Lecture 1:

# Introduction

FUNDAMENTALS OF COMPUTER GRAPHICS

## Animation & Simulation

Stanford CS248B, Fall 2022

PROFS. KAREN LIU & DOUG JAMES

# Animating Natural Phenomena

**A giant phantom jelly spotted with the ROV Doc Ricketts 990 meters deep in Monterey Bay**

https://twitter.com/MBARI_News/status/1465742426501312512

https://www.mbari.org/products/creature-feature/giant-phantom-jelly/

MBARI

# Course Logistics

# About Doug

**Affiliations:**
Stanford CS (ICME, CCRMA)
NVIDIA Research (Simulation)

**Expertise:**
Applied mathematics
Computer graphics & animation
Simulation & modeling
Computational physics
Acoustics
Fabrication

Doug L. James
STANFORD PROFESSOR, COMPUTER SCIENCE

BIO RESEARCH GROUP PUBLICATIONS TEACHING

## About Doug

Doug L. James is a Full Professor of Computer Science at Stanford University (since June 2015), and a member of Stanford's Center for Computer Research in Music and Acoustics (CCRMA) and the Institute for Computational and Mathematical Engineering (ICME). He holds three degrees in applied mathematics, including a Ph.D. in 2001 from the University of British Columbia. In 2002 he joined the School of Computer Science at Carnegie Mellon University as an Assistant Professor, and later became an Associate Professor of Computer Science at Cornell University (2006-2015). His research interests include computer graphics, computer sound, physically based modeling and animation, and reduced-order physics models. Doug is a recipient of a National Science Foundation CAREER award, and a fellow of both the Alfred P. Sloan Foundation and the Guggenheim Foundation. He received the ACM SIGGRAPH 2021 Computer Graphics Achievement Award, a 2012 Technical Achievement Award from The Academy of Motion Picture Arts and Sciences for "Wavelet Turbulence," and the 2013 Katayanagi Emerging Leadership Prize from Carnegie Mellon University and Tokyo University of Technology. He was the Technical Papers Program Chair of ACM SIGGRAPH 2015, and a consulting Senior Research Scientist at Pixar Animation Studios from 2015-2020. Since 2022 he has been a consulting Senior Research Scientist at NVIDIA.

**Doug L. James**
Professor of Computer Science and, by Courtesy, of Music

Stanford Profile

# Fracture Sound Synthesis

[SIGGRAPH 2010, SCA12]

# Regularized Kelvinlets

[de Goes and James 2017]

30 JULY – 3 AUGUST Los Angeles SIGGRAPH2017

## Elastic Deformations

Embedded geometry

Closed-form analytical displacements

$$\mathbf{u}(\mathbf{r}) = \left[\mathcal{A}(r)\mathbf{I} + \mathcal{B}(r)\mathbf{r}\mathbf{r}^\top\right]\mathbf{f}$$

# Magic Tricks! [James & Levin 2023]

# About Karen

**Affiliations:**
Stanford CS (HAI, ...)

**Expertise:**
Character animation and robotics
Computer graphics & animation
Simulation & modeling
Optimal control
Reinforcement learning
Computational biomechanics

# Course Staff

**Doug James**
[djames at stanford]

**Karen Liu**
[ckliu38 at stanford]

**Your fun and helpful TAs:**

**Connor Lin**

**Yifeng Jiang**

# Webpage

[Home] [Course Info] [Lectures/Readings] Welcome, Doug [Logout]

**Stanford CS248B, Fall 2022**

## Fundamentals of Computer Graphics:

# Animation and Simulation

This course provides a comprehensive introduction to computer graphics, focusing on fundamental concepts and techniques in Computer Animation and Physics Simulation. Topics include numerical integration, 3D character modeling, keyframe animation, skinning/rigging, inverse kinematics, rigid body dynamics, deformable body simulation, and fluid simulation.

## Basic Info

**Instructors:** **Doug James** and **Karen Liu**
**Time:** Tuesday and Thursday 1:30-2:50PM (First class on 9/27)
**Location:** Gates B3 (in person) and streamed live & recorded using Panopto (see links in Canvas)

See the **course info** page for more info on policies and logistics.

