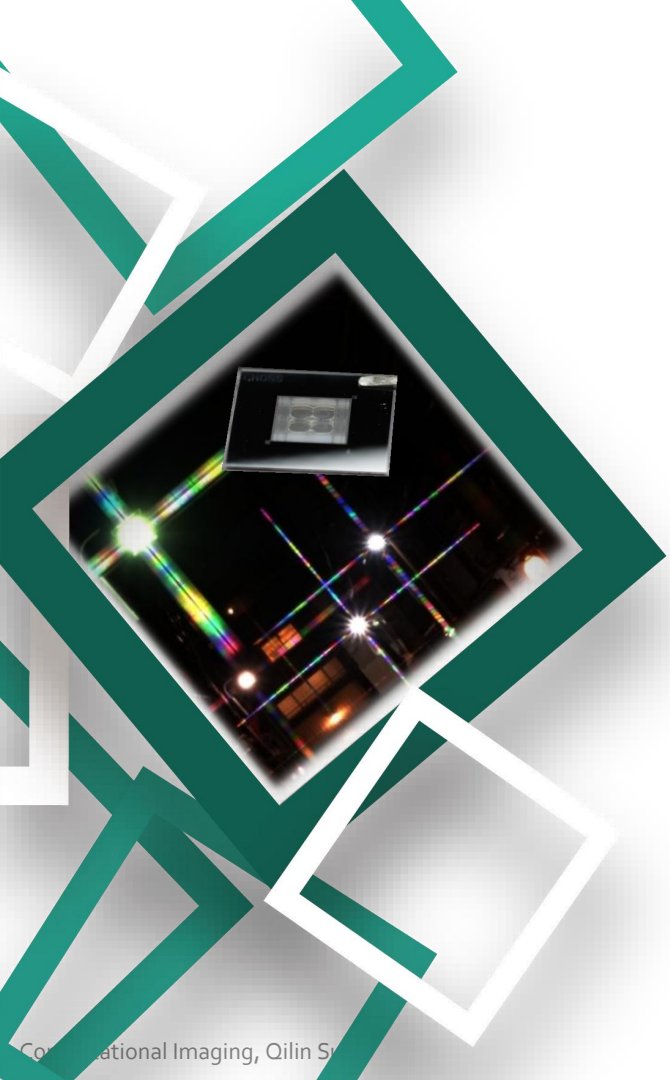
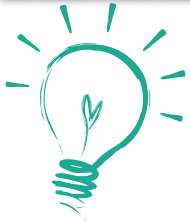


# Computational Imaging

## Lecture 01： Introduction to Computational Imaging

Qilin Sun

School of Data Science

The Chinese University of Hong Kong, Shenzhen

# Instructors

香港中文大學(深圳)
The Chinese University of Hong Kong, Shenzhen

## Qilin Sun（孙启霖）

- 2021-now: Assistant Professor @ The Chinese University of Hong Kong (Shenzhen)
- 2020-now: Founder @ 点昀技术 Pointspread Technology (Shenzhen, Nantong)
    - 2011-2015 B.s @HUST，2015-2021 Ph.D. @KAUST

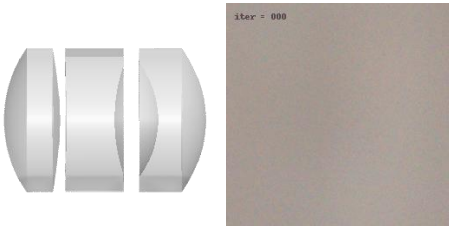
- Website: https://sds.cuhk.edu.cn/teacher/489
- Email: sunqilin@cuhk.edu.cn
- Office: DY507A

- Research: End-to-end Camera Design, Differentiable Optics, Optimization, Computational Imaging, VR/AR

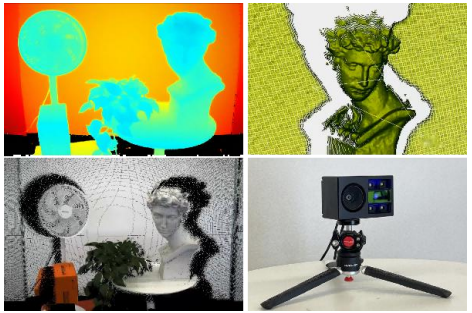
# Instructors' Achievement



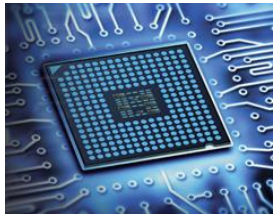
Maybe the world first differentiable diffractive optics model (proposed at 2018.5, ACM Trans. Graph. 2020)




The first differentiable/optimizable complex lens model all over the world. (ACM Trans. Graph. 2021)



High Speed, High Accuracy RGBD Camera (120fps, ~mm precision) for real time 3D reconstruction



RAW Domain **Realtime** 4K Hardware Accelerated **BM3D** (IP core)

Acedemic Achievements

Industral Achievements
(Point Spread Technology)

Source: https://pointspread.cn

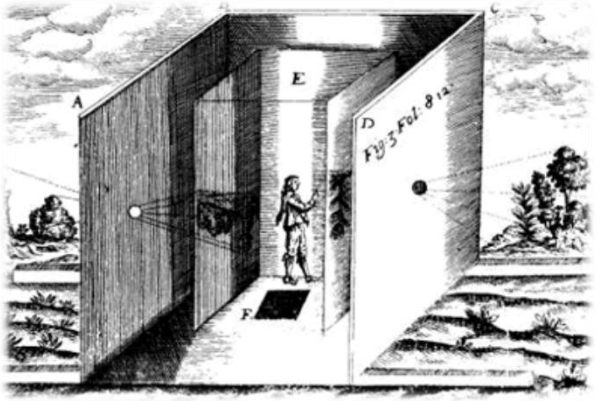

- Imaging History and Today
- What's Computational Imaging
  - Defination
  - Applications
- Computational Methodology Overview
- Course Road Map

# Imaging History and Today

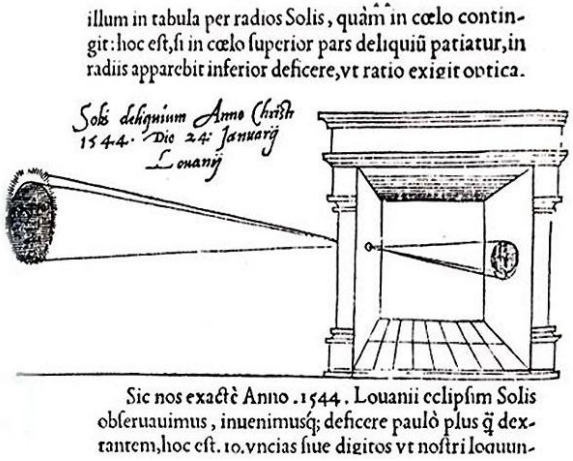
# Pinhole Camera



Mo-Ti, 470-390 BC




Aristotele, 300 BC

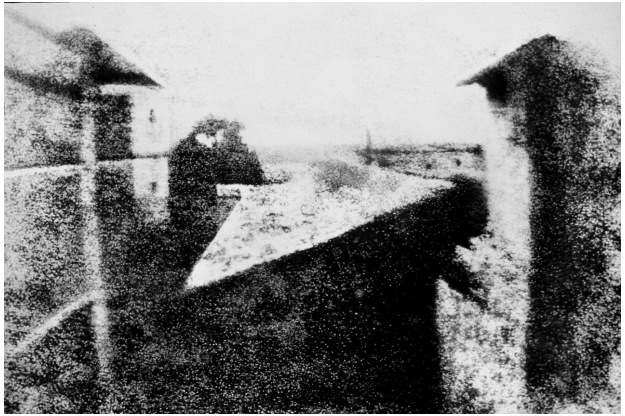



Gemma Frisius, 1544

# What's Photography?

- Heliograph (sun wrighting)

A wholly new,expressive medium(ca. 1830s)



The oldest surviving camera photograph, by Nicéphore Niépce, 1826 or 1827. Eight hours to develop and exposured.

Manipulated display of what we think, feel, want, …

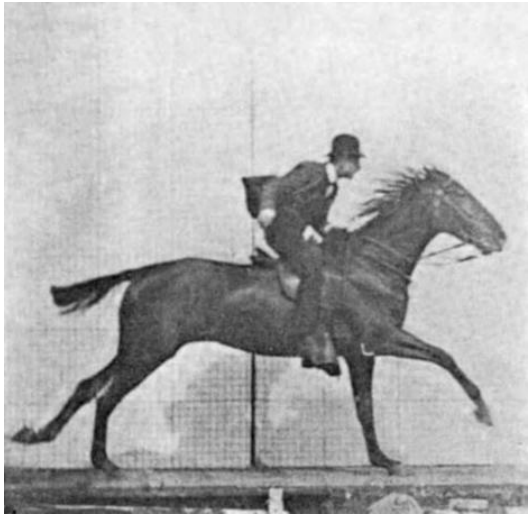
- Capture a memory, a visual experience in tangible form
- 'painting with light' express the subject's visual essence
- "Exactitude is not the truth." — Henri Matisse

# What's Photography?

- A bucket word: a neat container for messy notions (e.g. aviation, music, comprehension)

