COMPUTATIONAL METHODS FOR IMAGING (AND VISION)

JOHN MURRAY-BRUCE

UNIVERSITY OF SOUTH FLORIDA

WELCOME TO

CIS 4930 / CIS 6930

COMPUTATIONAL METHODS FOR IMAGING (AND VISION)

CLASS TIMES:
Mondays & Wednesdays
3:30 PM – 4:45 PM

INSTRUCTOR OFFICE HOURS:
Tuesday, 1:00 PM – 2:00 PM
Wednesday, 5:00 PM – 6:00 PM

MEET THE TEAM

MEET THE TEAM
INSTRUCTOR/MODERATOR

John Murray-Bruce
Assistant Professor
Office: ENG 117A (Pre-Covid)
Office hours: 1pm – 2pm Tues.,
5pm – 6pm Weds.
Email: murraybruce@usf.edu

Please prepend "[CIS 4930/6930]" to the subject of your email for a timely response.

BOSTON UNIVERSITY

2017 – 2019:
Post-doctoral training

Imperial College London

Electrical & Electronic Engineering

Ph.D., Dec. 2016
M.Eng., 2012

USF UNIVERSITY OF SOUTH FLORIDA

Spring 2020:
Go BULLS!

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UNIVERSITY OF SOUTH FLORIDA

Spring 2020:
Go BULLS!

How (I believe) I spend my time at USF:

- **Teaching**
  - Computational methods for Imaging & Vision (S '20, S '21)
  - Ethical issues and professional conduct (F '20)
- **Research**
  - Director of **Information Sciences & Computational Imaging (ISCI)** Lab
  - Pronounced: 'icy', or if you prefer /ˈīsē/
- **Service to the scientific community**

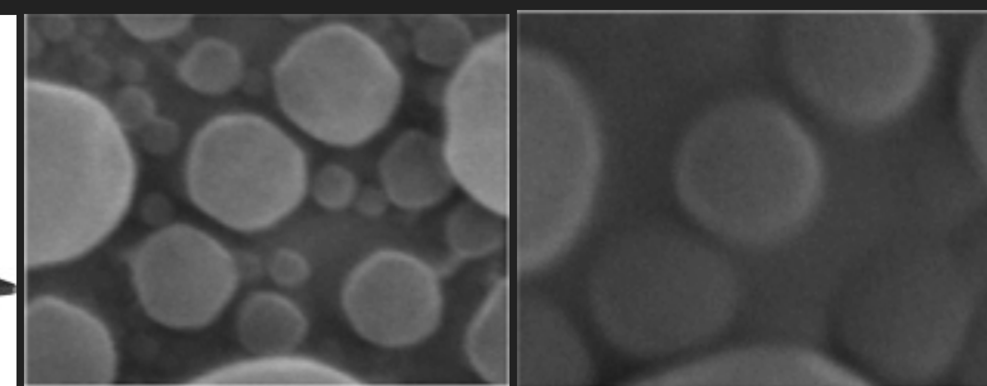
MEET THE TEAM
TEACHING ASSISTANT

Ryan Fogarty
Teaching Assistant
Office: –
Office hours: 13:00-14:00 MW
rfogarty@usf.edu

- **Ph.D. research**
  - In VISION lab with (Prof. Goldgof)

MEET THE TEAM
ISCI LAB RESEARCH THRUSTS

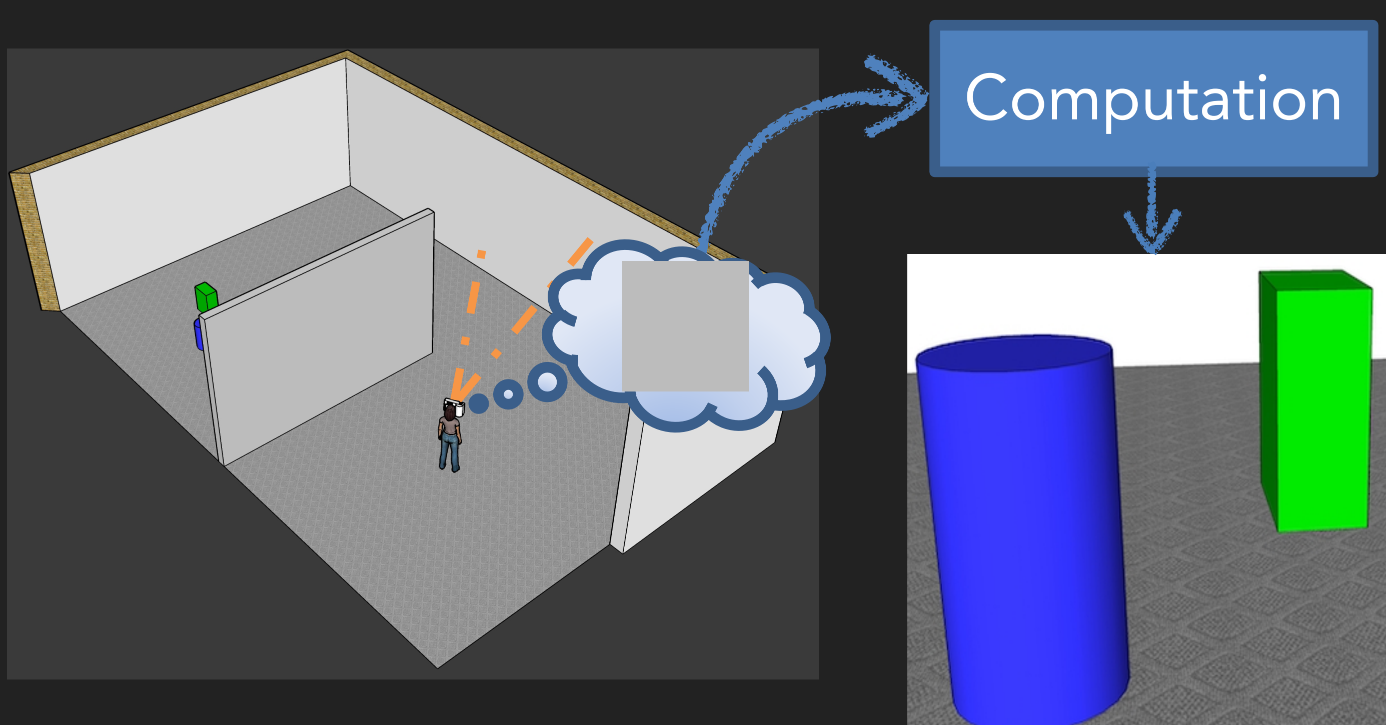
Focussed beam microscopy



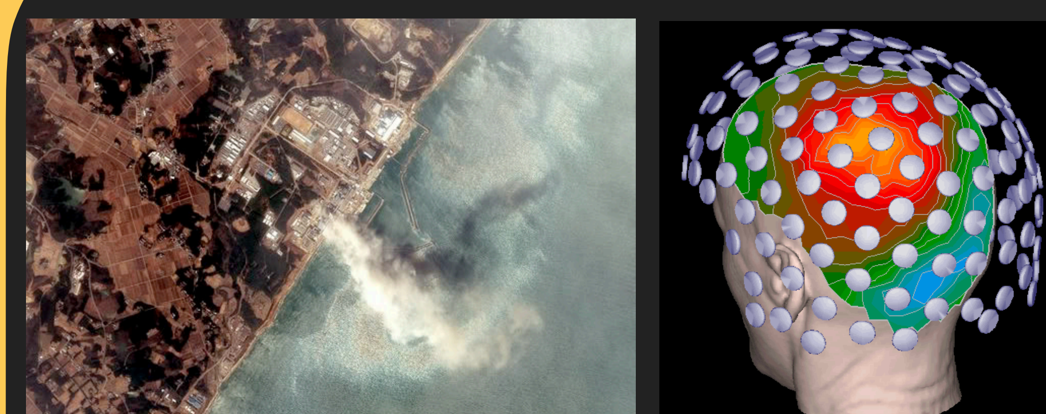
Reduced sample damage

$$\left(\eta+1\right)\left(1-\eta e^{-\eta}\right)$$

Computational Periscopy



PDE-constrained inverse problems



$$\frac{\partial u(\boldsymbol{x},t)}{\partial t} - \mu\nabla^2 u(\boldsymbol{x},t) = f(x,t)$$

MEET THE TEAM
THE REST OF THE TEAM

Our contract: do our best at maximizing both our learning experience and that of our fellow teammates.

HOW LONG IS THE SEMESTER

- 16 Weeks
  - First day of class: Today (Jan. 11, 2021)
  - Last day of class: Apr. 28, 2021
- Add/drop deadline: Jan. 15, 2021
- Test-free Week: Apr. 26, 2021 – Apr. 30, 2021

SYLLABUS
WHAT IS DUE, WHEN?

Week	Date	Main Topic	Lecture	Readings	Homework Out	Homework Due
1	11-Jan-21		Introduction to computational imaging - Forward and Inverse problems - Common computational imaging problems			
	13-Jan-21		Vectors - Preliminaries			
2	18-Jan-21		**Dr. Martin Luther King, Jr. Holiday (no class)**			
	20-Jan-21	Mathematical preliminaries	Vectors and Vector Spaces - Subspaces, Finite dimensional spaces	IIP Appendix A; FSP 2.1 - 2.2		
3	25-Jan-21		Vector Spaces - Hilbert spaces	IIP Appendix B; FSP 2.3		
	27-Jan-21		Bases and Frames I - Orthonormal and Reisz Bases	IIP Appendix C; FSP 2.4 and 2.B	**HW 1**	
4	1-Feb-21		Bases and Frames II - Orthogonal Bases - Linear operators	IIP Appendix C; FSP 2.5 and 2.B		
	3-Feb-21		Fourier Analysis I - FT (1D and 2D) - FT properties	IIP 2.1, Appendix D; FSP 4.4		
5	8-Feb-21		Sampling and Interpolation - BL functions - Sampling	IIP 2.2, 2.3; FSP 5.4, 5.5		**HW 1**
	10-Feb-21		Fourier Analysis II (DFT)	IIP 2.4; FSP 3.6	**HW 2**	
6	15-Feb-21	Forward Modeling	LSI imaging: Forward problem I - Convolution	IIP 2.5 - 2.6, 3		
	17-Feb-21		LSI imaging: Forward problem I - Transfer functions	IIP 2.6		
7	22-Feb-21		LSI imaging: Forward problem I - Linear operators	IIP 3		
	24-Feb-21		LSI imaging: Forward problem I - Linear operators, Adjoints, and Inverses		**HW 3**	**HW 2**
8	1-Mar-21		**Mid-term Exams**			
	3-Mar-21		LSI imaging: Forward problem II - Sampling and Discretization: Matrix-vector form	IIP 2.7, 4		
9	8-Mar-21		LSI imaging: Forward problem II - Convolution matrix			
	10-Mar-21		LSI imaging: Forward problem II - Sampling and Discretization: Matrix-vector form - PSF, and Transfer functions			**HW3**

The Simpsons

SYLLABUS
WHAT IS DUE, WHEN?

10	15-Mar-21	Forward Models and Inverse Problems	Linear Inversion - Inverse problems - Deconvolution and Denoising	IIP 4, Appendix E	**HW 4**	
	17-Mar-21		Intro to Regularized Inversion I - Tikhonov	IIP 5, Appendix E		
11	22-Mar-21	Regularization	Intro to Regularized Inversion II - Iterative methods - Steepest descent	IIP 6		
	24-Mar-21		Statistical methods I - ML estimation - Bayesian estimation	IIP 7.1 - 7.5		
12	29-Mar-21	Forward models and Inverse Problems II	LSV imaging systems: Forward problem - SVD - Inversion	IIP 8.1, 9, 10		
	31-Mar-21	Non-linear Regularization	Beyond L_2-regularization - Sparsity (l_0- and l_1-priors) - TV prior	SMIV 1.1 - 1.5 Papers & Handout		**HW 4**
13	5-Apr-21		Algorithms overview - ISTA/FISTA - ADMM	Papers & Handout		
	7-Apr-21	Introductory Optics	Geometrical/Ray Optics - Rays & pinhole cameras - Lenless imaging and Coded apertures	IIP 8.2, 8.3, 9.5 Papers & Handout		
14	12-Apr-21 14-Apr-21	**Spring Break (no classes)**				
15	19-Apr-21	Applications of Comp. Imaging	Looking around corners (NLOS imaging)	Papers & Handout		
	21-Apr-21		Compressive Imaging and Imaging from few photons	Papers & Handout		
16	26-Apr-21 28-Apr-21	**Group Presentations (Teams)**				
17	3-May-21	***no class**				
	5-May-21	**Final Exam: 12:30 PM - 2:30 PM**				

[IIP] M. Bertero and P. Boccacci, "Introduction to Inverse Problems in Imaging," Taylor and Francis. 1998, ISBN 9780750304351.

[SMIV] J. Mairal, F. Bach, and J. Ponce, Sparse Modeling for Image and Vision Processing, NOW 2014. [http://lear.inrialpes.fr/people/mairal/resources/pdf/review_sparse_arxiv.pdf]

[FSP] Martin Vetterli, Jelena Kovačević, and Vivek Goyal, Foundations of Signal Processing, Cambridge University Press 2014. [Free copy: http://fourierandwavelets.org/]

ASSESSMENTS AND GRADING

- **Four sets of homework assignments (30%)**
  - Best three pieces taken
- **Project (20%)**
- **Exams**
  - Mid-term exam (20%)
  - Finals (20%)
- **Participation (10%)**

GROUP PROJECT

- **Groups of four or five**
  - Randomly assigned unless you propose a project
- Will post papers related to computational imaging
  - Final presentation
  - Presenters share extra credit on offer
- You're totally encouraged to propose a project
  - Form your groups and send me proposal (Deadline: TBA)

GRADE BOUNDARIES

Grading scale [%]	
93 –	A
[90, 93)	A-
[87, 90)	B+
[83, 87)	B
[80, 83)	B-
[70, 80)	C
[60, 70)	D
[0, 60)	F

WHY SHOW UP FOR EACH SESSION

- Though attendance is neither mandatory nor (explicitly) graded
- Participation is graded
- Because you paid for it

ALSO, THIS LOOKS FUN!!!

TEXT

WELCOME TO

COMPUTATIONAL METHODS
FOR
IMAGING (AND VISION)

CIS 4930.006S20
CIS 6930.013S2

THE TEAM

John Murray-Bruce
Instructor
Office: ENG 117A (Teams)
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17:00-18:00 W
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Please prepend "[CIS 4390/6390]" to the subject of your email for a timely response.

Ryan Fogarty
TA
Office: –
Office hours: 13:00-14:00 MW

rfogarty@usf.edu

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COMPUTATIONAL METHODS
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CIS 4930.006S20

CIS 6930.013S2

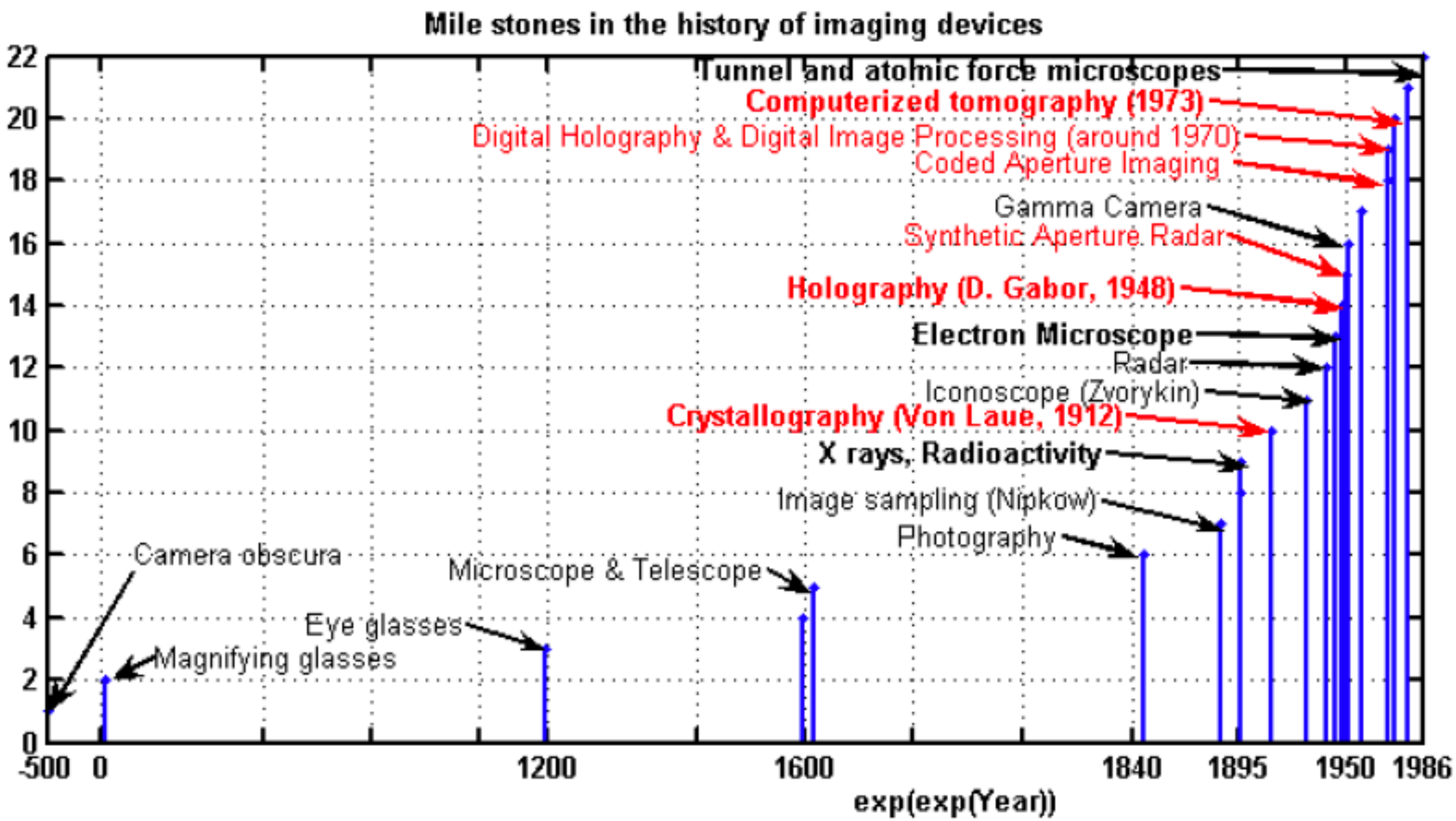
Quiz 0.0 - What do you think this Course is about?