**https://cs248b.su.domains/autumn23/index.php/home**

# Webpage

- Main place to get course content, e.g., slides
- Students + staff can login to the webpage
  - TODO: Create an account
  - CODEWORD: **GFXISFUN**
- Comment feature:
  - Login to post + read slide comments
  - A great way to ask and answer slide-specific questions
  - Example from CS348B

# Comment Example: CS348B-S22 Image Synthesis

[Home] [Feed] [Course Info] [Lectures/Readings] [Admin Console] Welcome, **djames** [Logout]

## Lecture 14: Participating Media and Volume Rendering

**Download slides as PDF**

1 comment

4 comments

4 comments

3 comments

2 comments

1 comment

3 comments

6 comments

1 comment

# Comment Example: CS348B-S22 Image Synthesis

[Home] [Feed] [Course Info] [Lectures/Readings] [Admin Console]

## Participating Media and Volume Rendering

### Absorption: Lower Density

Walt Disney Animation Studios

Previous | Next --- Slide 6 of 47 Back to Lecture Thumbnails

**syhunter** How is the shape of the cloud generated? A noise function?

**djames** It could be procedural noise with artistic weighting. FYI, the dataset webpage is here and does not say:

https://www.disneyanimation.com/resources/clouds/

A google search led me to this survey of atmospheric cloud generation:

# Ed

- Online discussion forum
- Access link through Canvas
- Main place to ask questions

https://edstem.org/us/courses/47420/discussion

# SCPD Students

## Stanford Center for Professional Development (SCPD)

- This is a hybrid SCPD class
  - Both in-person and remote attendees.
- All lectures are recorded and available to all students
  - Available in Canvas (see "Panopto Course Videos")
- All lectures are live streamed with live chat
  - Please feel free to ask questions
  - Course staff will answer them

# Office Hours

- Staff OH will be available over Zoom
  - Convenient and safe
  - Zoom links can be found in Canvas
- Some staff OHs will be hybrid
- Updated office hours on the webpage
- Can ask me questions after class

- E.g., Prof James's office hours:
  - Mon, Wed 4-5pm on Zoom.

# COVID-19 Considerations

- Face coverings are recommended in the classroom
- We care about your health & safety
  - We want everyone to complete their studies safely
  - We want everyone to graduate and have productive careers
- We will provide opportunities for you to reduce your exposure and stay safe
- Please do not come to class if you feel unwell, or have been exposed, etc.
  - You do not need a note
- Please take advantage of our numerous accommodations:
  - Lecture recordings
  - Lecture live stream + chat
  - Slide and Ed discussions
  - Virtual office hours
- If you have any concerns, please contact us

# Tentative Syllabus

# Lectures + Projects

- 20 Lectures
- 4 Written Homeworks (40%)
  - HW1: Math foundations
  - HW2: Numerical integration
  - HW3: Rigid body dynamics and kinematics
  - HW4: Animation control
- 3 Programming Assignments (60%)
  - The fun part :)
  - Details in a moment
- No Final Exam!

# Part I

## with Prof. Doug James

## (weeks 1-5)

# Week 1: Introduction

- Math Foundations
  - Recap of mathematical and geometrical concepts
  - Leads to first written homework (HW1)
- Programming Warm-up
  - p5.js is a JavaScript library for creative coding
    - https://p5js.org
  - OpenProcessing (OP)
    - https://openprocessing.org
    - Everyone in the course will get an OP course account
    - Enables easy group collaboration and sharing of your results
      - With or without sharing code
      - So... we can try each other's simulations and ... play each other's games

# Programming Assignment #0: Hello OpenProcessing

https://openprocessing.org/sketch/2015244

- Short assignment to get up to speed on Open Processing
- Explore two things:
  1. Basic drawing commands
  2. Vector math operations using p5.Vector
- Take a look in the Open Processing class. Submit for feedback, or not.
- Friday Tutorial: Jifeng and Connor will Zoom+Record a tutorial section on Friday 3-4pm

