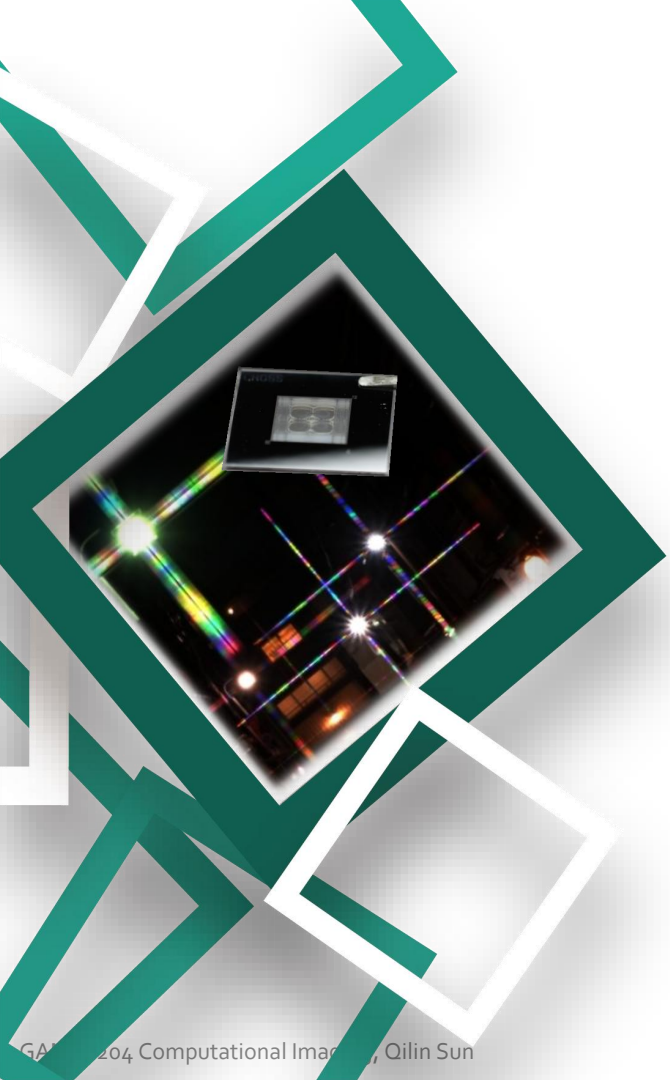


GAMES 204

Computational Imaging

Lecture 01： Introduction to Computational Imaging

Qilin Sun（孙启霖）

香港中文大学（深圳）

点昀技术（Point Spread Technology）

Instructors

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

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

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

点昀 POINT SPREAD

Instructors

PENG, Yifan (Evan Peng) （彭祎帆）

- 2022-now: Assistant Professor @ The University of Hong Kong
- 2018-2022 Postdoc @Stanford
    - 2013-2018 PhD @UBC. 2006-2013 MSc, BEs @ZJU

- Website: https://www.eee.hku.hk/~evanpeng/
- Email: evanpeng@hku.hk

- Research: Interdisciplinary field of Optics, Graphics, Vision, and Artificial Intelligence; Computational Microscope Imaging; Low-level Computer Vision; Human-centered Visual & Sensory Systems.

Course Staff

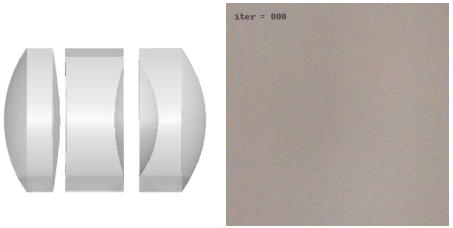
- Teaching Assistants
  - 柴子力（Apple/CMU，zilichai@gmail.com）
  - 杨辛格（KAUST，xinge.yang@kaust.edu.sa）
  - 蒋朴华（清华，jph21@mails.tsinghua.edu.cn）
  - 沈鹏飞（中科大，jerry_shen@mail.ustc.edu.cn）

- Register GAMES204 thourgh:
  https://www.cesalpha.org/course/register/GAMES204/

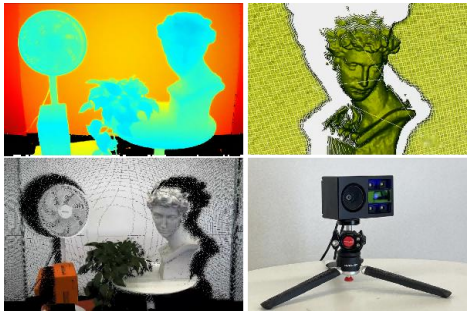
- Course Resources:
  http://pointspread.cn/page94

Instructors' Achievement

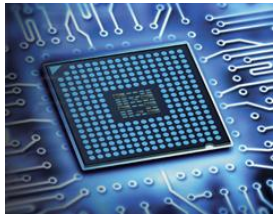
Maybe the world first differentiable diffractive optics model (proposed at 2018.5, ACM Trans. Graph. 2020)



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



Super low-power consumption, low latency full parallel heterogeneous ISP (IP core)

Acedemic Achievements

Industral Achievements
(Point Spread Technology)

Source: https://pointspread.cn

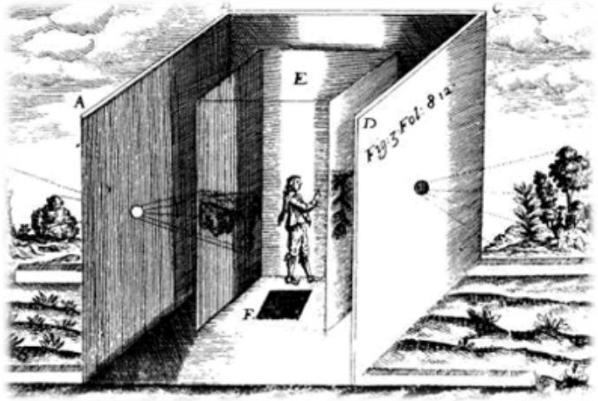
- Imaging History and Today
- What's Computational Imaging
  - Defination
  - Applications
- Computational Methodology Overview
- Course Road Map

Imaging History and Today

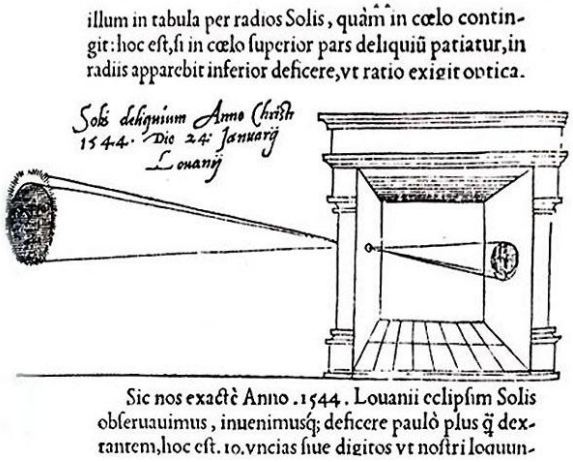
Pinhole Camera

Mo-Ti, 470-390 BC

《墨经》记载“景到，在午有端”、“景。光之人，煦若射，下者之人也高；高者之人也下”。



Aristotele, 300 BC

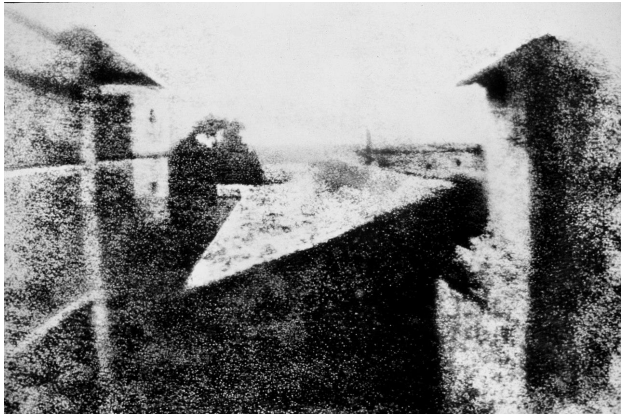


Gemma Frisius, 1544

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, …

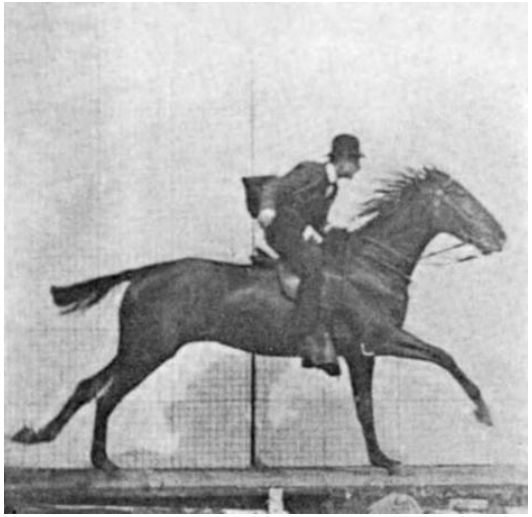
- Capture a memory, a visual experience in tangible form
- 'painting with light' express the subject's visual essence
- "Exactitude is not the truth." — Henri Matisse

What's Photography?

