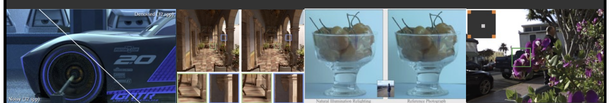
Sampling and Reconstruction of Visual Appearance: From Denoising to View Synthesis

CSE 274 [Fall 2022], Lecture 1

Ravi Ramamoorthi

http://www.cs.ucsd.edu/~ravir



1

Motivation: High-Dim. Appearance

Appearance in vision/graphics involves high-dimensional data

- **(Precomputed) Real-Time Rendering:** Light transport matrix stores variation across surface, light, view (4D-6D)
- **Monte Carlo Rendering:** Need to sample across time, light source, depth of field for each pixel (3D-7D)
- **Appearance Acquisition:** Acquire reflectance functions and light transport (4D-8D)
- **View Synthesis:** Predict new views or light field (4D)
- **Computer Vision:** Effect of lighting on images (4D)

Consider real-time rendering (6D): With ~100 samples/dimension ~ 10^{12} samples total!! : Intractable computation, rendering

2

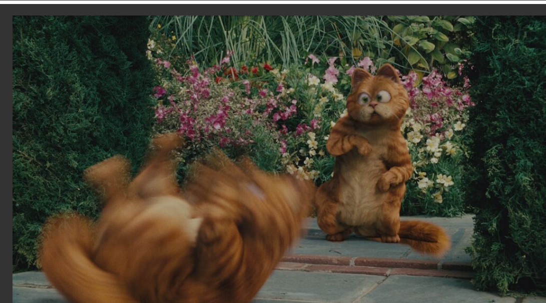
Instructor

Ravi Ramamoorthi http://www.cs.ucsd.edu/~ravir

- PhD Stanford, 2002 [with Pat Hanrahan, 2020 Turing Award] "*Spherical Harmonic Lighting*" widely used in games (e.g. Halo series), movies (e.g. Avatar), etc. (Adobe, …)
- At Columbia 2002-2008, UC Berkeley 2009-2014
- *"Monte Carlo denoising"* inspired raytracing offline, real-time
- At UCSD since Jul 2014: Director, Center for Visual Computing
- Awards for research: White House PECASE (2008), SIGGRAPH Significant New Researcher (2007), ACM Fellow
- https://www.youtube.com/watch?v=qpyCXqXGe7I
- *Key contributions in view synthesis (NeRFs ECCV 20)*
- *Key contributions in Monte Carlo denoising, consult NVIDIA*

3

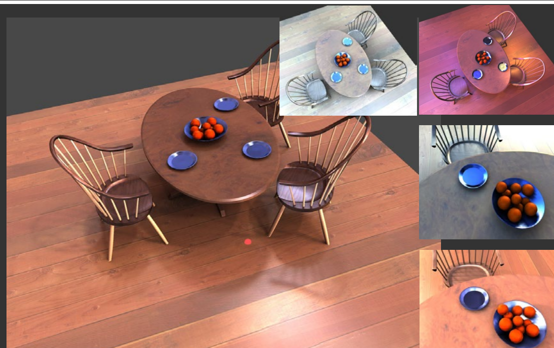
Fast Motion Blur Rendering (3D)



Garfield: A Tail of Two Kitties
Rhythm & Hues Studios
Twentieth Century-Fox Film Corporation

4

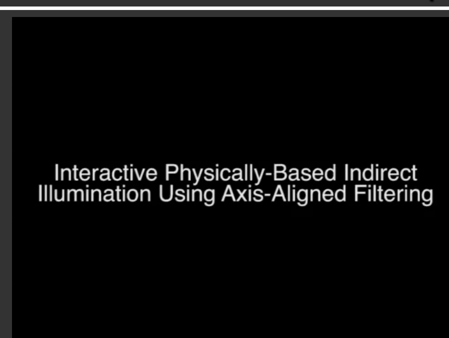
Precomputed Real-Time Rendering (6D)