# Week 2: Particle Systems

- Particle Systems
  - Dynamical systems
  - First- vs second-order motion models
  - Forces
  - Numerical integration schemes
- Collision Resolution Basics
  - Collision examples from animation (hair, cloth, rigid bodies, etc.)
  - Contact models; Position- vs velocity-level contact resolution
  - Contact conditions
  - Coefficient of restitution
  - Planar and nonplanar contact geometry
  - Signed distance fields (SDFs)

[Reeves 1983]

Lagoa

Nomination for best supporting actor:

# Signed distance fields (SDFs)

- Useful primitive for proximity queries (used in rendering, simulation, etc.)
- Definition: Let d(x) be the signed distance to a closed boundary/surface, where
  - d(x)<0 : x is inside the shape
  - d(x)=0 : x is on the shape
  - d(x)>0 : x is outside the shape
  - |d(x)| is the closest distance to the shape's boundary from x
- Analytical SDFs are know for many simple geometric shapes
  - 2D SDFs: https://iquilezles.org/articles/distfunctions2d
- Efficient evaluation for simulation and HW-accel. rendering
  - https://www.shadertoy.com/playlist/MXdSRf

# Programming Assignment #1: Simulating Pinball!

- Modify starter code to design your own virtual pinball game
- Robust collision processing using 2D SDFs
  - Ray-march SDFs for robust continuous collision checks
- Work alone or with a partner. Full creative control.
- Play each other's games on OpenProcessing (w/o sharing code)

Groovy Starter Code

# Fall 2022 Pinball Highlights

# Animating Deformable Models: Hair

Tangled [Disney]

Brave [Pixar]

Adaptive Nonlinearity for Collisions in Complex Rod Assemblies [Kaufman et al. 2014]

# Week 3: Collisions

- Collision Detection (CD) Methods
  - Broad vs narrow phase CD
  - All-pairs culling strategies
  - Primitive-level computations
  - Bounding volumes (fitting and evaluation)
  - Broad phase CD data structures
- Continuous collision detection methods
  - Discrete vs Continuous CD
  - CCD methods (2D, 3D)
  - Root finding schemes
    - Ray-marching SDFs (for pinball, of course)
  - Collision resolution strategies (conservative advancement, ...)

# Animating Deformable Models: Plastic Chairs

[James and Pai 2004]

# Animating Deformable Models: Sheet-based Cloth

# Animating Deformable Models: Yarn-level Cloth

[Kaldor et al. 2010]

[Kaldor et al. 2010]

# Animating Deformable Models: Blobs :)

[Zheng & James 2012]

# Week 4: Deformable Models

- Deformable Models in Animation
  - Examples from animation (hair, cloth, flesh, etc.)
  - Kinematic models
  - Constitutive force models
  - Numerical integration (stability and robustness)
  - Element inversion
- Robust Deformable Collision Processing
  - Detection vs resolution
  - Examples from cloth and hair simulation
  - Collision resolution schemes (impulses, penalty, etc.)
  - Untangling methods

[Bridson et al. 2002]

# OLD Animation Homework: Robust Collision Processing

- Code a 2D particle-based collision processor
- Make it robust to interpenetrations ... *at all cost!*

# OLD Animation Homework: Robust Collision Processing

# OLD Animation Homework: Robust Collision Processing

# OLD Animation Homework: Robust Collision Processing

# OLD Animation Homework: Robust Collision Processing

# Wait… real spaghetti has…

# More spaghetti

By Paul Liu (TA)

# CS348C-W19 HW3: Spaghetti Factory Results

Paul Liu (TA)

# Programming Assignment #2: Attack of the Blobs!

- Robust collision processing with 2D deformable models
- Components:
  - Explicit integration of 2D deformable models ("blobs")
  - Robust collision handling (both defo-rigid and defo-defo collisions)
- Theme: *Attack of the Blobs!*
  - Mechanically simulate *non-interpenetrating blobs* with point-edge collisions
  - Choose your favorite blobs (gummy bears, marshmallows, cells, balloons, etc.)
  - Bonus: Facial animation