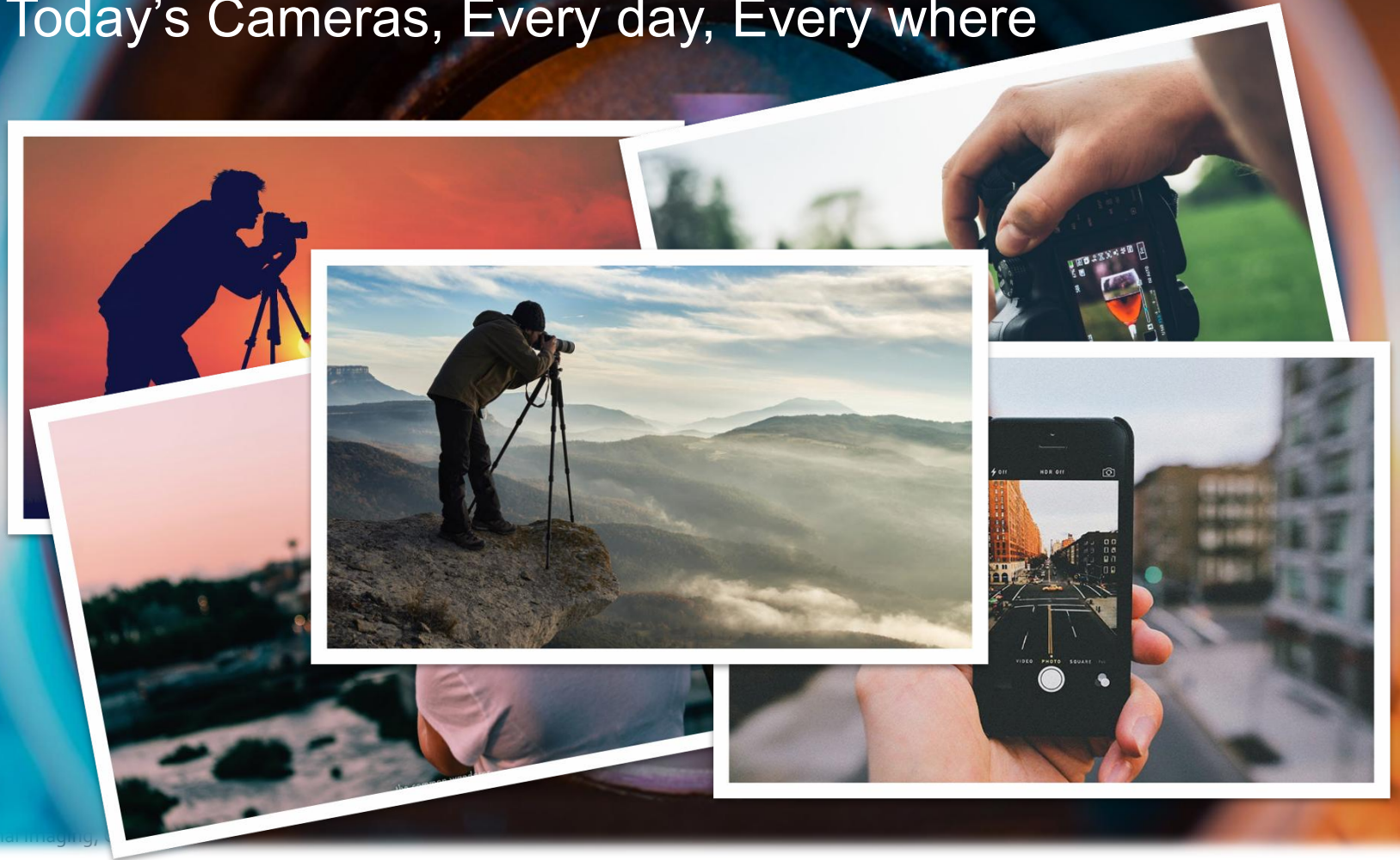
> A record of what we see, or would like to see, in tangible form.

Dose photography always capture it?

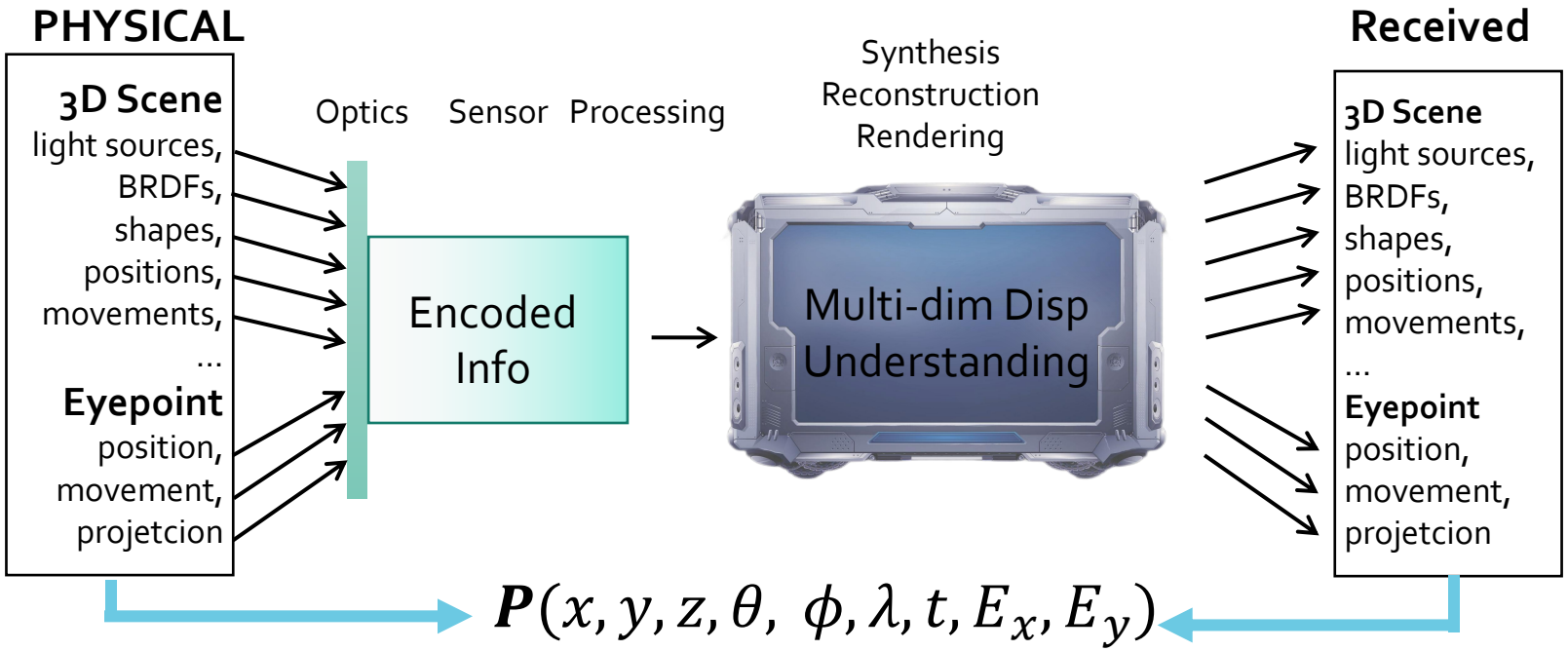


Muybridge used high-speed photography to make the first animated image sequences photographed in real-time (1878–1887)

# Today’s Cameras, Every day, Every where



# What's Beyond Film-Like Photography?



# What's Computational Imaging?

# What's Computational Imaging?

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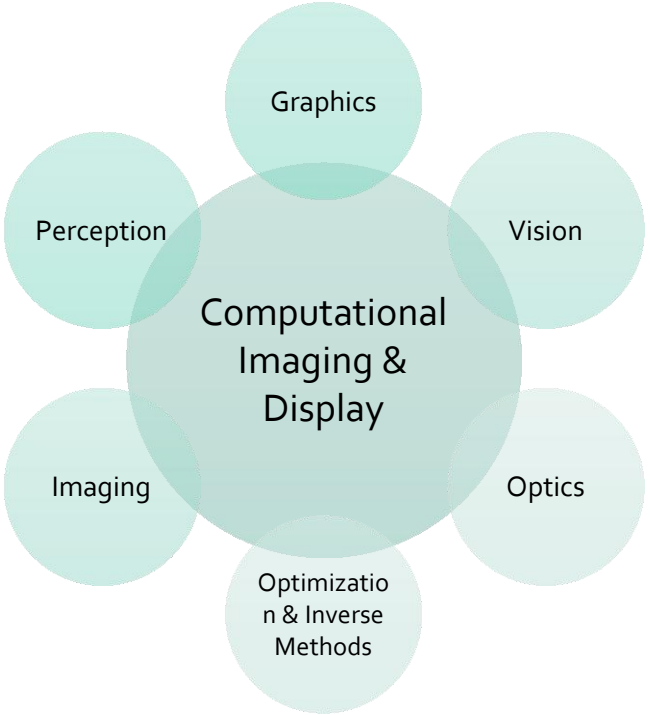
- **Computational Imaging (Photography)**
  optically encode
  information about the real world
  in images aimed for
  computational decoding

- **Computational Display**
  computationally encode
  information so that it can be
  optically decoded
  to form images to be presented to a user




**new optics** | **new sensors** | **new illumination** | **new algorithms**

# Computational Imaging vs Computational Photography?

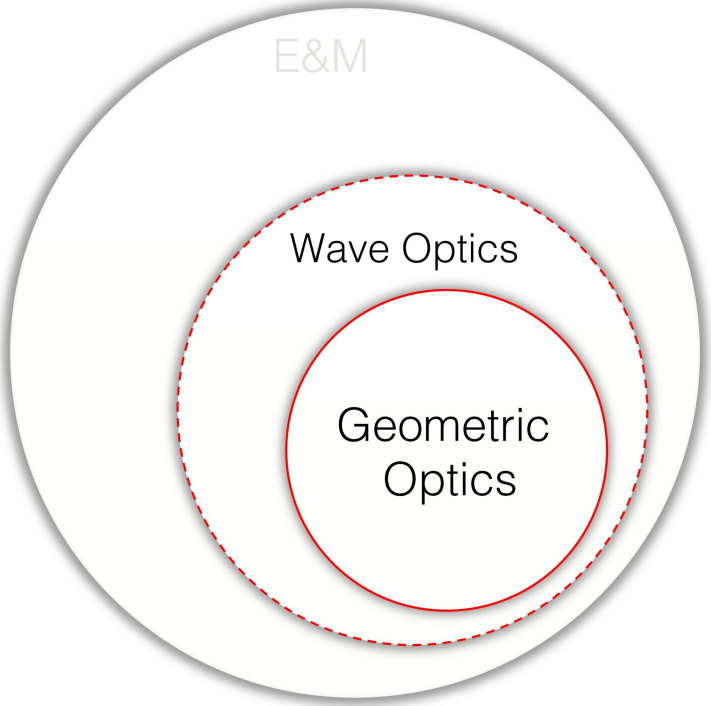
## No Strict Difference

Academic community and industral community are more accustomed to

- **Computational Imaging**
  - With Optics Optimized for Target
- **Computational Photography**
  - Traditional Optics
  - Mostly used for mobile camera

# What is Light?

- Light as rays
- Unit: (spectral) radiance
- Properties: wavelength, polarization, direction, …
- Only introduction & outlook for wave optics



# Applications of Computational Imaging

Google Pixel

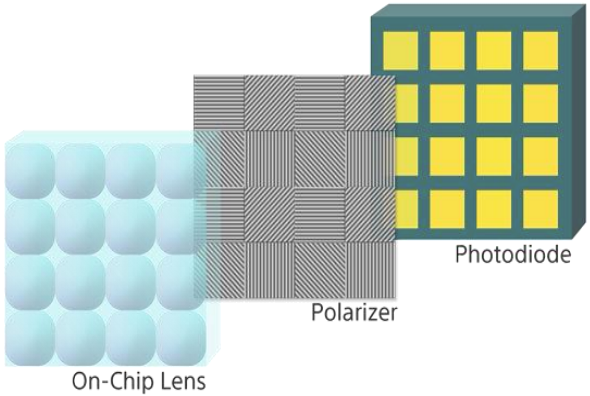
(a) Previously described result (b) Previously described result, gained (c) Our result

