



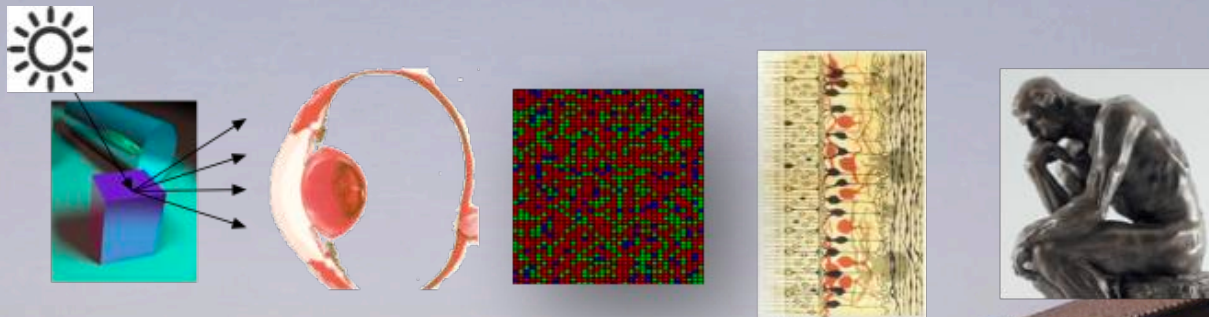
Modeling the Initial Steps of Human Vision

Brian Wandell, Stanford University

David Brainard, University of Pennsylvania

ISETBio and ISET3d: Modeling 3D scenes and human image formation

Brian Wandell and David Brainard



QUANTITATIVE MEASUREMENTS

∞

COMPUTATIONAL MODELS

∞

CHECK AND SHARE

What I review and why

- **Background:** ISETBio (Image Systems Engineering Tools for Biology) provides computational tools that implement the ideas developed by vision scientists.



- **What:** ISET3d is are tools that extend ISETBio computations from planar images into three-dimensional scenes. My goal today is to explain ISET3d.

- **Why:** The extension to 3D may be relevant to scientists and engineers who aim to
 - Model and understand the visual encoding of natural images and stereo vision,
 - Optimize devices, including cameras and displays, for capturing and rendering 3D scenes.



3D scene spectral radiance in the world and at the eye

Gershun (1936)

Ray intensities: $L(x,y,z,\alpha,\beta,\lambda,\theta)$

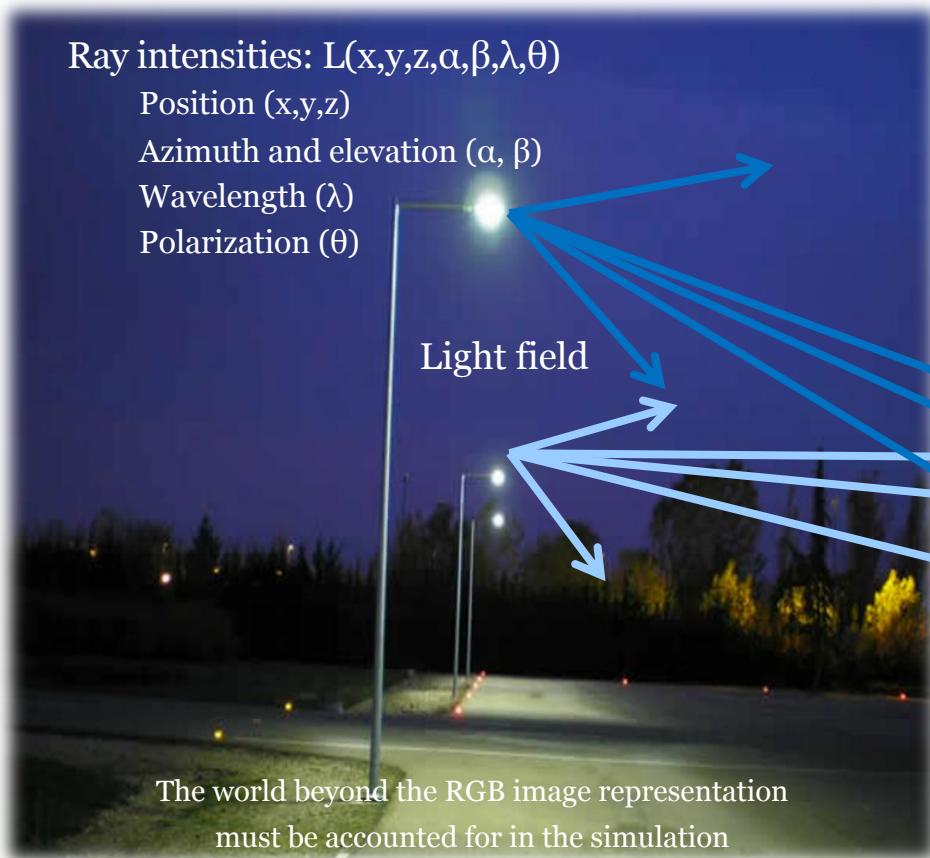
Position (x,y,z)

Azimuth and elevation (α, β)

Wavelength (λ)

Polarization (θ)

Light field



The world beyond the RGB image representation
must be accounted for in the simulation

Adelson and Bergen (1991)

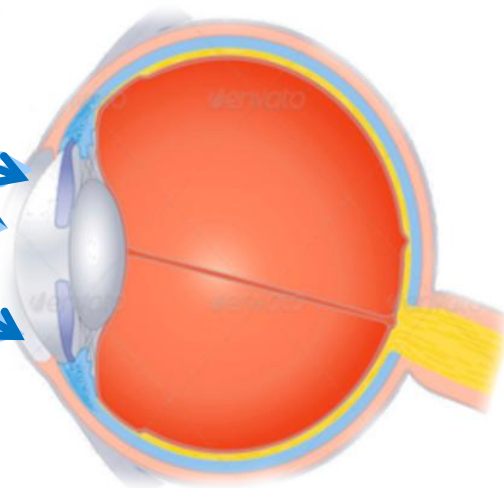
Ray intensities: $L(u,v,\alpha,\beta,\lambda)$

Position (u,v)

Azimuth and elevation (α, β)

Wavelength (λ)

Plenoptic
function



Graphics tools: Cinema 4D

- There are many tools for creating realistic 3D scene geometries
- We use Cinema 4D from Maxon because it integrates well with ray tracing methods
- Maxon offers **free** Cinema 4D licenses to students and teachers, and low- or no-cost “lab” licenses for schools.

PRODUCTS NEWS SOLUTIONS GALLERY LEARN TRY BUY

American English

OVERVIEW FEATURES NEW IN S22 SYSTEM REQUIREMENTS INTEGRATION

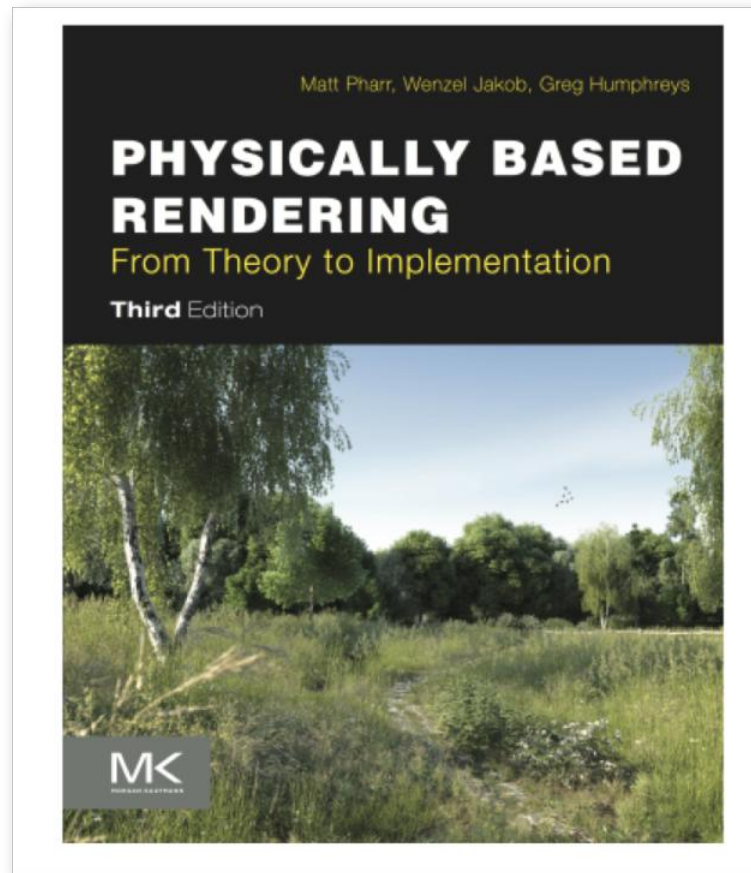
Why Cinema 4D?

Easy to learn and extremely powerful: Cinema 4D is the perfect package for all 3D artists who want to achieve breathtaking results fast and hassle-free. Beginners and seasoned professionals alike can take advantage of Cinema 4D's wide range of tools and features to quickly achieve stunning results. Cinema 4D's legendary reliability also makes it the perfect application for demanding, fast-paced 3D production.

WATCH SHOWREEL

Graphics tools: Quantitative computer graphics is a necessary component

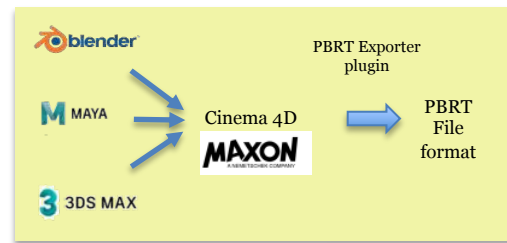
- Progress in computer graphics enables us to create synthetic and yet highly realistic input data.
- We use PBRT because it is open-source, extensible, and taught at Stanford
- The simulations can maintain meaningful units; quantitative computer graphics
- A GPU version is scheduled to be released by Pharr et al. in about 2 months



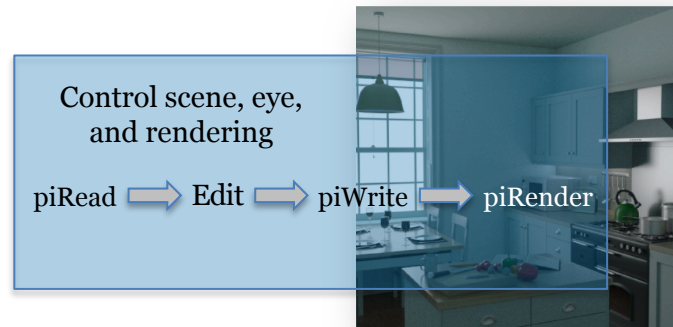
ISET3d: From PBRT to ISETBio (pi)

- In the next 15 minutes I illustrate the ISET3d computational framework
- I will show you
 - The **kinds of stimuli** that we are producing and
 - The programming approach in the specific case of simulating human **physiological optics** (image formation)
- David and I are producing YouTube videos of the tools that illustrate many more computations
- We use ISET3d for camera design, as well.