IMAGING SYSTEMS

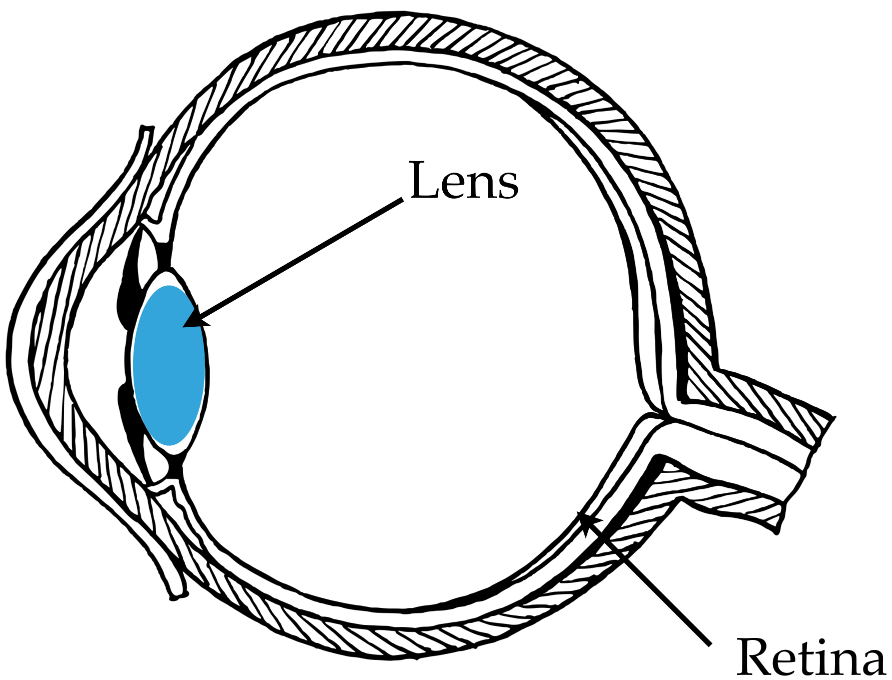
DESIRED PROPERTIES OF IMAGING SYSTEMS

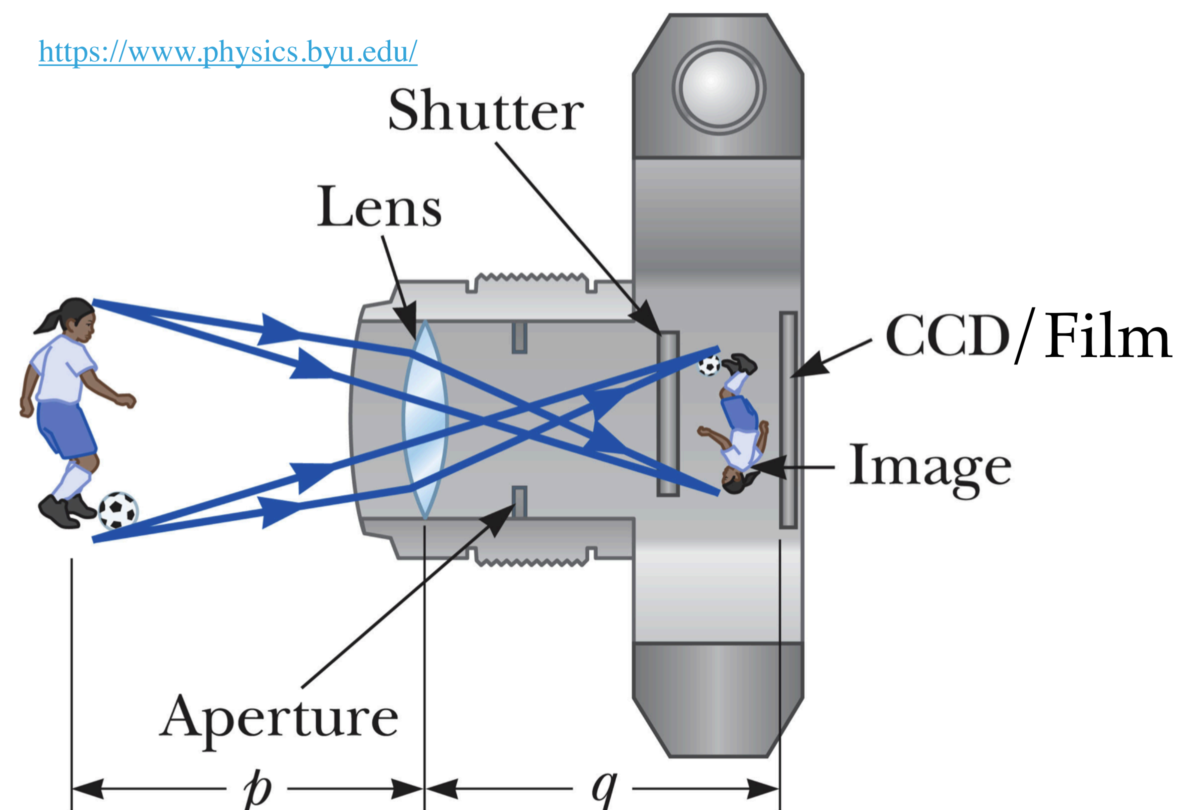
- Form images
  - With High Signal-to-Noise Ratio
  - High Contrast
  - Good resolution
- Cheap, Simple, and Robust
  - Microscopes (HIM ~$1.5m, but may be easily damaged without proper care)
  - Military applications

(VERY) BRIEF HISTORY OF IMAGING DEVICES



IMAGING SYSTEMS
SIMPLISTIC VIEW



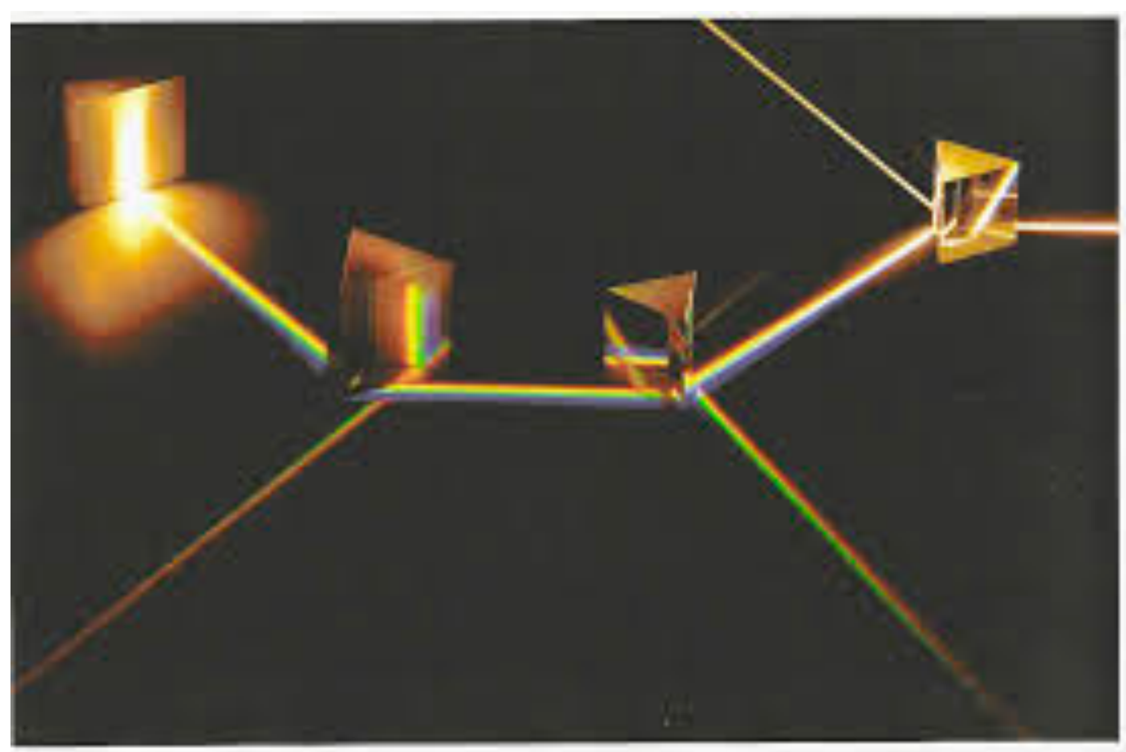


- Pupil allows light passage
- Lens focuses light to retina
- Muscles control size of pupil and focus of lens

- Aperture – light passage
- Lens focuses light to film
- Changing shape of lens difficult, but can slide along optical axis.

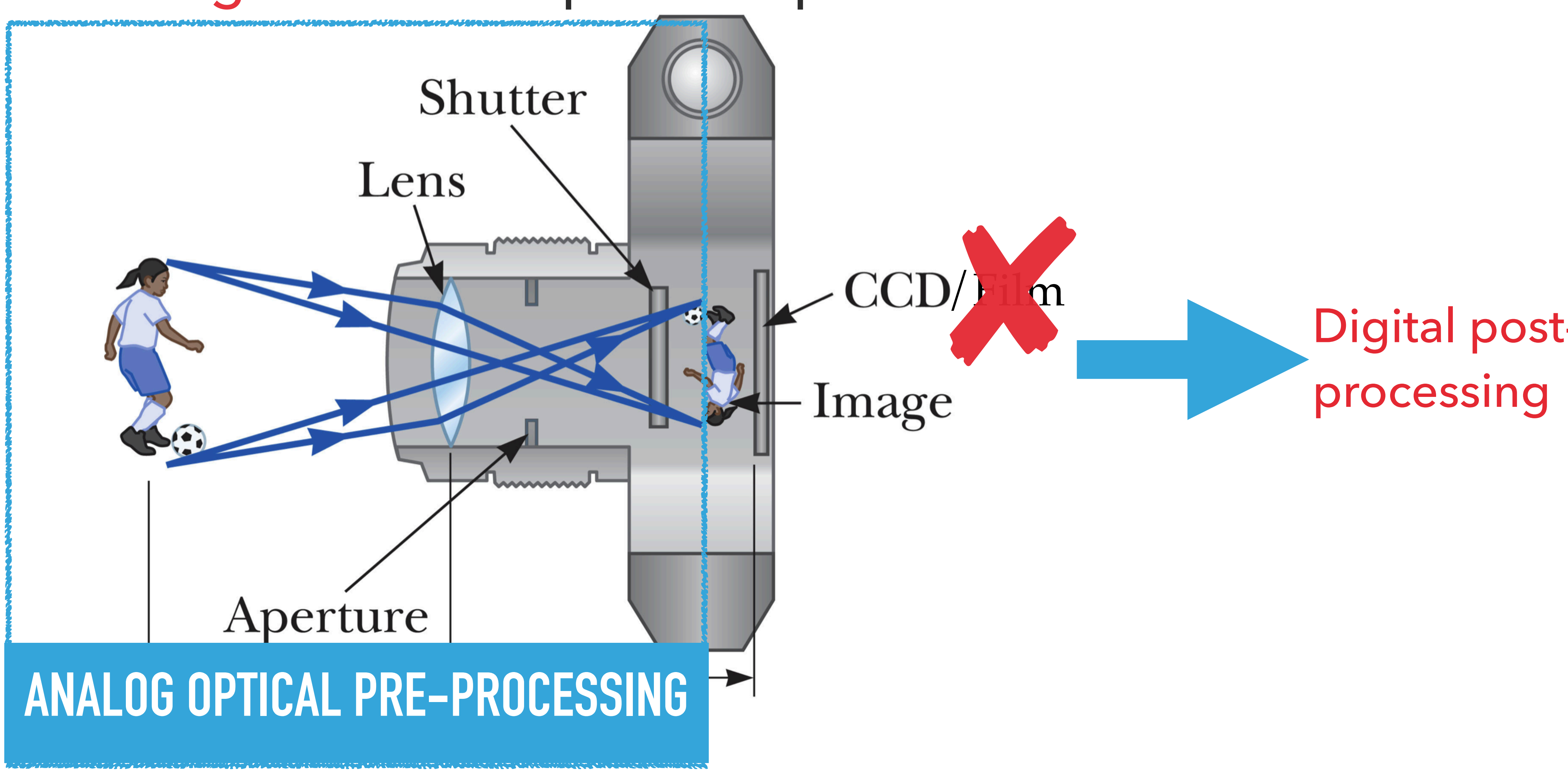
CAPABILITY OF OPTICS

- Image formation from (light) wave-front.
- Perform geometrical transformations on images.
- Even perform integral transformations (Fourier, Fresnel, Correlation & Convolution).



DIGITAL REVOLUTION
FROM FILMS TO DIGITAL SENSORS

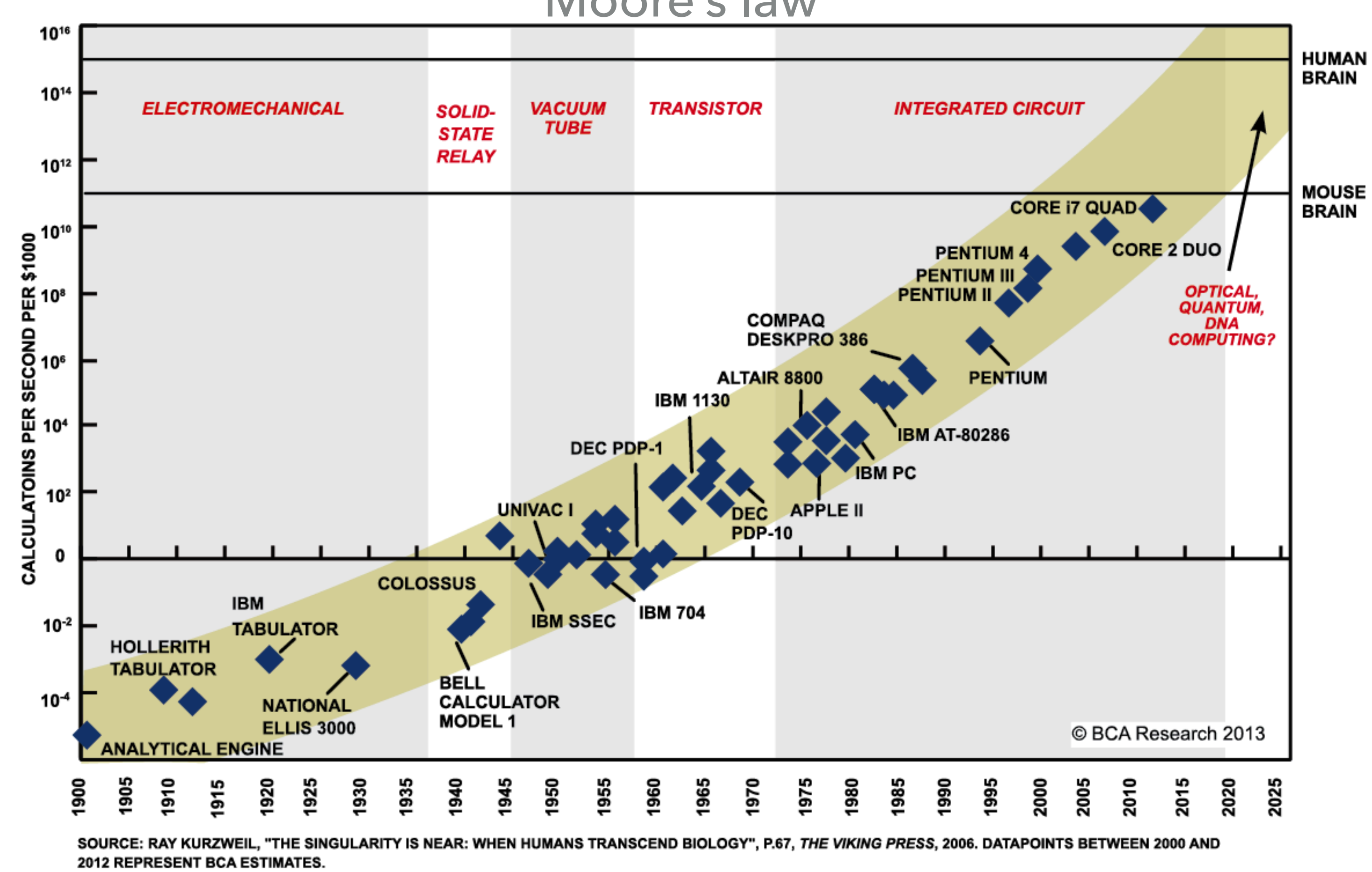
- Lenses and filters are perform analog (optical) processing.
- Detectors are digital and sample the optical field.