Mobile Photography in Low Light

Orly et.al 2019，Handheld Mobile Photography in Very Low Light

# Applications of Computational Imaging






Polarizer imager

Polarimetric Imaging and Applications

Source: https://www.sony-semicon.co.jp/e/products/IS/industry/technology/polarization.html

# Applications of Computational Imaging



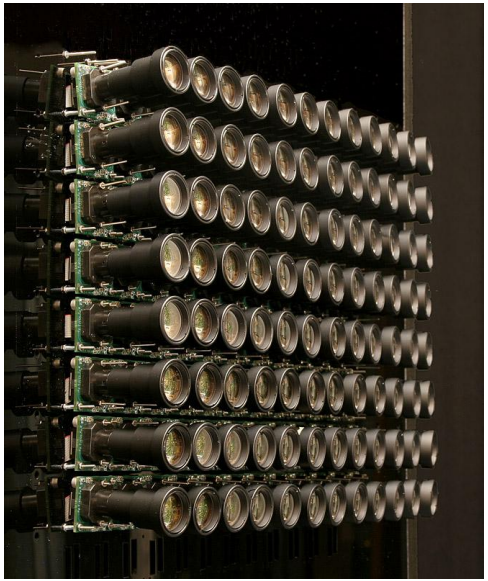
Computed Tomography
United Imaging 640-slice CT scanner

PET-CT
Prof. Qingguo Xie's "Digital PET"

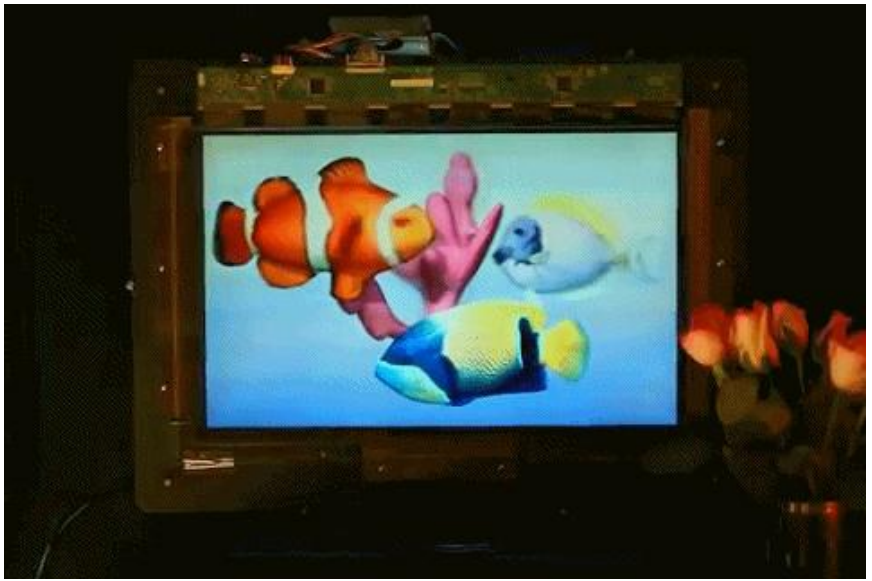
Source: https://www.sohu.com/a/366411143_118392

# Applications of Computational Imaging





Light Field Imaging



Light Field Display

Source: http://www.graphics.stanford.edu/projects/lightfield/

# Applications of Computational Imaging

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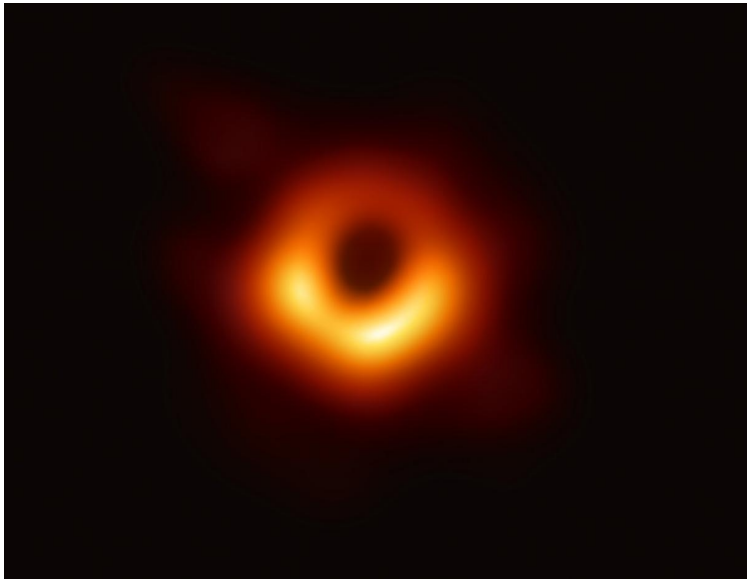
Atacama Large Millimeter Array

one of the 8 telescope facilities used in imaging a black hole. By ESO/B. Tafreshi (twanight.org)

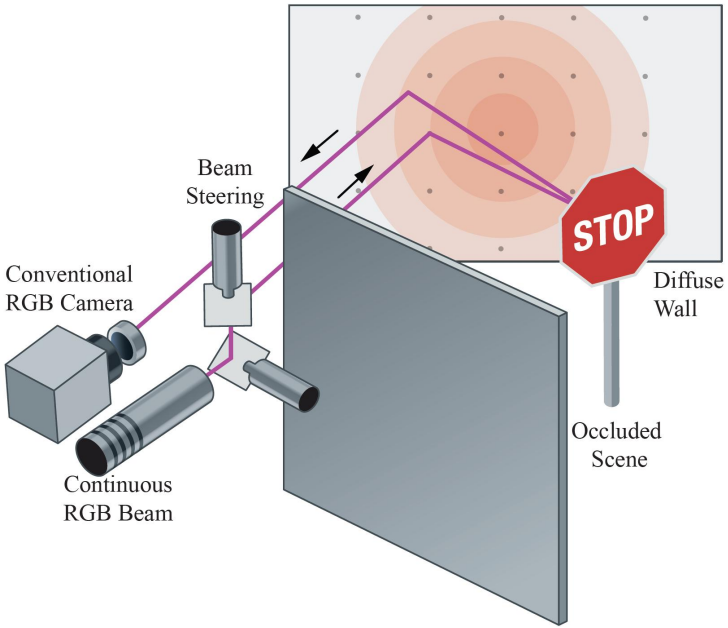


Imaging Black Holes

Source: https://www.nature.com/articles/35025179

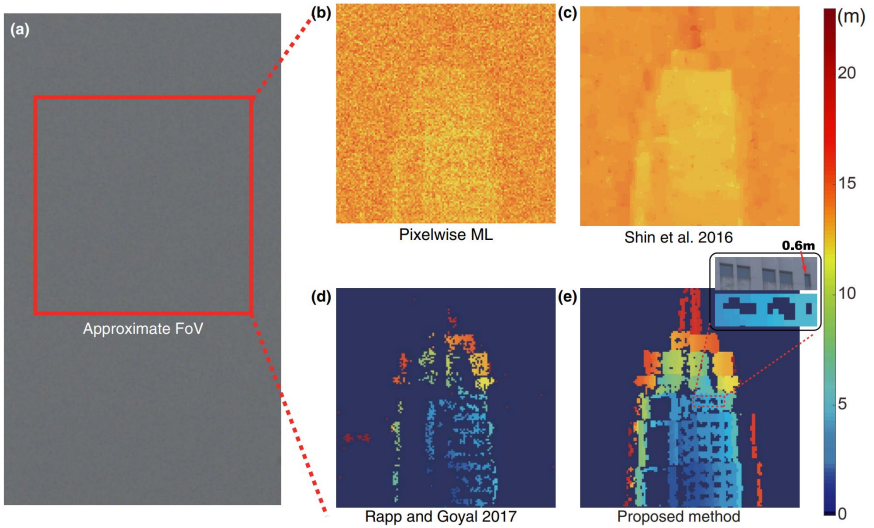
# Applications of Computational Imaging






Non-line-of-sight Imaging

By Felix Heide




Long Range 3D Imaging 45KM

By Jianwei Pan and Feihu Xu

Source: https://www.cs.princeton.edu/~fheide/steadystatenlos, https://opg.optica.org/prj/fulltext.cfm?uri=prj-8-9-1532&id=437808

