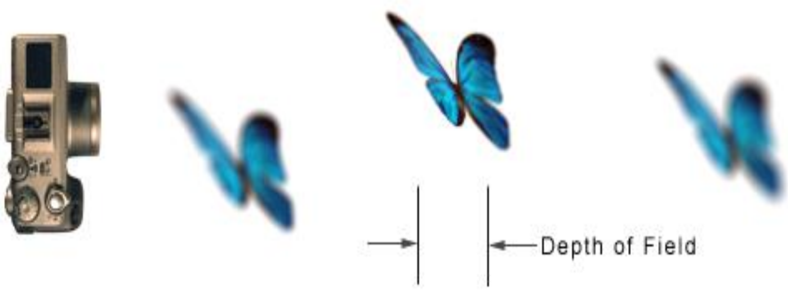
Cameras with lenses

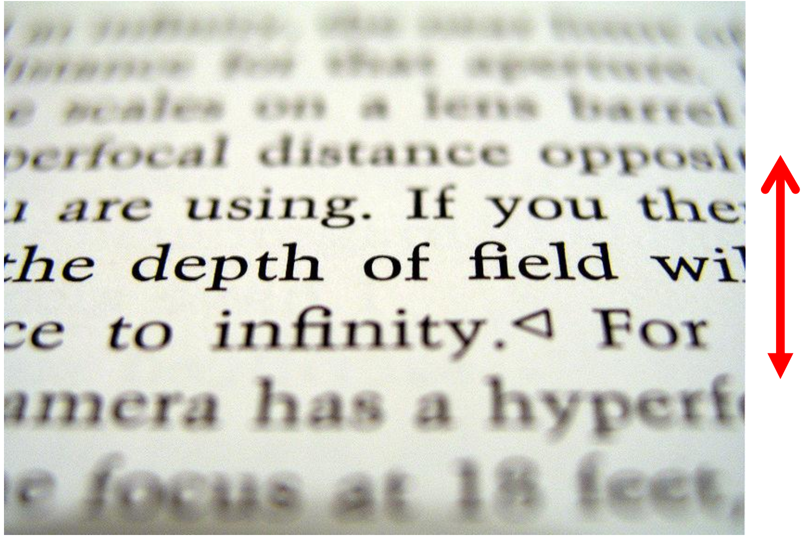


- A lens focuses parallel rays onto a single focal point
- It allows the camera to gather more light, while keeping focus
- Makes the pinhole perspective projection practical
- What happens if we decrease/increase the aperture?

Focus and depth of field

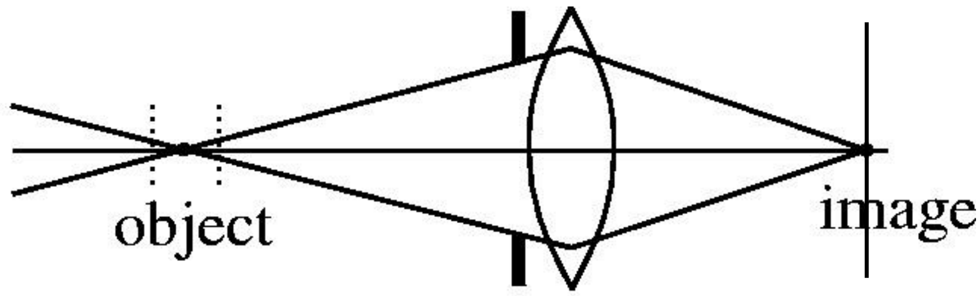
- Depth of field (DOF) is the distance between the nearest and farthest objects in a scene that appear acceptably sharp in an image.
- Although a lens can precisely focus at only one distance at a time, the decrease in sharpness is gradual on each side of the focused distance, so that within the DOF, the unsharpness is imperceptible under normal viewing conditions

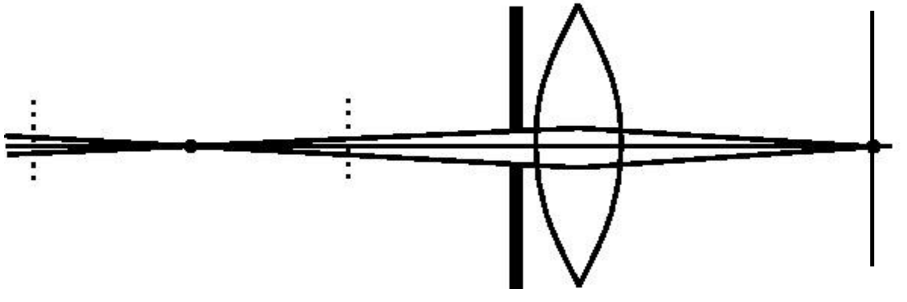




Focus and depth of field

- How does the aperture affect the depth of field?





