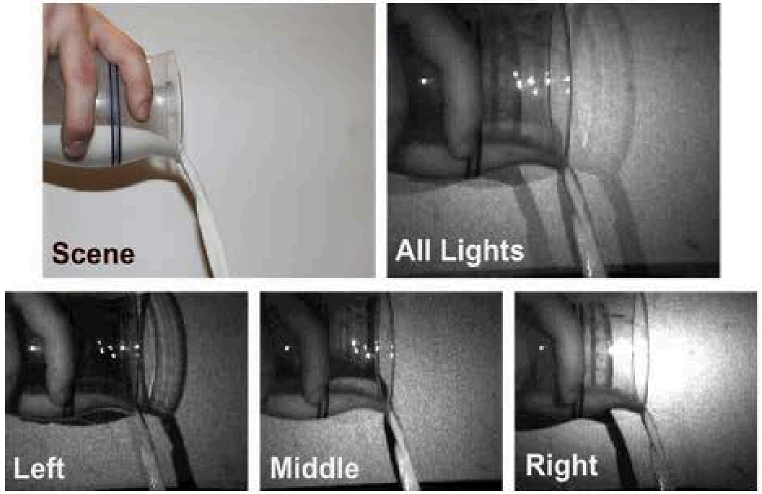
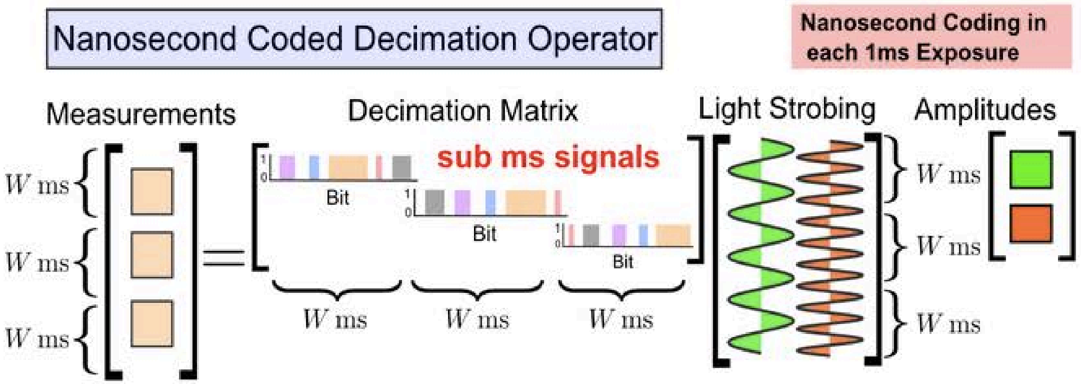
Demultiplexing Illumination via Low Cost Sensing and Nanosecond Coding





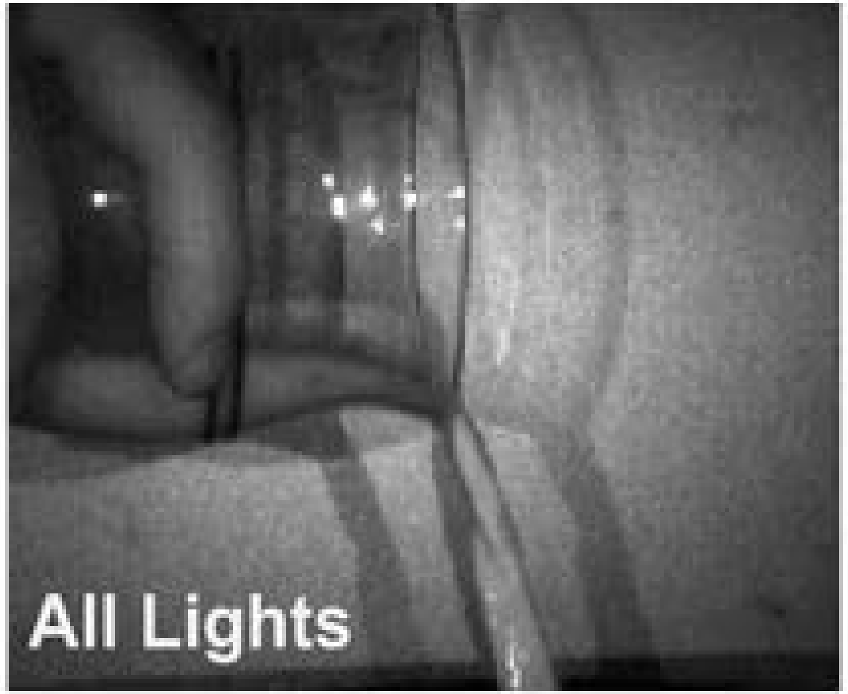
Forward Model for Illumination Multiplexing in Time of Flight Cameras