Stanford CS 248B Fall 2022 – Programming Assignment #2

# Attack of the Blobs!

## Deformable Collision Processing

## Summary

In your second programming assignment you will simulate 2D deformable “blobs” and process collisions between them and with a rigid environment. Warning: There are going to be a LOT of blobs–see the title. So you will need to make your simulation not too slow (it needn’t run in real time), and also robust so that you don’t miss any collisions. Along the way, you will model and animate the dynamics of some lovely little deforming blobs filling up a sterile world (a.k.a. “Attack of the Blobs!”).

# Fall 2022 Results

# Week 5: Particle-based Fluids

Position Based Fluids [Macklin & Müller 2013]

# Week 5: Grid-based Fluids

Schrödinger's Smoke [Chern et al. 2016]

https://youtu.be/5C9BLAXCe1I?t=1m43s

# Part II

## with Prof. Karen Liu

## (weeks 6-10)

## Lecture 1:

# Introduction

FUNDAMENTALS OF COMPUTER GRAPHICS

## Animation & Simulation

## Stanford CS248B, Fall 2022

# Week 6: Rigid Body Simulation

- 3D position and 3D orientation
- Rigid-body dynamics
- Collisions and constraints
- Articulated rigid bodies

# 3D position

# 3D orientation

# Rigid body simulation

- Objects that translate and rotate freely in 3D without deformation.
- Satisfy Newton-Euler equations.
- Contact and collision need to be handled through forces.

# Rigid body simulation

Furguson et al SIGGRAPH 2021

# Week 7: Character Modeling

- Human skeletal systems
  - Hierarchical transformations
  - Parameterization of human kinematics
- Skinning
  - Deformation of human body
  - Shape interpolation
  - Skeleton subspace and pose space deformation
  - Data-driven approach

# What's a compact representation for human poses?

# Simulate human as articulated rigid bodies

# Skinning

skinning parameters

$$\mathbf{p} = f(\mathbf{q}; \boldsymbol{\theta})$$

body shape

skeleton pose

# How do we control human motion?

physics without control

physics with control

neural excitation
muscle activation
joint torque
physics sim
external forces
skeleton pose

neural excitation
muscle activation
dynamics
joint torque
physics sim
kinematics
skeleton pose

neural excitation

muscle activation

joint torque

physics sim

skeleton pose

**“walk over there, don’t fall”**

trajectory

abstract goal

neural excitation
muscle activation
naturalness
generality
joint torque
physics sim
skeleton pose
trajectory
abstract goal

neural excitation
muscle activation
joint torque
physics sim
skeleton pose
Kinematic approach to motion synthesis
trajectory
abstract goal

# Week 8: Inverse Kinematics and Keyframes

- Inverse kinematics
  - IK constraints
  - Efficient computation for Jacobian matrix
  - Solving IK as a non-linear optimization
  - Heuristics-based IK methods
- Keyframe animation
  - Interpolation using cubic curves
  - Interpolating multiple keyframes using splines
  - Properties of splines

# Human kinematics

kin·e·mat·ics

/ˌkinəˈmadiks/

*noun*

the branch of mechanics concerned with the motion of objects without reference to the forces which cause the motion.

- the features or properties of motion in an object.
  plural noun: **kinematics**

# Forward kinematics

$$\mathbf{q} = x, y, z, \theta, \phi, \sigma, \theta_{thigh}, \phi_{thigh}, \sigma_{thigh}, \theta_{knee}, \theta_{ankle}, \phi_{ankle}, \cdots$$

Given a pose **q**, what is the 3D position of the finger tip in the world coordinate frame?

# Inverse kinematics

$$\mathbf{q} = x, y, z, \theta, \phi, \sigma, \theta_{thigh}, \phi_{thigh}, \sigma_{thigh}, \theta_{knee}, \theta_{ankle}, \phi_{ankle}, \cdots$$

Given the target 3D position of the finger tip in the world coordinate frame, what is the pose **q**?