DIGITAL REVOLUTION

- Advances in Digital Computing
  - Hardware (smaller, better, faster, cheaper)
  - Software (fast and efficient algorithms)
  - Digital signal processing on images

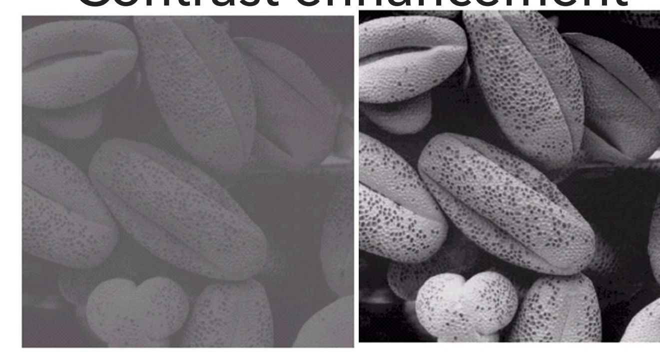
Moore's law



DIGITAL REVOLUTION

- Digital (post)-processing on images
    - Image compression
    - Image enhancement (deblurring, denoising, edge enhancement, super resolution, in-painting)
    - Image restoration (defocus, motion deblurring)

Contrast enhancement



Denoising

Edge enhancement

Deblurring

DIGITAL IMAGING (VS ANALOG PHOTOGRAPHY)

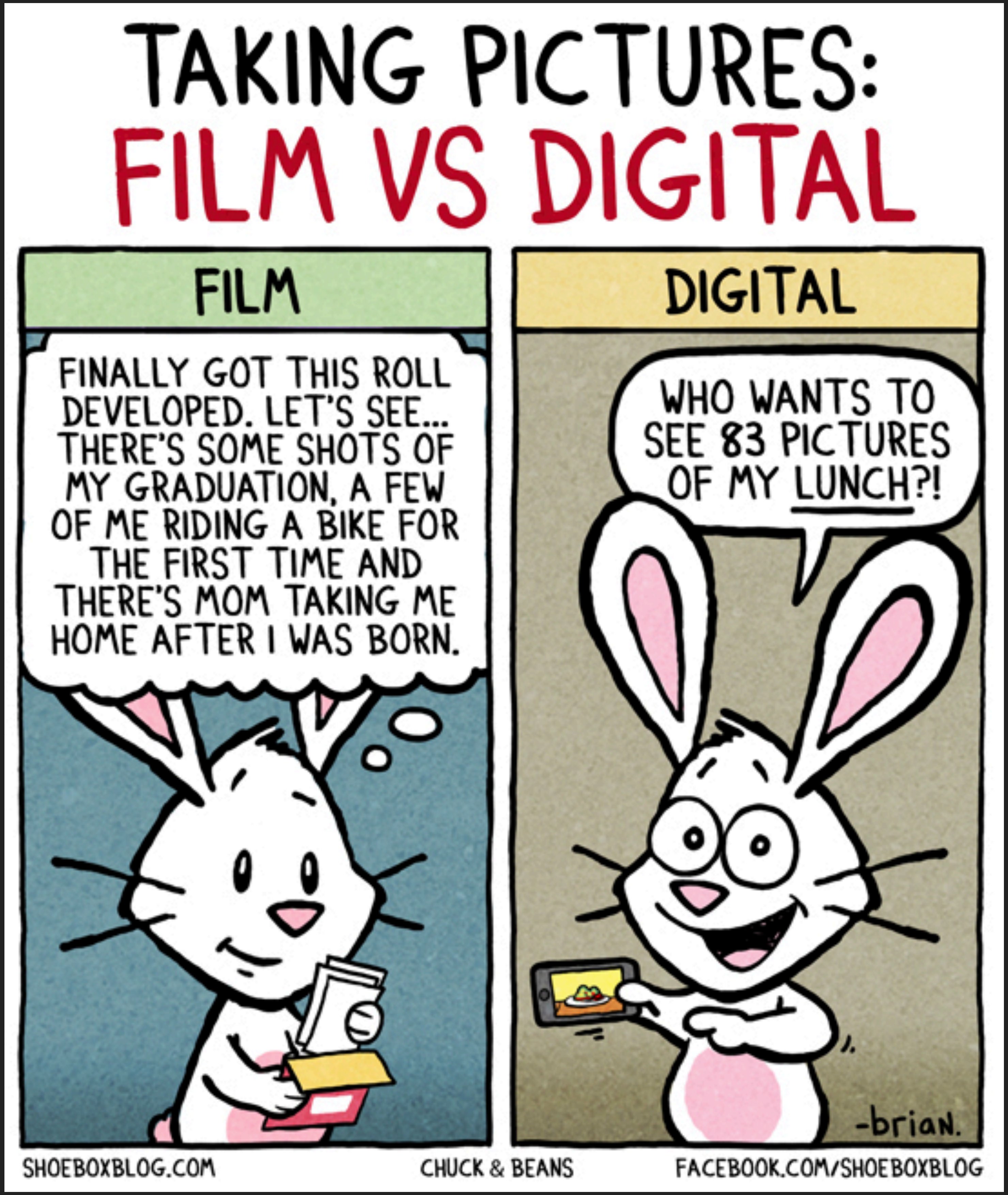
CONS

- Imaging resolution limited by pixel count
- Reduced dynamic range
- Reduced sensitivity

PROS

- Convenient storage
- Easily duplicated
- Digital manipulation

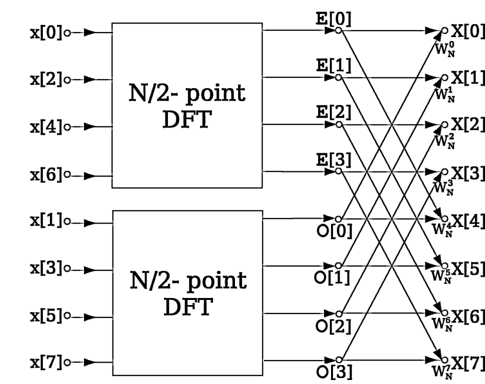
MORE INFORMATION VS MORE DATA

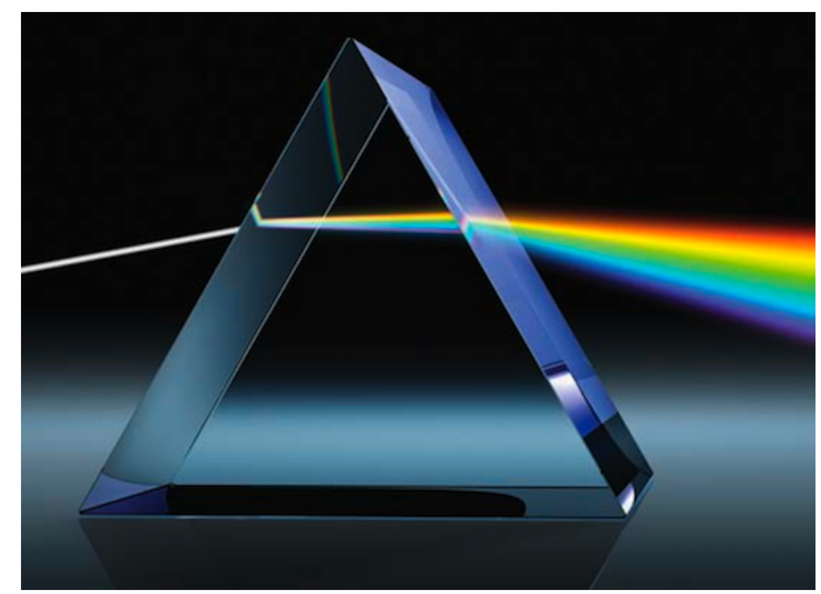


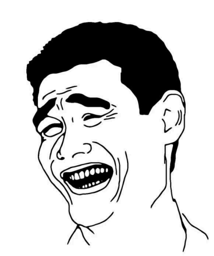
DIGITAL VS ANALOG IMAGING
THE TRADEOFF

- **Optics:** Fast, but
    - Limited by physical laws
    - Material constraints
    - Manufacturing capabilities
    - Cost, size, and …
- **Digital signal processing:** Fundamentally slower, but “easier” to work with
    - Flexible

Fast Fourier transform, you say?





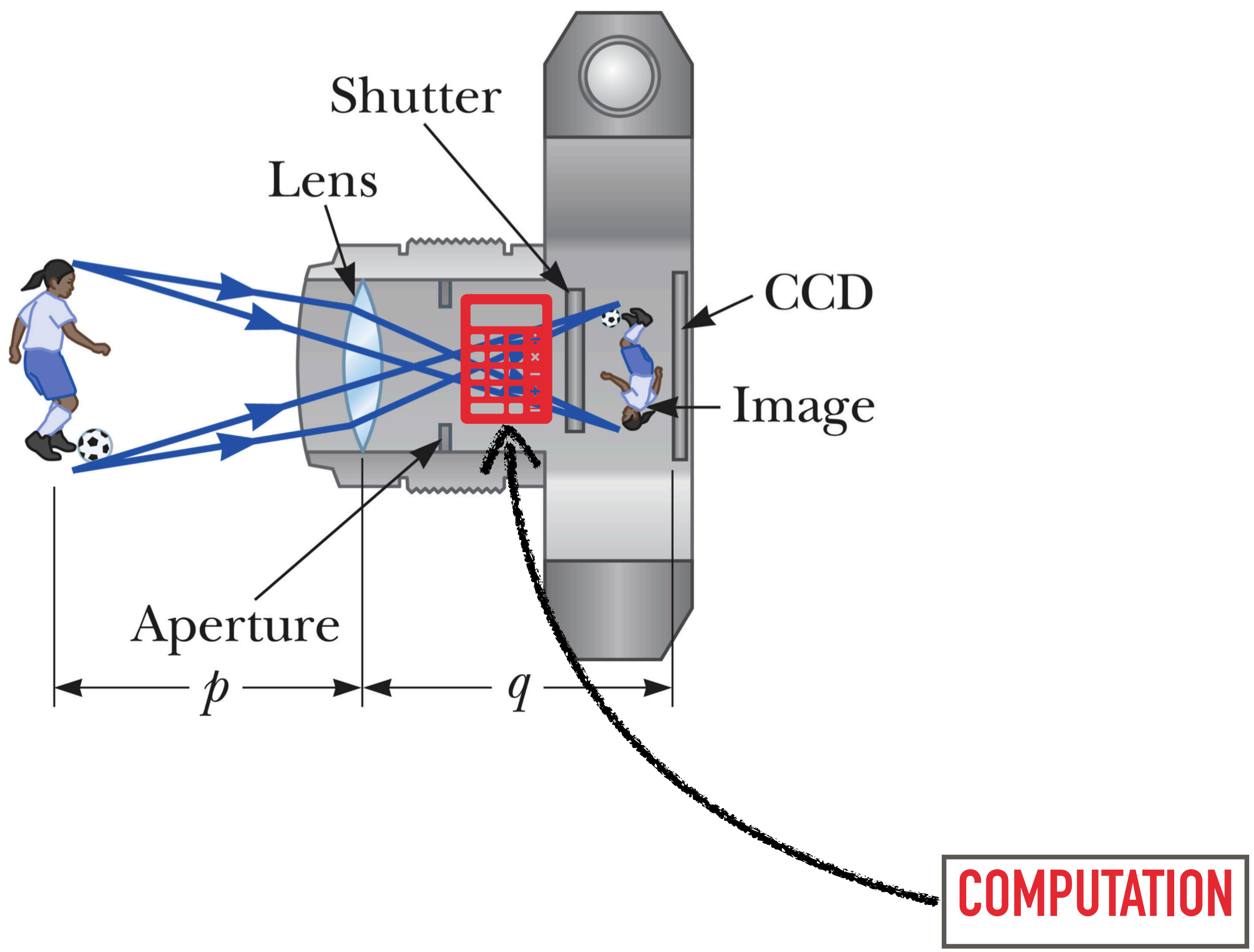


Please! I Fourier transform at the speed of light!

TOWARDS COMPUTATIONAL IMAGING

NEW IMAGING PARADIGM

- **Optimization:** best of analog optics and digital computation

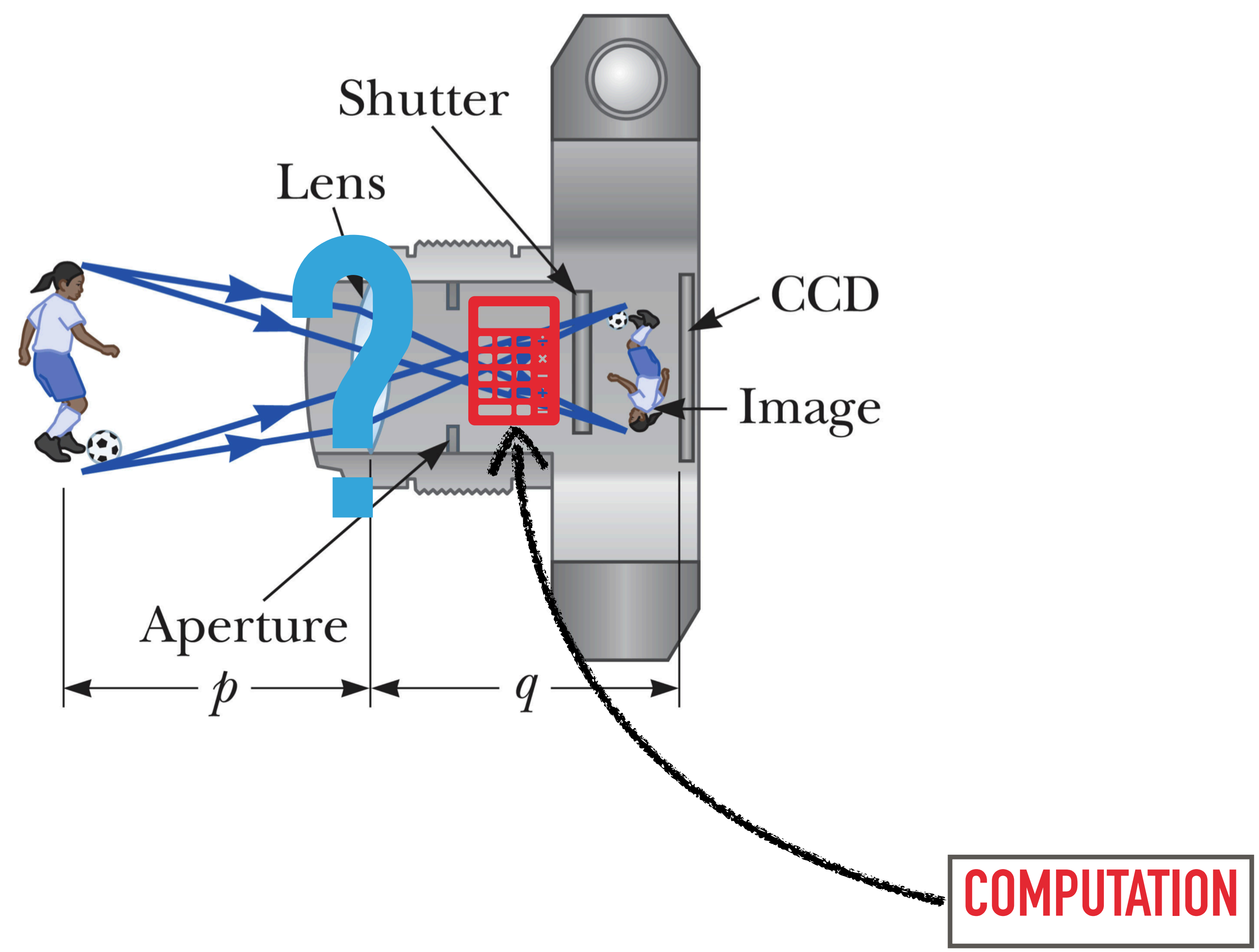


OPTIMAL DESIGN

Imaging systems require appropriate combination of analog and digital processing by taking into consideration advantages and limitations of both.

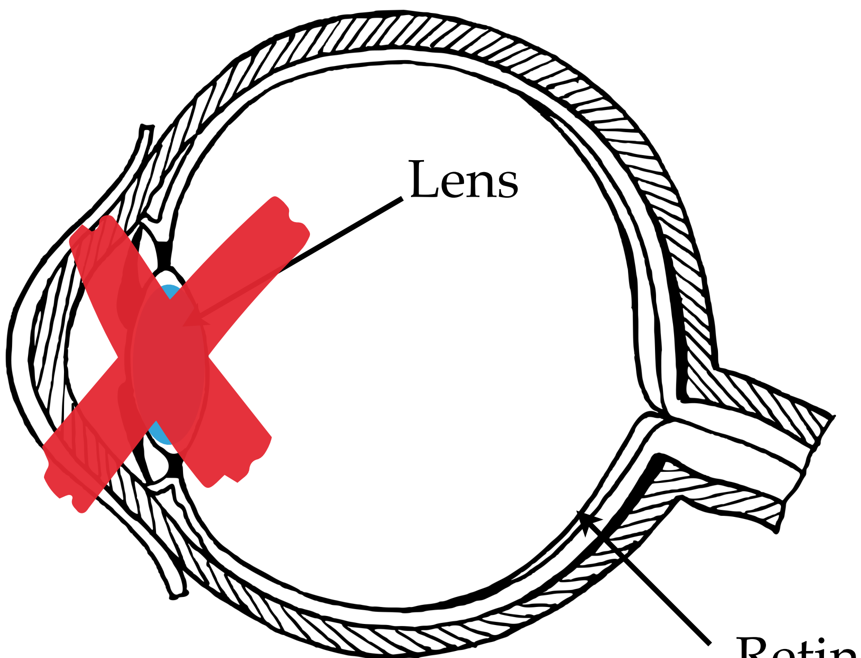
COMPUTATIONAL IMAGING

- Introduce computation
- Do we need lenses?