# Applications of Computational Imaging

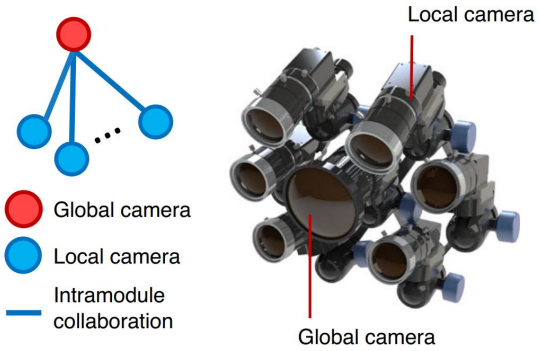

Facebook and Red 360VR Camera

Source: https://www.youtube.com/watch?v=lGkvOgfRPFk

# Applications of Computational Imaging




Light L16

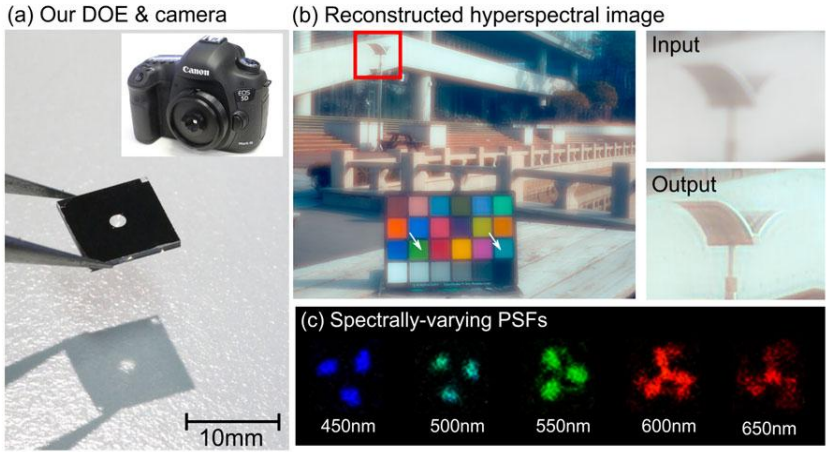



Unstructured Gigapixel Videography
By Qionghai Dai and Lu Fang

Source: https://www.nature.com/articles/s41377-021-00485-x

# Applications of Computational Imaging





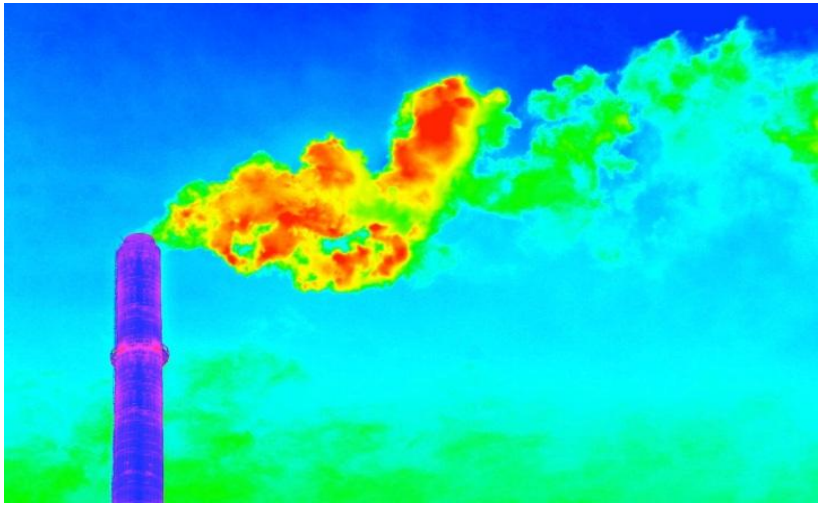

Snapshot Hyperspectral Imaging

Transient Imaging

By Qilin

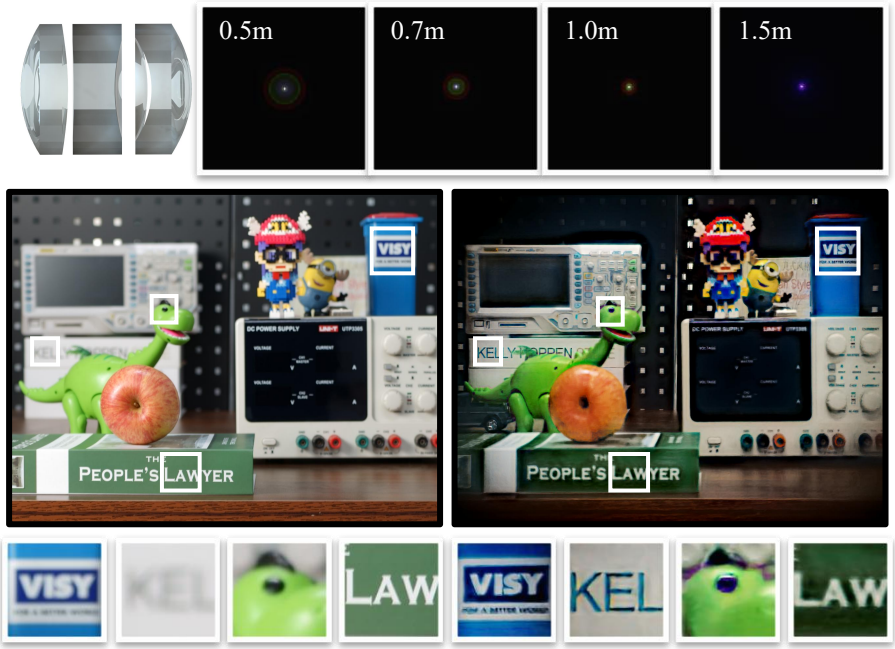
Source:https://vccimaging.org, , https://pointspread.cn

# Applications of Computational Imaging



Smart IR Sensor, Northeastern University

Supported by DARPA, triggered and enabled by signal




Sony standard zoom lens at *50mm/f4.5* Ours at *50mm/f4*

Extened Depth of Field Imaging

By Qilin, Siggraph 2021

Source:https://www.digitaltrends.com/cool-tech/darpa-northeastern-infrared-sensor/, https://pointspread.cn

# Applications of Computational Imaging

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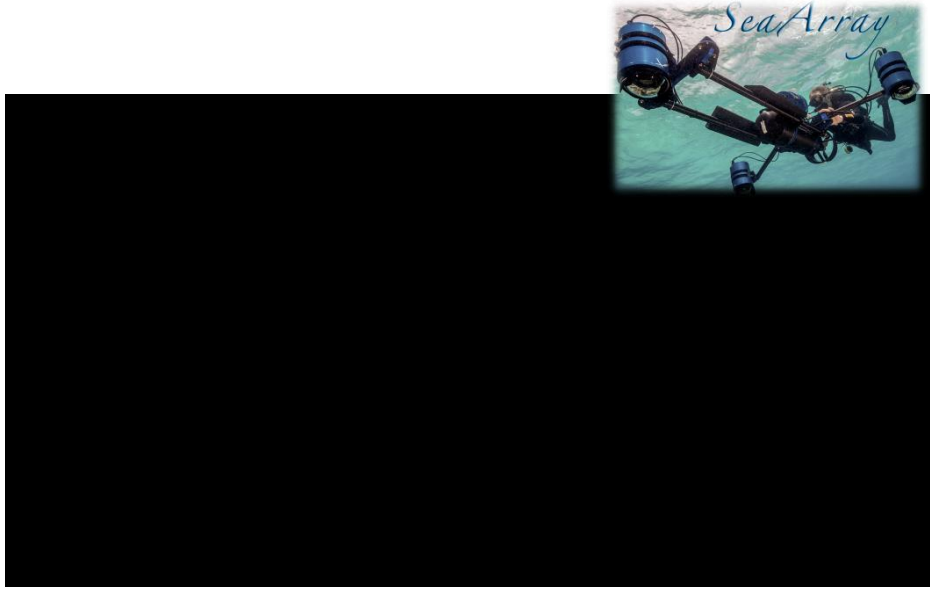
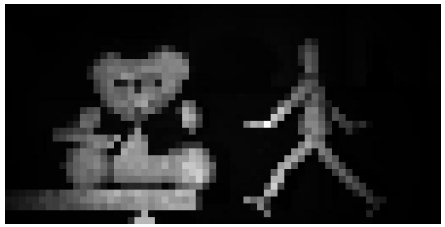
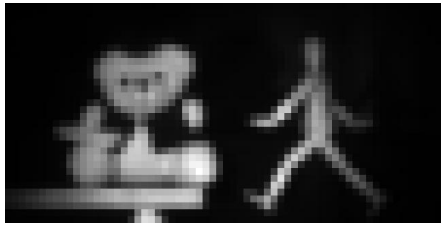