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

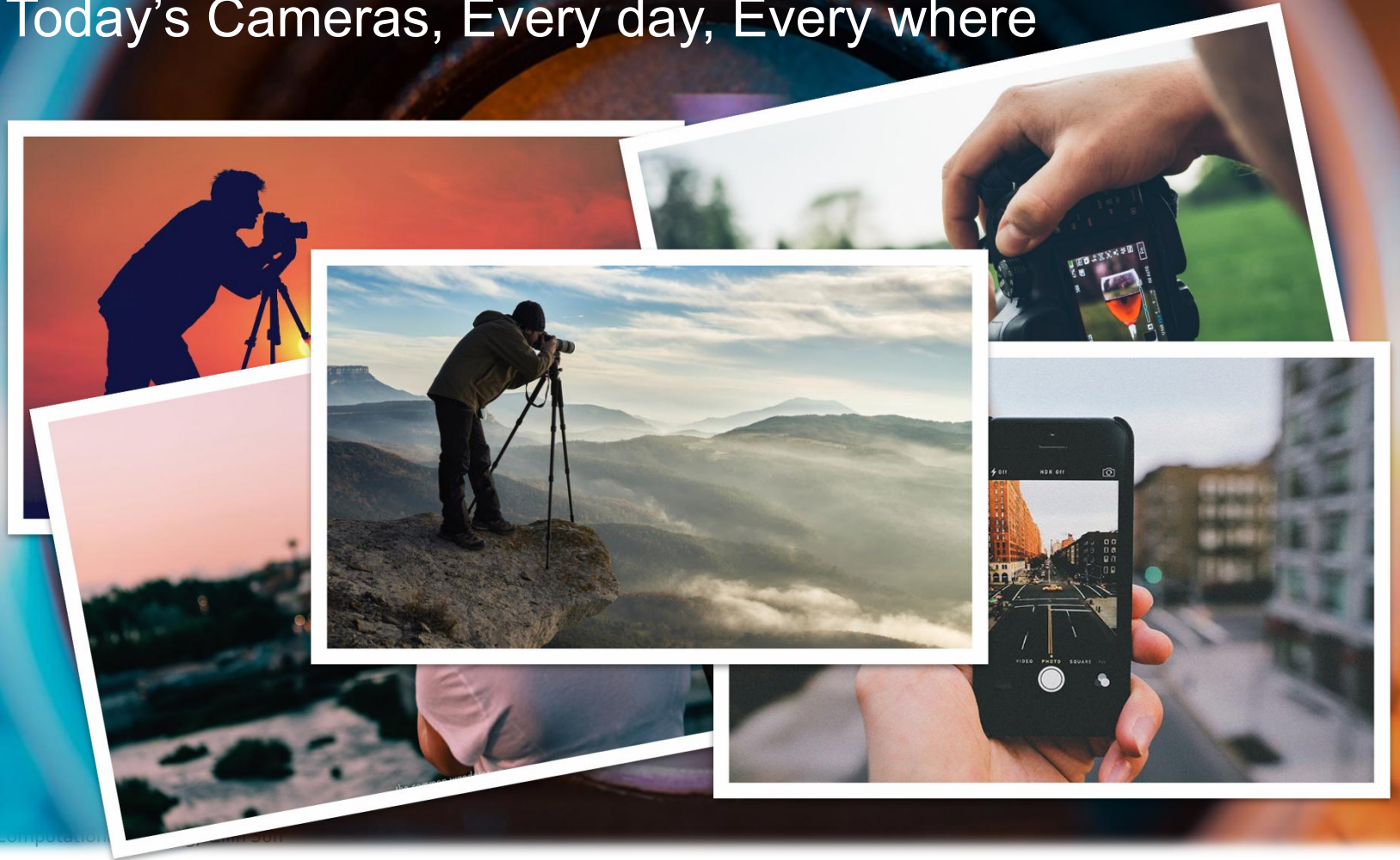
> A record of what we see, or would like to see, in tangible form.

Dose photography always capture it?

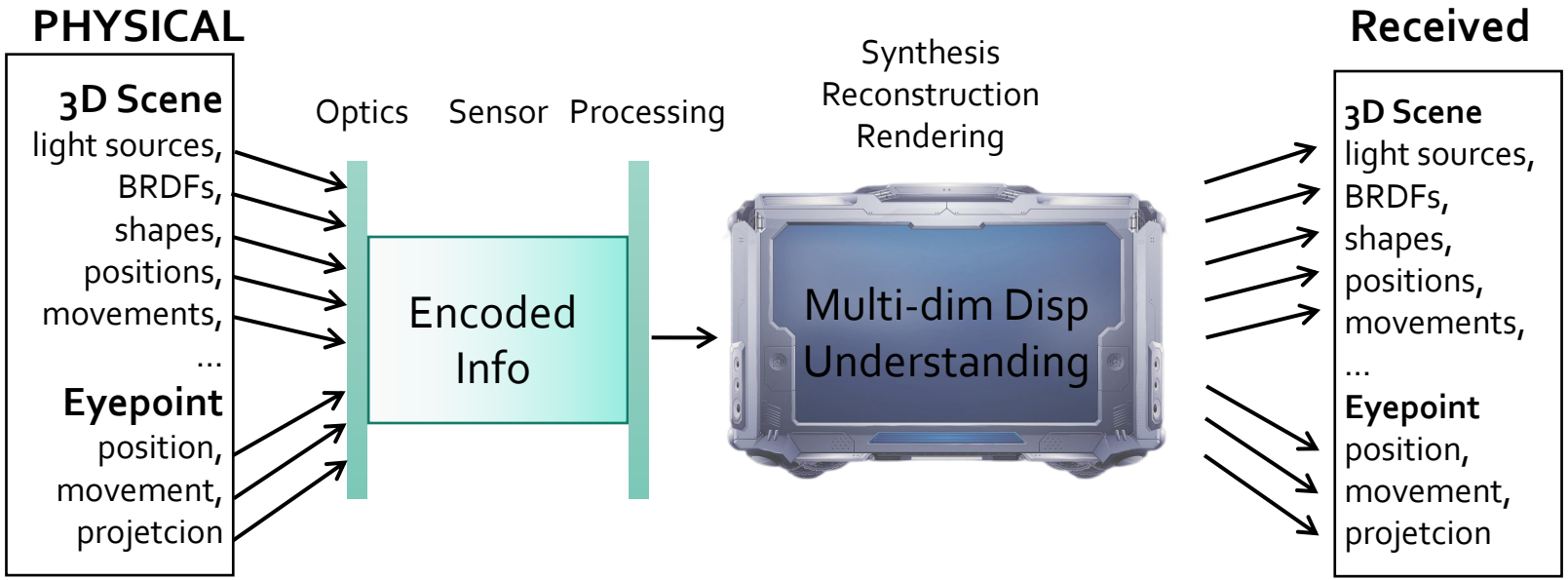


Muybridge used high-speed photography to make the first animated image sequences photographed in real-time (1878–1887)

Today’s Cameras, Every day, Every where



What's Beyond Film-Like Photography?

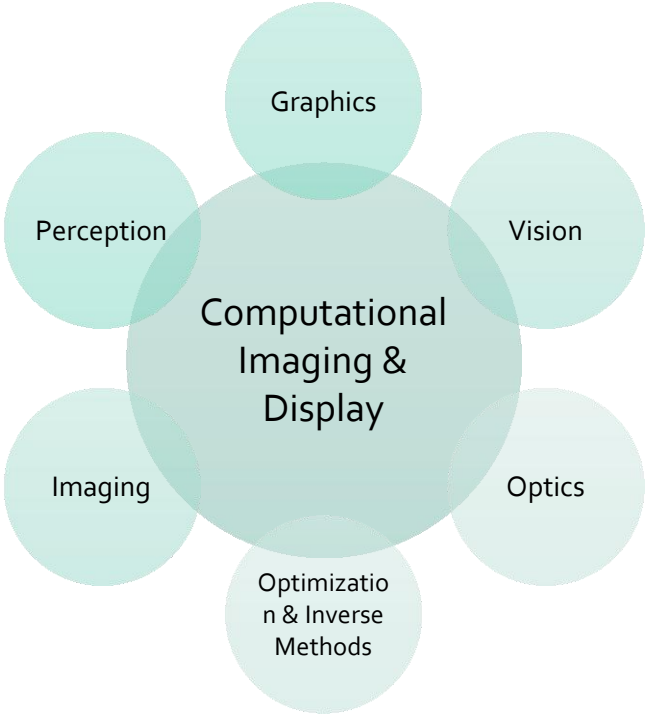


What's Computational Imaging?

What's Computational Imaging?

- **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?