Ng, Ramamoorthi, Hanrahan 03,04

5

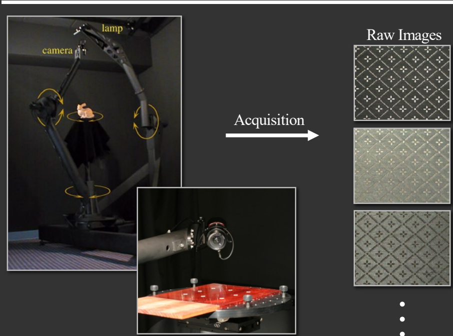
Real-Time Global Illumination (4D)



[Mehta, Wang, Ramamoorthi, Durand13]

6

Data-Driven Appearance Models (6D)



Stanford/Cornell Graphics Labs

Lawrence et al. 06

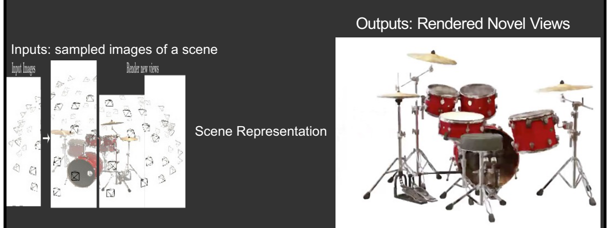
7

Volumetric Materials (Gigavoxels)

[Hasan and Ramamoorthi 13]

8

Novel View Synthesis Problem



Mildenhall et al. 20

9

Lighting-Insensitive Recognition

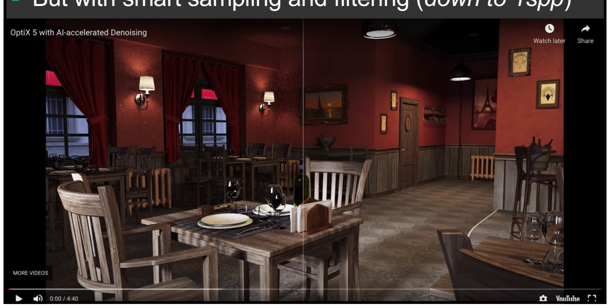
Illuminate subject from many incident directions
Understand space of images as lighting is varied
Low Dimensional Subspace [Ramamoorthi 02]

Debevec *et al.* 00

10

Sparse Sampling, Reconstruction

- Same algorithm as offline Monte Carlo rendering
- But with smart sampling and filtering (*down to 1spp*)



11

Overview

Many problems in graphics, vision are hard to solve directly
- ***Visual appearance*** is high-dimensional
- High sampling rate, computational cost
- Often prohibitive to even sample before compression

Mathematical and signal-processing approach
- Treat illumination and reflection functions as signals
- Exploit "sparsity" for acquisition of light transport and appearance
- *Reduces to efficient **sampling and** high quality **reconstruction***

Large range of applications in graphics, vision
- *Monte Carlo Rendering* (order-of-mag. advances classical problem)
- *View synthesis* (best results in decades)
- Imaging and Computational Photography
- Precomputed Rendering, Physics-Based Vision, Animation, …

Much recent work (esp at UCSD): CSE 274 Topics in Graphics: Sampling and Reconstruction of Visual Appearance

14

Outline of Lecture

- Motivation, sampling and reconstruction visual appearance
- *Historical Development and Overview of Applications*
- Logistics of course

15

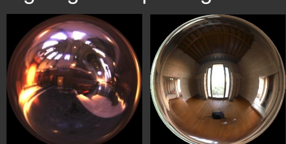
(My lens on) History

- Data-Driven Visual Appearance [~1993 -]
  - Image-Based Rendering
  - Sampled Representations (in many areas)
  - Even for synthetic relighting [Nimeroff 94, Sloan 02]

