Introduction

15-468, 15-668, 15-868
Physics-based Rendering
Spring 2023, Lecture 1

http://graphics.cs.cmu.edu/courses/15-468

Lecture etiquette

- Lecture slides (PPTX and PDF) are posted on the course website before each lecture.
- Lectures, including all discussions, **are recorded** using Zoom. This is to facilitate students that **occasionally** cannot attend the lectures live, or that want to revisit the lecture material.
- You are expected to attend lectures in person. You are **not** allowed to attend lectures over Zoom, unless you have explicit permission.
- Recordings become available on **Canvas** a few hours (usually <= 3) after the lecture. You are **not** allowed to share these recordings with anyone outside this class. This is to protect your and your fellow students' FERPA rights.
- Feel free to ask questions! Please make sure to raise your hand both to ask your own questions and to answer mine.

Overview of today's lecture

- Teaching staff introductions
- What is this course about?
- Course fast-forward and logistics

Teaching staff introductions

Instructor: Ioannis (Yannis) Gkioulekas

I won't hold it against you if you mispronounce my last name

Originally from Greece

National Technical University of Athens (2004-09)

Harvard University (2009-17)

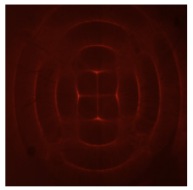
Carnegie Mellon University (2017-now)

Yannis at Harvard in 2011

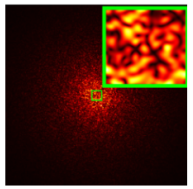
My website: http://www.cs.cmu.edu/~igkioule

See also: http://imaging.cs.cmu.edu/

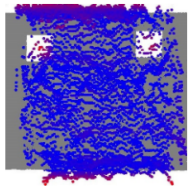
Broadly interested in computational imaging, physics-based vision, and physics-based rendering



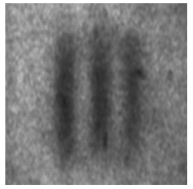
Rendering Near-Field Speckle Statistics in Scattering Media
Adithya Pediredla, Yasin Karimi Chalmiani, Matteo Giuseppe Scopelliti, Maysam Chamanzar, Srinivasa Narasimhan, **Ioannis Gkioulekas**
ACM Transactions on Graphics (SIGGRAPH Asia), 2020
paper | project page



Rendering Near-Field Speckle Statistics in Scattering Media
Chen Bar, **Ioannis Gkioulekas**, Anat Levin
ACM Transactions on Graphics (SIGGRAPH Asia), 2020
paper | project page



A Theory of Fermat Paths for 3D Imaging Sonar Reconstruction
Eric Westman, **Ioannis Gkioulekas**, Michael Kaess
IEEE International Conference on Intelligent Robots and Systems (IROS), 2020
paper | project page



Interferometric Transmission Probing with Coded Mutual Intensity
Alankar Kotwal, Anat Levin, **Ioannis Gkioulekas**
ACM Transactions on Graphics (SIGGRAPH), 2020
paper | project page

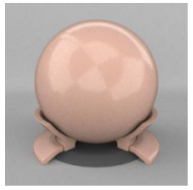
Langevin Monte Carlo Rendering with Gradient-based Adaptation
Fujun Luan, Shuang Zhao, Kavita Bala, **Ioannis Gkioulekas**
ACM Transactions on Graphics (SIGGRAPH), 2020
paper | project page

Path-Space Differentiable Rendering
Cheng Zhang, Bailey Miller, Kai Yan, Ioannis Gkioulekas, Shuang Zhao
ACM Transactions on Graphics (SIGGRAPH), 2020
paper | project page

Effect of Geometric Sharpness on Translucent Material Perception
Bei Xiao, Shuang Zhao, **Ioannis Gkioulekas**, Wenyan Bi, Kavita Bala Journal of Vision (JOV), 2020
paper | code

Use rendering to study human perception

A Volumetric Albedo Framework for 3D Imaging Sonar Reconstruction
Eric Westman, **Ioannis Gkioulekas**, Michael Kaess
IEEE International Conference on Robotics and Automation (ICRA), 2020
paper | project page



Towards Reflectometry from Interreflections
Kfir Shem-Tov, Sai Praveen Bangaru, Anat Levin, **Ioannis Gkioulekas**
IEEE International Conference on Computationa Photography (ICCP), 2020
paper | project page

Use rendering to make reflectometry easier

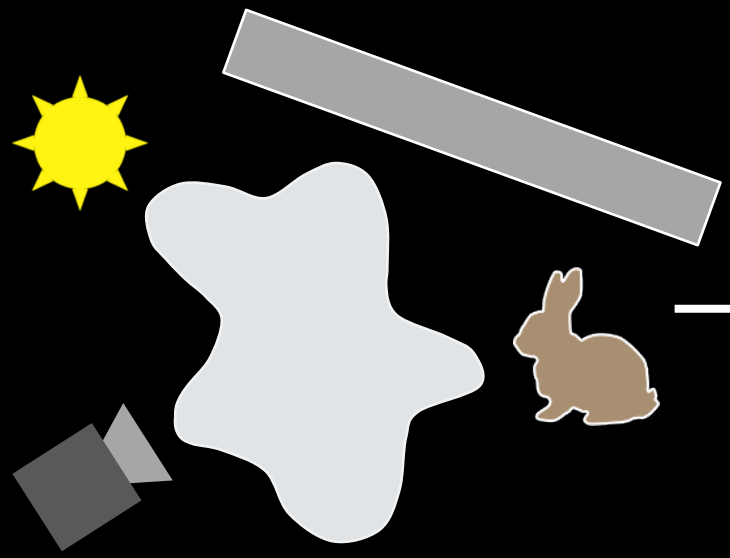
Towards Learning-based Inverse Subsurface Scattering
Chengqian Che, Fujun Luan, Shuang Zhao, Kavita Bala, **Ioannis Gkioulekas**
IEEE International Conference on Computationa Photography (ICCP), 2020
paper | project page

Use rendering to make neural networks better

TAs pending!

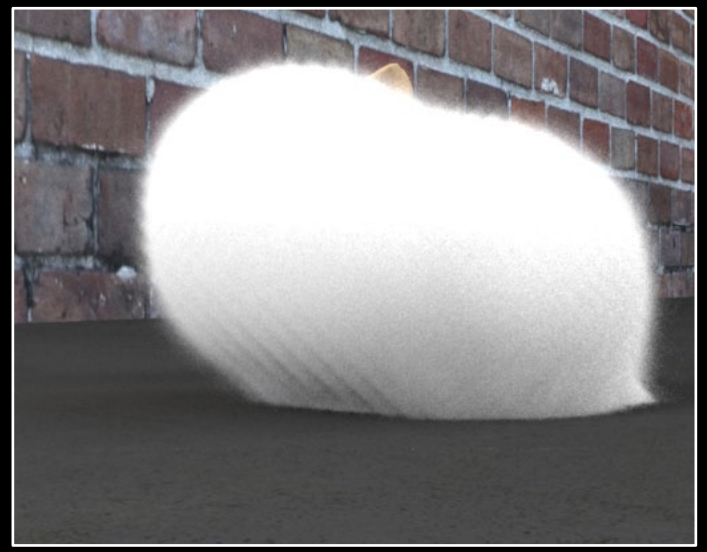
What is this course about?

Forward rendering



digital scene specification
(geometry, materials,
optics, light sources)

physically-accurate
rendering



photorealistic
simulated image

What is this class about?

Producing realistic images by:

- *simulating* light transport (global illumination)
- *simulating* light-material interactions (appearance modeling)

Understanding why things look the way they do:

- Why is the sky blue?
- Why is the grass green?
- Why does metal look different than marble?

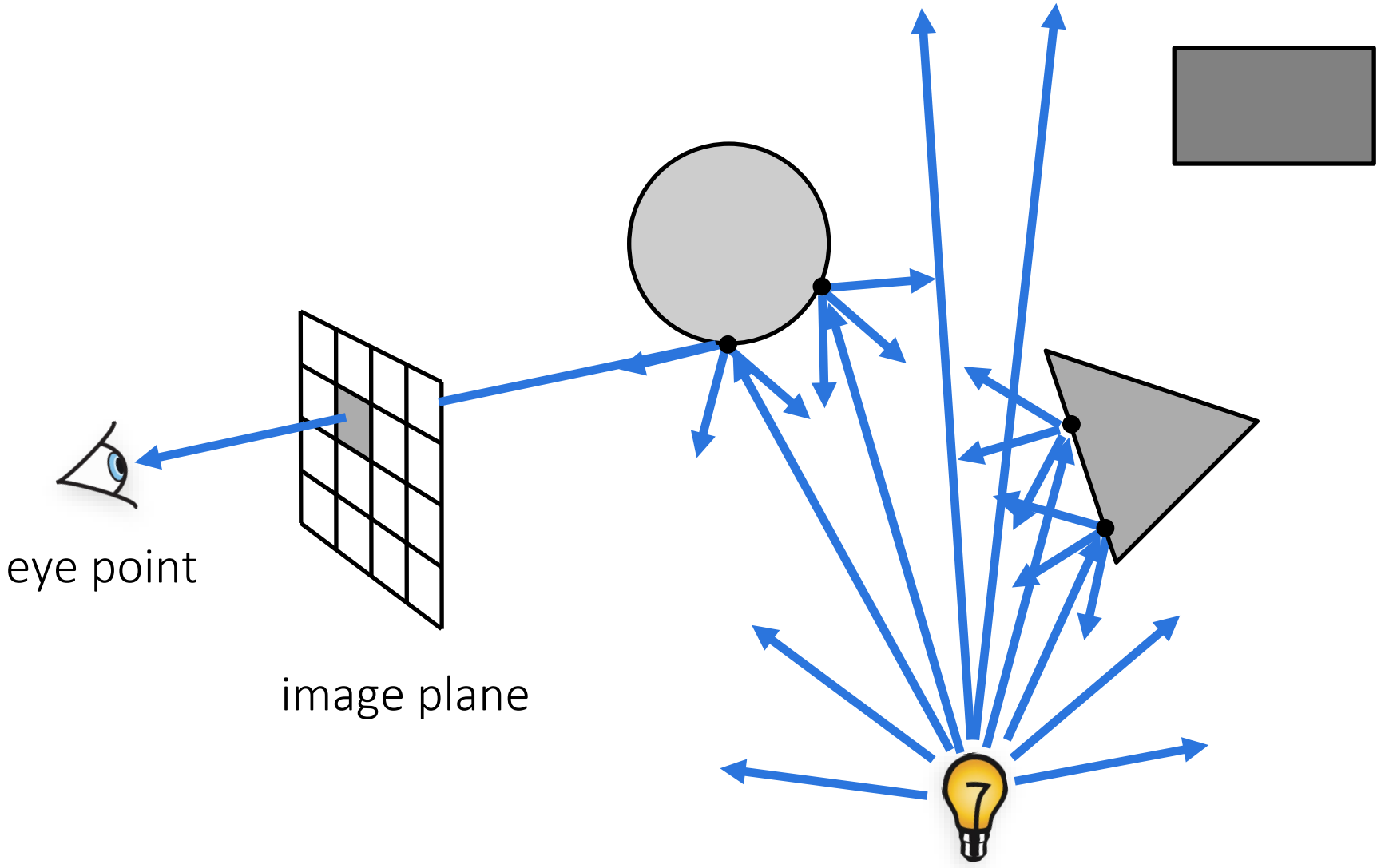
Motivation

Wojciech Jarosz

Light transport in the real world

After [Ritschel et al 2011]