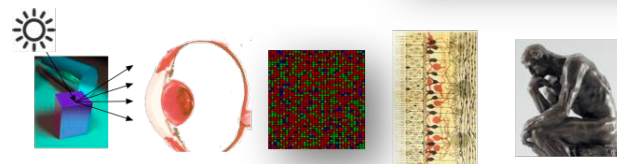
3d models

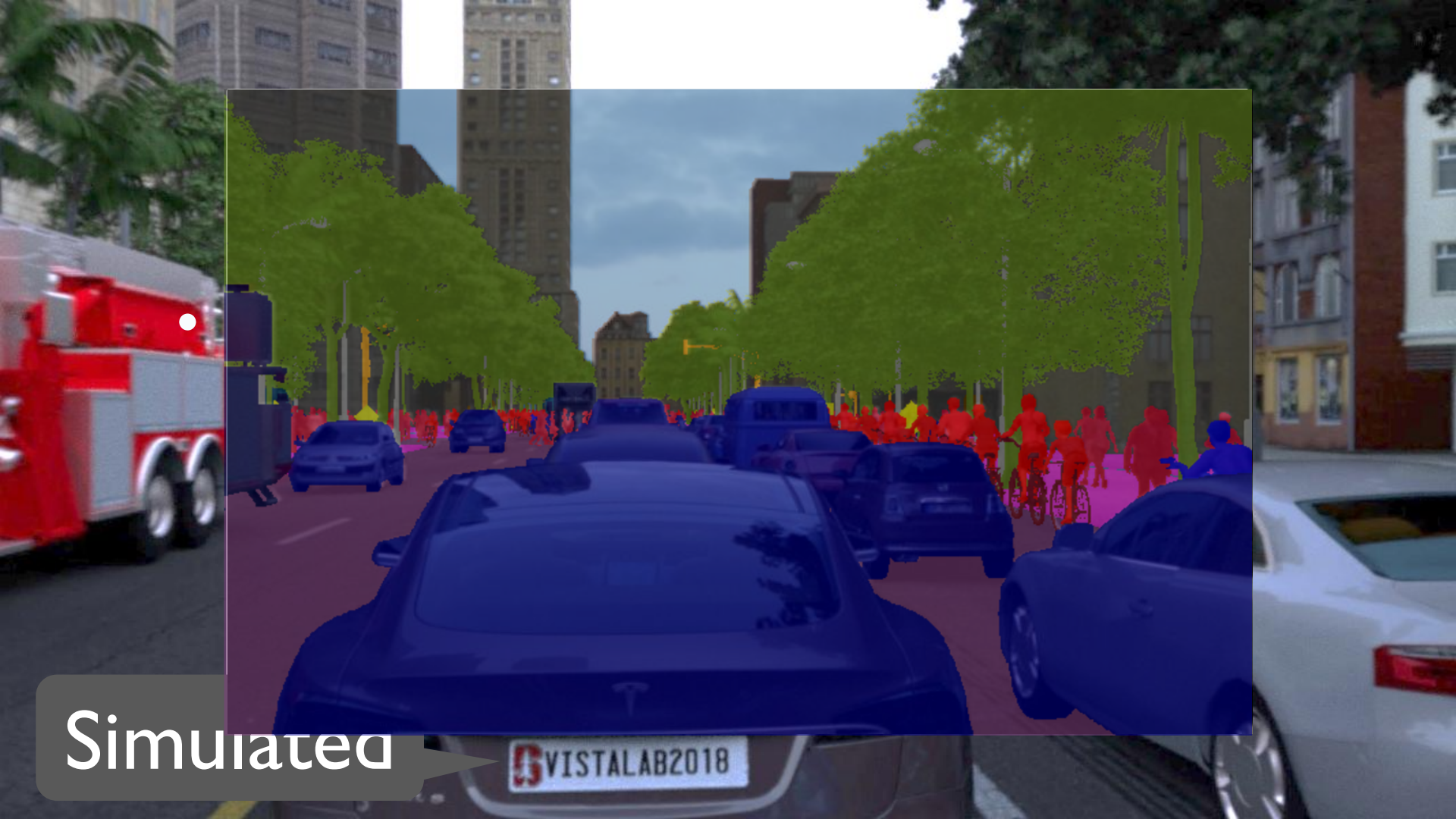


ISET3d



ISETBio





Simulated

ISET_{3D} extension to incorporate human optics

OPEN ACCESS

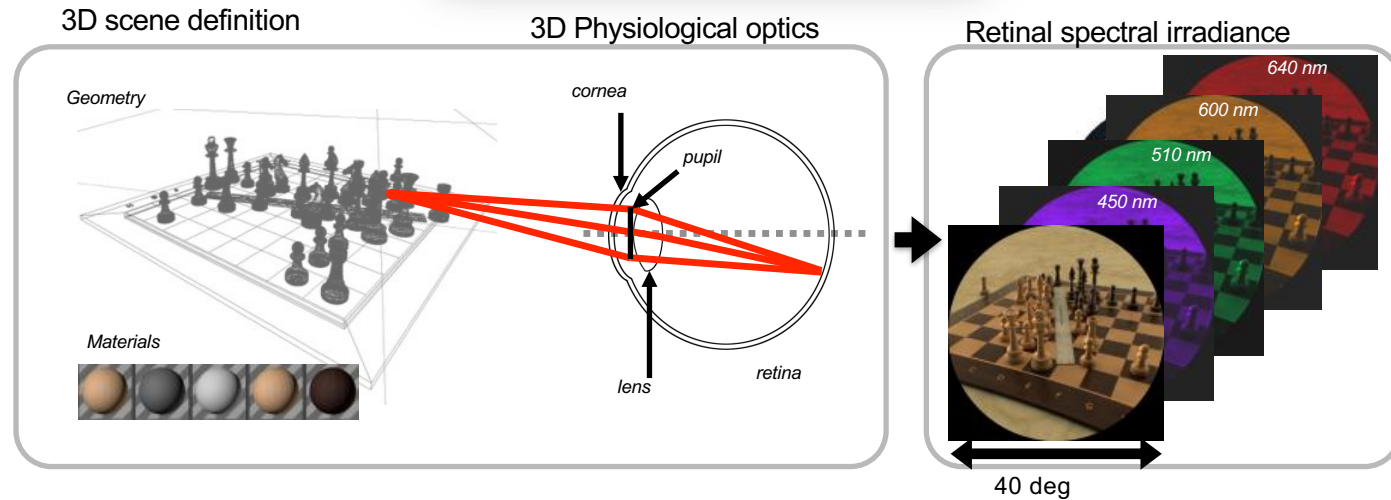
Article | October 2019

Ray tracing 3D spectral scenes through human optics models

Trisha Lian; Kevin J. MacKenzie; David H. Brainard; Nicolas P. Cottaris; Brian A. Wandell

+ Author Affiliations

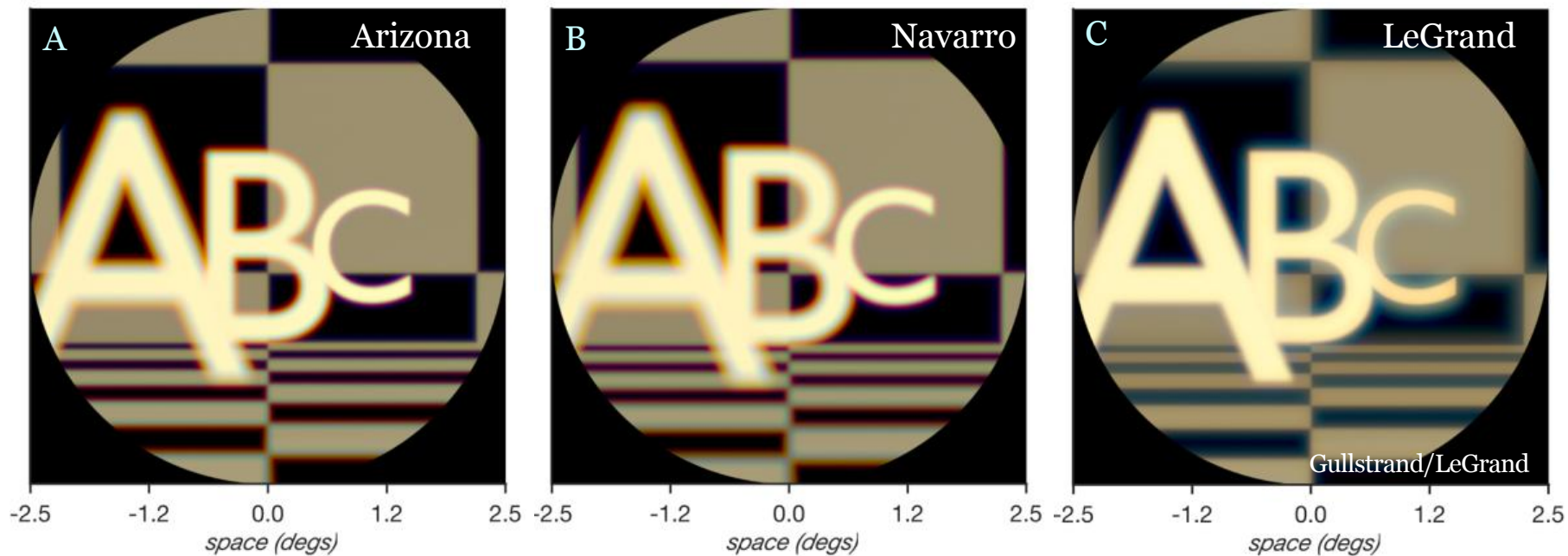
Journal of Vision October 2019, Vol.19, 23. doi:<https://doi.org/10.1167/19.12.23>



Use computer graphics and ray-tracing to model how spectral, 3D scenes are transformed by human optics to the retinal irradiance.

Comparison of eye models

The code flexibility accommodates the major human eye models
(Lian et al. 2019, Journal of Vision).



Example code

The sceneEye class constructor

- This script illustrates the programming philosophy from the user's perspective
- By default the sceneEye uses the Navarro model to render a 3D scene; LeGrand and Arizona eye models are also included

```
thisSE = sceneEye('letters at depth', 'human eye', 'legrand');
```

PBRT files

Human eye model

```
>> thisSE  
  
thisSE =  
  
sceneEye with properties:  
  
    name: 'lettersAtDepth'  
    modelName: 'legrand'  
    usePinhole: 0  
    recipe: [1×1 recipe]  
    lensDensity: 1
```

Example code

- The code doing the computational work in ISET3d is managed within
 - The set/get methods
 - PBRT calculations
- You can ‘set’ many camera, rendering, and scene parameters
- You can ‘get’ many more parameters by calculation
- There are a number of methods ‘render’, ‘summary’ and others

```
% Suppose you are in focus at the proper distance to the edge. And we turn
% on chromatic aberration. That will slow down the calculation, but makes
% it more accurate and interesting. We only use 8 spectral bands for
% speed. You can use up to 31.
nSpectralBands = 8;
thisSE.set('chromatic aberration',nSpectralBands);

% This is the distance we calculate above
thisSE.set('focal distance',1);

% Controls the rendering noise vs. speed by setting the number of rays.
thisSE.set('rays per pixel',128);

% Increase the spatial resolution by adding more spatial samples.
thisSE.set('spatial samples',384);


% This takes longer than the pinhole rendering, so we do not bother with
% the depth.
oi = thisSE.render('render type','radiance');
oiWindow(oi);
```

Image formation (optics) models and quantitative graphics

Stereo pairs: move the camera position by 6 cm
thisEye.set('from',loc)

Right eye

Right eye view



Optical image
Size: [512, 512] samples
Hgt,width: [8.75, 8.75] mm
Sample: 17.08 um
Wave: 400:10:690 nm
Illum: 10.0 lux
FOV (wide): 30.0 deg
Optics (DL)
Mag: 0.00e+00
Diameter: 6.00 mm