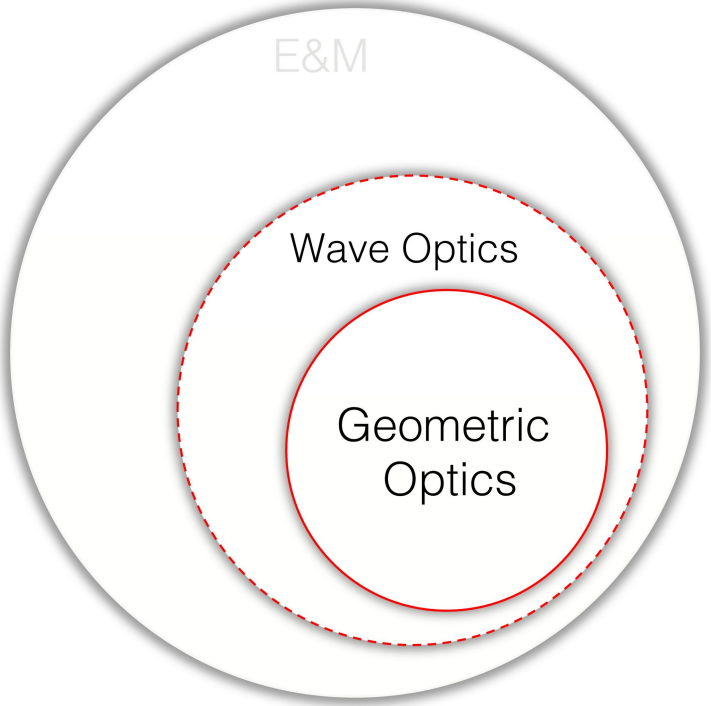
No Strict Difference

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

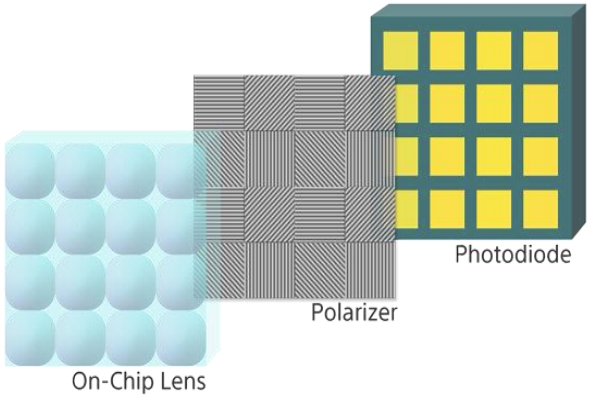
Google Pixel

(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

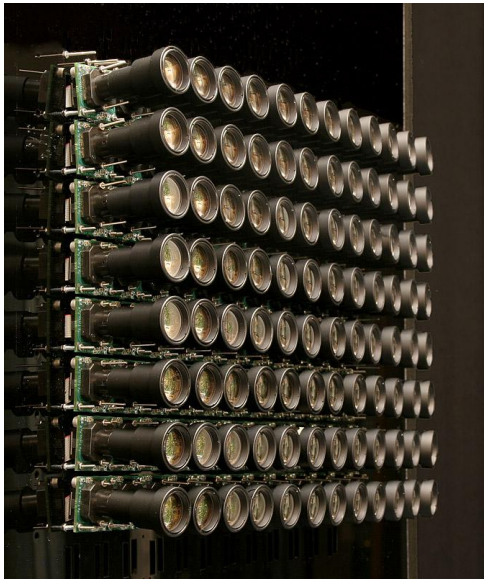
Applications of Computational Imaging

Computed Tomography
United Imaging 640-slice CT scanner

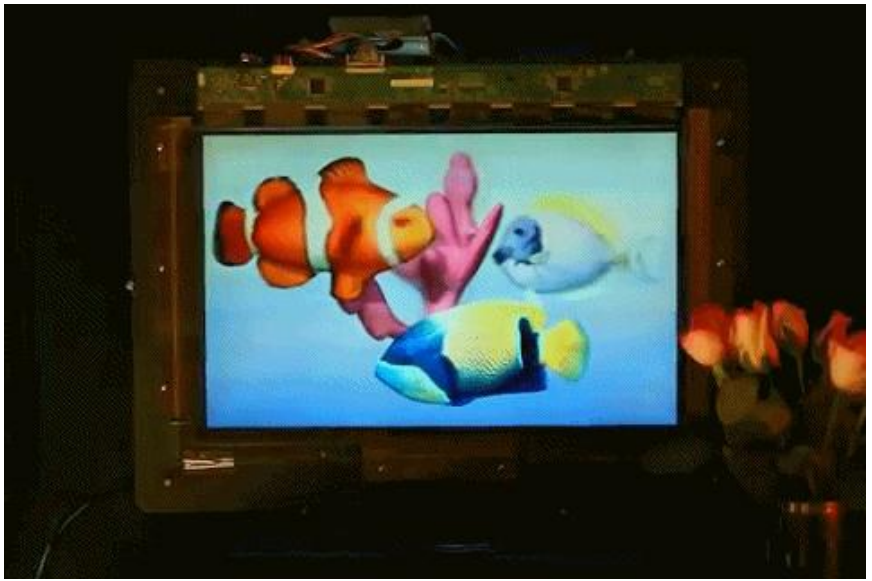
PET-CT
Prof. Qingguo Xie's "Digital PET"

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

Applications of Computational Imaging



Light Field Imaging



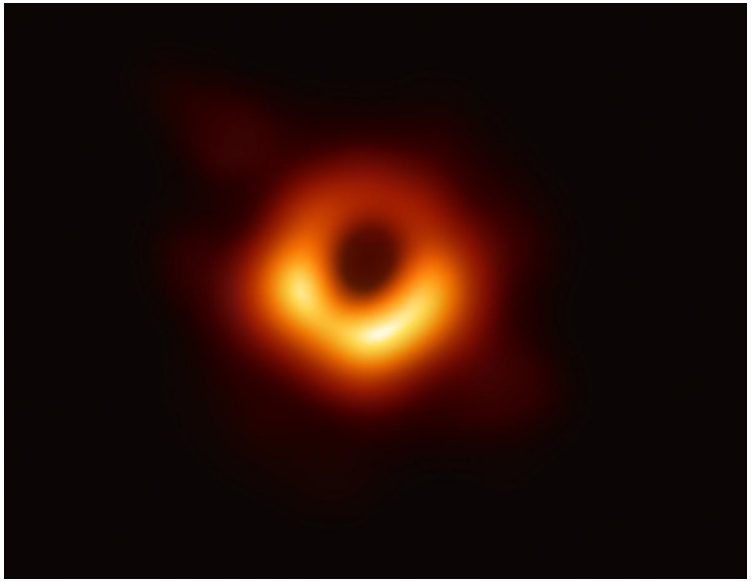
Light Field Display

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

Applications of Computational Imaging

Atacama Large Millimeter Array

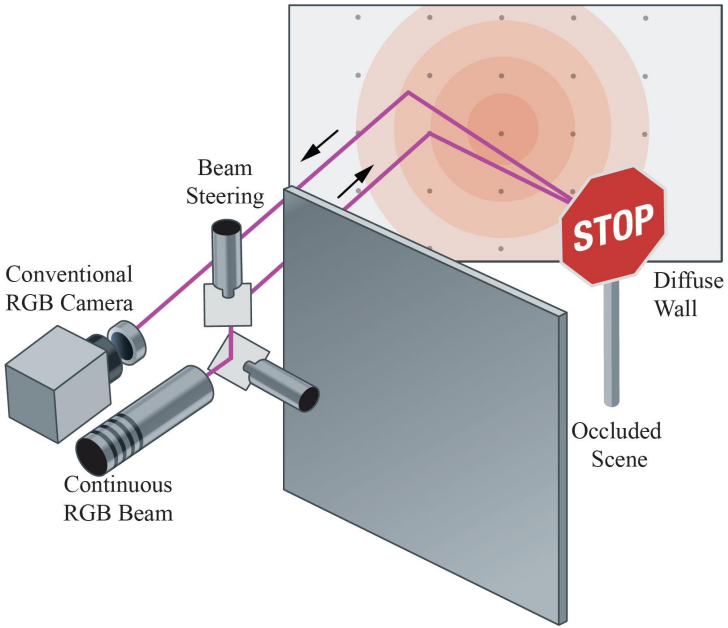
one of the 8 telescope facilities used in imaging a black hole. By ESO/B. Tafreshi (twanight.org)



Imaging Black Holes

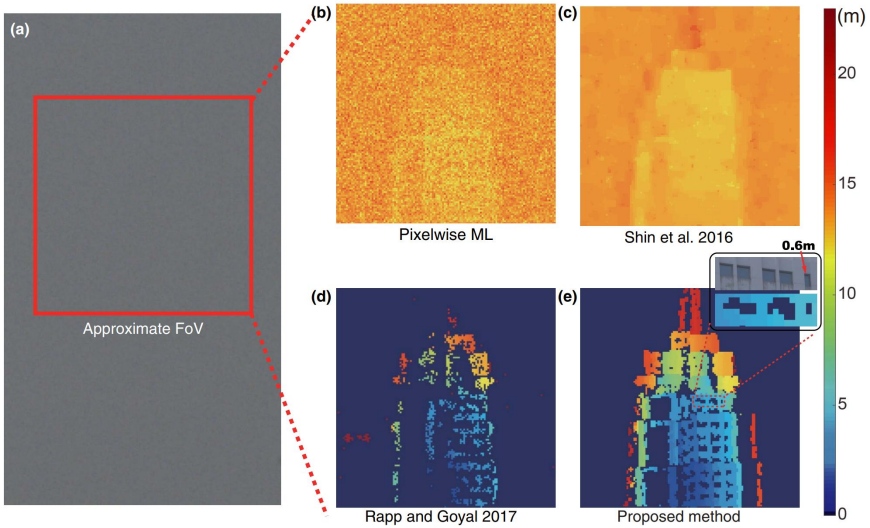
Source: https://www.nature.com/articles/35025179