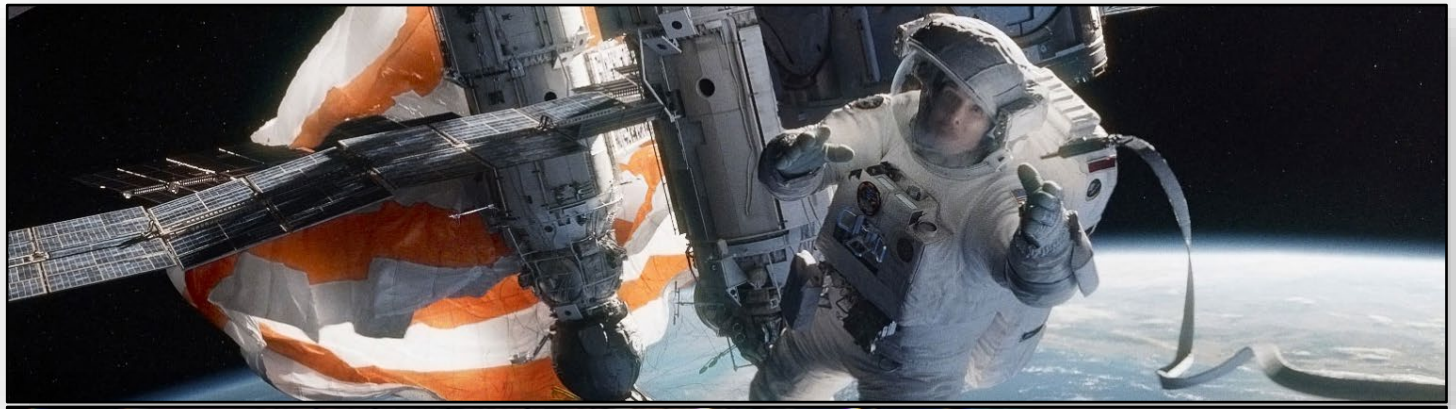
Physics-based rendering

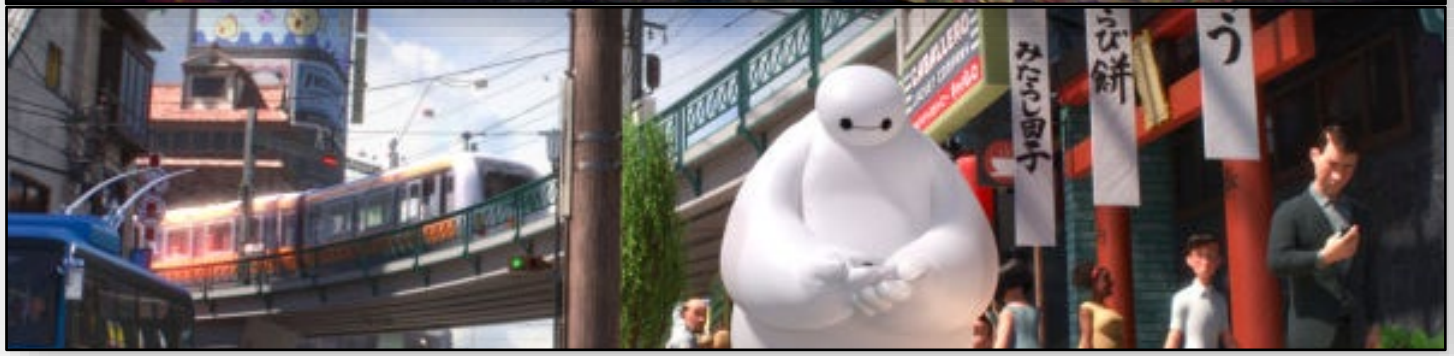


Mimic the physics of light transport using ray tracing

Wojciech Jarosz

Ray tracing in production





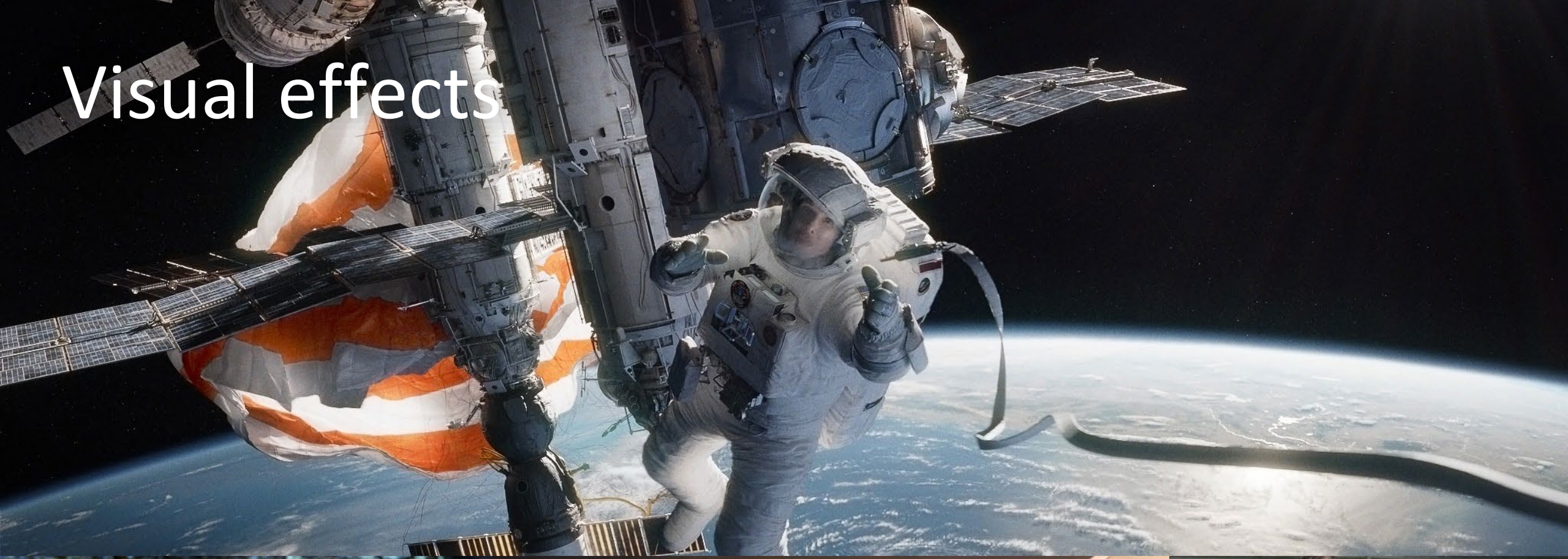
Arnold Renderer

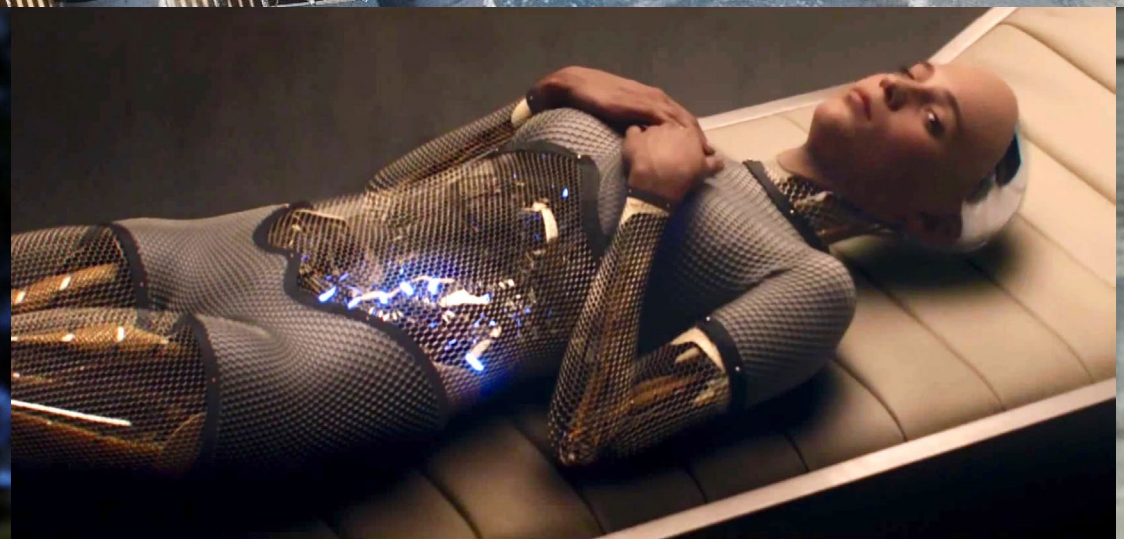
SOLIDANGLE

PIXAR's RenderMan

Hyperion

Visual effects





Wojciech Jarosz

Animated films

Wojciech Jarosz

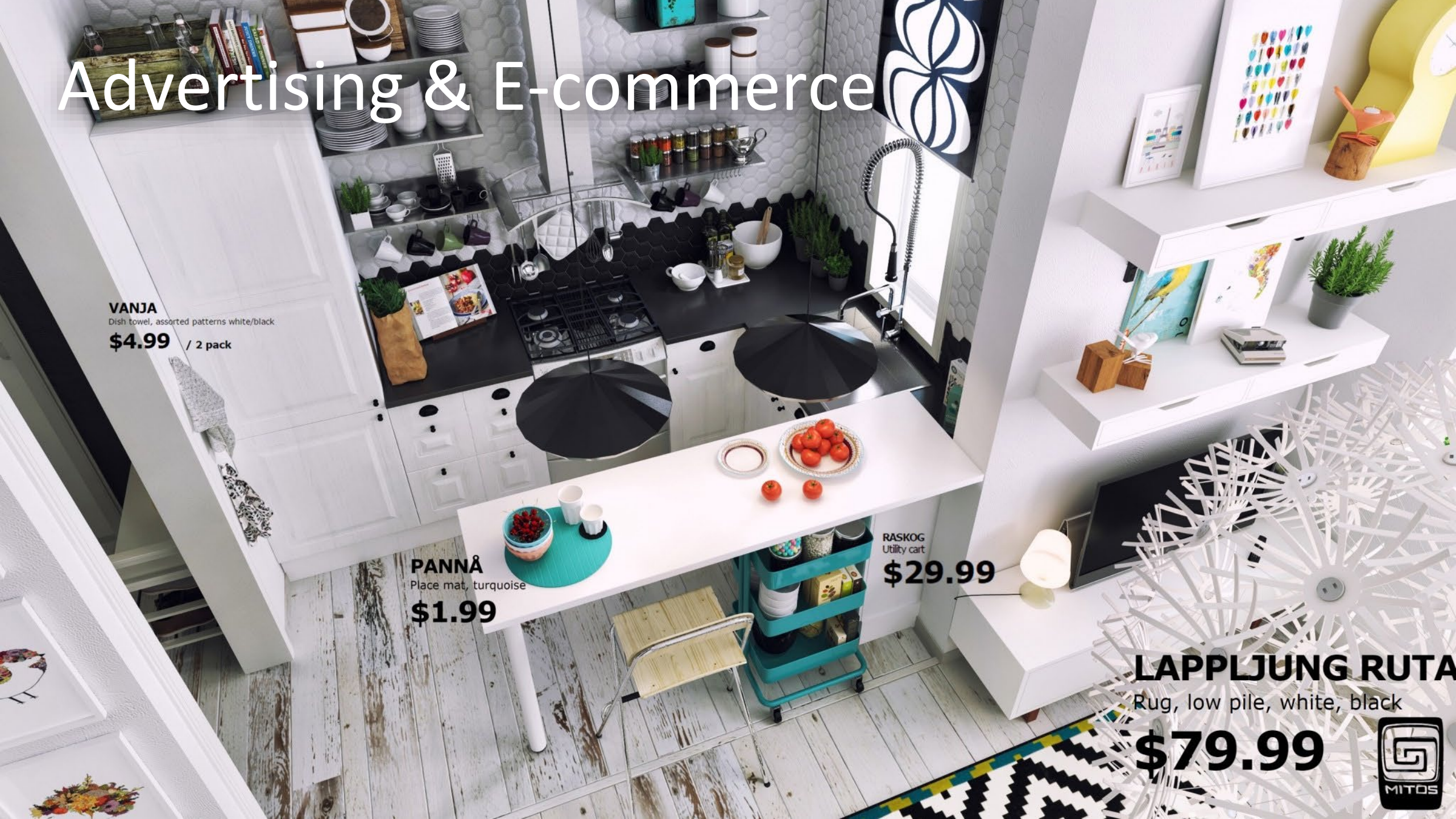
Video games

Wojciech Jarosz

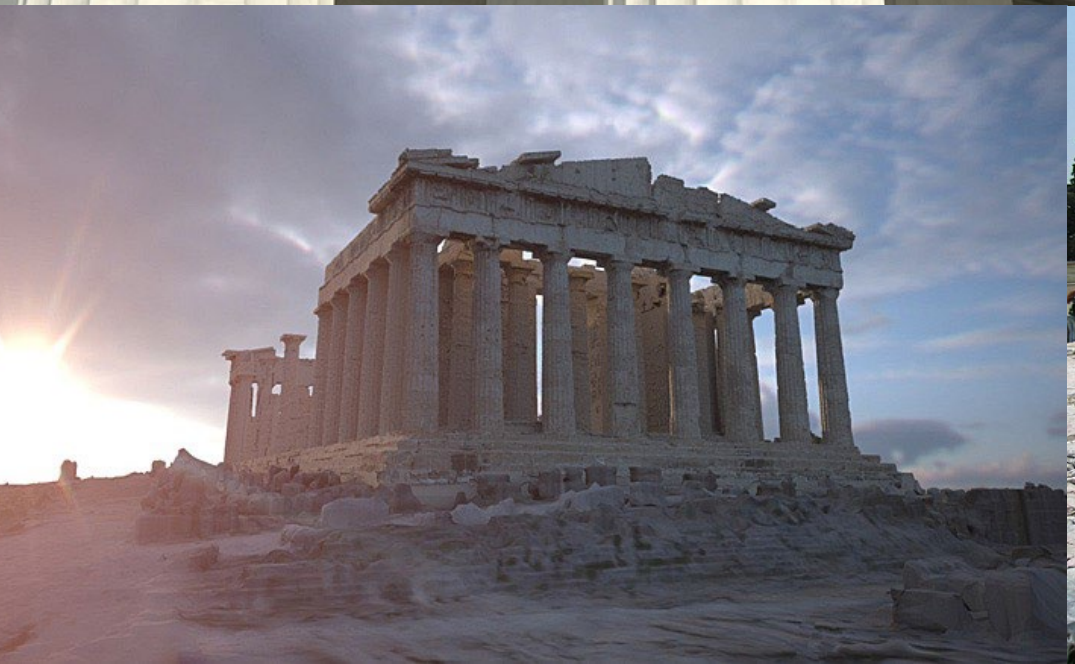
Architectural visualization

Wojciech Jarosz

Advertising & E-commerce



Cultural heritage

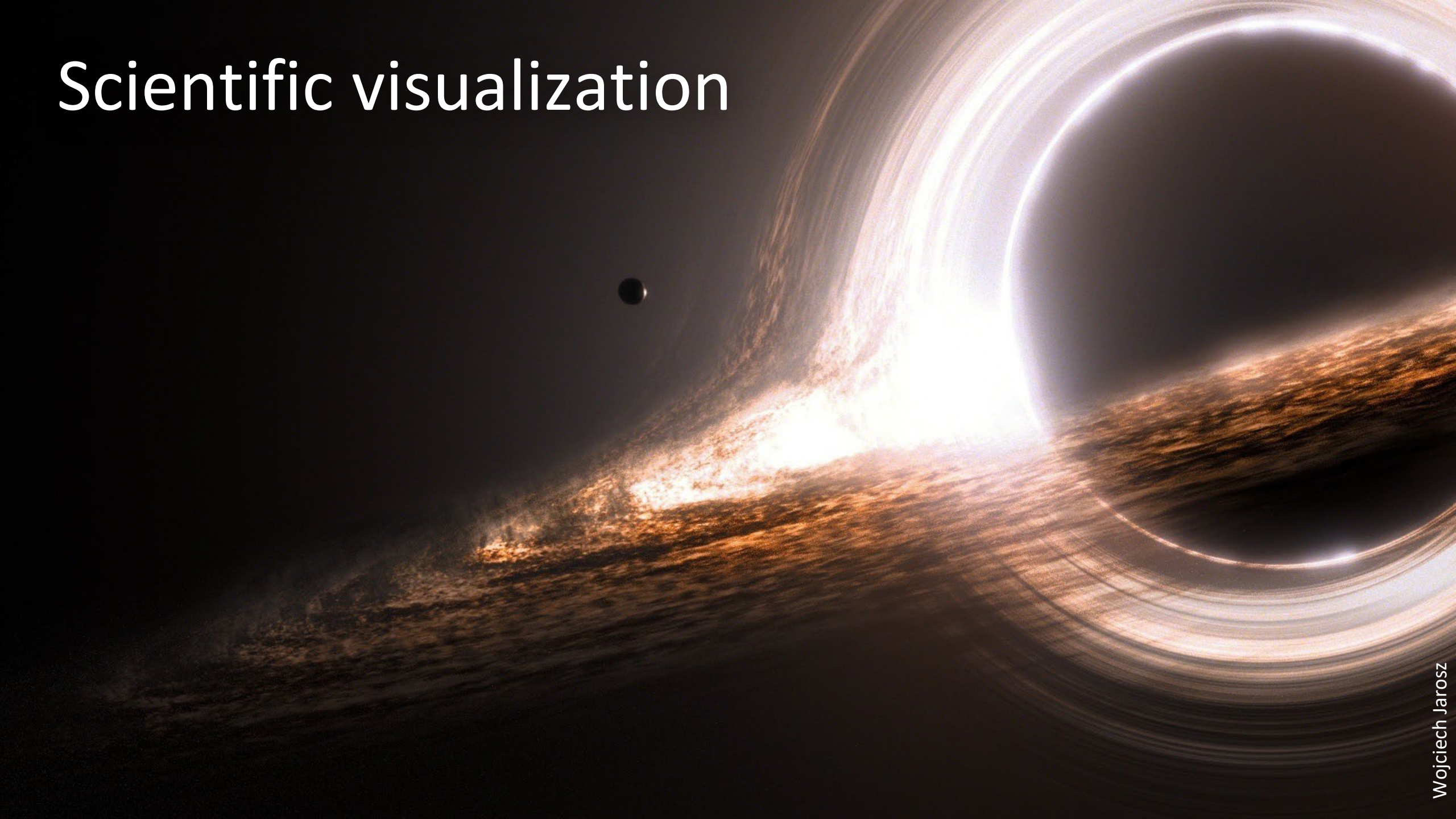


Wojciech Jarosz

Digital fabrication

Wojciech Jarosz

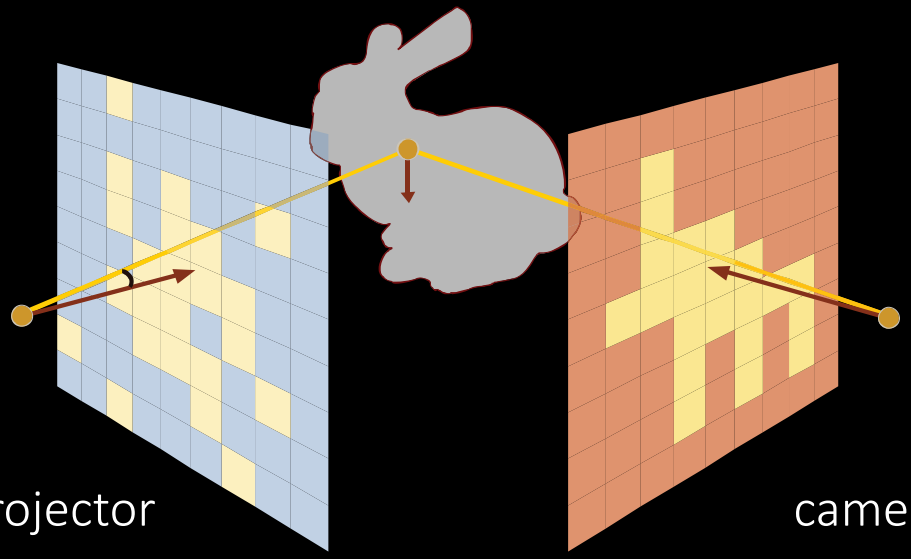
Scientific visualization



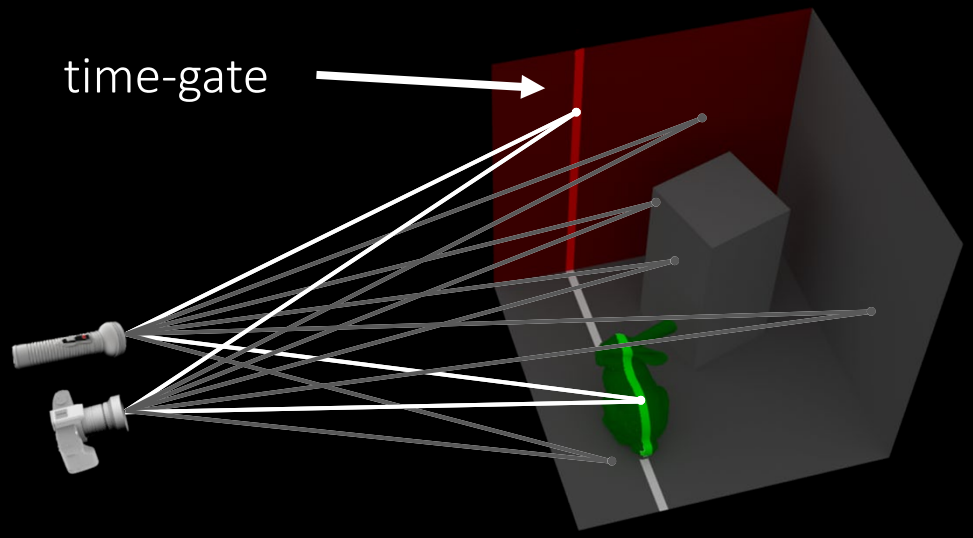
Wojciech Jarosz

Scientific imaging

rendering computational light transport

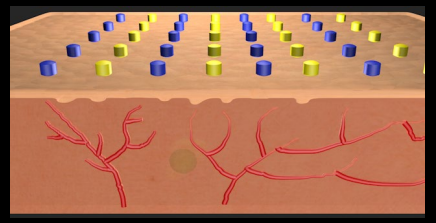


rendering time-of-flight sensors

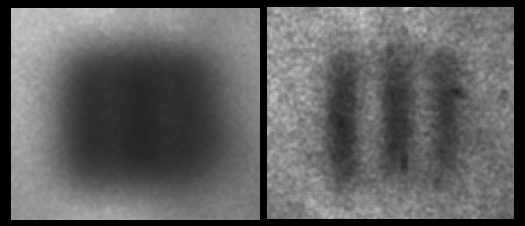


Used by CMU imaging projects:

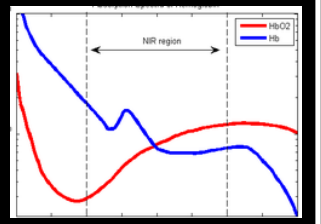
convolutional DOT



coded coherence

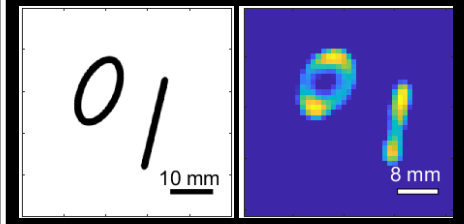


coded spectrum

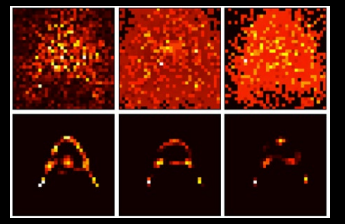


Used by CMU imaging projects:

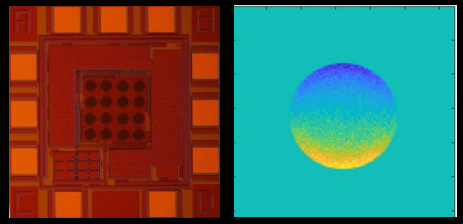
ToF DOT



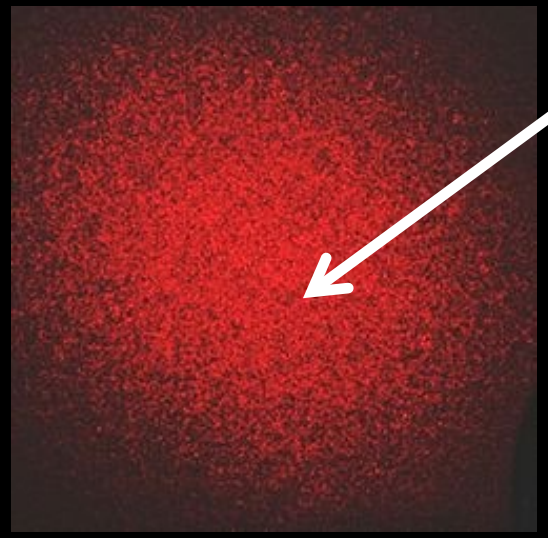
all-photon imag.



