# EE Lunch (Oct 28, 2024)

<u>Outline</u>

- 5 minutes about my relationship with EE
- 10 minutes about an idea

## Brian A. Wandell
## Psychology Department

EE, GSE, Ophthalmology (by courtesy)
Wu Tsai Neurosciences Institute
Stanford Center for Cognitive and Neurobiological Imaging
Stanford Center for Image Systems Engineering

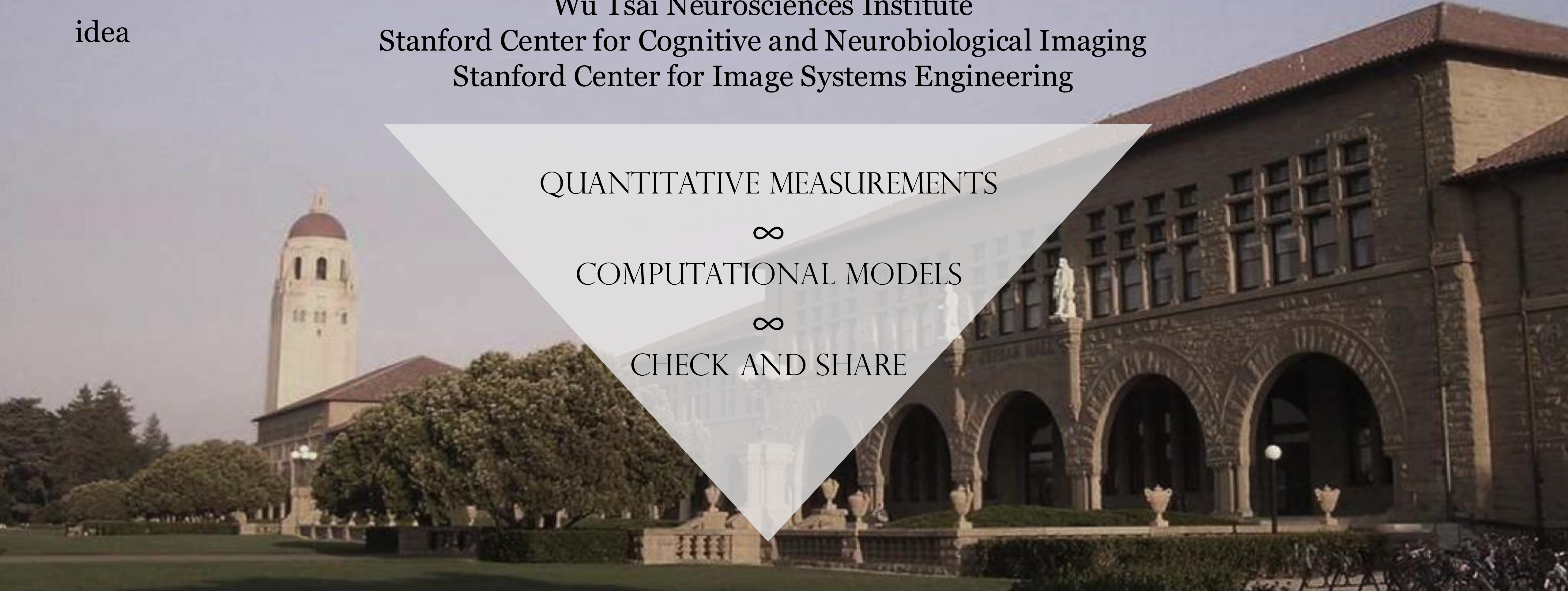
QUANTITATIVE MEASUREMENTS

∞

COMPUTATIONAL MODELS

∞

CHECK AND SHARE



# In the 1980s

Through the 1980s I studied human visual perception, particularly color vision; a number of EE faculty mentored me

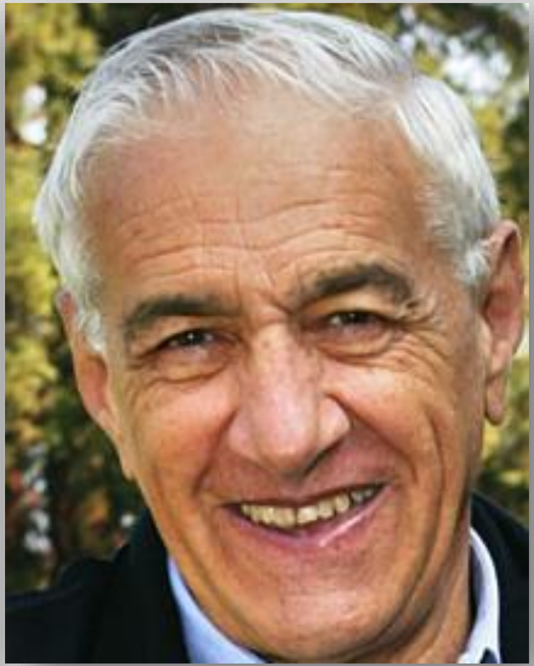


Image Systems Engineering at Stanford
Goodman and Wandell (1996) International Conference on Image Processing (ICIP).

## Image Systems Engineering at Stanford

*Joseph W. Goodman & Brian A. Wandell*
Center for Image Systems Engineering
McCullough 150, Stanford University
Stanford, CA 94305 USA

### Abstract

A new Image Systems Engineering Program (ISEP) has recently been launched at Stanford University. The program includes more than a dozen faculty participants drawn from four departments. The planned stages of growth of the Program are described, with emphasis on the anticipated respective roles of the university and industry.

end-to-end design of an image system also requires an unusual interdisciplinarity, and thus a special program is needed to serve as a vehicle to integrate the training and research from faculty in different disciplines. Finally, there exists a large and still-growing collection of companies whose products are mainly concerned with the creation, manipulation, and delivery of images. This industry is international in character, but a substantial computer-related segment resides in Silicon Valley, physically near

# Programmable digital camera project

In the late 1990s, Abbas and I cooperated on image systems

**Stanford Report**
**April 26, 2001**
Speedy camera-on-a-chip both captures and processes images
BY DAWN LEVY

Faster than a speeding bullet. Able to leap photographic obstacles with a single computer chip. It's a camera. It's a chip. It's a camera-on-a-chip.

Thanks to the efforts of electrical engineering Professor Abbas El Gamal, psychology and electrical engineering Professor Brian Wandell and their students, it's getting harder to take a bad picture.

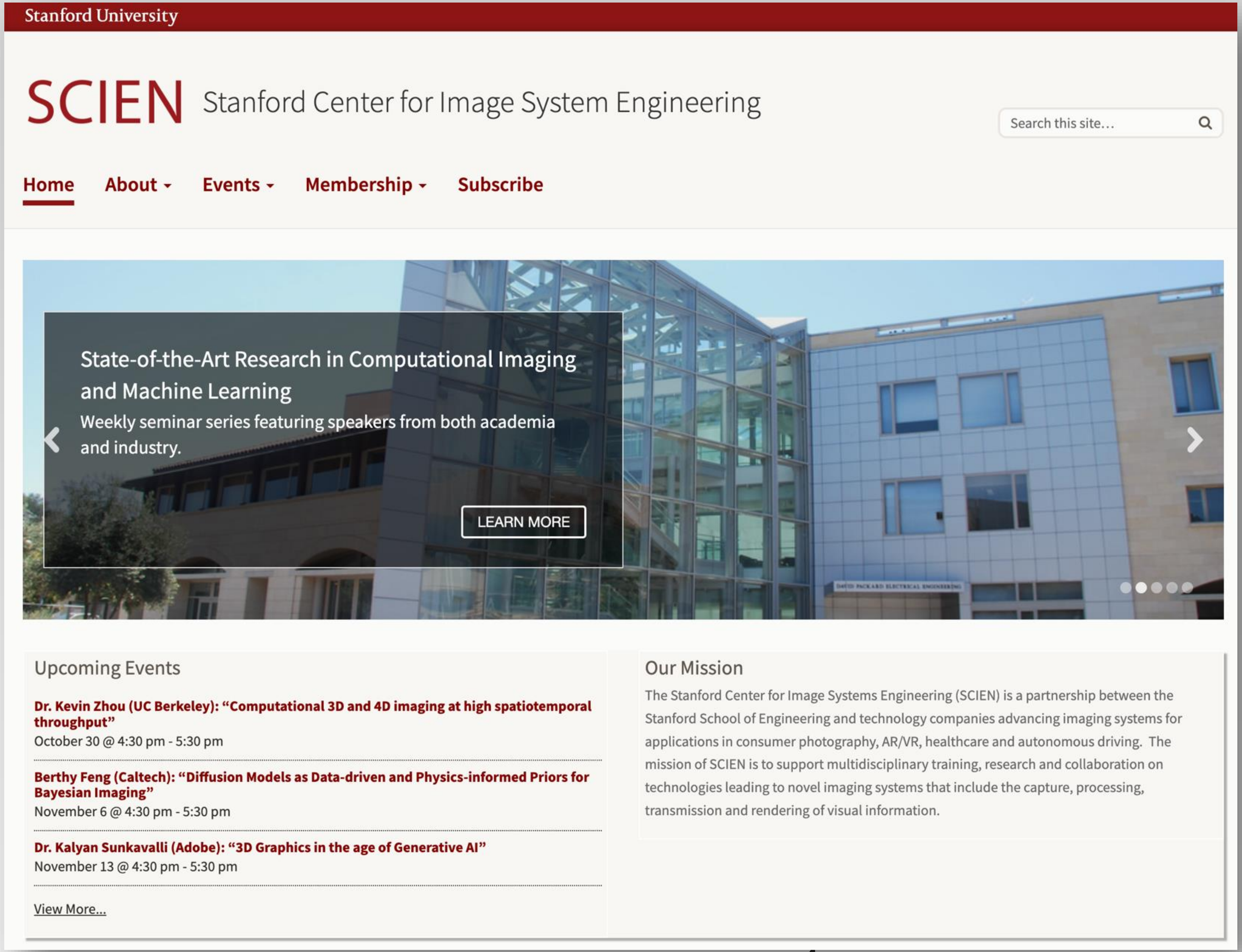
- Trisha Lian – Meta
- Henryk Blasinski - Apple
- Haomiao Jiang - Roblox
- Andy Lin - Apple
- Steven Lansel - Meta
- Peter Catrysse - Stanford
- Feng Xiao - Fengyun Vision
- Jeff DiCarlo – Intuitive Surgical
- Zheng Lyu – Gyges lab
- Zhenyi Liu – Apple
- Manu Parmar – Pyxd
- Xuemei Zhang - Apple

# Expansion to an industrial affiliates program

Joyce Farrell
Executive director
(2002-present)

Bernd Girod
Faculty director
(2000-2024)

Gordon Wetzstein
Faculty director
(2023-present)



# SCPD/CGOE Certificate and Psych 221 (former EE 362)

Home » Programs » Visual Computing Graduate Certificate

## Visual Computing Graduate Certificate

Stanford School of Engineering

- Graduate Certificate
- Online, instructor-led
- $19,682 - $25,738
- View Courses
- Academic Calendar

GET STARTED

### OVERVIEW

Visual computing is an emerging discipline that combines computer graphics and computer vision to advance technologies for the capture, processing, display and perception of visual information. The courses in this certificate program teach fundamentals of image capture, computer vision, computer graphics and human vision. Several of the courses offer hands-on experience prototyping imaging systems for augmented and virtual reality, robotics, autonomous vehicles and medical imaging. You'll gain skills that will allow you to play a critical role in your organization – whether developing cutting-edge technologies, pioneering new products, developing fresh research capabilities, or influencing strategic decisions.

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F24-PSYCH-22... › Pages › Image systems engineering

*Fall 2024*

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## Image systems engineering

**Instructors:** Brian Wandell, Joyce Farrell and David Cardinal

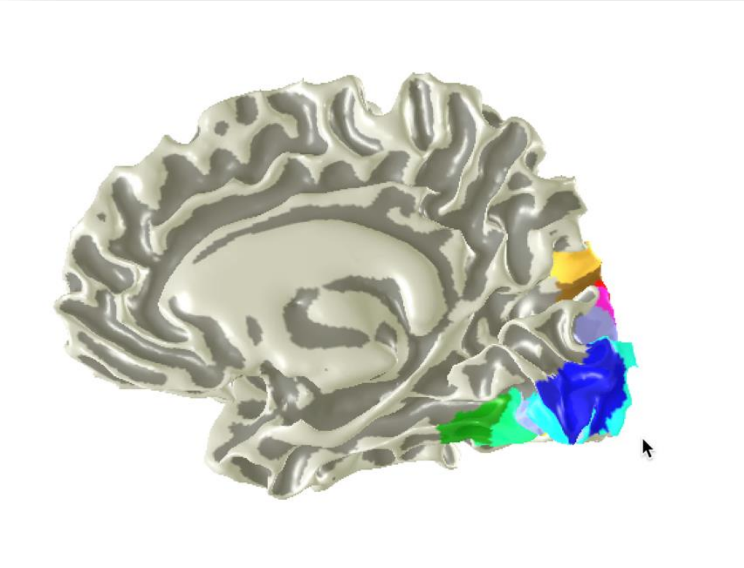
Psych 221 is an introduction to the School of Engineering's visual computing specialization. This course explains key concepts in image formation, image capture, and image processing. The course also introduces students to properties of the human visual system that are essential for understanding the design of image systems.


A key aspect of the course is the use of software for image systems simulation (ISETCam) and the associated homework problems (psych221). The software implements many of the principles we teach in the class, including specifying the scene radiance, optics, sensor capture and image processing. This software enables experimentation with the image system components (lens, sensor, post-processing). Through these experiments students learn to evaluate how image system components work together to produce image data for consumer photography, virtual and augmented reality, biomedical applications, autonomous driving, and convolutional neural networks.

