

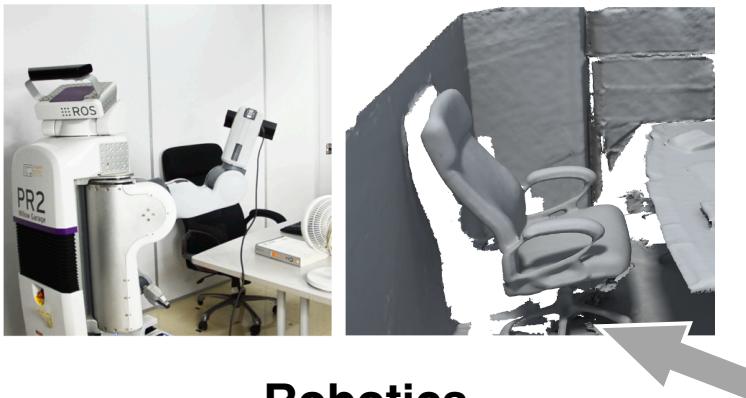
L1: Introduction

Hao Su

Agenda

- Syllabus
- Logistics
- Curve Theory

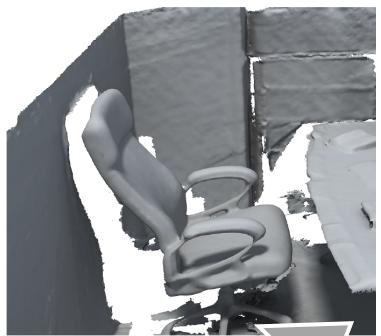
Geometry Understanding is Important



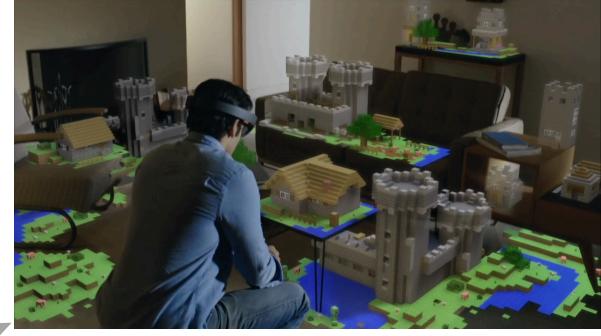
Robotics



Geometry Understanding is Important



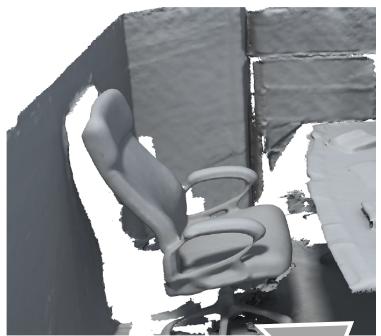
Robotics



Augmented Reality



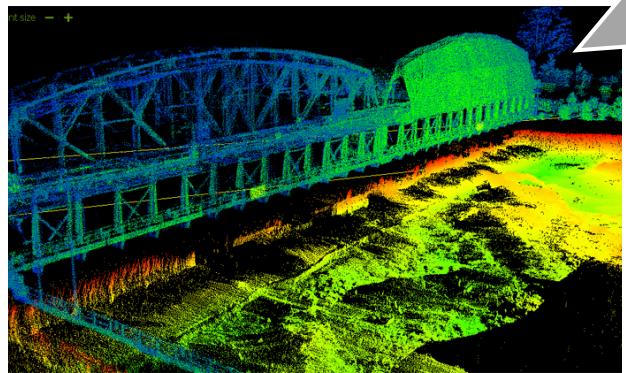
Geometry Understanding is Important



Robotics

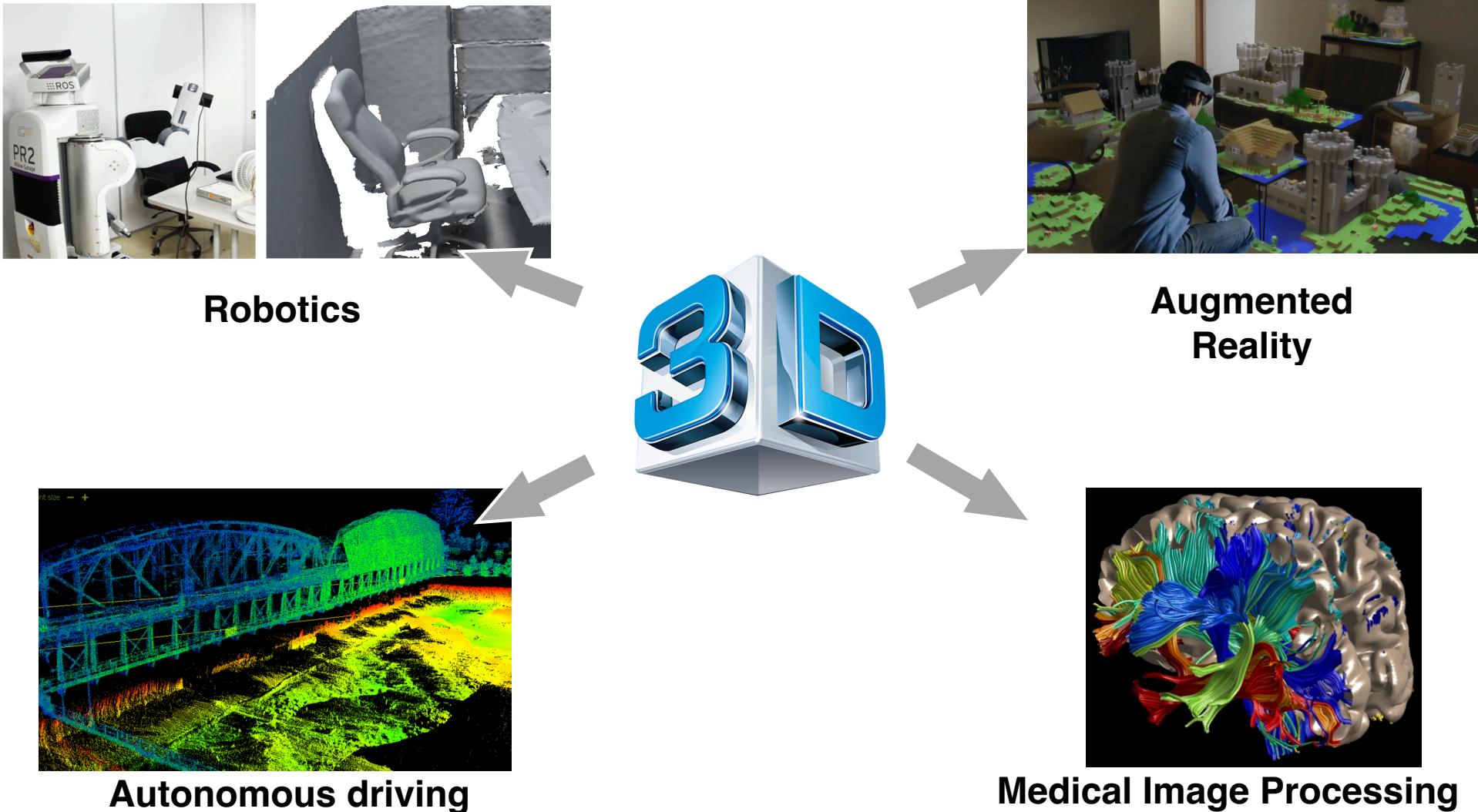


Augmented Reality

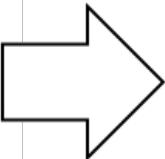


Autonomous driving

Geometry Understanding is Important



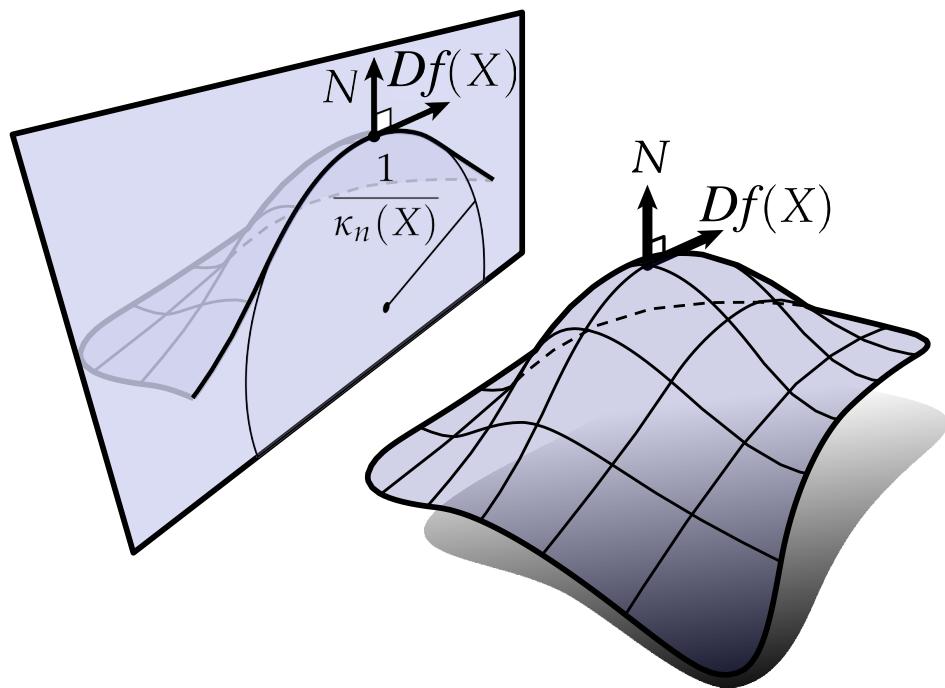
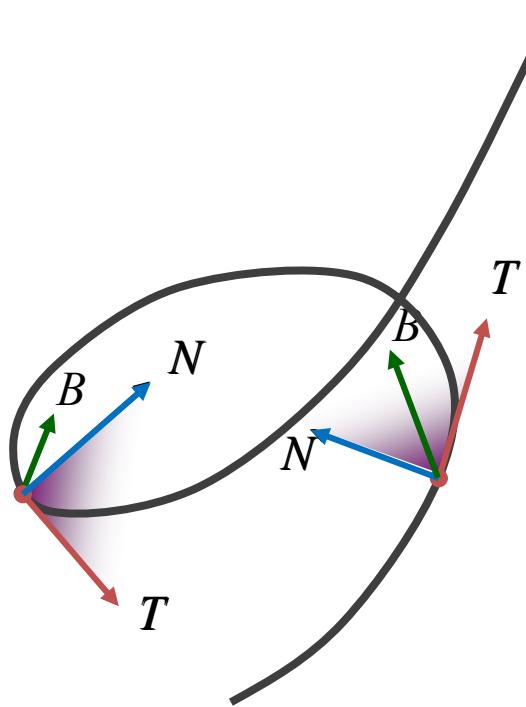
Use Machine Learning to Understand Geometries