Diffraction-limited

F-number Focal Length
2.72 16.32 mm

Off axis (cos4th)


Anti-alias
Skip

1 Standar... Compute Optical Image

Gamma Display

Left eye

Left eye view



Optical image
Size: [512, 512] samples
Hgt,width: [8.75, 8.75] mm
Sample: 17.08 um
Wave: 400:10:690 nm
Illum: 10.0 lux
FOV (wide): 30.0 deg
Optics (DL)
Mag: 0.00e+00
Diameter: 6.00 mm

Diffraction-limited

F-number Focal Length
2.72 16.32 mm

Off axis (cos4th)

Anti-alias
Skip

1 Standar... Compute Optical Image

Gamma Display

- This ISET3d code makes the stereo pair of the Chess retinal irradiance, imaged through the LeGrand model eye
- I set the lens density to 0 so the scene would not look very yellow. I will explain this in a moment

```
%% Make an oi of the chess set scene using the LeGrand eye model
```

```
thisSE = sceneEye('chess set scaled','human eye','legrand');
```

```
thisSE.set('lens density',0); % Just because I can
```

```
thisSE.set('rays per pixel',512); % Pretty quick, but not high quality
```

```
oiLeft = thisSE.render; % Render and show  
oiWindow(oiLeft);
```

```
%% Shift the eye position
```

```
% Change the eye position (from) but stay focused on the same object (to).  
% I shifted the eye position by a lot (12 mm) so the image difference is be  
% easy to see. The inter-pupil difference is really only 6-8 mm
```

```
from = thisSE.get('from'); % Current camera location
```

```
thisSE.set('from',from + [0.012,0,0]); % Shift it 12 mm
```


```
oiRight = thisSE.render;  
oiWindow(oiRight);
```

Natural images - Image formation (optics) models and quantitative graphics

Inert pigments (e.g. lens transmission) are included and controlled

Left eye

Left eye view



Optical image
Size: [512, 512] samples
Hgt,wdth: [8.75, 8.75] mm
Sample: 17.08 μ m
Wave: 400:10:690 nm
Illum: 10.0 lux
FOV (wide): 30.0 deg
Optics (DL)
Mag: 0.00e+00
Diameter: 6.00 mm

Diffraction-limited

F-number Focal Length
2.72 16.32 mm


Off axis (cos4th)

Anti-alias
 Skip

1 Standar... Compute Optical Image

Gamma Display

Left with Lens



Optical image
Size: [512, 512] samples
Hgt,wdth: [8.75, 8.75] mm
Sample: 17.08 μ m
Wave: 400:10:690 nm
Illum: 8.4 lux
FOV (wide): 30.0 deg
Optics (DL)
Mag: 0.00e+00
Diameter: 6.00 mm

Diffraction-limited

F-number Focal Length
2.72 16.32 mm

Off axis (cos4th)

Anti-alias
 Skip

1 Standar... Compute Optical Image

Gamma Display

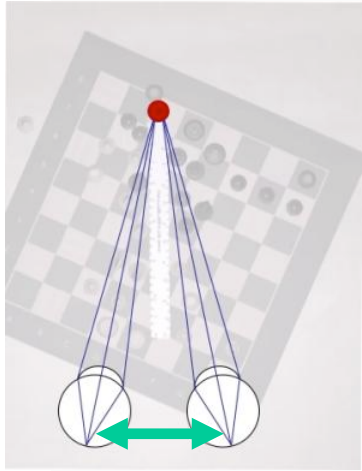
Vergence and Accommodation

Where the eye (or eyes) is looking is controlled
thisEye.set('to',loc)

1.66 D (Left)

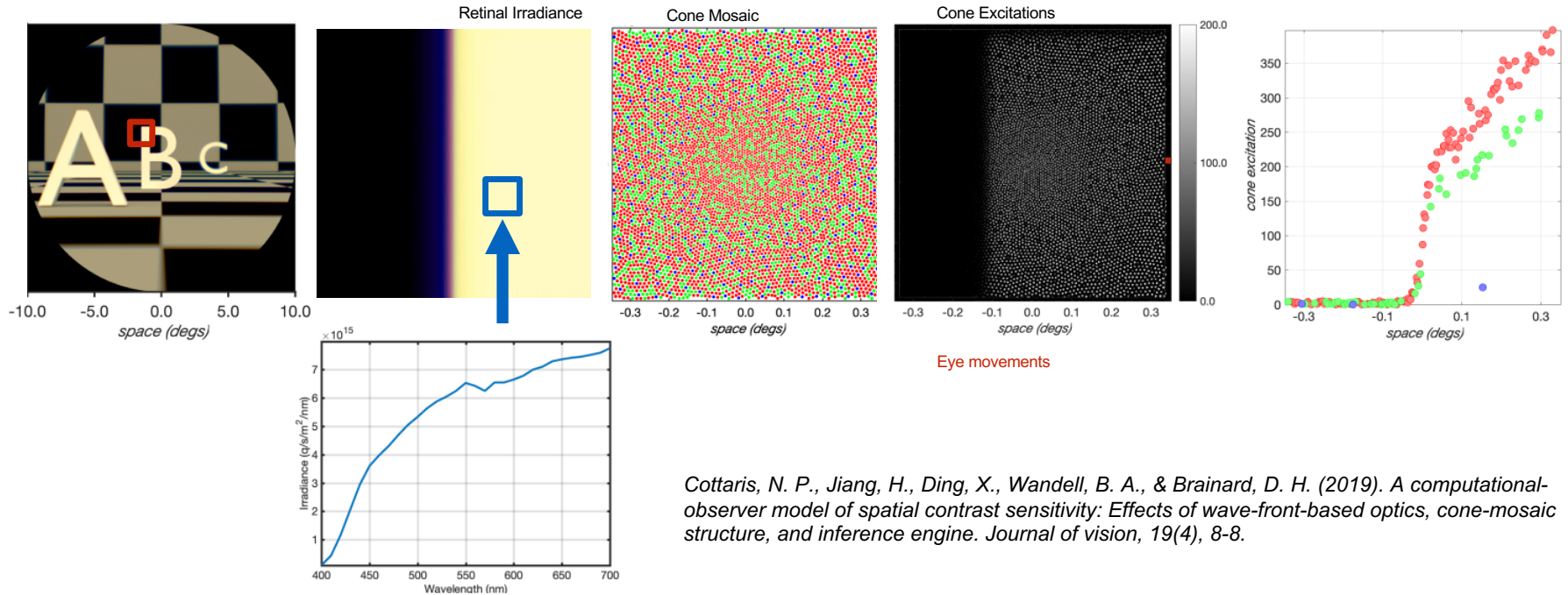


1.66 dpt (Right)



64 mm

Calculating cone responses and eye movements




Cottaris, N. P., Jiang, H., Ding, X., Wandell, B. A., & Brainard, D. H. (2019). A computational-observer model of spatial contrast sensitivity: Effects of wave-front-based optics, cone-mosaic structure, and inference engine. *Journal of vision*, 19(4), 8-8.

Scenes can be quite complex and realistic

- We have more than 25 high quality scenes like these
- The geometry, reflectance, lighting and textures can be edited (ask me)
- This collection will grow and already includes HDR, inter-reflections, many types objects, materials, textures, shadows, occlusions

<- bathroom-Jul-18,12:11 >-



Name: bathroom-Jul-18,12:11
(Row, Col): 512 by 512
Hgt, Wdth (,) um
Sample: um
Deg/samp:
Wave: 400:10:700 nm
DR: Inf
(max 3029, min 0.00 cd/m2)

Adjust scene size

X 1 Interp

Luminance
100.0 cd/m2

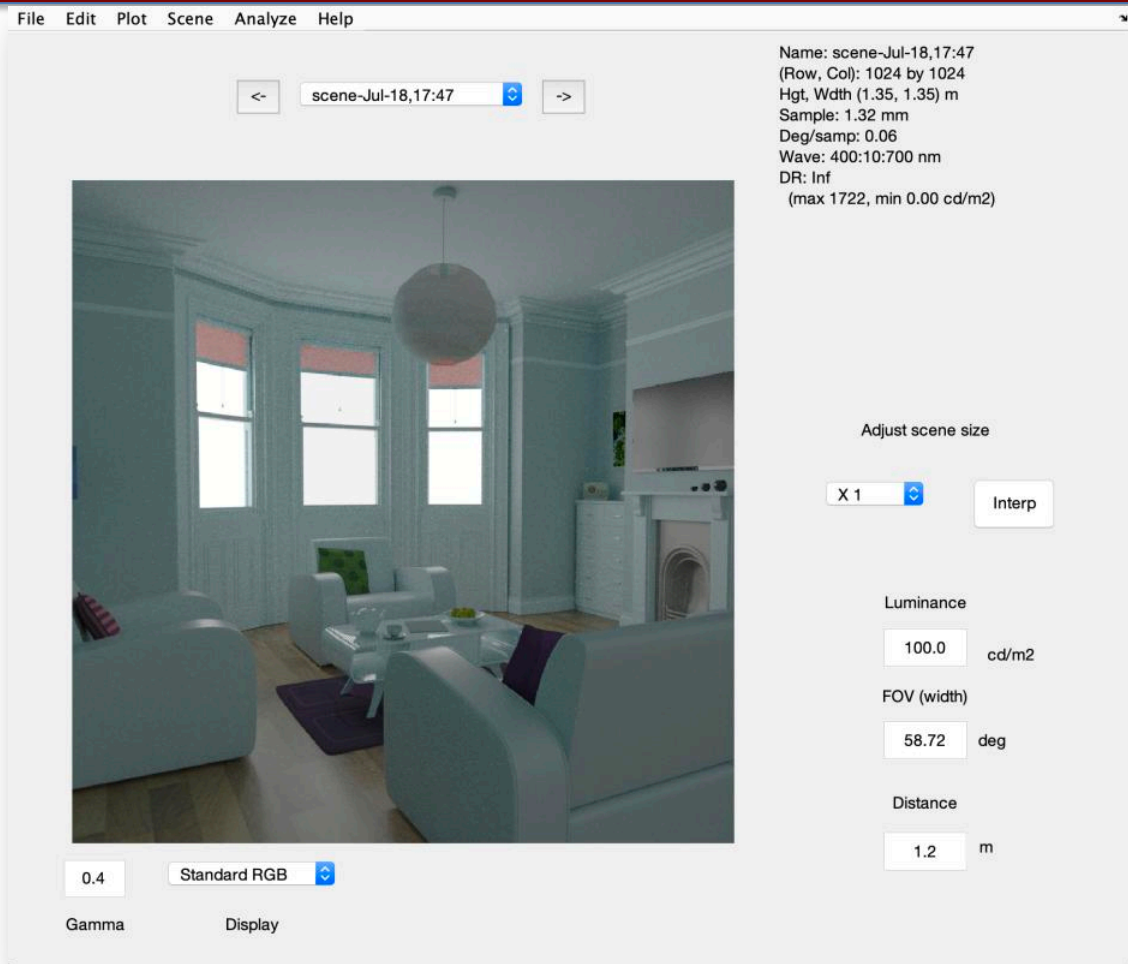
FOV (width)
deg

Distance
1.2 m

0.4 Standard RGB

Gamma Display

- We have more than 25 high quality scenes like these
- The geometry, reflectance, lighting and textures can be edited (ask me)
- This collection will grow and already includes HDR, inter-reflections, many types objects, materials, textures, shadows, occlusions




