CS 532: 3D Computer Vision
Lecture 1

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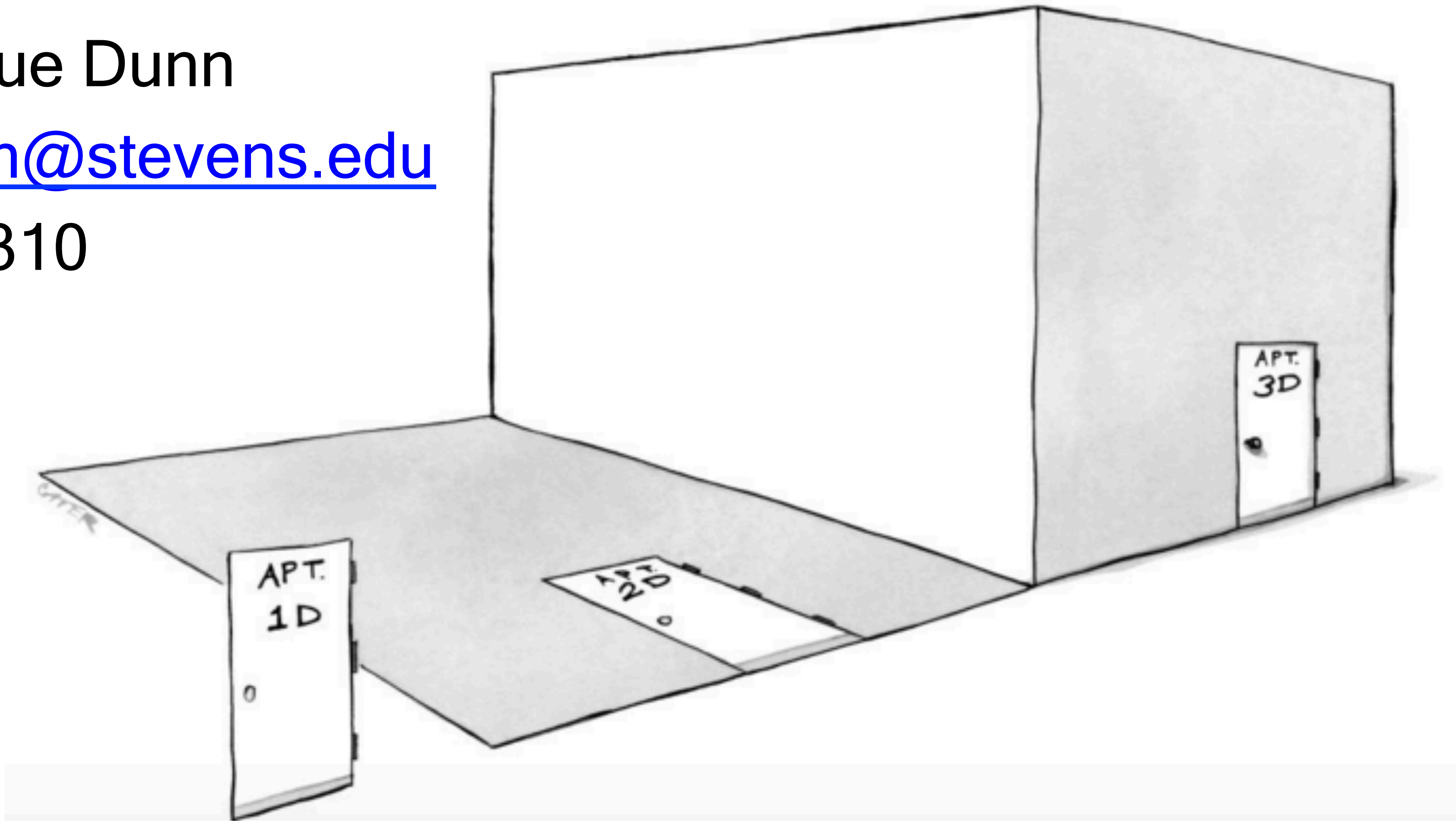
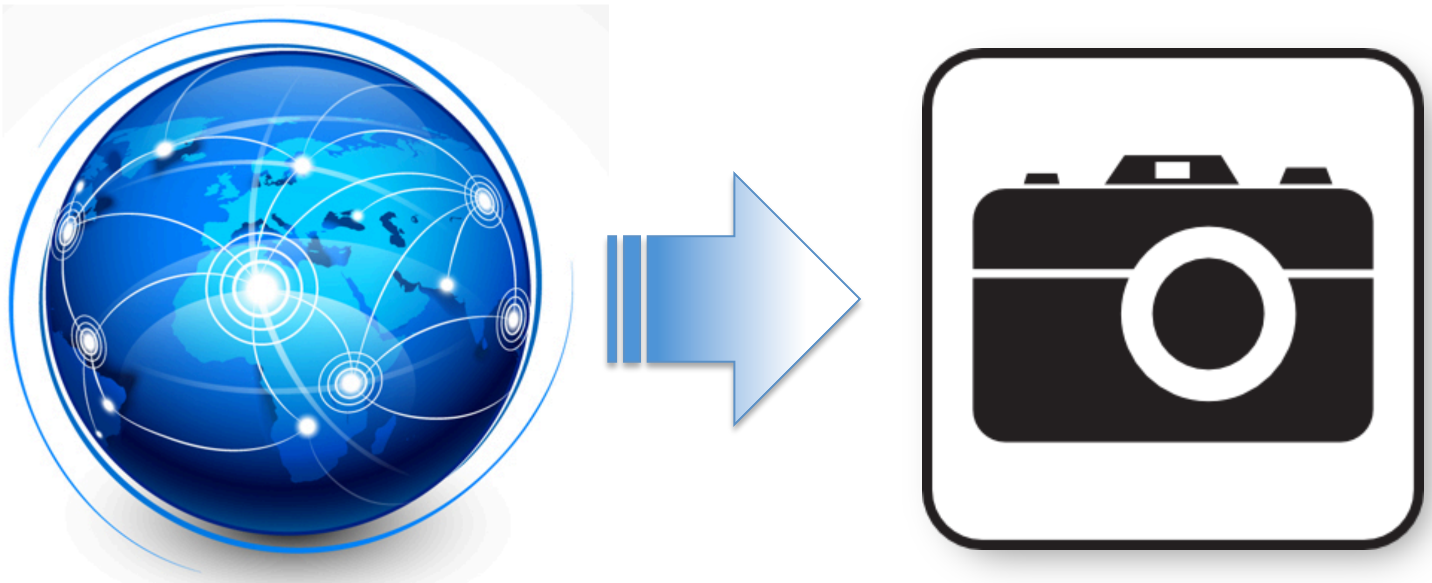
Lieb 310



What if …

we could turn the Internet into a camera?



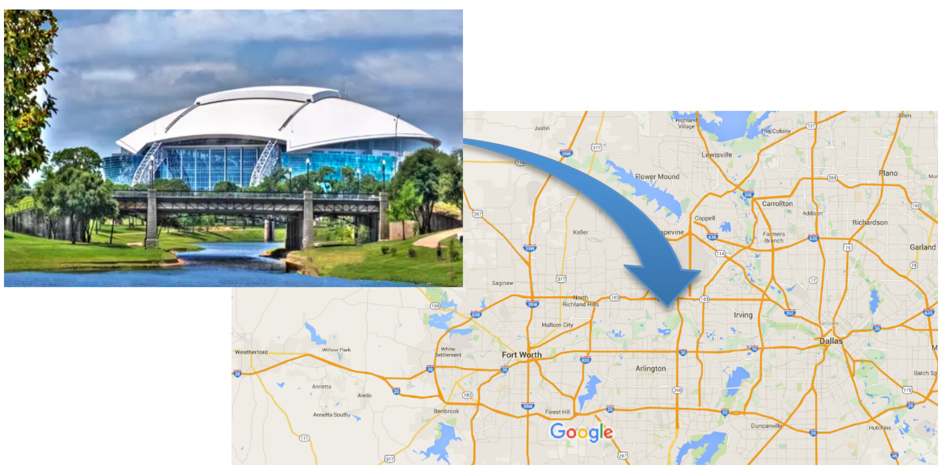
Uploads
per minute

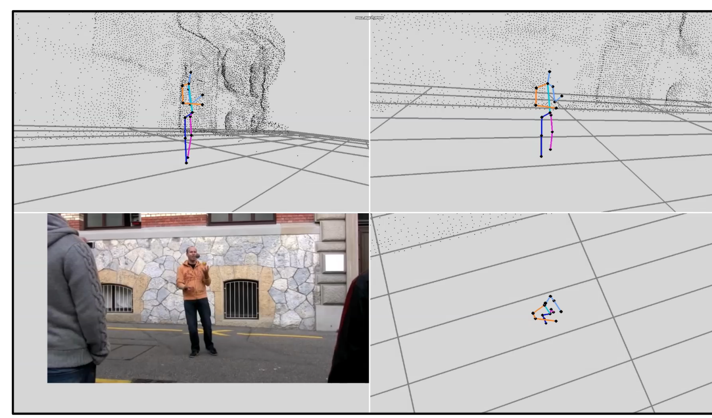
facebook	130,000 Images
YouTube	300 hrs. of video