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

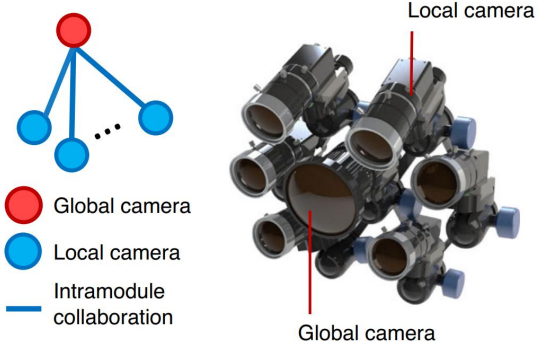
Applications of Computational Imaging

Facebook and Red 360VR Camera

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

Applications of Computational Imaging

Light L16

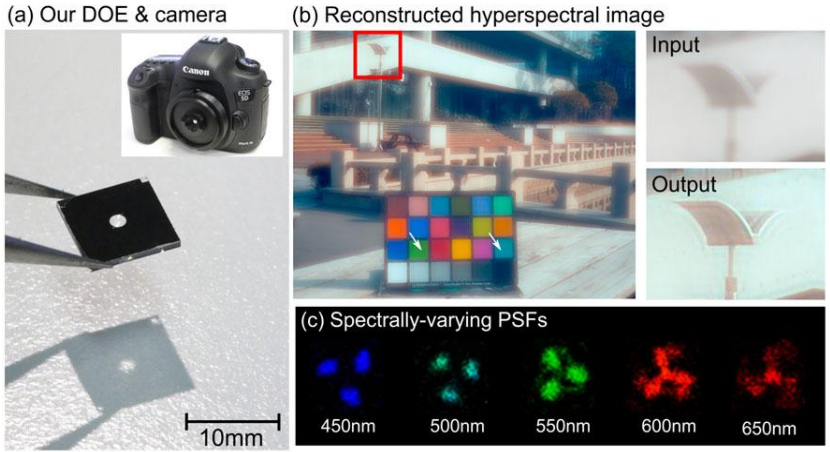


Unstructured Gigapixel Videography

By Qionghai Dai and Lu Fang

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

Applications of Computational Imaging



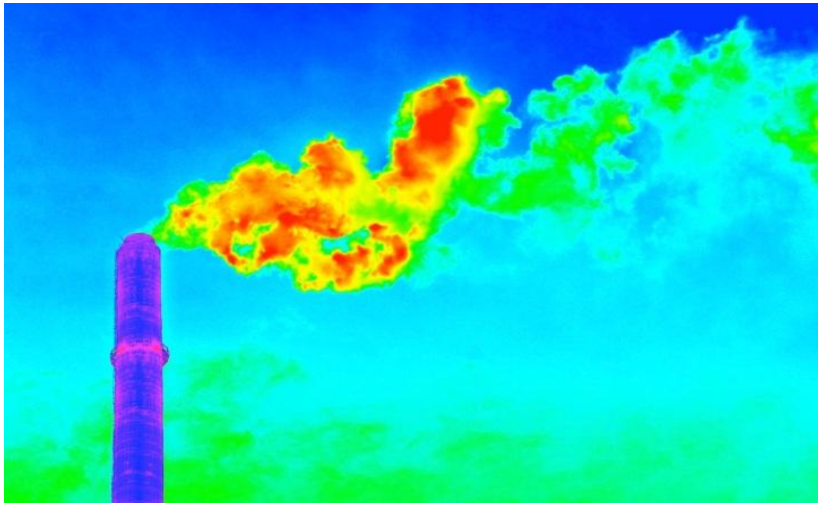
Snapshot Hyperspectral Imaging

Transient Imaging

By Qilin

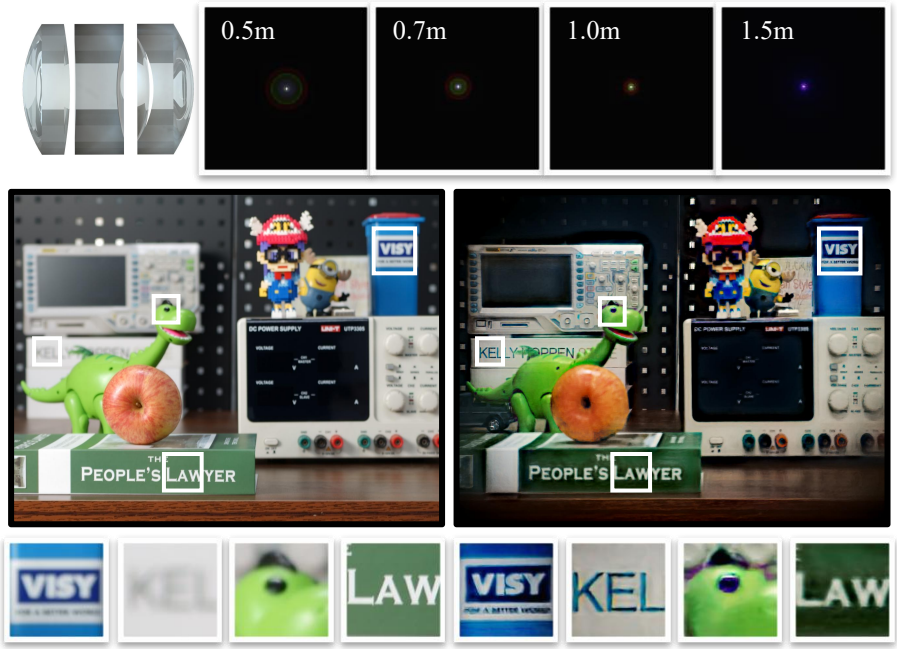
Source:https://vccimaging.org, , https://pointspread.cn

Applications of Computational Imaging



Smart IR Sensor, Northeastern University

Supported by DARPA, triggered and enabled by signal



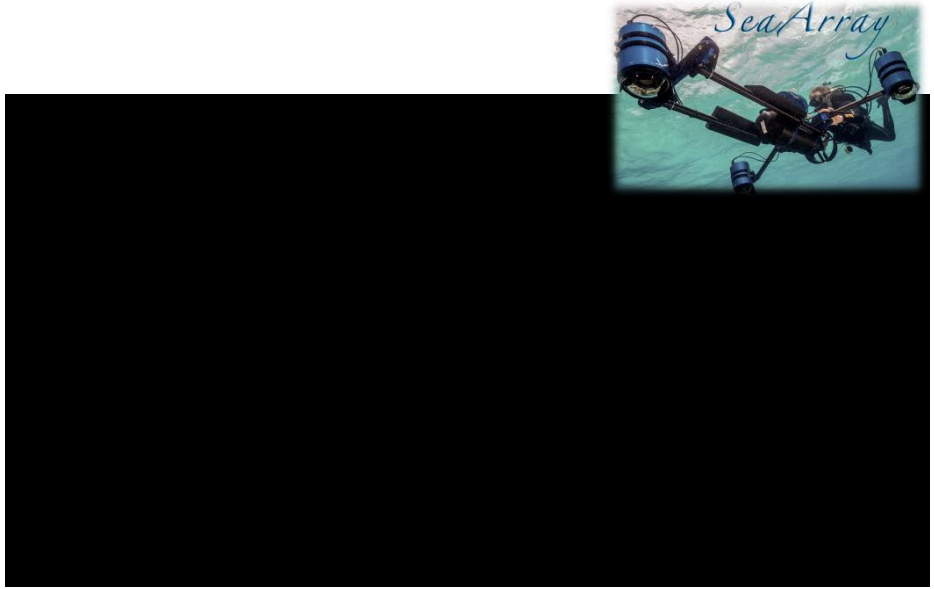
Sony standard zoom lens at *50mm/f4.5* Ours at *50mm/f4*

Extened Depth of Field Imaging

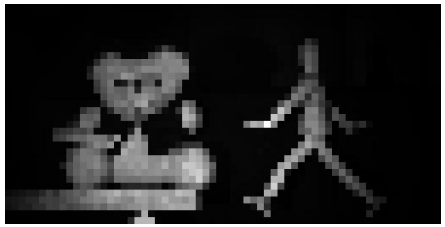
By Qilin, Siggraph 2021

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

Applications of Computational Imaging

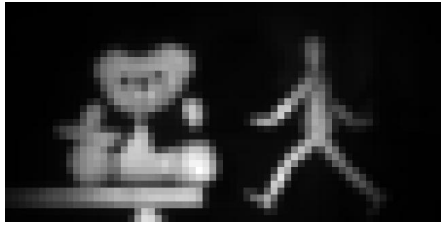


Marine Imaging's Photogrammetry System

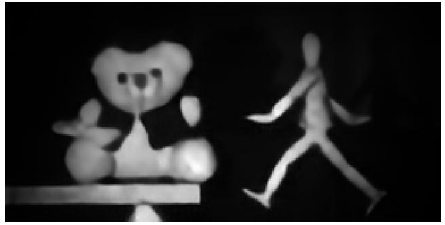


Raw image without mask

Result without mask



Raw image with mask



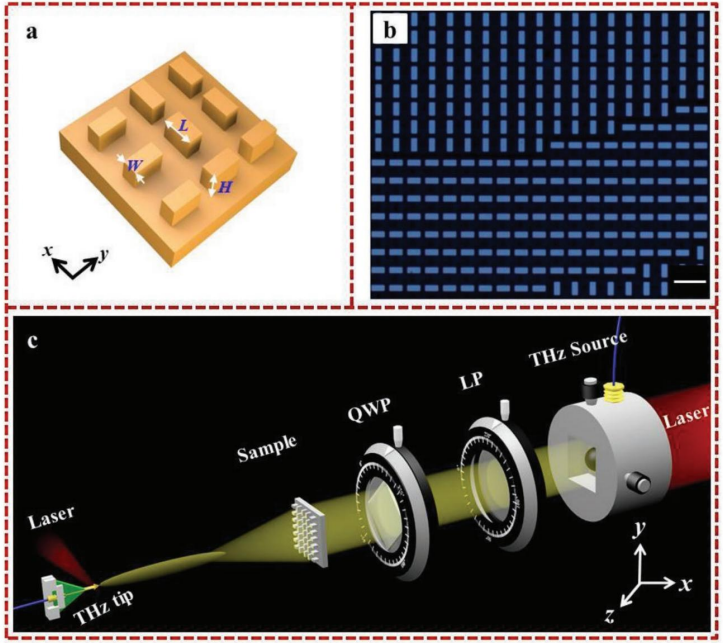
Result with mask

Optimal Optics Encoding

By Qilin, TOG/Siggraph 2020

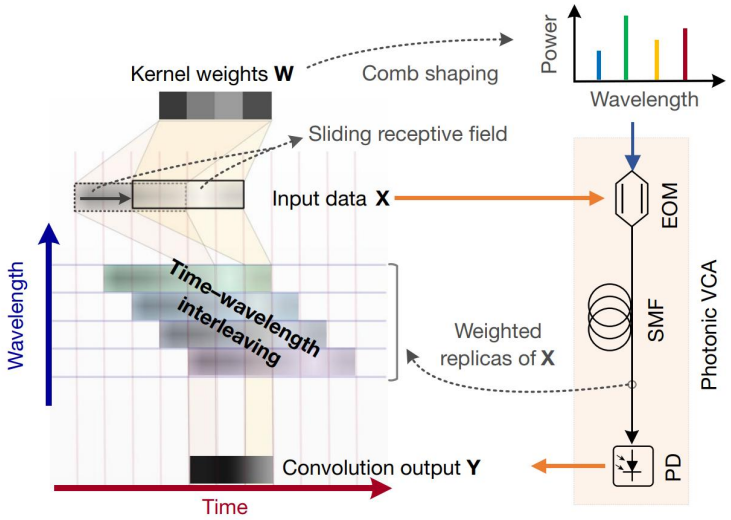
Source:https://marineimagingtech.com/, https://pointspread.cn