A priori knowledge of
the 3D world

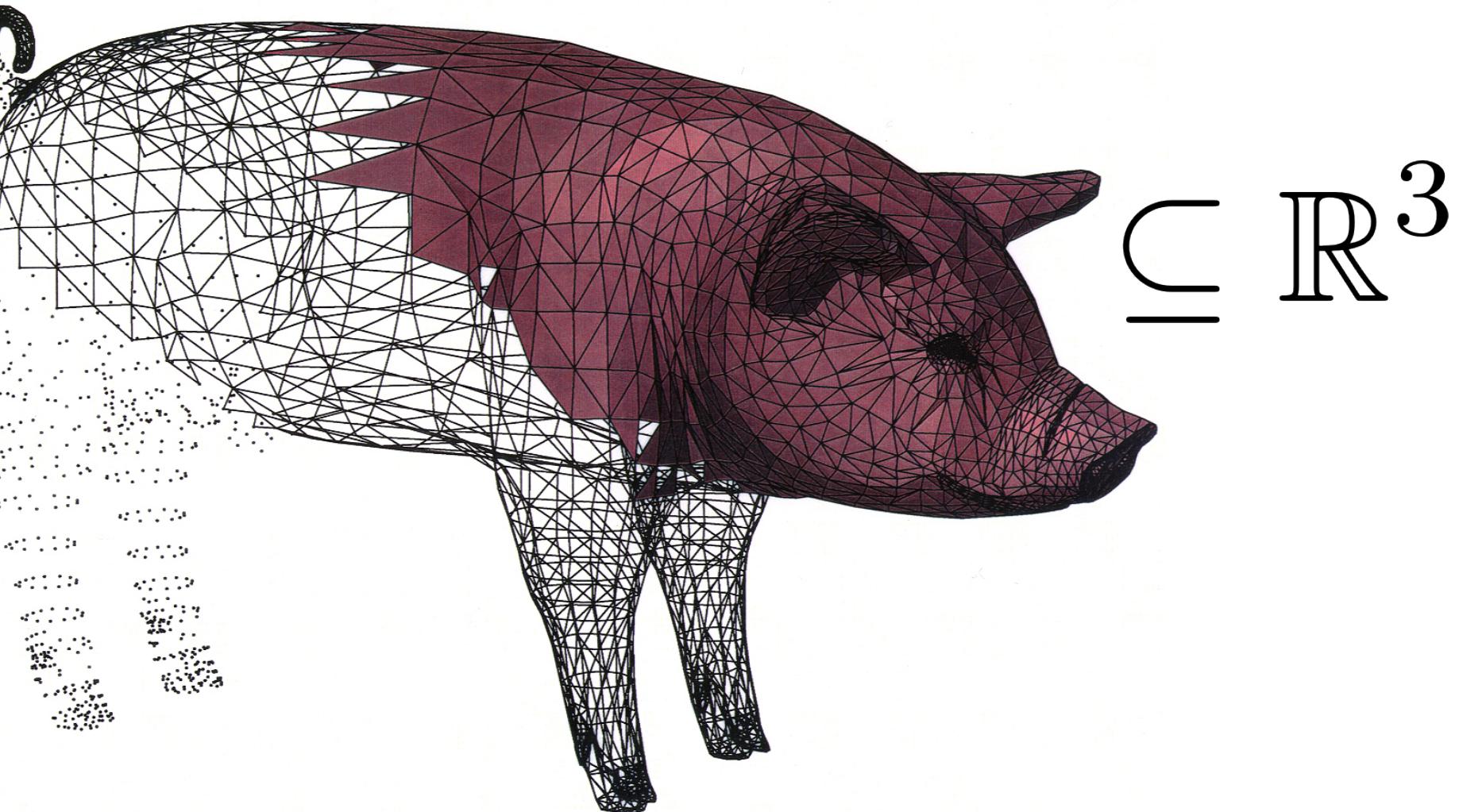
Topics Covered in This Course

- Geometry theories



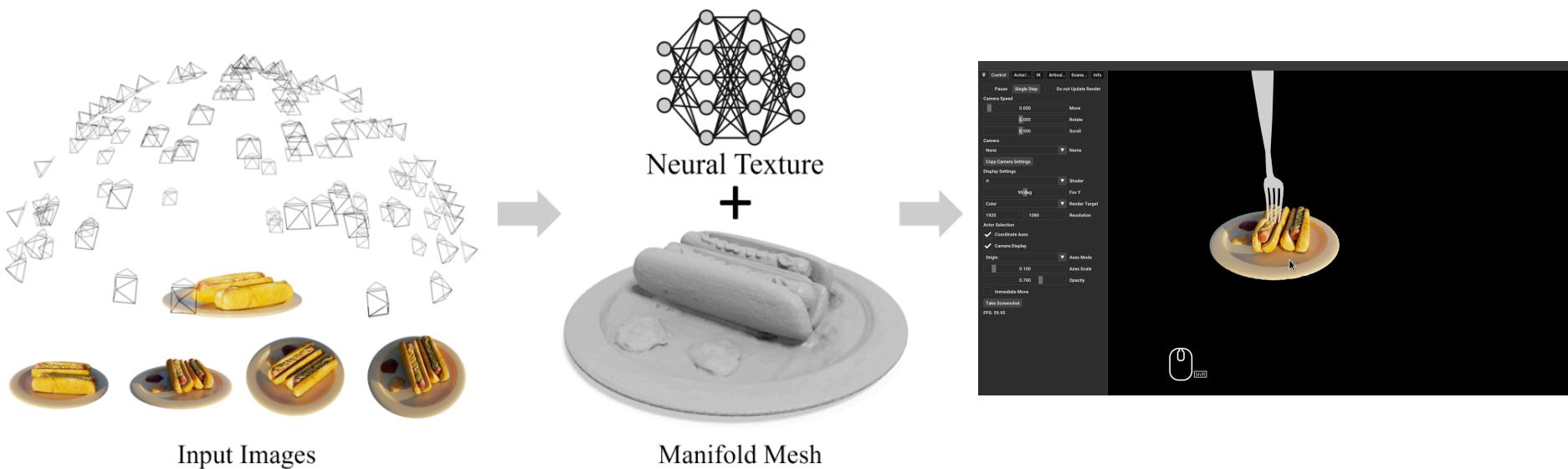
Topics Covered in This Course

- Computer Representation of Geometries



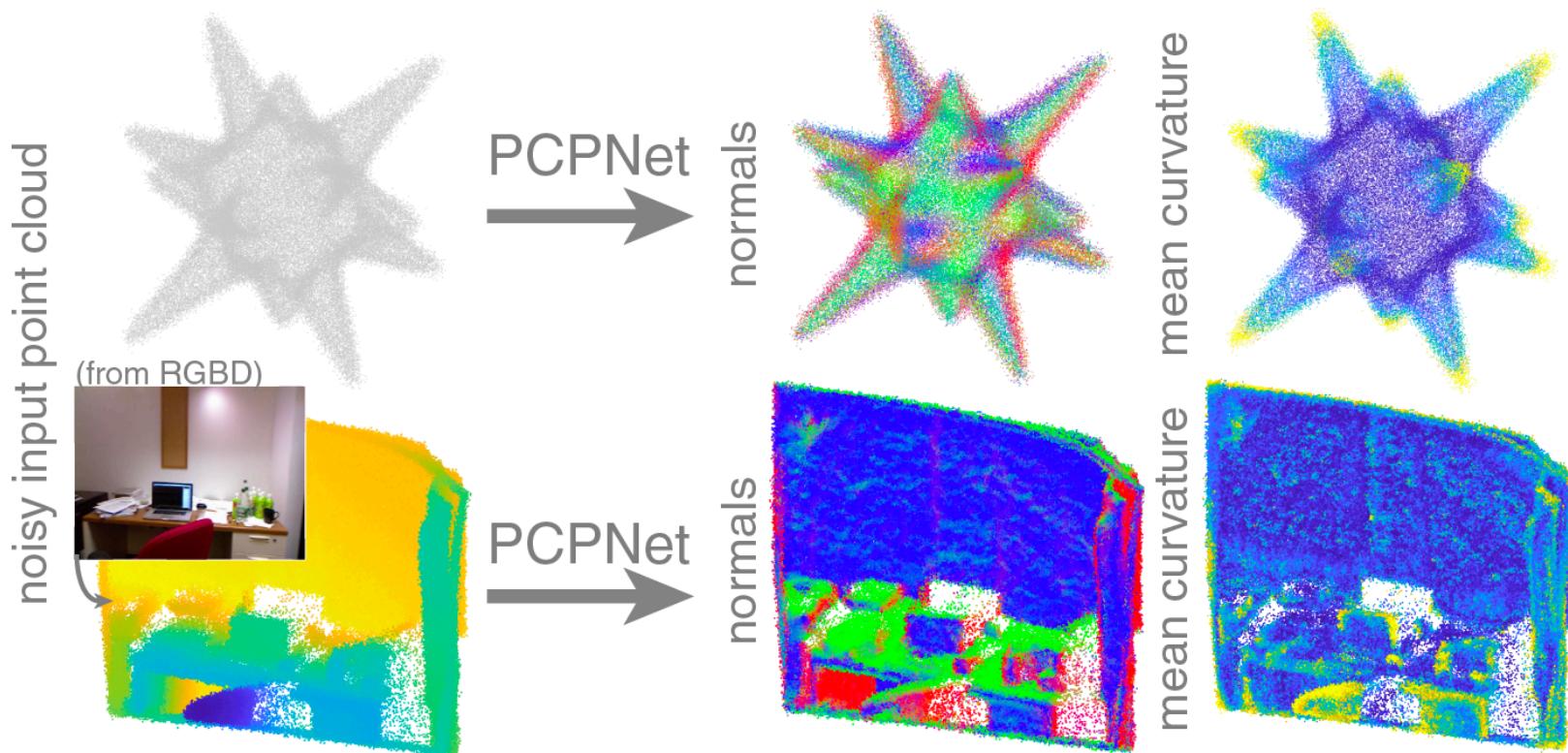
Topics Covered in This Course

- Modeling: 3D reconstruction from multiple views



Topics Covered in This Course

- Modeling: Local geometric property estimation



Topics Covered in This Course

- Modeling: multi-modality modeling foundation model



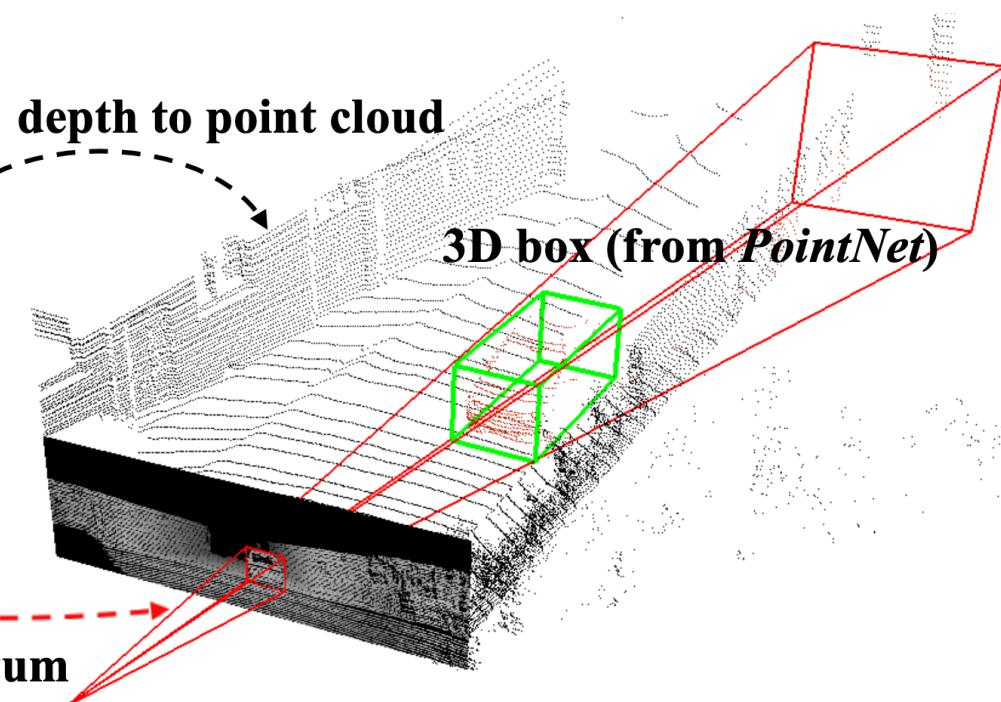
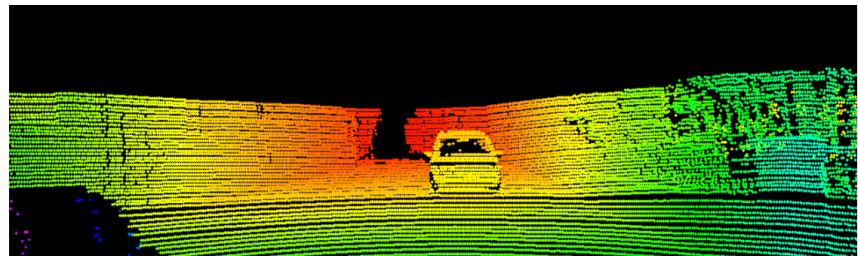
Topics Covered in This Course