- A smaller aperture increases the range in which the object appears approximately in focus

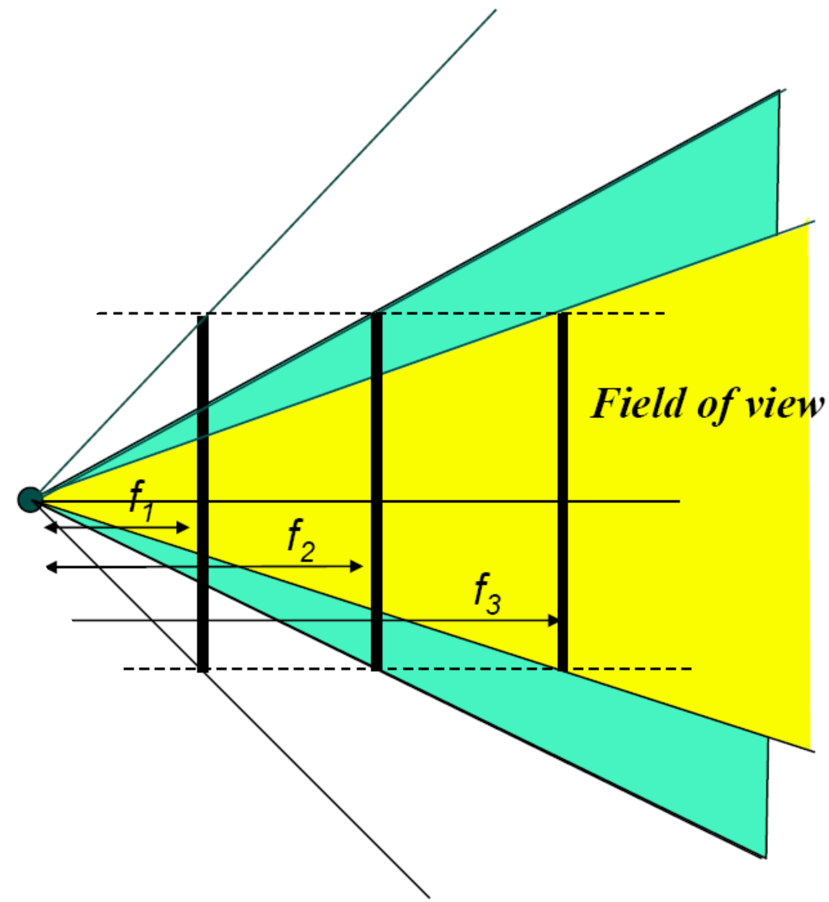
Varying the aperture

Large apeture = small DOF

Small apeture = large DOF

Field of view depends on focal length

- As ***f*** gets smaller, image becomes more *wide angle*
  - more world points project onto the finite image plane
- As ***f*** gets larger, image becomes more *narrow angle*
  - smaller part of the world projects onto the finite image plane