Applications of Computational Imaging



Terahertz Imaging with Metasurface

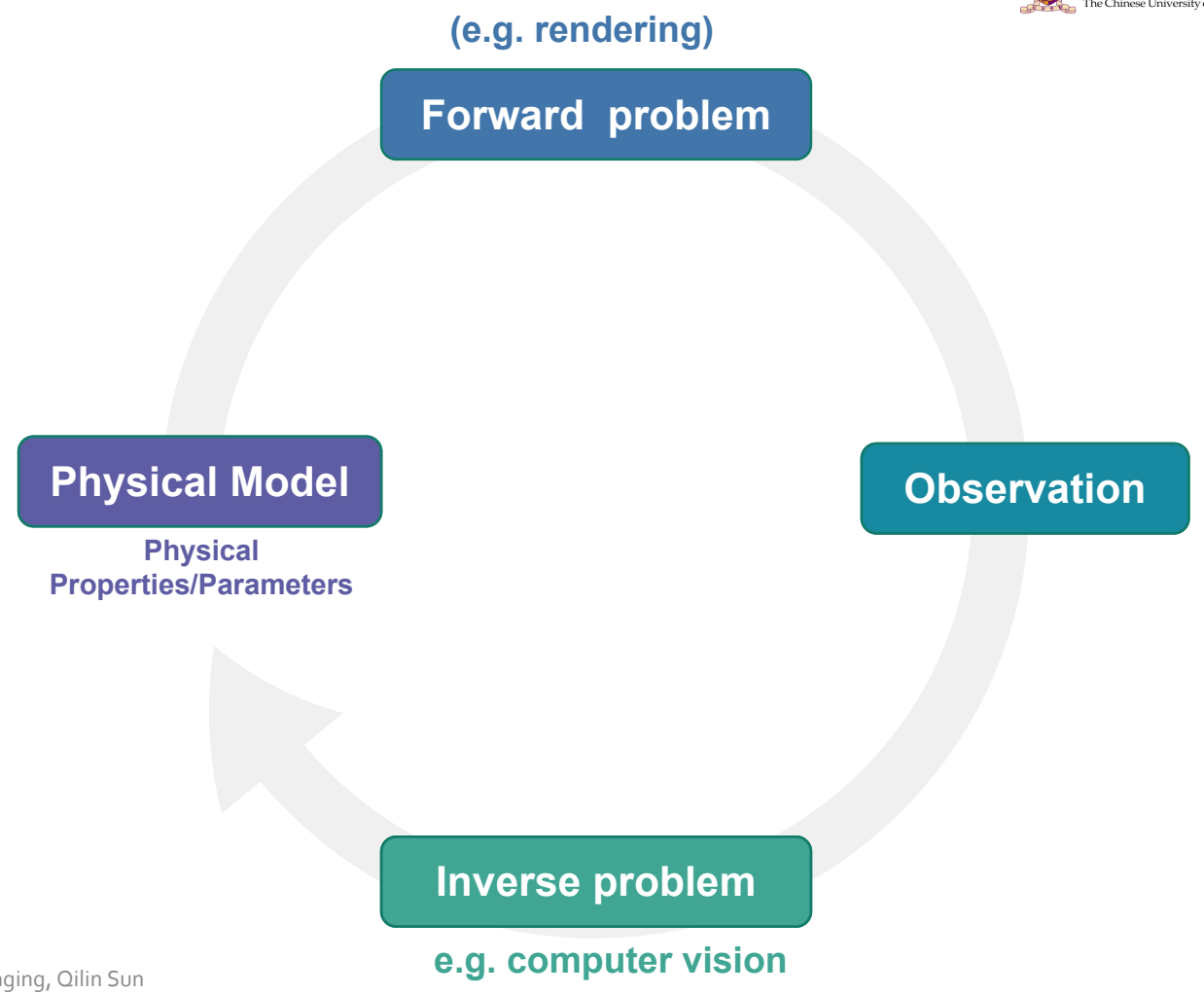
By Songlin Zhuang, Yiming Zhu



11 TOPS Optical CNN

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

Computational Methodology


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

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

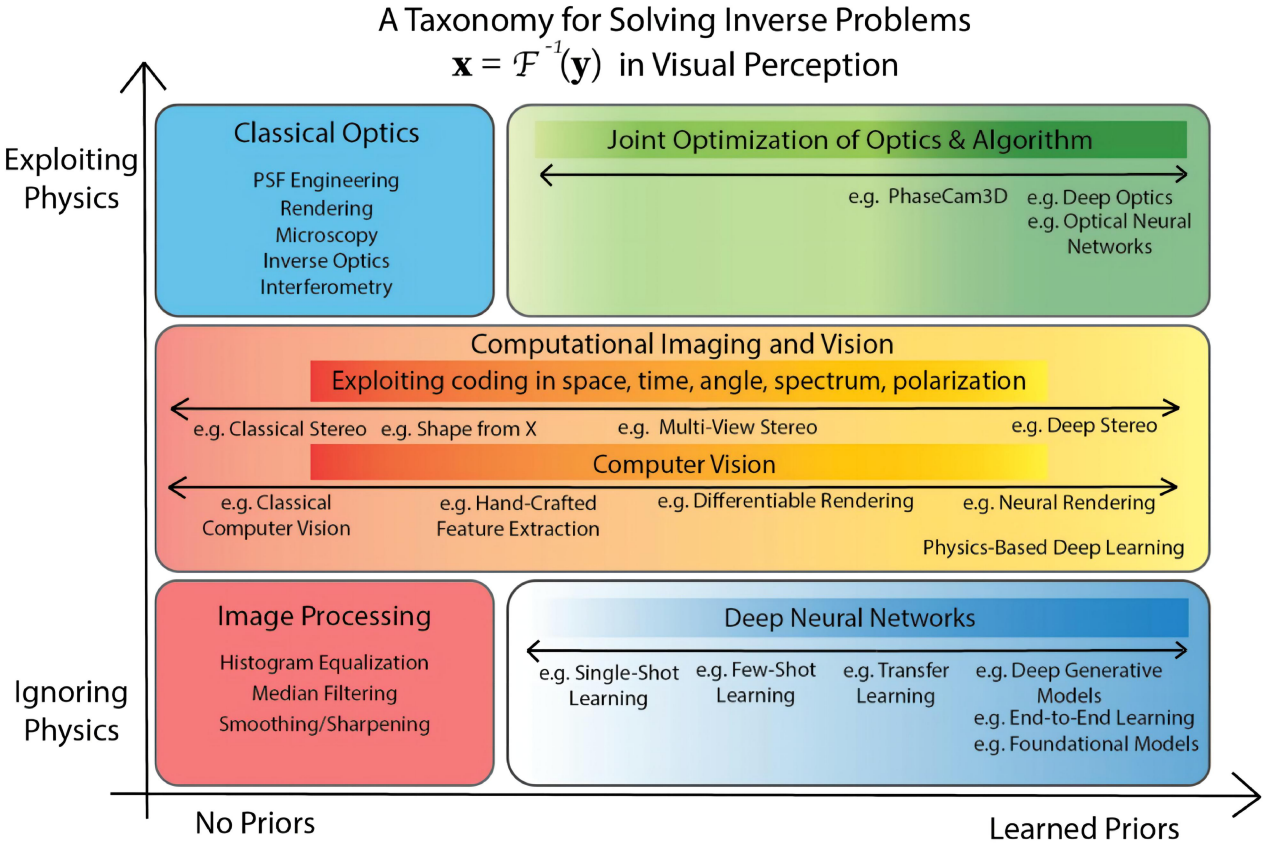
Generic bases (Wavelets, Fourier)

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
- Γ 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