Achuta Kadambi (MIT) Ayush Bhandari (MIT) Refael Whyte (Waikato)
Adrian Dorrington (Waikato) Ramesh Raskar (MIT)

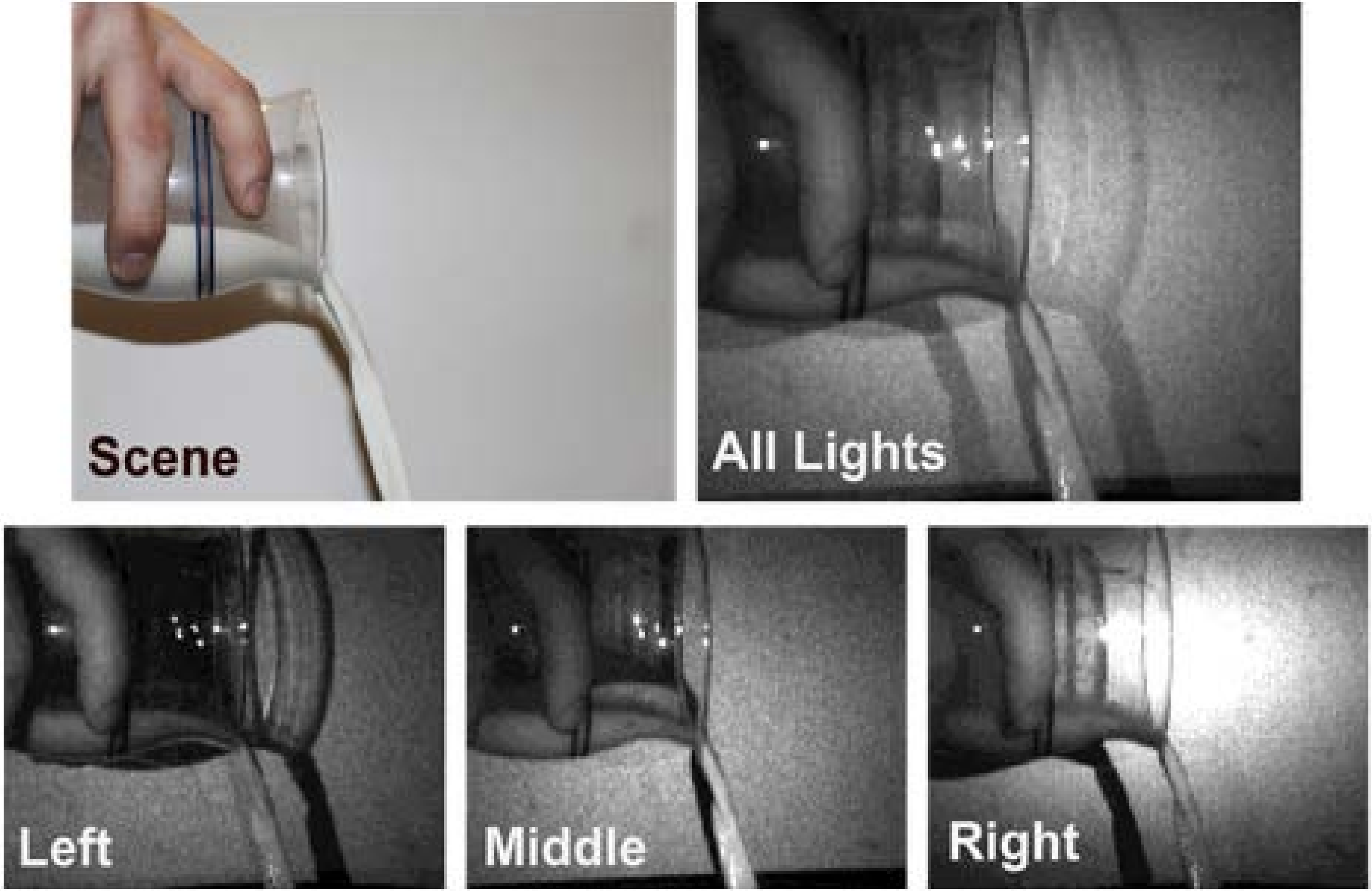
http://media.mit.edu/~achoo/demux
Presented at ICCP 2014 in Santa Clara