Field of view

Angular measure of portion of 3d space seen by the camera

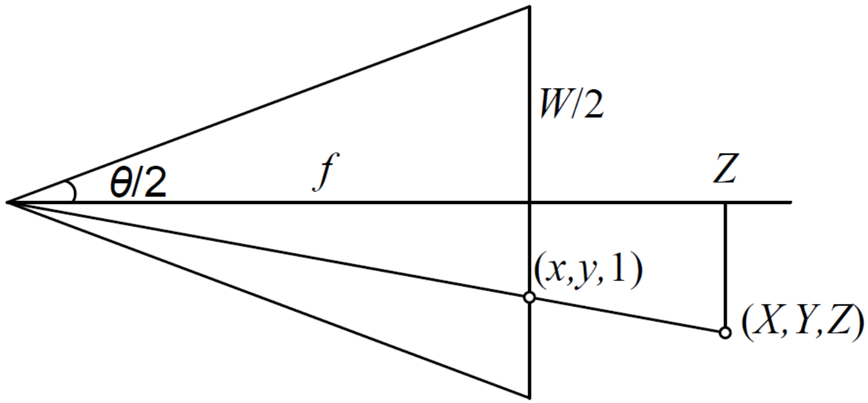
28 mm lens, 65.5° × 46.4°

50 mm lens, 39.6° × 27.0°

70 mm lens, 28.9° × 19.5°

210 mm lens, 9.8° × 6.5°

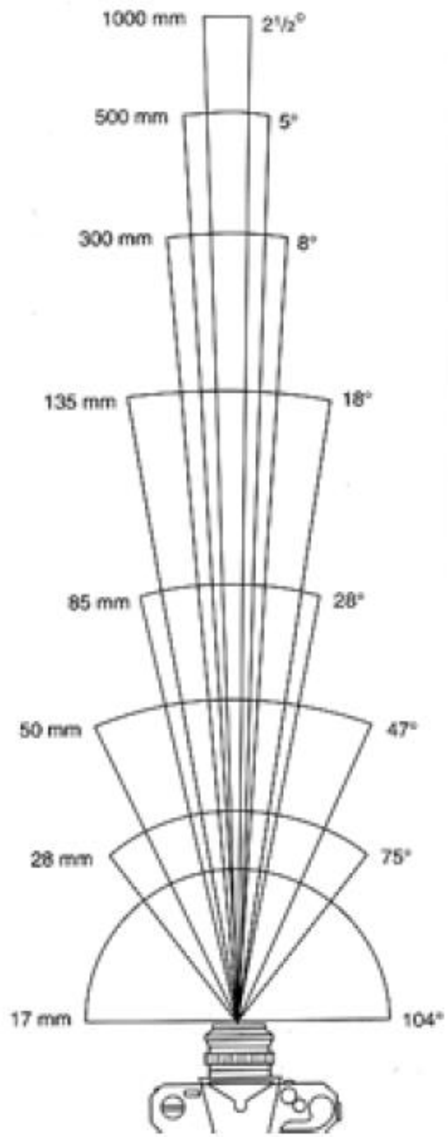
Field of view

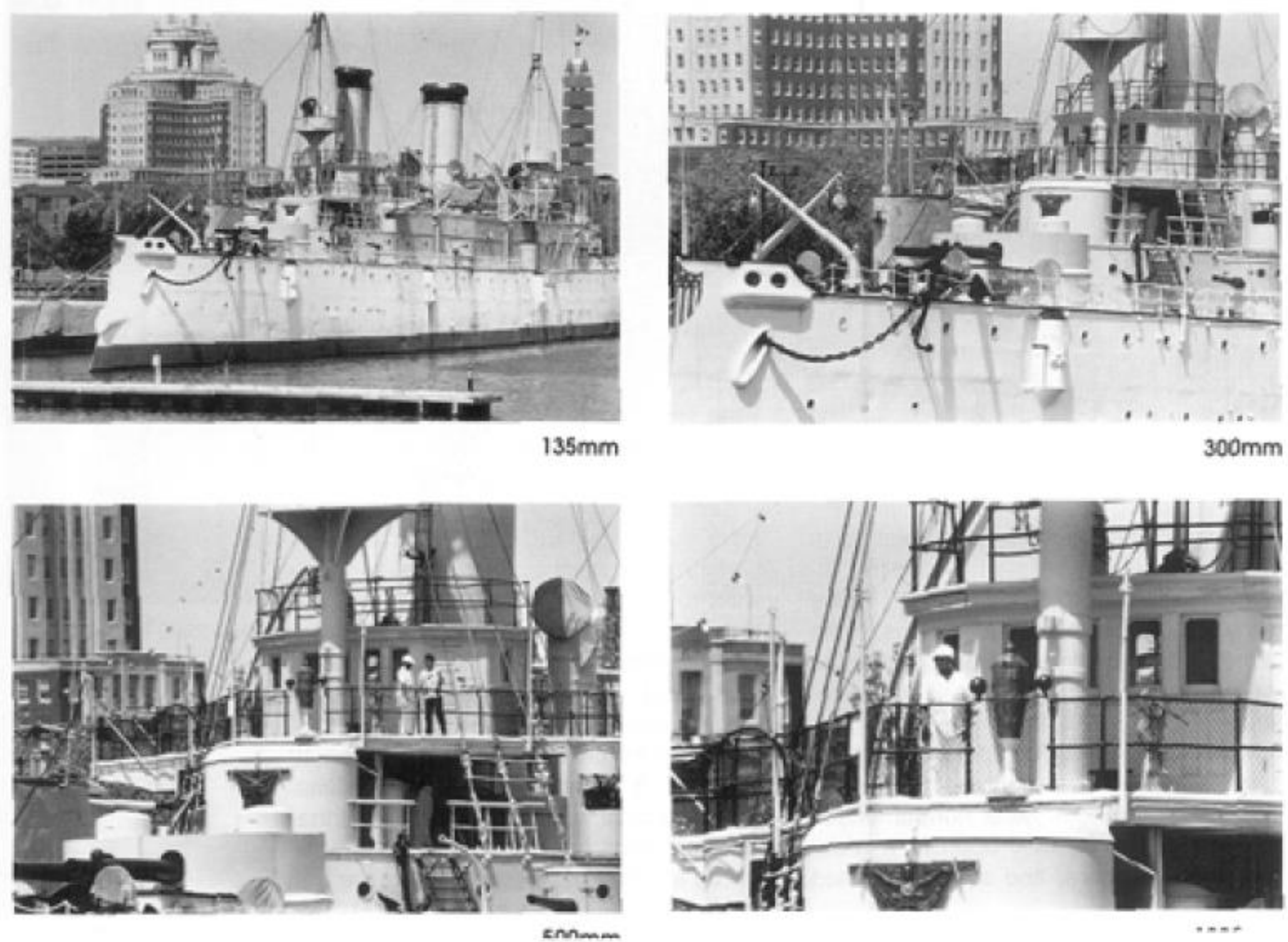


$$\tan\frac{\theta}{2} = \frac{W}{2f} \quad \text{or} \quad f = \frac{W}{2}\left[\tan\frac{\theta}{2}\right]^{-1}$$

Smaller FOV = larger Focal Length

Field of View (Zoom) = Cropping





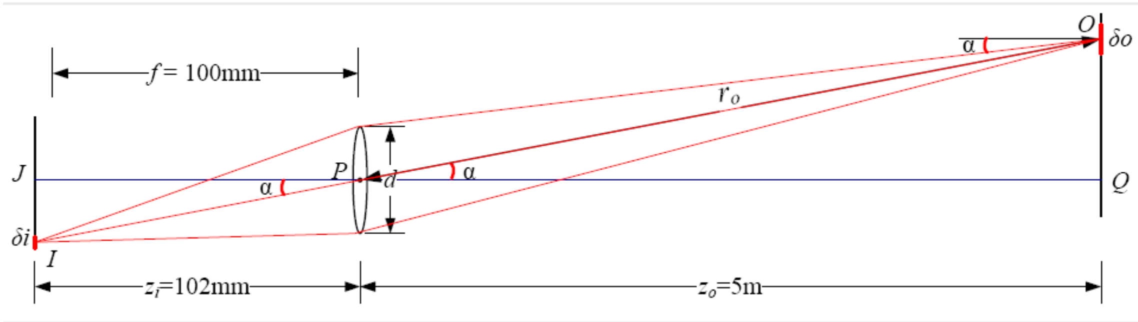
From London and Upton

Vignetting

- Tendency of the brightness of the image to fall off towards the edge of the image
- Why and how can we remove it?