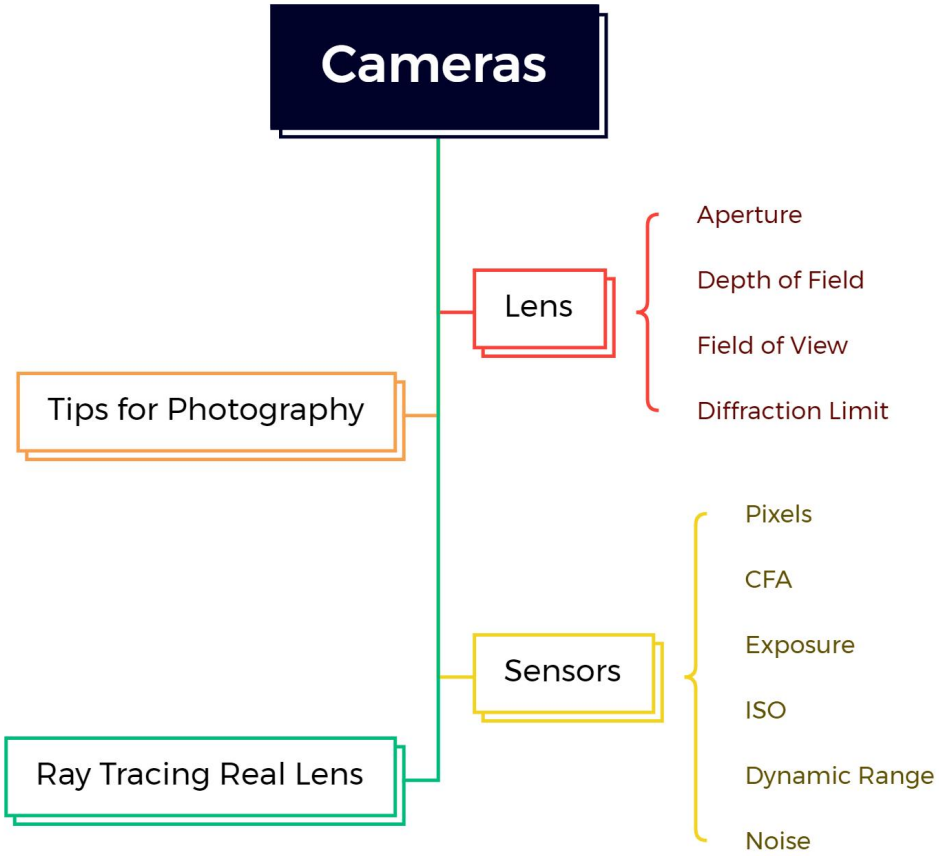
Human Visual System

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

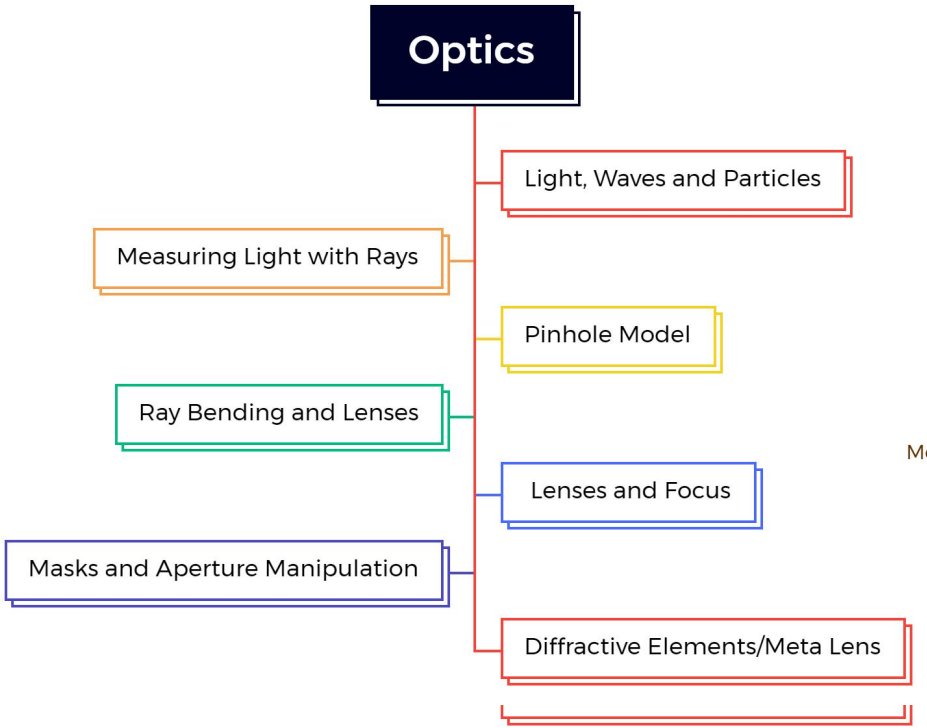
Color and Display

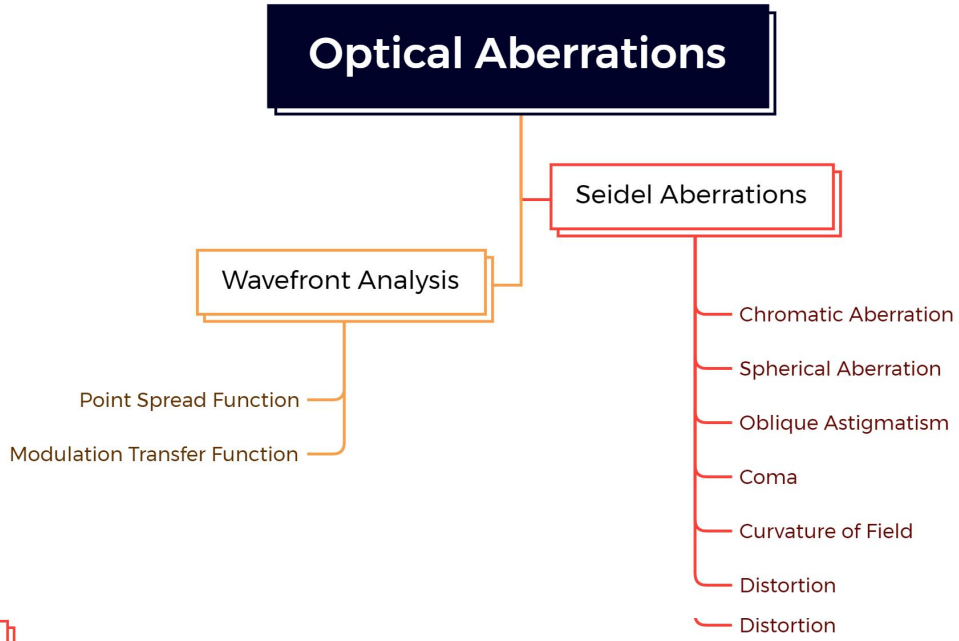
- Spectrum Power Distribution
- Biological Basis of Color
  - Human Eye
  - Photosensor Response
  - Cone Cell Response (L, M, S)
- CFA Array Response
- Metamerism
  - Primary Light
  - Color Matching
- Displays Reproducing Color
- Color Reproduction
  - Matching Fuctions
  - Linear Algebra
  - Pseudo-Geometric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

Cameras

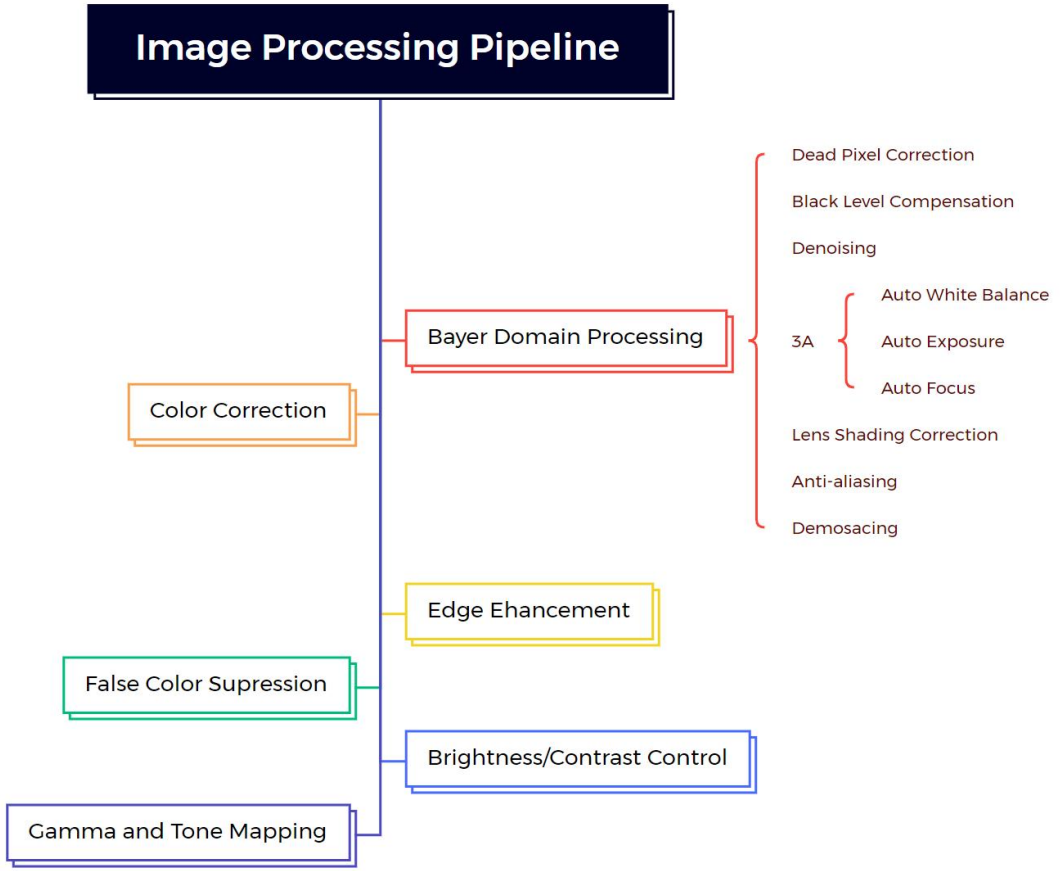

Cameras
Lens
Aperture
Depth of Field
Field of View
Diffraction Limit
Tips for Photography
Sensors
Pixels
CFA
Exposure
ISO
Dynamic Range
Noise
Ray Tracing Real Lens