- Recognition: Object classification



Topics Covered in This Course

- Recognition: Object detection



Topics Covered in This Course

- Recognition: multi-modality recognition foundation model

+ “in a large desert”

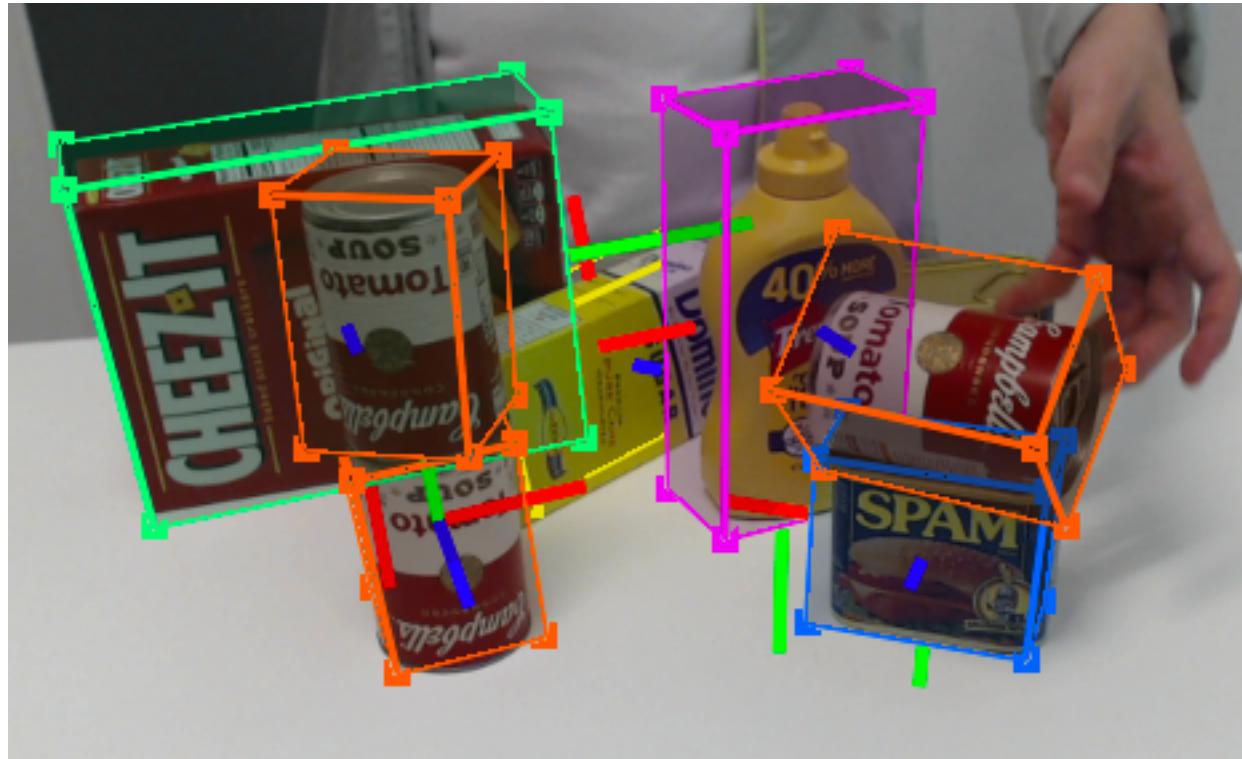


+ “in the woods”



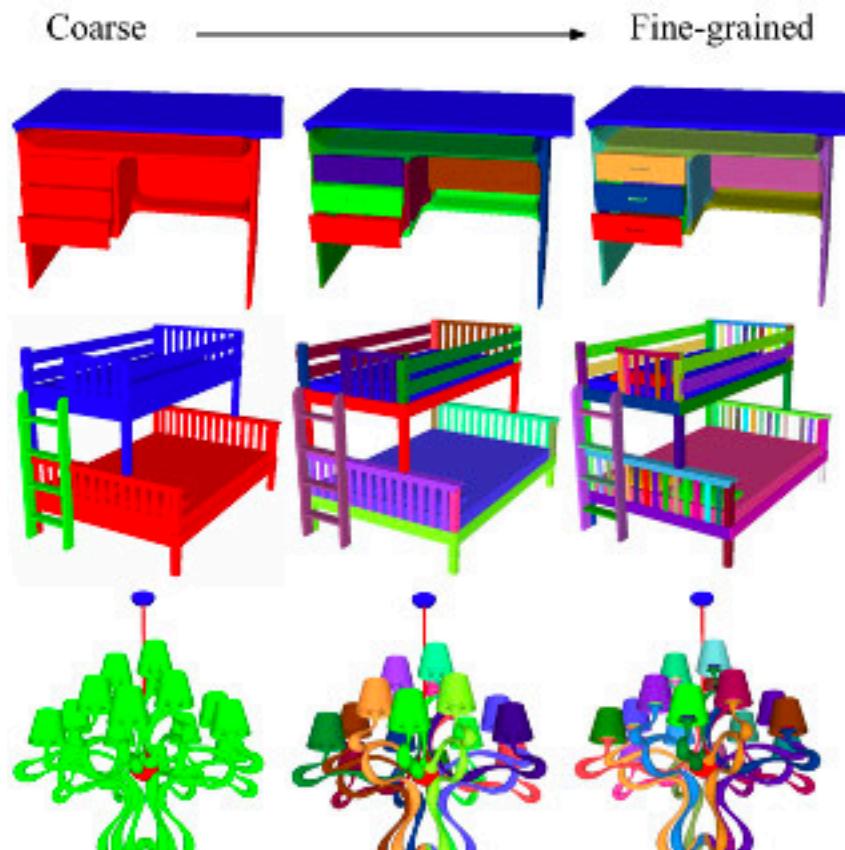
Topics Covered in This Course

- Recognition: 6D pose estimation

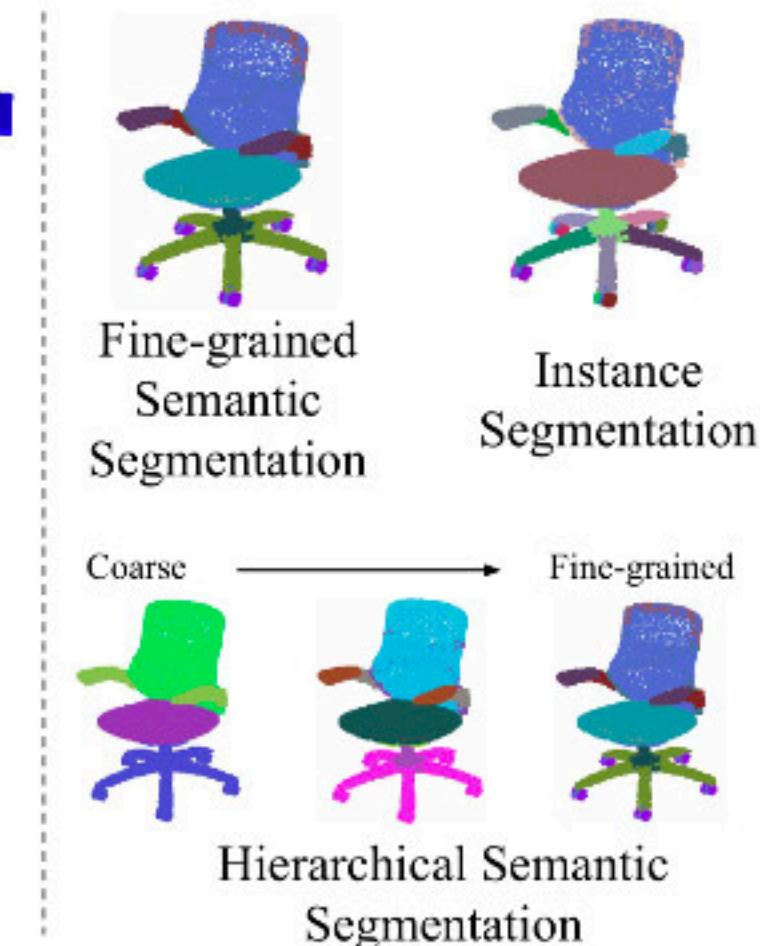


Topics Covered in This Course

- Recognition: Segmentation

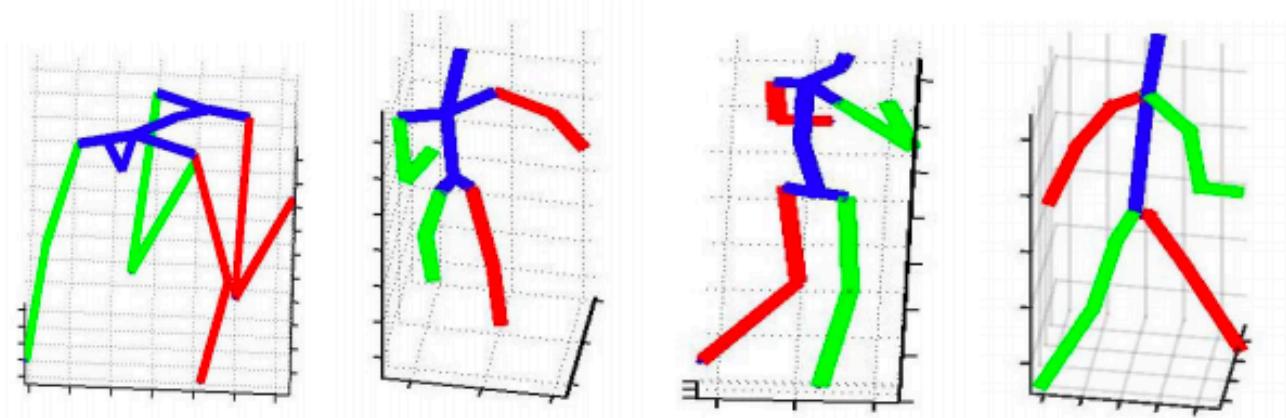
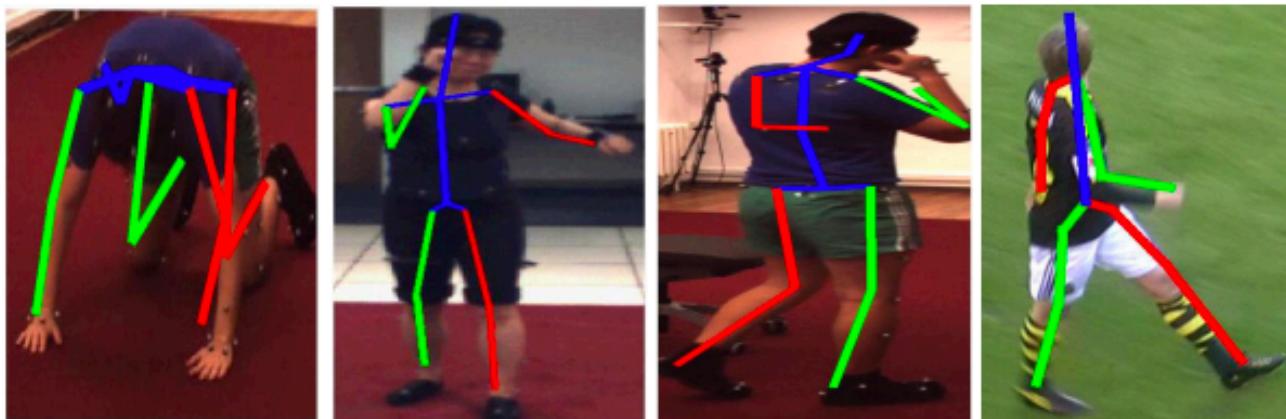