Scenes can be quite complex and realistic

- We have more than 25 high quality scenes like these
- The geometry, reflectance, lighting and textures can be edited (ask me)
- This collection will grow and already includes HDR, inter-reflections, many types objects, materials, textures, shadows, occlusions

File Edit Plot Scene Analyze Help

<- scene-Jul-18,12:43 >-



Name: scene-Jul-18,12:43
(Row, Col): 512 by 512
Hgt, Wdth (0.78, 0.78) m
Sample: 1.52 mm
Deg/samp: 0.07
Wave: 400:10:700 nm
DR: 114.83 dB (max 1241 cd/m²)

Adjust scene size

X 1 Interp

Luminance
100.0 cd/m²

FOV (width)
35.98 deg

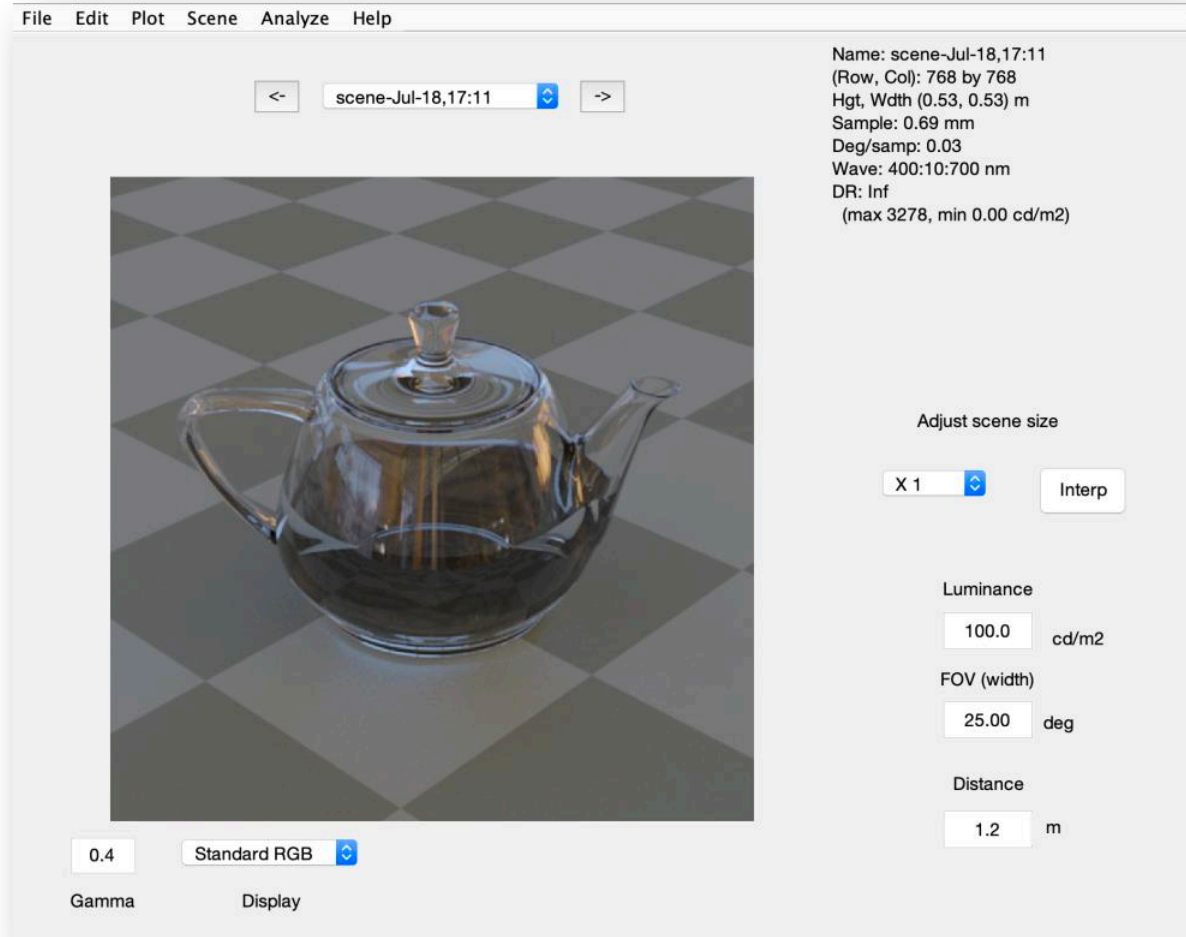
Distance
1.2 m

0.4 Standard RGB

Gamma Display

Scenes can be quite complex and realistic


- We have more than 25 high quality scenes like these
- The geometry, reflectance, lighting and textures can be edited (ask me)
- This collection will grow and already includes HDR, inter-reflections, many types objects, materials, textures, shadows, occlusions



Scenes can be quite complex and realistic

- We have more than 25 high quality scenes like these
- The geometry, reflectance, lighting and textures can be edited (ask me)
- This collection will grow and already includes HDR, inter-reflections, many types objects, materials, textures, shadows, occlusions

<- scene-Jul-18,12:22 >-



Name: scene-Jul-18,12:22
(Row, Col): 512 by 512
Hgt, Wdth (1.35, 1.35) m
Sample: 2.64 mm
Deg/samp: 0.11
Wave: 400:10:700 nm
DR: Inf
(max 2933, min 0.00 cd/m2)

Adjust scene size

X 1 Interp

Luminance
100.0 cd/m2

FOV (width)
58.72 deg

Distance
1.2 m

0.4 Standard RGB

Gamma Display

ISETBio Team and Funding



Brian Wandell



Trisha Lian



Haomio Jiang



James Golden



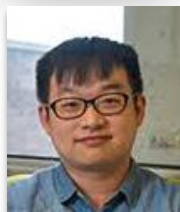
David Brainard



Nicolas Cottaris



Xiaomao Ding



Lingqi Zhang



E.J. Chichilnisky



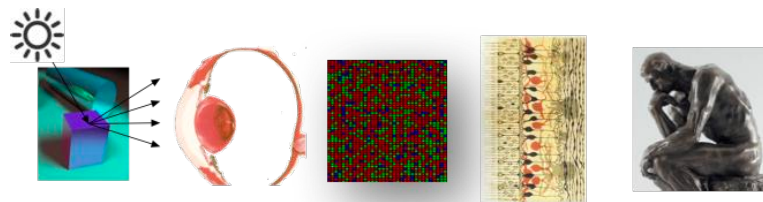
Fred Rieke



Joyce Farrell



Jon Winawer



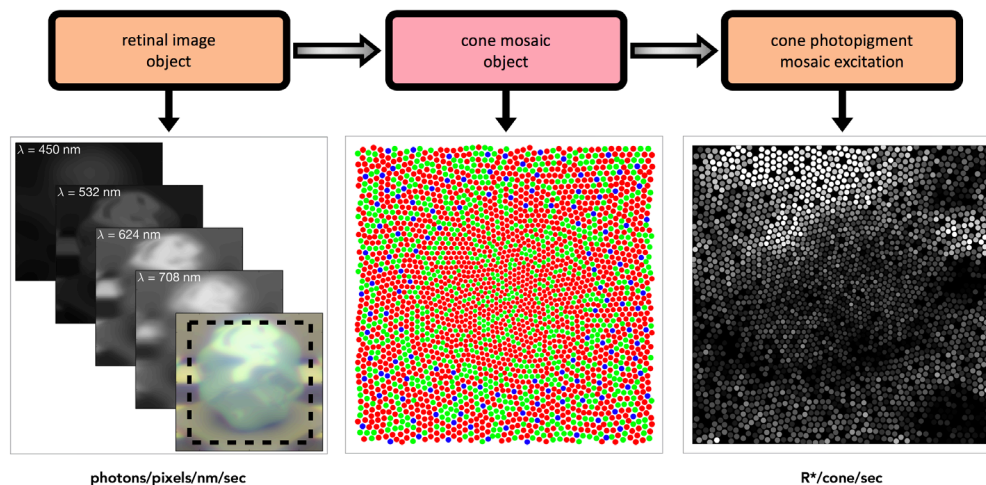
facebook research

SIMONS FOUNDATION



ISETBio: Modeling the Initial Steps of Human Vision

David H. Brainard and Brian A. Wandell
Thanks to Nicolas P. Cottaris



ISSETBio Team and Funding



Brian Wandell



Trisha Lian



Haomio Jiang



James Golden



David Brainard



Nicolas Cottaris



Xiaomao Ding



Lingqi Zhang



E.J. Chichilnisky



Fred Rieke



Joyce Farrell



Jon Winawer

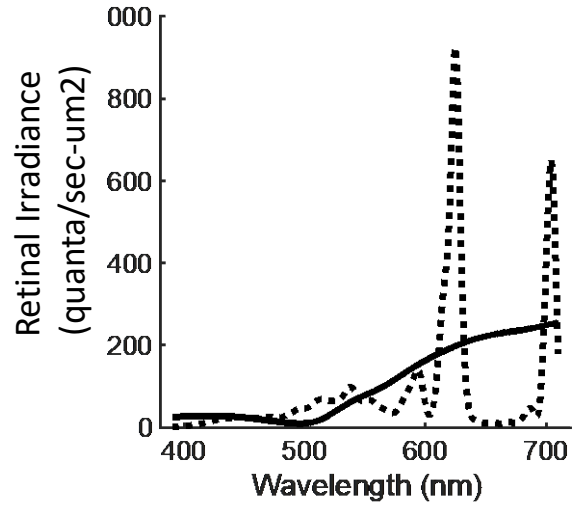
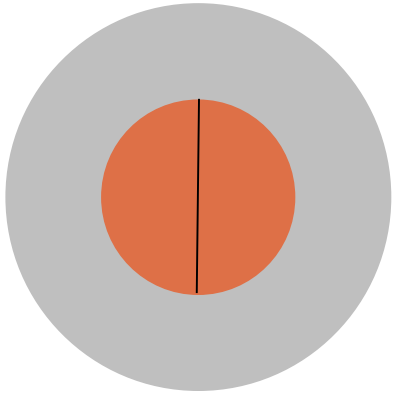
facebook research