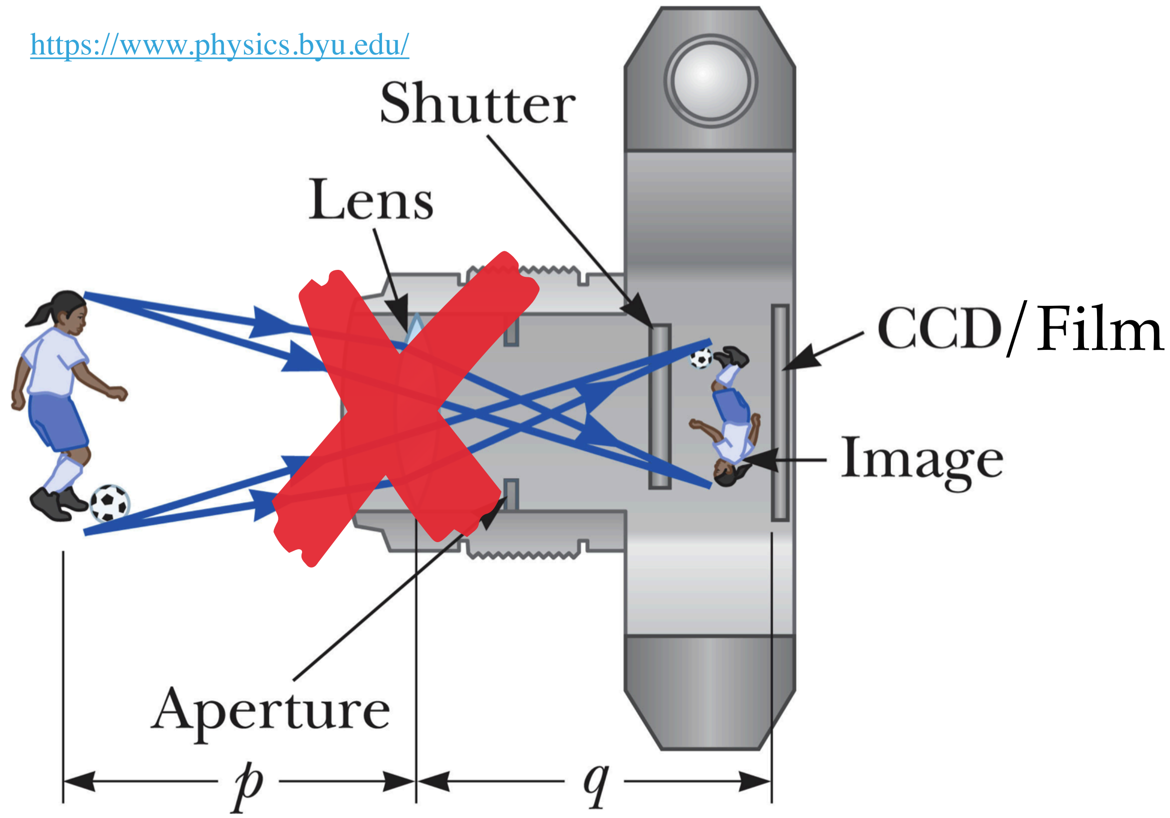


LENSLESS IMAGING

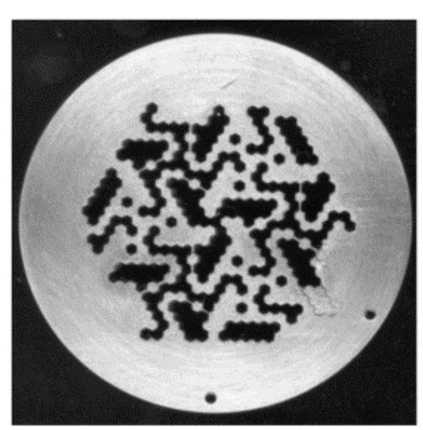
COMPUTATIONAL IMAGERS DON'T NEED LENSES

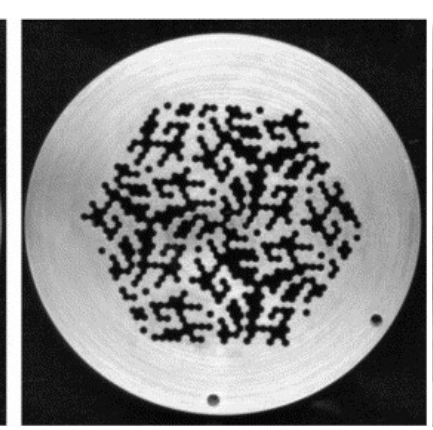


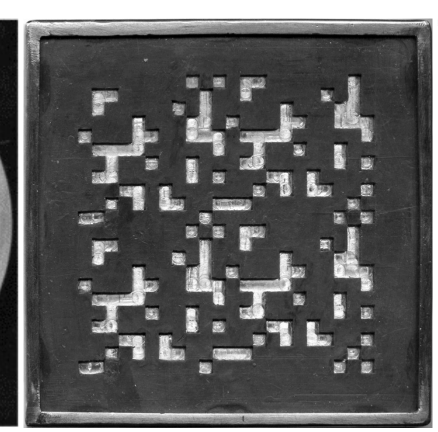
https://www.physics.byu.edu/

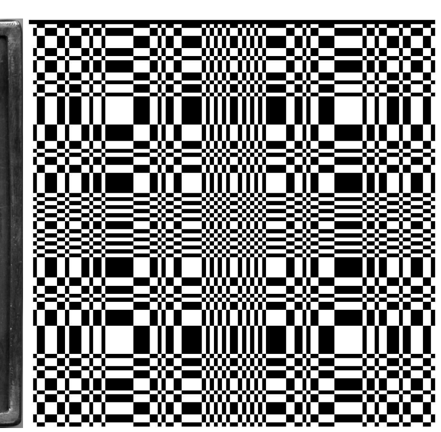


Masks!



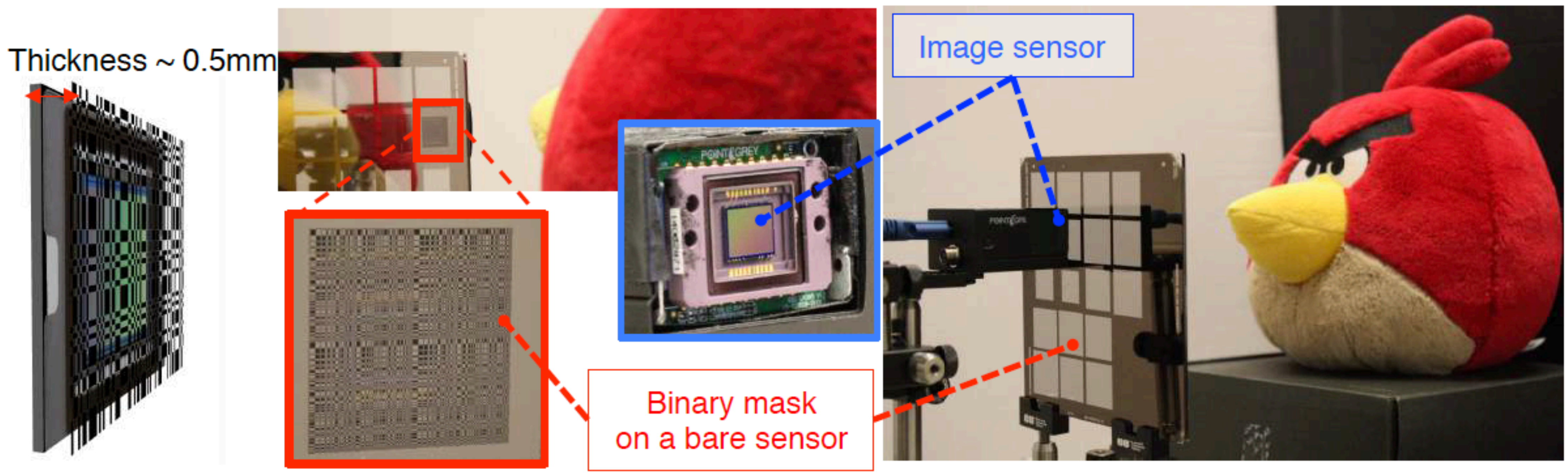




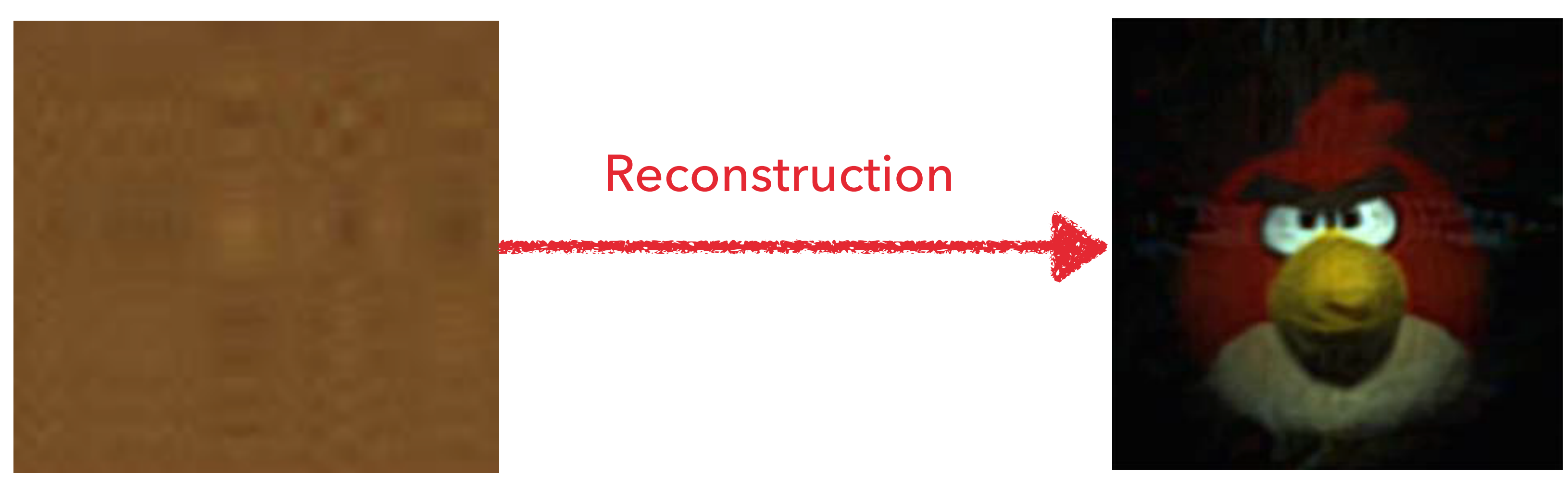


LENSLESS IMAGING

FLATCAM: RANDOM BINARY MASK

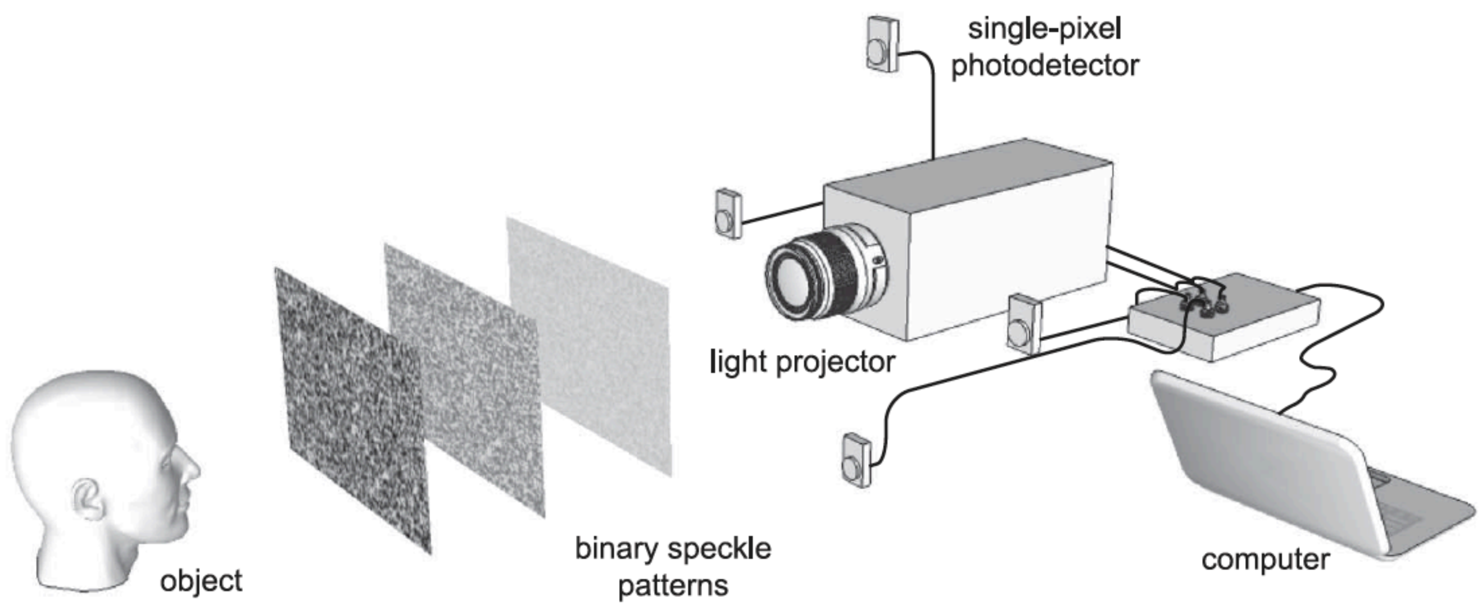


- Known binary mask replaces lens.
- Bare sensors measure light through mask.

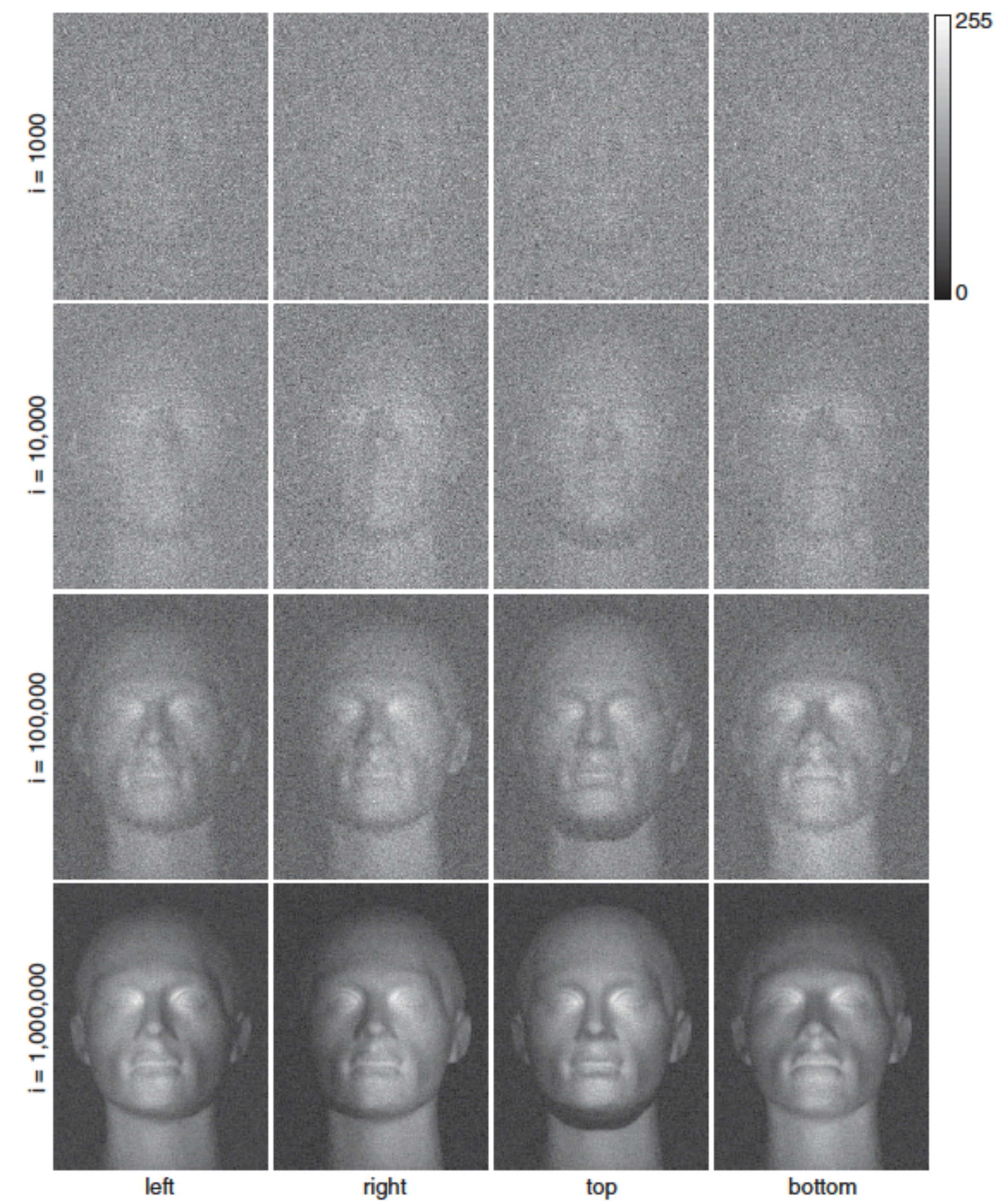


Asif *et al.*, *Trans. Comp. Imaging* **3** (3), 384-397, 2016.