PartNet Dataset

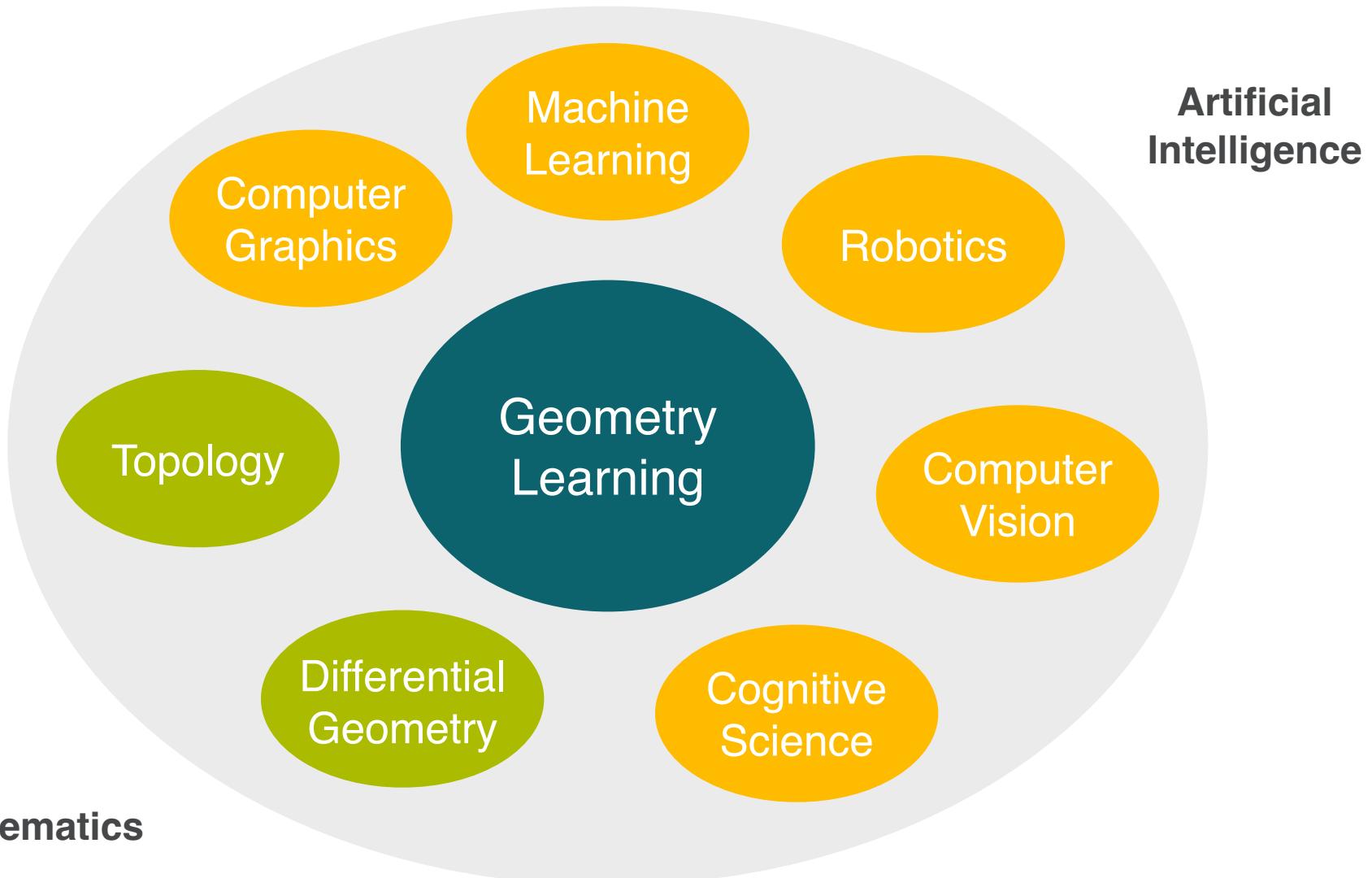


Topics Covered in This Course

- Recognition: Human pose estimation

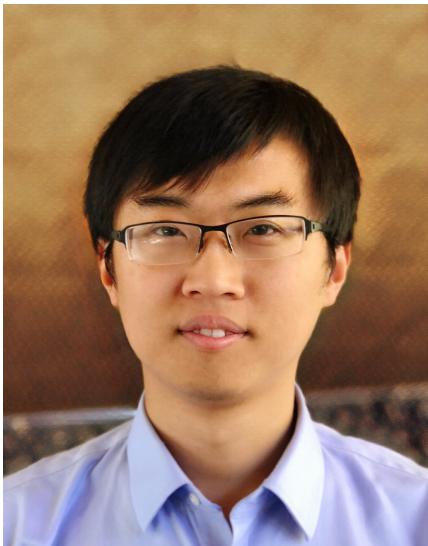


Highly Interdisciplinary Field



Course Logistic

Instructors



Instructor: Hao Su



TA: Yunhao Fang

Teaching Goal

- State-of-the-art
 - **Enable** you to read and replicate recent 3D learning papers in top CV/CG conferences
- Hands-on
 - **Heavy and competitive** programming assignments to exercise what are taught in class
- Foundational
 - Theory problems are **proof based**
 - Programming problems ask you to **implement low-level modules from scratch**

Pre-requisite: Technique

- **Skilled** in Linear Algebra
- **Familiar** with Multi-variable Calculus
- **Familiar** with Probability and Numerical Methods
- **Strong** programming skills
 - Familiar with Linux toolchain
 - Familiar with python, numpy, and pytorch
- Course/project experiences in computer vision or deep learning

Background Check

- On Piazza now (HW0)
 - Visible to enrolled and waitlist students
- 5 points in your final grade
- **Mandatory!** We will not grade your subsequent homeworks without seeing your HW0.
- If you are in the waitlist and intend to enroll, you need to submit HW0 by this deadline
- **Due: 10/3 23:59pm**

Pre-requisite: Resources

- This course requires deep learning resources (to run 3D recognition and reconstruction challenges)
- Unfortunately, we do not have computational resources to support the entire class
- Please find the server with the following configuration:
 - $\geq 50\text{G}$ disk space
 - ≥ 1 GPU with 10G memory

Google Colab satisfies the requirement most of the time

Assignments

- 4 assignments and 1 final project
 - HW0: 5 points
 - HW1: 30 points
 - HW2: 30 points
 - HW3: 35 points
 - No mid-term/final exams
- Extra credit for participation 5% (ask/answer questions in class, attend office hours)
- HW0-HW3: theory problems + programming
- Late policy: 15% grade reduction for each 12 hours late. No acceptance 72 hours after the due time.

Competitions

- HW2: 3D registration challenge
- HW3 (two tracks):
 - 3D recognition challenge
 - 3D reconstruction challenge
- Score is based on ranking and absolute performance
- According to past offering of the course, parameter tuning can be time-consuming for beginners of CV
- We estimate **>=15 hrs per week** (out of class) solid time commitment
- We allow you to see homework (through Piazza) and attend the competition *even if you audit the course*

Course Resources

- Course website: <https://haosulab.github.io/ml-meets-geometry/FA23/index.html> (Google “Hao Su” → Prof. Homepage → Teaching → this link)
 - Collaboration policy
 - Lecture slides
 - Office hour and location
- Piazza
 - Homework/Solution release
 - Discussions

Office Hour

- See course website

Lab Opening

- <https://cseweb.ucsd.edu/~haosu/opening.html>
-

Questions?

Curve

- Definition of curve
- Describing the shape of curves by calculus

Parameterized Curves

Intuition:

- A particle is moving in space
- At time t its position is given by

$$\gamma(t) = (x(t), y(t))$$

Example

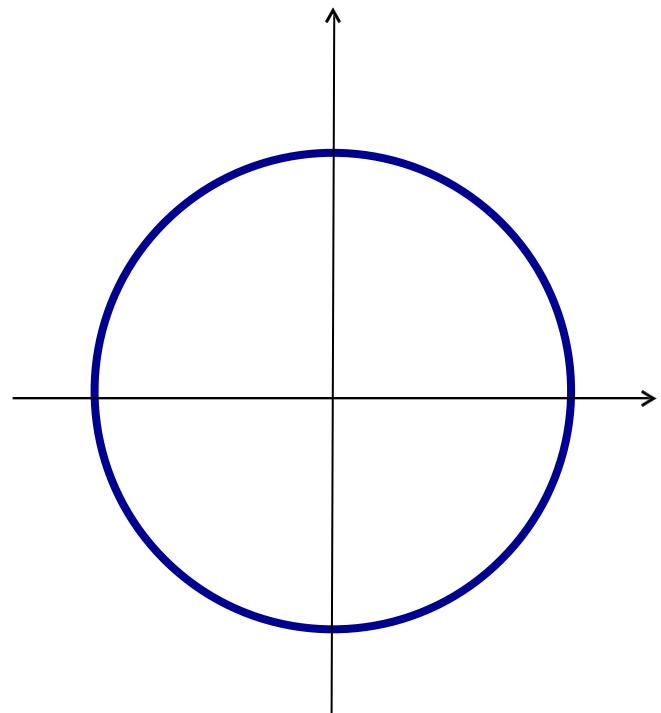
Explicit curve/circle in 2D

$$\mathbf{p} : \mathbb{R} \rightarrow \mathbb{R}^2$$

$$t \mapsto \mathbf{p}(t) = (x(t), y(t))$$

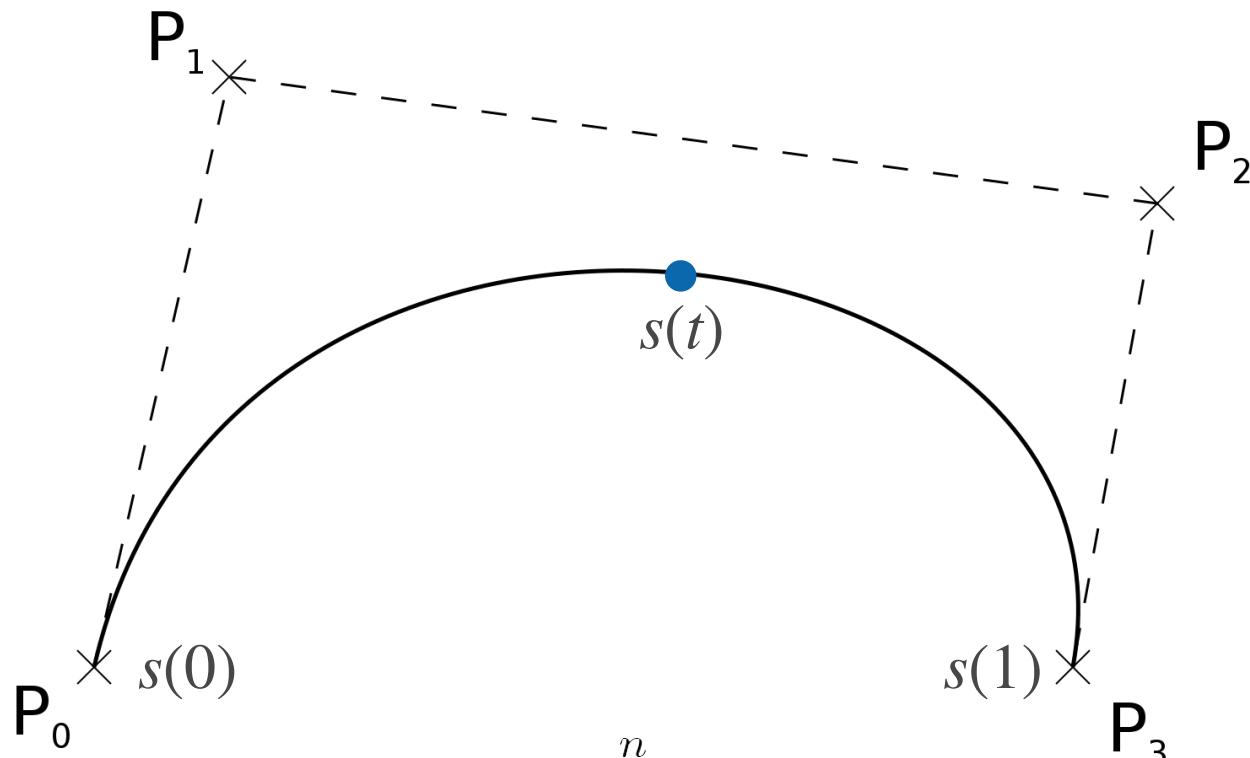
$$\mathbf{p}(t) = r (\cos(t), \sin(t))$$

$$t \in [0, 2\pi)$$



Application: Bezier Curves, Splines

- Smoothly “interpolate” between a set of points P_i
- Widely used in design (e.g., in your Powerpoint)