Problem Statement

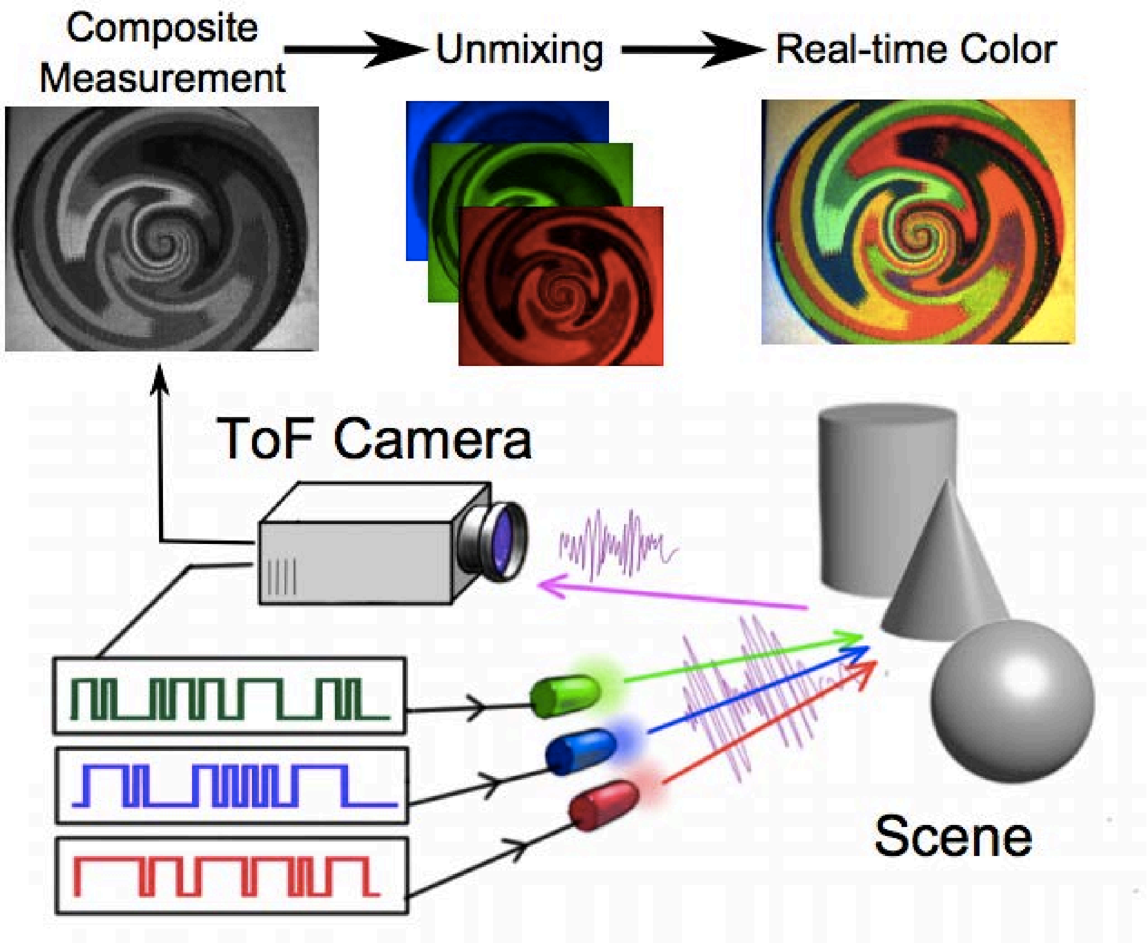

Scene



Amplitude Image from a 3D ToF camera


Scene
All Lights
Left
Middle
Right

Application: Color Time of Flight



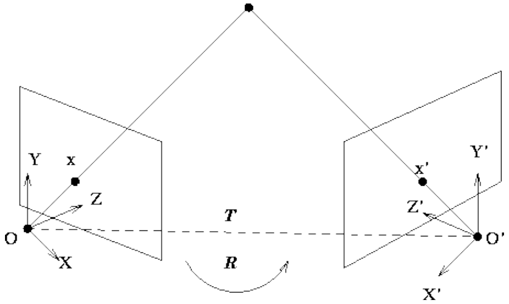
3D Time of Flight Cameras

(Background)

3D Cameras

Stereo Cameras

Leap Motion (2013)

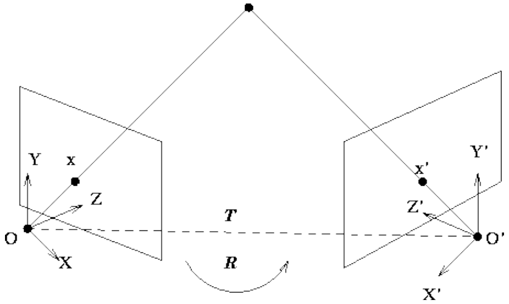


Parallax and Correspondence Matching: Sensitive to object texture, occlusions, translucency.