differential SPAD

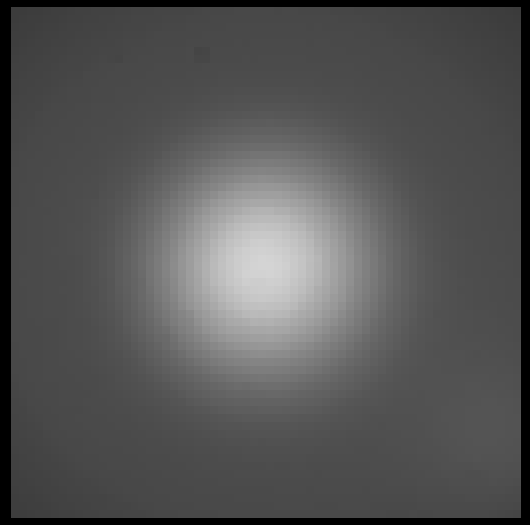


Rendering wave effects



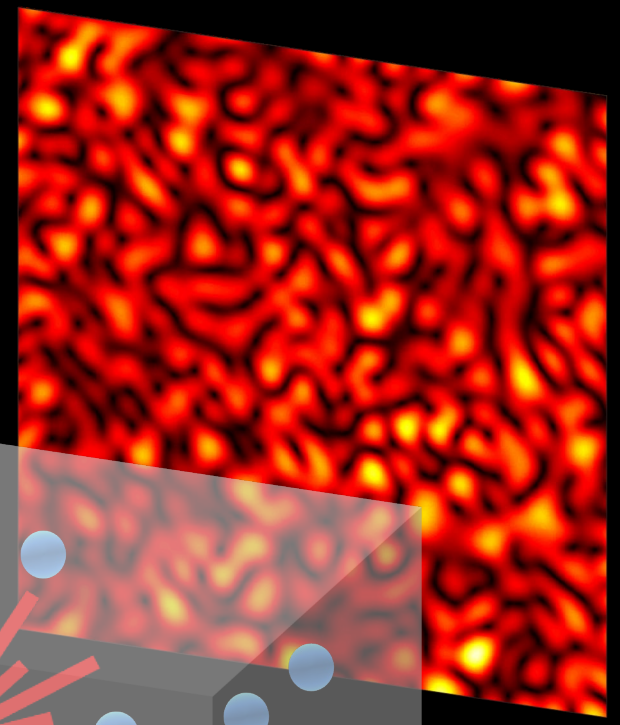
speckle: noise-like pattern

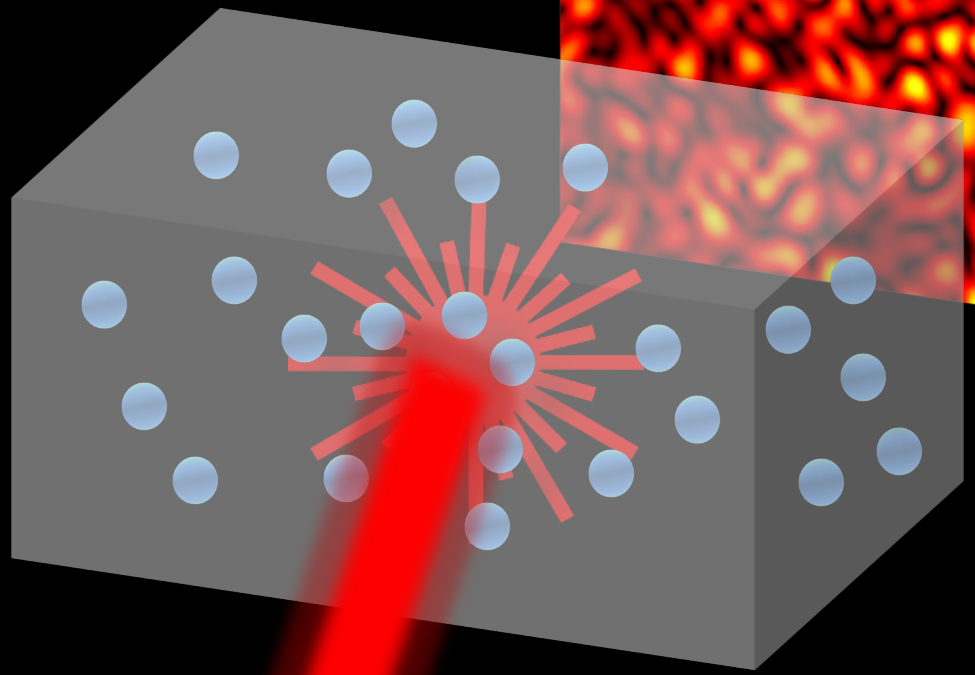
what real laser images look like



what standard rendered images look like

projected speckle image

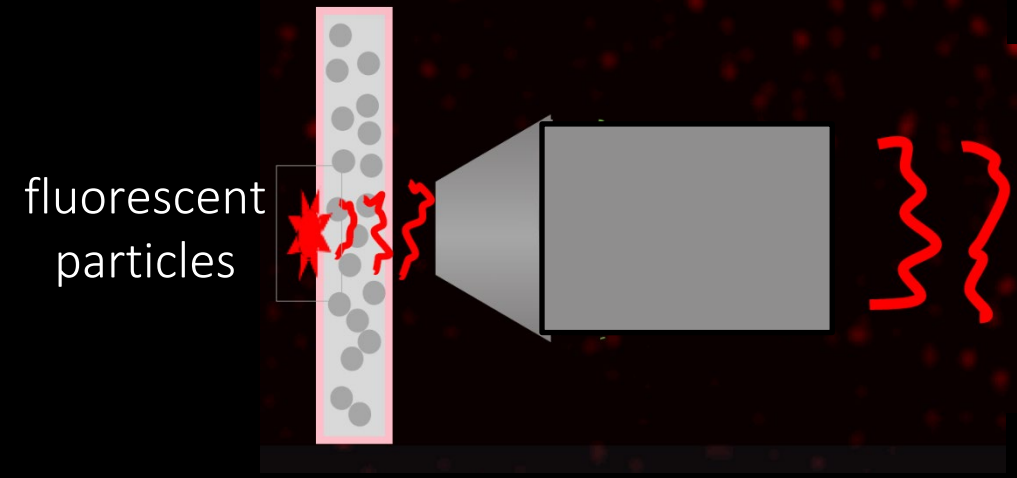


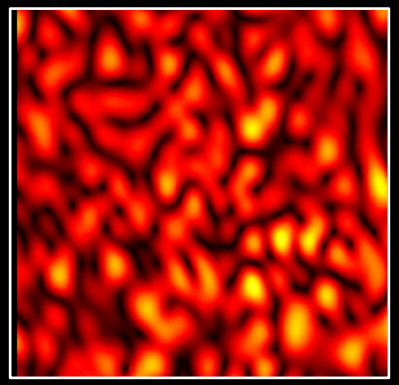


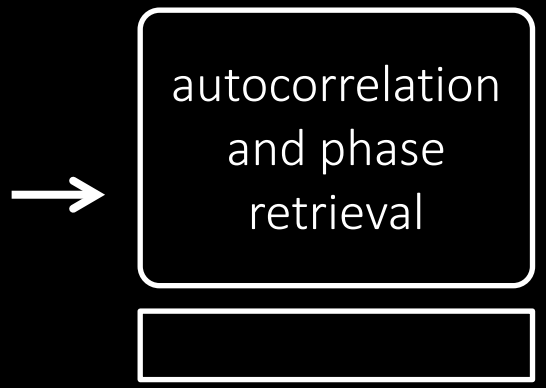
laser beam

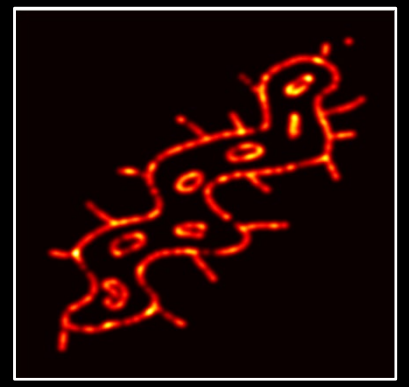
scattering volume

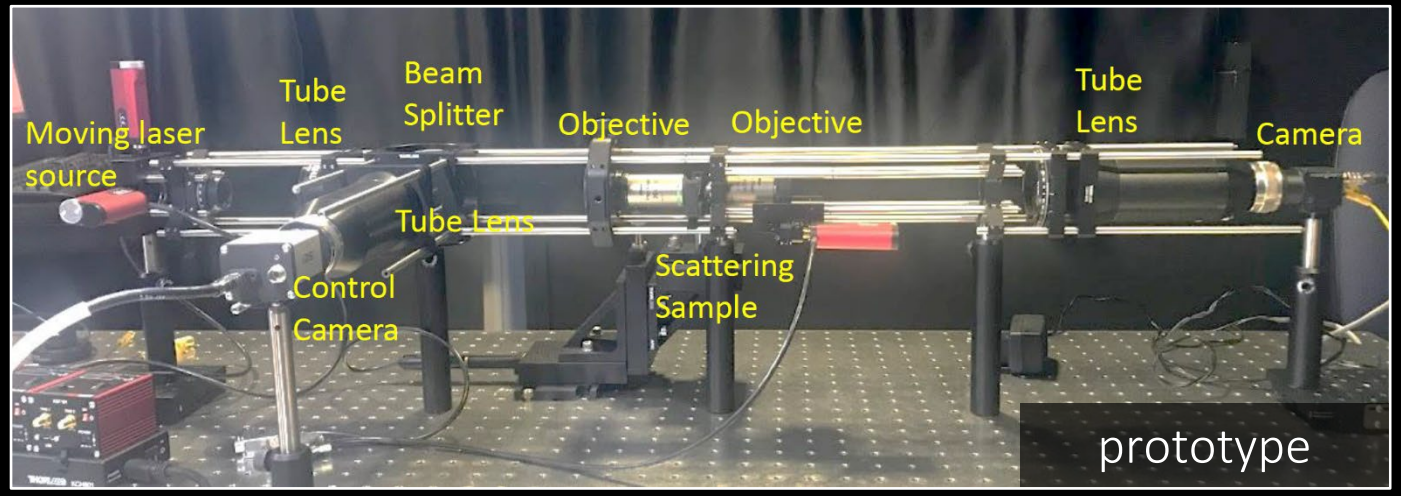
Application: fluorescence Microscopy




captured image




scattering-free image

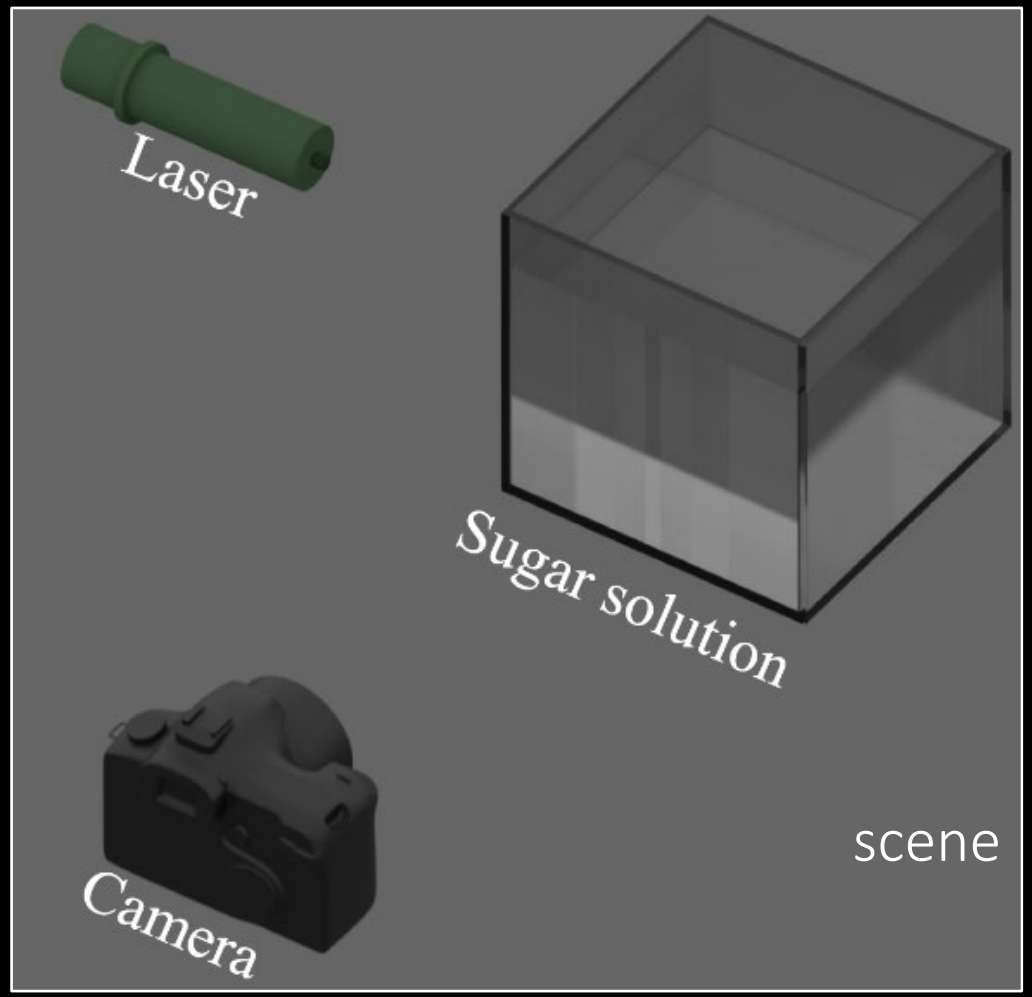


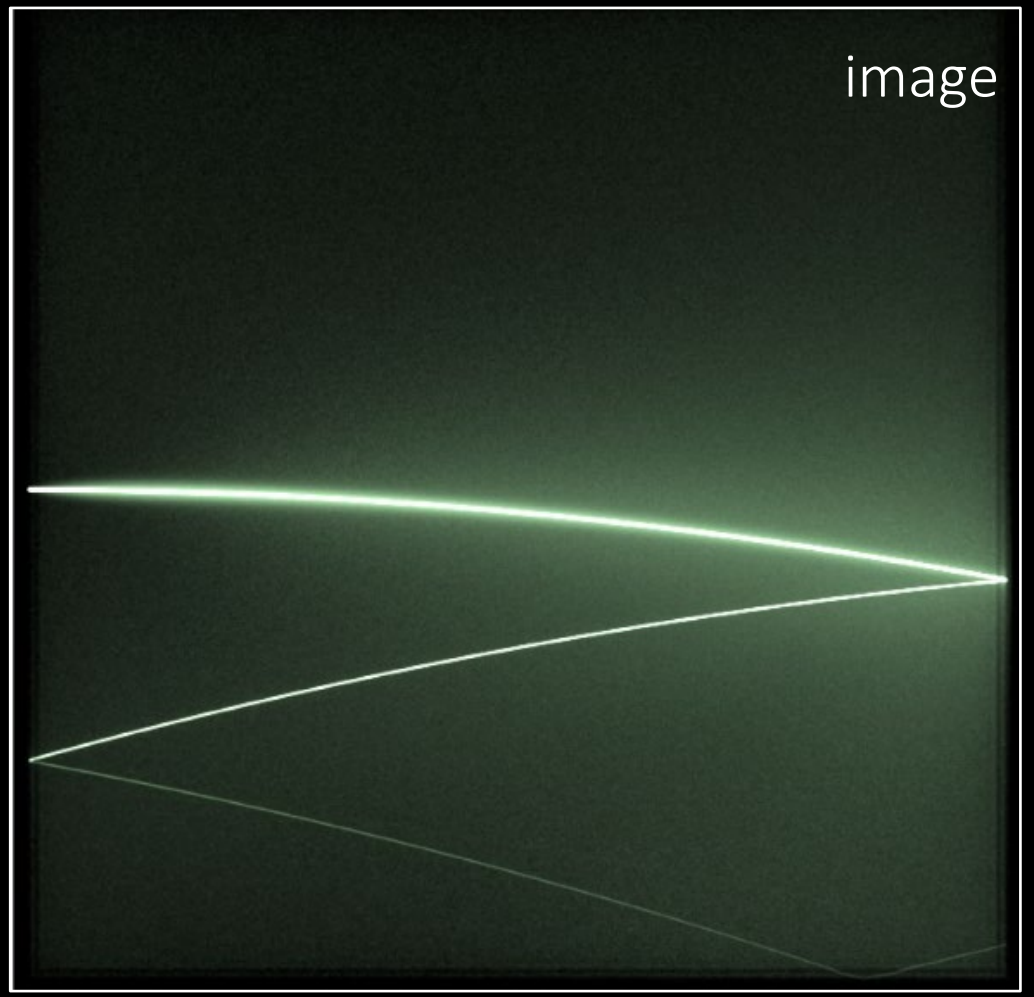
Performance strongly depends on:

- speckle statistics
- image priors
- tissue parameters

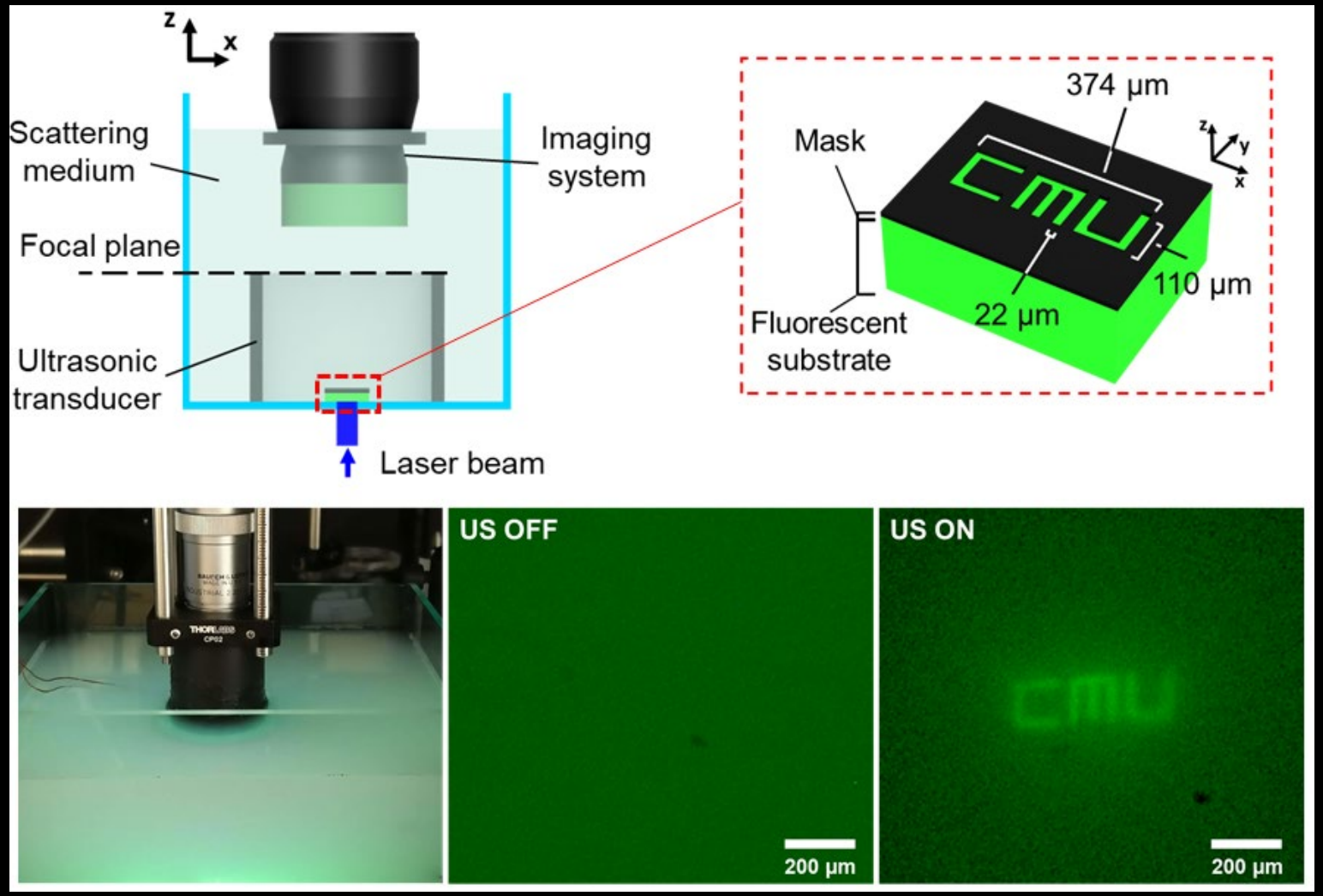
Rendering-assisted exploration and new algorithms!

Rendering eikonal transport

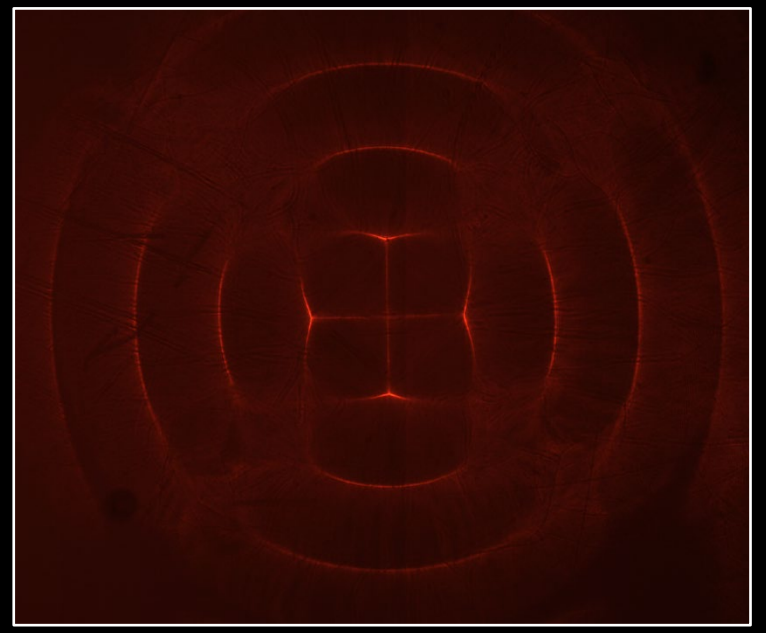




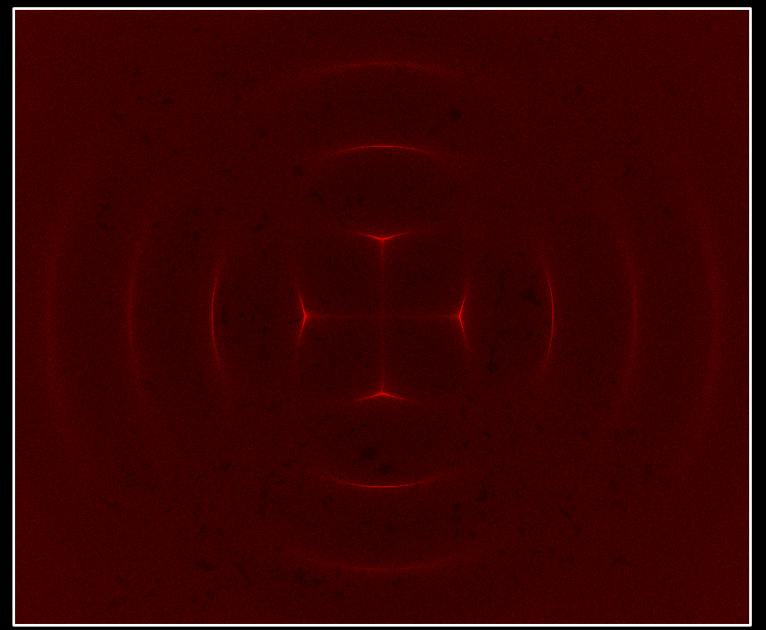
Application: acousto-optics



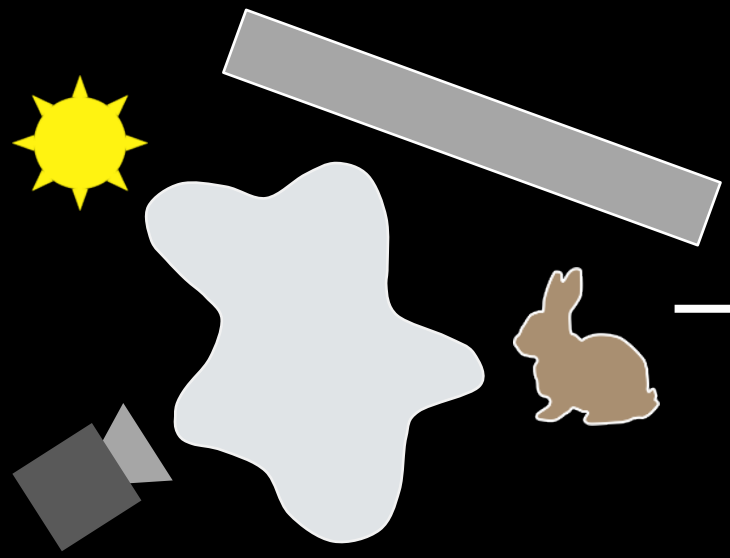
real capture



our algorithm

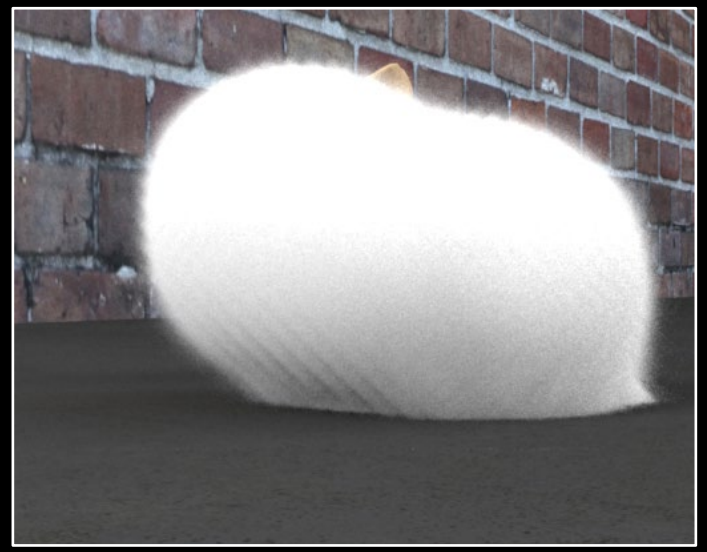


Forward rendering



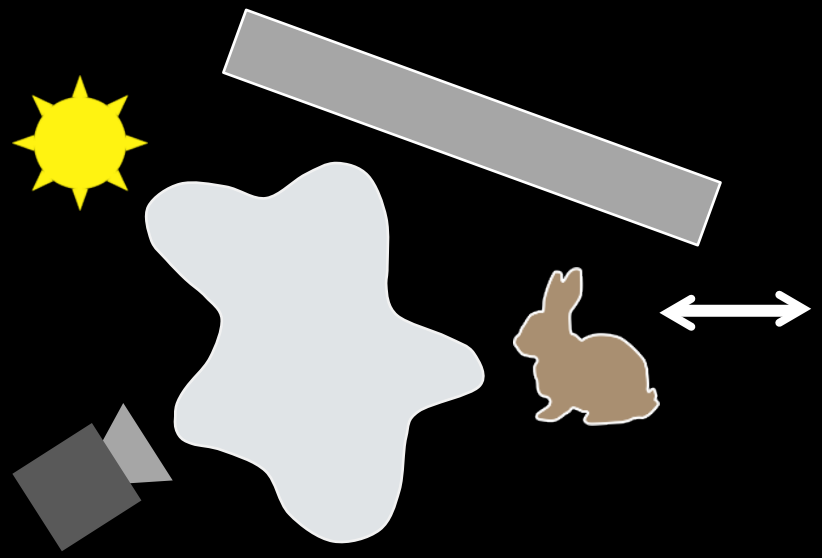
digital scene specification
(geometry, materials,
optics, light sources)

physically-accurate
rendering



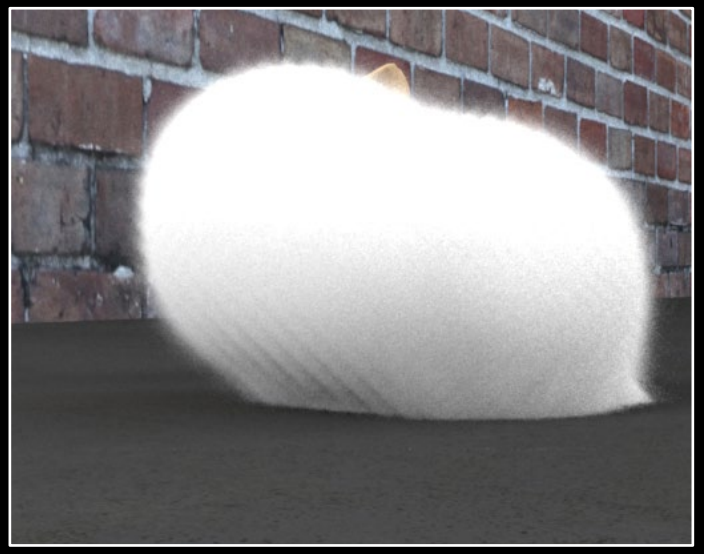
photorealistic
simulated image

Inverse rendering



digital scene specification
(geometry, materials,
camera, light sources)