# Keyframe animation

# Keyframe animation

# Interpolation

**Linear**

**Cubic**

**Cosine**

**Hermite**

# Week 9: Animation Techniques

- Data-driven and ML-based character animation
  - Motion graphs
  - Learning-based motion matching
  - Generative models for kinematic motion
- Physics-based character animation
  - Feedback control
  - Trajectory optimization
  - Reinforcement learning

# Motion graphs

# Neural motion synthesis

2021 2022 2023

Human dance dataset

A generative dance model to imitate human motor skills and musicality in dance

Tseng et al CVPR 2023

Tseng et al CVPR 2023

Egocentric Video

Li et al CVPR 2023

Li et al, SIGGRAPH Asia 2023

neural excitation
muscle activation
joint torque
physics sim
skeleton pose
Dynamic approach with joint actuation
trajectory
abstract goal

# Control human motion

# Physics simulation

# Control a dynamic system

# Control a dynamic system

# Tracking human motion

Liu et al SIGGRAPH 2012

# Trajectory optimization

$$\min_{\boldsymbol{\tau},\boldsymbol{q}} \sum \boldsymbol{\tau}^2 + C_{task}(\boldsymbol{q})$$

subject to

$$\ddot{\boldsymbol{q}} = f_{skelDyn}(\boldsymbol{q}, \dot{\boldsymbol{q}}, \boldsymbol{\tau})$$

$$\boldsymbol{\tau}_{low} \leq \boldsymbol{\tau} \leq \boldsymbol{\tau}_{high}$$

$$\boldsymbol{q}_{low} \leq \boldsymbol{q} \leq \boldsymbol{\tau}_{high}$$

# Trajectory optimization

$$\min_{\boldsymbol{\tau},\boldsymbol{q}} \sum \boldsymbol{\tau}^2 + C_{task}(\boldsymbol{q})$$

subject to

$$\ddot{\boldsymbol{q}} = f_{skelDyn}(\boldsymbol{q}, \dot{\boldsymbol{q}}, \boldsymbol{\tau})$$

$$\boldsymbol{\tau}_{low} \leq \boldsymbol{\tau} \leq \boldsymbol{\tau}_{high}$$

$$\boldsymbol{q}_{low} \leq \boldsymbol{q} \leq \boldsymbol{\tau}_{high}$$

Tan et al SIGGRAPH 2012

# Reinforcement learning

Learn a control policy that maps a state to an action…

…such that $\mathcal{J}(\tau) = \mathbb{E}_{\tau \sim p_\tau}[\sum_{t=0}^{\infty} \gamma^t r(s_t, a_t)]$ is optimized.

# Reinforcement learning

Learn a control policy that maps a state to an action…

…such that $\mathcal{J}(\tau) = \mathbb{E}_{\tau \sim p_\tau}[\sum_{t=0}^{\infty} \gamma^t r(s_t, a_t)]$ is optimized.

# Reinforcement learning

Learn a control policy that maps a state to an action…

…such that $\mathcal{J}(\tau) = \mathbb{E}_{\tau \sim p_\tau}[\sum_{t=0}^{\infty} \gamma^t r(s_t, a_t)]$ is optimized.

# Reinforcement learning

actuated degrees of freedom

# Uncontrolled dynamic system

Tan et al SIGGRAPH 2014

Tan et al SIGGRAPH 2014

Tan et al SIGGRAPH 2014

Tan et al SIGGRAPH 2014

# Deep reinforcement learning

First, we have a target speed task,

neural excitation
muscle activation
Dynamic approach with muscle actuation
joint torque
physics sim
skeleton pose
trajectory
abstract goal

# Week 10: Final Week

- Musculoskeletal animation
- Future directions in visual computing
- Guest lecture from the graphics industry

# Muscle activation

# Muscle activation

- Model and simulate dynamics of muscles and tendons, in addition to skeleton dynamics
- As muscles contract, they pull the attached bones to generate torques around joints
- Parameters for muscles and tendons can be obtained from biomechanics experiments
- Muscle activation becomes the control variables instead of joint torques