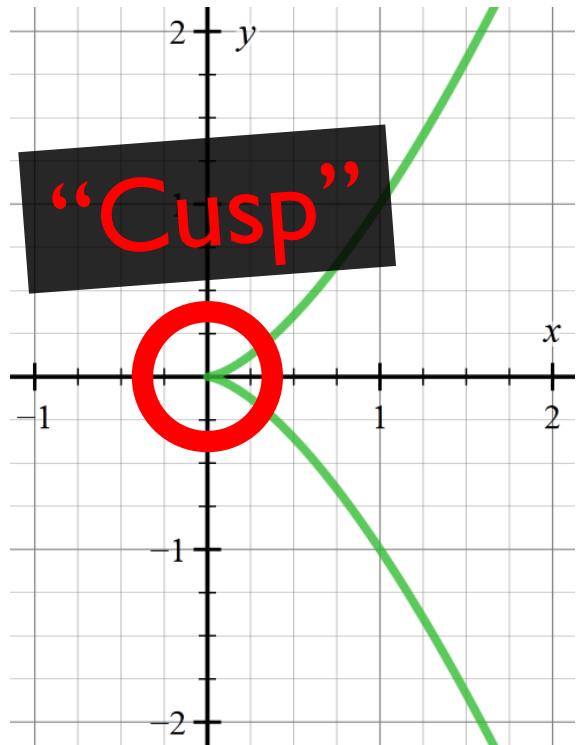
$$s(t) = \sum_{i=0}^n p_i B_i^n(t)$$

One-dimensional “Manifold”

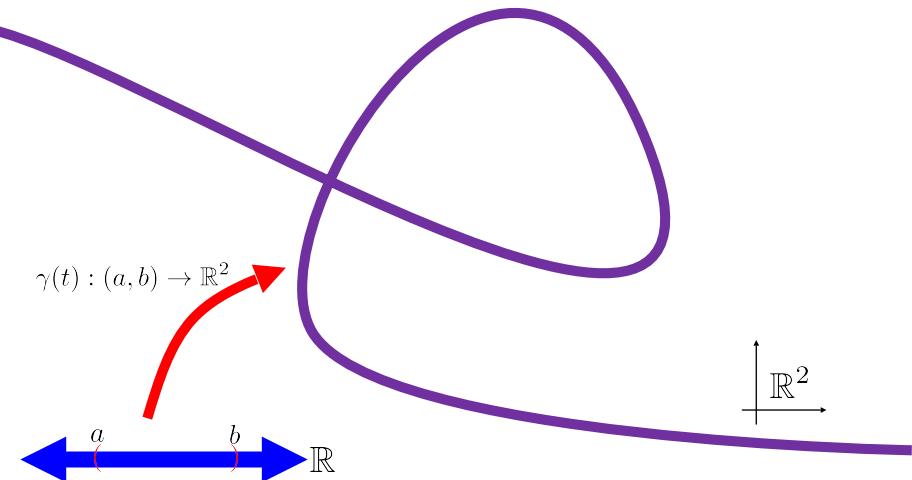


Set of points that locally looks like a line.

Negative Examples of Manifolds



$$f(t) = (t^2, t^3)$$

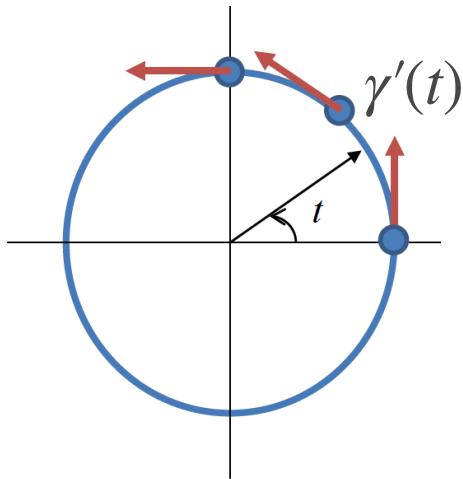


Tangent

- $\gamma'(t) = (x'(t), y'(t)) \in \mathbb{R}^2$ is the tangent vector of the curve at t

Quiz: Tangent of a Circle

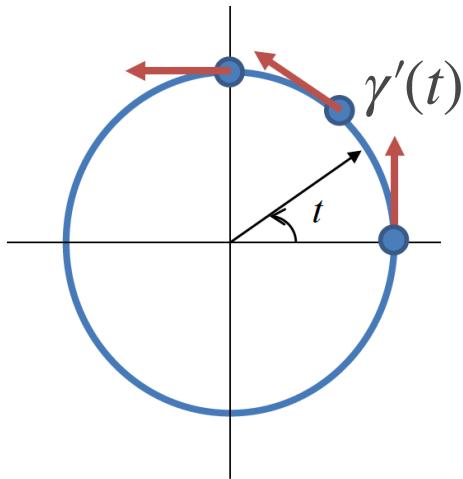
- $\gamma'(t) = (x'(t), y'(t)) \in \mathbb{R}^2$ is the tangent vector of the curve at t



$$\gamma(t) = (\cos(t), \sin(t))$$

Quiz: Tangent of a Circle

- $\gamma'(t) = (x'(t), y'(t)) \in \mathbb{R}^2$ is the tangent vector of the curve at t



$$\gamma(t) = (\cos(t), \sin(t))$$

$$\gamma'(t) = (-\sin(t), \cos(t))$$

$\gamma'(t)$ - direction of movement

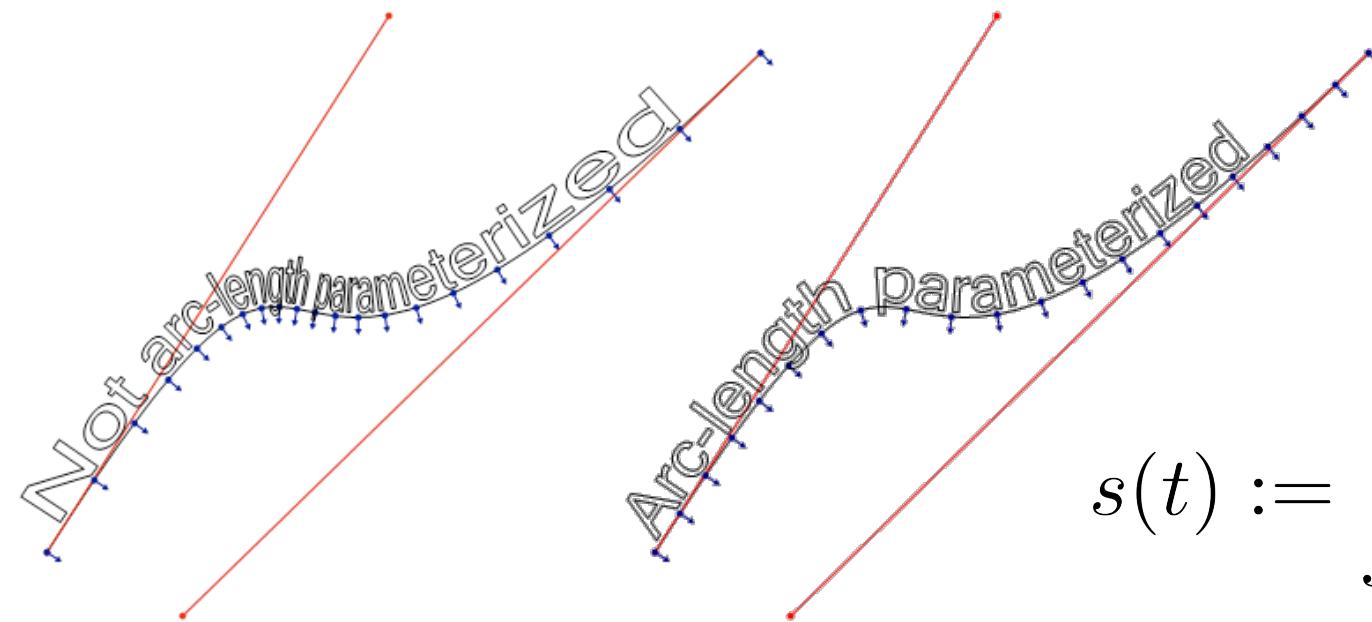
$\|\gamma'(t)\|$ - speed of movement

Arc Length

$$\int_a^b \|\gamma'(t)\| dt$$

Parameterization by Arc Length

<http://www.planetclegg.com/projects/WarpingTextToSplines.html>



$$s(t) := \int_{t_0}^t \|\gamma'(t)\| dt$$

$$t(s) := \text{inverse of } s(t)$$

$$\bar{\gamma}(s) = \gamma(t(s))$$

Constant-speed parameterization

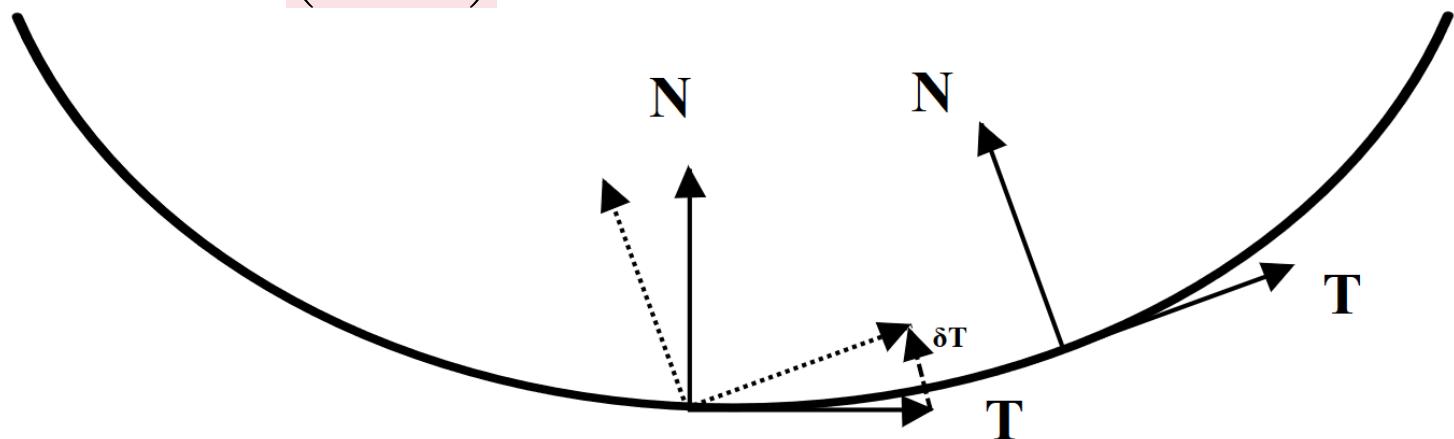
Moving Frame in 2D

$$T(s) := \gamma'(s)$$

\implies (on board) $\|T(s)\| \equiv 1$

$$N(s) := JT(s)$$

$$\begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}$$



Lemma

$$\frac{d}{ds} \langle u(s), v(s) \rangle = \left\langle \frac{du}{ds}, v \right\rangle + \left\langle u, \frac{dv}{ds} \right\rangle$$