# Magnetic resonance imaging

MRI instrumentation can be used in many ways to learn about brain tissue, structure, and activity

# Visual field map reviews



- Maps tile the occipital lobe
- Extend into IPS and VOT
- Response properties differ
- Identification from gross anatomy

366 Neuron 56, October 25, 2007

Cell PRESS
Neuron
Review

## Visual Field Maps in Human Cortex

Brian A. Wandell,[1,*] Serge O. Dumoulin,[1] and Alyssa A. Brewer[2]
[1]Psychology Department, Stanford University, Stanford, CA 94305-2130, USA
[2]Department of Cognitive Sciences, University of California, Irvine, Irvine, CA 92697, USA
*Correspondence: wandell@stanford.edu
DOI 10.1016/j.neuron.2007.10.012

Much of the visual cortex is organized into visual field maps: nearby neurons have receptive fields at nearby locations in the image. Mammalian species generally have multiple visual field maps with each species having similar, but not identical, maps. The introduction of functional magnetic resonance imaging made it possible to identify visual field maps in human cortex, including several near (1) medial occipital (V1,V2,V3), (2) lateral occipital (LO-1,LO-2, hMT+), (3) ventral occipital (hV4, VO-1, VO-2), (4) dorsal occipital (V3A, V3B), and (5) posterior parietal cortex (IPS-0 to IPS-4). Evidence is accumulating for additional maps, including some in the frontal lobe. Cortical maps are arranged into clusters in which several maps have parallel eccentricity representations, while the angular representations within a cluster alternate in visual field sign. Visual field maps have been linked to functional and perceptual properties of the visual system at various spatial scales, ranging from the level of individual maps to map clusters to dorsal-ventral streams. We survey recent measurements of human visual field maps, describe hypotheses about the function and relationships between maps, and consider methods to improve map measurements and characterize the response properties of neurons comprising these maps.

Vision Research 51 (2011) 718-737

Contents lists available at ScienceDirect
Vision Research
journal homepage: www.elsevier.com/locate/visres
ELSEVIER
VISION RESEARCH

Review

## Imaging retinotopic maps in the human brain

Brian A. Wandell *, Jonathan Winawer
*Psychology Department, Stanford University, Stanford, CA 94305, United States*

ARTICLE INFO

*Article history:*
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Available online 6 August 2010

ABSTRACT

A quarter-century ago visual neuroscientists had little information about the number and organization of retinotopic maps in human visual cortex. The advent of functional magnetic resonance imaging (MRI), a non-invasive, spatially-resolved technique for measuring brain activity, provided a wealth of data about human retinotopic maps. Just as there are differences amongst non-human primate maps, the human maps have their own unique properties. Many human maps can be measured reliably in individual sub-

# Stanford's Center for Cognitive and Neurobiological Imaging (CNI)


# Introductory class with a focus on magnetic resonance imaging (Psych 204A)

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*Winter 2024*

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## Human Neuroimaging Methods

### An introduction to human neuroimaging using magnetic resonance

PSYCH 204A | 3 units | UG Reqs: None | Class # 12129 | Section 01 | Grading: Letter or Credit/No Credit | SEM | Session: 2023-2024 Winter 1 | In Person

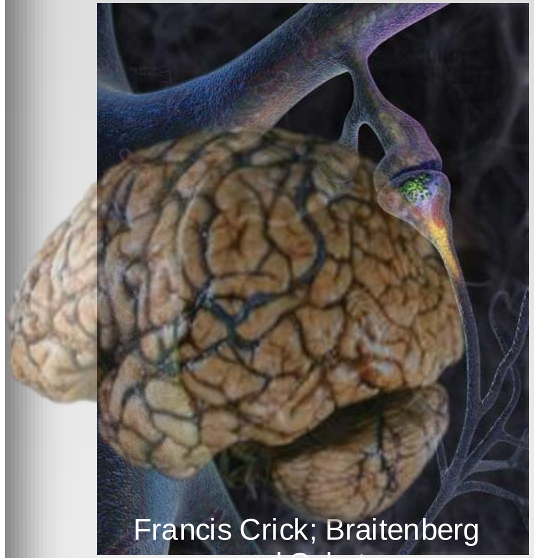
01/08/2024 - 03/15/2024

Tue, Thu 1:30 PM - 2:50 PM

Sequoia Hall 200

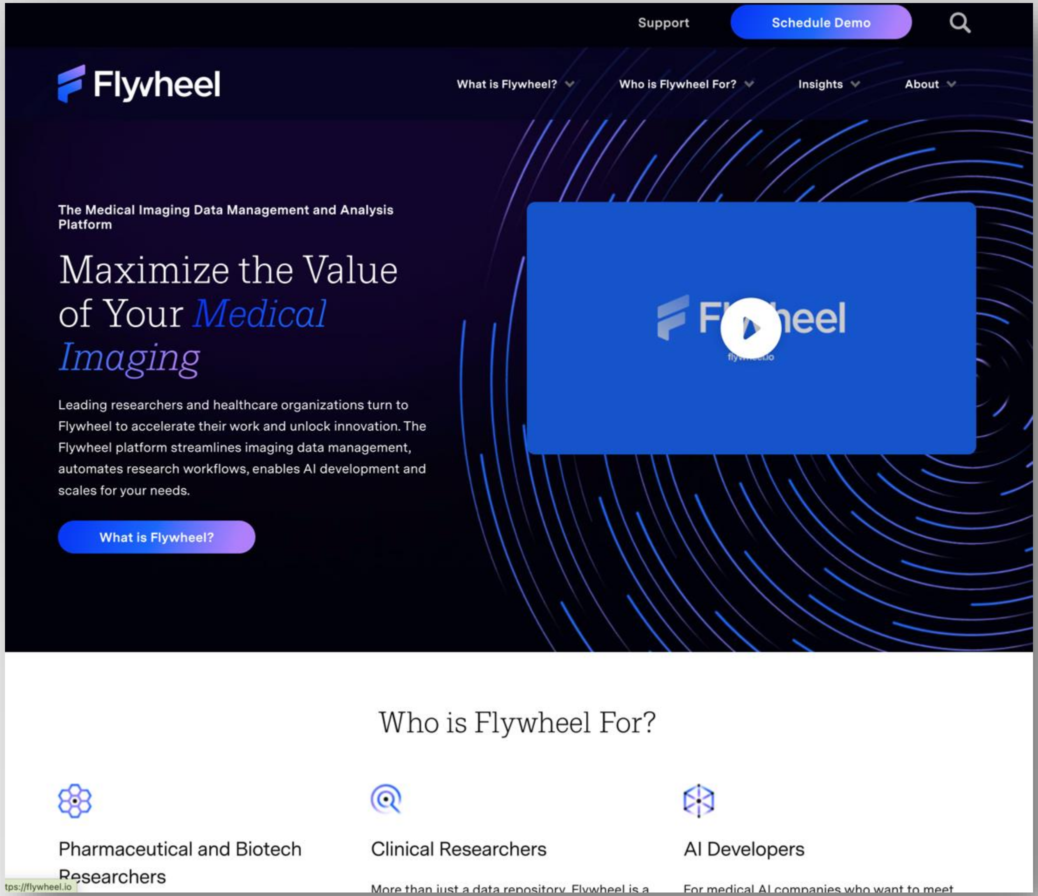
Instructors: Wandell, B. (PI); Yan, R. (TA)

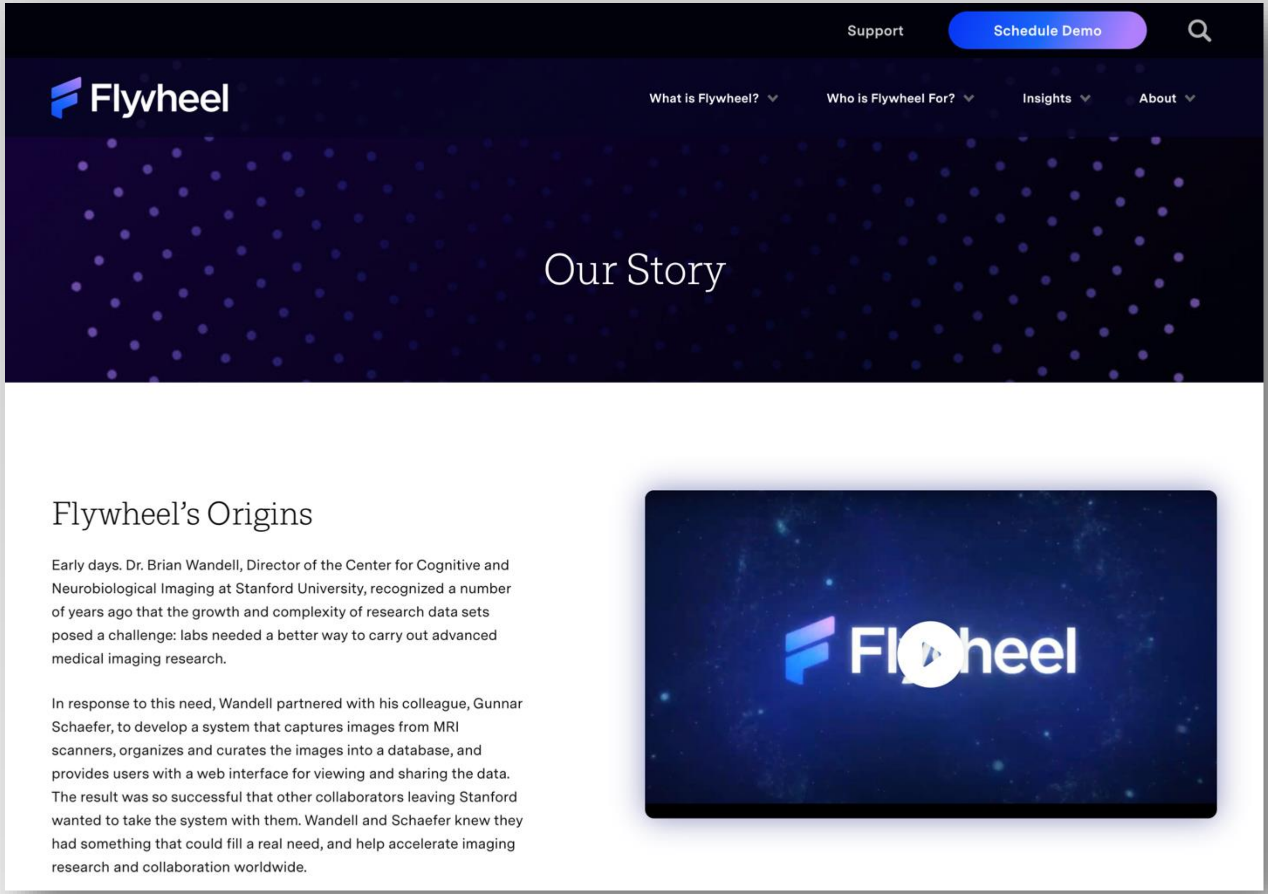
Magnetic resonance imaging (MRI) has become an important scientific tool for measuring living human brain structure and function. This course is for students who would like to learn the physical basis of MRI and how the method is used to make anatomical images of brain structures (sMRI and dMRI), measure quantitative tissue properties (qMRI), and assess brain activity (fMRI).



Francis Crick; Braitenberg and Schutz
Synapse image from Grahm Johnson

# Founded Flywheel.io for Reproducible Science and Medicine



# The main work now: Image systems simulation

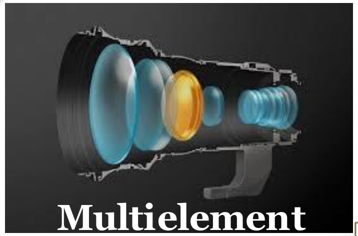
Measuring system performance using **quantified** (units) throughout

## Scenes

Ray traced spectral scene simulations

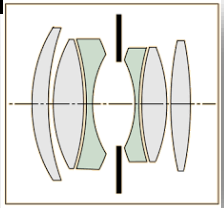
PBRT, ISET3D

## Optics

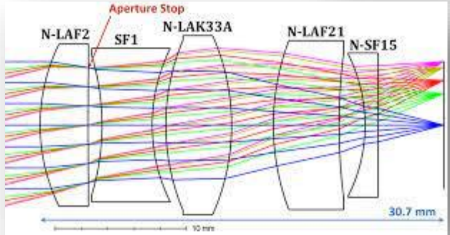


**Multielement**

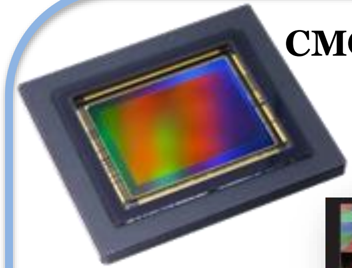
**Spherics**



**Aspherics**

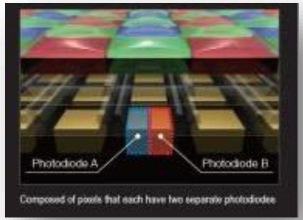



## Sensors

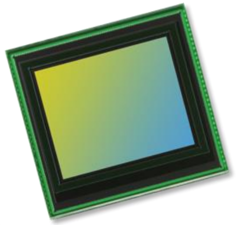


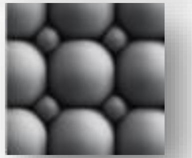
**CMOS Bayer**

**Microlens**




**Dual or multipixel autofocus**

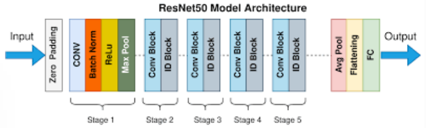




**Automotive (split pixel, RCCC)**

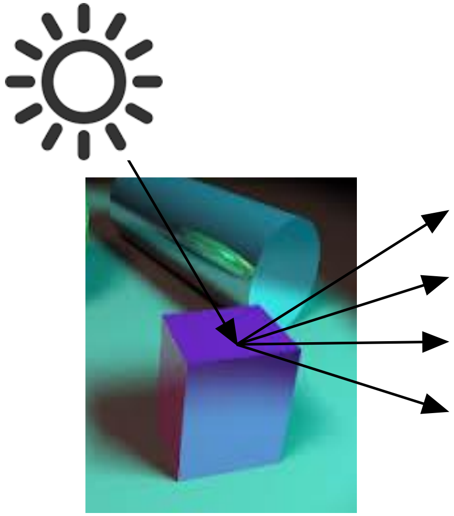
## Processing

Deep networks




PyTorch

# Image systems simulation for biology



Scene spectral radiance

Physiological optics

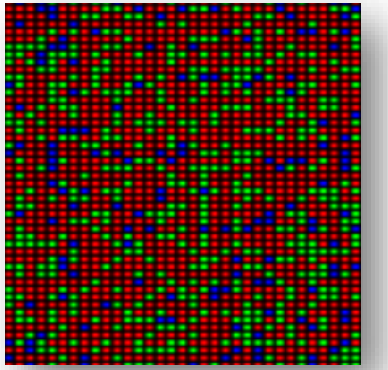
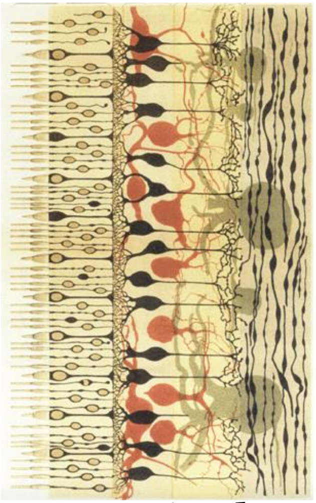
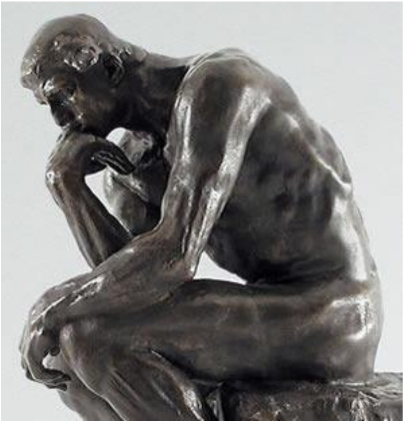