Visual Index of the World

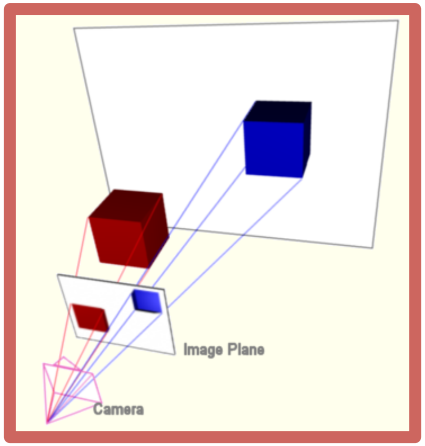
Visual Index of the World

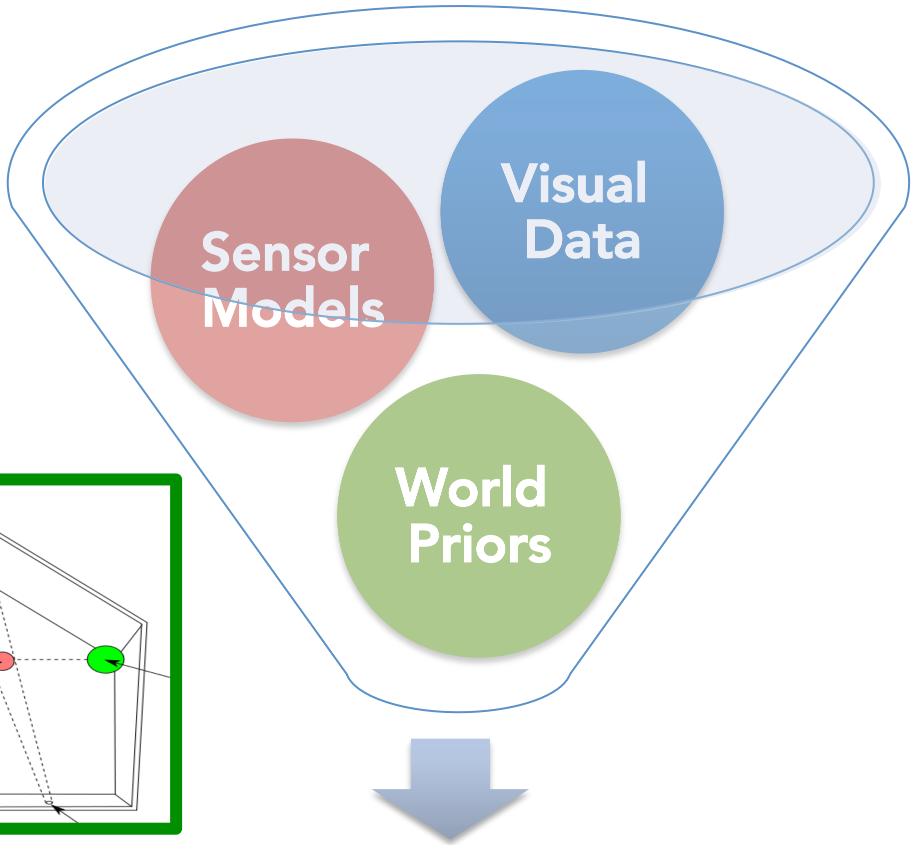
Applications

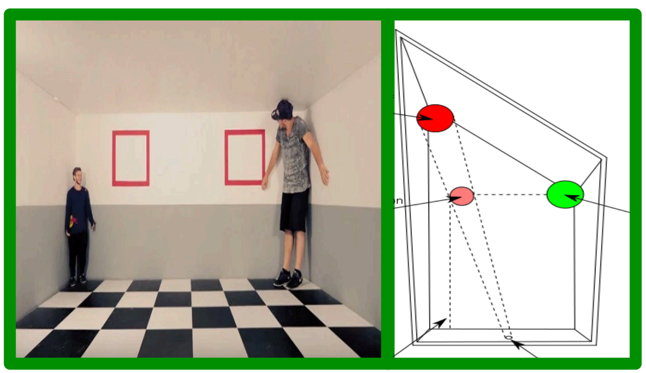




Computer Vision

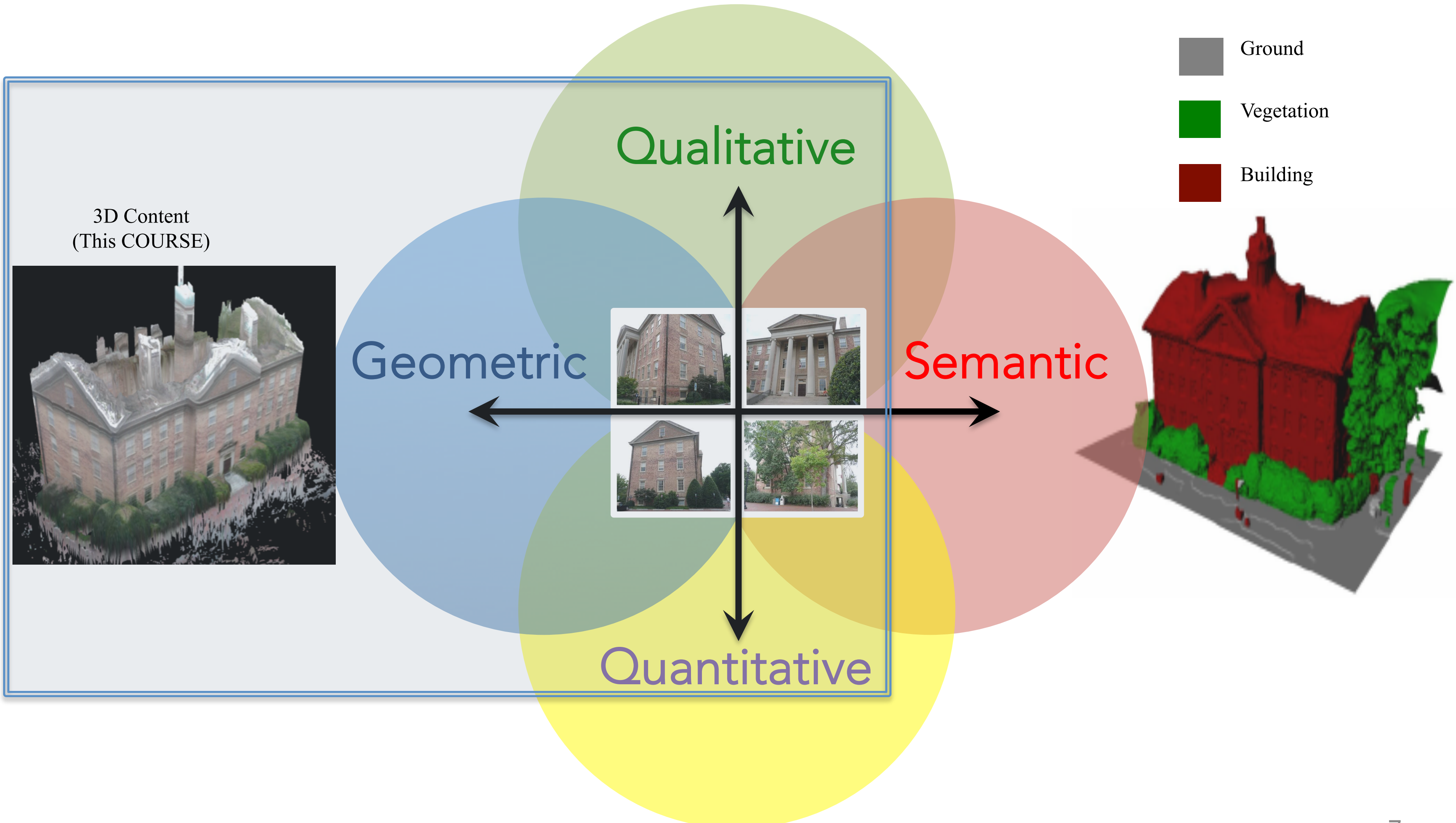






Visual Concepts

Visual Concepts



Objectives

- Approach Computer Vision from a geometric, 3D perspective
  - Negligible overlap with traditional Computer Vision course (CS 558)
  - Explain image formation, single and multi-view geometry, structure from motion
- Introduce Computational Geometry concepts
  - Point clouds, meshes, Delaunay triangulation

Important Points

- This is an elective course. You chose to be here.
- Expect to work and to be challenged.
- Exams won't be based on recall. They will be open book and you will be expected to solve new problems.

Logistics

- Office hours: Wednesday 5-6 and by email
- Evaluation:
  - 5 homework sets (50%)
  - Quizzes and participation (10%)
  - Mid-term exam (15%)
  - Final exam (25%)

Textbooks

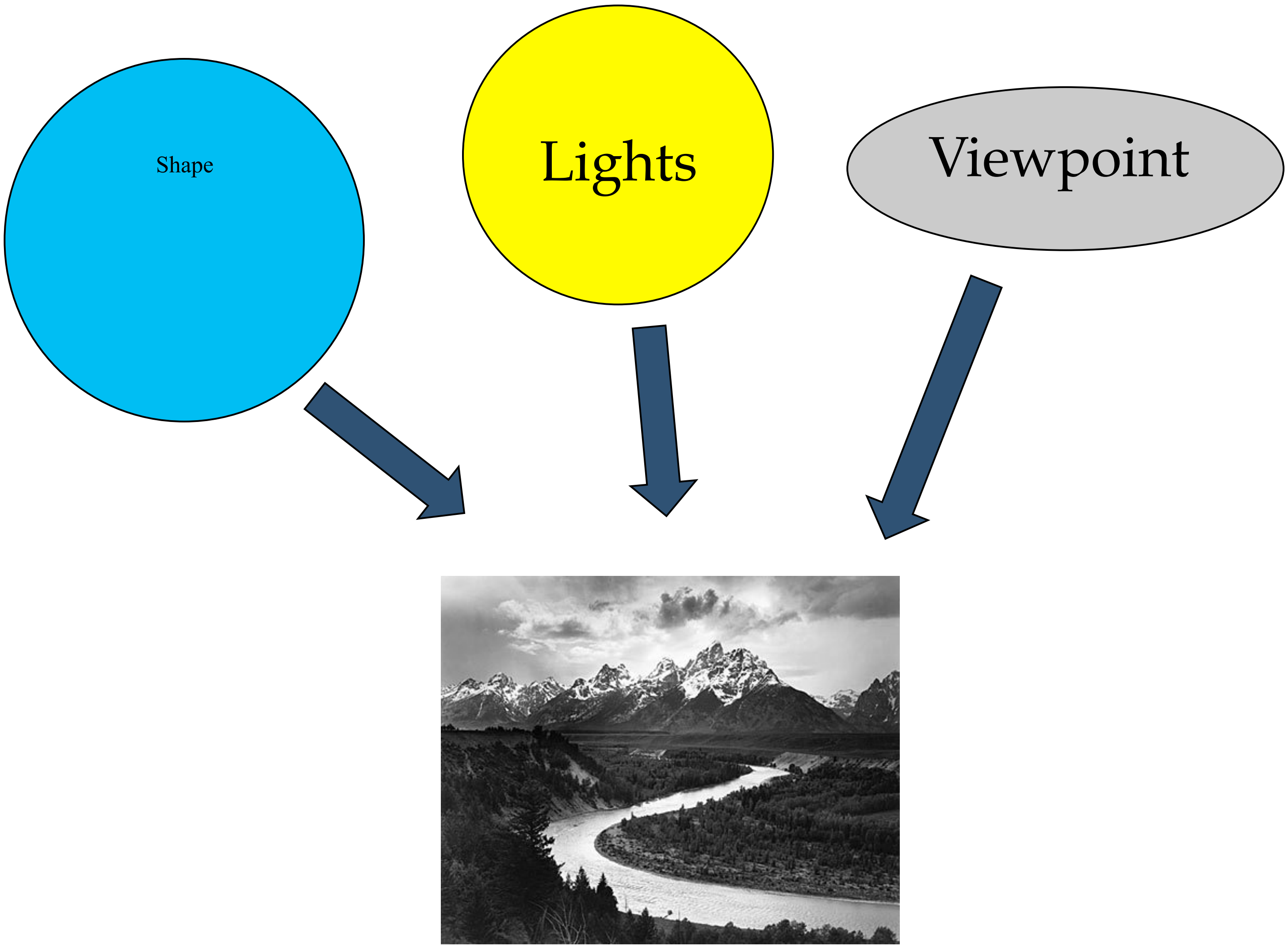
- Richard Szeliski, Computer Vision: Algorithms and Applications, Springer, 2010
- David M. Mount, CMSC 754: Computational Geometry lecture notes, Department of Computer Science, University of Maryland, Spring 2012