16

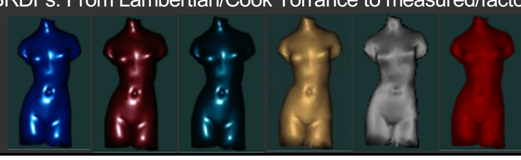
Types of Measured Visual Appearance

- Lighting: From point lights to environment maps and beyond



Grace Cathedral and Kitchen light probes
Courtesy Paul Debevec www.debevec.org

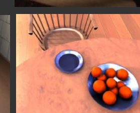
- BRDFs: From Lambertian/Cook Torrance to measured/factored



17

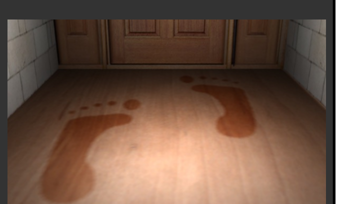
Types of Measured Visual Appearance

- "Reflectance Fields": Variation with lighting and/or view
- Subsurface and Volumetric Scattering
- Time-Varying Surface Appearance
- BTFs or Bi-Directional Texture Functions
- And many more (full taxonomy next)



18

Time-Varying Appearance: Video



19

General Plenoptic Function

- All knowledge of light in scene [Adelson 91]
- Anywhere in space (x, y, z)
- In any direction (θ, ϕ)
- At any time instant (t)
- For any wavelength of light (λ)
- Function of 7 variables, therefore 7D function
- We care about taxonomy of *scattering functions*
  - *General Scattering Function is 14D (bet. two plenoptics)*

$$f(x_i, y_i, z_i, \theta_i, \phi_i, \lambda_i, t_i \,;\, x_o, y_o, z_o, \theta_o, \phi_o, \lambda_o, t_o)$$

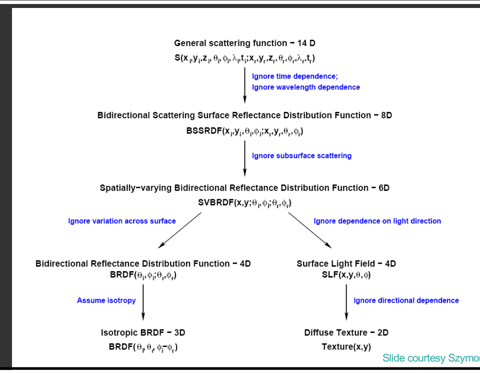
20

Common Assumptions

- Ignore time dependence (no phosphorescence or time-varying BRDF properties)
- Ignore wavelength (no fluorescence, assume RGB)
- Travel in free space, parameterize on surfaces (no z)
  - Alternative for light fields: 4D space of rays (intersections in 2 planes)
- Each of these removes 1D of plenoptic, 2D of scattering
- Left with 8D function of greatest importance for class
- 8D Bi-Directional Surface Scattering Distribution Function (BSSRDF) $f(x_i, y_i, \theta_i, \phi_i; x_o, y_o, \theta_o, \phi_o)$

21

Taxonomy of Appearance



Slide courtesy Szymon Rusinkiewicz

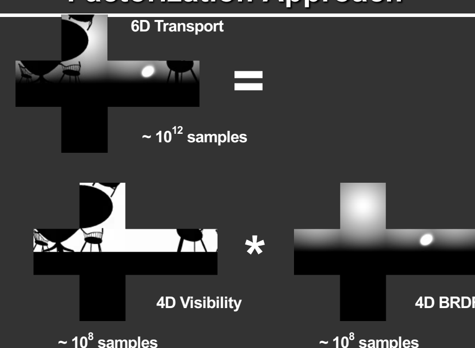
22

(My lens on) History

- Data-Driven Visual Appearance [~1993 -]
  - Image-Based Rendering
  - Sampled Representations (in many areas)
  - Even for synthetic relighting [Nimeroff 94, Sloan 02]
- Mathematical and Computational Fundamentals [~2000 -] (my term, topic of my Career Award)
  - Lower-Dimensional Factorizations [e.g. 6D -> 4D]
  - Efficient Mathematical Representations [spherical harmonics, wavelets, radial basis functions]
  - New Computational Methods [analytic formulae, convolution, triple products, Nystrom, …]
  - New machine learning representations (recent)