Vignetting

- “natural”: the light that reaches the patch on the image sensor is reduced by an amount that depends on angle α



- “mechanical”: occlusion of rays near the periphery of the lens elements in a compound lens

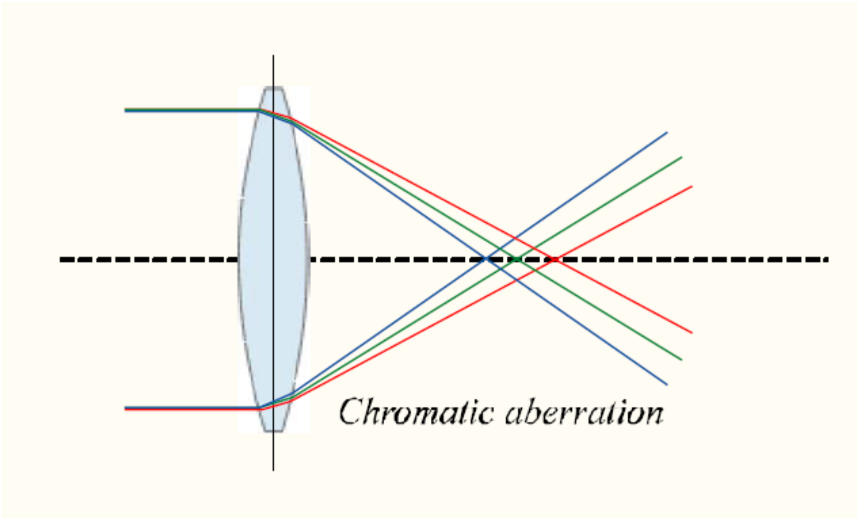
Chromatic aberration

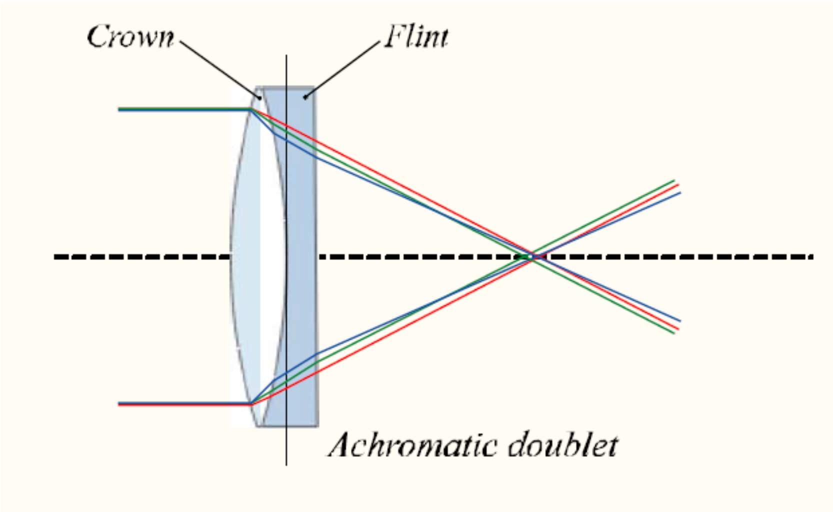
What causes it?

Chromatic aberration

- Because the index of refraction for glass varies slightly as a function of wavelength, light of different colors focuses at slightly different distances (and hence also with slightly different magnification factors)

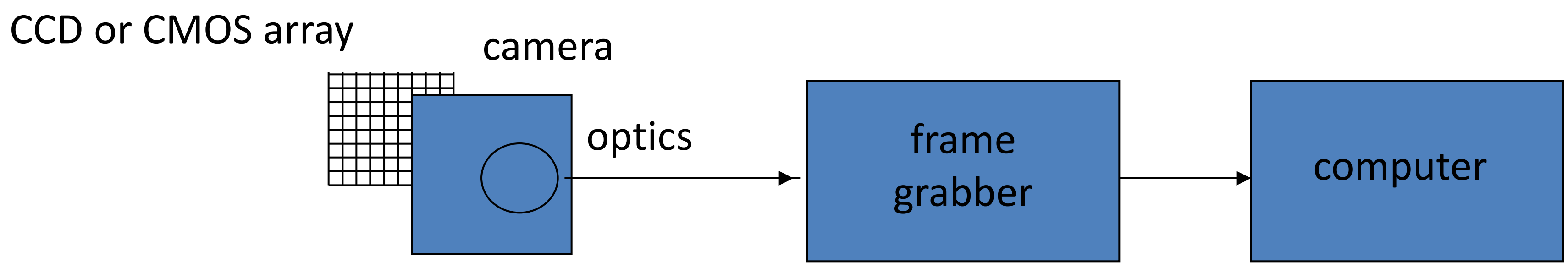
- In order to reduce chromatic aberration, most photographic lenses today are compound lenses made of different glass elements (with different coatings).