Marine Imaging's Photogrammetry System

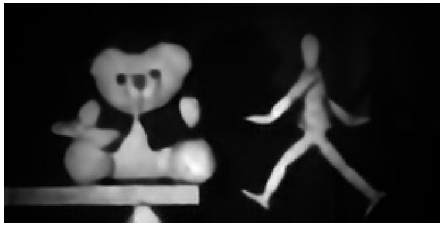


Raw image without mask

Result without mask



Raw image with mask



Result with mask

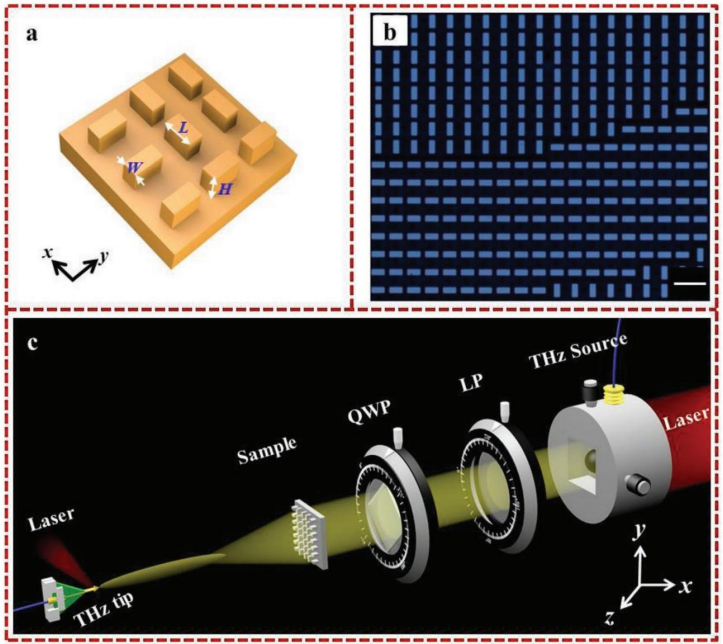
Optimal Optics Encoding

By Qilin, TOG/Siggraph 2020

Source:https://marineimagingtech.com/, https://pointspread.cn

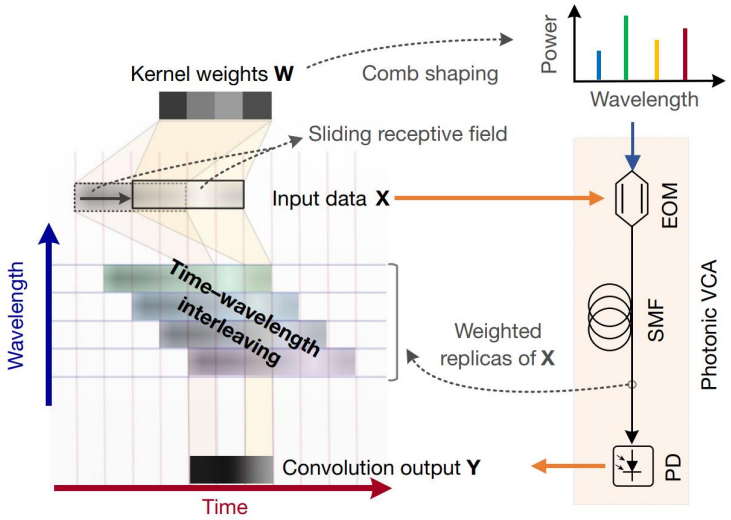
# Applications of Computational Imaging






Terahertz Imaging with Metasurface

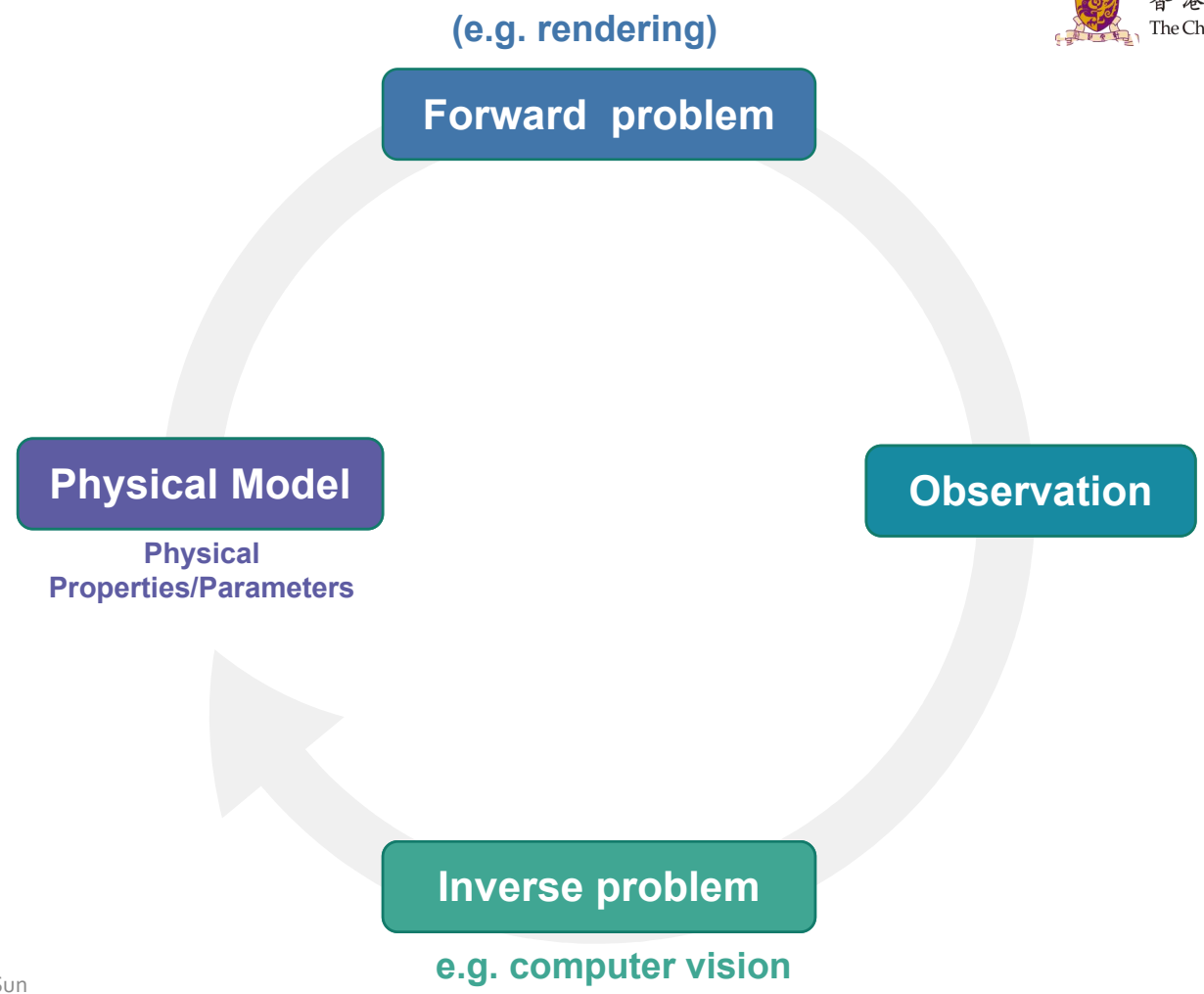
By Songlin Zhuang, Yiming Zhu




11 TOPS Optical CNN

Source:https://vccimaging.org, https://www.nature.com/articles/s41586-020-03063-0

# Computational Methodology


(e.g. rendering)
Forward problem
Physical Model
Physical
Properties/Parameters
Observation
Inverse problem
e.g. computer vision

# Inverse Problems



- Forward problems describe how given physical objects and parameters result in observations, i.e. model->observation
  - These are classical simulation problems, e.g. computer graphics, image operations such as blur filters etc.

- Inverse problems describe how to estimate physical objects and parameters from observations, i.e. observation->model
  - Computer vision is in some sense an inverse problem, as are the standard imaging problems covered today

- Linear inverse problems are inverse problems where the forward model is a linear operator (e.g. matrix, tensor, etc).

# Image Priors



generic

specific

Weak priors

Strong priors

Distributions of gradients/ intensities/frequencies

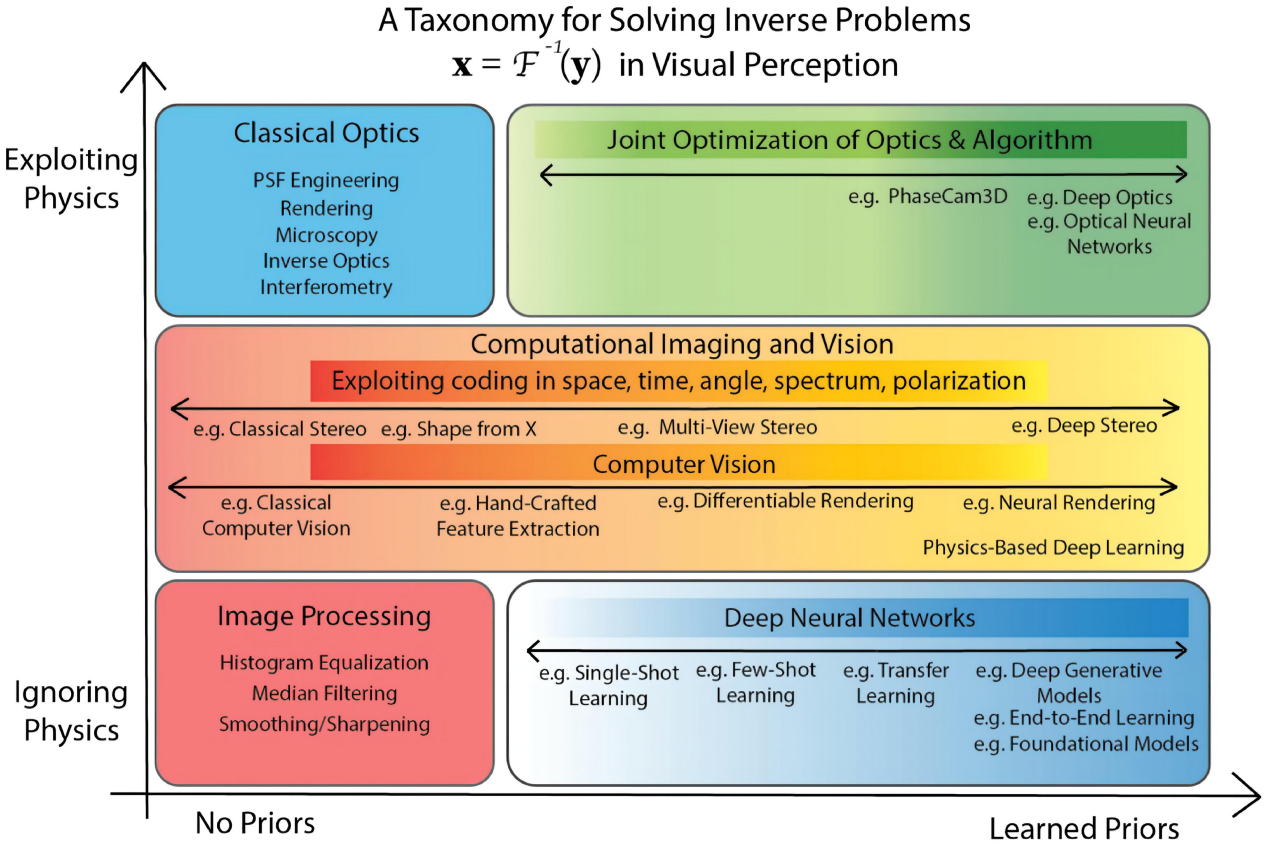
Generic bases (Wavelets, Fourier)

Learned bases

Specific target scenes “Eiffel tower”

Exploit Sparsity

# Image Priors




Tzofi et.al 2022
Physics vs. Learned Priors: Rethinking Camera and Algorithm Design for Task-Specific Imaging

# Classification of Computational Imaging Problems



| | Space | Time | Angle | Spectrum | Polarization |
|---|---|---|---|---|---|
| **Coding with Illumination** | Direct-Global Separation [16] Photometric Stereo [17] | Light Transport [18], [19] Multipath Interference [20] Fluorescence Imaging [21] | Refraction Measurement [22] | Multispectral Imaging [23] Low-Light Photography [24] | Descattering [25] |
| **Coding with Optics** | HDR Imaging [26] Single-Shot Depth [27], [28], [29] | Time Stretch Imaging Motion Deblurring [30] | Digital Refocusing [31] Novel View Estimation [32] | Multispectral Imaging [33], [34], [35], [36], [37] | Shape Estimation [38], [39] Stokes Imaging [40] Light Transport Decomposition [41], [42] |
| **Coding with Sensors** | Stereo Vision [43] HDR Imaging [44] Gradient Camera [45] | Depth Estimation (ToF) NLOS Imaging [46] Imaging Through Scattering [47] | Wavefront Sensing [48] | Spatio-Spectral Superresolution [49] Seeing Occluded Objects [50], [51] | 3D Imaging [39] |

A classification of computational imaging problems based on how physics is encoded

Tzofi et.al 2022 Physics vs. Learned Priors: Rethinking Camera and Algorithm Design for Task-Specific Imaging

# Linear Inverse Problem + Regularization

- Write imaging problem as optimization problem:

$$\hat{\mathbf{x}} = \operatorname{argmin}_{\mathbf{x}} \frac{\mu}{2} \left\| \mathbf{b} - \mathbf{A} \cdot \mathbf{x} \right\|_2^2 + \Gamma(\mathbf{x})$$

Where

- $\mathbf{x}$ is intrinsic/latent image, $\hat{\mathbf{x}}$ is its estimate
- $\mathbf{b}$ is the measurement / observation
- $\mathbf{A}$ describes imaging system
- $\Gamma$ is an image prior or regularizer

- Examples:
  - Deblurring: $\mathbf{A}$ = image blur, $\mathbf{b}$ = blurred image, $\mathbf{x}$ = sharp image
  - Tomography: $\mathbf{A}$ = projection matrix, $\mathbf{b}$ = projected images, $\mathbf{x}$ = volume

Slides Credit: Wolfgang Heidrich

# Course Road Map

# Why Study Computational Imaging?

- Huge Market Size:  2024-p 29 Billion USD  for just 3D Imaging, AR, VR and MR
- Build the bridge from realistic world to virtual world!
- A revolution of capturing the information

- Huge imaginary space!
- Fascinating!