COMPUTATIONAL GHOST IMAGING



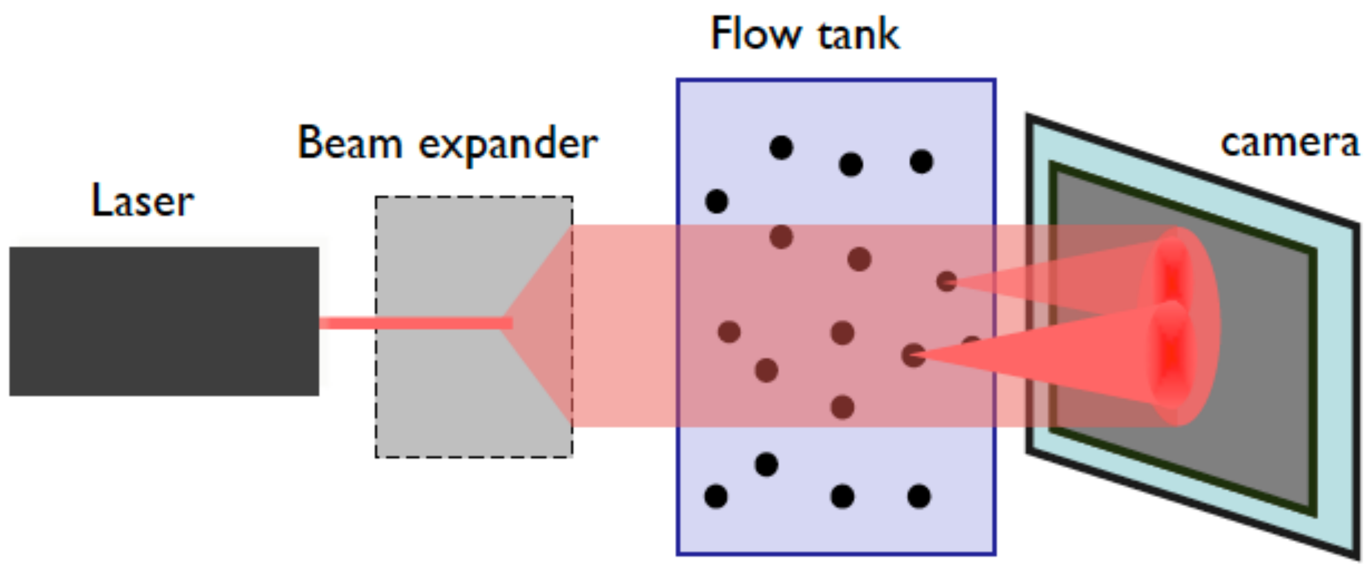
- Known pseudo-random binary patterns projected on scene.
- Reflected light collected by (four) single-pixel cameras.
- Reconstruction from camera measurements.



Reconstructed images from the four single-pixel detectors from 1000 to 1 million iterations.

[1] Shapiro, J.H. *Phy. Rev. A.*, 78(6), 2008.
[2] Sun *et al.*, *Science* **340** (6134), 844-847, 2013.

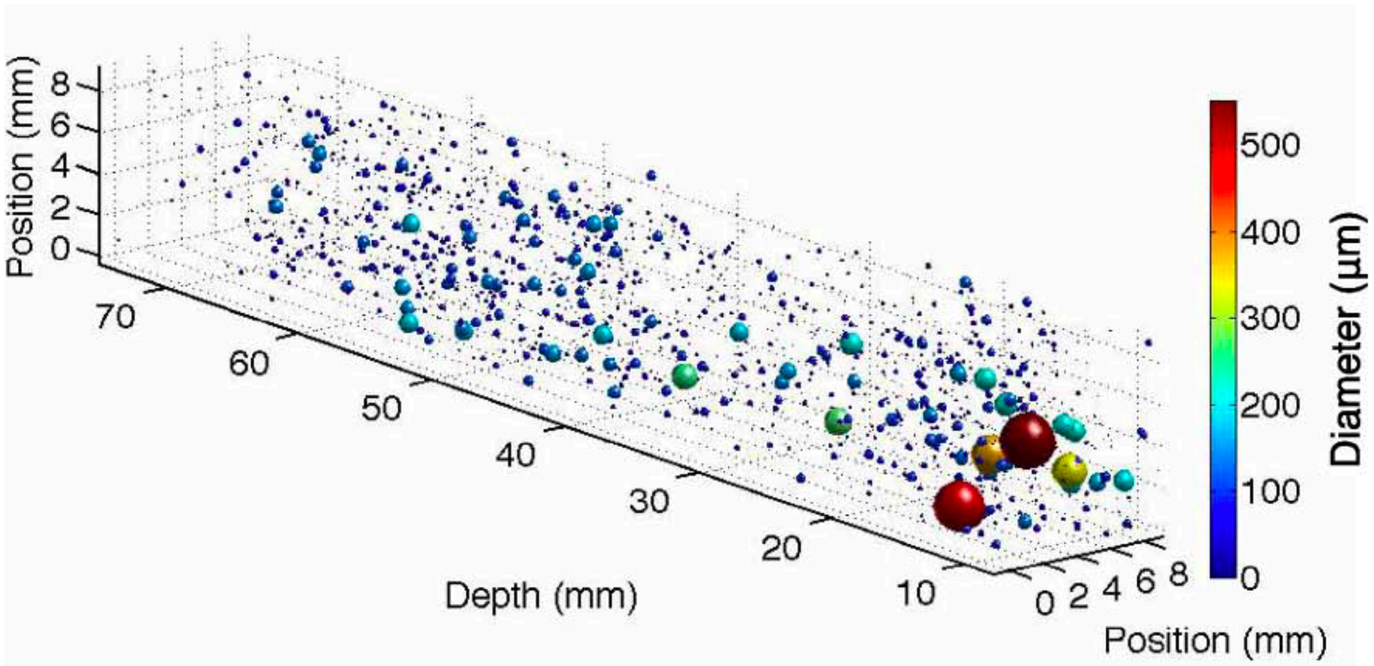
LENSLESS DIGITAL HOLOGRAPHY



Physics of (laser) light propagation well-known

Measuring field at one plane give information about the others

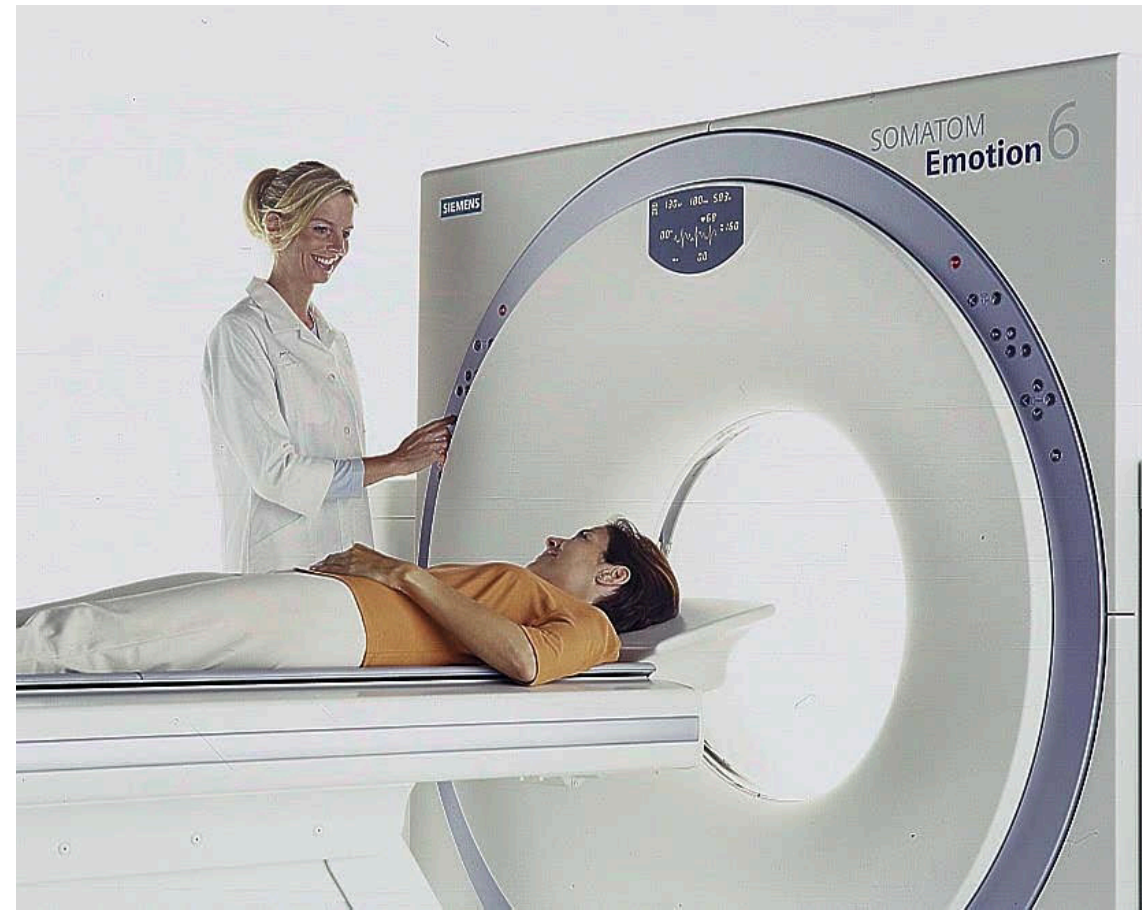
3D information from 2D measurements



TOMOGRAPHY

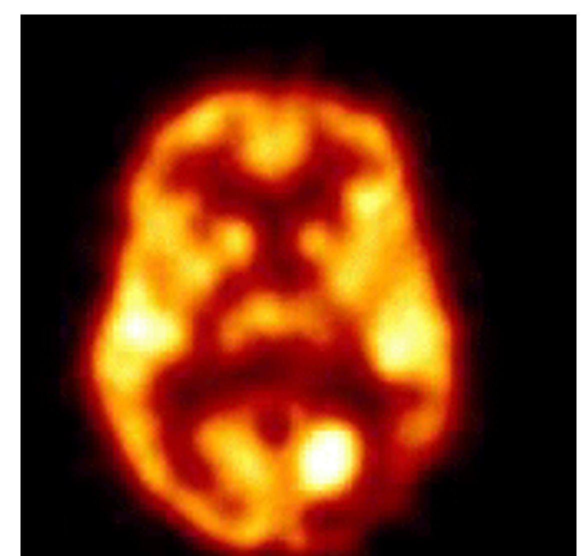
Tomo - “to slice”

Graphy - “to write”




CAT

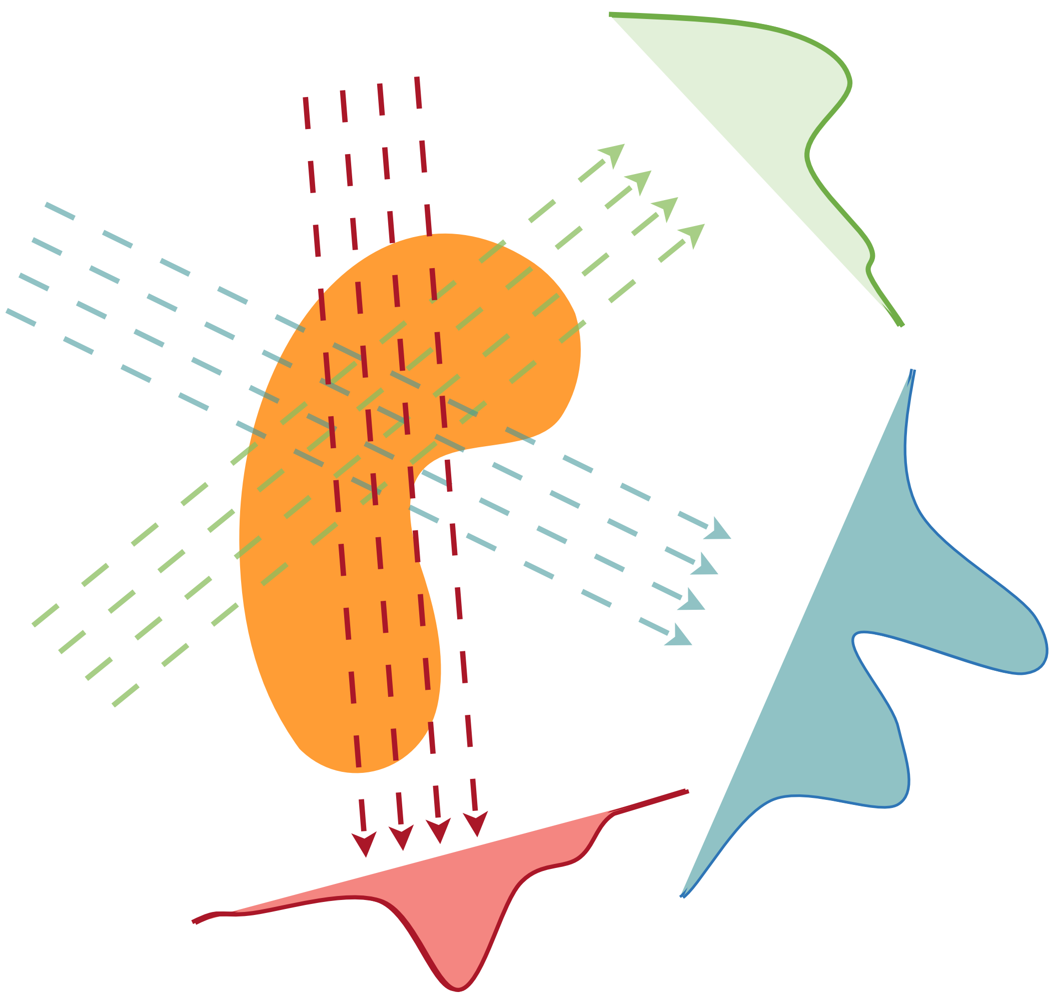

MRI

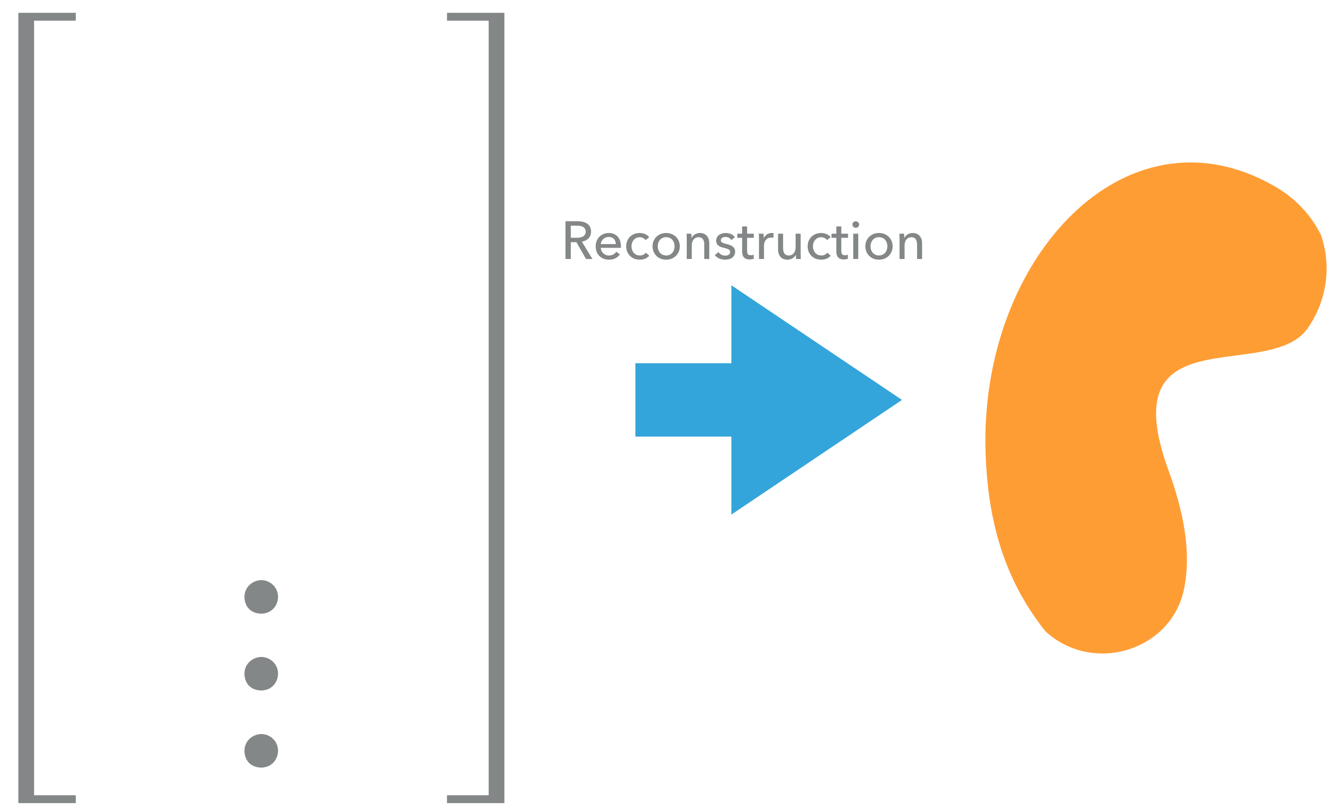

PET

TOMOGRAPHY

Tomo - “to slice”

Graphy - “to write”