23

Factorization Approach



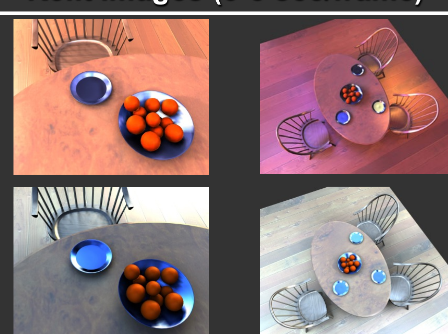
Ng, Ramamoorthi, Hanrahan 04

24

Triple Product Integral Relighting

25

Relit Images (3-5 sec/frame)



26

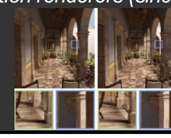
(My lens on) History and Future

- Data-Driven Visual Appearance [~1993 -]
  - Sampled representations and real-world data
  - *How do we make the data practical and usable?*
- Mathematical and Computational Fundamentals [~2000 -] (my term, topic of my Career Award)
  - Lower-Dimensional Factorizations [e.g. 6D -> 4D]
  - *Data still is acquired or precomputed by brute force*
- Sampling Theory of Appearance [~2007 -]
  - How many samples do we need for final representation?
  - Theory and efficient acquisition/computation strategies
  - Really a core signal-processing problem (Chai et al 00)
  - Newest approaches based on machine learning
  - *Sampling and Reconstruction of Visual Appearance*

27

Applications and Context

- Monte Carlo global illumination rendering (CSE168)
  - One of main application areas discussed in course
  - Often perceived as mature: “rendering is a solved problem”
  - But not widely used in production rendering until 2011
- Production Rendering is now Physically-Based
  - Sea change since 2011. Ad-hoc methods gone. MC used.
  - *Sampling and Reconstruction (denoising) is key*
  - *Leads to 1-2 order of magnitude speedup in mature area*
  - *Essential part of today’s production renderers (since ~2014)*

28

Fast 4D Sheared Filtering for Interactive Rendering of Distribution Effects

ACM ToG 2015

Ling-Qi Yan Soham Uday Mehta
Ravi Ramamoorthi Fredo Durand

All clips rendered at 720x720

NO AUDIO

29

Multiple Effects in Real Time

Multiple Axis-Aligned Filters for Rendering of Combined Distribution Effects

Online submission ID: 1000

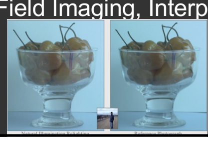
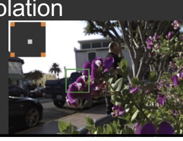
NO AUDIO

Recent product: NVIDIA Optix 5 with denoising, NRD https://youtu.be/OC637pfAJs8

30

Applications and Context

- Fast Enough for Real-Time Rendering
  - Sample and reconstruct for real-time started ~2012
  - Latest papers machine learning + 1 sample per pixel
  - Video ; TuringRT 10G rays/sec: Video ; Tiger Demo: Video
- Fast precomputation of light transport matrices
  - Precomputed rendering widely used in games etc.
- Sparse acquisition of Light Transport, View Synthesis
- Light Field Imaging, Interpolation

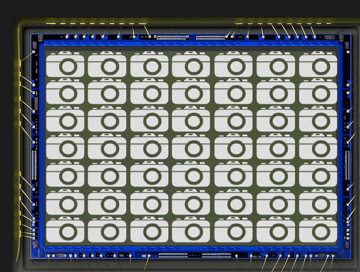
31

Resolution trade-off

Limited resolution

High angular

Low spatial



UC San Diego Kalantari et al.

32

Solution: angular super-resolution

UC San Diego Kalantari et al.

33

Our result

UC San Diego Kalantari et al.