- Both available online

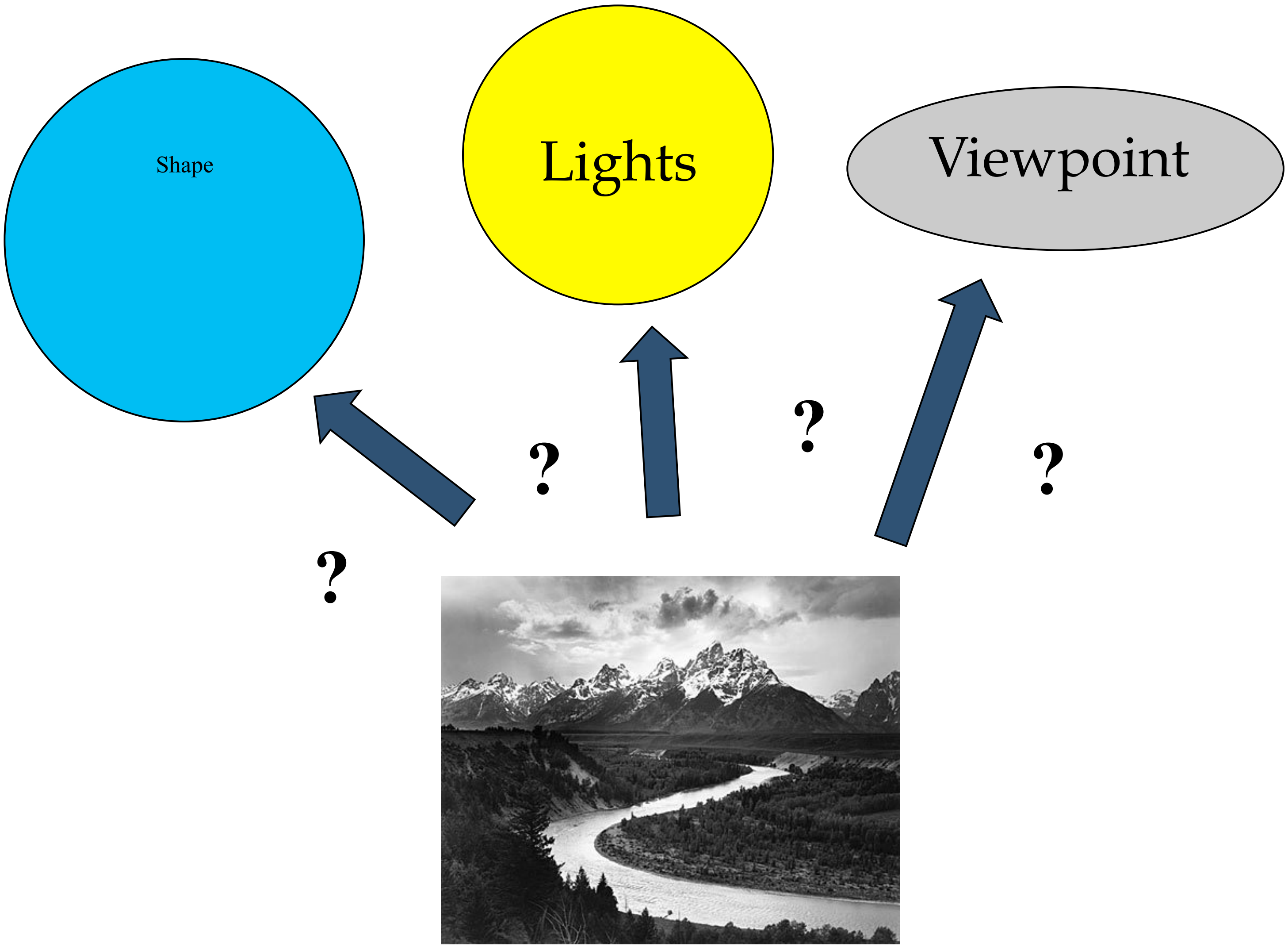
What is Computer Vision

- Why is it not image processing?