# Control muscle activation

Wang et al SIGGRAPH 12

Nakada et al SIGGRAPH19

# Learning muscle activation

Learning **without** reference motion

Learning **with** reference motion

# Week 10: Final Week

- Musculoskeletal animation
- Future directions in visual computing
- Guest lecture from the graphics industry

# Visual Computing Track

**Undergraduate Major in Computer Science**
**Stanford University**

**(For MSCS, see the Visual Computing Specialization)**

# Visual Computing Track NEW!

Starting Fall 2022, the CS department will introduce a new Track, “Visual Computing”, which is a specialization at the intersection of AI/ML, Graphics, and Systems. “Visual Computing Track” takes a broader view than the former “Graphics Track” by giving students the increased flexibility to decide what areas of visual computing they want to focus on.

Creating, manipulating, and interpreting visual information (images, videos, 3D geometry, and simulated virtual worlds) is pervasive in modern computing. Today, we see “visual computing” play a huge role in applications ranging from entertainment (games, CGI for TV and film), digital imaging (smartphone cameras, AR/VR capture, scientific imaging), robotics (driver assistance, autonomous vehicles, health-care robotics), engineering, and commerce. The visual computing track aims to give students the background needed to master the fundamental techniques of visual computing and to advance the development of new visual computing techniques and applications.

You can find all the details about the Visual Computing Track here, including the course requirements, possible curriculum paths, changes to the former Graphics Track and more.

If you have any questions, please email Kayvon, Doug, or Karen.

# Visual Computing Track NEW!

**Principles of the Visual Computing track's design: (compared to the old graphics track)**

- Take a broader view of visual computing than the former "Graphics" track by giving students the increased flexibility to decide what areas of visual computing they want to focus on, regardless of whether that focus is AI/ML heavy, "traditional graphics" heavy, or systems heavy.
- Make the track attractive to a broad range of students:
  - Reduce friction by providing students the ability to "start" the track within any quarter.
  - Allow track credit for AI/ML-centric methods courses, since those techniques play a big part in modern computer graphics. (We believe some AI track students would be better served as visual computing track students since they are already focused on applying AI/ML to visual computing applications.)
  - Design an elective system that gives students the ability to get track credit for courses that are highly relevant to modern visual computing, and that they are likely to take anyway.

# Visual Computing Track

NEW!

## Track Requirements

### TL;DR

In addition to the standard CS core, students must take seven courses from the offerings listed in Tier 1, Tier 2, or Tier 3 of the track. Of these seven:

- At least two courses must be from Tier 1 (Visual Computing Core)
- At least five courses must be from Tier 1 or 2 (Visual Computing Core or Depth)
- One of the courses used to satisfy the Tier 3 (Visual Computing Elective) requirement can be any course from the general CS elective pool.

# Visual Computing Track

NEW!

## Tier 1: Fundamentals Courses

Students are required to take at least two Tier 1 courses (in any order).

- CS248A - Computer Graphics: Rendering, Geometry, and Image Manipulation (Winter)
- CS248B - Computer Graphics: Animation, Simulation, Optimization (Fall)
- CS231N - Deep Learning for Computer Vision (Spring)

**Faculty rationale for Tier 1's design:**

- We want students to have technical foundations in at least one "modeling the visual world" course (248-level), but the track is not opinionated about whether that should be focused on rendering/image processing or animation/simulation/optimization.
- We wanted to present a schedule where one of the fundamentals courses is offered each quarter. Therefore, students can "start" the Tier 1 part of the track with a fundamentals course at any time.
- We anticipate that two courses listed under Tier 3 electives (CS148 and CS131) will serve as important "feeder" courses to the visual computing track. Students will be able to get track credit for those courses, but not Tier 1 credit. Please see the comments in the Tier 3 section.

# Visual Computing Track

NEW!

## Tier 2: Depth Courses

Tier 2 courses give students the opportunity to conduct detailed study of visual computing topics. Tier 2 courses provide technical depth that builds upon the fundamentals established in Tier 1.