Photo transduction



Retinal processing

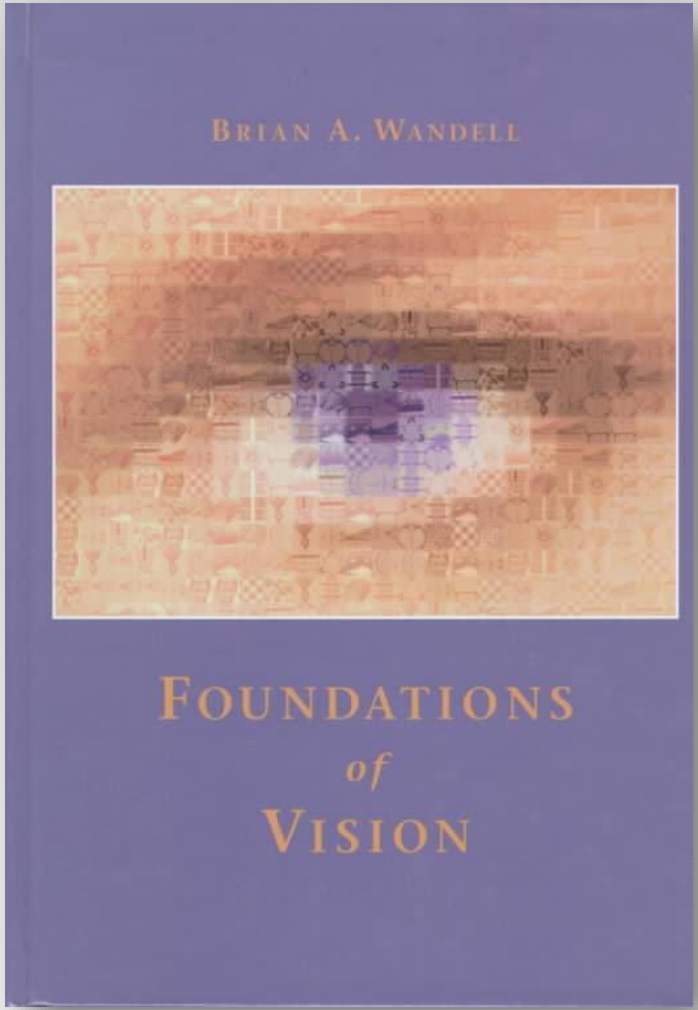


Inference

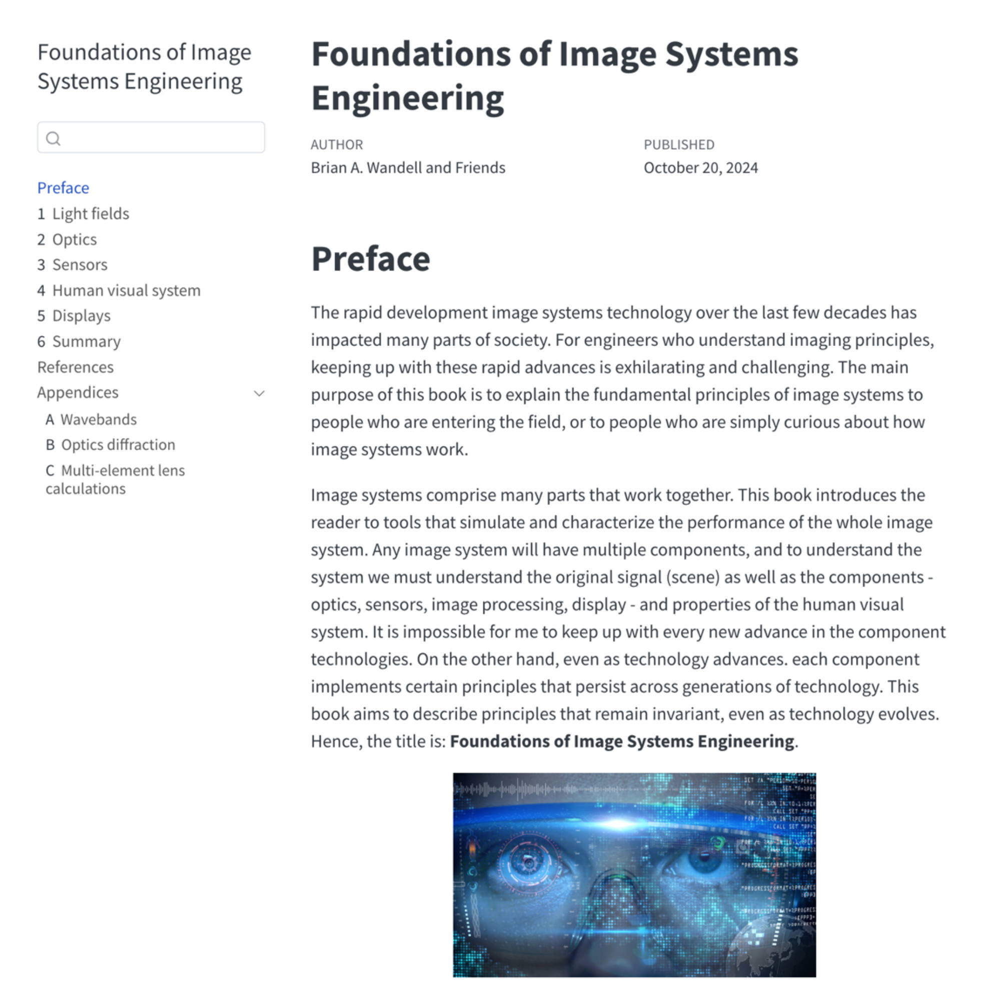
# Book writing

- I am working on web-first versions of these two books
- Using Quarto from POSIT; let me know if you are interested in this approach and want to share tips and ideas

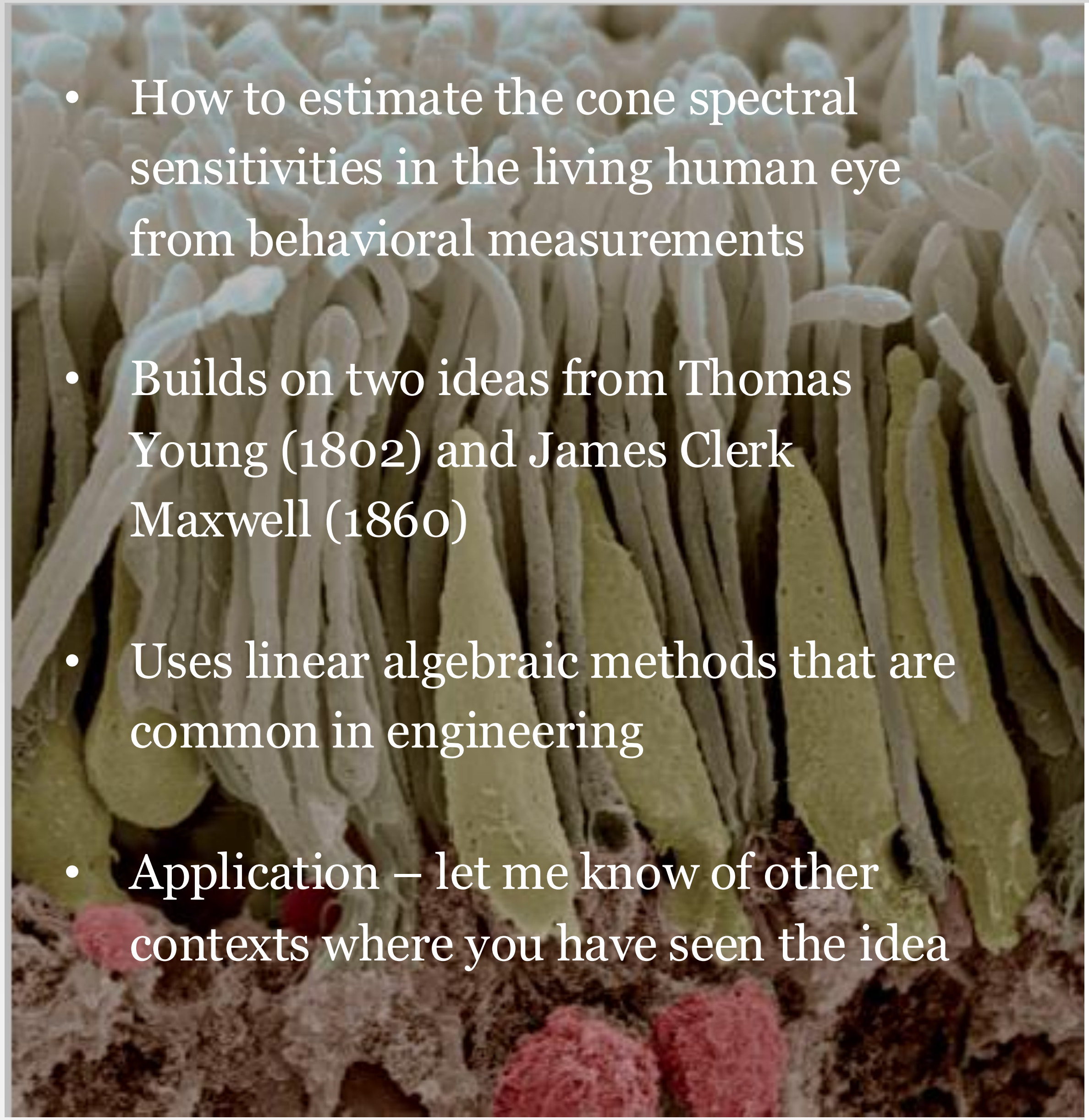
New edition of my vision book



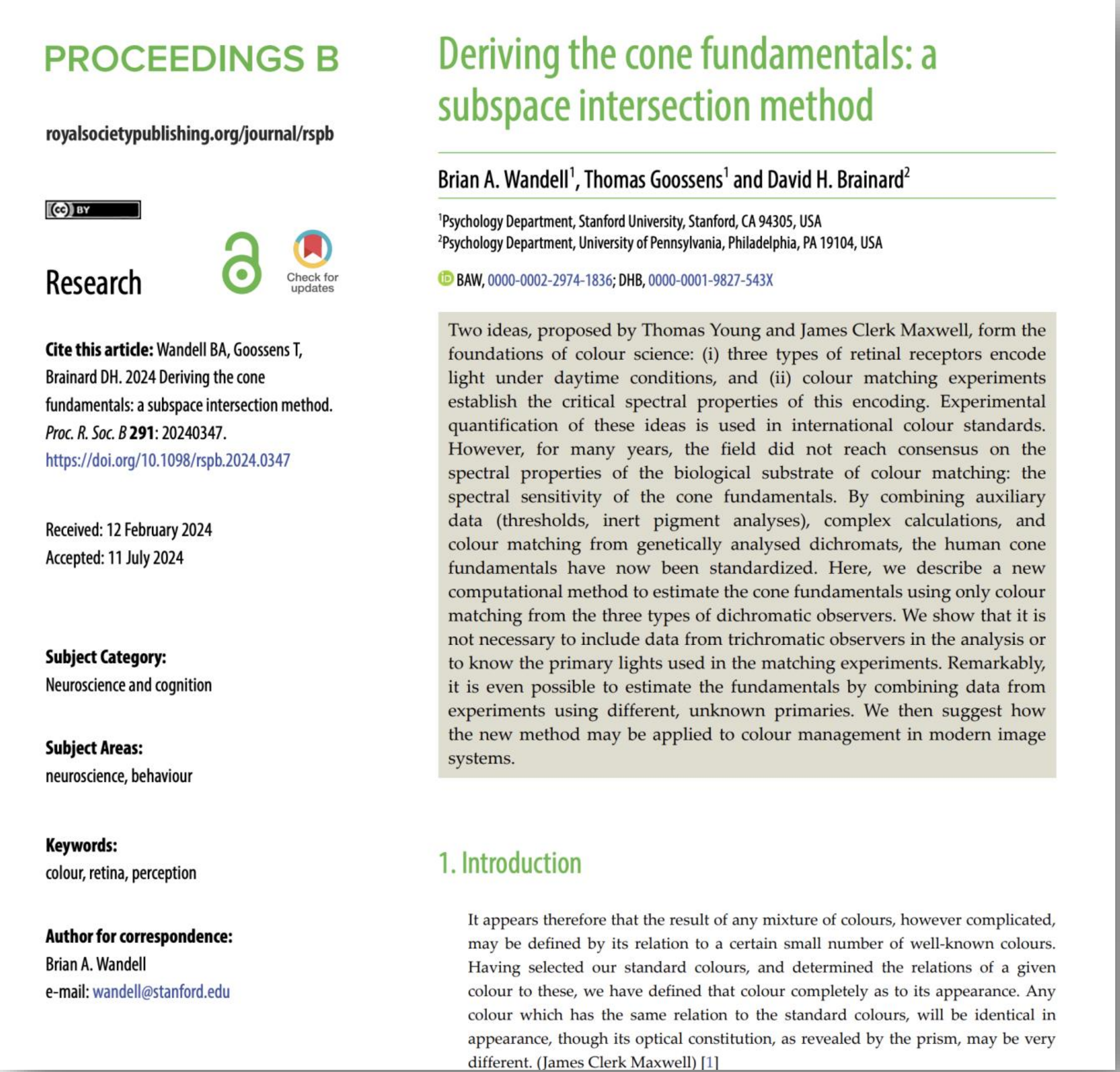

New book based on Psych 221



# An idea to illustrate my current work



- How to estimate the cone spectral sensitivities in the living human eye from behavioral measurements
- Builds on two ideas from Thomas Young (1802) and James Clerk Maxwell (1860)
- Uses linear algebraic methods that are common in engineering
- Application – let me know of other contexts where you have seen the idea