Graphics vs. Vision



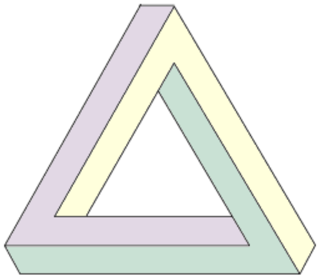
Graphics vs. Vision

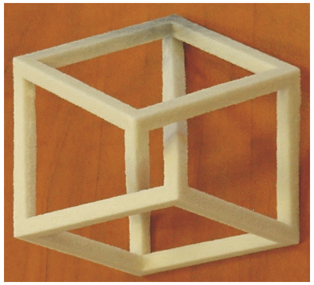


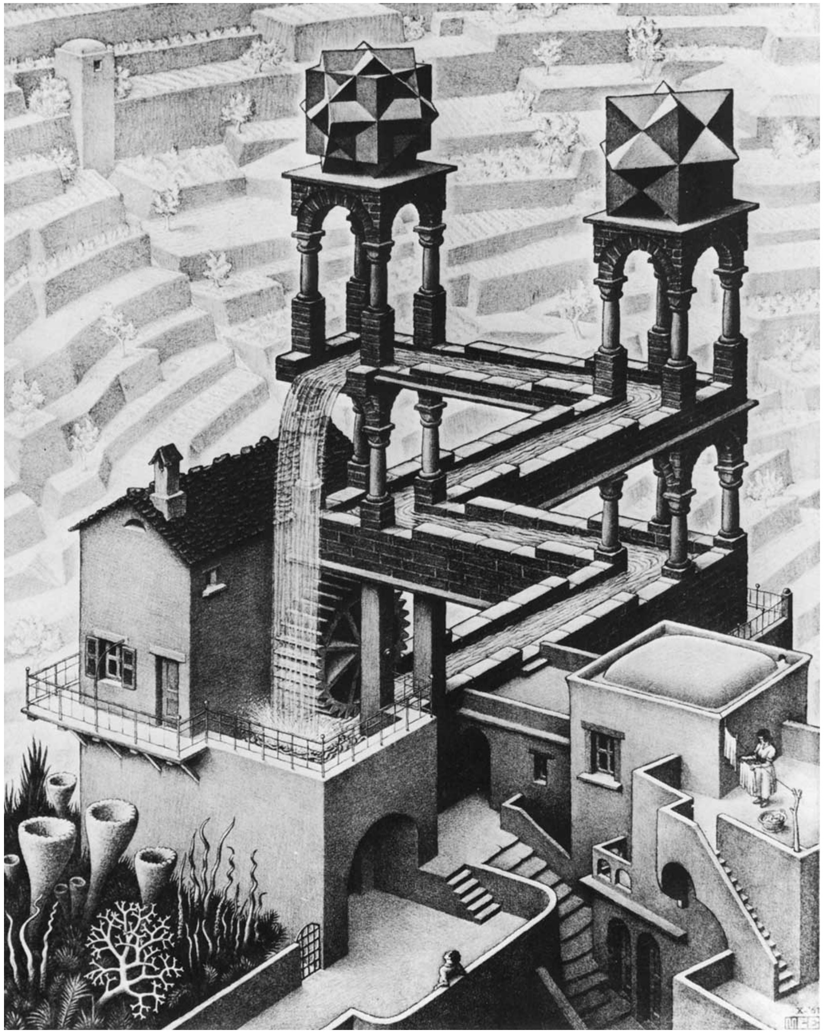
Vision is Hard

Vision is Hard

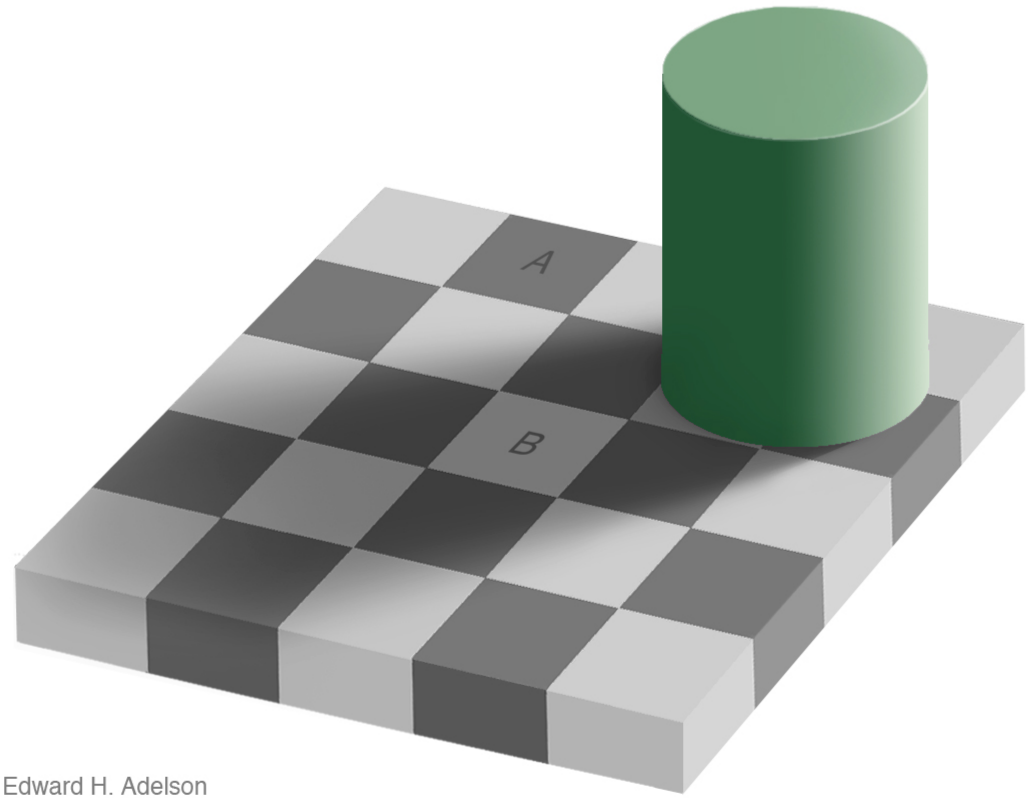
Vision is Hard





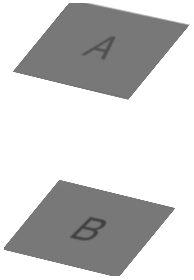


Vision is Hard

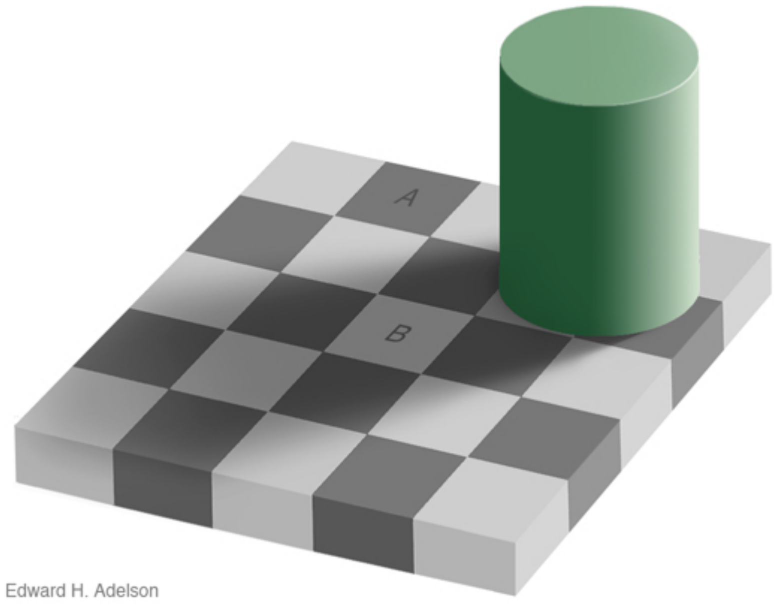


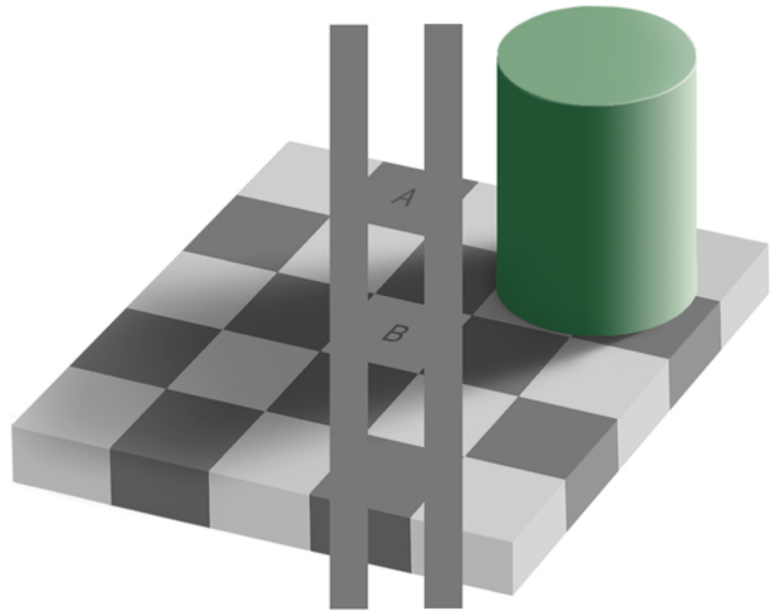
Edward H. Adelson

Vision is Hard



Vision is Hard



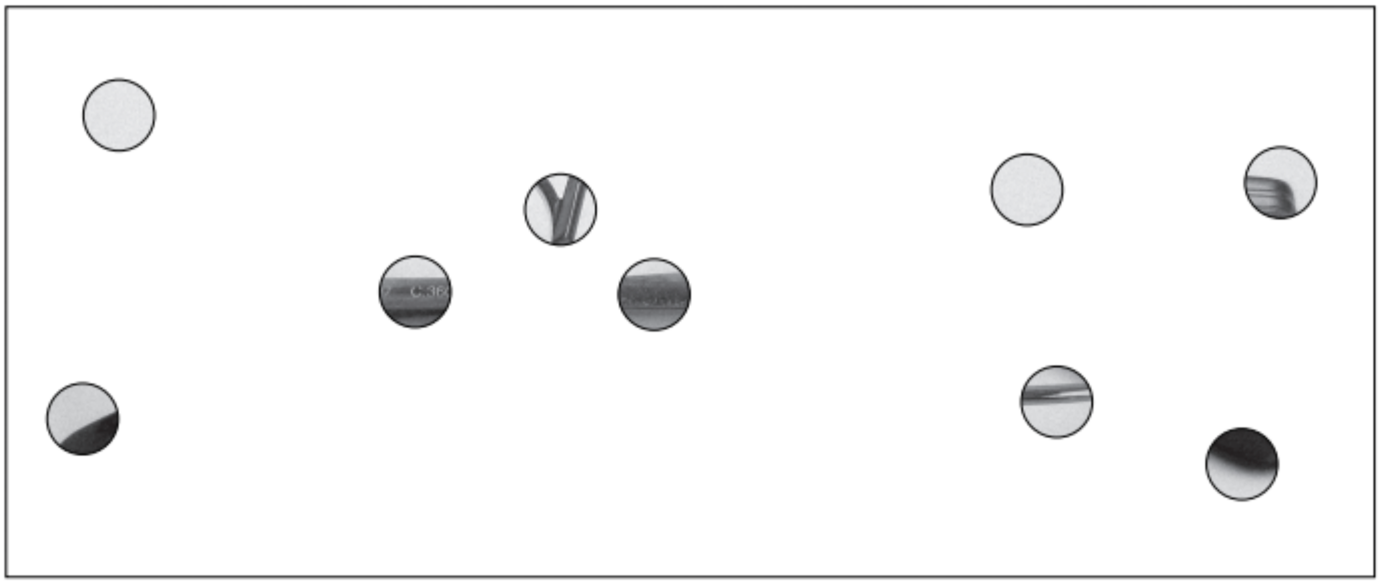


Vision is Hard

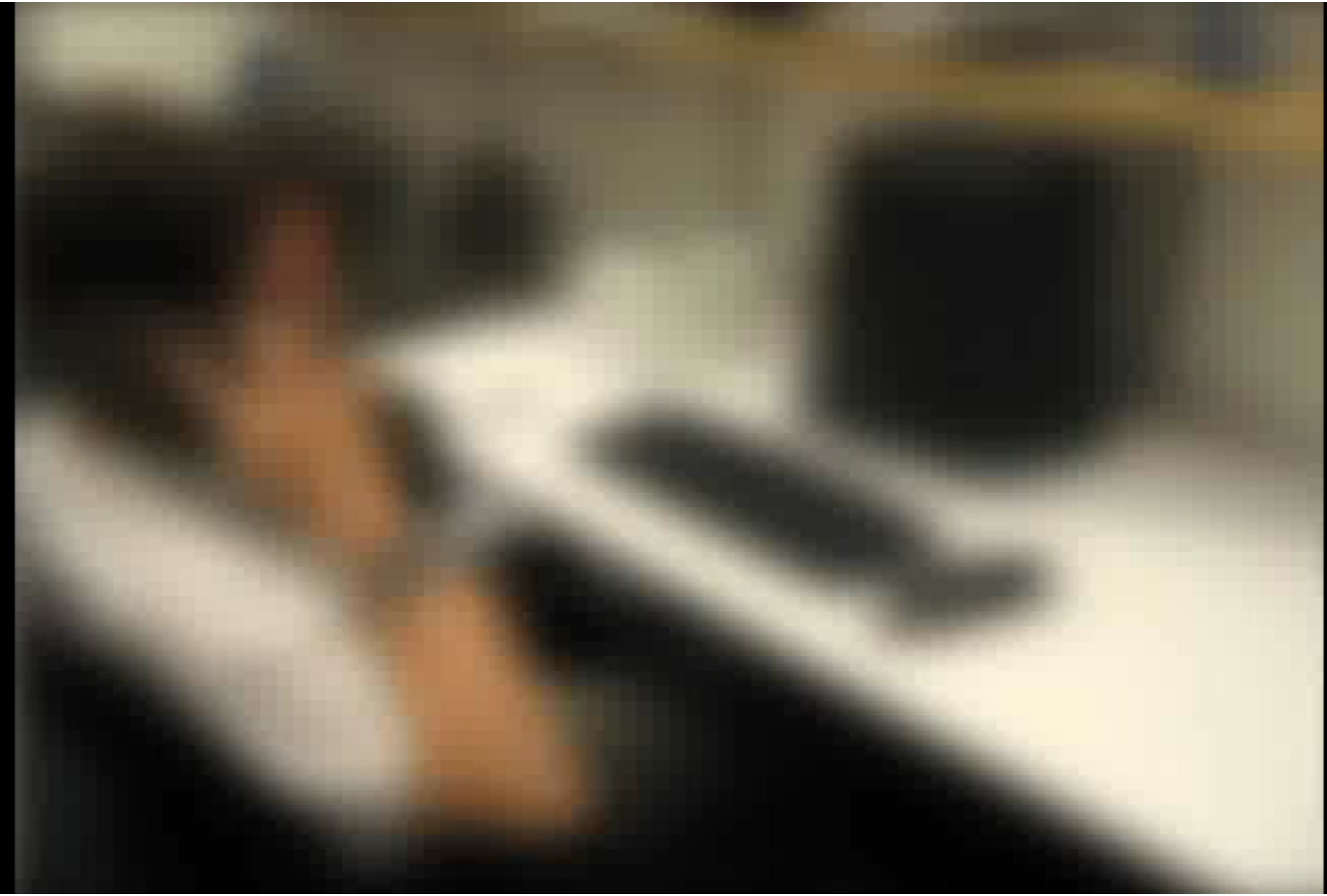
Vision is Hard

- A 2D picture may be produced by many different 3D scenes


Vision is Hard



Vision is Hard



Why is Vision Hard?

- Loss of information due to projection from 3D to 2D
  - Infinite scenes could have generated a given image
- Image colors depend on surface properties, illumination, camera response function and interactions such as shadows
  - HVS very good at ignoring distractors
- Noise
  - sensor noise and nonlinearities, quantization
- Lots of data
- Conflicts among local and global cues
  - Illusions

The Horizon

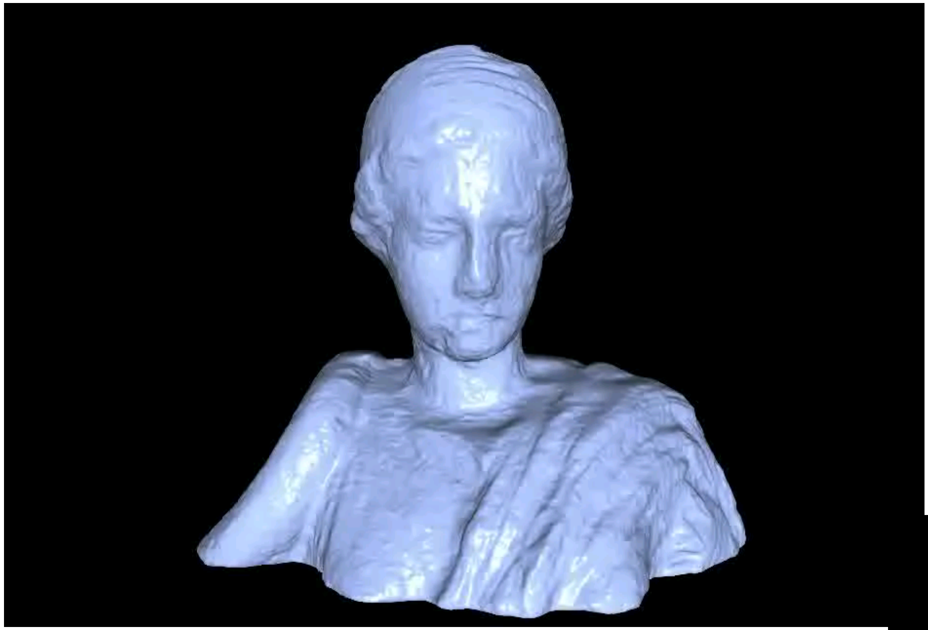
- Not all hard to explain phenomena are unusual…

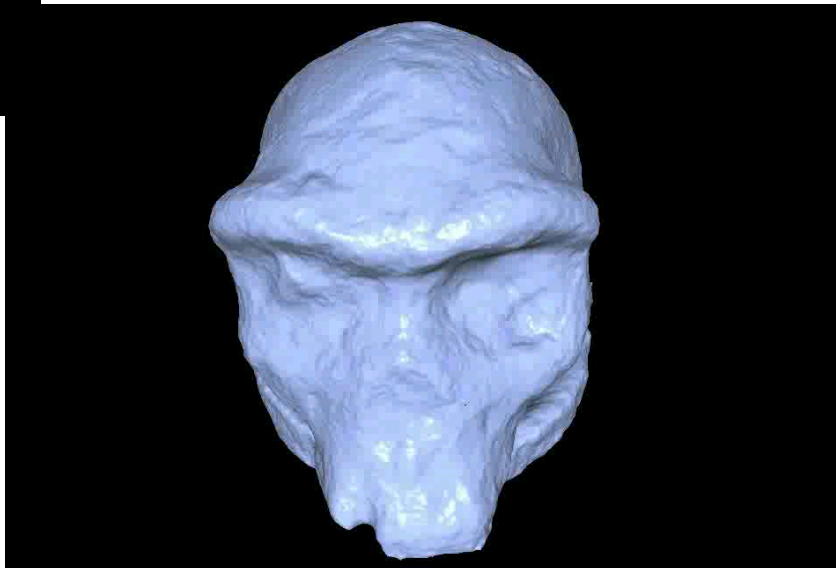
Vanishing Points

Why 3D Vision?