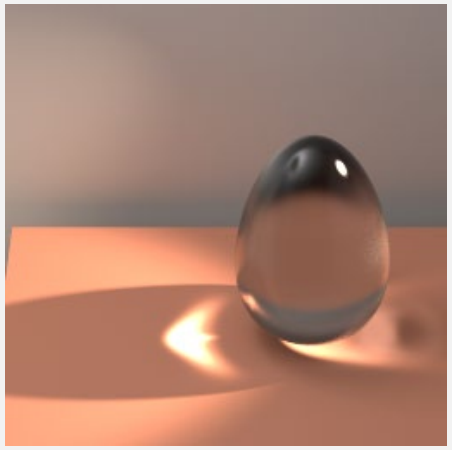
physically-accurate
inverse rendering



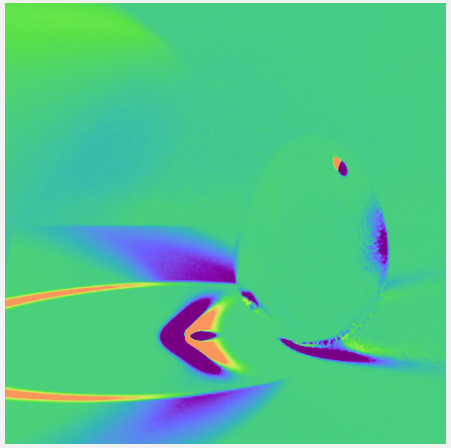
photorealistic
synthetic image

Differentiable rendering

Original image

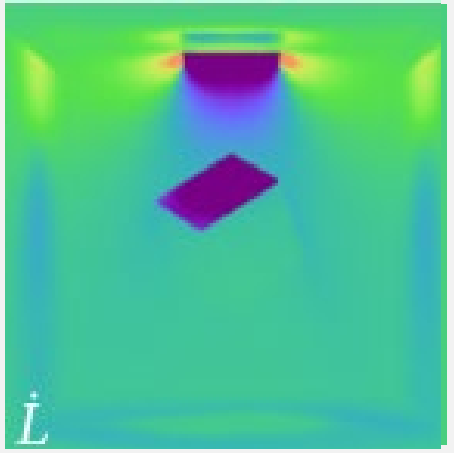


Derivative image



Original image

Derivative image



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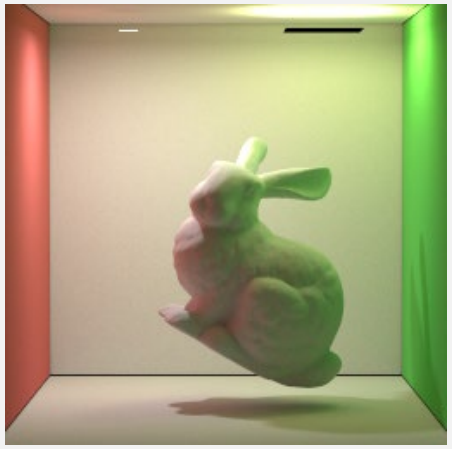

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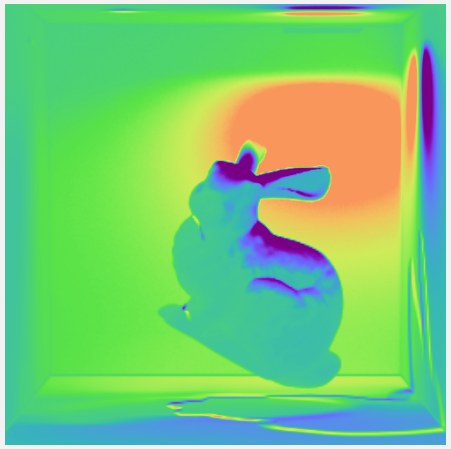

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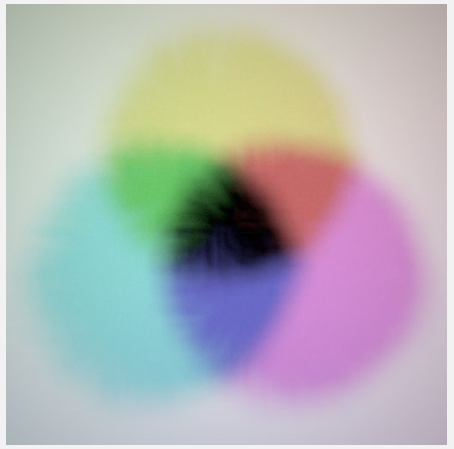

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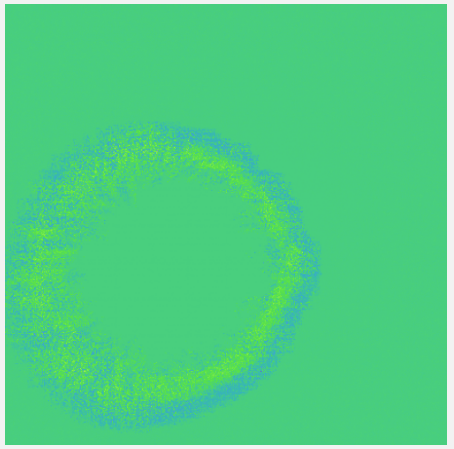
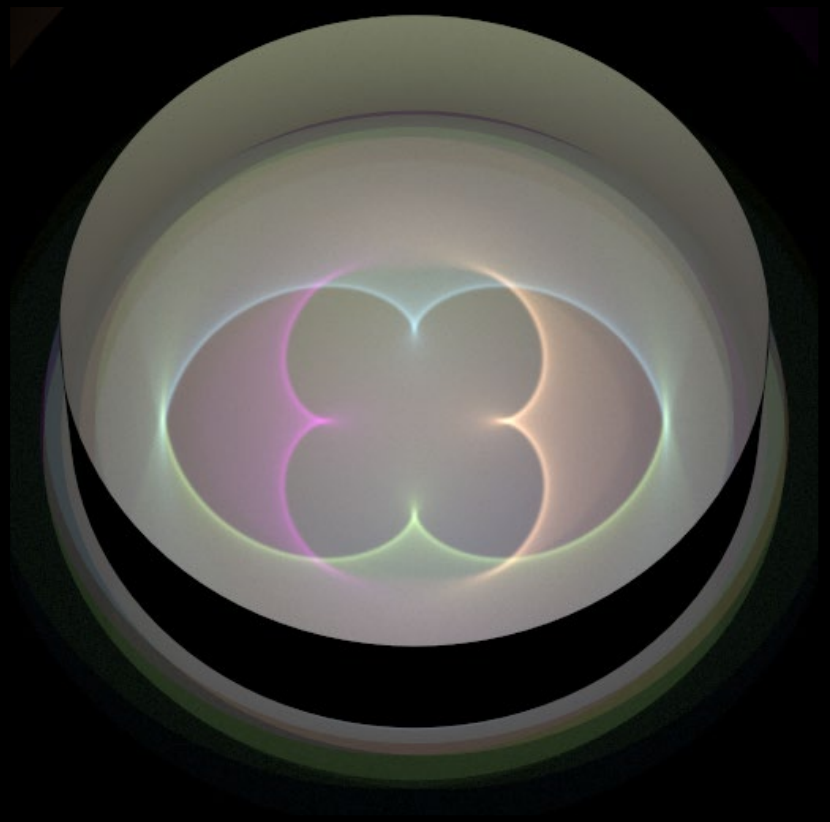
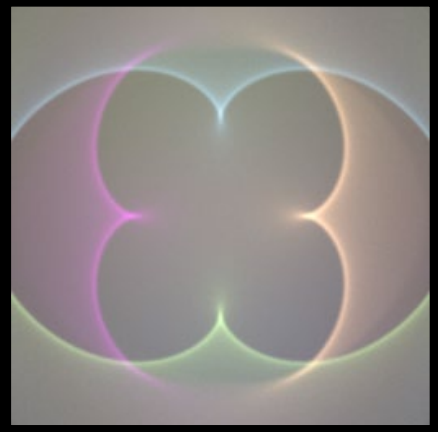