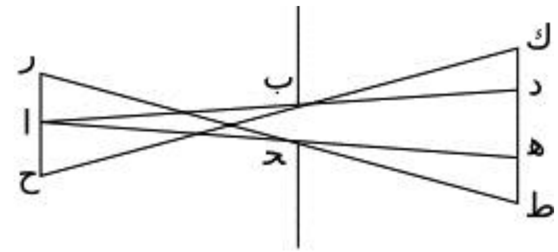
Digital cameras

- Film → sensor array
- Often an array of charge coupled devices
- Each CCD/CMOS is light sensitive diode that converts photons (light energy) to electrons



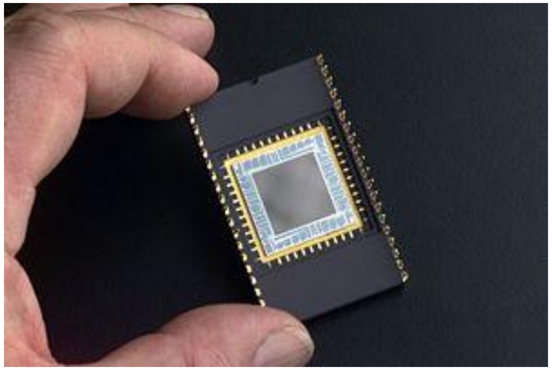
Historical context

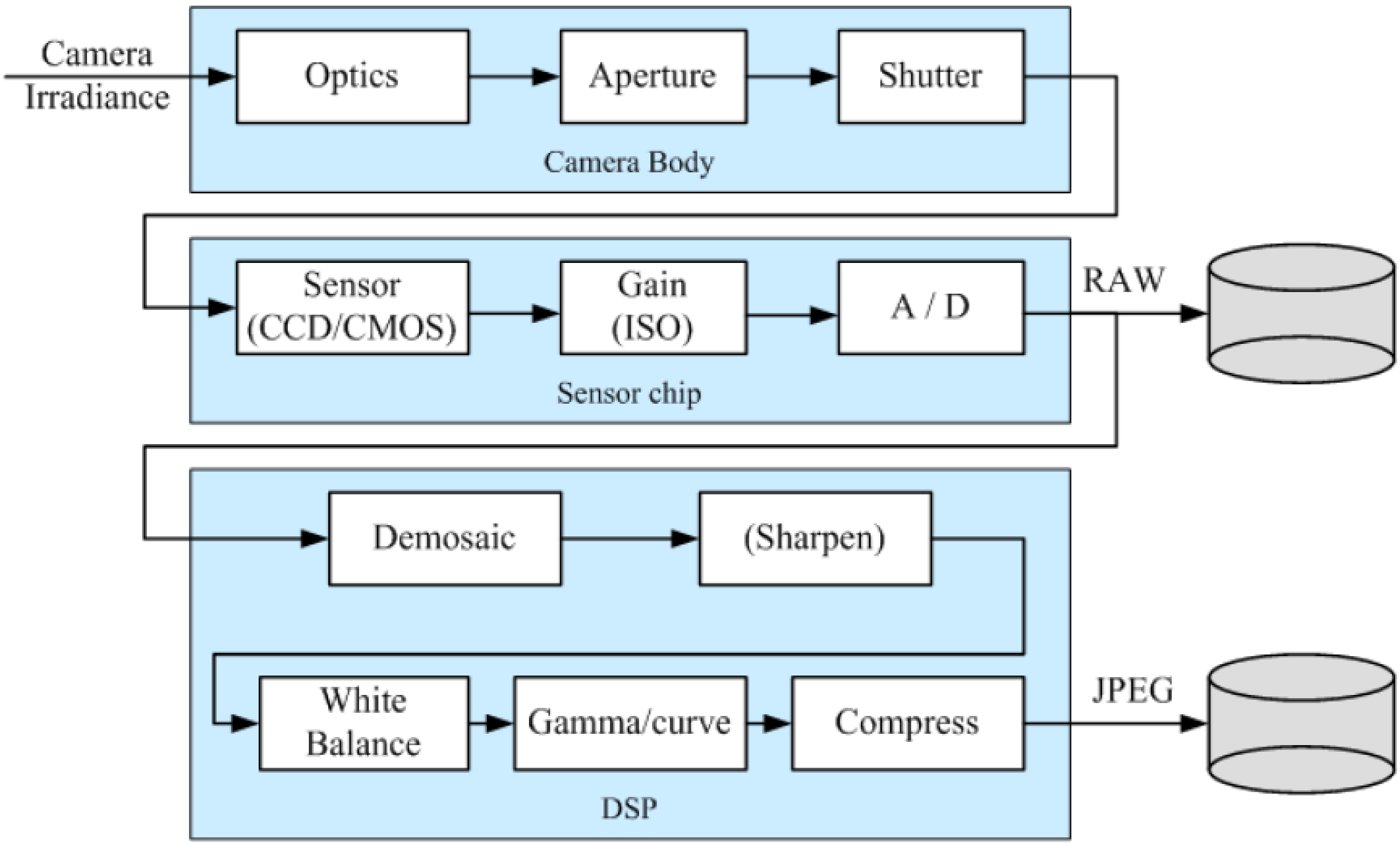
- **Pinhole model:** Mozi (470-390 BCE), Aristotle (384-322 BCE)
- **Principles of optics (including lenses):** Alhacen (965-1039 CE)
- **Camera obscura:** Leonardo da Vinci (1452-1519), Johann Zahn (1631-1707)
- **First photo:** Joseph Nicephore Niepce (1822)
- **Daguerréotypes** (1839)
- **Photographic film** (Eastman, 1889)
- **Cinema** (Lumière Brothers, 1895)
- **Color Photography** (Lumière Brothers, 1908)
- **Television** (Baird, Farnsworth, Zworykin, 1920s)
- **First consumer camera with CCD**: Sony Mavica (1981)
- **First fully digital camera**: Kodak DCS100 (1990)