- Structure from Motion
  - Simultaneous Localization and Mapping
- 3D reconstruction
  - Dense mapping …
- 3D motion capture
- Medical applications
- Robotics and autonomous driving
  - Driver assistance

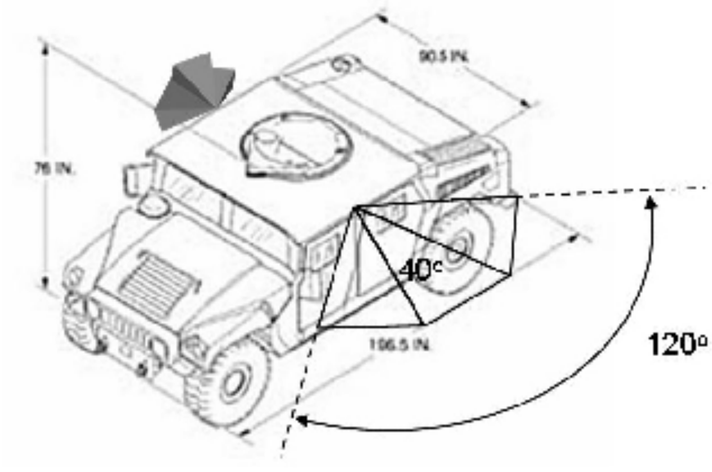
3D Models



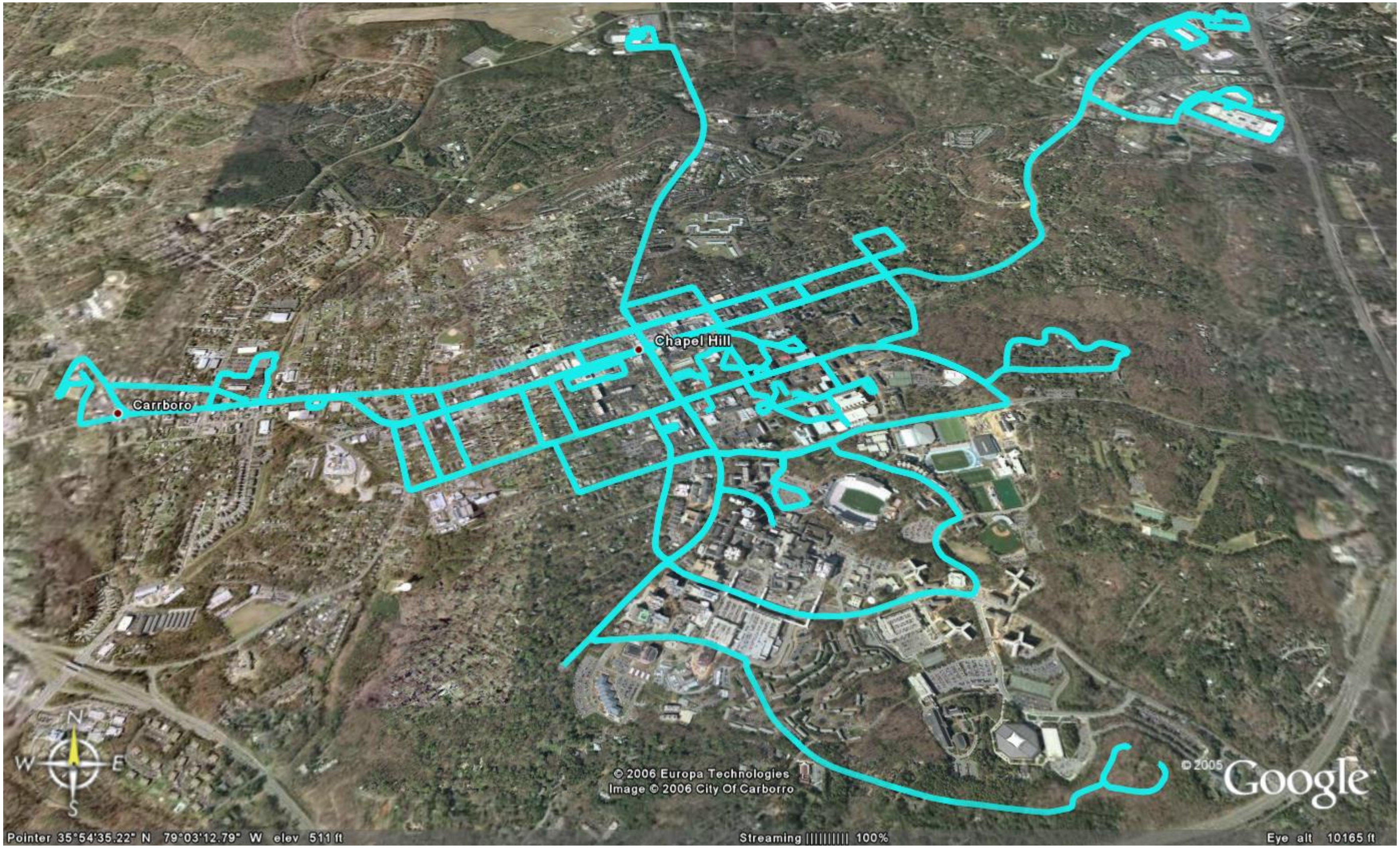


Real-Time Video-based 3D Reconstruction

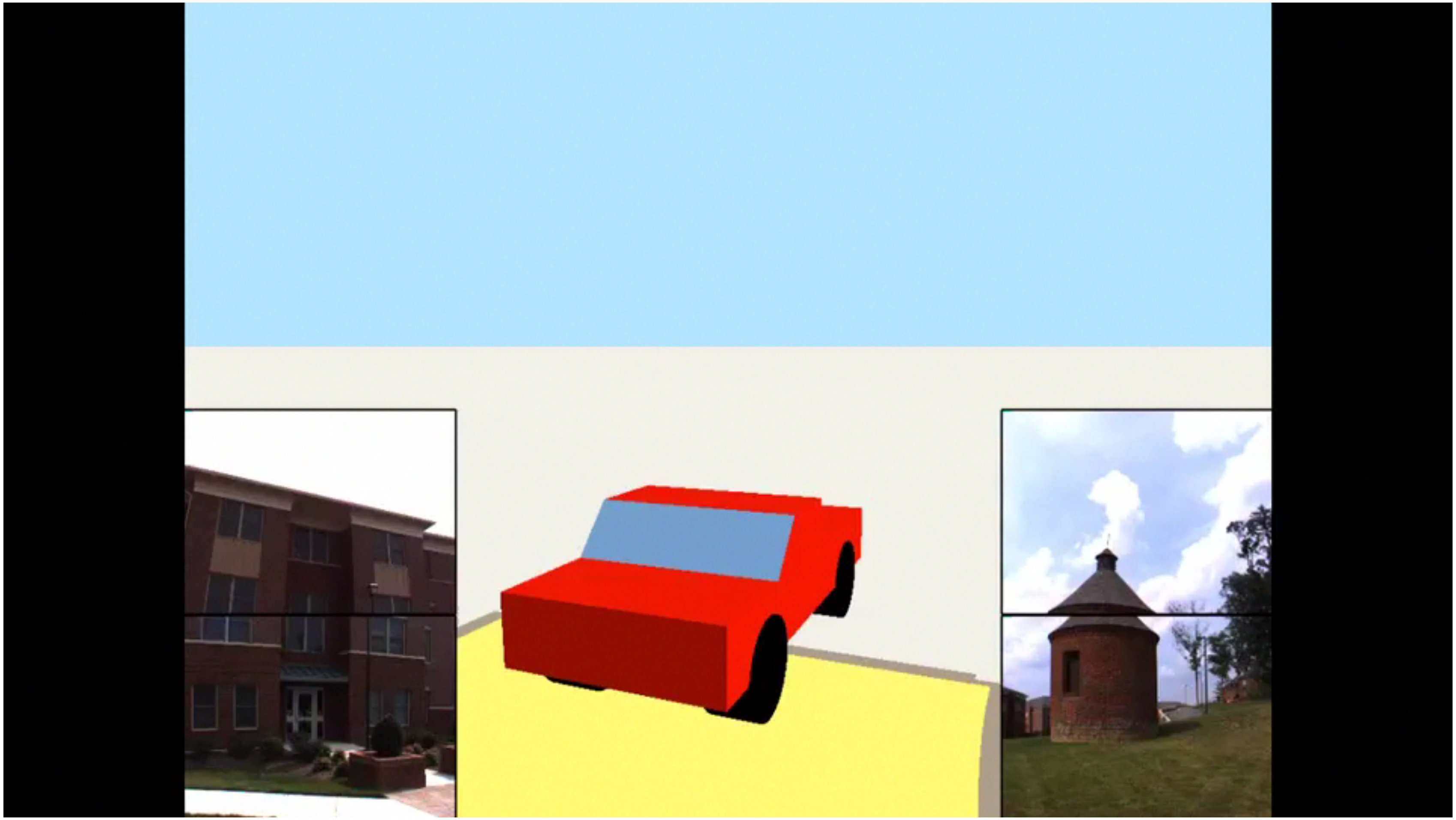
- Goal: real-time reconstruction of urban environments for visualization and training
- Platform:
  - 8 *non-overlapping* cameras
  - Differential GPS
  - Inertial Navigation System