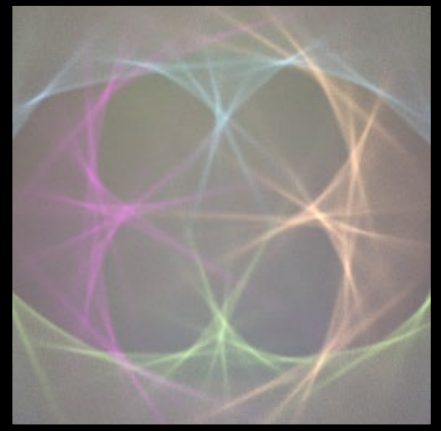
Application: shape optimization

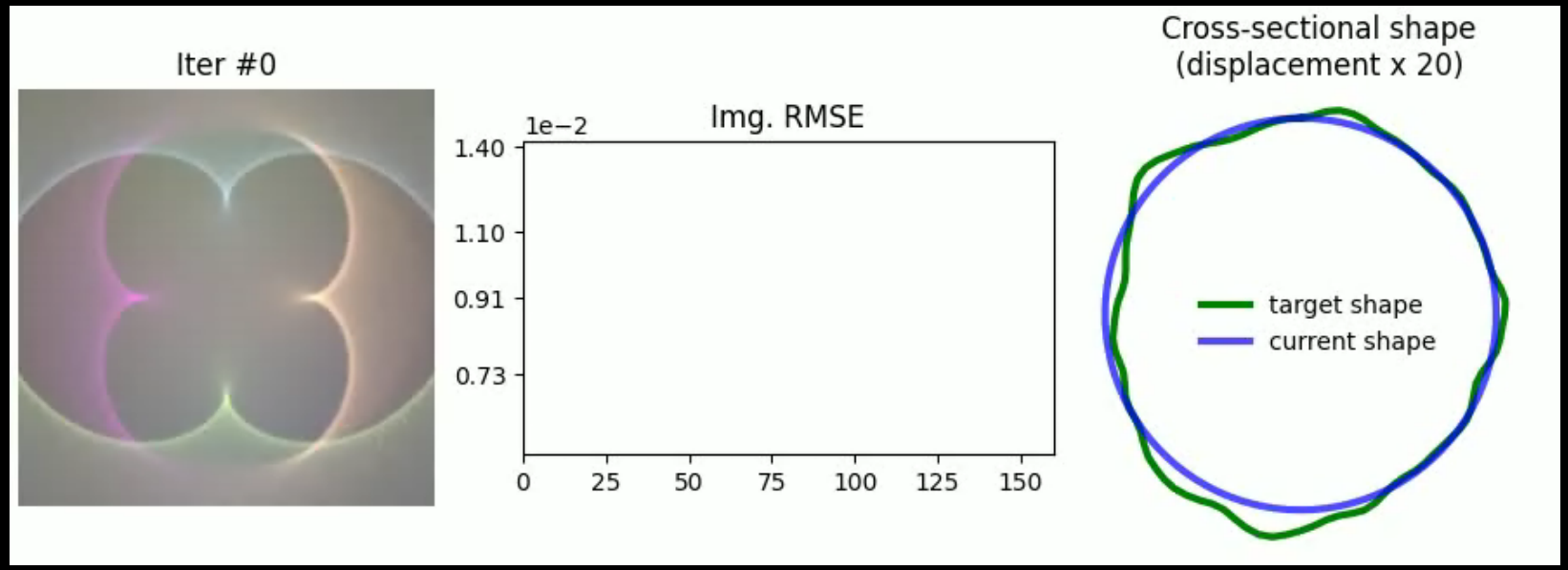


Initial

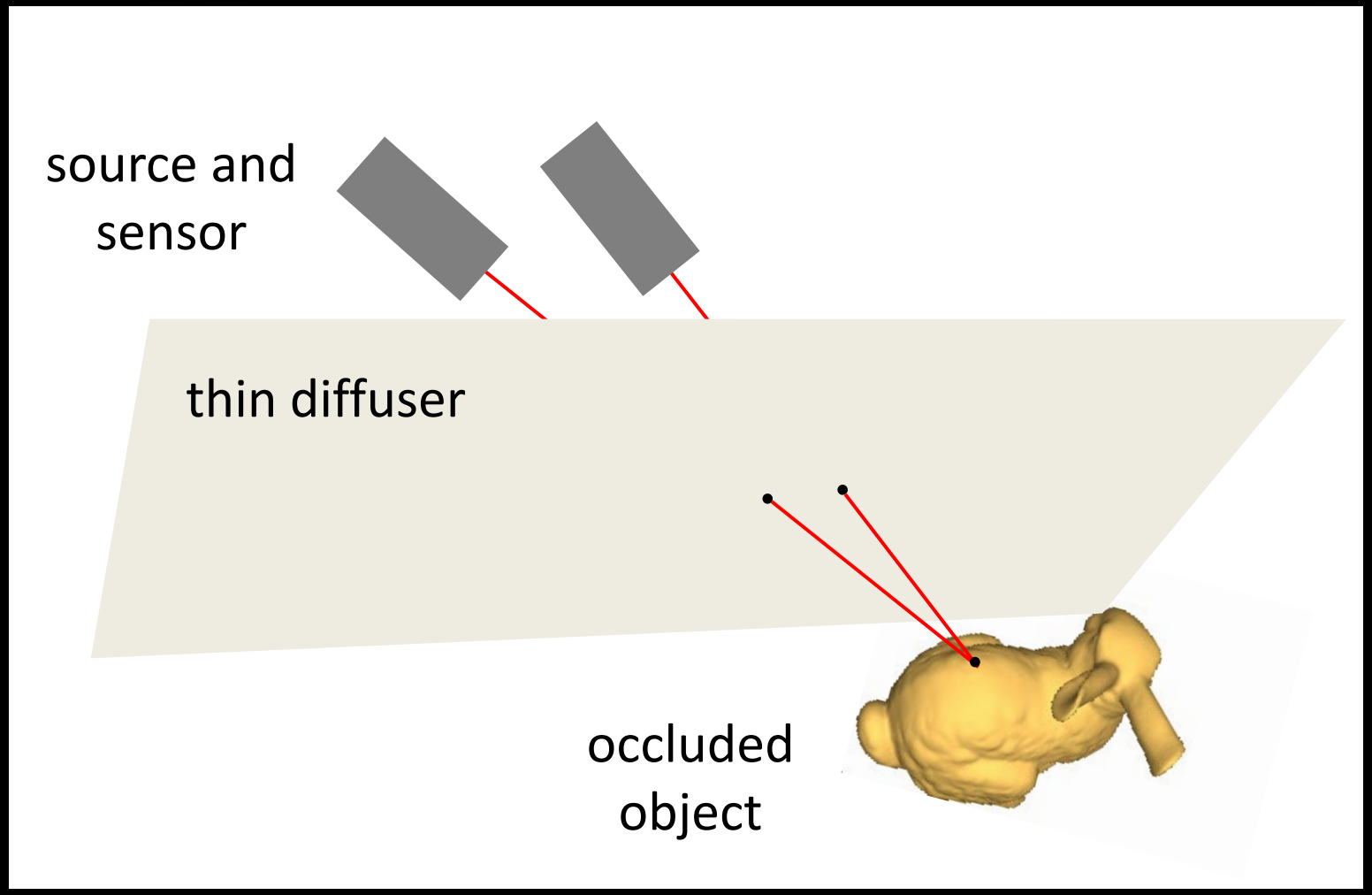


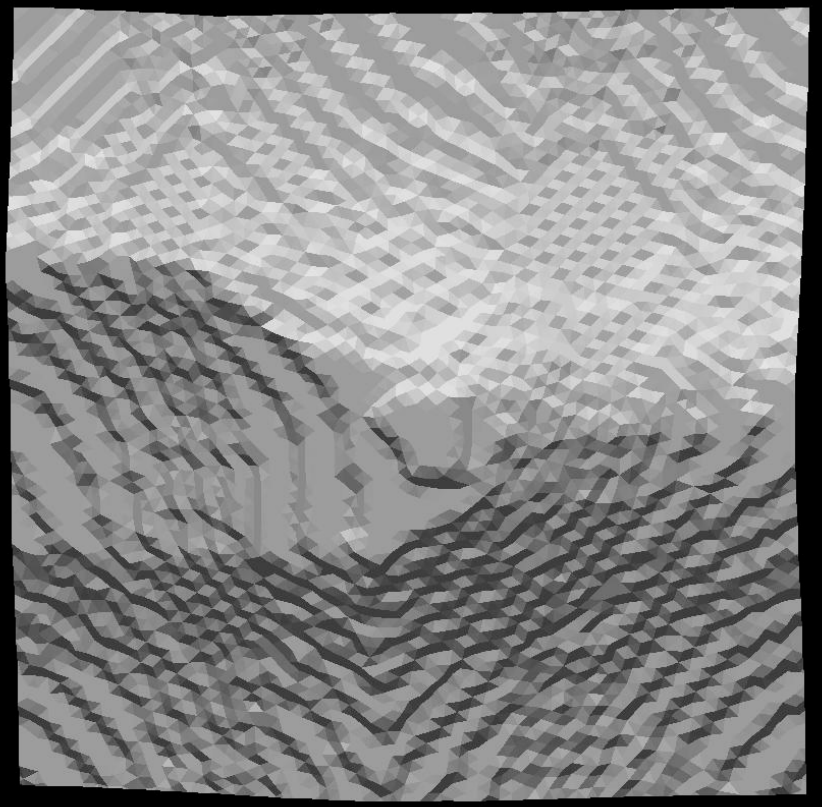
Target image





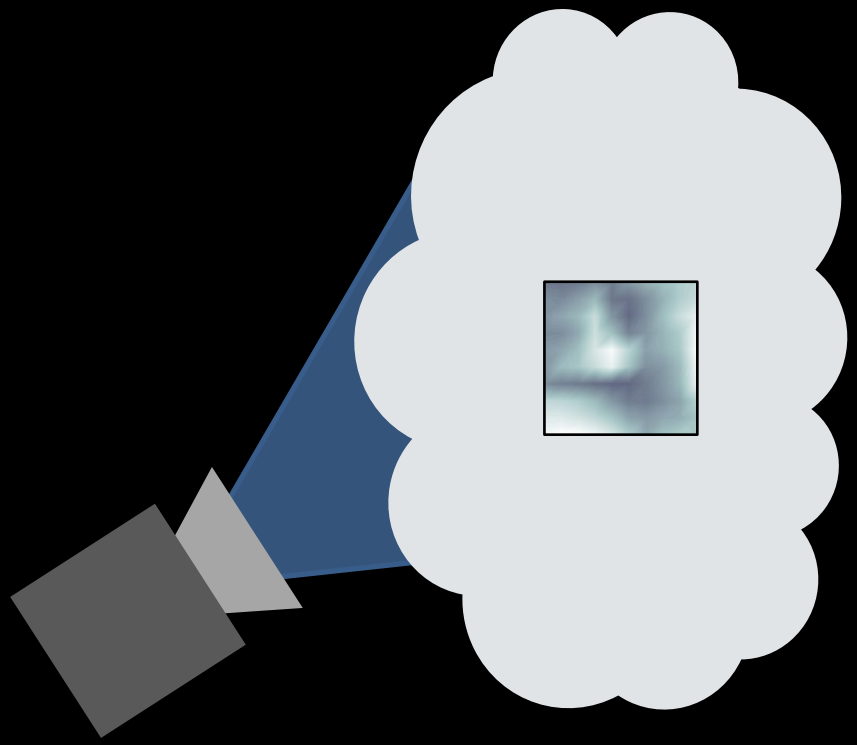
Application: non-line-of-sight imaging





reconstruction evolution

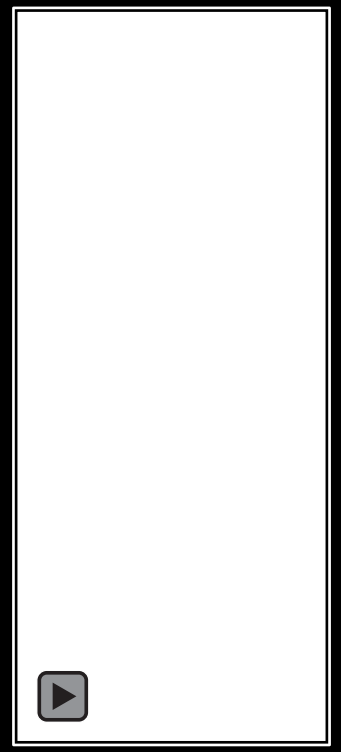
Application: non-invasive tomography



camera

thick smoke cloud

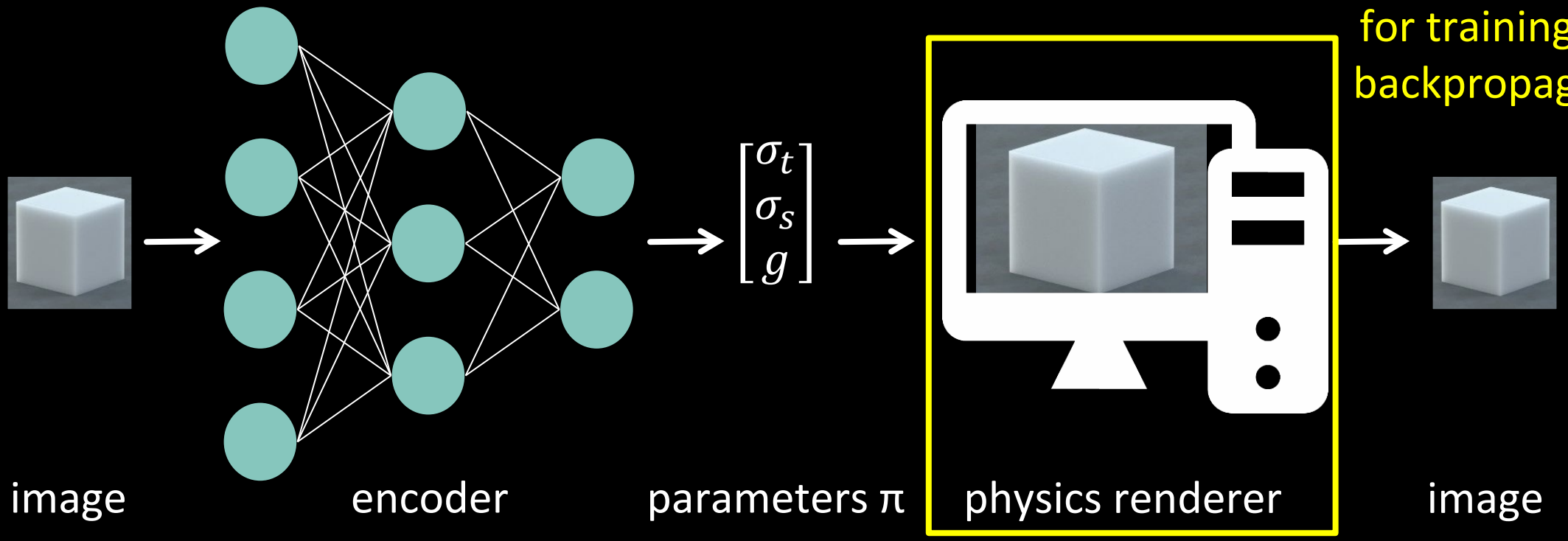
simulated camera measurements



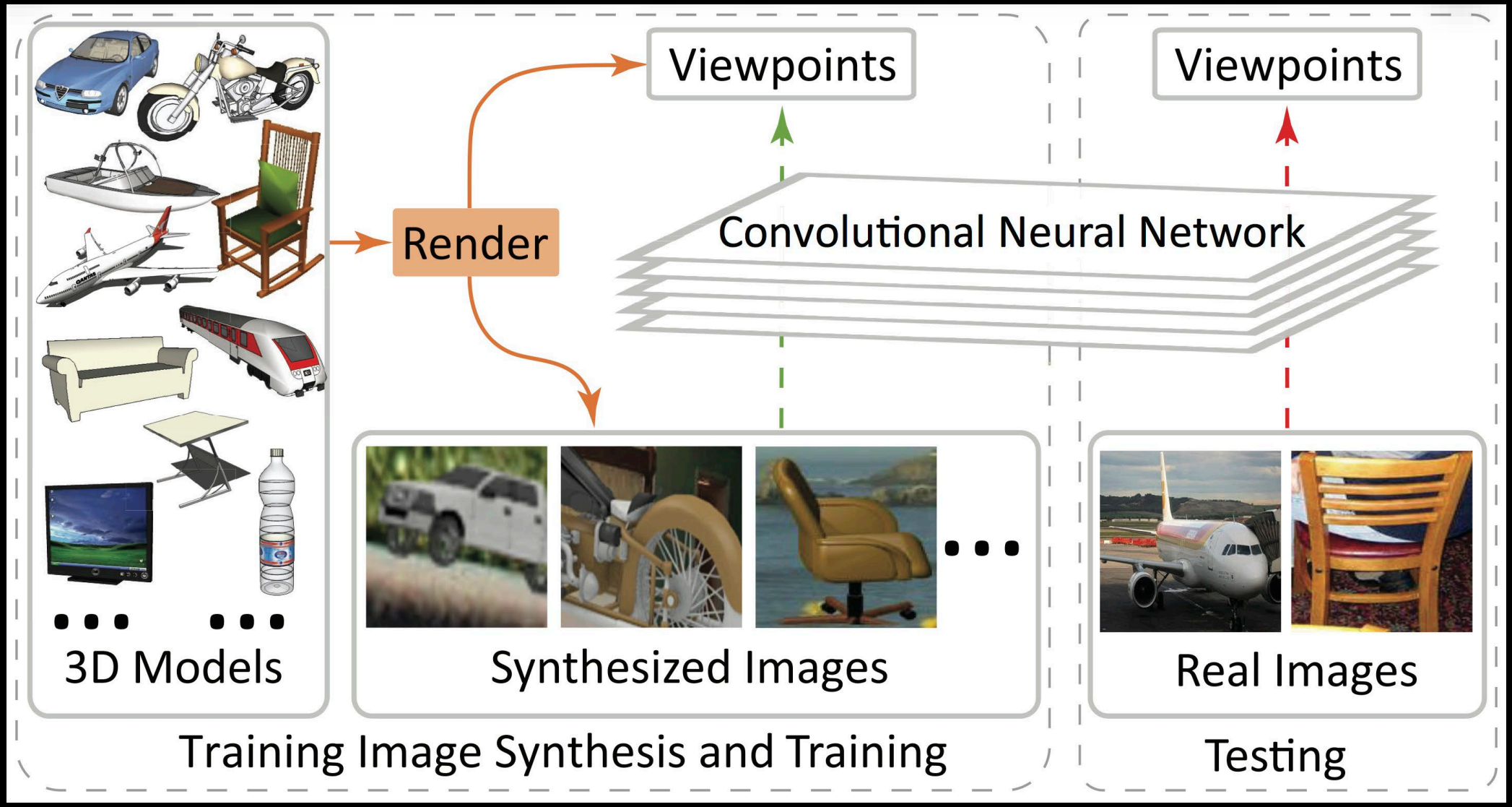
reconstructed cloud volume

slice through the cloud

Application: vision and machine learning

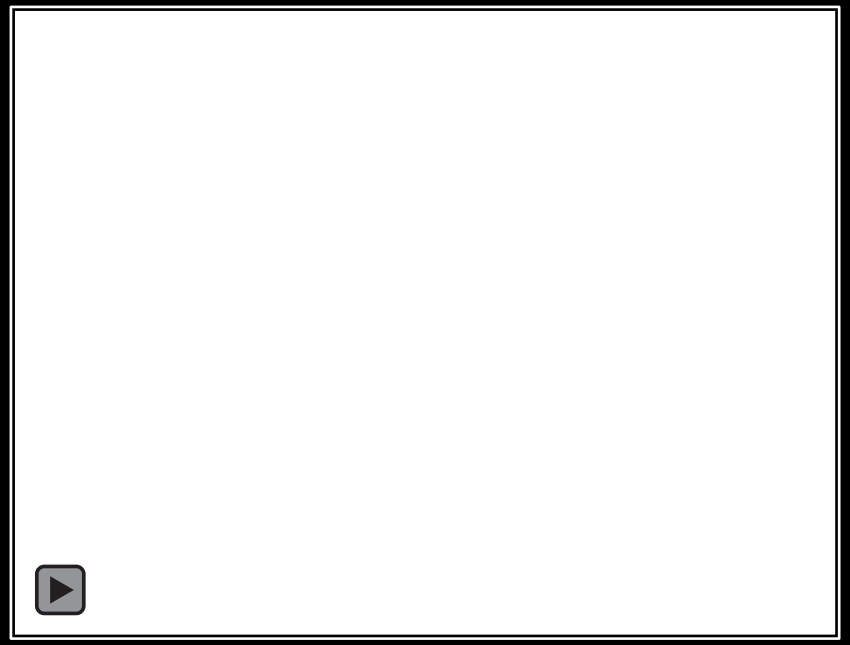


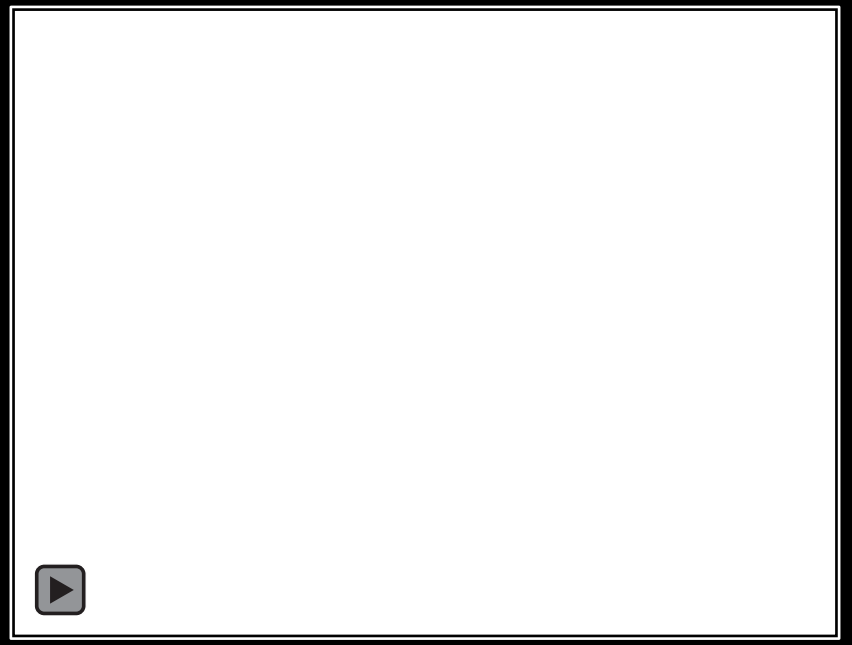
Application: vision and machine learning

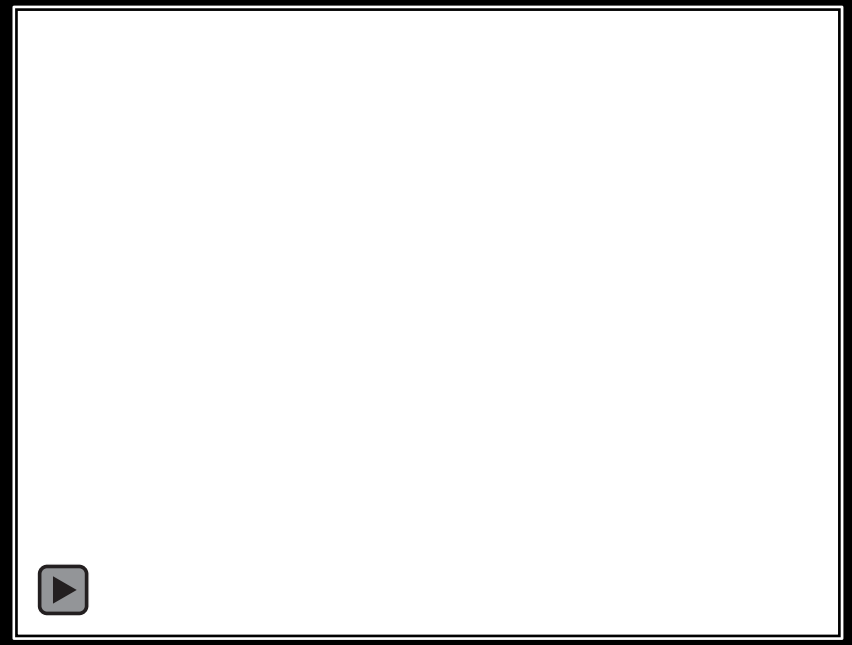


Render for CNN: Viewpoint Estimation in Images Using CNNs Trained with Rendered 3D Model Views [Su et al. ICCV 2015]

Application: neural rendering







NeRF: Representing Scenes as Neural Radiance Fields for View Synthesis [MildenHall et al. ECCV 2020]

Course fast-forward and logistics

Course logistics

- Course website:

  http://graphics.cs.cmu.edu/courses/15-468

- Piazza for discussion and announcements (sign up!):

  https://piazza.com/class/lctj7gng8wql4

- Canvas for homework submissions, Zoom links, and recordings:

  https://canvas.cmu.edu/courses/33678

- Slack server for real-time discussion:

  See Piazza for the invite link

Please take the start-of-semester survey!

- Posted on Piazza as well:

https://docs.google.com/forms/d/e/1FAIpQLSck7-jEcCVsFCUA-WBp4y9pvCHl2g_NSAGXvXv7y7iMDdBlyw/viewform

- We use the survey to:
  - Get a better idea of students' background.
  - Decide on day and time of recitations.
  - Decide on day and time of office hours.
  - Decide on day and time of reading groups.