SIMONS FOUNDATION

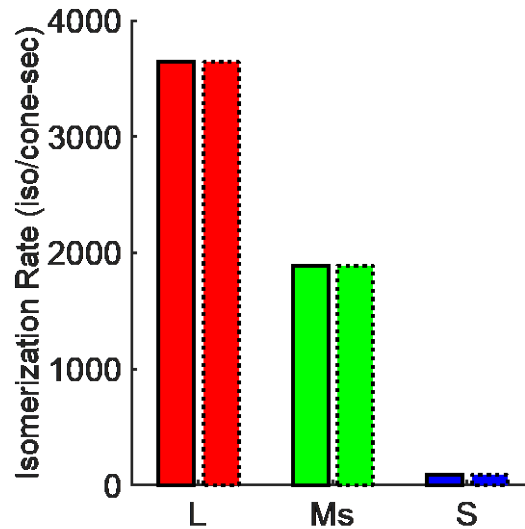
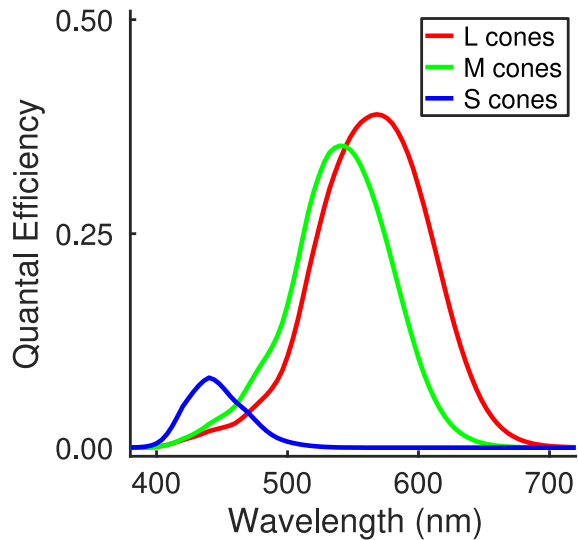
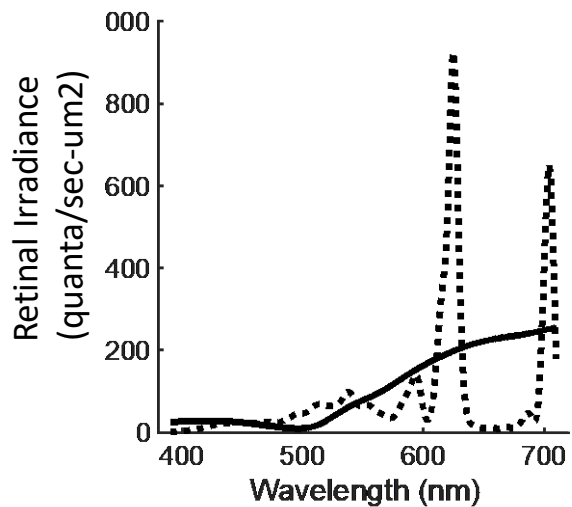
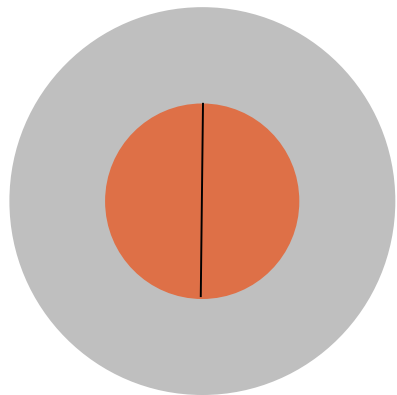


National Eye Institute

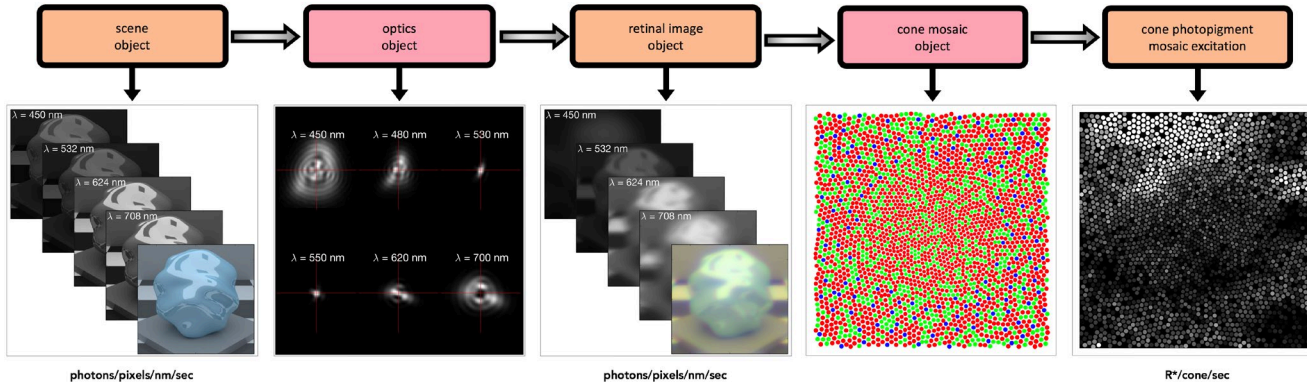
Encoding of light at the retina has large implications for perception



Color matching is mediated by encoding of light spectra by the cones

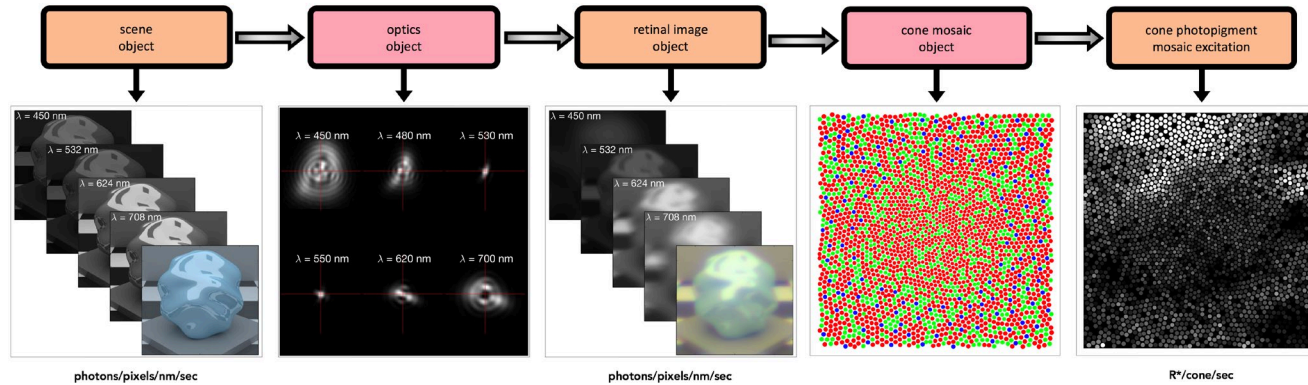


We would like to understand more generally implications of early vision



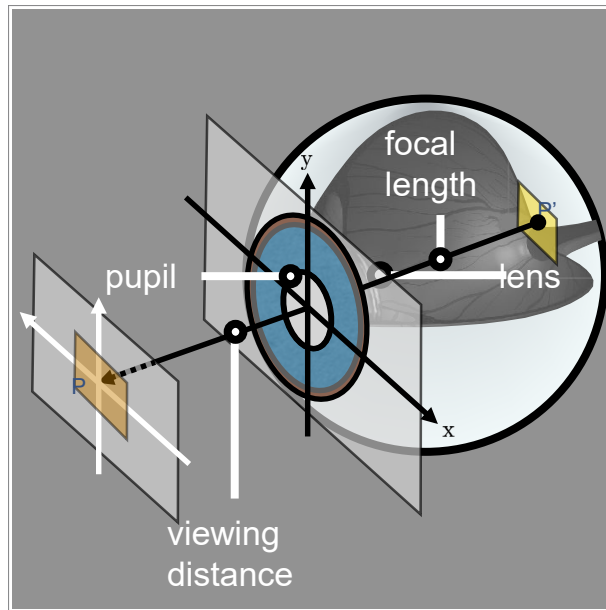
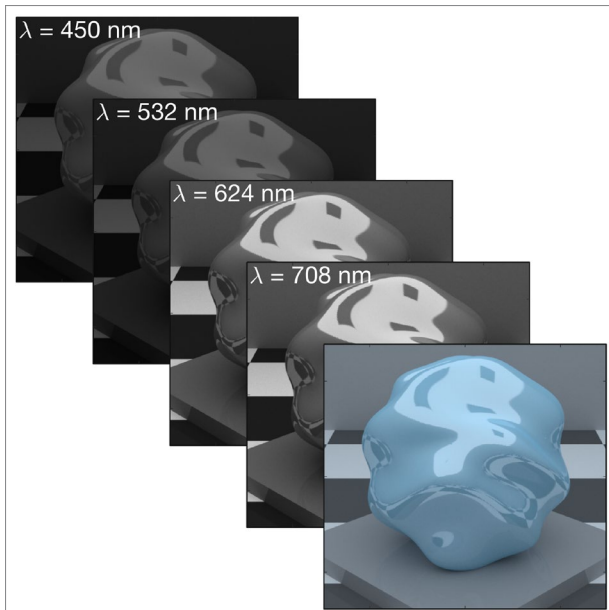
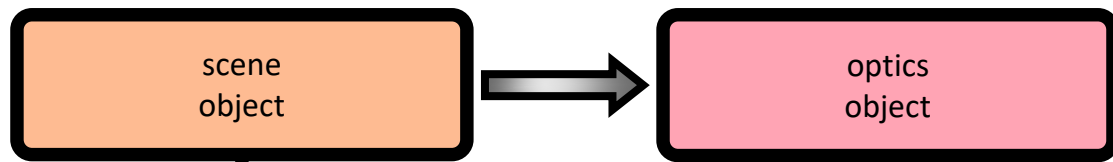
- Formation of the retinal image and optical blur
 - Including effects of 3D scene structure
- Spatial and spectral sampling by the interleaved cone mosaic
- Phototransduction
- Fixational eye movements
- Bipolar and retinal ganglion cell processing

Image System Engineering Tools for Biology (ISETBio)



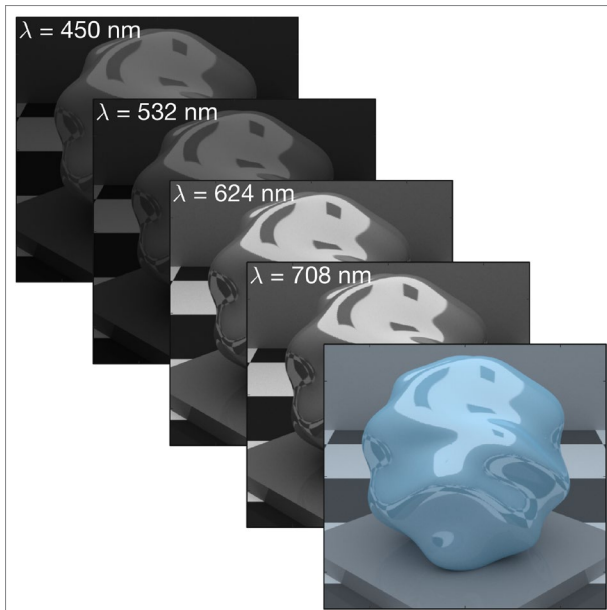
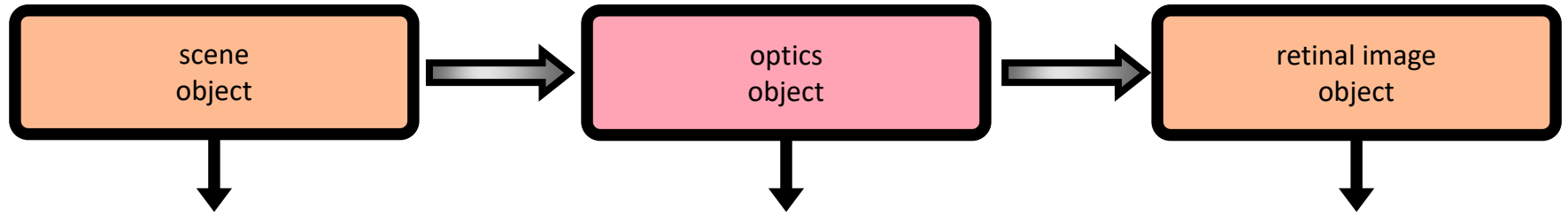
- ISETBio is a set of open source Matlab tools that quantitatively model early vision.
- ISETBio is image computable.
- Helps clarify how different elements of the eye and neural processing impact visual perception.
- Today's webinar is an introduction to ISETBio.