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Research

Check for updates

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https://doi.org/10.1098/rspb.2024.0347

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Neuroscience and cognition

**Subject Areas:**
neuroscience, behaviour

**Keywords:**
colour, retina, perception

**Author for correspondence:**
Brian A. Wandell
e-mail: wandell@stanford.edu

## Deriving the cone fundamentals: a subspace intersection method

Brian A. Wandell[1], Thomas Goossens[1] and David H. Brainard[2]

[1]Psychology Department, Stanford University, Stanford, CA 94305, USA
[2]Psychology Department, University of Pennsylvania, Philadelphia, PA 19104, USA

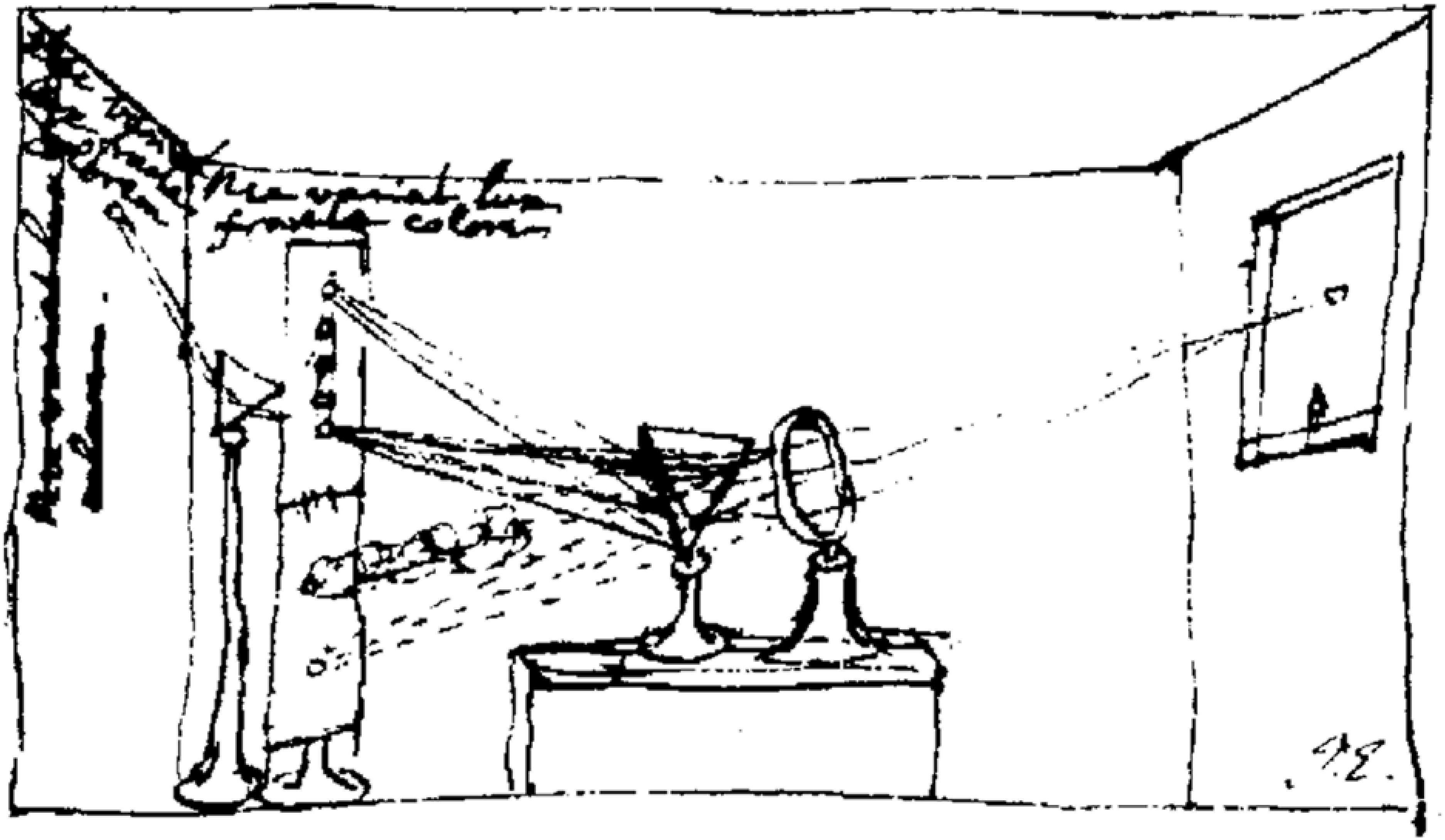
BAW, 0000-0002-2974-1836; DHB, 0000-0001-9827-543X

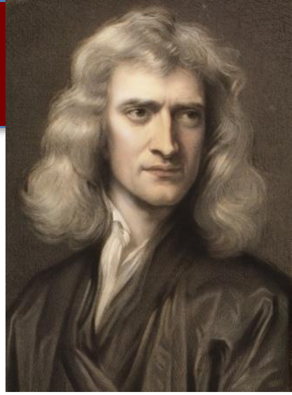
Two ideas, proposed by Thomas Young and James Clerk Maxwell, form the foundations of colour science: (i) three types of retinal receptors encode light under daytime conditions, and (ii) colour matching experiments establish the critical spectral properties of this encoding. Experimental quantification of these ideas is used in international colour standards. However, for many years, the field did not reach consensus on the spectral properties of the biological substrate of colour matching: the spectral sensitivity of the cone fundamentals. By combining auxiliary data (thresholds, inert pigment analyses), complex calculations, and colour matching from genetically analysed dichromats, the human cone fundamentals have now been standardized. Here, we describe a new computational method to estimate the cone fundamentals using only colour matching from the three types of dichromatic observers. We show that it is not necessary to include data from trichromatic observers in the analysis or to know the primary lights used in the matching experiments. Remarkably, it is even possible to estimate the fundamentals by combining data from experiments using different, unknown primaries. We then suggest how the new method may be applied to colour management in modern image systems.

### 1. Introduction

> It appears therefore that the result of any mixture of colours, however complicated, may be defined by its relation to a certain small number of well-known colours. Having selected our standard colours, and determined the relations of a given colour to these, we have defined that colour completely as to its appearance. Any colour which has the same relation to the standard colours, will be identical in appearance, though its optical constitution, as revealed by the prism, may be very different. (James Clerk Maxwell) [1]

# The fundamental components of light





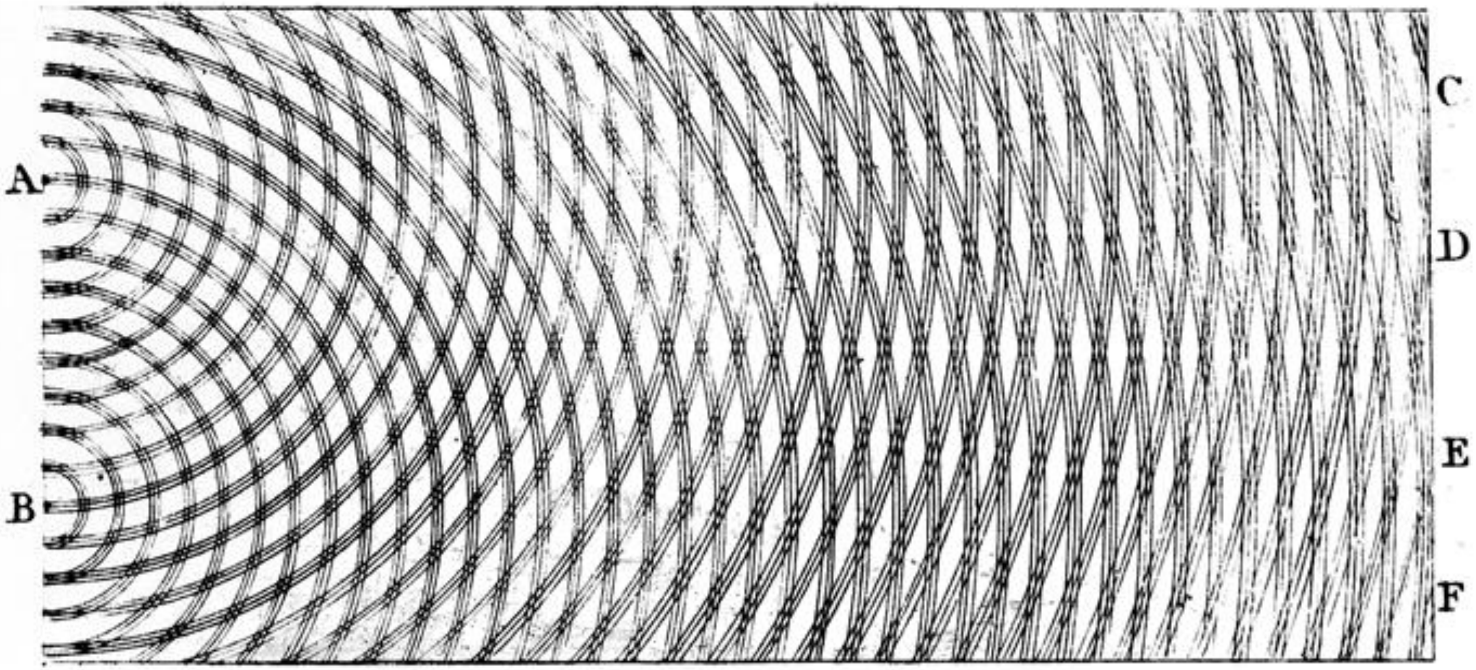
Isaac Newto

# Thomas Young – Double slit experiment and diffraction

Thomas Young (1802) On the theory of lights and colours. Philosophical Transactions of the Royal Society 92, 12-48.

Thomas Young's sketch supporting the wave theory of light presented to the Royal Society, 1803

http://en.wikipedia.org/wiki/Diffraction



# Thomas Young – Trichromacy from his Royal Society presentation

Thomas Young (1802) On the theory of lights and colours. Philosophical Transactions of the Royal Society 92, 12-48.

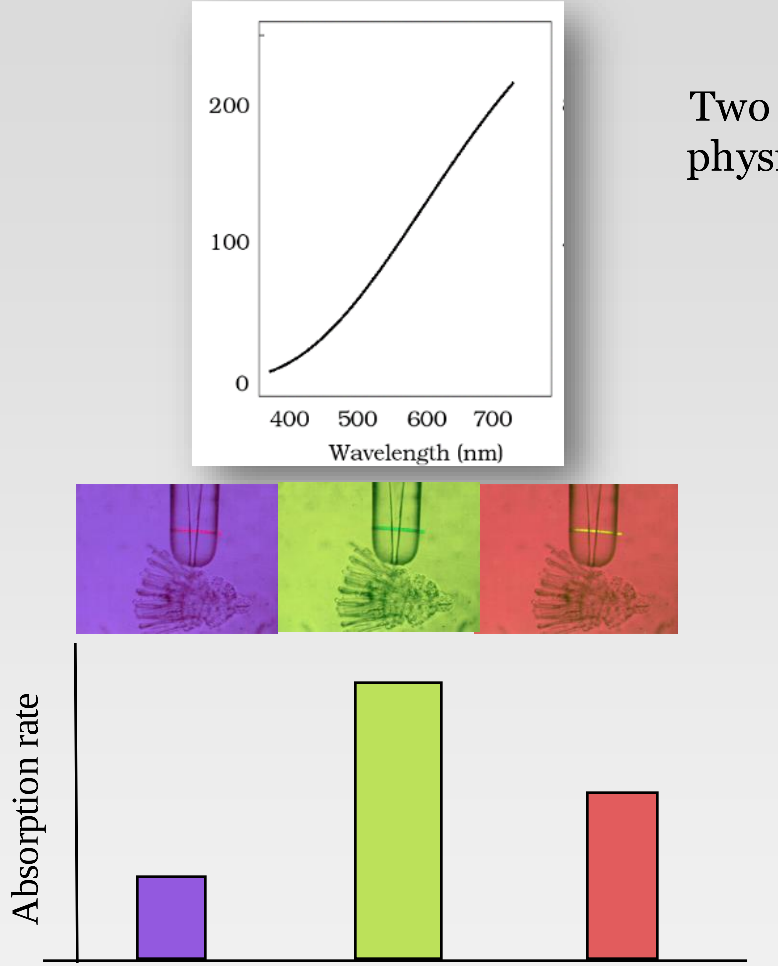
Thomas Young "II. The Bakerian Lecture. On the theory of light and colours" presented to the Royal Society Nov. 12, 1801

"Now, as it is almost impossible to conceive each sensitive point of the retina to contain an infinite number of particles, each capable of vibrating in perfect units with every possible undulation, it becomes necessary to suppose the number limited for instance to the three principal colours ..."