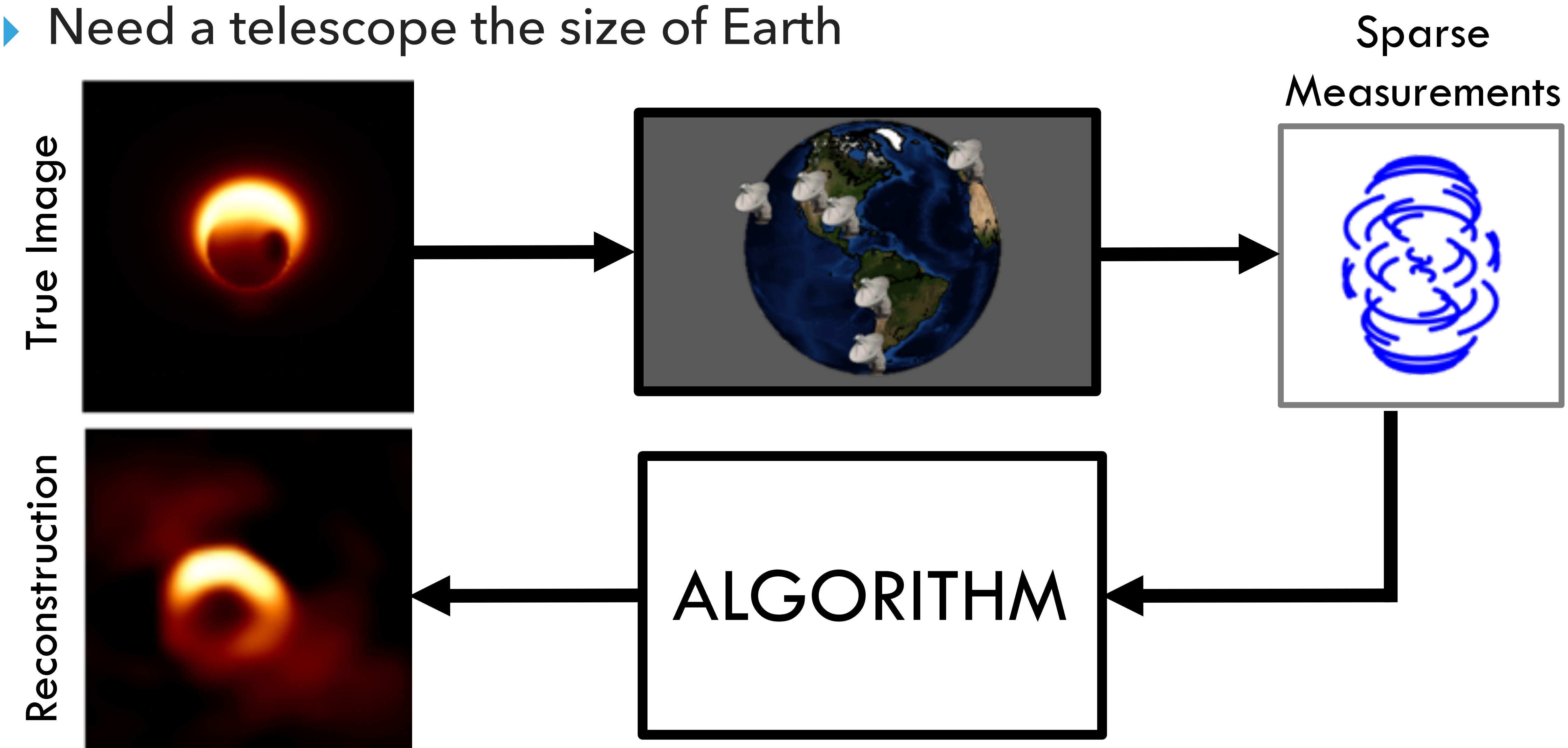


1D Projections of a 2D object –> 2D Recovery

2D Projections of a 3D object –> 3D Recovery

ASTRONOMICAL IMAGING
IMAGING A BLACKHOLE

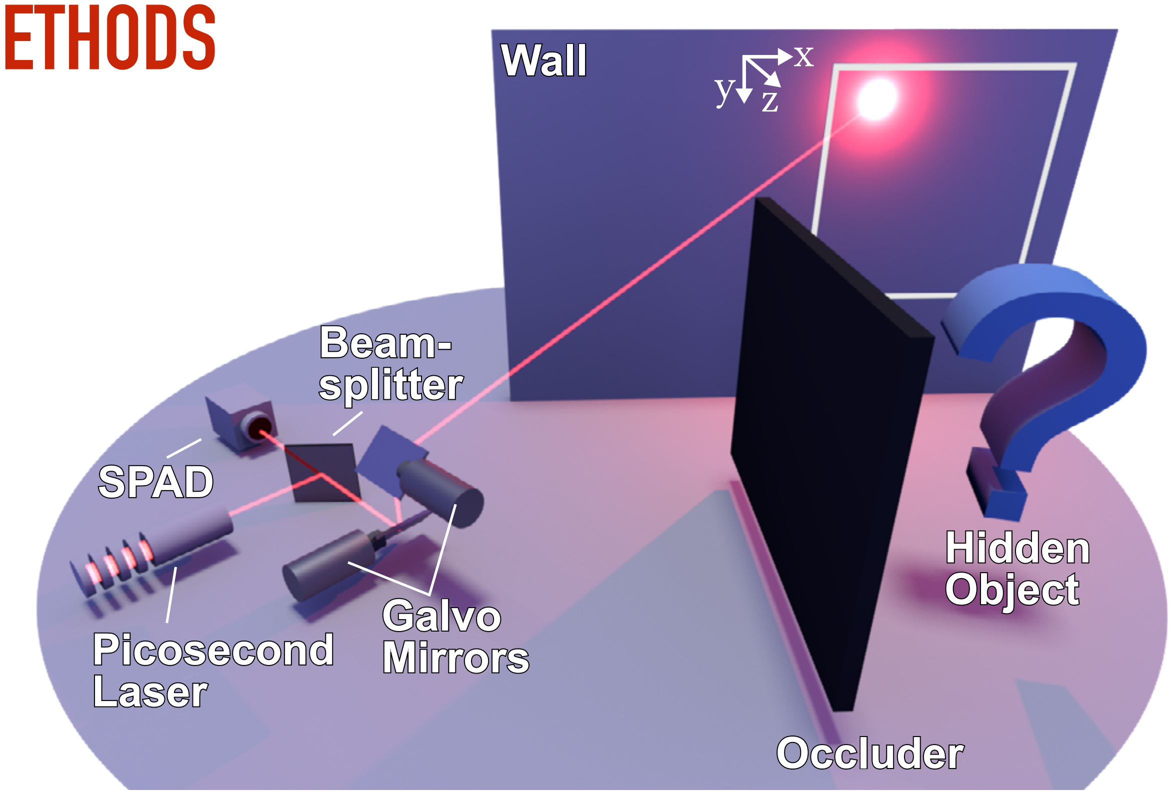
- Roughly equivalent to imaging an orange on the moon
- Need a telescope the size of Earth



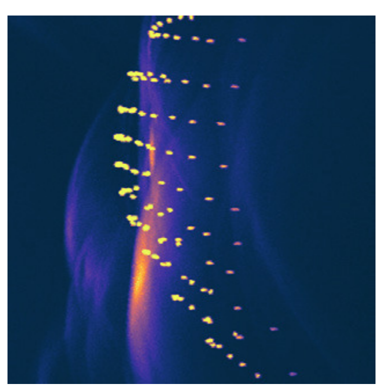
Bouman, 2019

NON-LINE-OF-SIGHT IMAGING
ACTIVE METHODS

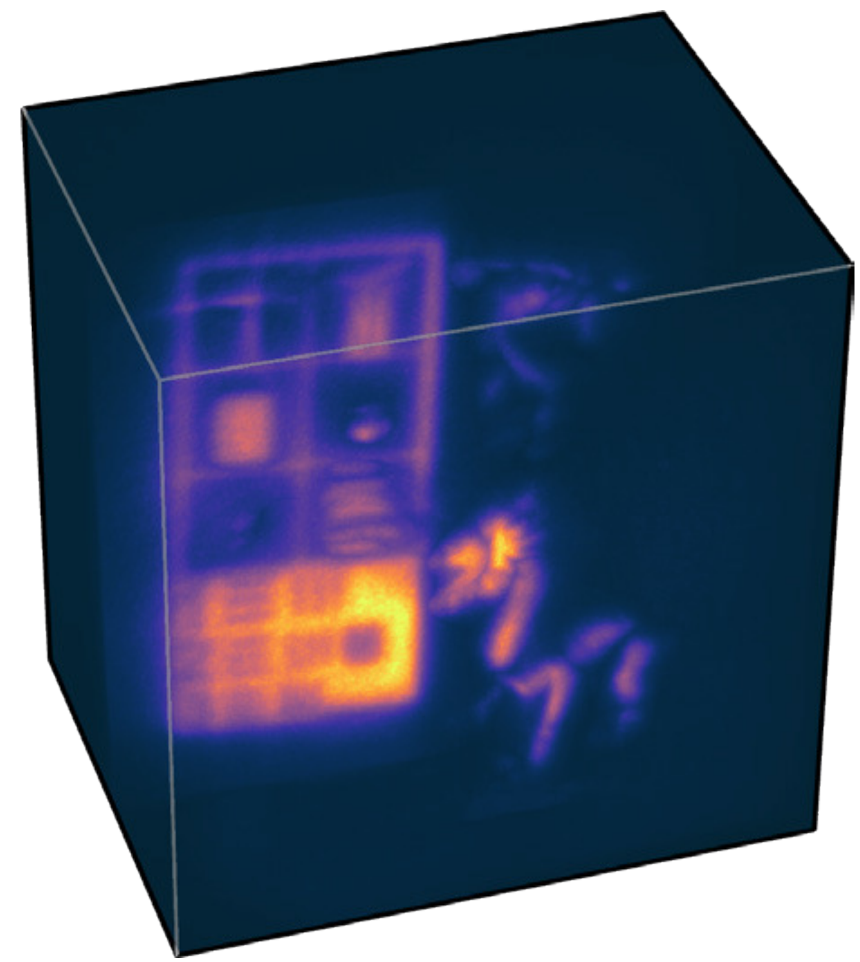
Hidden scene



SPAD measurements



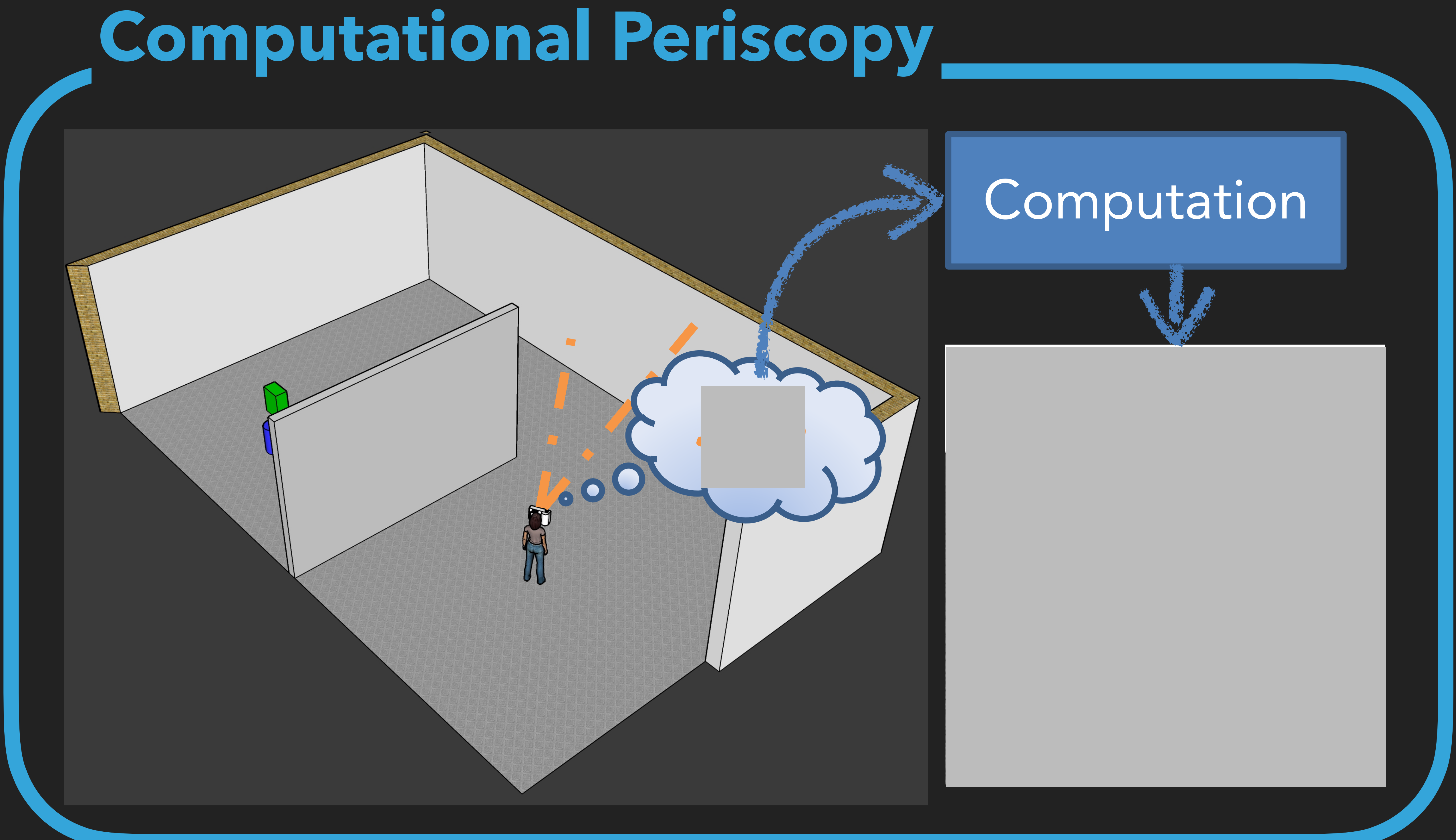
Reconstruction Algorithm



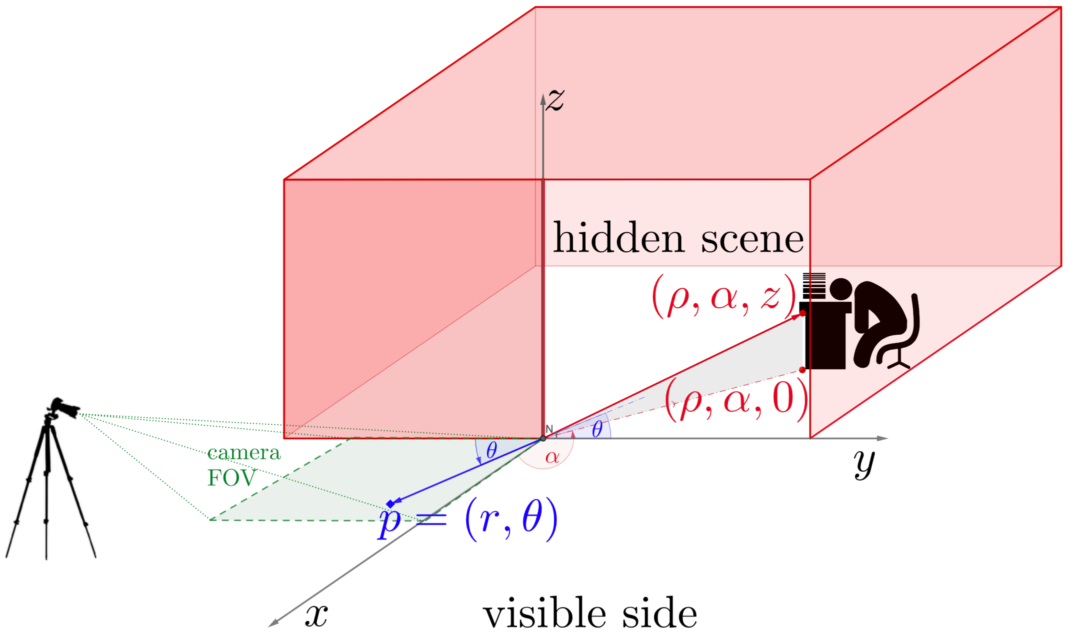
[1] Wetzstein, Stanford, computationalimaging.org

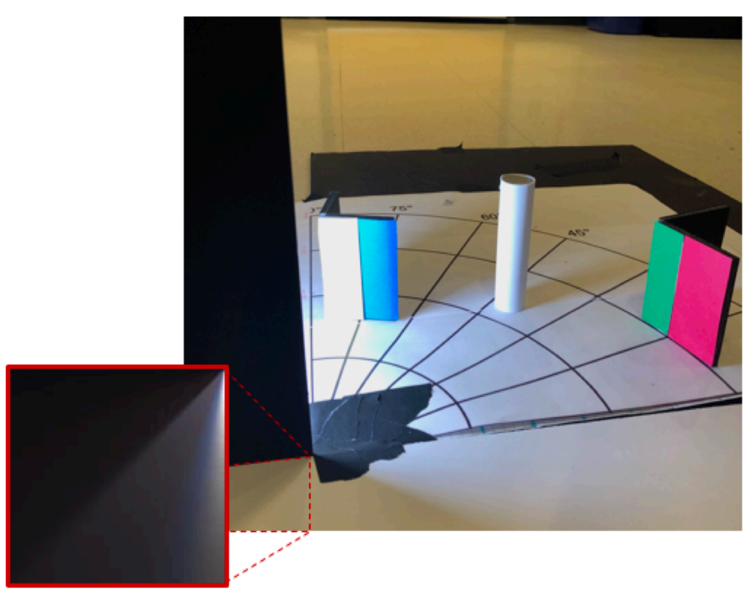
COMPUTATIONAL PERISCOPE WITH ORDINARY CAMERAS