ISETBio components – scene and retinal image

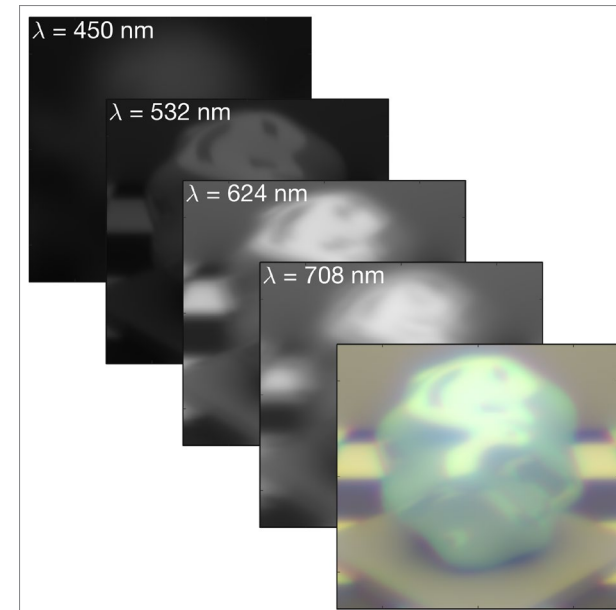
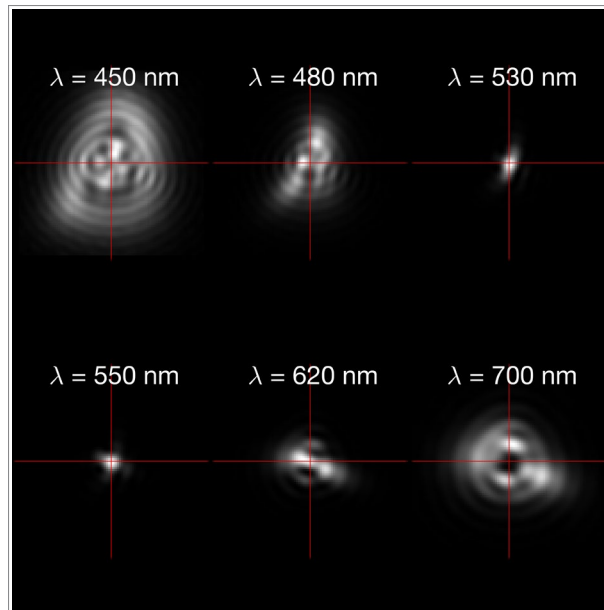


photons/pixels/nm/sec

ISETBio components – scene and retinal image

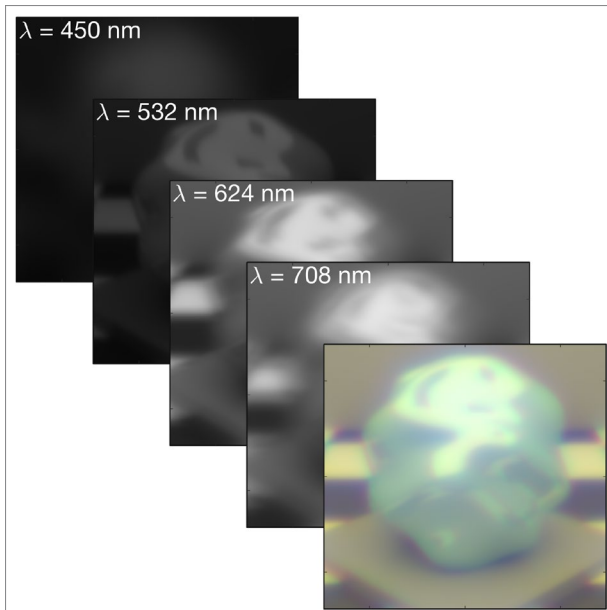
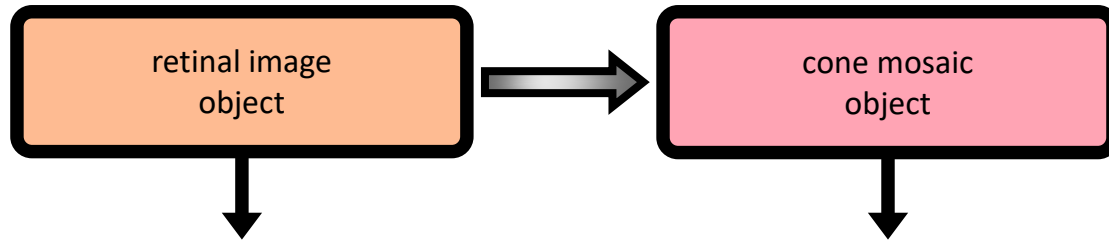


photons/pixels/nm/sec

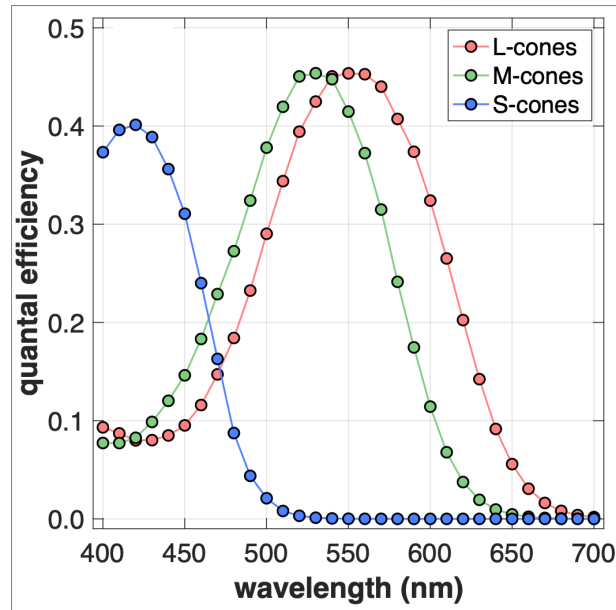


photons/pixels/nm/sec

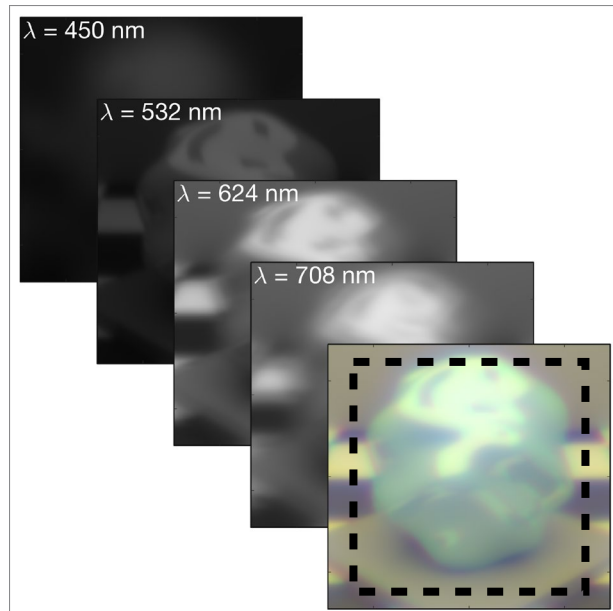
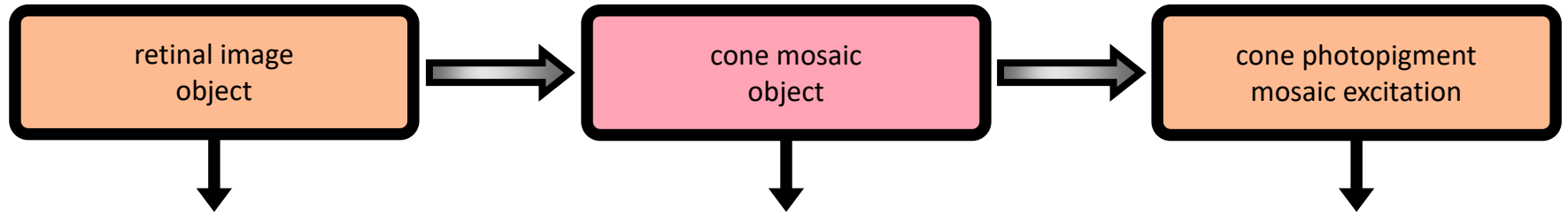
ISETBio components – retinal image and cone isomerizations



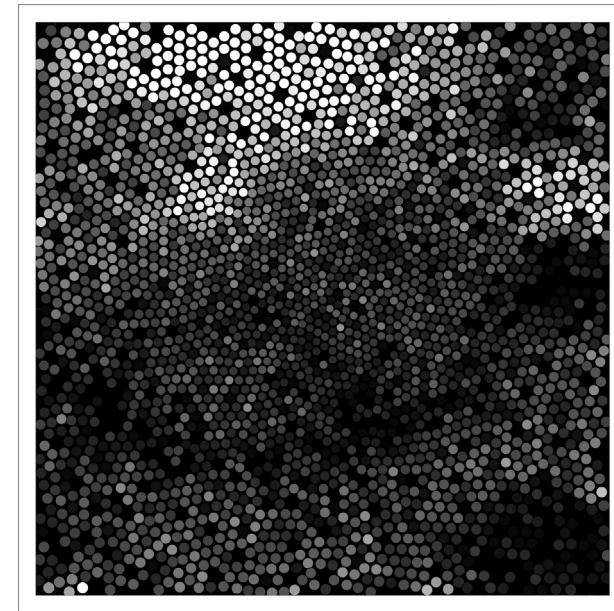
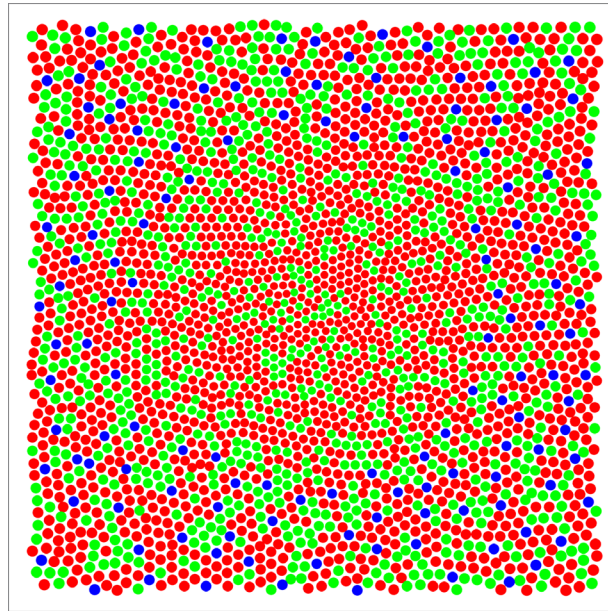
photons/pixels/nm/sec