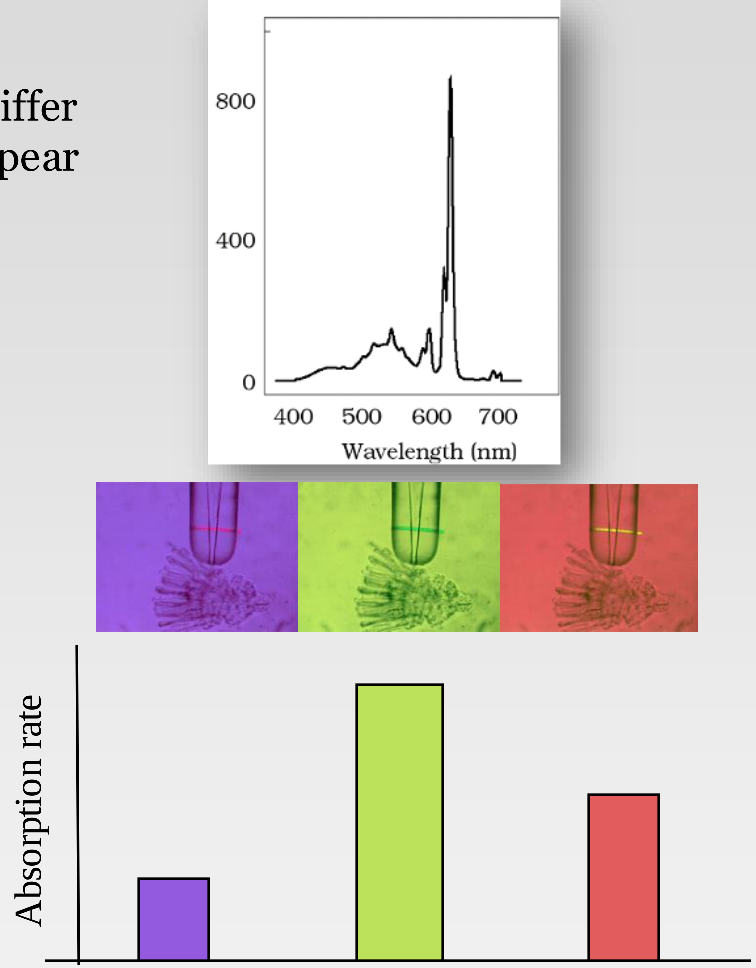
- Brewster didn't buy it – he thought color was a property of light
- Helmholtz mis-estimated the number of cone types
- Maxwell got it right in a series of remarkable papers

# Thomas Young – Trichromacy

Thomas Young (1802) On the theory of lights and colours. Philosophical Transactions of the Royal Society 92, 12-48.

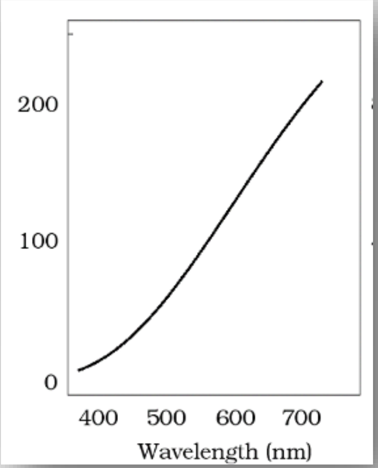



Two lights that differ physically but appear identical (metamers)

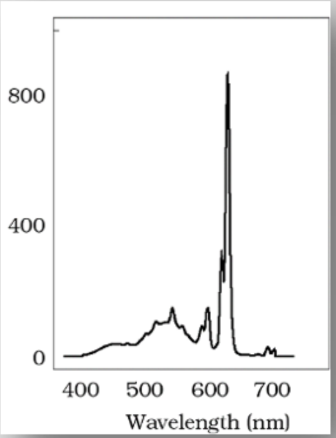


# Thomas Young – Trichromacy

Thomas Young (1802) On the theory of lights and colours. Philosophical Transactions of the Royal Society 92, 12-48.




Two lights that differ physically but appear identical (metamers)

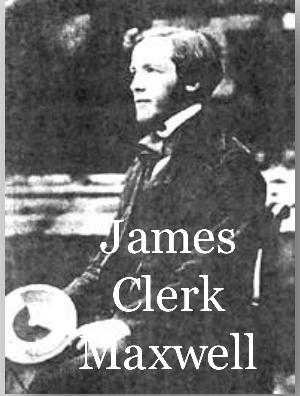



????

What is the biological basis of this equivalence

???

Maxwell JC. 1860
On the theory of compound colours, and the relations of the colours of the spectrum.
Phil. Trans. R. Soc. Lond. 150, 57–84. (doi:10.1098/rstl.1860.0005)




IV. *On the Theory of Compound Colours, and the Relations of the Colours of the Spectrum.* By J. Clerk Maxwell, *M.A., Professor of Natural Philosophy in Marischal College and University of Aberdeen. Communicated by Professor* Stokes

It appears therefore that the result of any mixture of colours, however complicated, may be defined by its relation to a certain small number of well-known colours. Having selected our standard colours, and determined the relations of a given colour to these, we have defined that colour completely as to its appearance. Any colour which has the same relation to the standard colours, will be identical in appearance, though its optical constitution, as revealed by the prism, may be very different. (James Clerk Maxwell)

light.

Newton has also shown† how to combine the different rays of the spectrum so as to form a single beam of light, and how to alter the proportions of the different colours so as to exhibit the result of combining them in any arbitrary manner.

The number of different kinds of homogeneous light being infinite, and the proportion in which each may be combined being also variable indefinitely, the results of such combinations could not be appreciated by the eye, unless the chromatic effect of every

# Maxwell's color-matching apparatus

- Color-mixing with spectral lights (1860)
- Channel C provides a constant daylight, channels XYZ provide three spectral lights

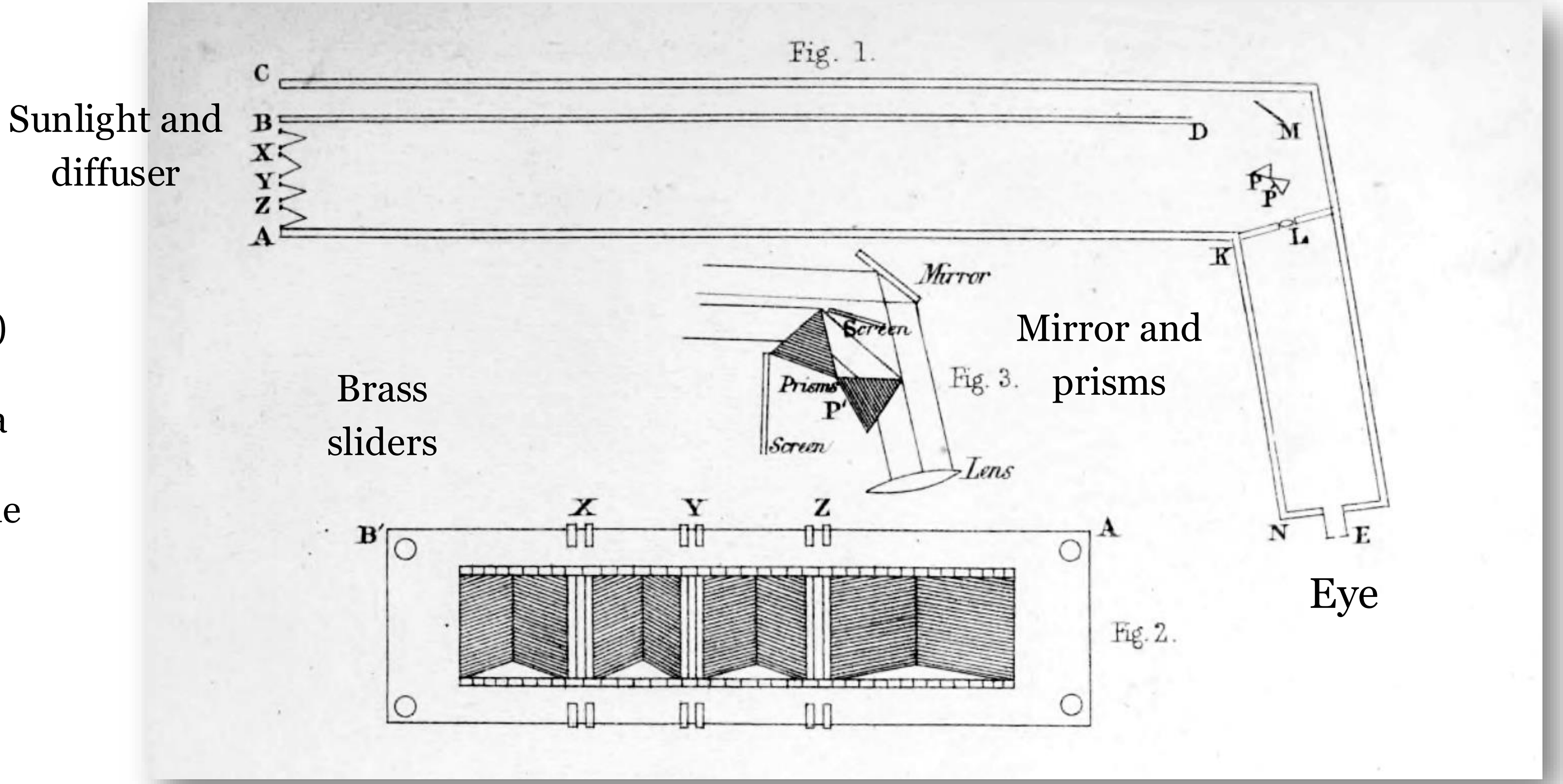



Fig. 1, Plate I. represents the instrument for making the observations. It consists of two tubes, or long boxes, of deal, of rectangular section, joined together at an angle of about 100°. The part AK is about 5 feet long ...

# Data and analyses are included in the 1860 paper

TABLE VI.

| Observer (K.). | (24.) | (44.) | (68.) |
|---|---|---|---|
| 44·3(20)= | 18·6 | + 0·4 | + 2·8 |
| 16·1(28)= | 18·6 | + 5·8 | − 0·1 |
| 22·0(32)= | 18·6 | +19·3 | − 0·1 |
| 25·2(36)= | 12·2 | +31·4 | − 0·8 |
| 26·0(40)= | 3·3 | +31·4 | − 0·2 |
| 35·0(46)= | − 1·2 | +31·4 | + 0·3 |
| 41·4(48)= | − 2·6 | +31·4 | + 3·5 |
| 62·0(52)= | − 3·4 | +31·4 | +17·5 |
| 61·7(56)= | − 3·1 | +21·0 | +30·5 |
| 40·5(60)= | − 1·9 | + 7·7 | +30·5 |
| 33·7(64)= | − 1·1 | + 1·1 | +30·5 |
| 32·3(72)= | + 0·6 | + 0·2 | +30·5 |
| 44·0(76)= | + 1·1 | + 0·7 | +30·5 |
| 63·7(80)= | + 0·3 | − 1·8 | +30·5 |

TABLE IX.

Observations by J., October 1859.

| | (24.) | (44.) | (68.) |
|---|---|---|---|
| 44·3(20)= | 18·1 | − 2·5 | + 2·3 |
| 16·0(28)= | 18·1 | + 6·2 | − 0·7 |
| 21·5(32)= | 18·1 | +25·2 | − 0·7 |
| 19·3(36)= | 8·1 | +27·5 | − 0·3 |
| 20·7(40)= | 2·1 | +27·5 | − 0·5 |
| 52·3(48)= | − 1·4 | +27·5 | +10·7 |
| 95·0(52)= | − 2·4 | +27·5 | +37·0 |
| 51·7(56)= | − 2·2 | + 4·8 | +37·0 |
| 37·2(60)= | − 1·2 | + 0·8 | +37·0 |
| 36·7(64)= | − 0·2 | + 0·8 | +37·0 |
| 35·0(72)= | + 0·6 | − 0·2 | +37·0 |
| 40·0(76)= | + 0·9 | + 0·5 | +37·0 |
| 51·0(80)= | + 1·1 | + 0·5 | +37·0 |

may be considered complete, and the operator must measure the breadth of each slit by means of the wedge, as before described, and write down the result as a colour-equation, thus—

Oct. 18, J. $$18{\cdot}5(24)+27(44)+37(68)=W^{*}. \qquad (13.)$$

This equation means that on the 18th of October the observer J. (myself) made an observation in which the breadth of the slit X was 18·5, as measured by the wedge, while its centre was at the division (24) of the scale; that the breadths of Y and Z were 27 and 37, and their positions (44) and (68); and that the illumination produced by these slits was exactly equal, in my estimation as an observer, to the constant white W.

The position of the slit X was then shifted from (24) to (28), and when the proper adjustments were made, I found a second colour-equation of this form—

Oct. 18, J. $$16(28)+21(44)+37(68)=W. \qquad (14.)$$

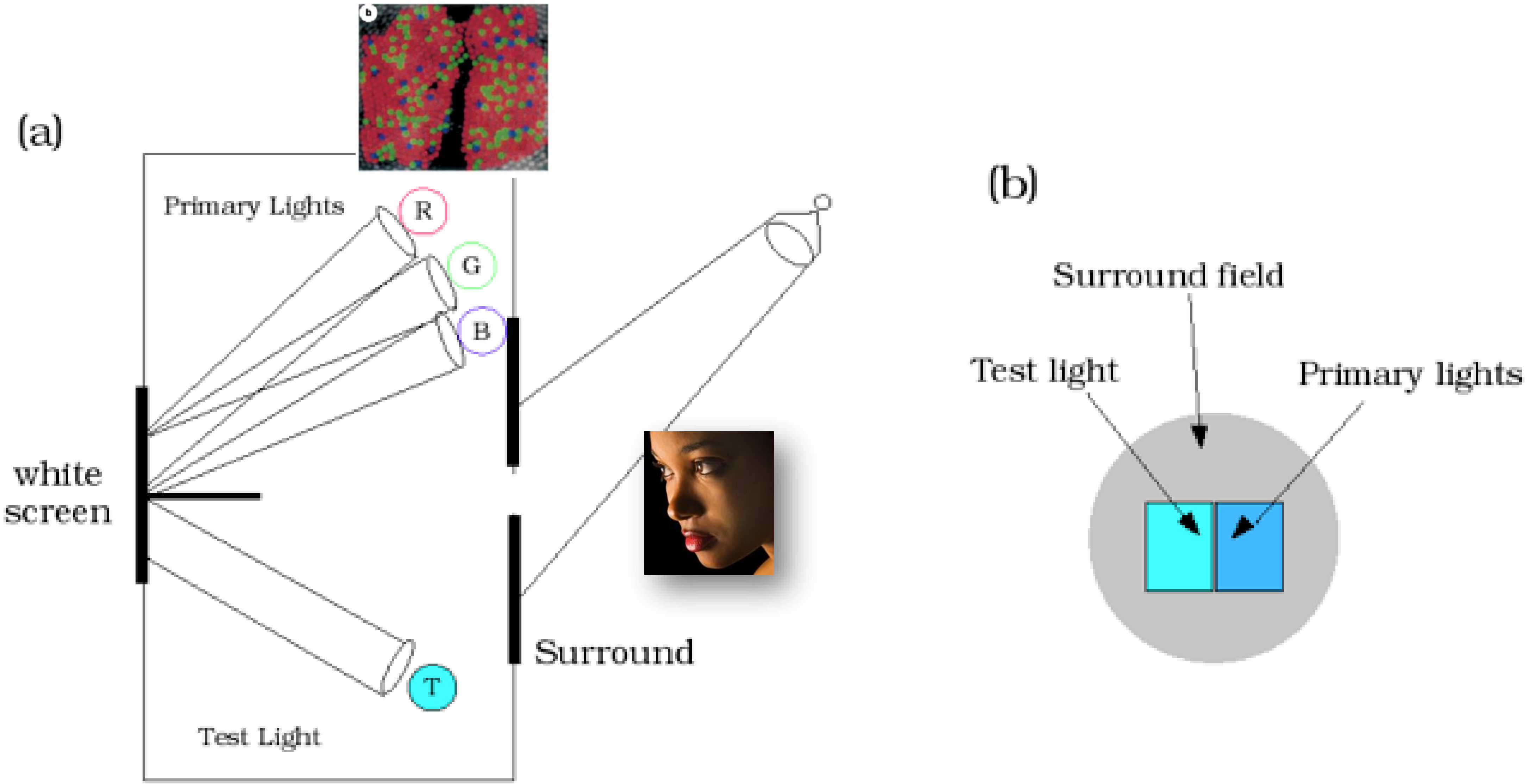
Subtracting one equation from the other and remembering that the figures in brackets are merely symbols of position, not of magnitude, we find

$$16(28)=18{\cdot}5(24)+6(44), \qquad (15.)$$

showing that (28) can be made up of (24) and (44), in the proportion of 18·5 to 6.