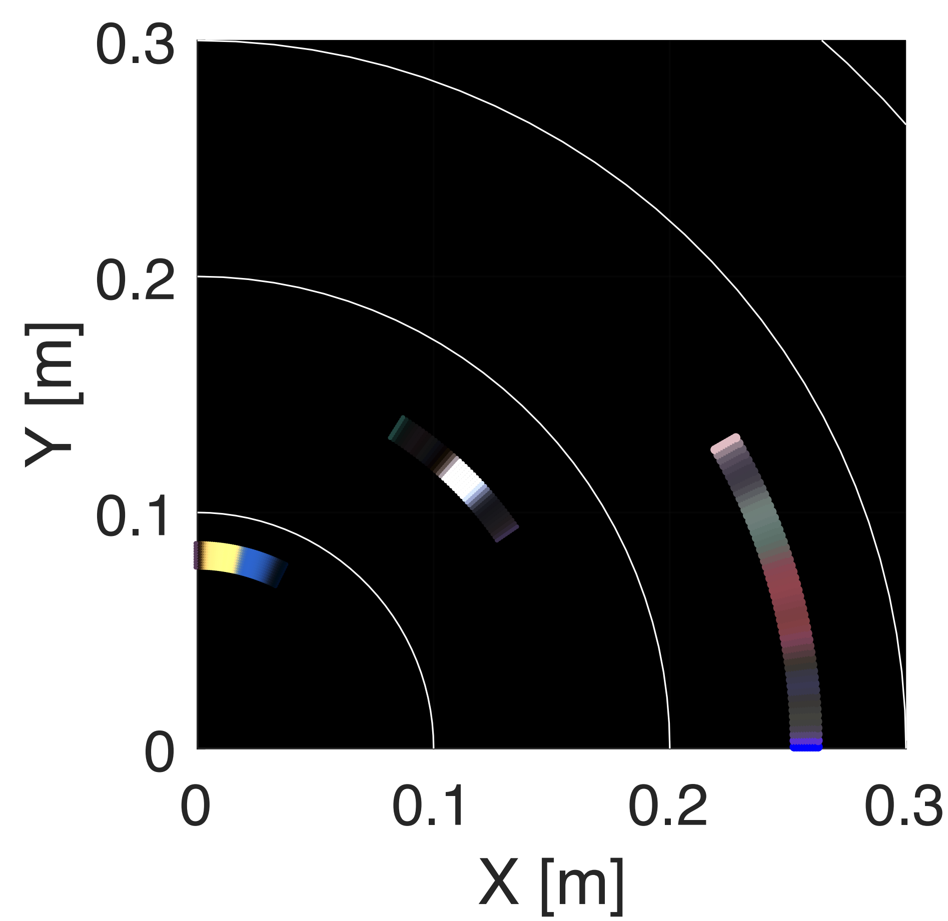
PASSIVE NLOS IMAGING



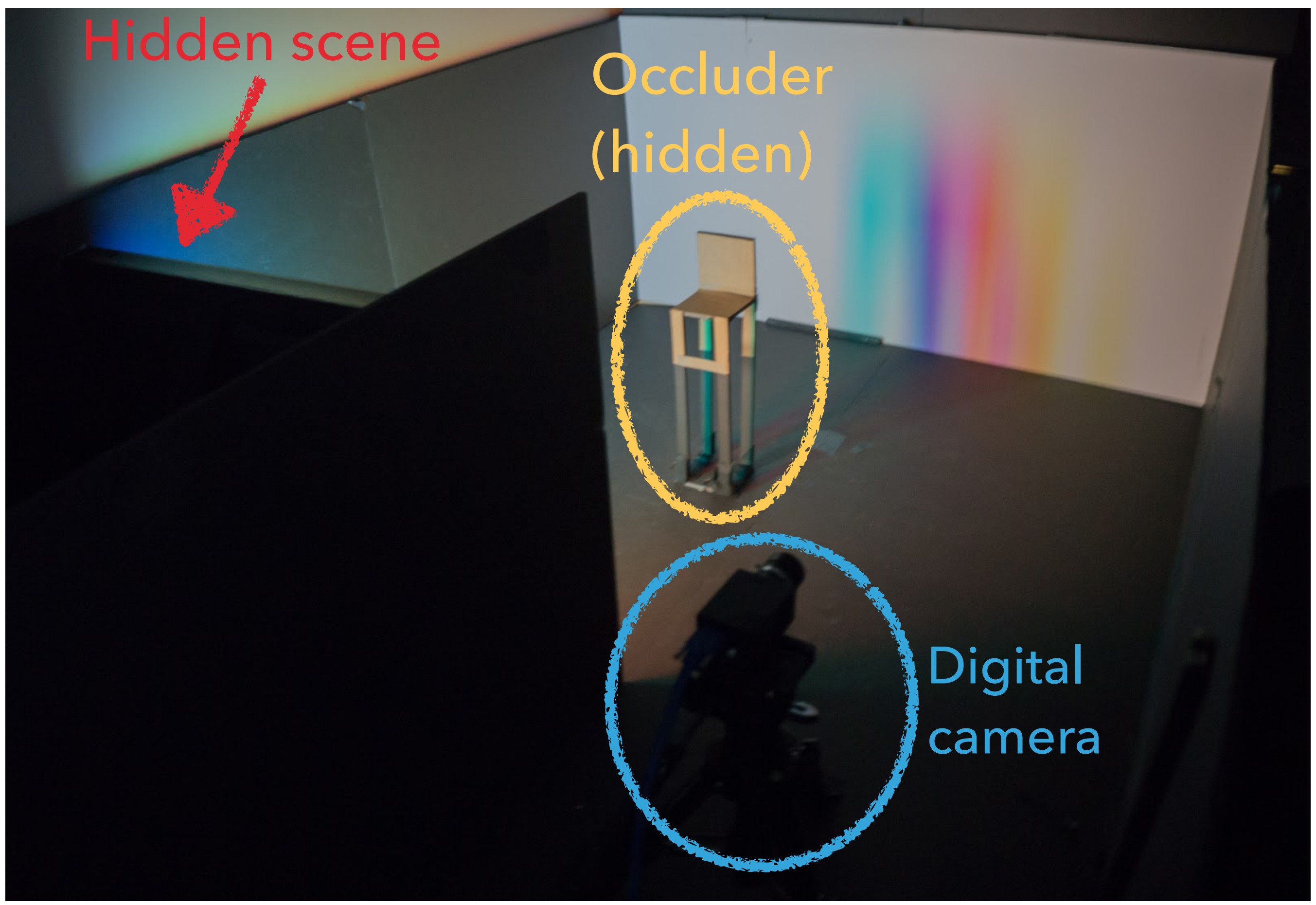
NON-LINE-OF-SIGHT IMAGING
2D CORNER CAMERA

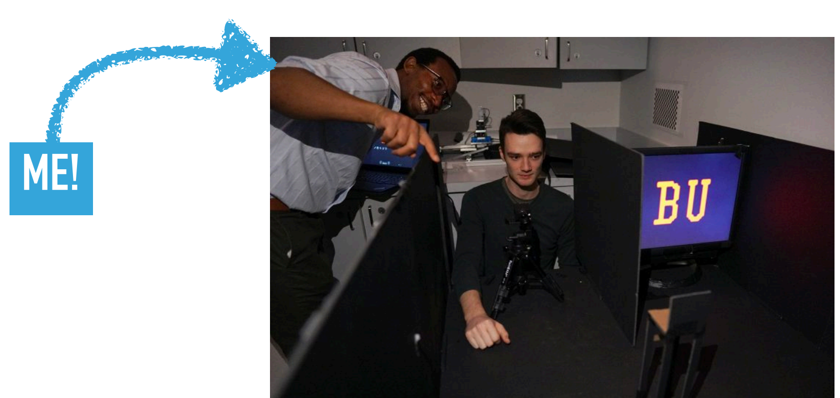






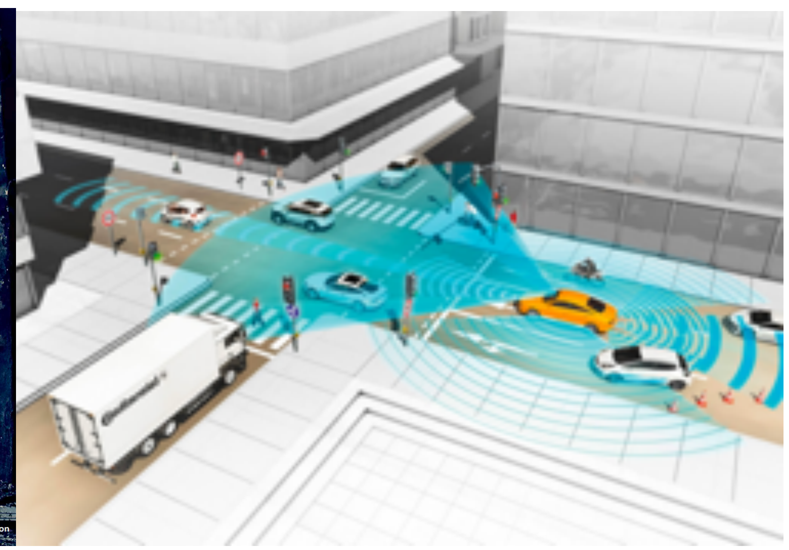
NON-LINE-OF-SIGHT IMAGING
PASSIVE METHODS





C.S., **Murray-Bruce**, & V.K.G. *Nature*, ***565***,472–475 (2019).

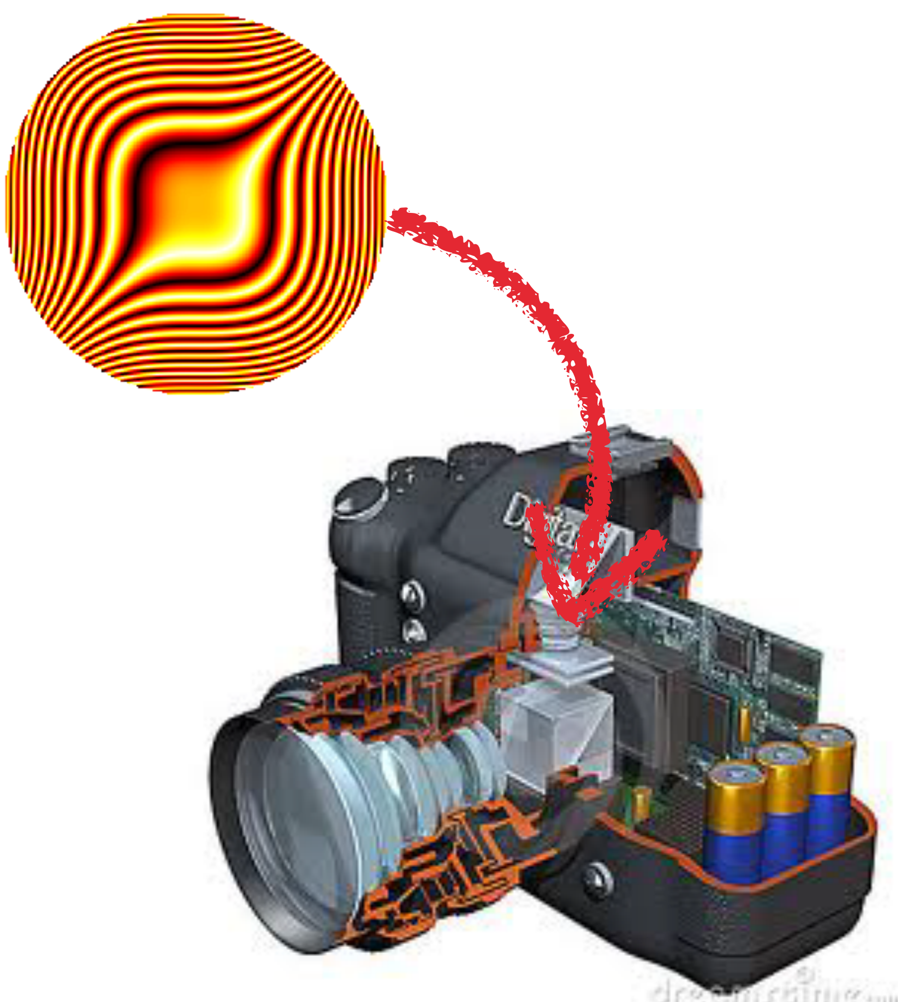
NON-LINE-OF-SIGHT IMAGING
POTENTIAL APPLICATIONS

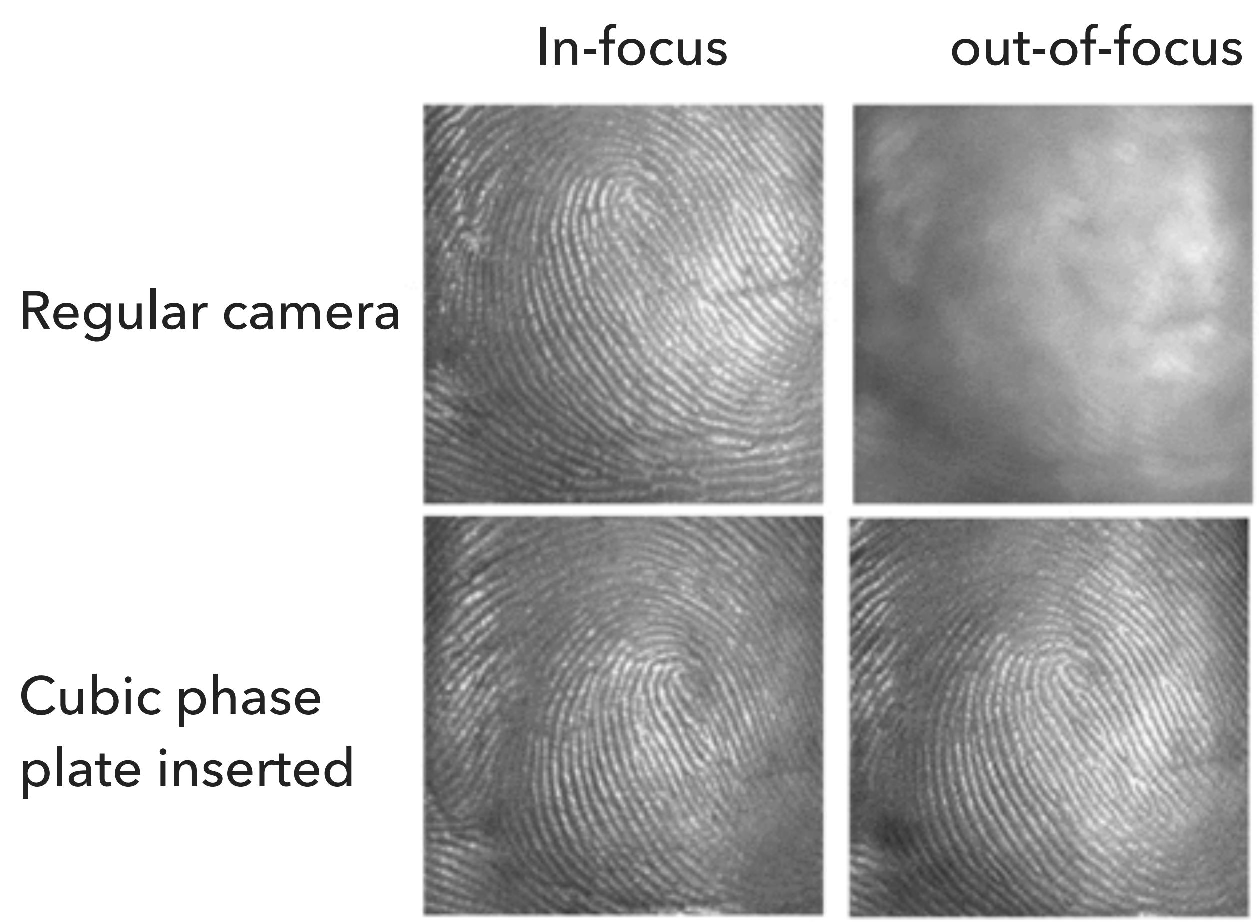




- Search and rescue
- Medical imaging
- Autonomous navigation

CUBIC PHASE MASK CODED CAMERA

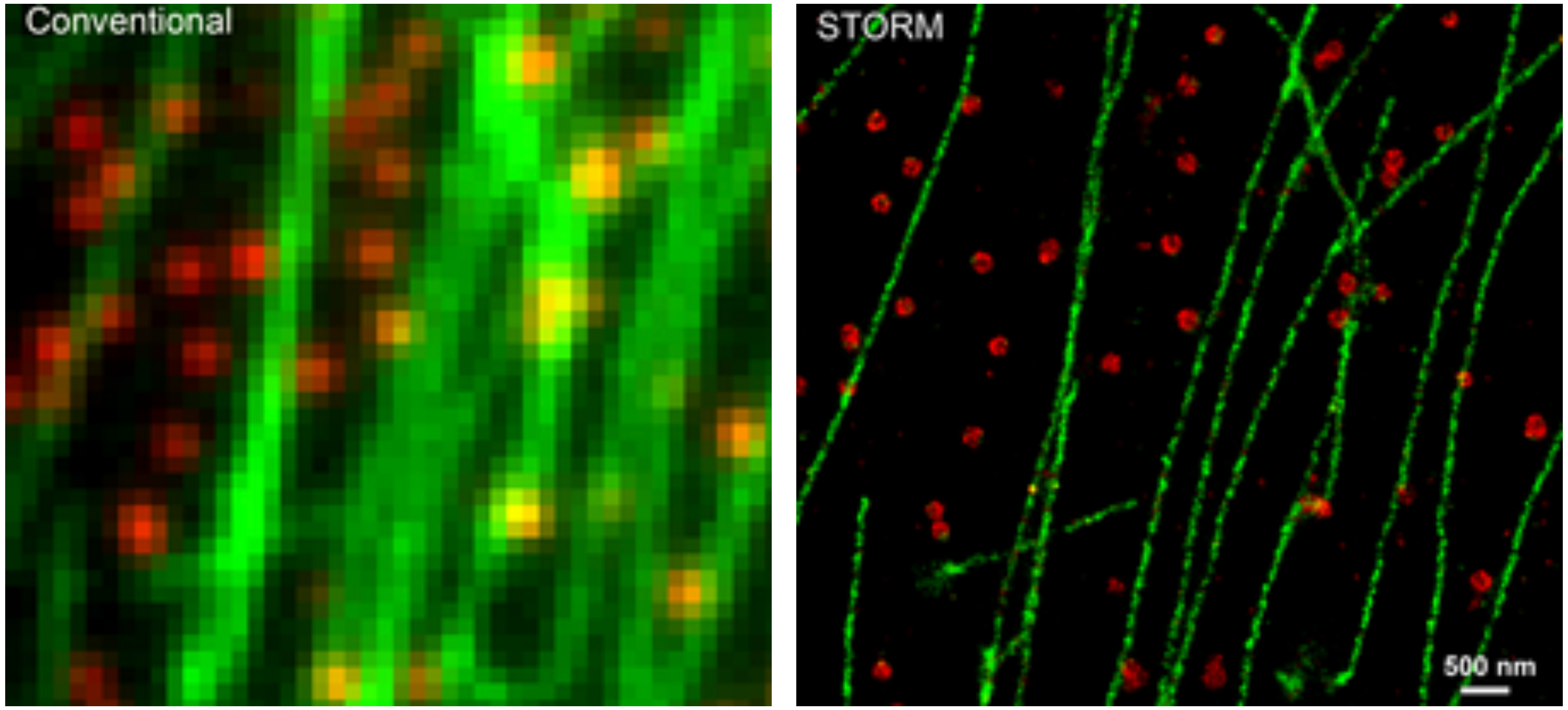
Glass plate with a cubic phase mask gives uniformly blurred image, that can be refocussed at any plane, using computation.