# Human Visual System， Color and Display

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## Human Visual System

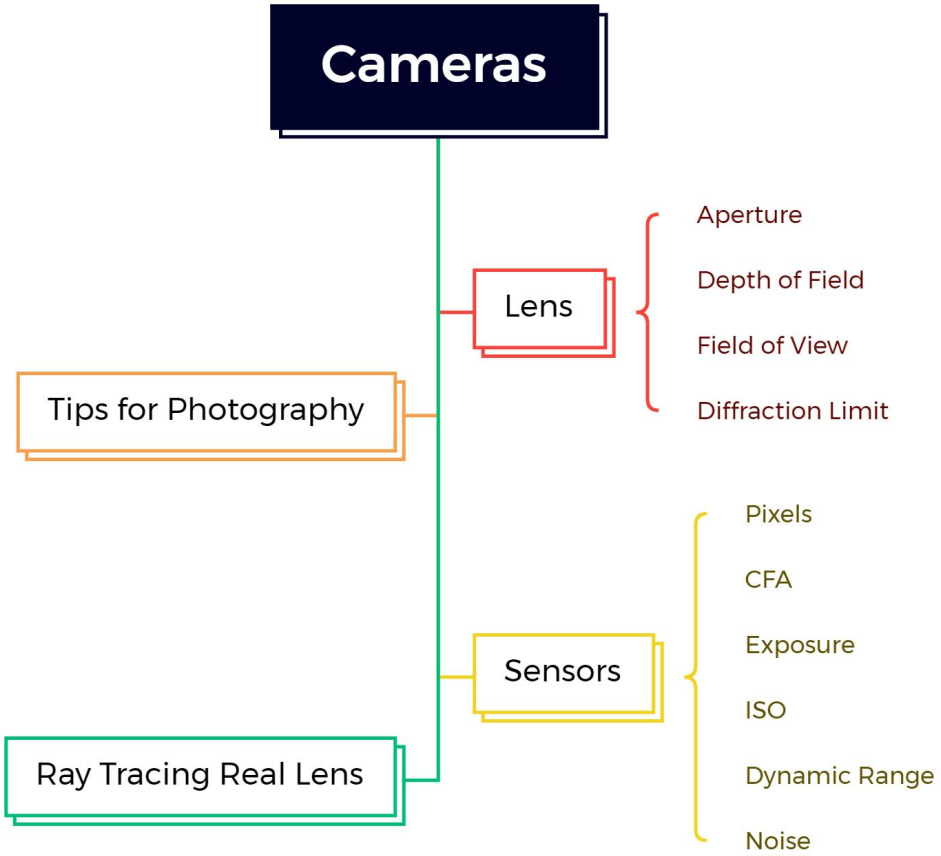
- Parameters
- Oculomotor Processes
- Visual Field
- Visual Acuity
- Retina Displays
- Dynamic Range
- Refractive Errors
- Contrast
- Color Response

## Color and Display

- Spectrum Power Distribution
- Biological Basis of Color
  - Human Eye
  - Photosensor Response
  - Cone Cell Response (L, M, S)
- CFA Array Response
- Metamerism
  - Primary Light
  - Color Matching
- Displays Reproducing Color
- Color Reproduction
  - Matching Fuctions
  - Linear Algebra
  - Pseudo-Geometric Interpretation
- Color Space
  - CIE XYZ
  - HSV
  - YCrCb
  - Color Gamut
  - Perceptually Organized Color Spaces
  - Perceptual Adaptation

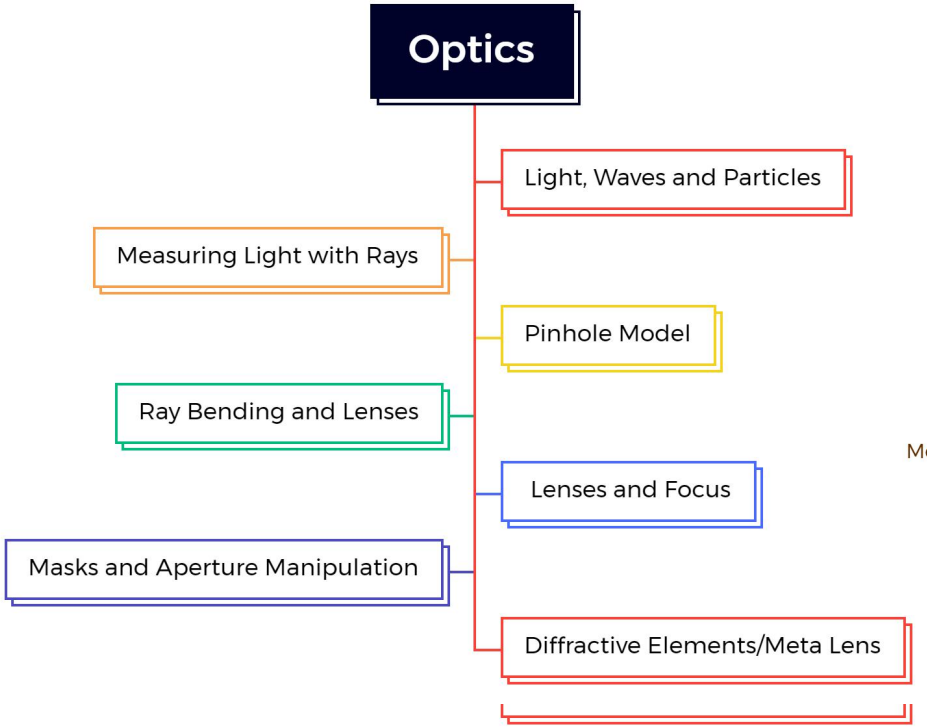
# Cameras

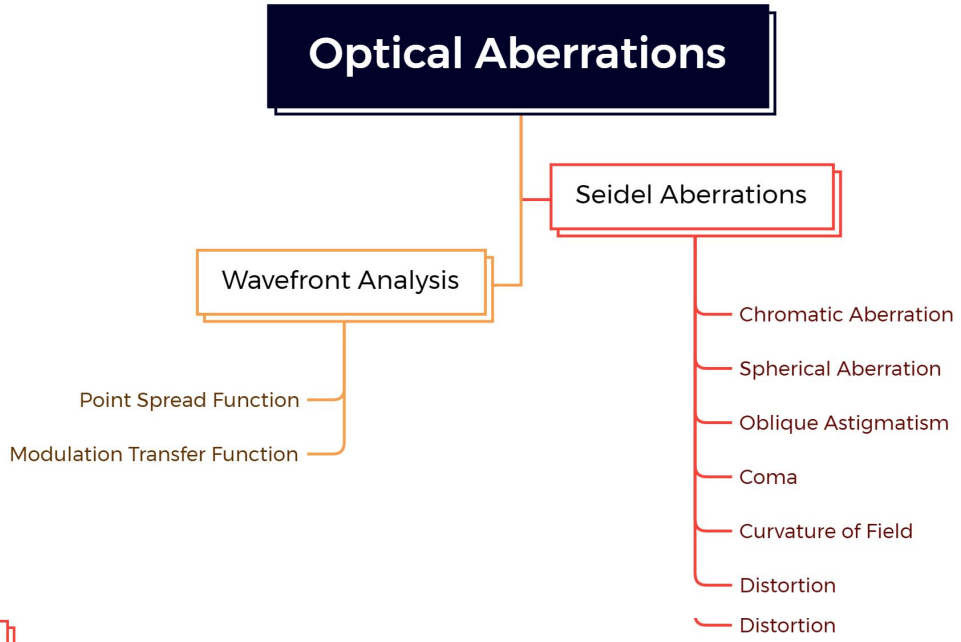



Cameras
Lens
Aperture
Depth of Field
Field of View
Diffraction Limit
Tips for Photography
Sensors
Pixels
CFA
Exposure
ISO
Dynamic Range
Noise
Ray Tracing Real Lens