In this way, by combining each colour with two standard colours, we may produce a white equal to the constant white. The red and yellow colours from (20) to (32) must be combined with green and blue, the greens from (36) to (52) with red and blue, and the blues from (56) to (80) with red and green.

# Cone color matching experiment (cone vision)

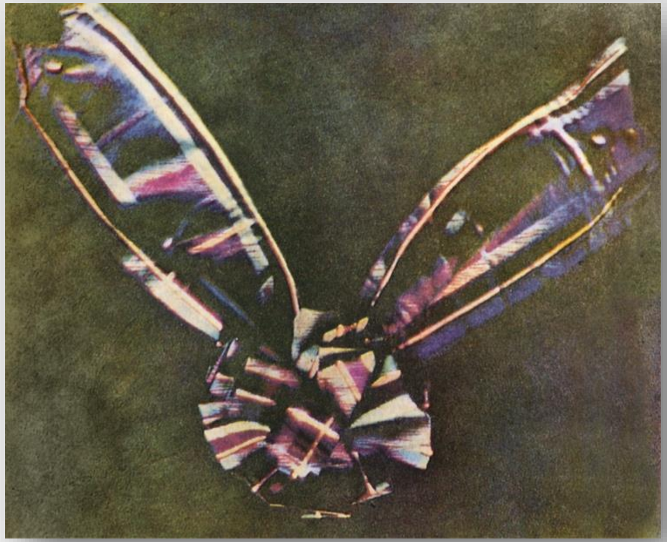


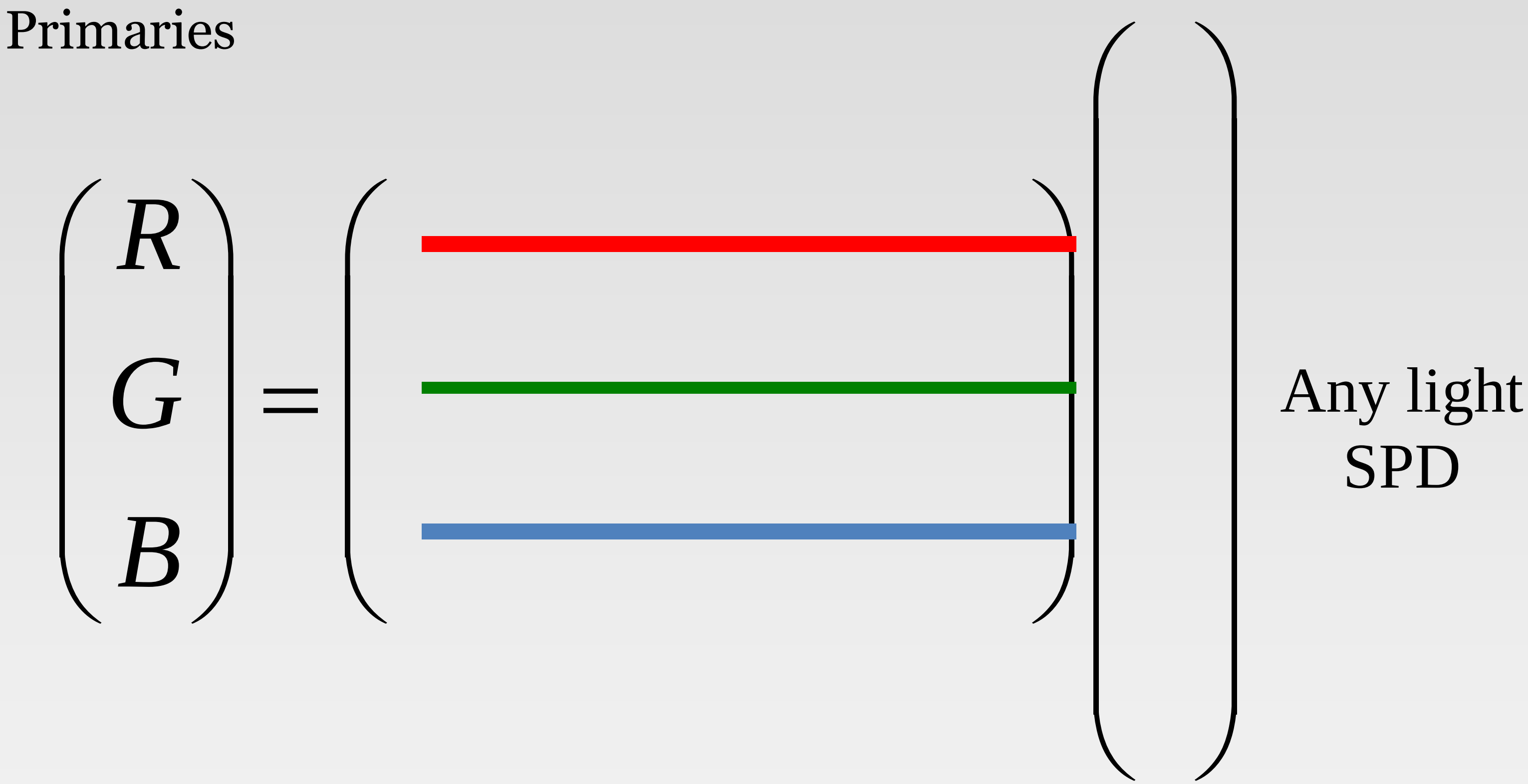
# Color matching equations:  Origins of linear algebra

Grassmann
(history)

- From his experiments and calculations, Maxwell derived and plotted the rows of this matrix, which we now call the color matching functions

- With Sutton, he went on to use this to produce the first color photograph

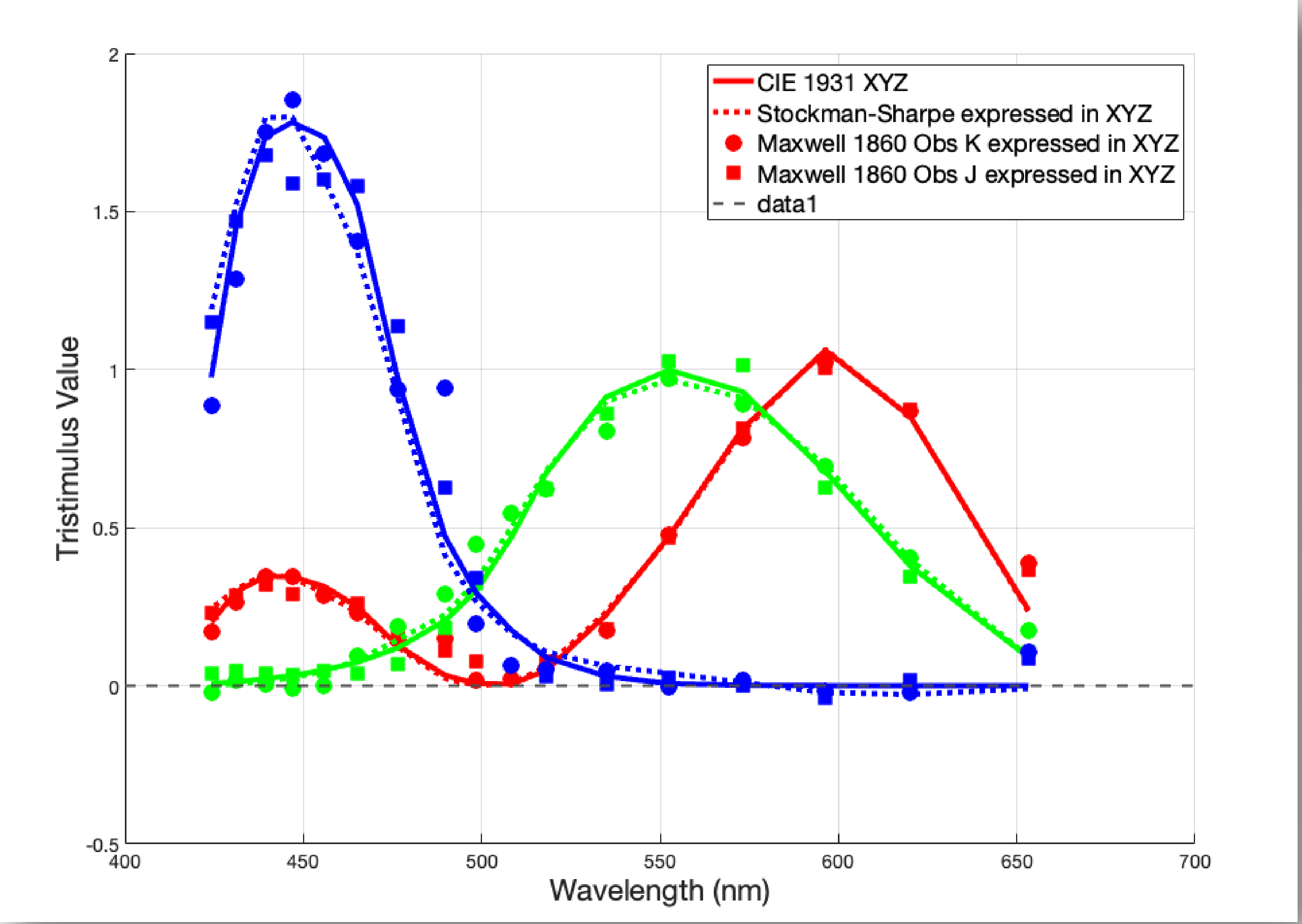




# Maxwell – in 1860 – and the CIE today

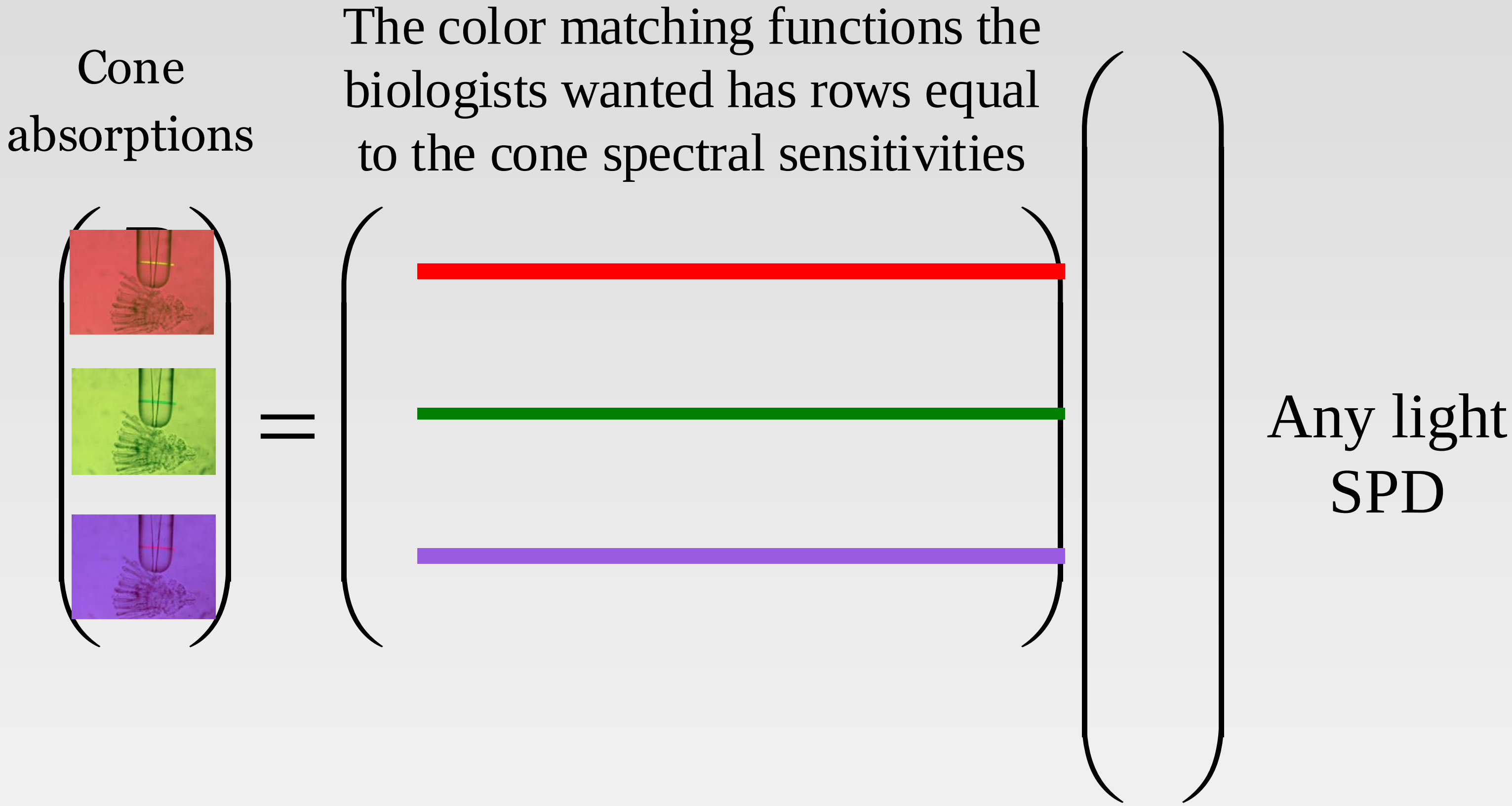
- We compared Maxwell's data with modern standards