ISETBio components – retinal image and cone isomerizations



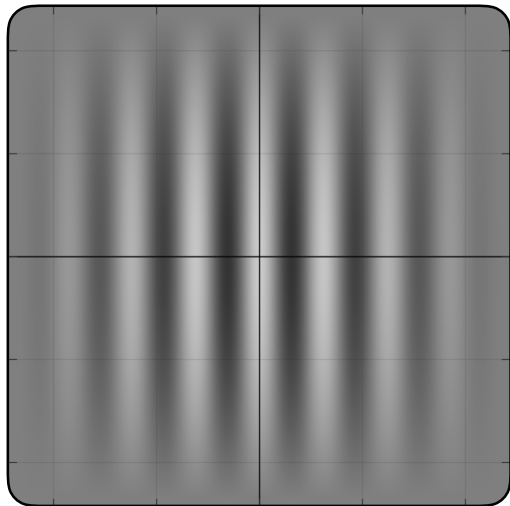
photons/pixels/nm/sec



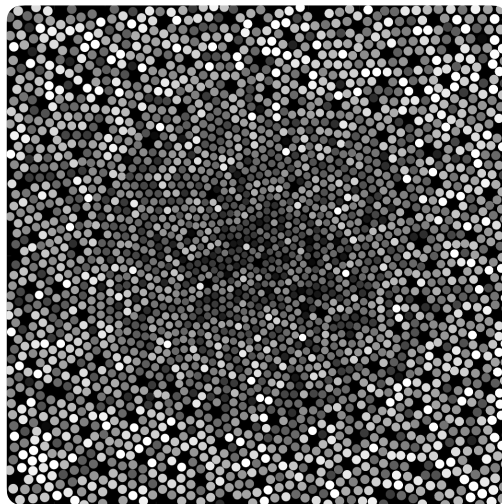
$R^*/\text{cone}/\text{sec}$

Example: cone mosaic isomerizations to gratings at different contrasts

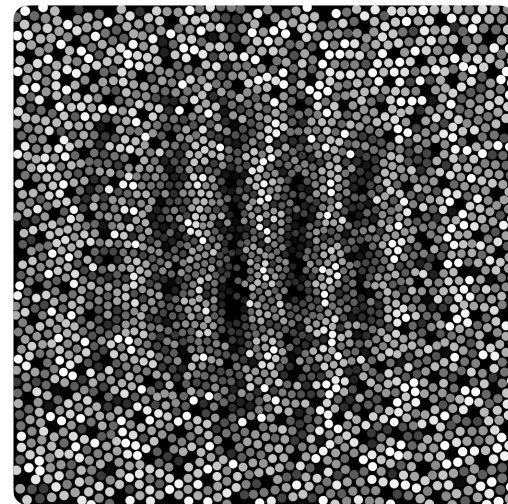
scene (c, sf)



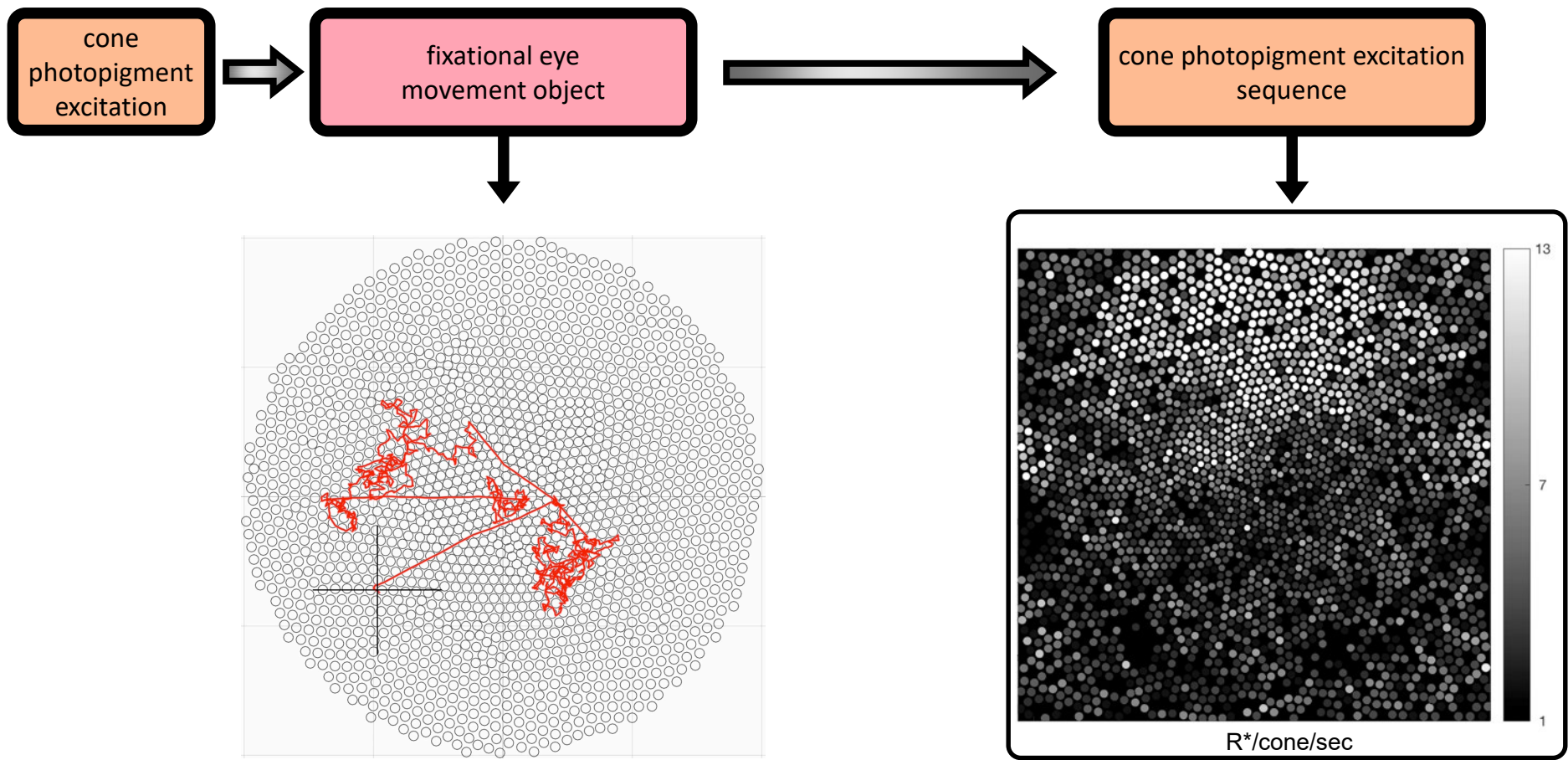
$c = 0$



$c = 100\%$, $sf = 16$ c/deg

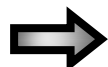


Accounting for absolute sensitivity: fixational drift



Accounting for absolute sensitivity: photocurrent transduction

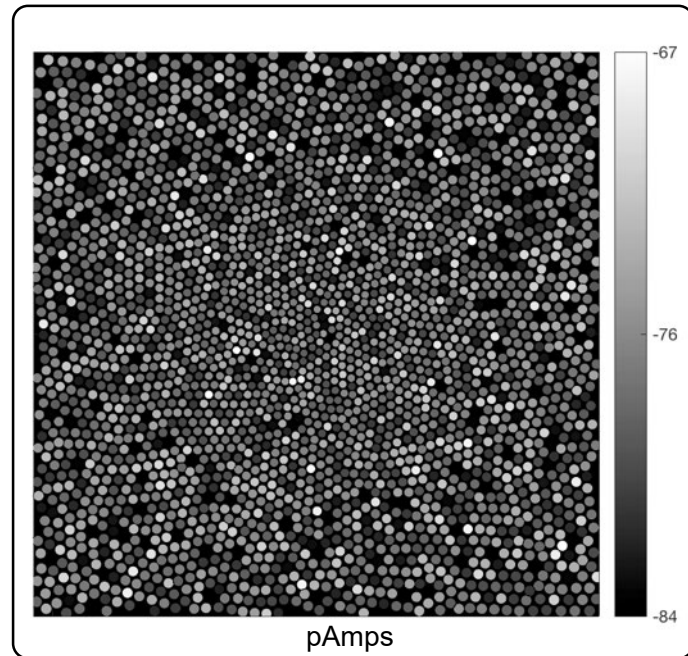
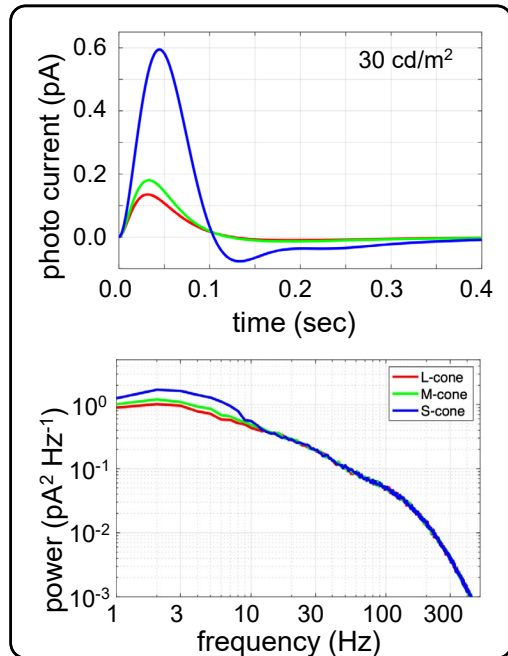
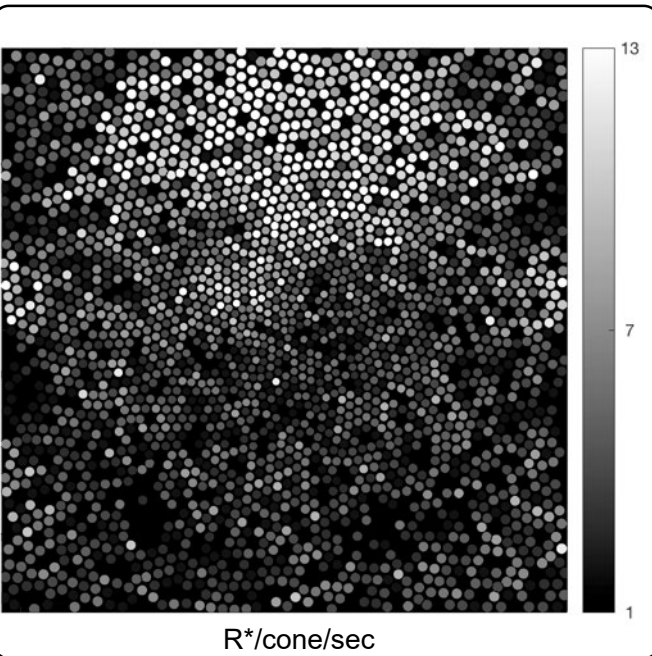
cone photopigment
excitation sequence



outer segment
object

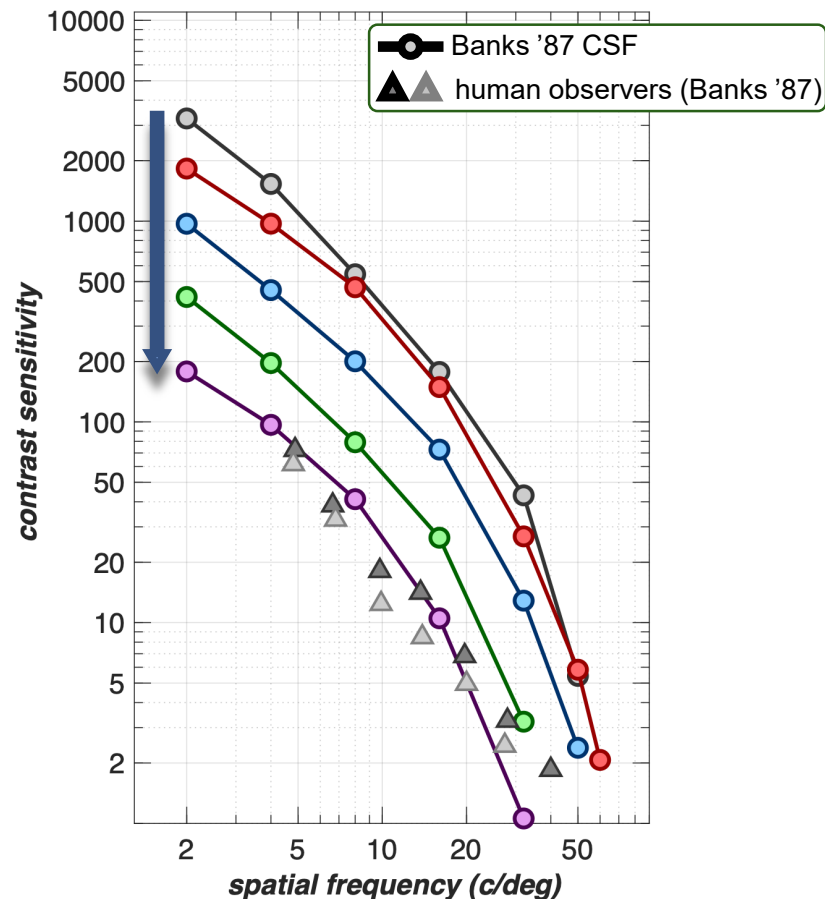


cone outer-segment
photocurrent response



Accounting for contrast sensitivity

1. Updated optics & cone mosaic modeling has a minor impact relative to the Banks '87 estimate (factor of 1.7 at 2 c/deg),
2. Computational observers, which learn visual tasks by observing neural responses, result in a significant sensitivity drop across the entire spatial frequency range (accumulated factor of 2-3).
3. Inclusion of fixational eye movements, requires non-linear computational observers, and further reduces sensitivity across the entire spatial frequency range (accumulated factor: 7-10).
4. Inclusion of photocurrent encoding further reduces sensitivity approaching psychophysical limits (accumulated factor: 18-30).