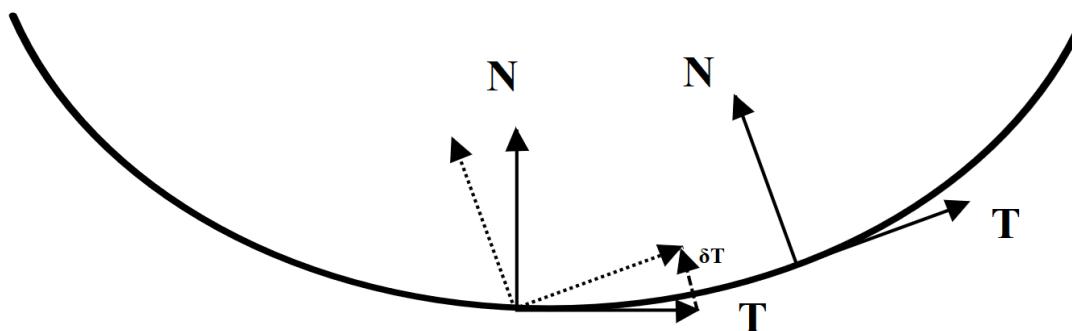
Derivation of $\|T(s)\| \equiv 1$

(See notes)

Turtles All The Way Down

On the board:

$$\frac{d}{ds} \begin{pmatrix} T(s) \\ N(s) \end{pmatrix} := \begin{pmatrix} 0 & k(s) \\ -k(s) & 0 \end{pmatrix} \begin{pmatrix} T(s) \\ N(s) \end{pmatrix}$$



https://en.wikipedia.org/wiki/Frenet%E2%80%93Serret_formulas

Use coordinates *from the curve* to express its shape!

$$\frac{d}{ds} \begin{pmatrix} T(s) \\ N(s) \end{pmatrix} := \begin{pmatrix} 0 & k(s) \\ -k(s) & 0 \end{pmatrix} \begin{pmatrix} T(s) \\ N(s) \end{pmatrix}$$

(See notes)

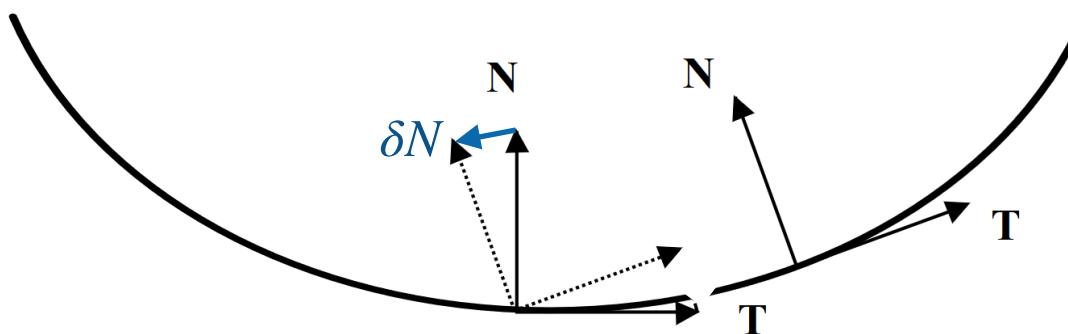
$$\frac{d}{ds} \begin{pmatrix} T(s) \\ N(s) \end{pmatrix} := \begin{pmatrix} 0 & k(s) \\ -k(s) & 0 \end{pmatrix} \begin{pmatrix} T(s) \\ N(s) \end{pmatrix}$$

(See notes)

Perspective of Normal Change

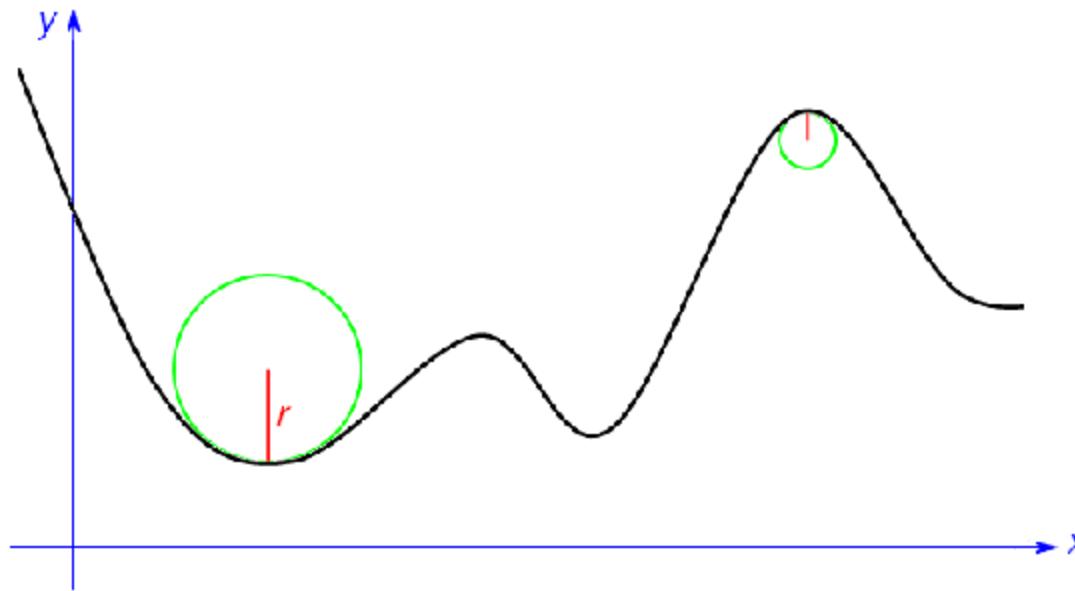
$$\mathbf{N}'(s) = -\kappa(s)\mathbf{T}(s)$$

- Curvature indicates how much the **normal** changes in the direction **tangent to the curve**



- Curvature is always positive

Radius of Curvature



$$r(s) := \frac{1}{k(s)}$$

Invariance is Important

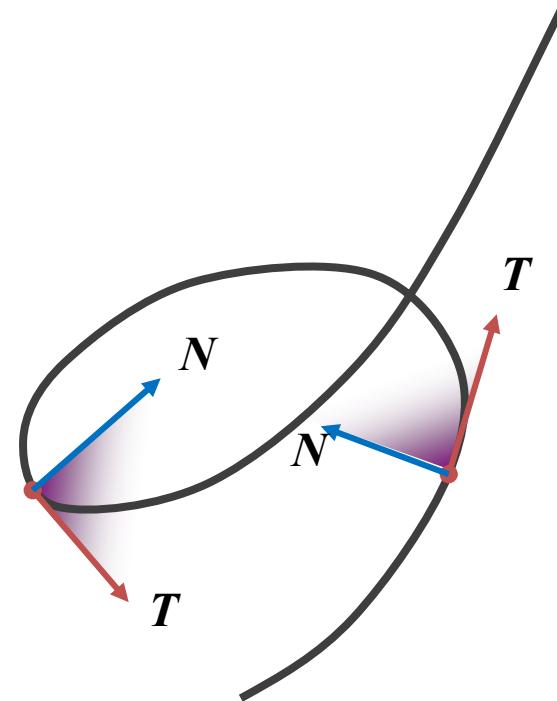
Fundamental theorem of the local theory of plane curves:

$\kappa(s)$ characterizes a **planar curve** up to rigid motion.

3D Curves

- Osculating Plane

The plane determined by the unit tangent and normal vectors $T(s)$ and $N(s)$ is called the *osculating plane* at s

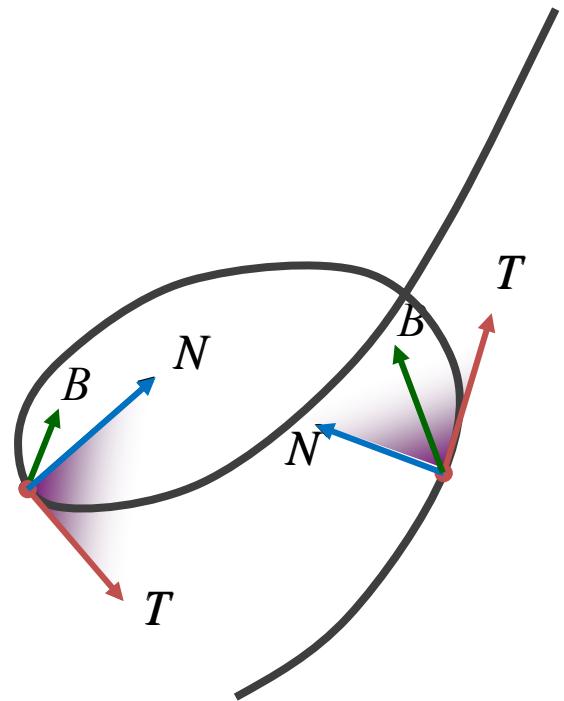


The Binormal Vector

For points s , s.t. $\kappa(s) \neq 0$, the *binormal vector* $B(s)$ is defined as:

$$B(s) = T(s) \times N(s)$$

The binormal vector defines the osculating plane



$$\mathbf{T}'(s)$$

- Already used it to define the curvature:

$$\mathbf{T}'(s) = \kappa(s) \mathbf{N}(s)$$

↑
Unit vector

- Orthogonal to $\mathbf{T}(s)$ (the same derivation as 2D curve)
- Since along the direction of $\mathbf{N}(s)$, also orthogonal to $\mathbf{B}(s)$

$$\mathbf{N}'(s)$$

We know: $\langle \mathbf{N}(s), \mathbf{N}(s) \rangle = 1$

From the lemma $\longrightarrow \langle \mathbf{N}'(s), \mathbf{N}(s) \rangle = 0$

(Derivative orthogonal to itself)

We know: $\langle \mathbf{N}(s), \mathbf{T}(s) \rangle = 0$

From the lemma $\longrightarrow \langle \mathbf{N}'(s), \mathbf{T}(s) \rangle = \langle -\mathbf{N}(s), \mathbf{T}'(s) \rangle$

From the definition $\longrightarrow \kappa(s) = \langle \mathbf{N}(s), \mathbf{T}'(s) \rangle$

$\longrightarrow \langle \mathbf{N}'(s), \mathbf{T}(s) \rangle = -\kappa(s)$

The Torsion

- From previous slide:

$$\langle \mathbf{N}'(s), \mathbf{N}(s) \rangle = 0$$

$$\langle \mathbf{N}'(s), \mathbf{T}(s) \rangle = -\kappa(s)$$

The remaining component of $\mathbf{N}'(s)$ is along $\mathbf{B}(s)$ direction:

$$\langle \mathbf{N}'(s), \mathbf{B}(s) \rangle = \tau(s)$$

Now we can express $N'(s)$ as

$$\mathbf{N}'(s) = -\kappa(s)\mathbf{T}(s) + \tau(s)\mathbf{B}(s)$$

Perspective of Normal Change

$$\mathbf{N}'(s) = -\kappa(s)\mathbf{T}(s) + \tau(s)\mathbf{B}(s)$$

- Curvature indicates how much the normal changes in the direction tangent to the curve
- Torsion indicates how much normal changes in the direction orthogonal to the osculating plane of the curve
- Curvature is always positive but torsion can be negative

$$\mathbf{B}'(s)$$

We know: $\langle \mathbf{B}(s), \mathbf{B}(s) \rangle = 1$

From the lemma $\rightarrow \langle \mathbf{B}'(s), \mathbf{B}(s) \rangle = 0$

We know: $\langle \mathbf{B}(s), \mathbf{T}(s) \rangle = 0, \langle \mathbf{B}(s), \mathbf{N}(s) \rangle = 0$