Students must take at least two Tier 2 courses. Three Tier 2 courses are required if a student only takes two courses from Tier 1.

- CS205L - Continuous Mathematical Methods with an Emphasis on Machine Learning (Winter)
- CS223A - Introduction to Robotics (Winter)
- CS231A - Computer Vision, From 3D Reconstruction to Recognition (Winter)
- CS233 - Geometric and Topological Data Analysis (Spring)
- CS348B - Computer Graphics: Image Synthesis Techniques (Spring)
- CS348C - Computer Graphics: Animation and Simulation (Winter)
- CS348E - Character Animation: Modeling, Simulation, and Control of Human Motion (Spring)
- CS348K - Visual Computing Systems (Spring)
- CS348I - Computer Graphics in the Era of AI (Fall)
- CS348N - Neural Models for 3D Geometry (Winter)
- CS448I - Computational Imaging (also EE 367) (Winter)
- EE267 - Virtual Reality (Spring)

# Visual Computing Track

NEW!

## Tier 3: Track Electives

Students may count up to two Tier 3 courses to the seven course requirement of the track. Students may also count up to one 1 general CS course as a Tier 3 course toward this requirement.

Tier 3 electives aim to give students the opportunity to count a wide variety of courses toward the track. These might be courses that are “funnel courses” that introduce fundamentals, but don’t have the technical or implementation rigor to receive Tier 1 classification, courses that are not specific to visual computing but teach relevant techniques, or advanced special topics in visual computing.

Introductory courses that serve to bring students into the track:

- CS148 - Introduction to Computer Graphics and Imaging
- CS131 - Computer Vision: Foundations and Applications

Courses teaching fundamental techniques of high relevance to advanced visual computing methods and applications:

- CS149 - Parallel Computing
- CS221 - Artificial Intelligence: Principles and Techniques
- CS229 - Machine Learning
- CS230 - Deep Learning
- CS236 - Deep Generative Models
- CS236G - Generative Adversarial Networks (GANs)
- EE261 - The Fourier Transform and its Applications

Advanced special topics:

- CS331B - Interactive Simulation for Robot Learning (Spring)
- CS448B - Data Visualization
- CS448M - Making Making Machines for Makers
- CS448Z - Physically Based Animation and Sound

# Visual Computing Track

NEW!

## Example Student Paths

Here is the list of Tier 1 and Tier 2 courses sorted and **colored** by the quarter they are offered.

| Autumn | Winter | Spring |
|---|---|---|
| • CS 248B: Computer Graphics: Animation, Simulation, Optimization<br>• CS 348I: Computer Graphics in the Era of AI | • CS 248A: Computer Graphics: Rendering, Geometry, Image Manipulation<br>• CS 205L: Continuous Mathematical Methods<br>• CS 223A: Introduction to Robotics<br>• CS 231A: Computer Vision, from 3D Reconstruction to Recognition<br>• CS 348C: Animation and Simulation<br>• CS 348N: Neural Models for 3D geometry<br>• CS 448I: Computational Imaging (EE367) | • CS 231N: Deep Learning for Computer Vision<br>• CS233: Geometric and Topological Data Analysis<br>• EE 267: Virtual Reality<br>• CS 348B: Image Synthesis Techniques<br>• CS 348E: Character Animation<br>• CS 348K: Visual Computing Systems |

Students can create different paths to satisfy Tier 1 and Tier 2 requirements based on their own interests. Below we show some examples of curriculum paths:

# Visual Computing Track

NEW!

## Canonical Visual Computing Path

# Visual Computing Track

NEW!

## Traditional Computer Graphics Path

# Visual Computing Track

NEW!

## Traditional Computer Graphics Path

# Visual Computing Track

NEW!

## Rendering/Geometry Specialization Paths

CS 248A → CS 231N → CS 348I → CS 348N → CS 348B

or

CS 248A → CS 231N + CS 348B → CS 348N → CS 348K

# Visual Computing Track

NEW!

## Animation/Robotics Specialization Path