# Imaging Toolkit: Optics

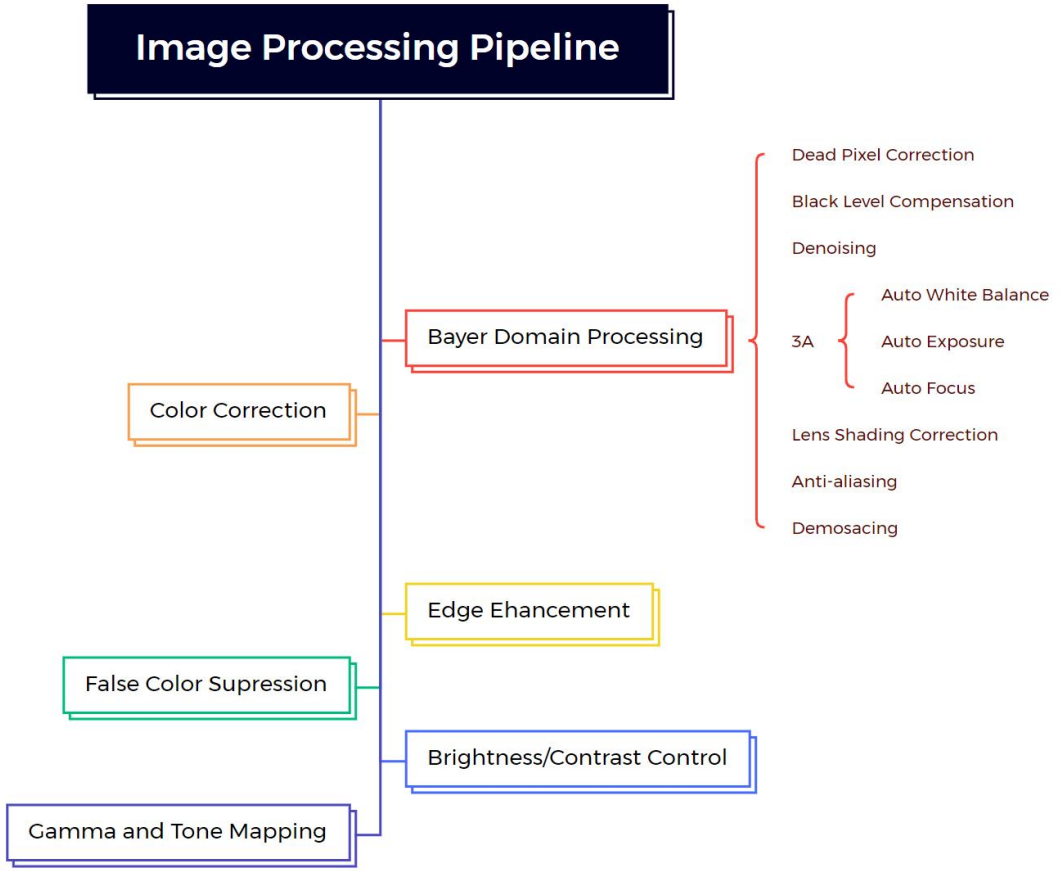




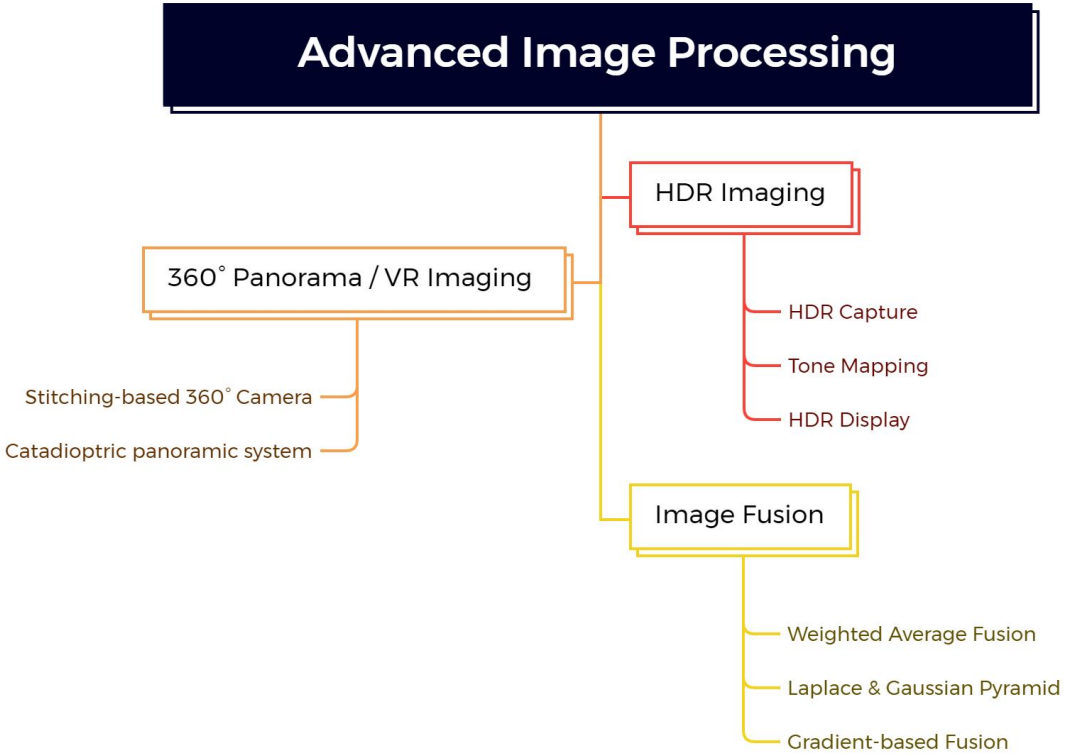
# Imaging Toolkit: Image Processing Pipeline





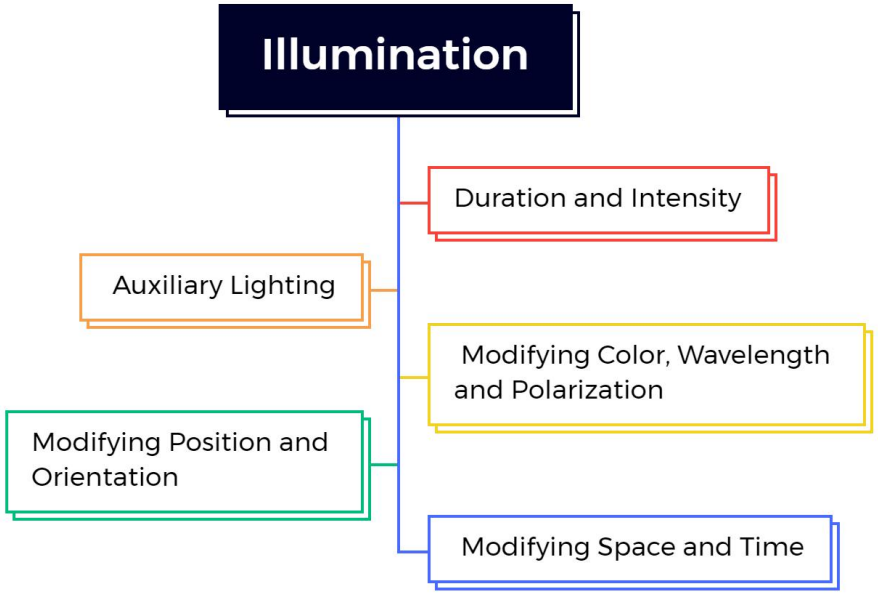
# Imaging Toolkit: Advanced Processing Pipeline