From the lemma \rightarrow

$$\langle \mathbf{B}'(s), \mathbf{T}(s) \rangle = \langle -\mathbf{B}(s), \mathbf{T}'(s) \rangle = \langle -\mathbf{B}(s), \kappa(s)\mathbf{N}(s) \rangle = 0$$

From the lemma \rightarrow

$$\langle \mathbf{B}'(s), \mathbf{N}(s) \rangle = \langle -\mathbf{B}(s), \mathbf{N}'(s) \rangle = -\tau(s)$$

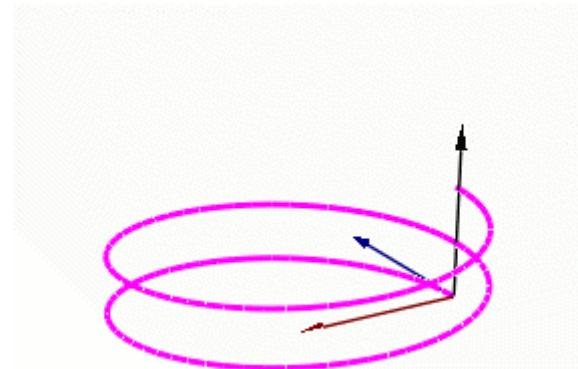
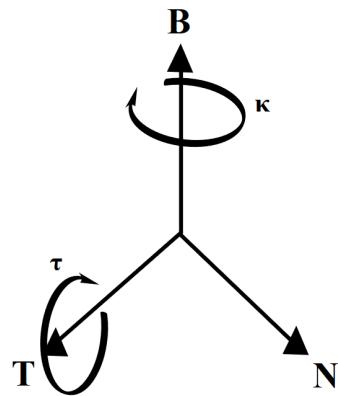
Now we express $\mathbf{B}'(s)$ as:

$$\mathbf{B}'(s) = -\tau(s)\mathbf{N}(s)$$

Frenet Frame: Curves in \mathbb{R}^3

- Binormal:
 - **Curvature:** In-plane motion
 - **Torsion:** Out-of-plane motion

$$\frac{d}{ds} \begin{pmatrix} T \\ N \\ B \end{pmatrix} = \begin{pmatrix} 0 & \kappa & 0 \\ -\kappa & 0 & \tau \\ 0 & -\tau & 0 \end{pmatrix} \begin{pmatrix} T \\ N \\ B \end{pmatrix}$$



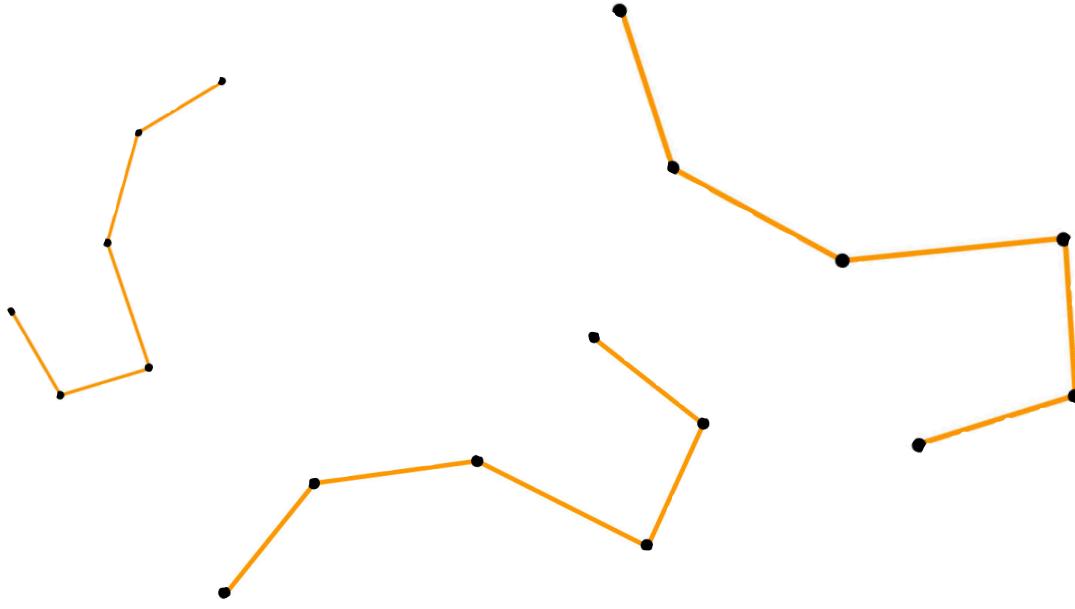
Self-reading

Fundamental theorem of the local theory of space curves:

Curvature and torsion
characterize a 3D curve up to
rigid motion.

Summary

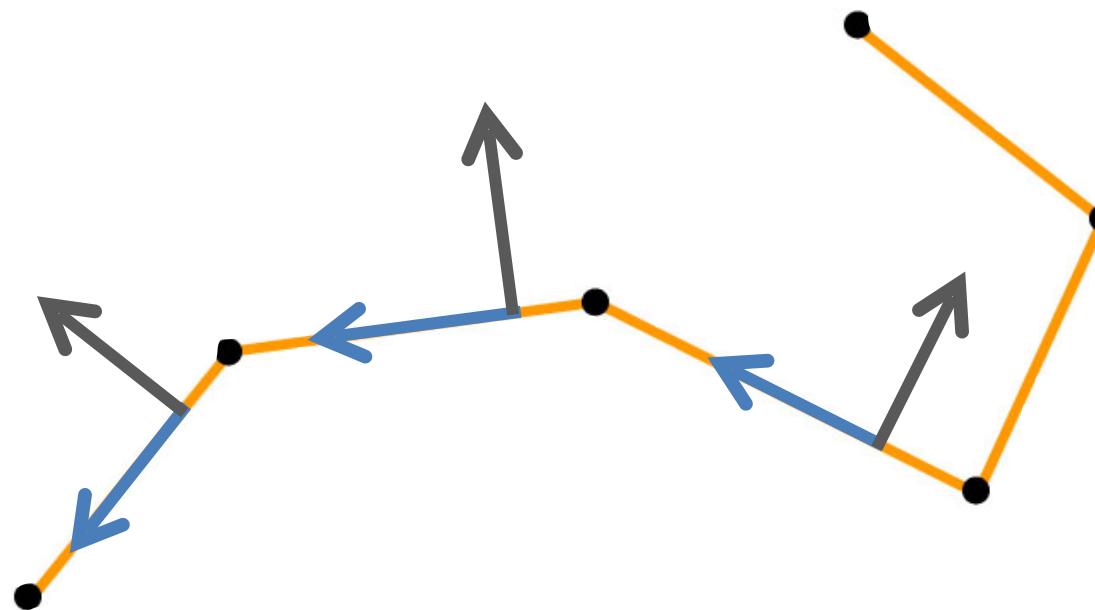
- Curve is a map from an interval to \mathbb{R}^n
- Tangent describes the moving direction
- The derivative of tangent under arc-length parameterization is normal
- Curvature (and torsion) both characterize the change of normal direction, uniquely describing the shape of a curve (up to rigid transformation)
- Tangent, normal, and binormal form a moving frame (Frenet frame)



Discrete Planar Curves

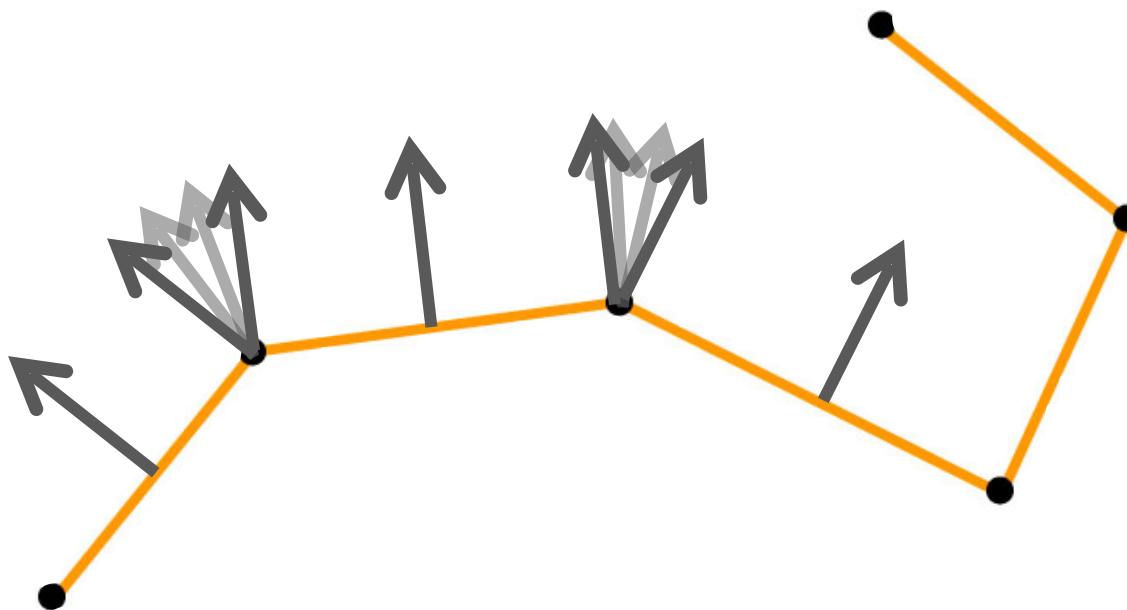
Tangents, Normals

- For any point on the edge, the tangent is simply the unit vector along the edge and the normal is the perpendicular vector