Imaging Toolkit: Optics

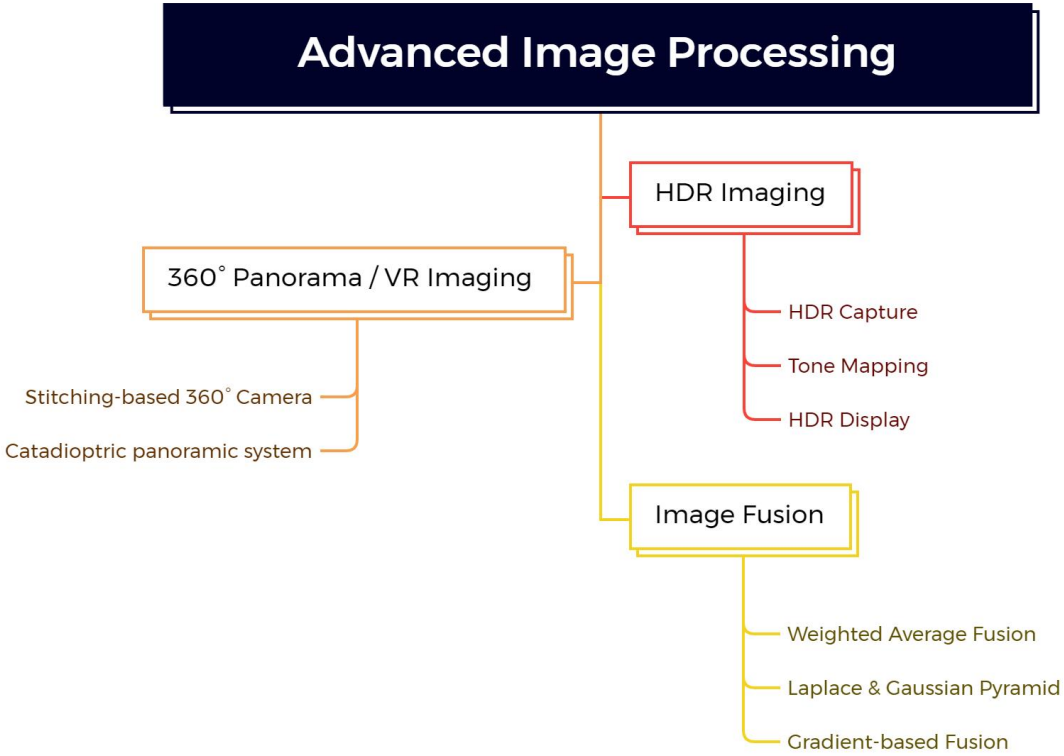




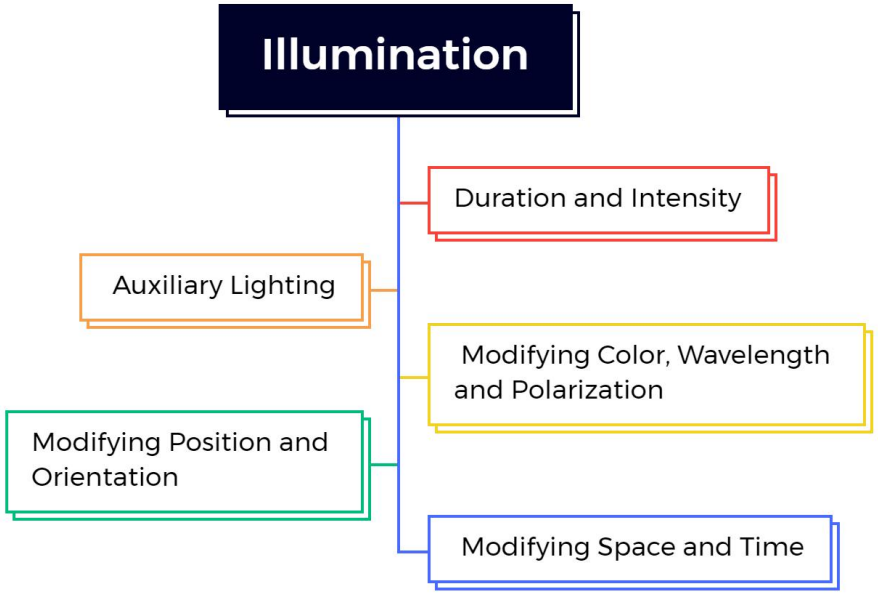
Imaging Toolkit: Image Processing Pipeline



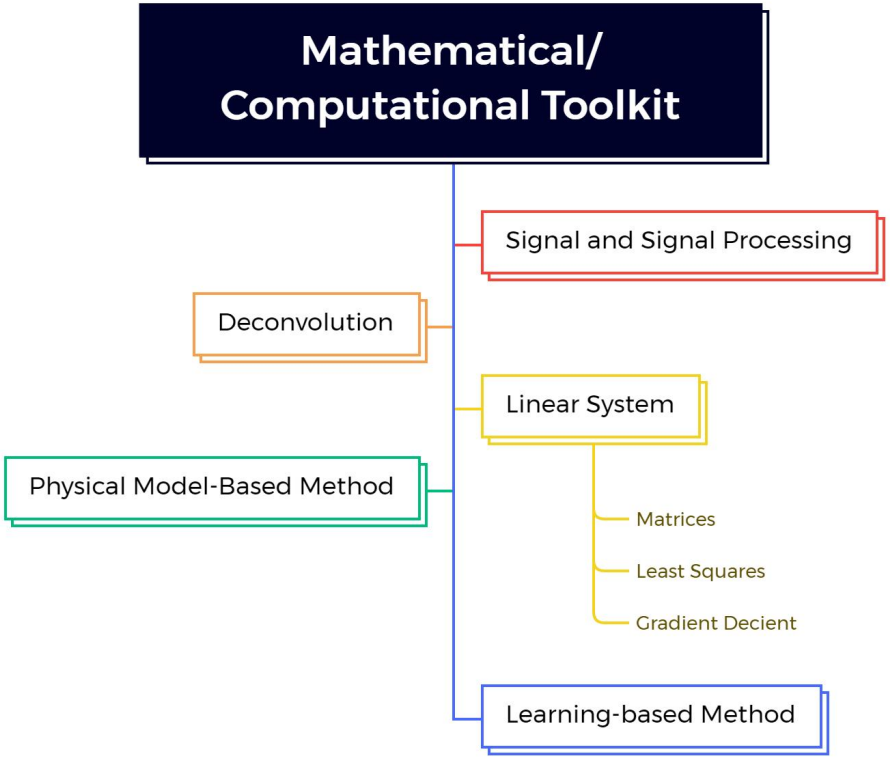
Imaging Toolkit: Advanced Processing Pipeline