Alhacen's notes


Niepce, "La Table Servie," 1822


CCD chip


Camera
Irradiance
Optics
Aperture
Shutter
Camera Body
Sensor
(CCD/CMOS)
Gain
(ISO)
A / D
RAW
Sensor chip
Demosaic
(Sharpen)
White
Balance
Gamma/curve
Compress
JPEG
DSP

An example camera datasheet

mvBlueFOX-IGC / -MLC

Technical Details

Sensors

mvBlueFOX-IGC mvBlueFOX-MLC		Resolution (H x V pixels)	Sensor size (optical)	Pixel size (µm)	Frame rate	Sensor technology	Readout type	ADC resolution / output in bits	Sensor
-200w[1,2]	G/C	752 x 480	1/3"	6 x 6	90	CMOS	Global	10 → 10 / 8	Aptina MT9V
-202b	G/C	1280 x 960	1/3"	3.75 x 3.75	24.6	CMOS	Global	10 → 10 / 8	Aptina MT9M
-202d[1]	G/C	1280 x 960	1/3"	3.75 x 3.75	24.6	CMOS	Rolling	10 → 10 / 8	Aptina MT9M
-205[2]	G/C	2592 x 1944	1/2.5"	2.2 x 2.2	5.8	CMOS	Global Reset	10 → 10 / 8	Aptina MT9P

[1] High Dynamic Range (HDR) mode supported

[2] Software trigger supported

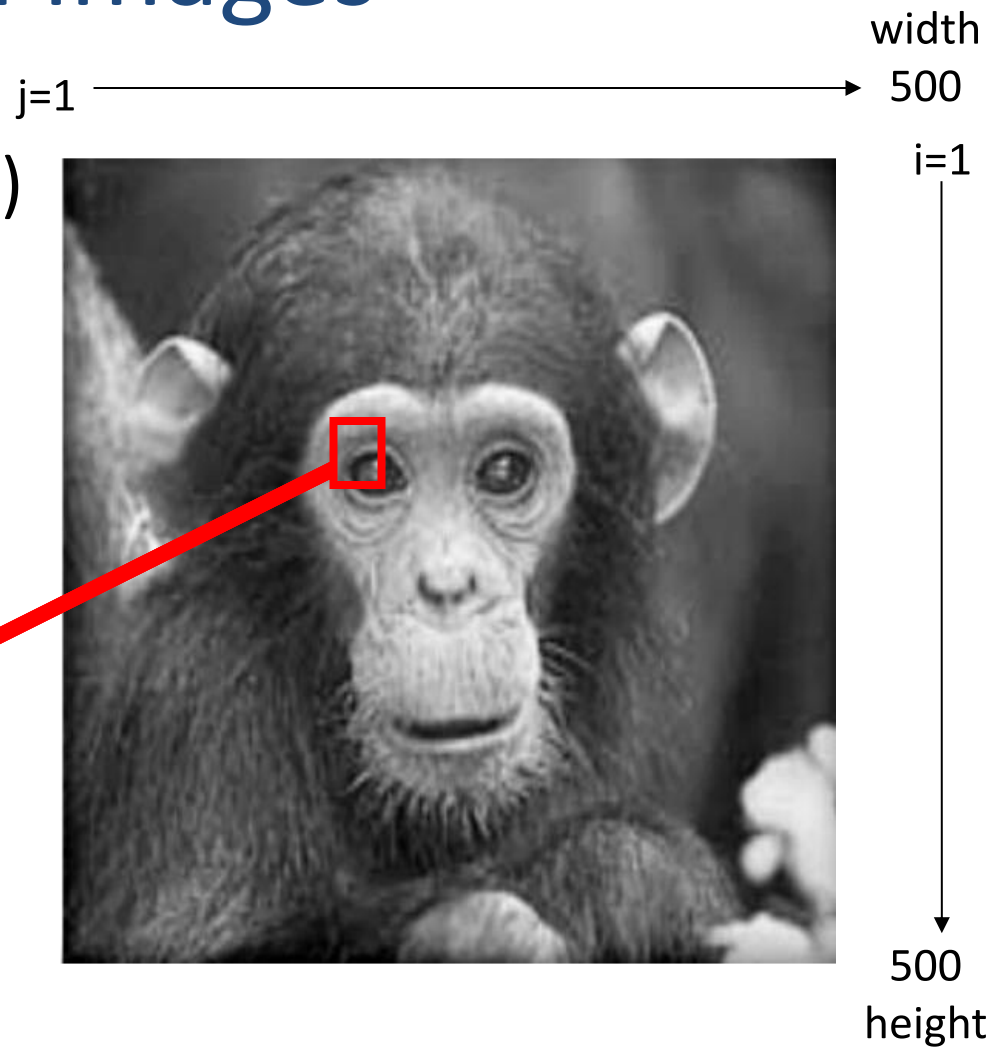
Sample: **mvBlueFOX-IGC200wG** means version with housing and 752 x 480 CMOS gray scale sensor.
mvBlueFOX-MLC200wG means single-board version without housing and with 752 x 480 CMOS gray scale sensor.