Course fast-forward

Tentative syllabus at:

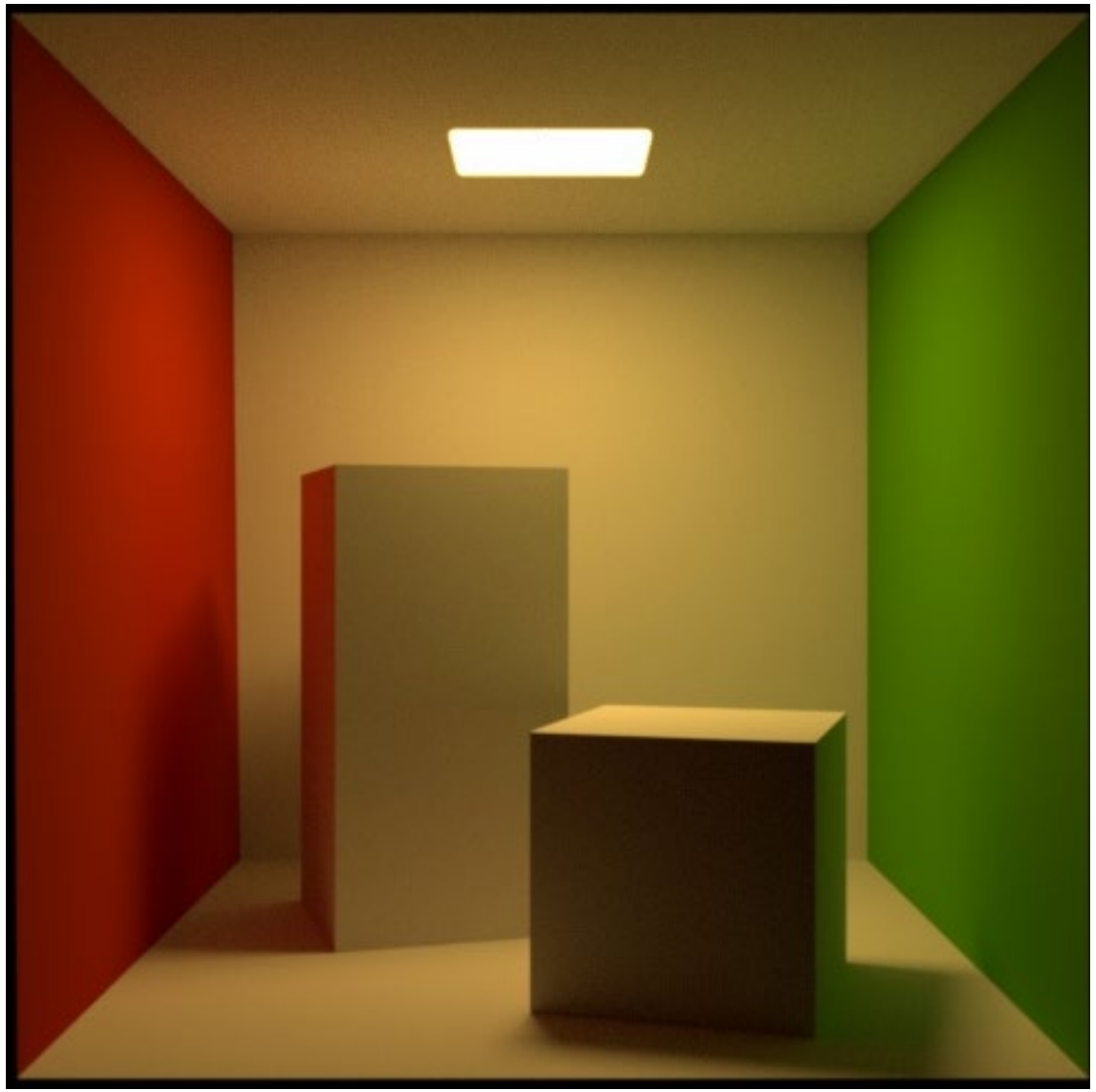
http://graphics.cs.cmu.edu/courses/15-468

- schedule and exact topics will almost certainly change during semester
- keep an eye out on the website for updates

Topics to be covered

Basics of ray tracing:

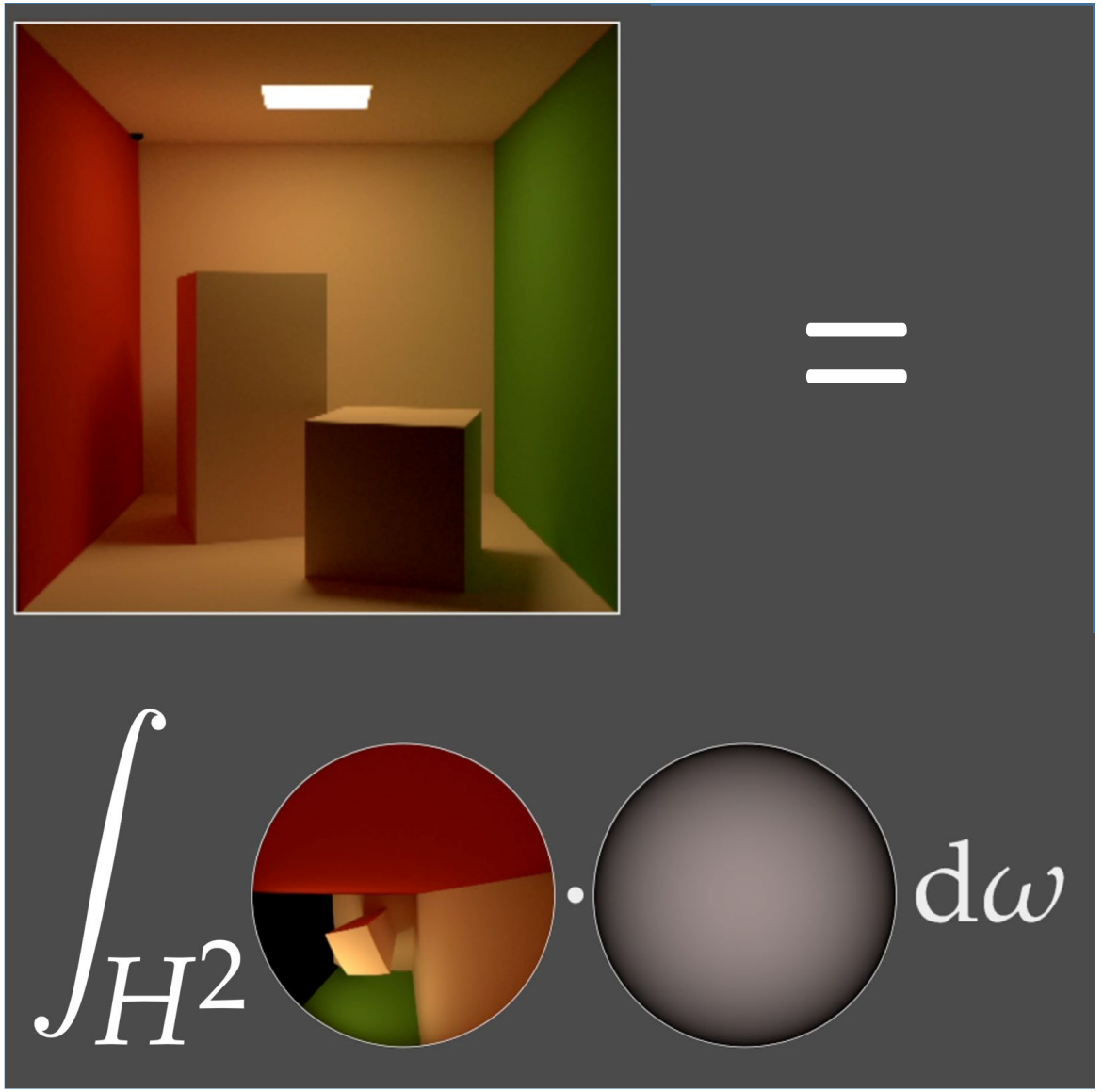
- trace-intersect recursions
- basic camera and illumination models
- shading
- intersection queries
- texture mapping



Topics to be covered

Theory of light transport and materials:

- rendering equation
- radiative transfer equation
- path integral formulations
- microfacet reflectance models
- statistical scattering models



Topics to be covered

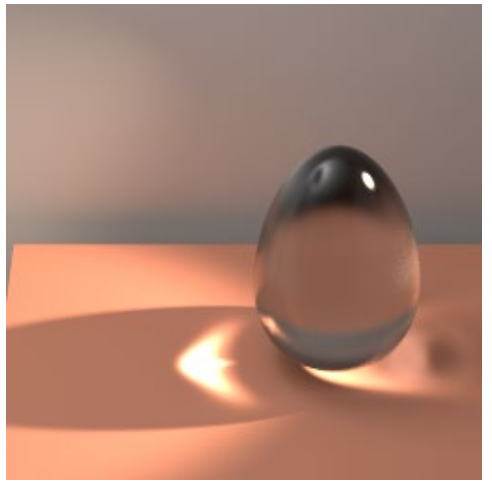
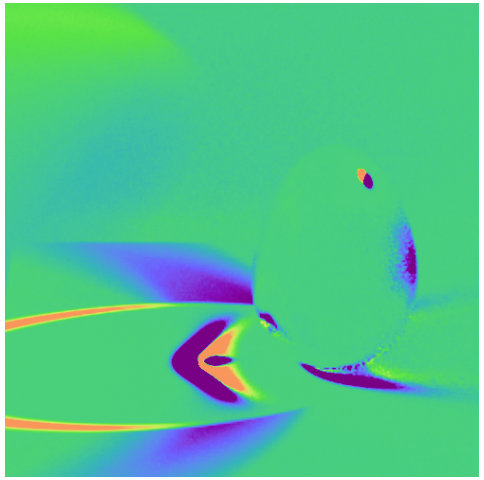
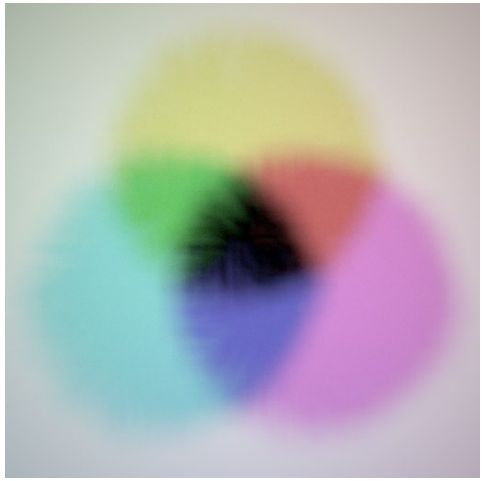
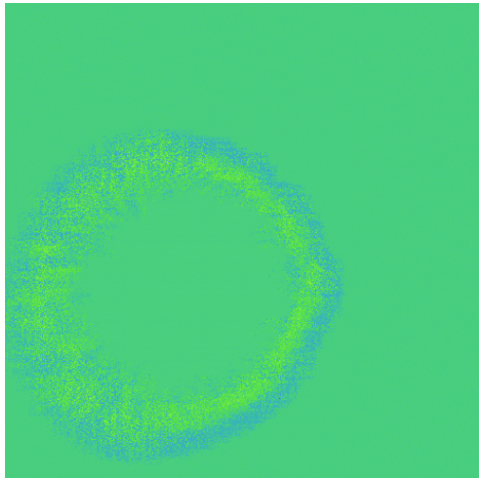
Monte Carlo rendering algorithms:

- unidirectional and bidirectional estimators
- Markov chain Monte Carlo techniques
- volumetric rendering
- importance sampling techniques
- quasi-Monte Carlo techniques

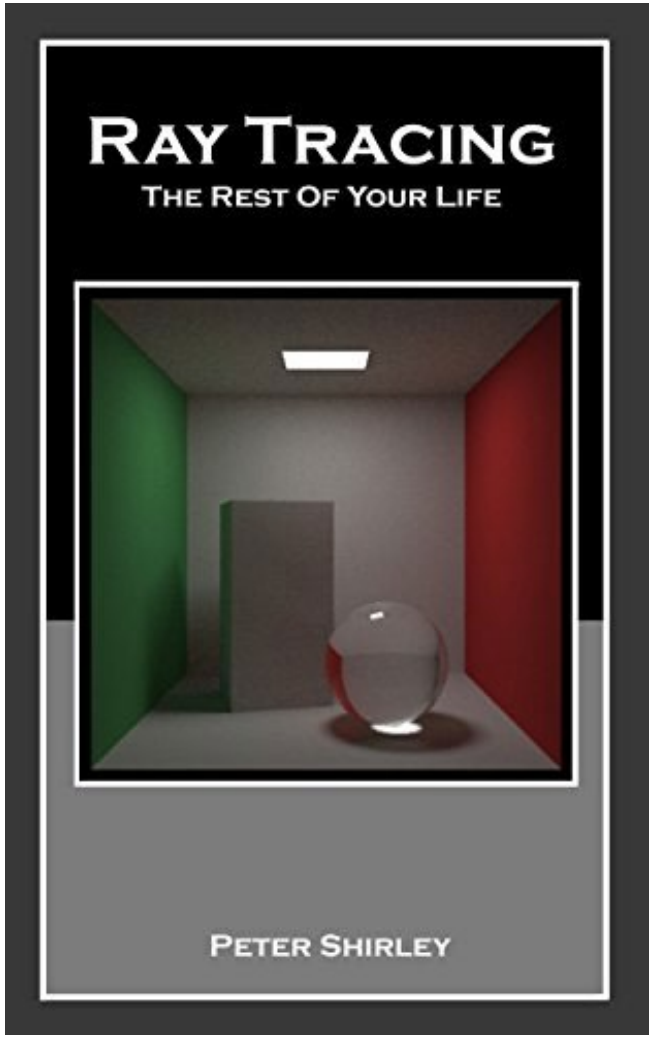
Topics to be covered

Advanced topics:

- differentiable rendering
- neural rendering
- rendering wave-optics effects
- rendering specular transport effects
- rendering eikonal transport effects

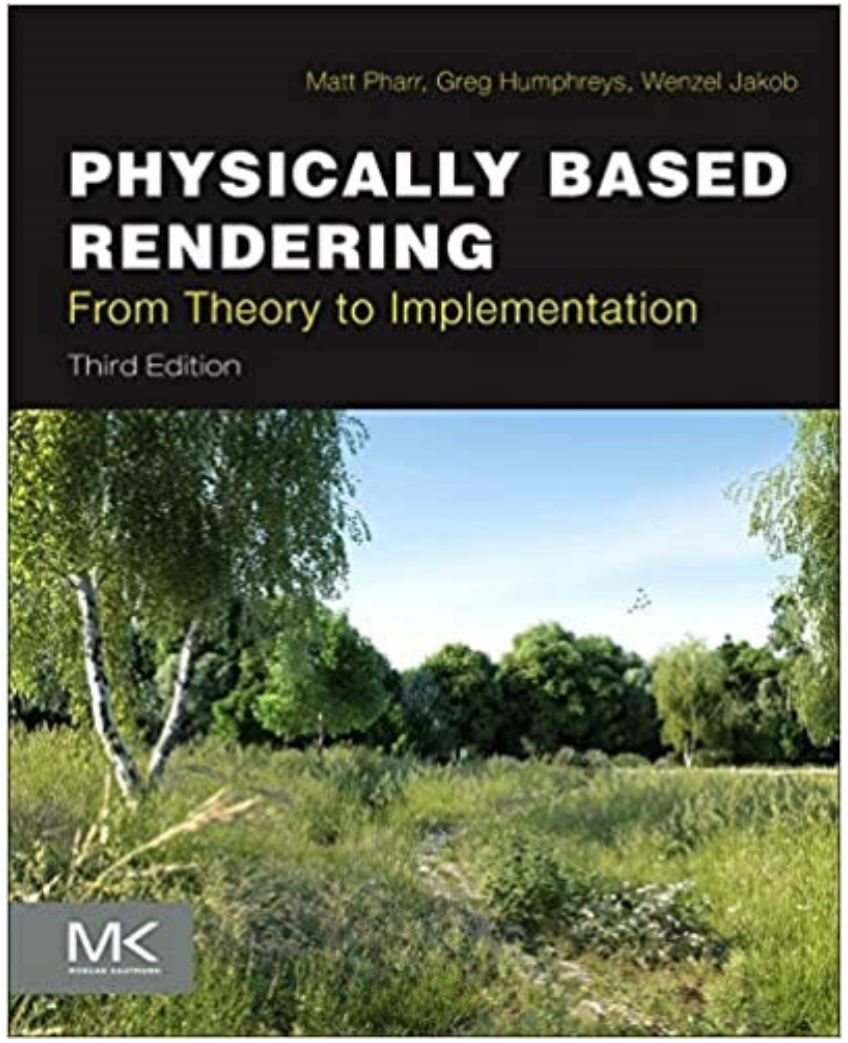
Books



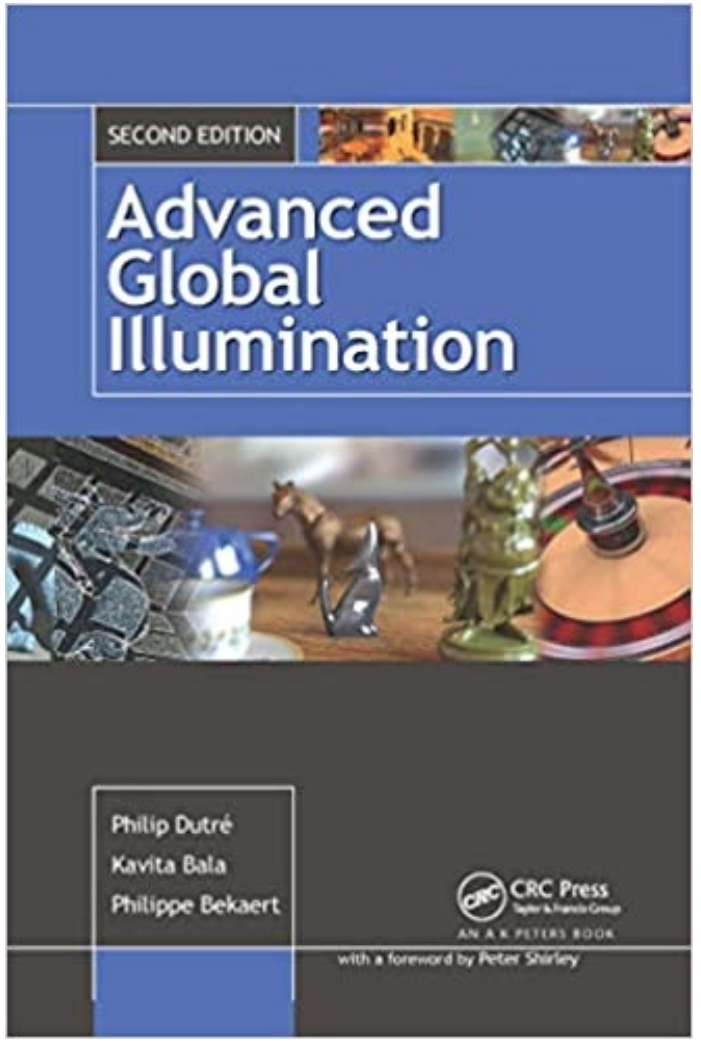
Peter Shirley's "Ray Tracing" series.