- We had to make only one small adjustment to Maxwell's wavelength estimates, via Judd (10 nm)



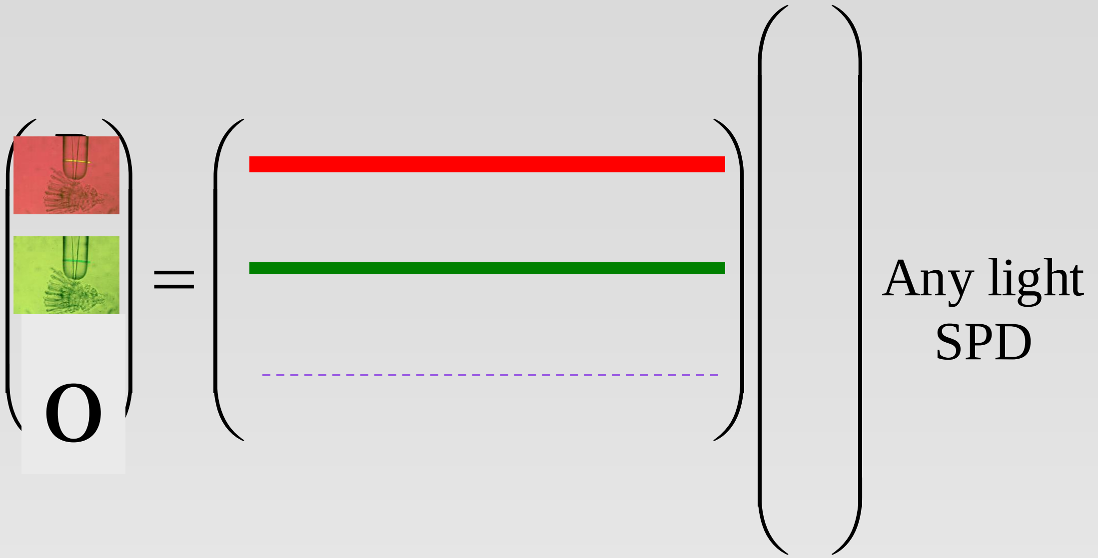
# Color matching equations: Cone fundamentals

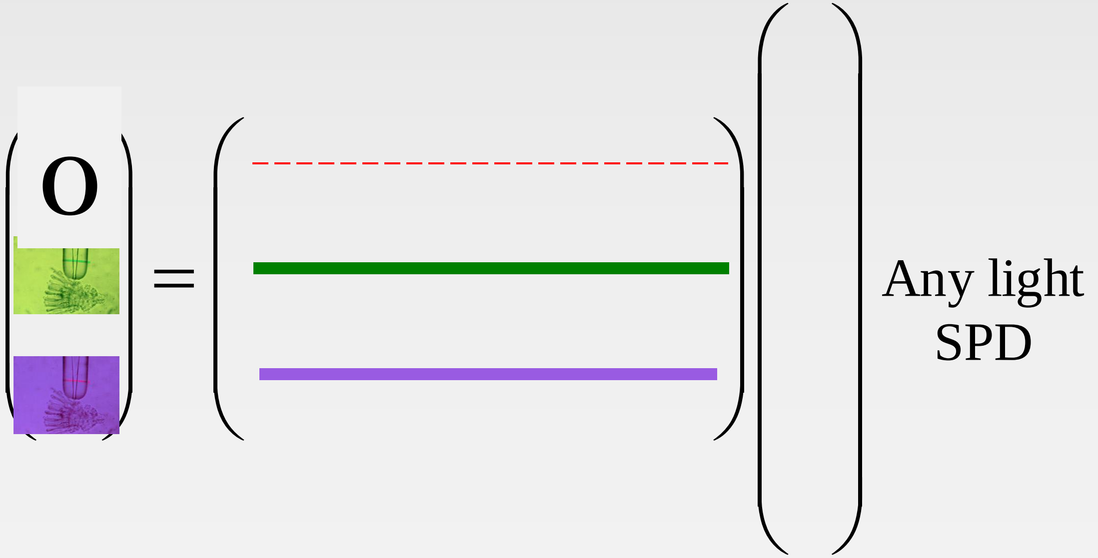
- The color matching functions the biologists wanted has rows equal to the cone spectral sensitivities
- Over the years, these were estimated using a wide variety of auxiliary experimental methods
- A standard was established in the year 2000 by the CIE based on Stockman



# Color matching equations:  Dichromats

- There are people who have only two of the three types of cone fundamentals
- Reduction dichromats
- Genetically detectable



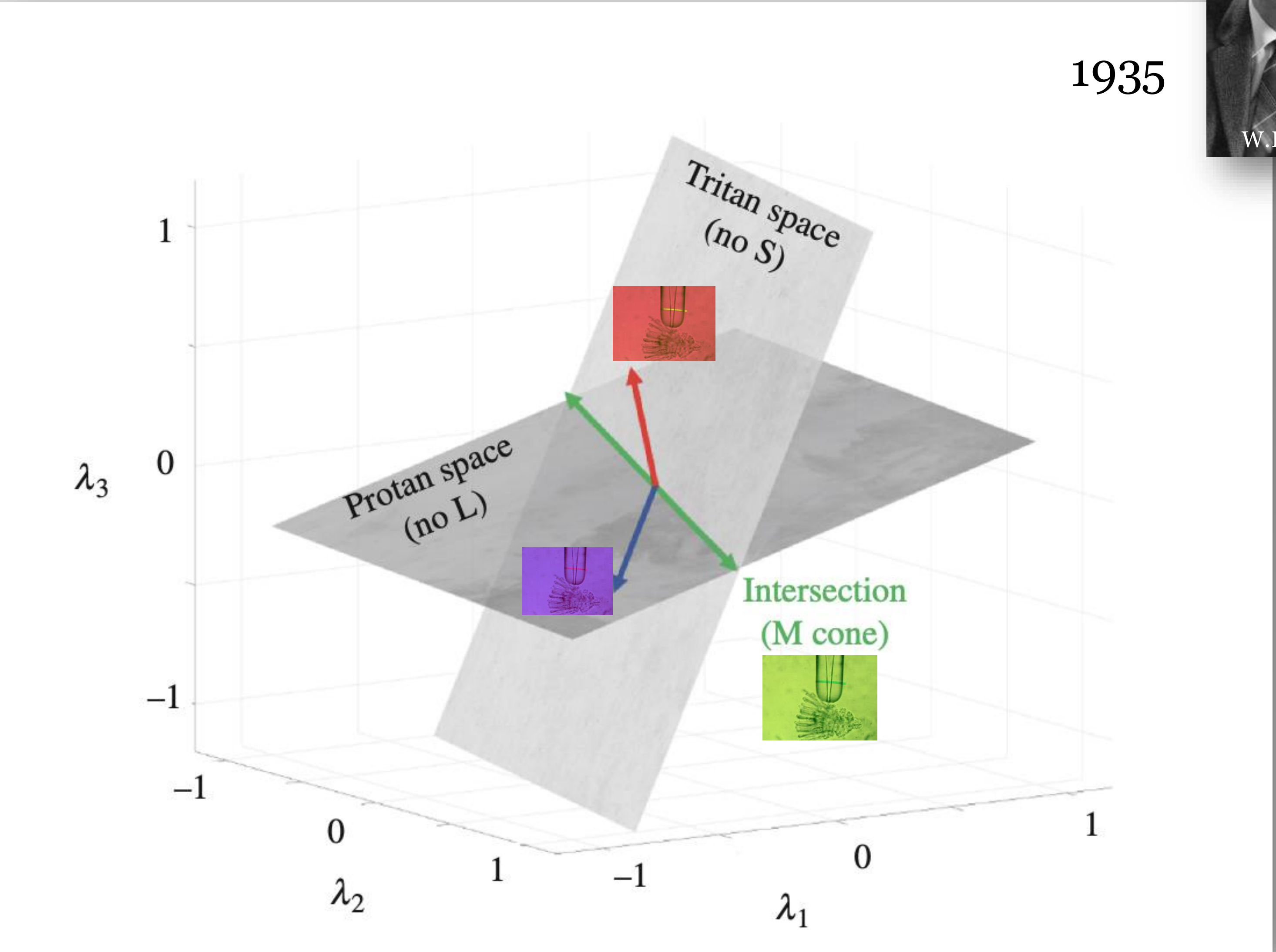



# Here is the idea we understood and implemented in the paper

Dichromatic color matching functions have two rows, not 3

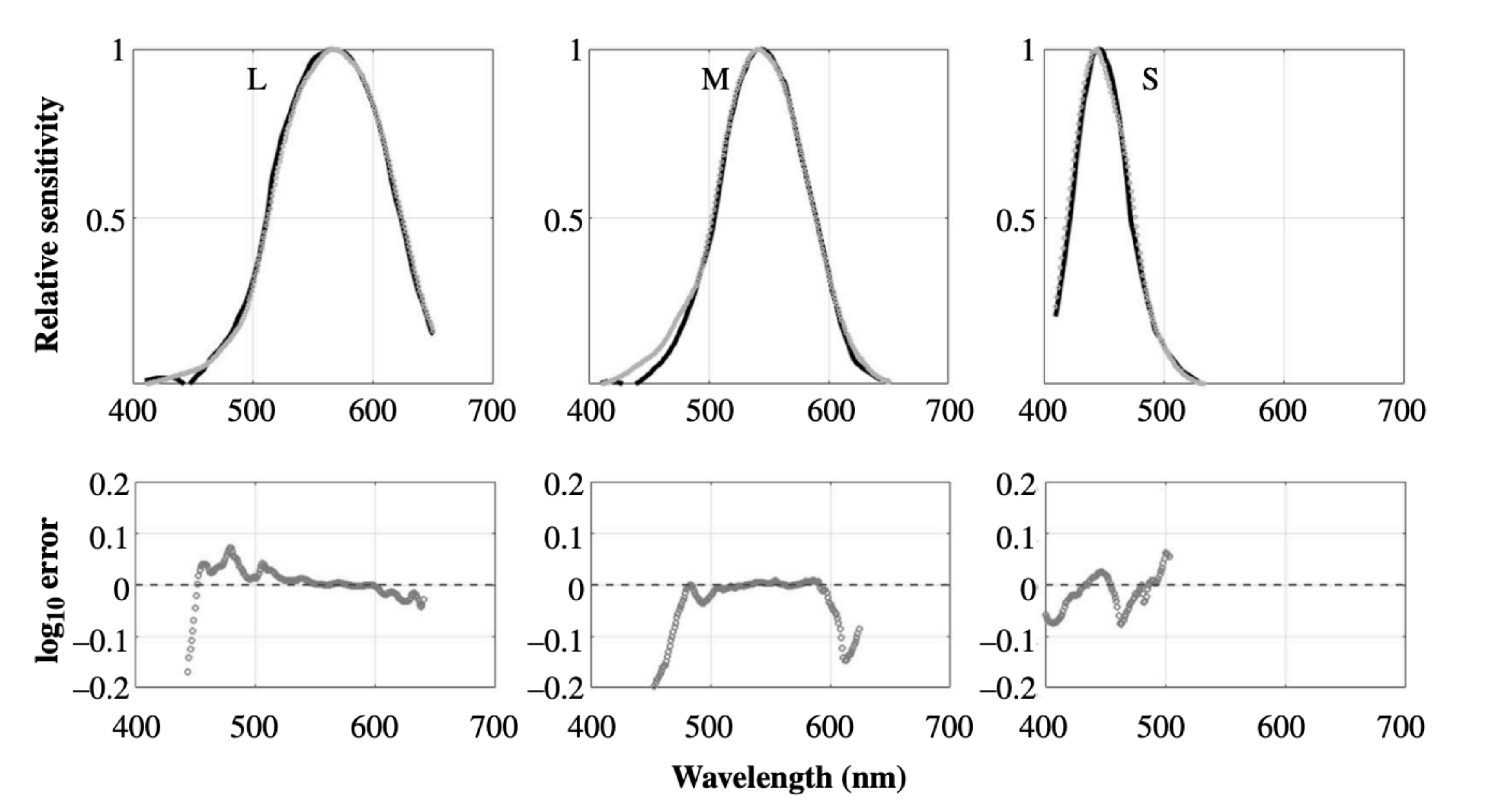
$$\mathbf{C}_p = [\mathbf{c}_1^p\ \mathbf{c}_2^p] = [\mathbf{m}\ \mathbf{s}]\,\mathbf{A}_p,$$
$$\mathbf{C}_d = [\mathbf{c}_1^d\ \mathbf{c}_2^d] = [\mathbf{l}\ \mathbf{s}]\,\mathbf{A}_d,$$
$$\mathbf{C}_t = [\mathbf{c}_1^t\ \mathbf{c}_2^t] = [\mathbf{l}\ \mathbf{m}]\,\mathbf{A}_t\,.$$

Using only color matching functions from dichromats, we can solve for the three cone fundamentals