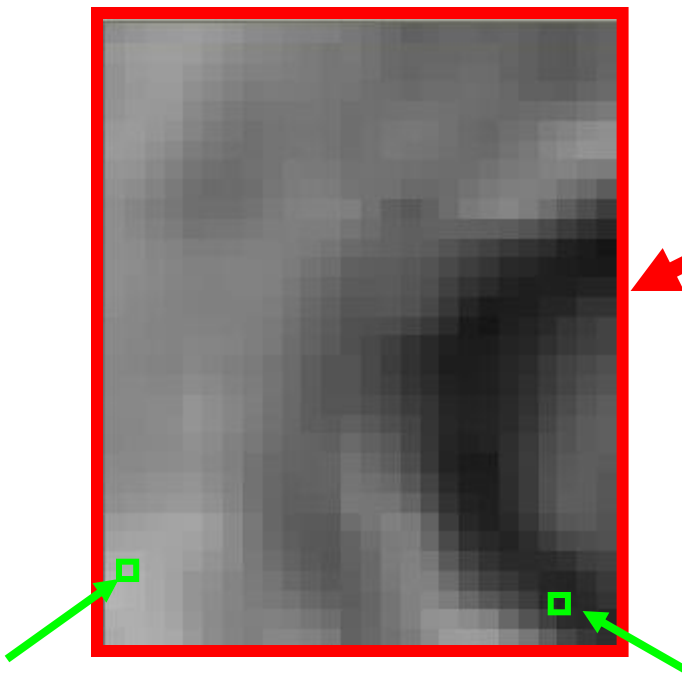
Hardware Features

Gray scale / Color	Gray scale (G) / Color (C)
Interface	USB 2.0 (up to 480 Mbit/s)
Image formats	Mono8, Mono10, BayerGR8, BayerGR10
Triggers	External hardware based (optional), software based (depending on the sensor) or free run
Size w/o lens (W x H x L) | Weight w/o lens	mvBlueFOX-IGC: 39.8 x 39.8 x 16.5 mm | approx. 10 g mvBlueFOX-MLC: 35 x 33 x 25 mm (without lens mount) | approx. 80 g
Permissible ambient temperature	Operation: 0 .. 45 °C / 30 to 80 % RH Storage: -20 .. 60 °C / 20 to 90 % RH
Lens mounts	Back focus adjustable C/CS-mount lens holder / C-mount, CS-mount or optional S-mount
Digital I/Os	mvBlueFOX-IGC (optional): 1 / 1 opto-isolated mvBlueFOX-MLC: 1 / 1 opto-isolated or 2 / 2 TTL compliant
Conformity	CE, FCC, RoHS
Driver	mvIMPACT Acquire SDK
Operating systems	Windows®, Linux® - 32 bit and 64 bit
Special features	Micro-PLC, automatic gain / exposure control, binning, screw lock connectors

Digital images

Pixel Intensity : [0,255] (8 bits)