Tangents, Normals

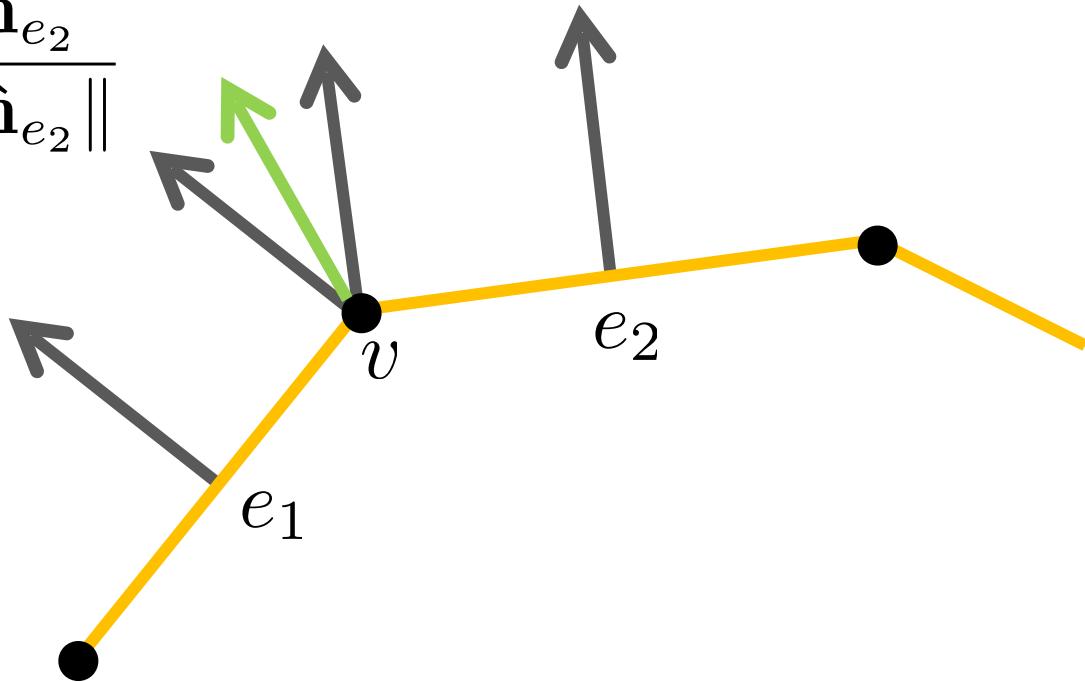
- For vertices, we have many options



Tangents, Normals

- Can choose to average the adjacent edge normals

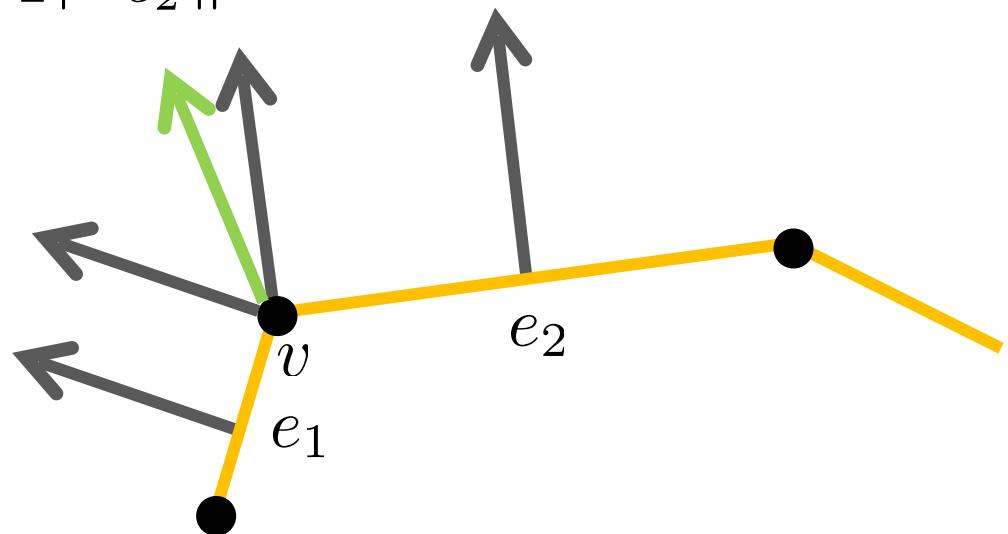
$$\hat{\mathbf{n}}_v = \frac{\hat{\mathbf{n}}_{e_1} + \hat{\mathbf{n}}_{e_2}}{\|\hat{\mathbf{n}}_{e_1} + \hat{\mathbf{n}}_{e_2}\|}$$



Tangents, Normals

- Weight by edge lengths

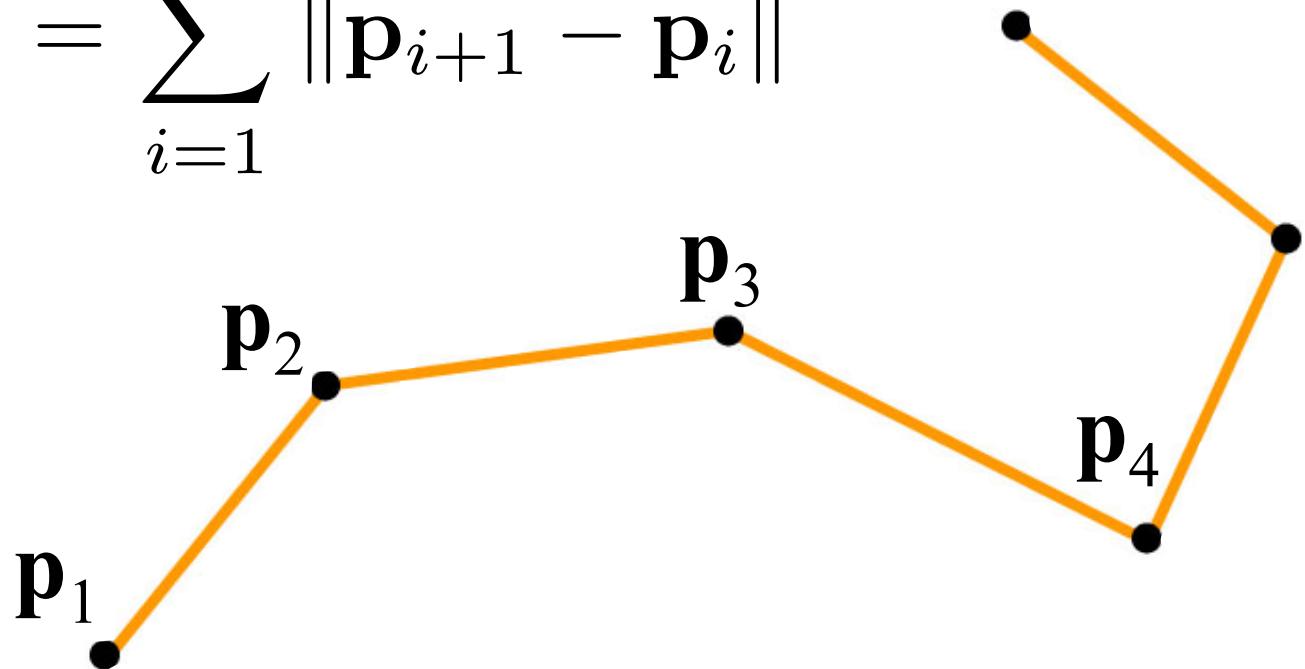
$$\hat{\mathbf{n}}_v = \frac{|e_1| \hat{\mathbf{n}}_{e_1} + |e_2| \hat{\mathbf{n}}_{e_2}}{\| |e_1| \hat{\mathbf{n}}_{e_1} + |e_2| \hat{\mathbf{n}}_{e_2} \|}$$



The Length of a Discrete Curve

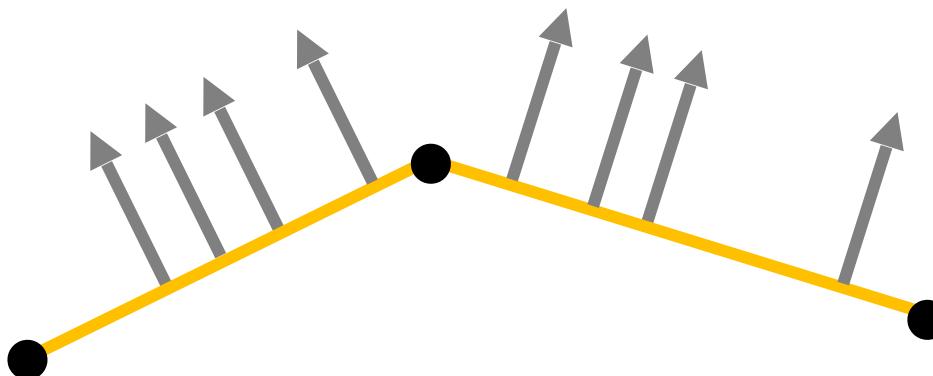
- Sum of edge lengths

$$\text{len}(p) = \sum_{i=1}^{n-1} \|\mathbf{p}_{i+1} - \mathbf{p}_i\|$$



Curvature of a Discrete Curve

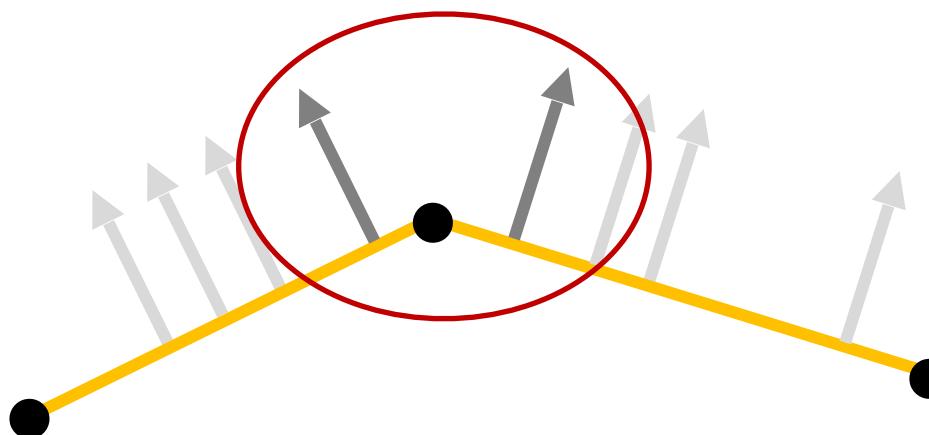
- Curvature is the change in normal direction as we travel along the curve



no change along each edge –
curvature is zero along edges

Curvature of a Discrete Curve

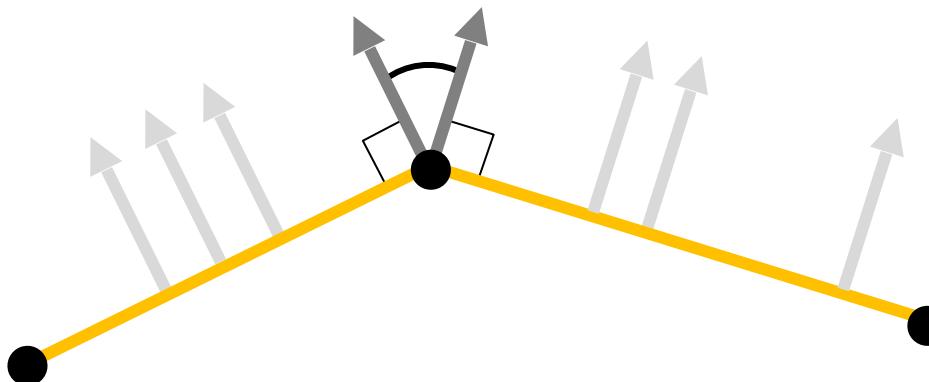
- Curvature is the change in normal direction as we travel along the curve



normal changes at vertices –
record the turning angle!

Curvature of a Discrete Curve

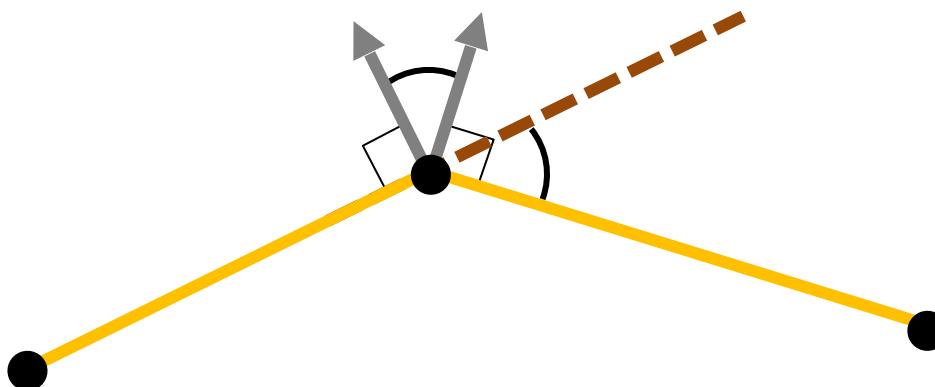
- Curvature is the change in normal direction as we travel along the curve



normal changes at vertices –
record the turning angle!

Curvature of a Discrete Curve

- Curvature is the change in normal direction as we travel along the curve



same as the turning angle
between the edges