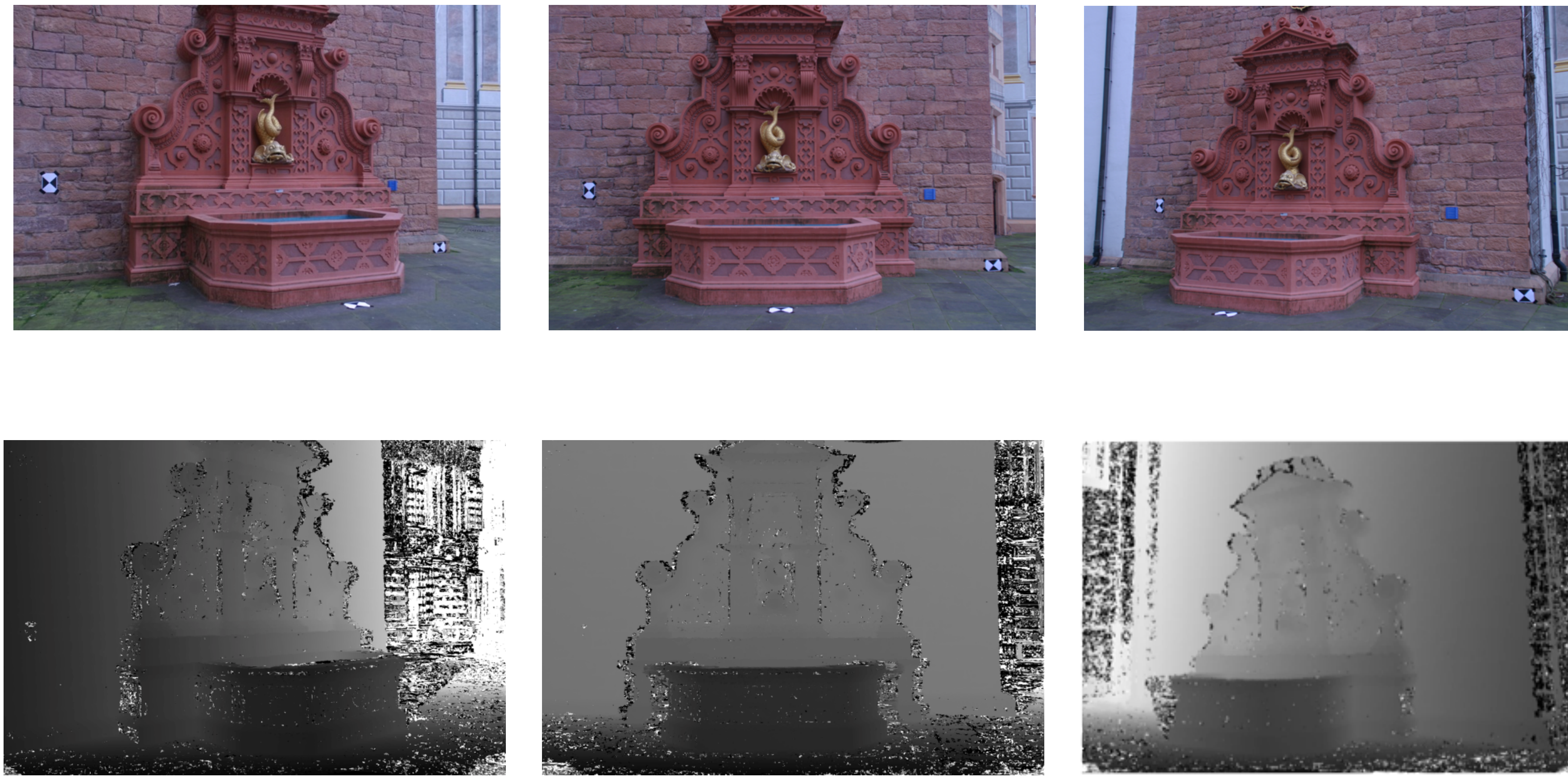
Data Collection



Results: Chapel Hill

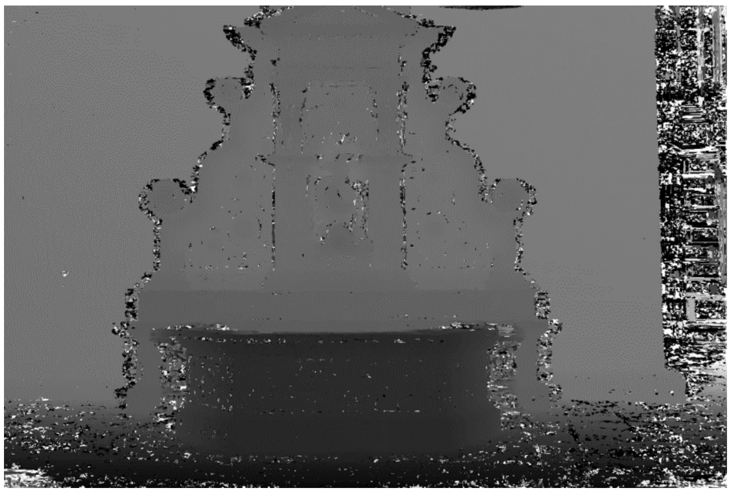


Depth Map Estimation



3 of 11 images and corresponding depth maps

Depth Map Fusion



Raw Depth Map

Fused Depth Map

Colored Point Clouds

Rome in a Day

The World in Six Days

Building the World in Six Days

CVPR 2015

Paper 964

Visual Turing Test (UW)

Shan, Adams, Curless, Furukawa and Seitz (2013)

Visual SLAM

Dynamic Reconstruction

Introduction to Geometry

Based on slides by M. Pollefeys (ETH)
and D. Cappelleri (Purdue)

Points and Lines in 2D

- A point (x, y) lies on a line (a, b, c) when:
  - ax+by+c = 0 or $(a, b, c)\,(x, y, 1)^T = 0$
- Use homogeneous coordinates to represent points => add an extra coordinate
  - Note that scale is unimportant for determining incidence: k(x, y, 1) is also on the line
  - Homogeneous coordinates (x_1, x_2, x_3), but only two degrees of freedom
  - Equivalent to inhomogeneous coordinates (x, y)

Points from Lines and Vice Versa

- The intersection of two lines l and l’ is given by: l×l’
- The line connecting two points x and x’ is given by: x×x’

$$\vec{C} = \vec{A} \times \vec{B} = \begin{pmatrix} A_x \\ A_y \\ A_z \end{pmatrix} \times \begin{pmatrix} B_x \\ B_y \\ B_z \end{pmatrix} = \begin{pmatrix} A_y \cdot B_z - A_z \cdot B_y \\ A_z \cdot B_x - A_x \cdot B_z \\ A_x \cdot B_y - A_y \cdot B_x \end{pmatrix}$$

Ideal Points and the Line at Infinity

- Intersection of two parallel lines:
  - $l = (a, b, c)$ and $l' = (a, b, c')$
  - $l \times l' = (b, -a, 0)$

- Ideal points: $(x_1, x_2, 0)$
- Belong to the line at infinity $l = (0, 0, 1)$

- $\mathbf{P}^2 = \mathbf{R}^3 - (0, 0, 0)$ (projective space)
  - In $\mathbf{P}^2$ there is no distinction between regular and ideal points

Rotation in 2D

- Matrices are operators that transform vectors
  - 2D rotation matrix R= $\begin{bmatrix} cos\theta & -sin\theta \\ sin\theta & cos\theta \end{bmatrix}$

- In homogeneous coordinates $\begin{bmatrix} R & 0 \\ 0 & 1 \end{bmatrix}$

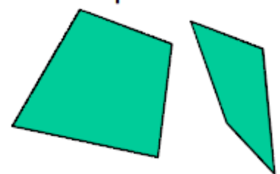
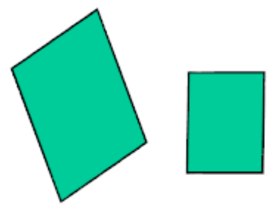
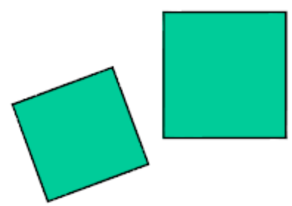
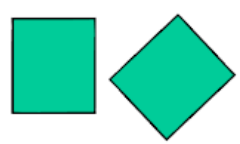
Hands-on: 2D Transformations

- How to translate a point in homogeneous and inhomogeneous coordinates?
- How to rotate a point around the origin?
- How to rotate a point around a center other than the origin?

$$R=\begin{bmatrix} cos\theta & -sin\theta \\ sin\theta & cos\theta \end{bmatrix}$$

$$\begin{bmatrix} r_{11} & r_{12} & t_x \\ r_{21} & r_{22} & t_y \\ 0 & 0 & 1 \end{bmatrix}$$

Hierarchy of 2D Transformations

		transformed squares	invariants
Projective 8dof	$\begin{bmatrix} h_{11} & h_{12} & h_{13} \\ h_{21} & h_{22} & h_{23} \\ h_{31} & h_{32} & h_{33} \end{bmatrix}$		Concurrency, collinearity, order of contact (intersection, tangency, inflection, etc.), cross ratio
Affine 6dof	$\begin{bmatrix} a_{11} & a_{12} & t_x \\ a_{21} & a_{22} & t_y \\ 0 & 0 & 1 \end{bmatrix}$		Parallellism, ratio of areas, ratio of lengths on parallel lines (e.g midpoints), linear combinations of vectors (centroids). **The line at infinity l_∞**
Similarity 4dof	$\begin{bmatrix} sr_{11} & sr_{12} & t_x \\ sr_{21} & sr_{22} & t_y \\ 0 & 0 & 1 \end{bmatrix}$		Ratios of lengths, angles. **The circular points I,J**
Euclidean 3dof	$\begin{bmatrix} r_{11} & r_{12} & t_x \\ r_{21} & r_{22} & t_y \\ 0 & 0 & 1 \end{bmatrix}$		lengths, areas.

ETH

Transformation of Points and Lines

Point transformation

$$\mathrm{x}' = \mathbf{H}\,\mathrm{x}$$

Line transformation

$$\mathrm{l}' = \mathbf{H}^{-\mathrm{T}}\,\mathrm{l}$$

3D points

3D point

$(X, Y, Z)^{\mathsf{T}}$ in $\mathbf{R}^3$

$\mathrm{X} = (X_1, X_2, X_3, X_4)^{\mathsf{T}}$ in $\mathbf{P}^3$

$$\mathrm{X} = \left(\frac{X_1}{X_4}, \frac{X_2}{X_4}, \frac{X_3}{X_4}, 1\right)^{\mathsf{T}} = (X, Y, Z, 1)^{\mathsf{T}} \quad (X_4 \neq 0)$$

projective transformation

$$\mathrm{X}' = \mathbf{H}\,\mathrm{X} \quad \text{(4x4-1=15 dof)}$$

Planes

3D plane

$$\pi_1 X + \pi_2 Y + \pi_3 Z + \pi_4 = 0$$

$$\pi_1 X_1 + \pi_2 X_2 + \pi_3 X_3 + \pi_4 X_4 = 0$$

$$\pi^{\mathsf{T}} \mathrm{X} = 0$$

Transformation

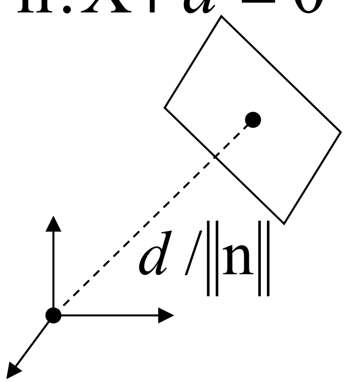
$$\mathrm{X}' = \mathbf{H}\,\mathrm{X}$$

$$\pi' = \mathbf{H}^{-\mathsf{T}}\,\pi$$

Euclidean representation

$$\mathrm{n}.\widetilde{\mathrm{X}} + d = 0 \qquad \mathrm{n} = (\pi_1, \pi_2, \pi_3)^{\mathsf{T}} \qquad \widetilde{\mathrm{X}} = (X, Y, Z)^{\mathsf{T}}$$

$$\pi_4 = d \qquad X_4 = 1$$



Planes from points

Solve π from $X_1^T\pi = 0$, $X_2^T\pi = 0$ and $X_3^T\pi = 0$

$$\begin{bmatrix} X_1^T \\ X_2^T \\ X_3^T \end{bmatrix} \pi = 0$$ (solve as right nullspace of π) $$\begin{bmatrix} X_1^T \\ X_2^T \\ X_3^T \end{bmatrix}$$

Or implicitly from coplanarity condition

$$\det \begin{bmatrix} X_1 & (X_1)_1 & (X_2)_1 & (X_3)_1 \\ X_2 & (X_1)_2 & (X_2)_2 & (X_3)_2 \\ X_3 & (X_1)_3 & (X_2)_3 & (X_3)_3 \\ X_4 & (X_1)_4 & (X_2)_4 & (X_3)_4 \end{bmatrix} = 0$$

$$X_1 D_{234} - X_2 D_{134} + X_3 D_{124} - X_4 D_{123} = 0$$
$$\pi = \left(D_{234}, -D_{134}, D_{124}, -D_{123}\right)^T$$

Points from planes

Solve X from $\pi_1^{\mathsf{T}}\mathrm{X}=0$, $\pi_2^{\mathsf{T}}\mathrm{X}=0$ and $\pi_3^{\mathsf{T}}\mathrm{X}=0$

$$\begin{bmatrix} \pi_1^{\mathsf{T}} \\ \pi_2^{\mathsf{T}} \\ \pi_3^{\mathsf{T}} \end{bmatrix} \mathrm{X} = 0$$

(solve as right nullspace of $\begin{bmatrix} \pi_1^{\mathsf{T}} \\ \pi_2^{\mathsf{T}} \\ \pi_3^{\mathsf{T}} \end{bmatrix}$)

Lines are complicated…

Rotations

- Rotation matrices around the 3 axes

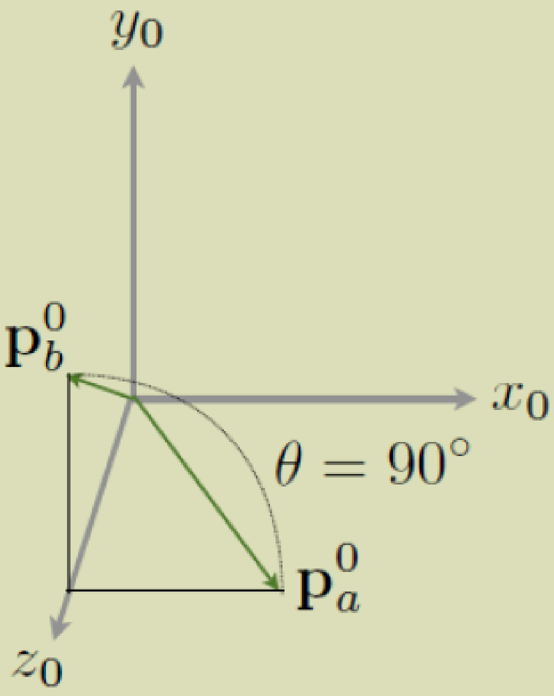
=> What is the inverse of a rotation matrix?