- Great reference material for first programming assignment.

Books

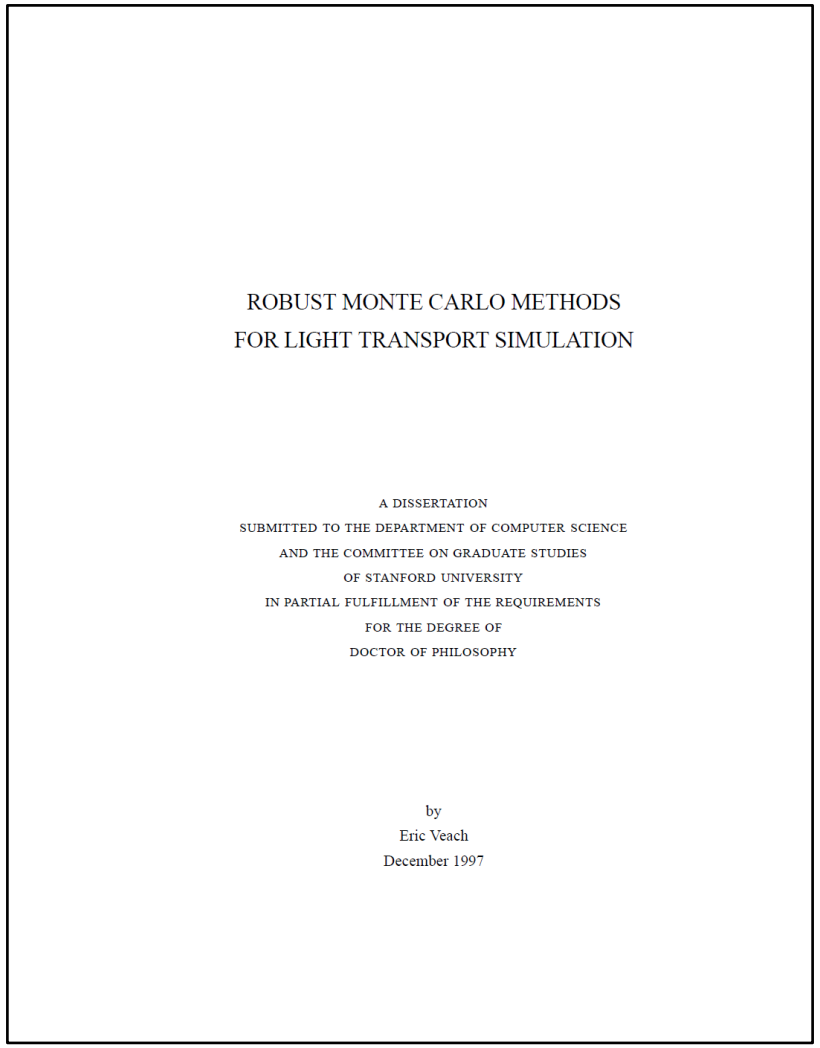


"PBR(T)", great reference for later programming assignments.



"AGI", great reference for theoretical aspects of the course.

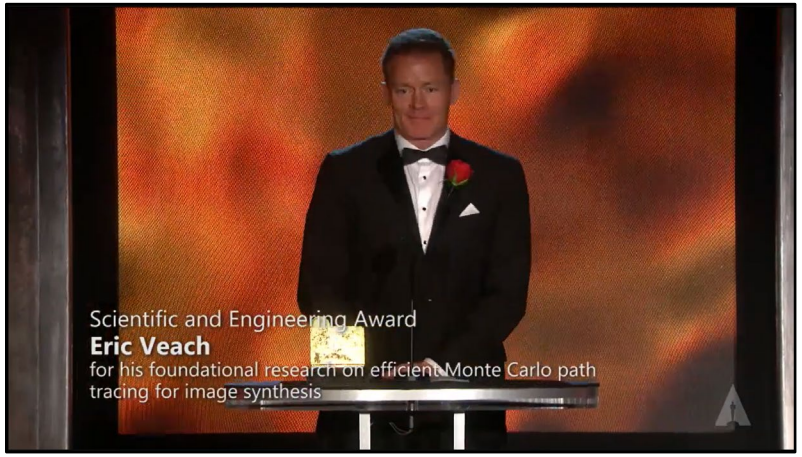
Books



ROBUST MONTE CARLO METHODS
FOR LIGHT TRANSPORT SIMULATION

A DISSERTATION
SUBMITTED TO THE DEPARTMENT OF COMPUTER SCIENCE
AND THE COMMITTEE ON GRADUATE STUDIES
OF STANFORD UNIVERSITY
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

by
Eric Veach
December 1997



This thesis has won an Oscar!

Eric Veach's thesis, probably the best *technical* reference for physics-based rendering

Prerequisites

At least one of the following:

- A computer vision course at the level of 16-385 or 16-720.
- A computer graphics course at the level of 15-462/15-662.
- A computational photography course at the level of 15-463/15-663/15-862.

Pop quiz

How many of you know or have heard of the following terms:

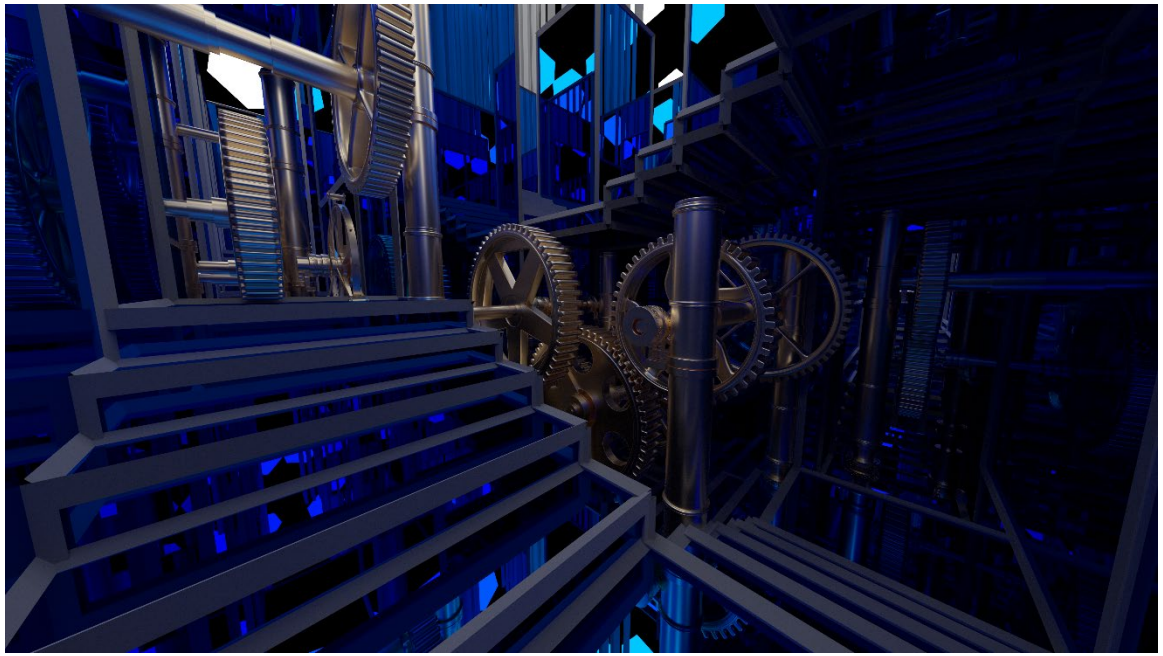
- Gaussian and box filtering.
- Convolution and Fourier transform.
- Aliasing and anti-aliasing.
- Homogeneous coordinates.
- Affine transforms and homographies.
- Pinhole, perspective, and orthographic camera.
- Triangular mesh.
- Ray-mesh intersections.
- Texture mapping.
- Radiometry and radiance.
- Lambertian, diffuse, and specular BRDFs.
- n-dot-l lighting.
- Environment map.
- Point and directional light sources.
- Ray tracing.
- Monte Carlo estimation.
- Refraction and diffraction.

Evaluation

- Four programming assignments (50%):
  - implement progressively more advanced features within an existing barebones rendering framework.
  - all programming will be in **C++**.
  - 0-th assignment will serve as a gentle introduction to our simplified version of Nori educational renderer.
  - five late days, no more than three per assignment, 10% penalty per additional late day.
- Ten take-home quizzes (20%):
  - solve 2-3 simple math problems related to each week's lectures.
  - **no late days, we will do solutions in recitations.**
  - you can skip two out of ten quizzes without penalty.
- Final project and rendering competition (25%):
  - implement rendering features of your choice and produce compelling imagery.
  - compete for **two free SIGGRAPH registrations (technical award and artistic award)!**
  - we will provide more information towards the end of February.
  - 15-668, 15-868 require more substantive project.
  - **no exam, but final project presentations are during the exam period.**
- Class, Piazza, and Slack participation (5%):
  - be around for (at least one of) lectures, office hours, recitations, reading groups.
  - participate in Piazza and Slack discussions.
  - ask questions and answer other people's questions.

Submission deadlines will be enforced strictly!

Final project competition, Spring 2021

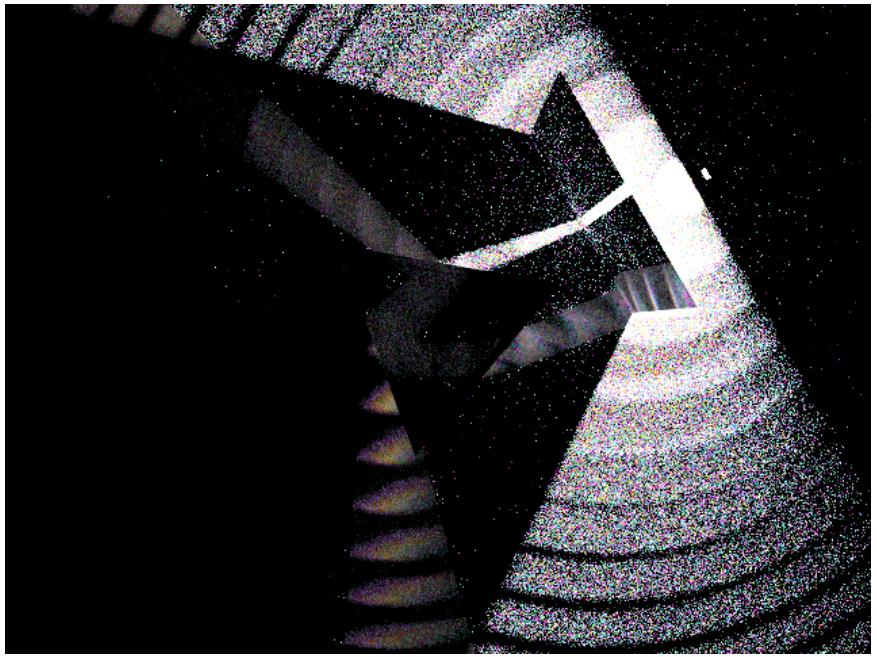


Technical award winner: Max Slater

Art award winner: Arpit Agarwal

- All of Spring 2021's final projects:
  - presentations - https://docs.google.com/presentation/d/1qeFYNXn3Z_pbmvTCtEUOtU8JGy1v8zeaQ9MlUJgCP-8/edit
  - renderings - http://graphics.cs.cmu.edu/courses/15-468/2021_spring/rendering_competition.html

Final project competition, Spring 2022



Technical award winner: George Ralph

Art award winner: Daria Mashanova

- All of Spring 2022's final projects:
  - presentations - https://docs.google.com/presentation/d/1Pjs-Gp3uNeQy4wy-LQrn937t2DGYEJGzShBtXPuJQIM/edit
  - renderings - http://graphics.cs.cmu.edu/courses/15-468/2022_spring/rendering_competition.html

Rendering competitions elsewhere

Look at rendering competitions for similar courses at other universities for inspiration!

- Dartmouth (2019, 2017, 2016)
- EPFL (2019, 2018, 2017)
- ETH Zurich (2017, 2016, Fall 2015, Spring 2015, 2014, 2013, 2012)
- UC San Diego (2011, 2010, 2008, 2007, 2006, 2005, 2004, 2003)
- Stanford.

Wednesday recitations

- Every Wednesday, there will be a recitation, where we go over the solutions to that week's take-home quiz.
- Typically, recitations take the form of whiteboard derivations, and free-form discussion.
- **Participation is completely optional.**
- Time will be decided by vote in the start-of-semester survey.

Friday reading groups

- Every second Friday, there will be a reading group to cover in detail an advanced topic selected by students and instructors.
- Typically, reading groups take the form of a review of a group of papers, whiteboard derivations, and free-form discussion.
- **Participation is completely optional.**
- Time will be decided by vote in the start-of-semester survey.
- Topics covered in previous years: specular next-event estimation, Metropolis light transport, null-scattering, optimal multiple importance sampling, ReSTIR, BRDF acquisition, path guiding, transmittance, neural field representations.

Contact information, office hours, and discussion

- Feel free to email us about administrative questions.
  - please use [15468] in email title!
- Technical questions should be asked on Piazza or Slack.
  - we won't answer technical questions through email.
  - you can post anonymously if you prefer.
- Office hours will be determined by vote in the start-of-semester survey.
  - office hours will be in person at the Smith Hall (EDSH) graphics lounge.
  - feel free to email Yannis about additional office hours.
  - you can also just drop by Yannis' office (Smith Hall (EDSH) Rm 225).
  - you can also post on Piazza or DM on Slack for additional office hours.
  - office hours for this week will be announced on Piazza.
- Post-lecture Q&A for 30 minutes.

This course is still highly experimental!

- Third time this course is offered, so expect things to inevitably change throughout the semester.

Interested in research?

- Visit the graphics lab and imaging group websites:

http://graphics.cs.cmu.edu/
https://imaging.cs.cmu.edu/

- Email Yannis if you want to be added to the graphics lab mailing list and attend our weekly meetings (**Wednesdays, 5 – 6 pm ET**).

- We are actively recruiting research assistants for projects relating to **rendering**, imaging, and graphics in general. Please email Yannis if interested.

Please take the start-of-semester survey!

- Posted on Piazza as well:

https://docs.google.com/forms/d/e/1FAIpQLSck7-jEcCVsFCUA-WBp4y9pvCHl2g_NSAGXvXv7y7iMDdBlyw/viewform

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