34

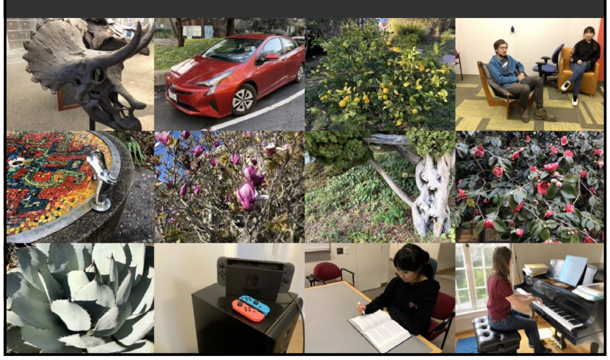
Input Images

35

Output Virtual Experience

36

Light Fields with 4000x fewer views



37

Relation to Signal Processing, Learning

- Signal processing itself undergoing revolution
  - From Nyquist to compressive to sparse low rank to learning
  - Will cover these topics briefly where relevant
  - Exciting time to work in this area
  - *Unified Sampling Theory of Appearance?*
- Newest advances in machine learning
  - Deep Convolutional Neural Networks (CNNs)
  - Introduced for computer vision but many exciting applications for image synthesis
  - Latest denoising, view synthesis methods leverage CNNs
  - *Convergence real-time, offline rendering, machine learning*
- This is a graphics course, but we will touch on above methods as needed. Exciting convergence.

38

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39

Course Goals, Format

- Goal: Background and current graphics research
  - Topic: Sampling and Reconstruction of Visual Appearance: *From Denoising to View Synthesis*
  - Need to cover a lot of background research papers
  - Then discuss current frontiers in the field
- Also basics of rendering to cover for CSE 168
- UCSD is the best place for this!!
- Format: Alternate lectures, student presentations of papers
- Website: http://viscomp.ucsd.edu/classes/cse274/fa22/274.html

40

Course Logistics

- No textbooks. Required readings are papers available online (and some handouts for books)
  - Handouts at http://viscomp.ucsd.edu/classes/cse274/fa22/readings
- Office hours: after class or email. My contact info is on my webpage: http://www.cs.ucsd.edu/~ravir
- Zoom: https://ucsd.zoom.us/my/ravir11 (if we need to move to remote instruction temporarily or permanently)
- TA: Kaien Lin (k2lin@eng.ucsd.edu) Office hours in CSE 4150 MTh 12-1pm or email for another time.
- Should count for PhD, MS, BS electives in graphics and vision, see me if there is a problem or you need a certification

41

Requirements

- Pass-Fail (2 units)
  - Show up to class regularly
  - Present 1 or 2 paper(s) if needed
  - Prefer you do this rather than just sit in
- Grades (4 units)
  - Attend class, participate in discussions
  - Present 1 or 2 papers (please do this well)
  - If class is large, groups of 2 can present 1 paper
  - Project (key part of grade)

42

Project

- Wide flexibility if related to course. Can be done groups of 2
  - Default: Implement (part of) one of papers and produce an impressive demo for real-time or offline rendering, or for image-based rendering or view synthesis
  - See/e-mail me re ideas
  - Best projects will go beyond simple implementation (try something new, some extensions)
- Alternative (less desirable): Summary of 3+ papers in an area
  - Best projects will explore links/framework not discussed by authors, and suggest future research directions

43

Prerequisites

- Strong interest in graphics, rendering
- Computer graphics experience (167 or equivalent)
  - Experience with rendering not required; first few weeks will cover basic background (CSE 168). But also doesn't hurt, consider UCSD online CSE 168
- Course will move quickly
  - Covering recent and current active research
  - Some material quite technical
  - Considerable background material is covered
  - Assume some basic knowledge
  - Many topics. Needn't fully follow each one, but doing so will be most rewarding.

44

Assignment this week

- E-mail me (ravir@cs.ucsd.edu) [only if not done already]
  - Name, e-mail, status (Senior, PhD etc.)
  - Will you be taking course grades or P/F
  - Background in graphics/any special comments
  - *Optional for all: Papers you'd like to present FCFS (only those that say "presented by students")*

46

Questions?

47