$$\mathbf{R}_{x,\theta} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{bmatrix}$$

$$\mathbf{R}_{y,\theta} = \begin{bmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{bmatrix}$$

$$\mathbf{R}_{z,\theta} = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Rotation Example



The rotation matrix can be used to perform arbitrary rotations on vectors

$$\mathbf{v}_p^0 = \mathbf{R}_1^0 \, \mathbf{v}_p^1$$

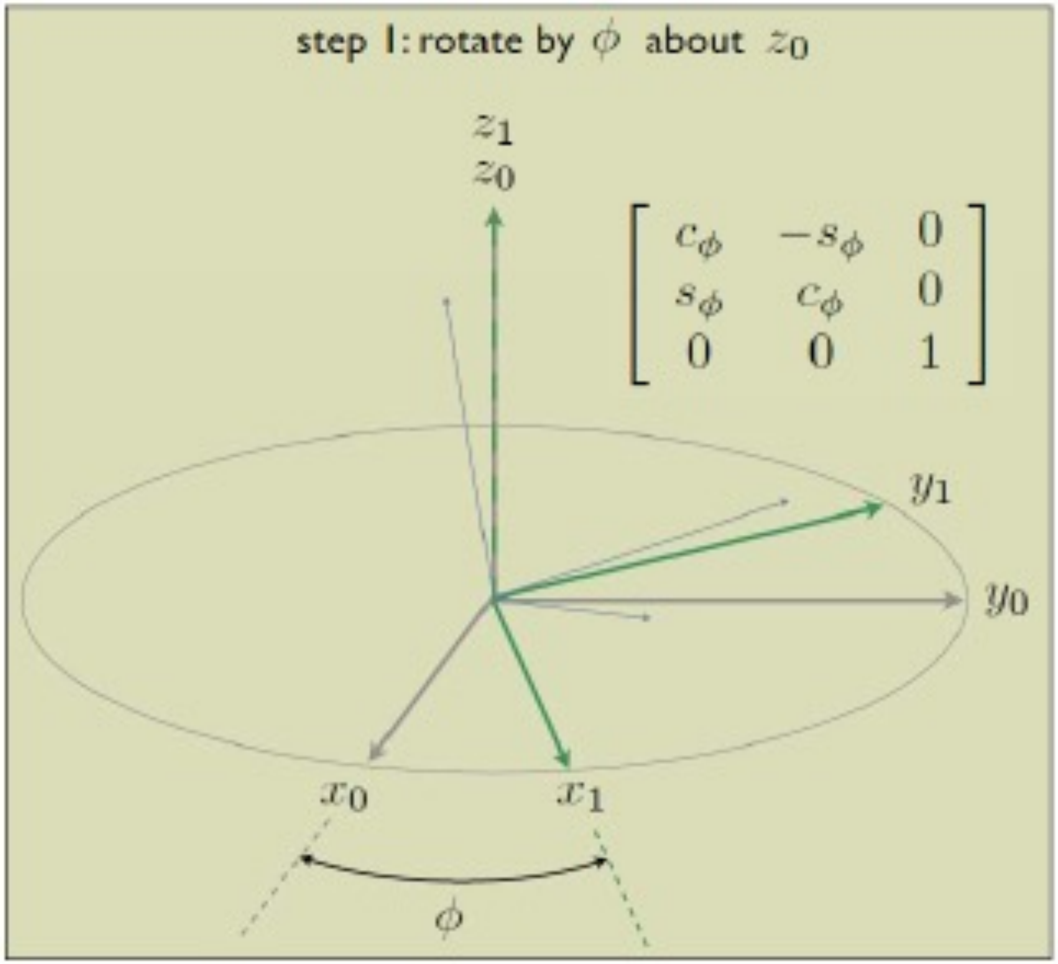
$$\mathbf{p}_a^0 = \begin{bmatrix} 1 \\ 0 \\ 1 \end{bmatrix}$$

$$\mathbf{p}_b^0 = \mathbf{R}_{z,\theta} \, \mathbf{p}_a^0 = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 \\ 0 \\ 1 \end{bmatrix} = \begin{bmatrix} 0 \\ 1 \\ 1 \end{bmatrix}$$

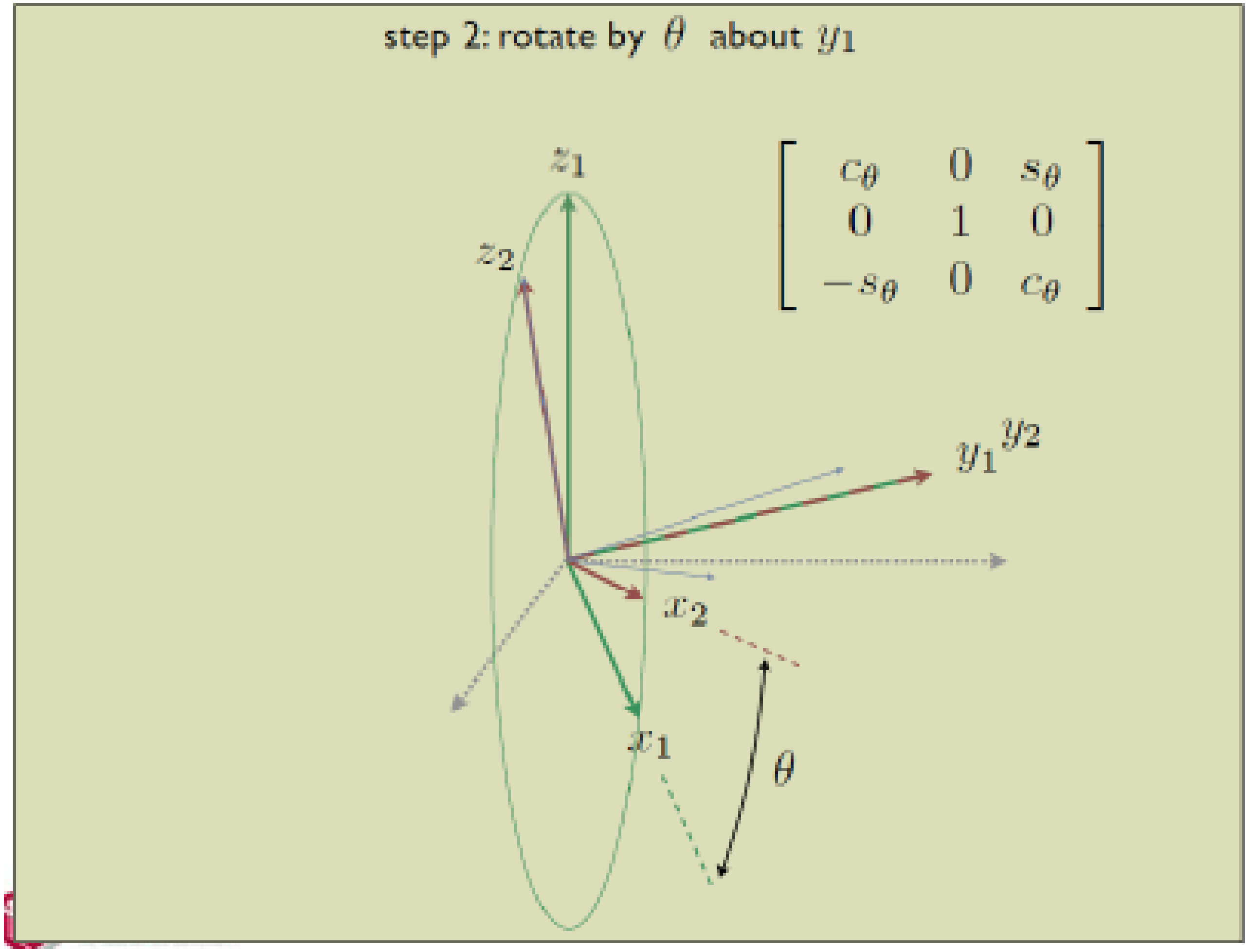
Parameterization of Rotations

- In 3D, the 9-element rotation matrix has 3 DOF
- Several methods exist for representing a 3D rotation
  - Euler angles
  - Pitch, Roll, Yaw angles
  - Axis/Angle representation
  - Quaternions

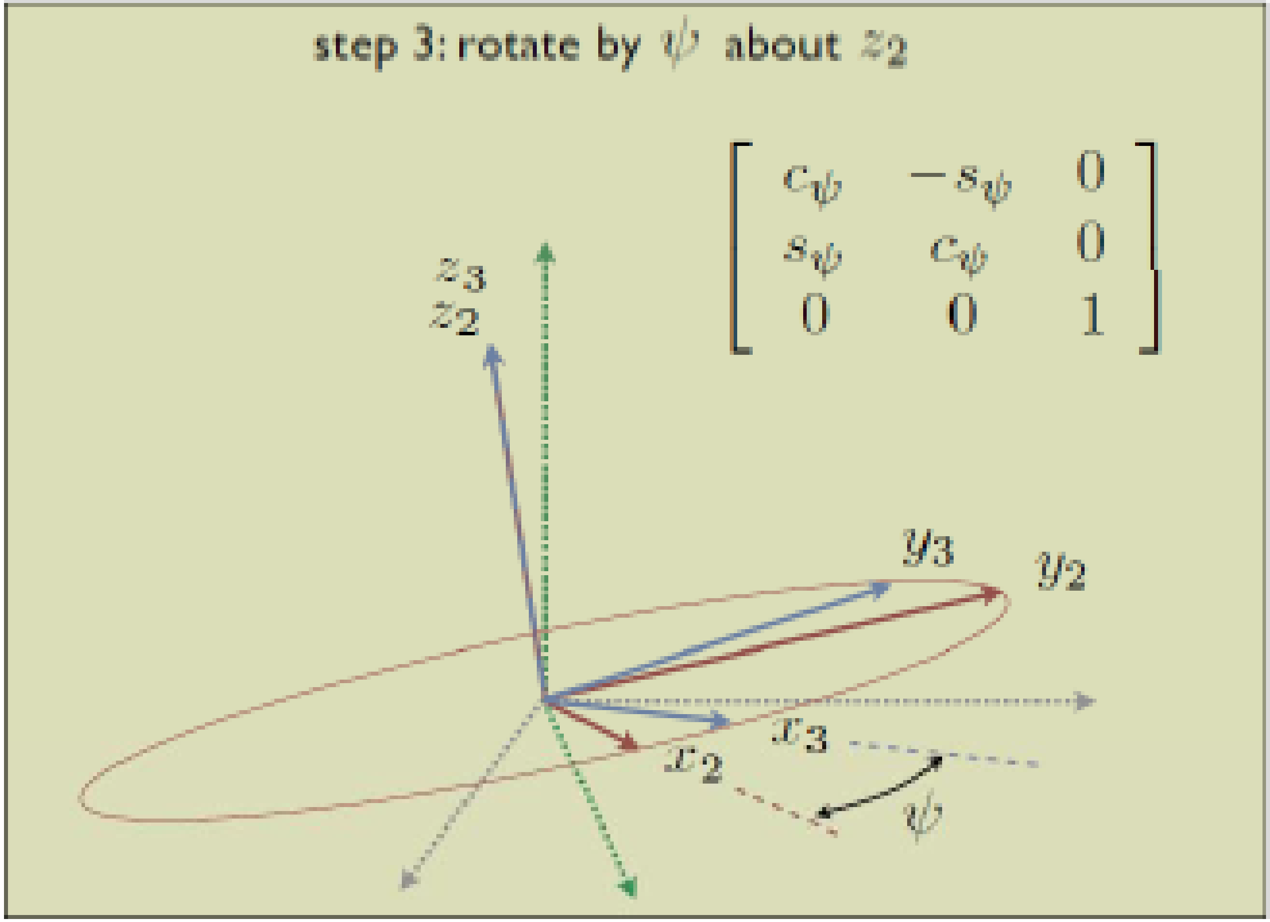
Euler Angles



Euler Angles



Euler Angles



Euler Angles to Rotation Matrix

(**post**-multiply using the **basic rotation matrices**)