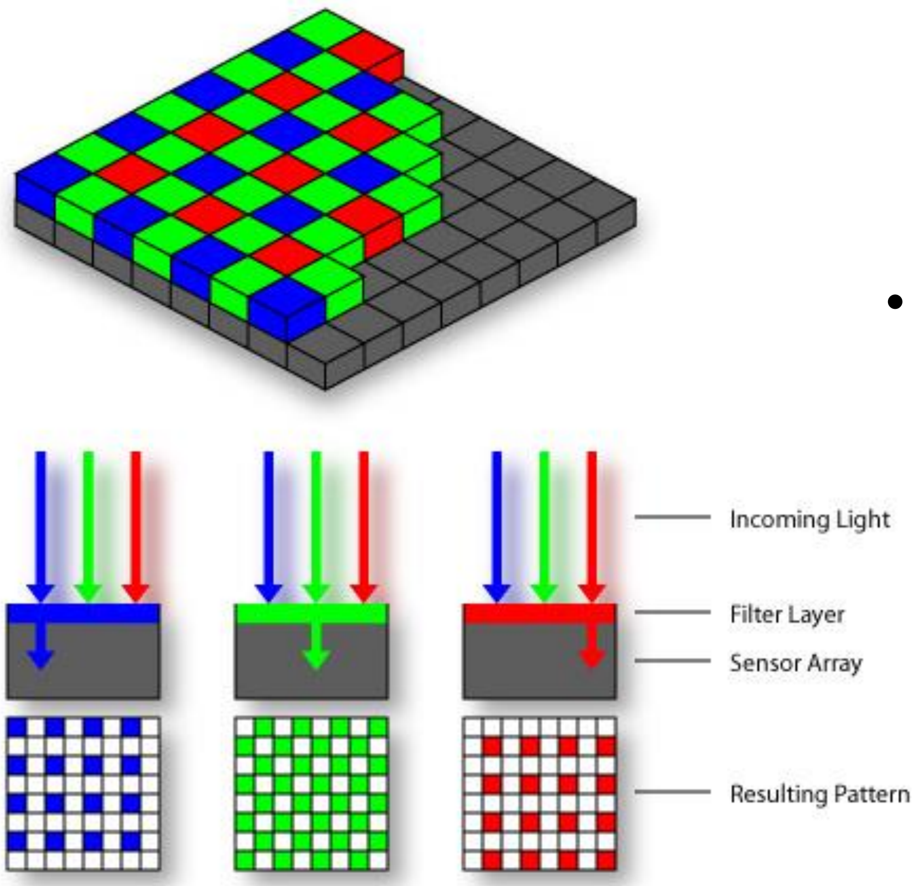


im[176][201] has value 164

im[194][203] has value 37

Color sensing in digital cameras

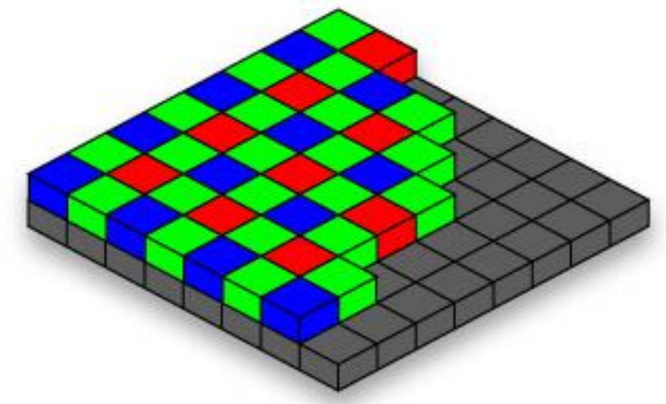
Bayer grid



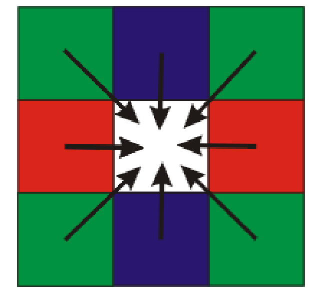
- The Bayer pattern (Bayer 1976) places green filters over half of the sensors (in a checkerboard pattern), and red and blue filters over the remaining ones.
- This is because the luminance signal is mostly determined by green values and the human visual system is much more sensitive to high frequency detail in luminance than in chrominance.

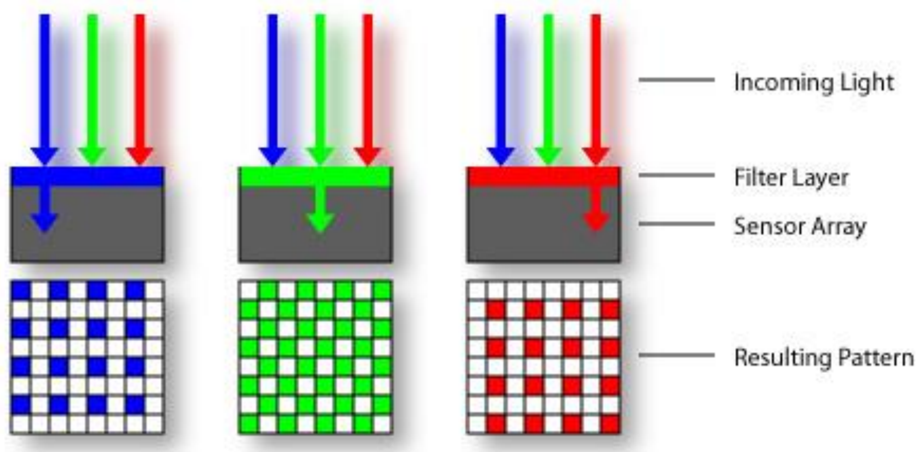
Color sensing in digital cameras

Bayer grid



Estimate missing components from neighboring values (demosaicing)





A newer chip design by Foveon (http://www.foveon.com) stacks the red, green, and blue sensors beneath each other, but it has not yet gained widespread adoption.

Color images:

RGB color space

… but there are also many other color spaces… (e.g., YUV)

R

G

B

Summary (things to remember)

- Definition of computer vision
- Computer-vision challenges
- Computer-vision applications
- Camera obscura
- Thin-lens model
- Perspective effects and Ames room
- Definitions
  - Cromatic aberration
  - Depth of field
  - Digital-image-formation pipeline
  - Bayer grid
- Readings for today: 1.1, 1.2, 2.2.3, 2.3, and page 76

Next time

- Image Formation
- Readings for next lecture: 2.1