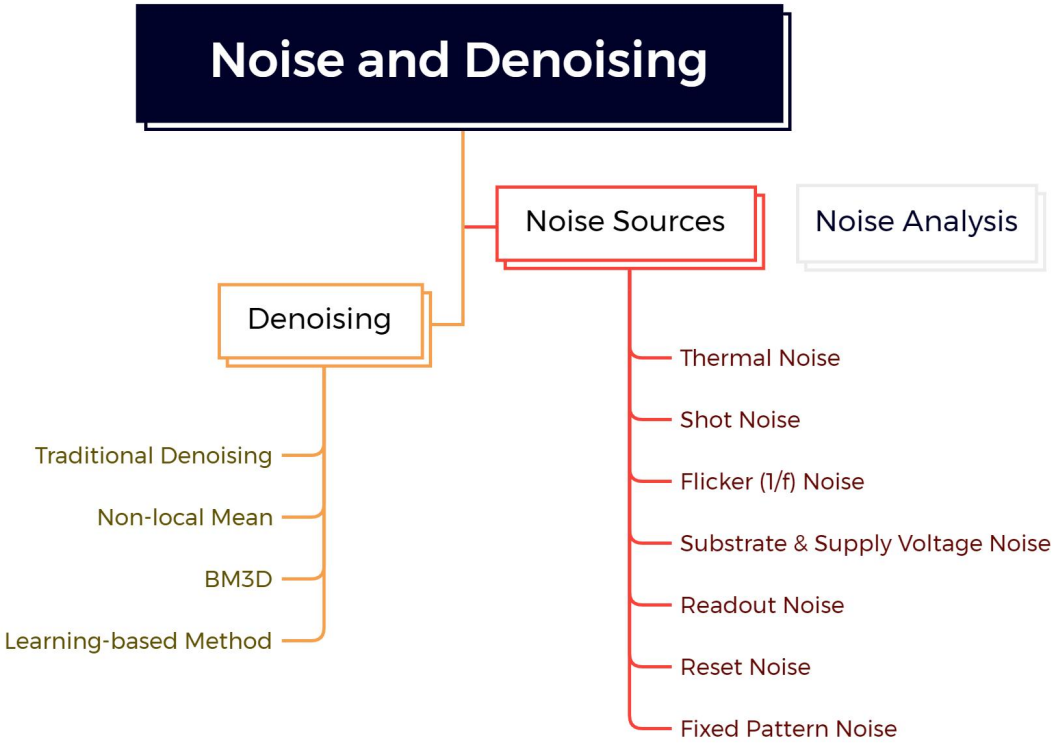
Imaging Toolkit: Illumination



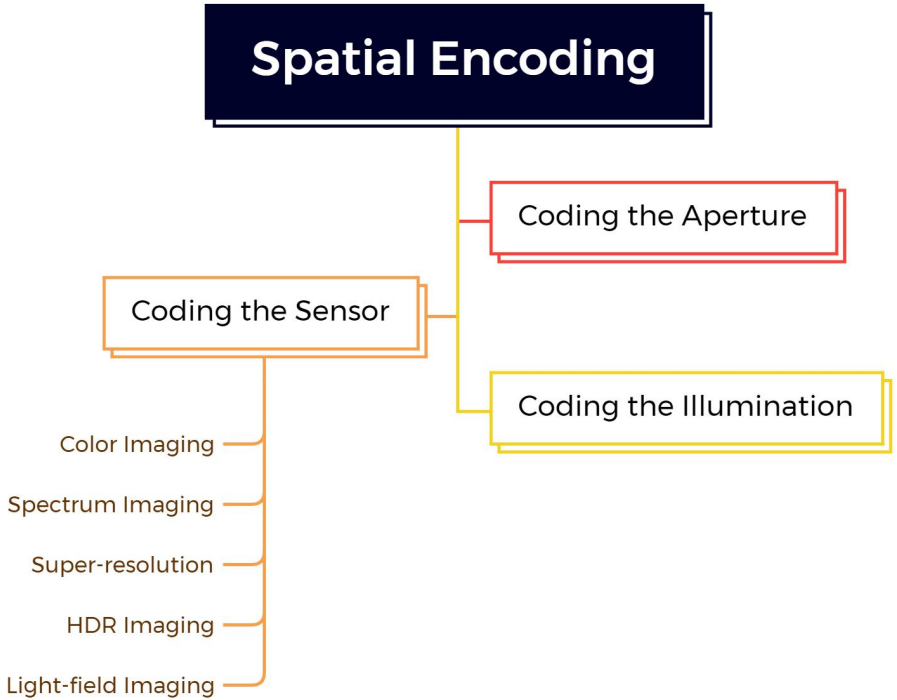
Mathematical/Computational Toolkit



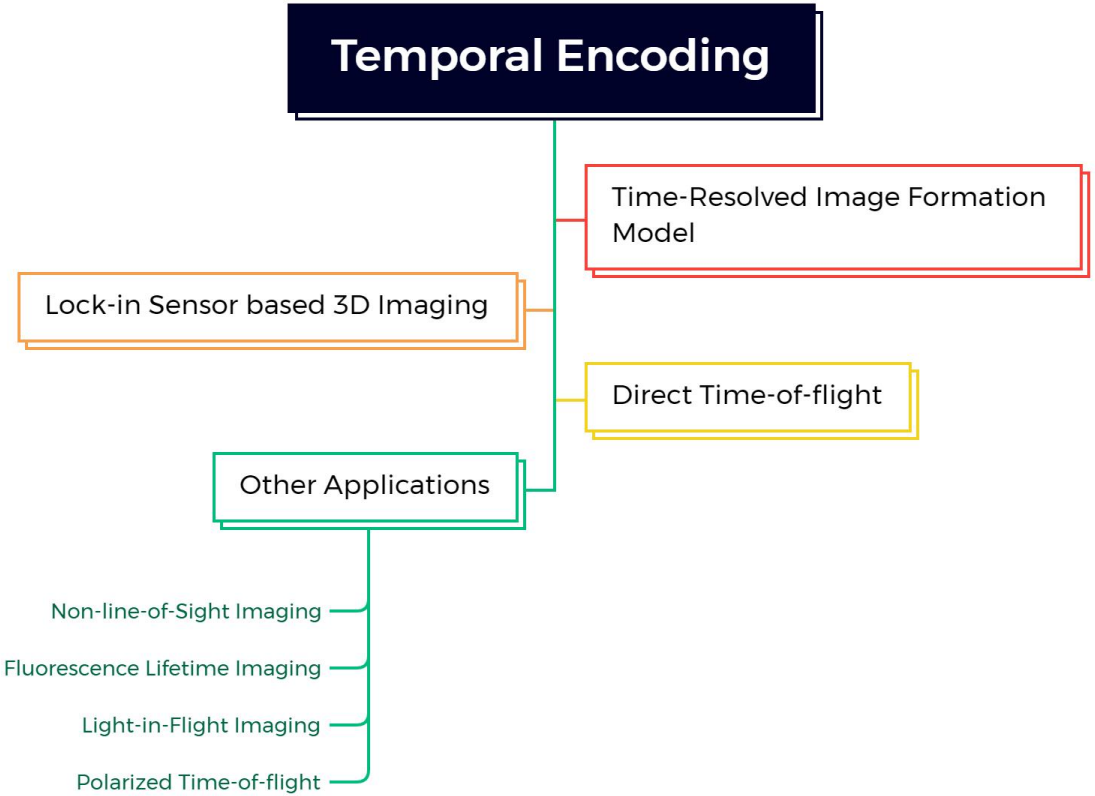
Noise


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

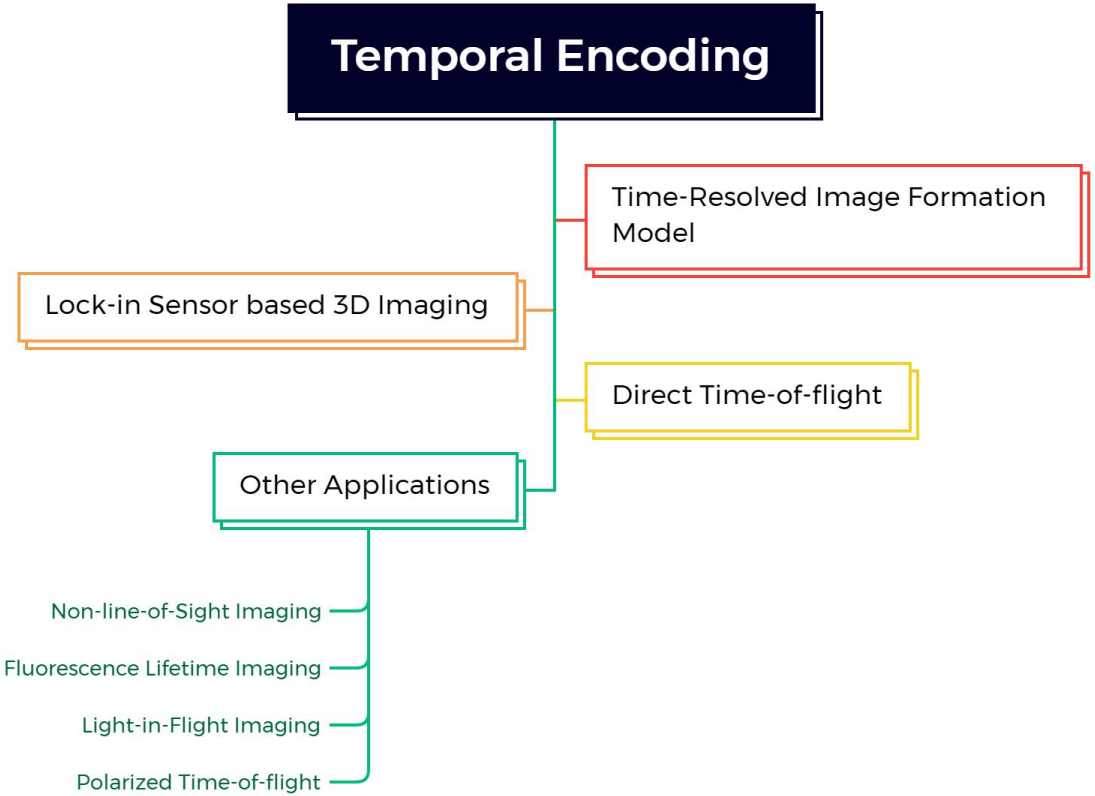
Spatial Encoding



Temporal Encoding



Temporal Encoding



Advanced Topics and Applications

Light-field Imaging

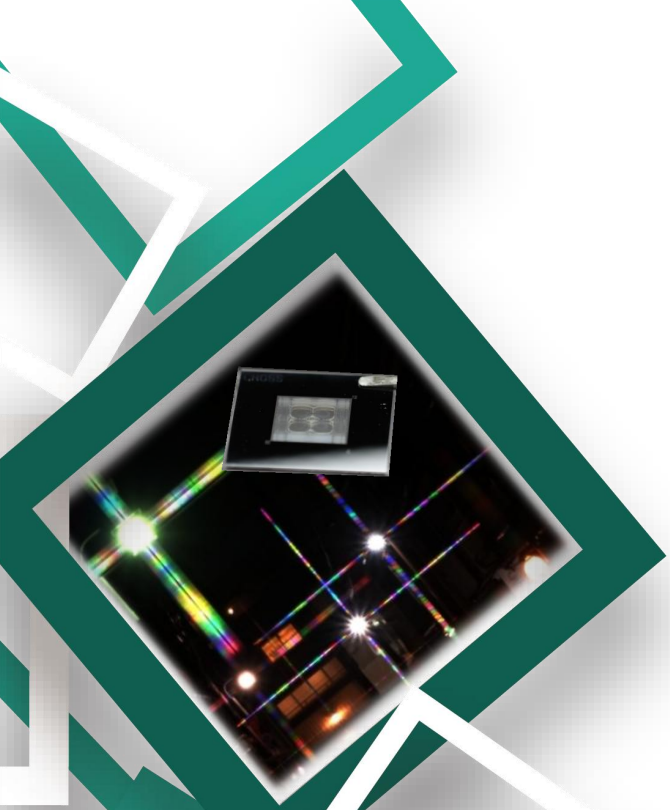
Spectrum Imaging

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



GAMES 204

Thank You!

Qilin Sun（孙启霖）

香港中文大学（深圳）

点昀技术（Point Spread Technology）