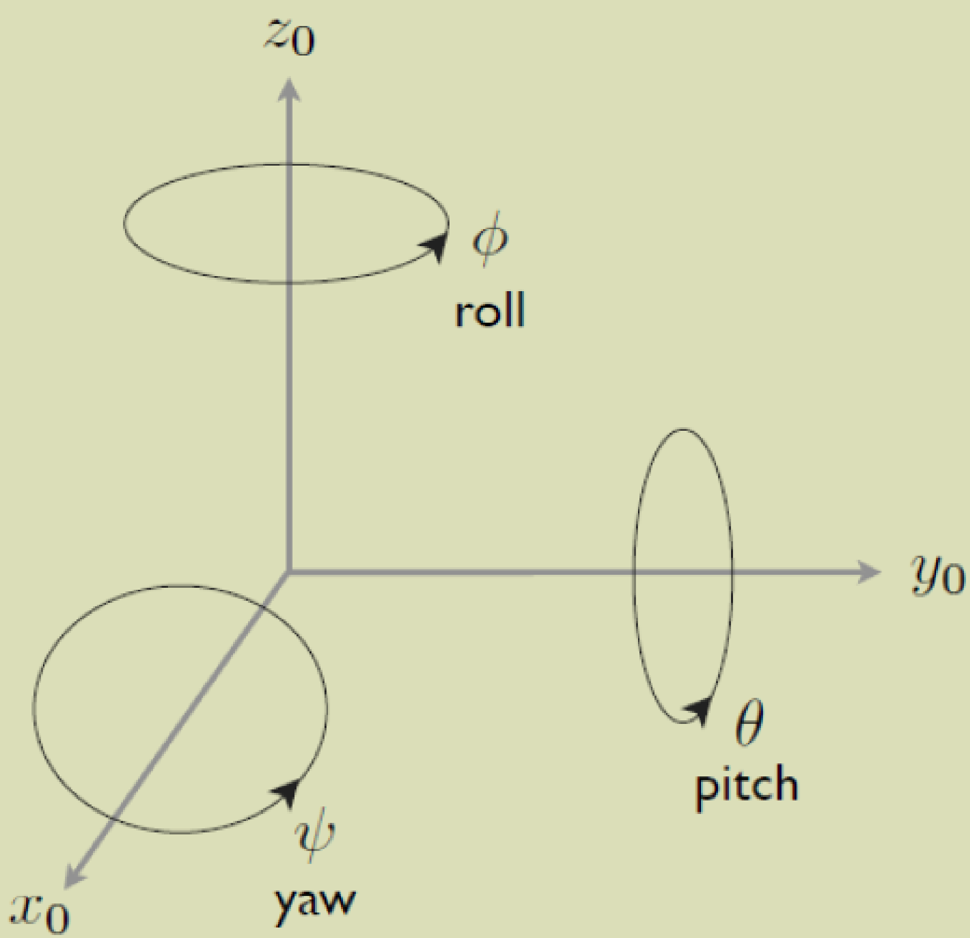
$$\mathbf{R} = \mathbf{R}_{z,\phi}\,\mathbf{R}_{y,\theta}\,\mathbf{R}_{z,\psi}$$

$$= \begin{bmatrix} c_\phi & -s_\phi & 0 \\ s_\phi & c_\phi & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} c_\theta & 0 & s_\theta \\ 0 & 1 & 0 \\ -s_\theta & 0 & c_\theta \end{bmatrix} \begin{bmatrix} c_\psi & -s_\psi & 0 \\ s_\psi & c_\psi & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} c_\phi c_\theta c_\psi - s_\phi s_\psi & -c_\phi c_\theta s_\psi - s_\phi c_\psi & c_\phi s_\theta \\ s_\phi c_\theta c_\psi + c_\phi s_\psi & -s_\phi c_\theta s_\psi + c_\phi c_\psi & s_\phi s_\theta \\ -s_\theta c_\psi & s_\theta s_\psi & c_\theta \end{bmatrix}$$

Roll, Pitch, Yaw Angles

defined as a set of three angles about a **fixed** reference



Roll, Pitch, Yaw Angles to Rotation Matrix

(**pre**-multiply using the **basic rotation matrices**)

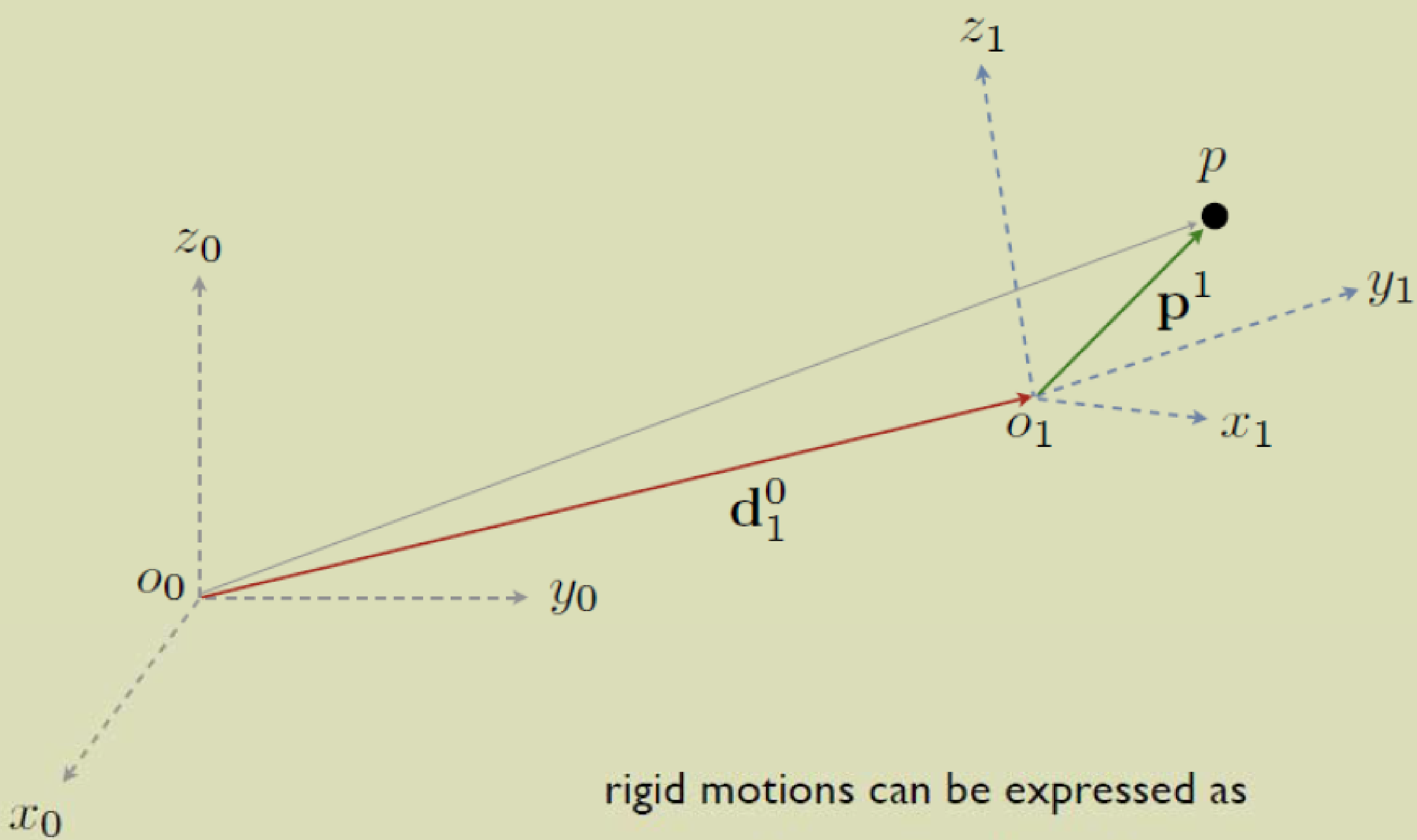
$$\mathbf{R} = \mathbf{R}_{z,\phi}\,\mathbf{R}_{y,\theta}\,\mathbf{R}_{x,\psi}$$

$$= \begin{bmatrix} c_\phi & -s_\phi & 0 \\ s_\phi & c_\phi & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} c_\theta & 0 & s_\theta \\ 0 & 1 & 0 \\ -s_\theta & 0 & c_\theta \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_\psi & -s_\psi \\ 0 & s_\psi & c_\psi \end{bmatrix}$$

$$= \begin{bmatrix} c_\phi c_\theta & c_\phi s_\theta s_\psi - s_\phi c_\psi & s_\phi s_\psi + c_\phi s_\theta c_\psi \\ s_\phi c_\theta & s_\phi s_\theta s_\psi + c_\phi c_\psi & s_\phi s_\theta c_\psi - c_\phi s_\psi \\ -s_\theta & c_\theta s_\psi & c_\theta c_\psi \end{bmatrix}$$

Rigid Motion

a **rigid motion** couples pure translation with pure rotation



rigid motions can be expressed as

$$\mathbf{p}^0 = \mathbf{R}_1^0\, \mathbf{p}^1 + \mathbf{d}_1^0$$

Homogeneous Transformation

a **homogeneous transform** is a matrix representation of rigid motion, defined as

$$\mathbf{H} = \begin{bmatrix} \mathbf{R} & \mathbf{d} \\ \mathbf{0} & 1 \end{bmatrix}$$

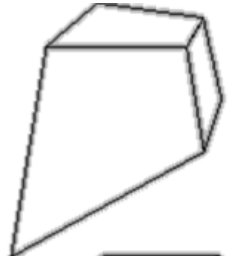
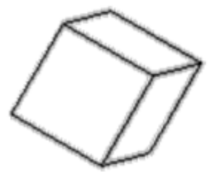
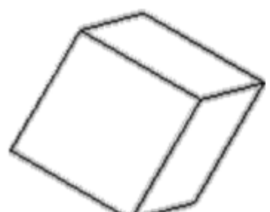
where $\mathbf{R}$ is the 3x3 rotation matrix, and $\mathbf{d}$ is the 1x3 translation vector

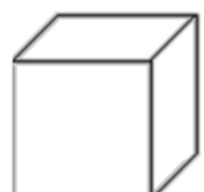
$$\mathbf{H} = \begin{bmatrix} n_x & s_x & a_x & d_x \\ n_y & s_y & a_y & d_y \\ n_z & s_z & a_z & d_z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

the **inverse** of a homogeneous transform can be expressed as

$$\mathbf{H}^{-1} = \begin{bmatrix} \mathbf{R}^\top & -\mathbf{R}^\top d \\ 0 & 1 \end{bmatrix}$$

Hierarchy of 3D Transformations

Projective 15dof	$\begin{bmatrix} A & t \\ v^T & v \end{bmatrix}$		Intersection and tangency
Affine 12dof	$\begin{bmatrix} A & t \\ 0^T & 1 \end{bmatrix}$		Parallellism of planes, Volume ratios, centroids, **The plane at infinity π_∞**
Similarity 7dof	$\begin{bmatrix} sR & t \\ 0^T & 1 \end{bmatrix}$		Angles, ratios of length **The absolute conic Ω_∞**
Euclidean 6dof	$\begin{bmatrix} R & t \\ 0^T & 1 \end{bmatrix}$		Volume



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