SUPER-RESOLUTION FLUORESCENCE MICROSCOPY

- **Imaging with wave-fields:**
  - There is a fundamental limit in resolution (Abbe, ~1873).
  - Recently been broken.

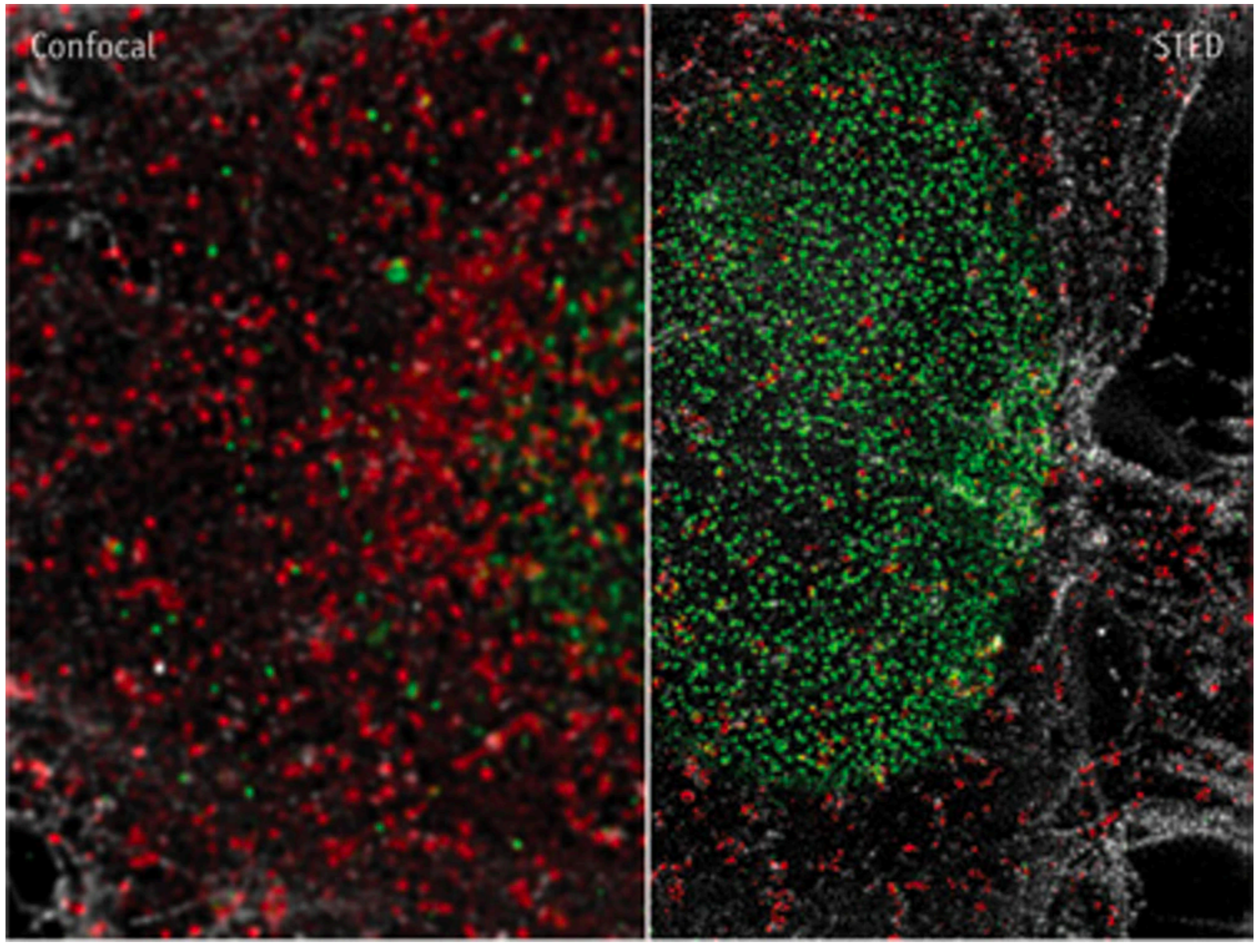


Bates *et al.*, Science 317, 1749-1753 (2007).

SUPER-RESOLUTION FLUORESCENCE MICROSCOPY

NOBEL PRIZE, 2014

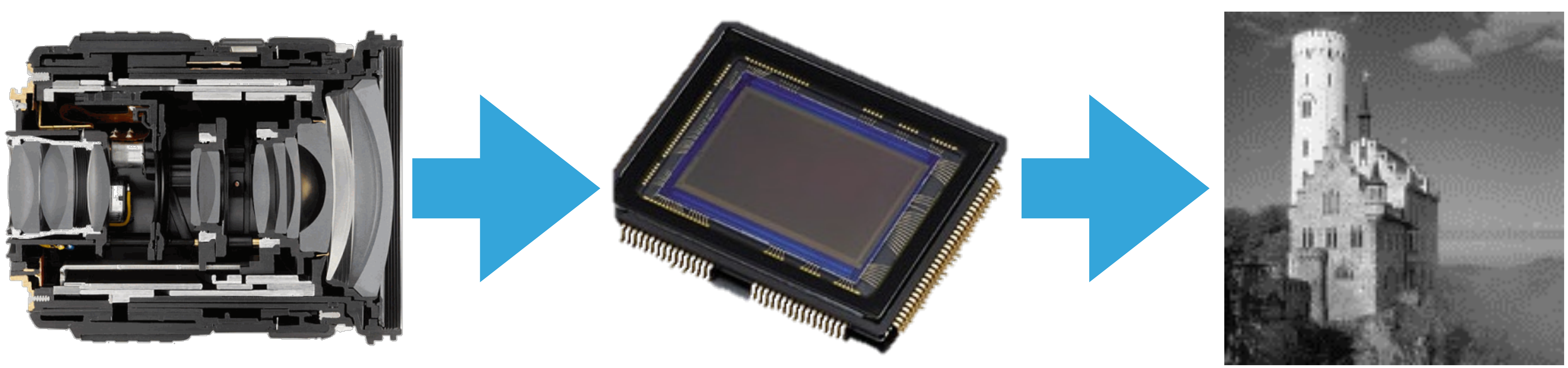
Stimulated emission depletion (STED) microscopy



WHAT IS COMPUTATIONAL IMAGING?

TRADITIONAL IMAGING SYSTEMS

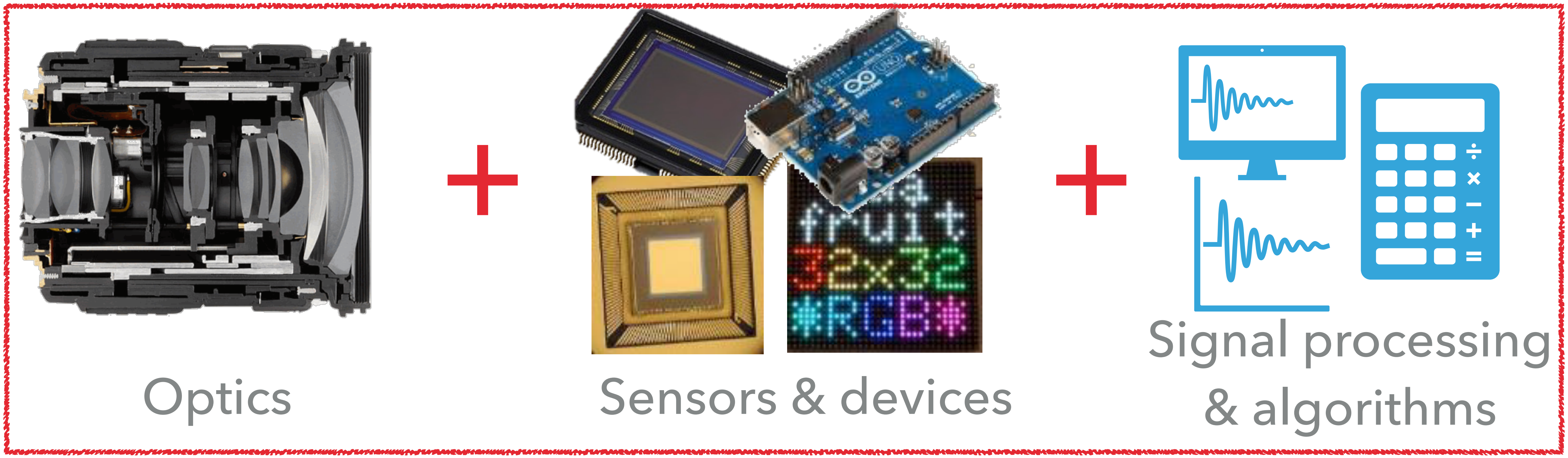
- Rely solely on optics
- Fundamentally limited, due to physical laws, material constraints, manufacturing capabilities, cost, and so on.



Optics Sensors Image

COMPUTATIONAL IMAGING

INTEGRATED SYSTEMS APPROACH



- System-level integration creates new imaging pipelines:
  - Encode information with hardware
  - Computational reconstruction
- Design flexibility
- Enabling new capabilities, e.g. super-resolution, 3D, phase

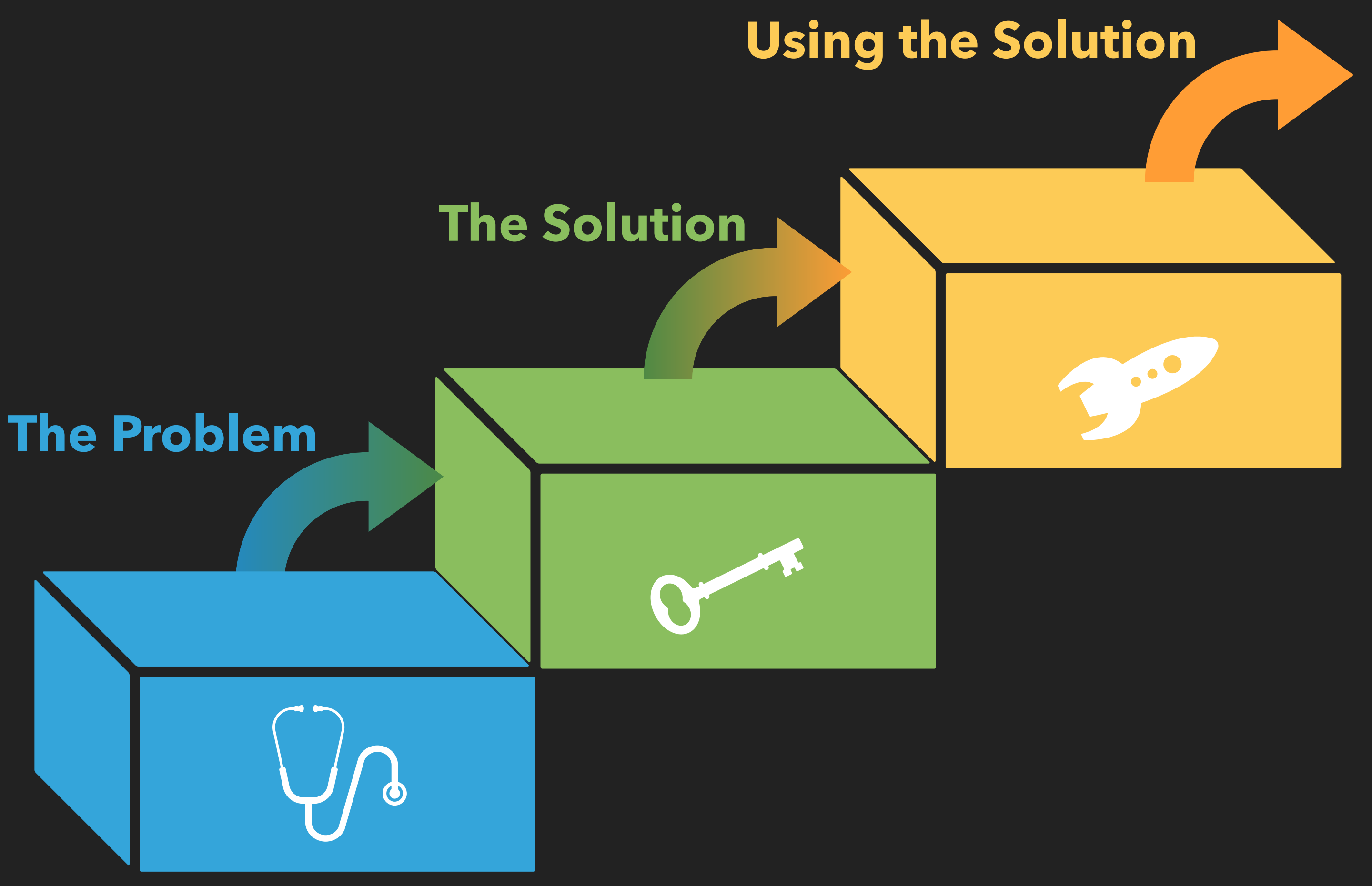
TO BE DISCUSSED

- Tools that underpin the basis of computational imaging systems
  - Converting physical reality into digital signals
  - Discrete representations of imaging transforms
  - Inverse problems and algorithms
- Computational imaging example applications
  - Super-resolution
  - Image recovery from sparse data

COURSE PRE-REQUISITES

- COP 4530 (Data Structures)
- CDA 3201 (Program Design)
- So you'll be familiar with Calculus I and II, General Physics I and II.
    - Linear algebra, multivariable calculus, probability

HOW WE WILL ORGANIZE EACH CLASS



TEXTBOOKS

- Main textbook:
  - **[IIP]** M. Bertero and P. Boccacci, "Introduction to Inverse Problems in Imaging," Taylor and Francis, 1998, ISBN 9780750304351.
- Supplements:
  - **[FSP]** M. Vetterli, J. Kovačević, and V. Goyal, Foundations of Signal Processing, CUP 2014. [Available: http://fourierandwavelets.org/].
  - **[SMIV]** Jed Julien Mairal, Francis Bach, and Jean Ponce, Sparse Modeling for Image and Vision, NOW 2014. [Available:http://lear.inrialpes.fr/people/mairal/resources/pdf/review_sparse_arxiv.pdf].

COURSE POLICIES

- **Extra credit:** available on certain assignments and the project.
- **Late submissions:** will incur penalty of 20% per day (24 hrs).
- **Group work and collaboration:** encouraged in this course, but please acknowledge your collaborator(s) and turn in your own individual piece of work.
- **Course webpage:** www.learn.usf.edu
  - Take part in discussions
  - Post questions and respond: participation is graded

STUDENT EXPECTATIONS

- **Disability access/accommodation:** consult ‘Students with Disability Services’ to arrange accommodations.
    - Reasonable notices required.
- **Attendance:** not compulsory, but strongly encouraged.
    - Class participation graded.
- **End of semester evaluations:** please complete them to help your peers.
- **Be Professional**
    - Zero for the work
    - Possibly an F, even FF for entire course.

TO TEACH IS TO LEARN TWICE.

Joseph Joubert

“one remembers about 5% of what is heard in a lecture, and about 90% of what is used immediately, or is taught to others.”

MY PHILOSOPHY

- Active and engaging learning environment :-|
- Collaborative environment :-/
- Challenging homework and exam questions :-(
- But, reasonable grading :-)

BEFORE YOU GO!

QUIZ 0.1: NOT GRADED BUT MANDATORY

- Answer either question (or both questions):
  - Write down **one thing you want to learn** by the end of this course.
  - Write down **why you decided to take this course**.
- Email me – by end of day.
- Remember to append [CIS4930/CIS6930] to the email subject

SEE YOU NEXT TIME !

MATHEMATICAL PRELIMINARIES: VECTORS