A computational observer model of spatial contrast sensitivity: Effects of photocurrent encoding, fixational eye movements and inference engine

© Nicolas P. Cottaris, © Brian A. Wandell, © Fred Rieke, © David H. Brainard

doi: <https://doi.org/10.1101/759811>

ISETBio Code and Examples

Open-Source, Matlab. ISETBio itself is available here:

<https://github.com/isetbio/isetbio>

Download and add to your Matlab path

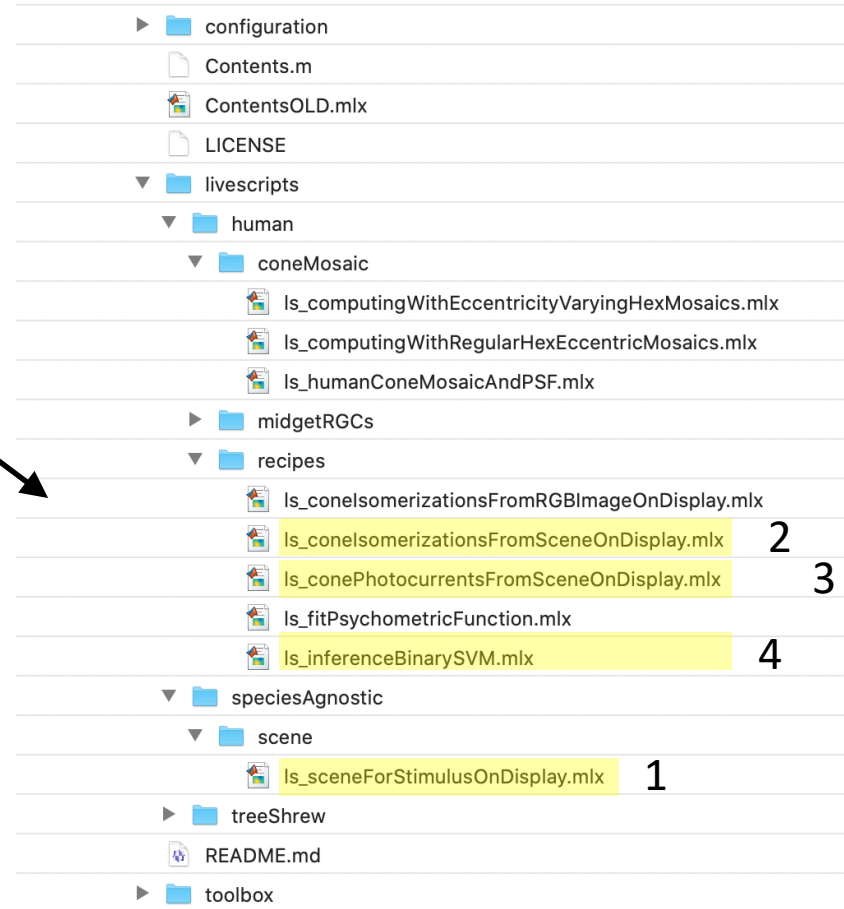
Examples from the next part of this talk are here:

<https://github.com/isetbio/ISETBioLiveScript>

Download and put wherever you like

Videos on YouTube. Search Google with “ISETBio Tutorials” and look under videos:

- 1) ISETBio SceneLiveScriptTutorial
- 2) ISETBio ComputelsomerizationsTutorial
- 3) ISETBio EyeMovementsPhotocurrentTutorial
- 4) ISETBio ContrastDetectionPerformanceTutorial



ISETBio Documentation

isetbio / isetbio

Unwatch 22 Star 44 Fork 29

<> Code Issues 96 Pull requests 1 Actions Projects 1 Wiki Security 0 Insights Settings

Tools for modeling image systems engineering in the human visual system front end Edit

Manage topics

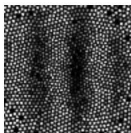
3,531 commits 10 branches 0 packages 3 releases 1 environment 15 contributors View license

Branch: master New pull request Create new file Upload files Find file Clone or download

Nicolas Cottaris Undoing the (wrong) y-coordinate flip. Latest commit 30db4ec 22 minutes ago

calculators	Merge branch 'RGCmodeling'	last month
configuration	Put guest user back	6 months ago
data	Experiments with cmQuad. Reading optics data from EK experiments. Det...	11 months ago
demoapps/fixationalEyeMovements	Updates to the demo app.	2 years ago
external	Synchronize with current PTB	7 months ago
isettools	Undoing the (wrong) y-coordinate flip.	22 minutes ago
local	Forces the local directory to appear in the distribution.	3 years ago
scripts	Comments	11 months ago
tutorials	Updating for the AO tutorial	7 days ago
validation	Removed RNG option 'CombRecursive' in fixEM.compute()	4 months ago
.gitignore	Fix version dependency in example. Ignore image output in git.	4 months ago
Contents.m	Merge branch 'master' of https://github.com/isetbio/isetbio into pull...	10 months ago
LICENSE	Initial import of clean version of 0.1 dev branch, now the master bra...	5 years ago
README.md	Update README.md	4 months ago

Some Papers that Use ISETBio



[A computational-observer model of spatial contrast sensitivity: Effects of wave-front-based optics, cone-mosaic structure, and inference engine](#)

OPEN ACCESS

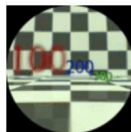
Nicolas P. Cottaris; Haomiao Jiang; Xiaomao Ding; Brian A. Wandell; David H. Brainard

Journal of Vision April 2019, Vol.19, 8. doi:<https://doi.org/10.1167/19.4.8>

A computational observer model of spatial contrast sensitivity: Effects of photorecurrent encoding, fixational eye movements and inference engine

 Nicolas P. Cottaris,  Brian A. Wandell,  Fred Rieke,  David H. Brainard

doi: <https://doi.org/10.1101/759811>



[Ray tracing 3D spectral scenes through human optics models](#)

Trisha Lian; Kevin J. MacKenzie; David H. Brainard; Nicolas P. Cottaris; Brian A. Wandell

Journal of Vision October 2019, Vol.19, 23. doi:<https://doi.org/10.1167/19.12.23>

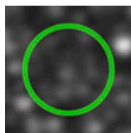
Modeling visual performance differences ‘around’ the visual field: A computational observer approach

Eline R. Kupers , Marisa Carrasco, Jonathan Winawer

Version 2



Published: May 24, 2019 • <https://doi.org/10.1371/journal.pcbi.1007063>



[Spatial summation in the human fovea: Do normal optical aberrations and fixational eye movements have an effect?](#) **OPEN ACCESS**

William S. Tuten; Robert F. Cooper; Pavan Tiruveedhula; Alfredo Dubra; Austin Roorda; Nicolas P. Cottaris; David H. Brainard; Jessica I. W. Morgan

Journal of Vision August 2018, Vol.18, 6. doi:<https://doi.org/10.1167/18.8.6>

Eye Movement Model Demo

Open-Source, Matlab. ISETBio itself is available here:

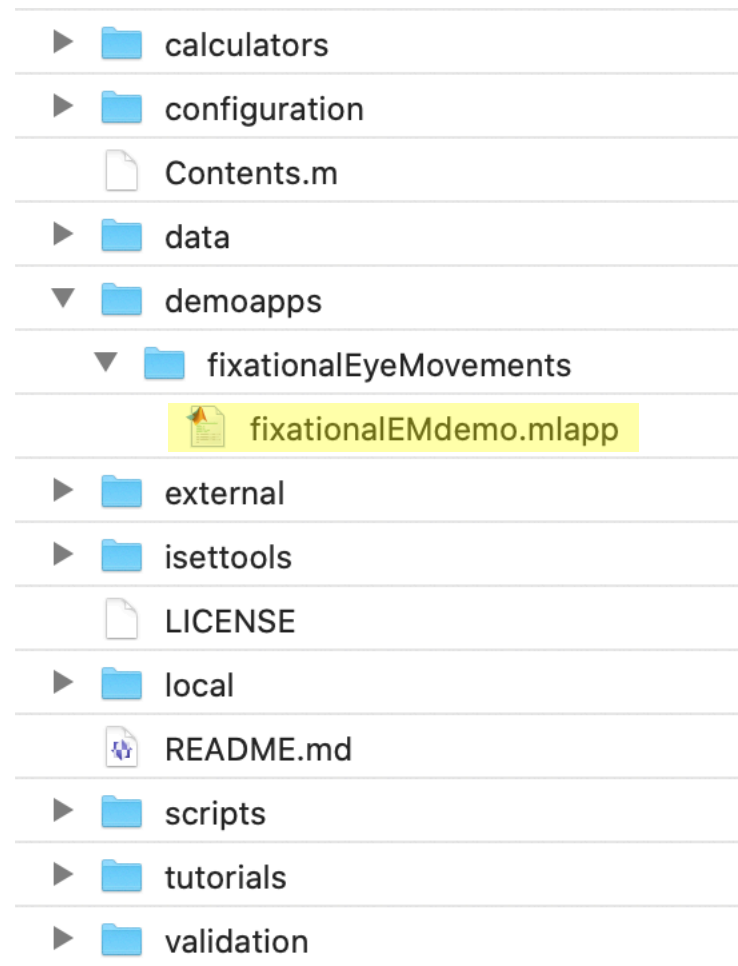
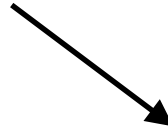
<https://github.com/isetbio/isetbio>

Download and add to your Matlab path

Examples from the next part of this talk are here:

<https://github.com/isetbio/ISETBioLiveScript>

Download and put wherever you like



A computational observer model of spatial contrast sensitivity: Effects of photocurrent encoding, fixational eye movements and inference engine

 Nicolas P. Cottaris,  Brian A. Wandell,  Fred Rieke,  David H. Brainard

doi: <https://doi.org/10.1101/759811>

Mergenthaler, K., & Engbert, R. (2007). Modeling the control of fixational eye movements with neurophysiological delays. Phys. Rev. Lett., 98, 138104.