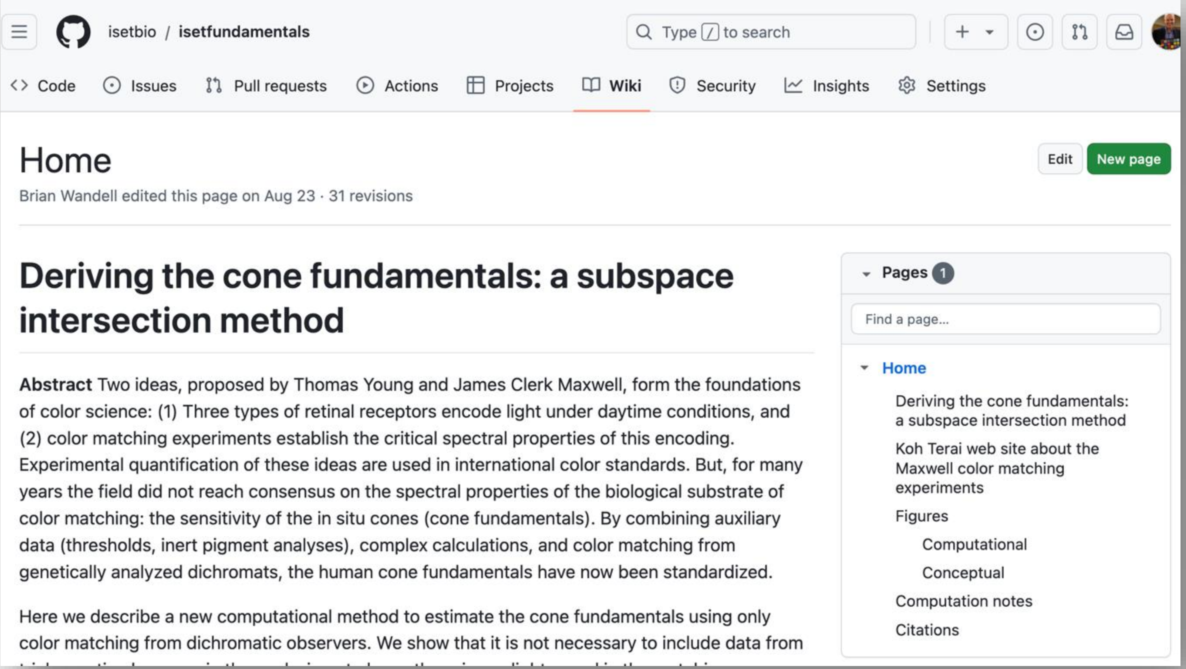


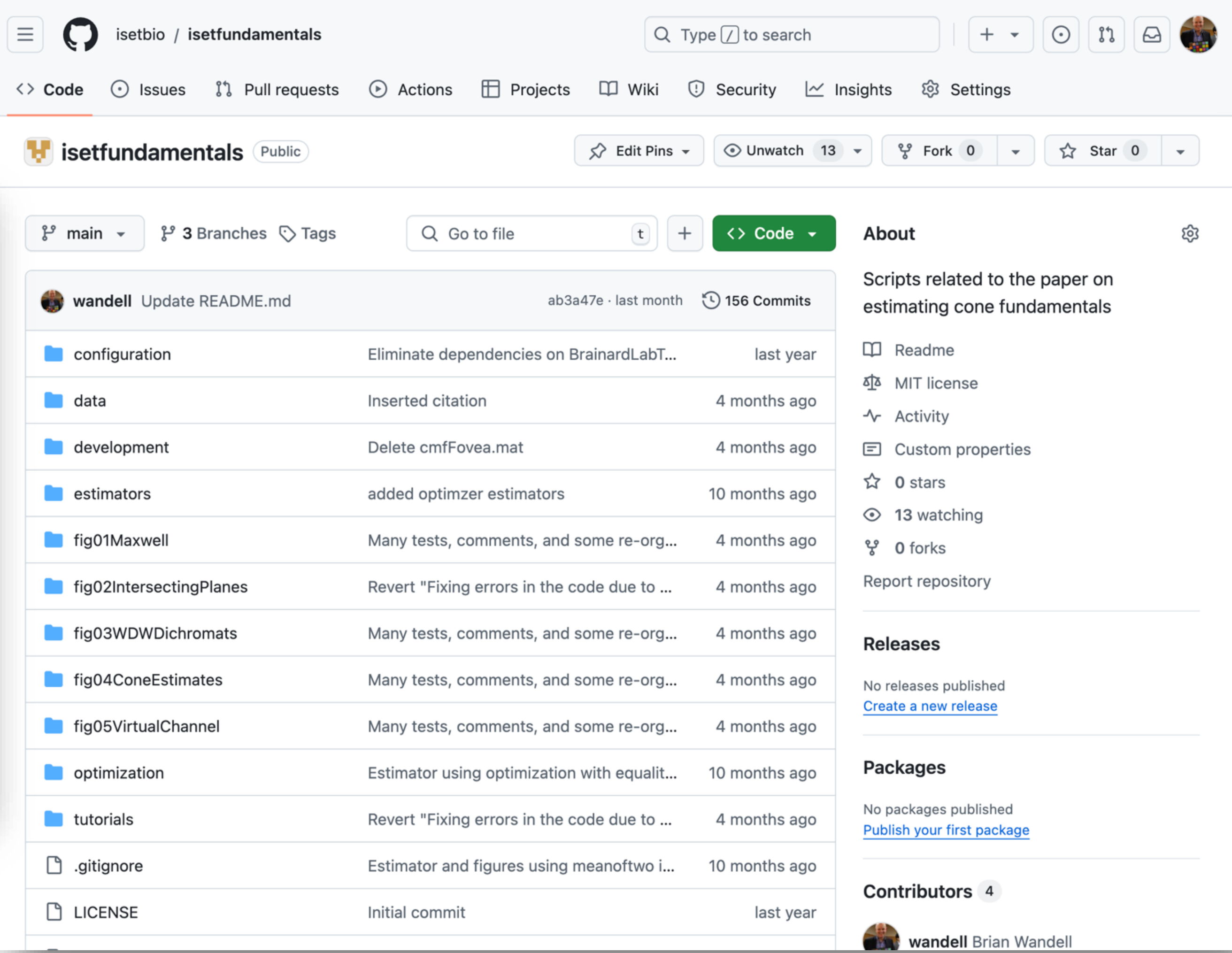

# Comparison of CIE 2000 standard and our estimates from color-matching only

- This is how well the procedure did compared to the CIE 2007 standard (proposed by Stockman in 2000).
- The differences are within the variation in the human population



# Methods and data are on GitHub and SDR, as usual

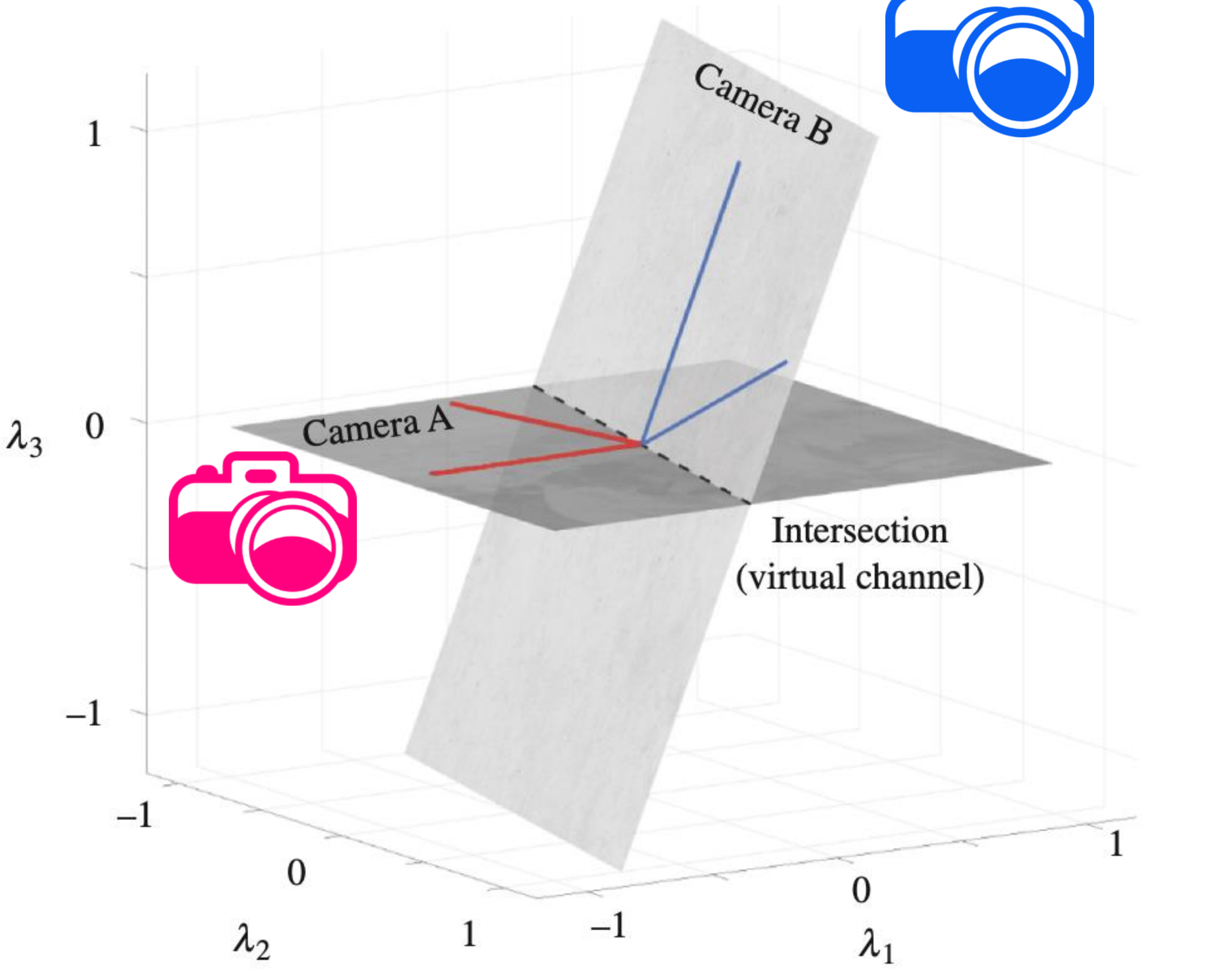


# The engineering application: between device comparison

- Suppose we have two cameras from different vendors
- Their color channels typically have different spectral responsivities
- Hundreds of papers try to fit each of the channels in, say, A from the channels in B
- In this example, a good fit is hopeless

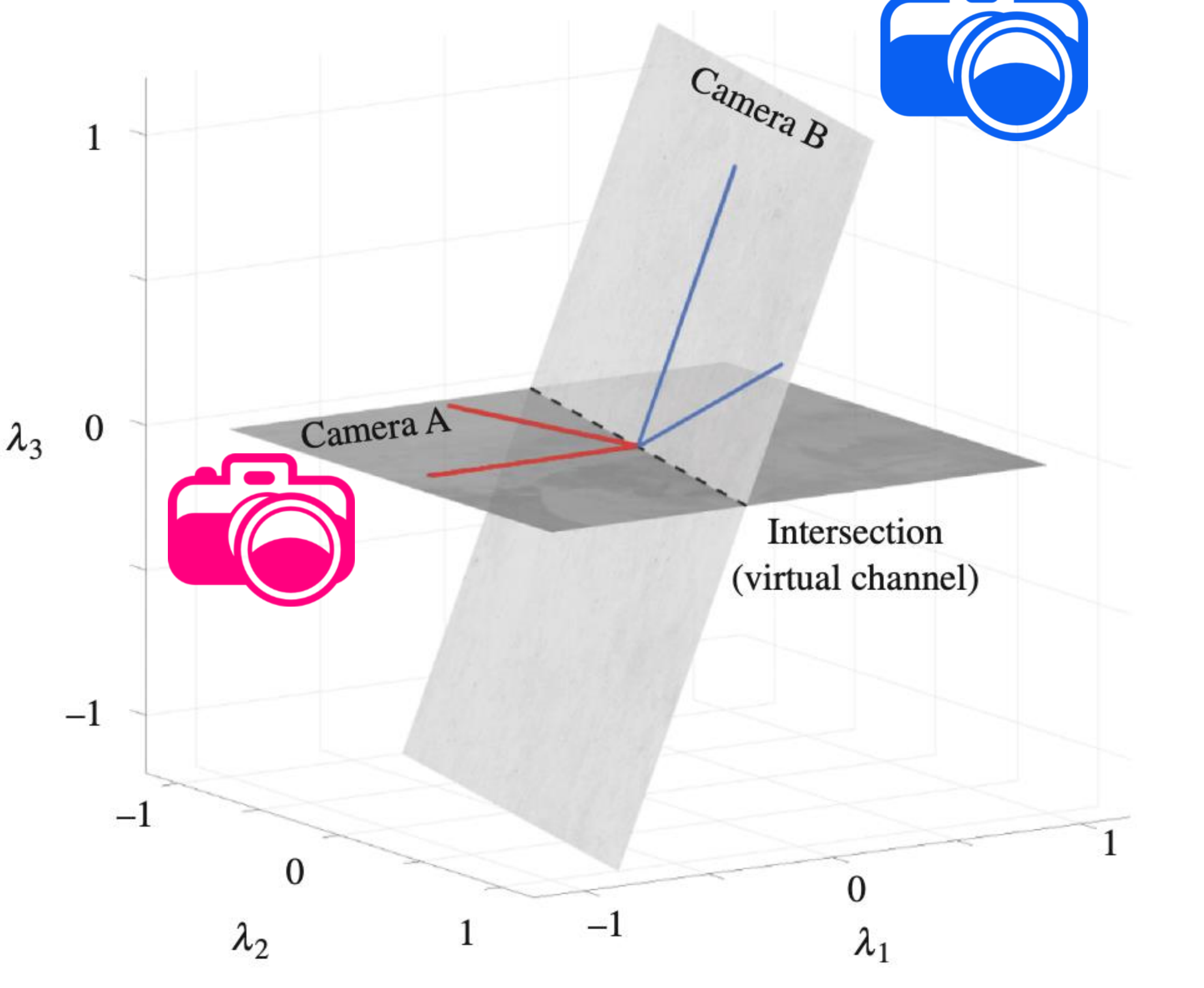
Who uses this idea in other fields?



# The engineering application: between device comparison

- What is possible, however, is to find common ground between the two systems
- We can find the intersection of the spaces spanned by the two cameras (virtual channels)
- Neither camera has this channel, but both can render their data as if they did
- This will let us have the two systems check whether they are seeing the same object
- If they agree, we can combine the measurements to learn more about the object

Who uses this idea in other fields?



# Thanks for the lunches and the years of collegiality

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