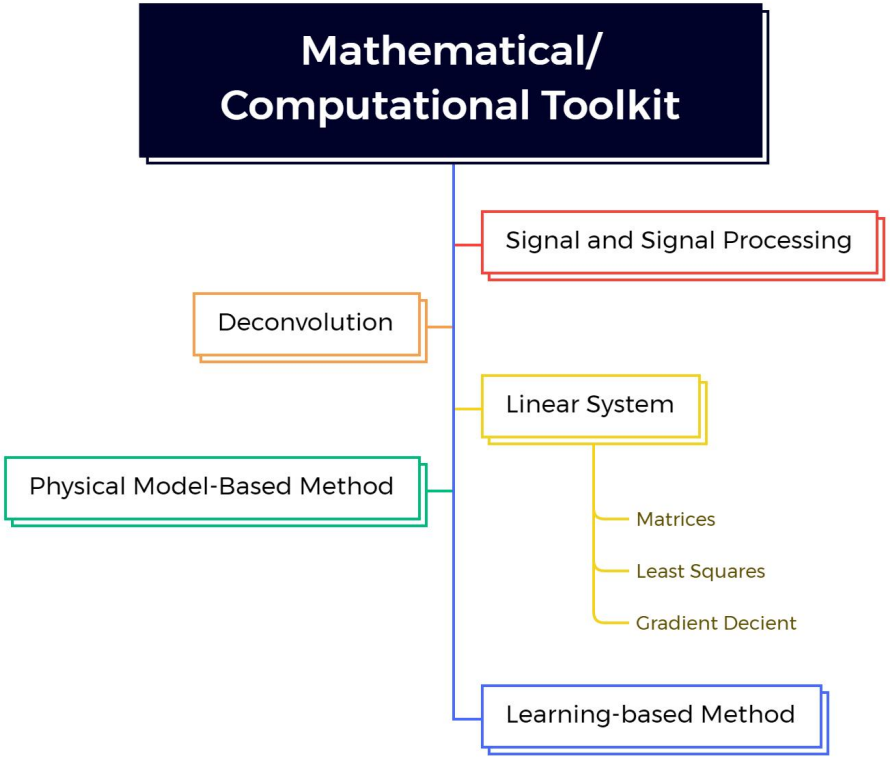
# Imaging Toolkit: Illumination

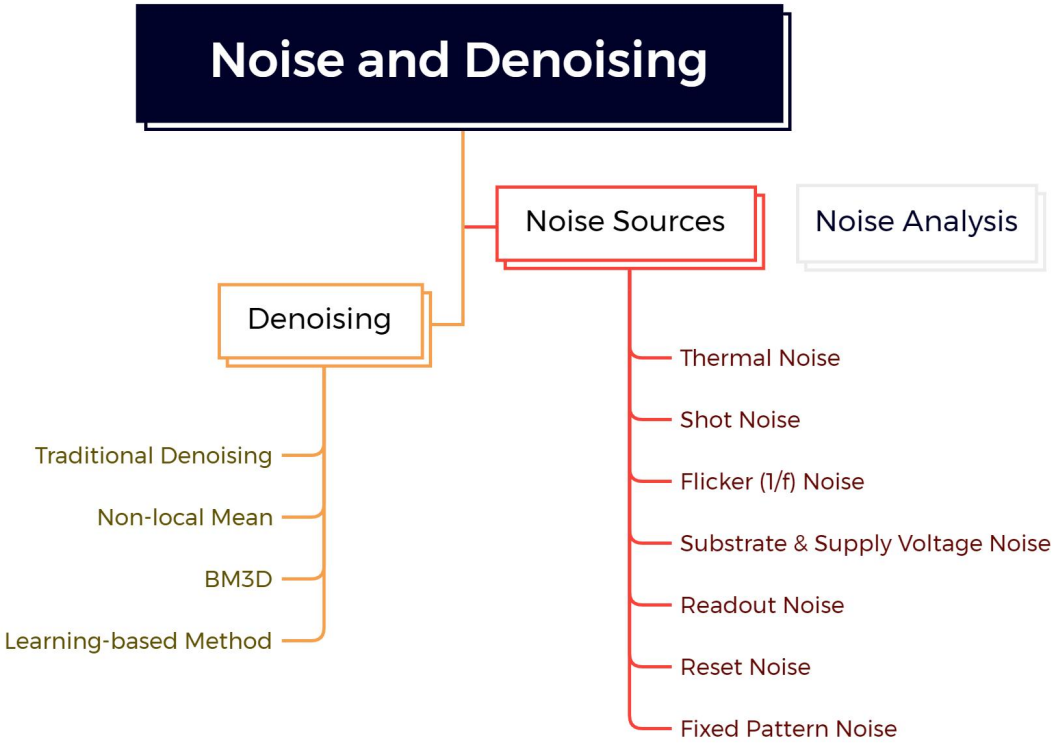




# Mathematical/Computational Toolkit

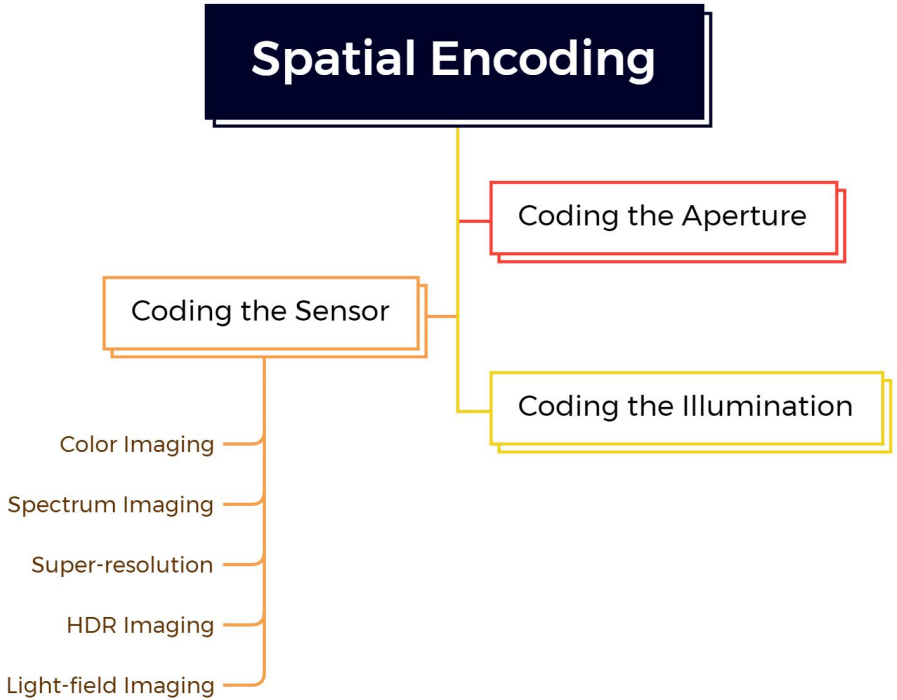


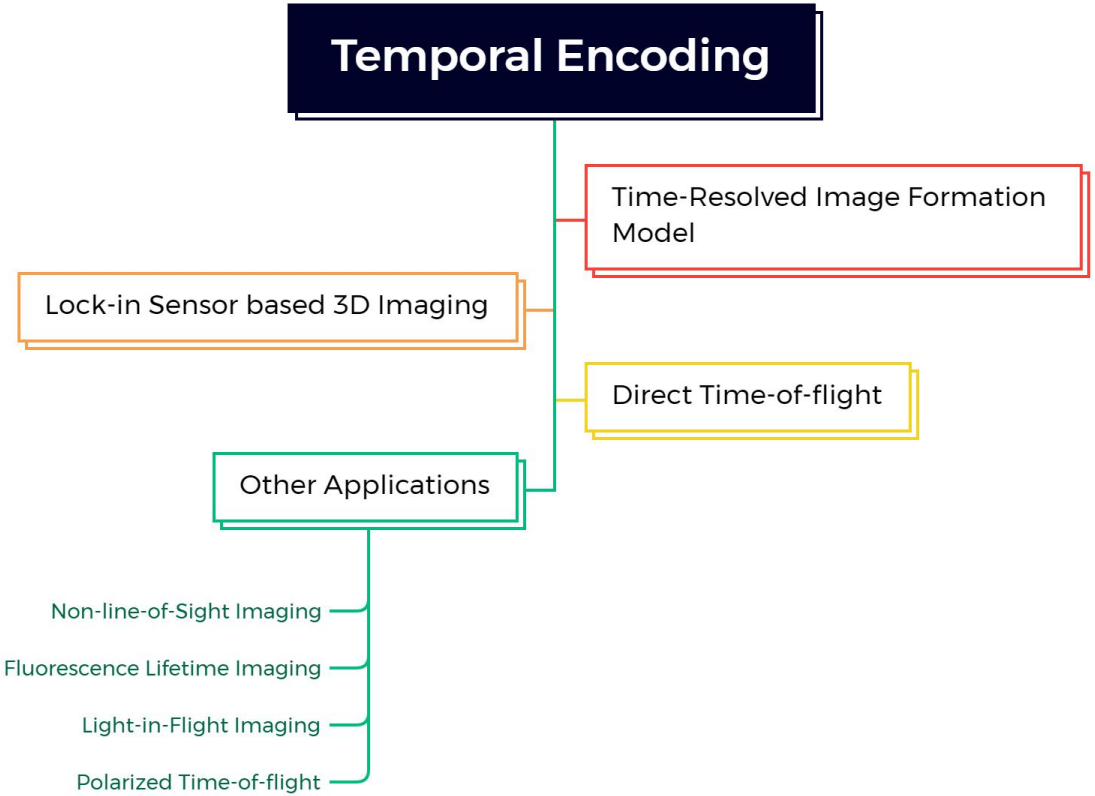


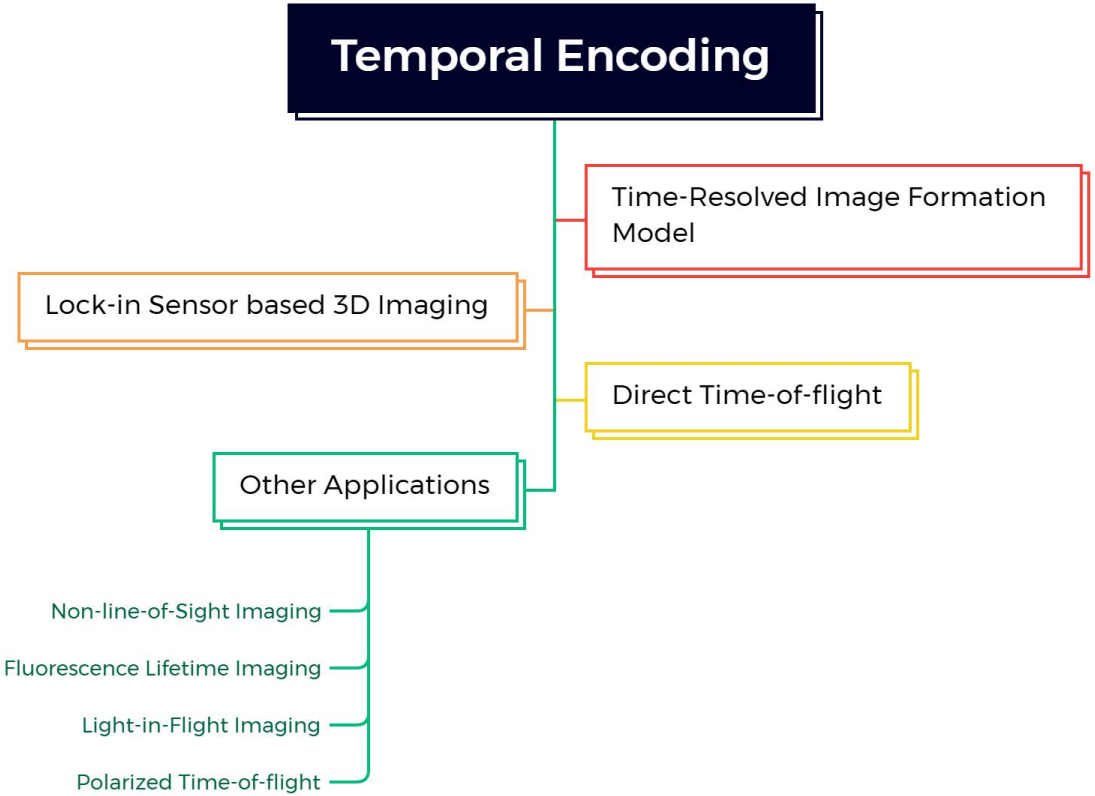

Noise and Denoising
Noise Sources
Noise Analysis
Denoising
Thermal Noise
Shot Noise
Flicker (1/f) Noise
Substrate & Supply Voltage Noise
Readout Noise
Reset Noise
Fixed Pattern Noise
Traditional Denoising
Non-local Mean
BM3D
Learning-based Method

# Spatial Encoding






Temporal Encoding
Time-Resolved Image Formation Model
Lock-in Sensor based 3D Imaging
Direct Time-of-flight
Other Applications
Non-line-of-Sight Imaging
Fluorescence Lifetime Imaging
Light-in-Flight Imaging
Polarized Time-of-flight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# Advanced Topics and Applications



**Light-field Imaging**

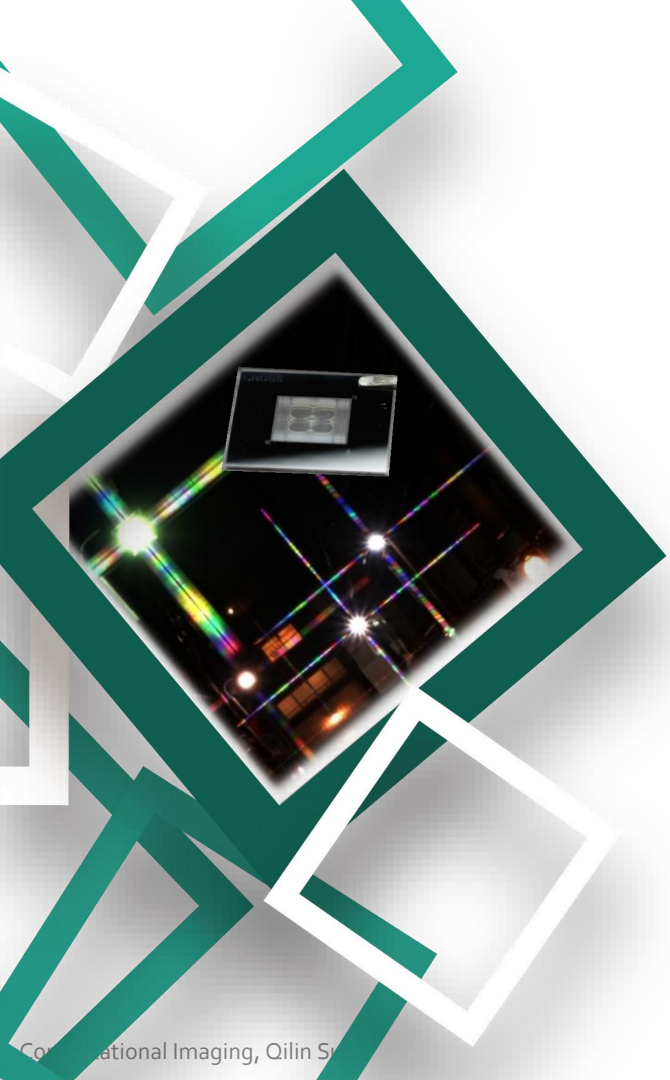
**Spectrum Imaging**

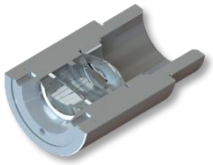
**Polarimetric Imaging**

**Differentiable End-to-End Camera Design**

A lot of instersting Topics!


- Imaging History and Today
- What's Computational Imaging
  - Defination
  - Applications
- Computational Methodology Overview
- Course Road Map








Computational Imaging

# Thank You!

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