Real-time 3D Devices

Stereo Cameras

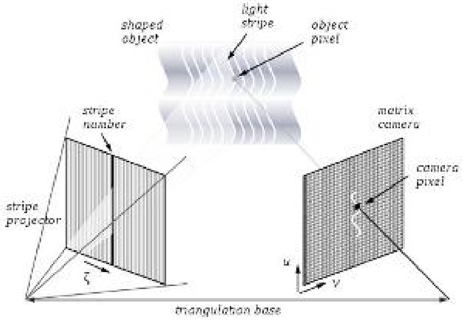
Leap Motion (2013)



Parallax and Correspondence Matching: Sensitive to object texture, occlusions, translucency.

Structured Light Cam

Kinect 360 (2009)

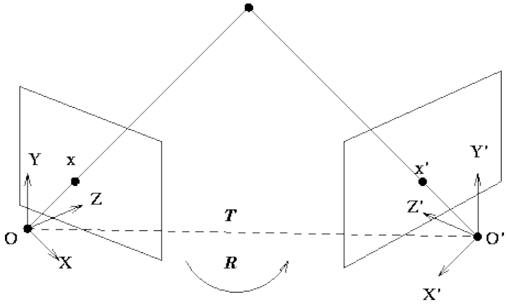


Correspondence Matching but projects active pattern, so texture not an issue.

Real-time 3D Devices

Stereo Cameras

Leap Motion (2013)



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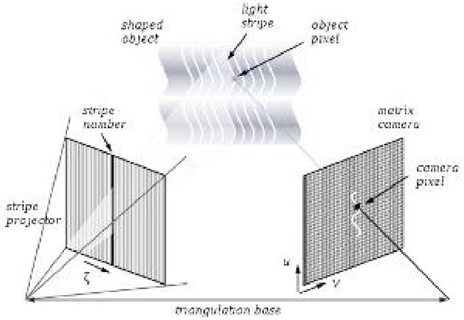
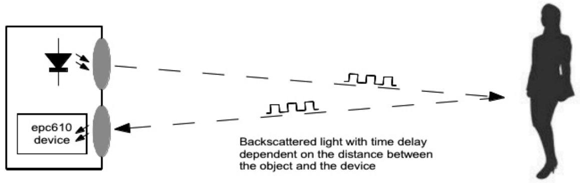


Correspondence Matching but projects active pattern, so texture not an issue.

Time of Flight Cameras

Kinect One (2013)

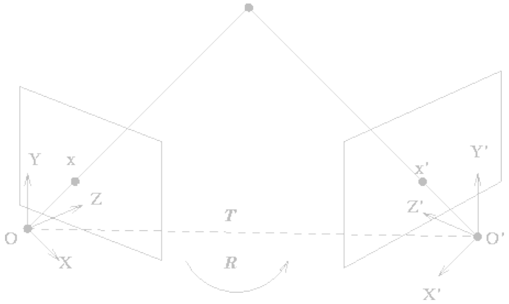


Relies on Optoelectronic delays and does not require parallax.

Real-time 3D Devices

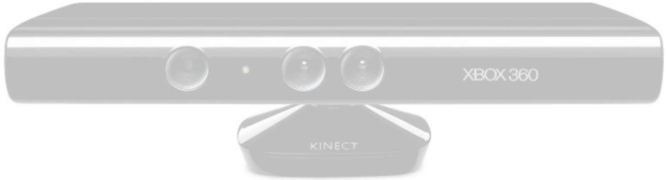
Stereo Cameras

Leap Motion (2013)

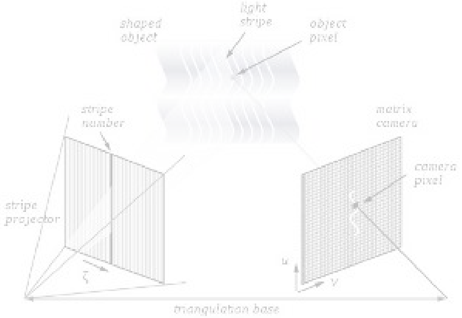


Parallax and Correspondence Matching: Sensitive to object texture, occlusions, translucency.

Structured Light Cam



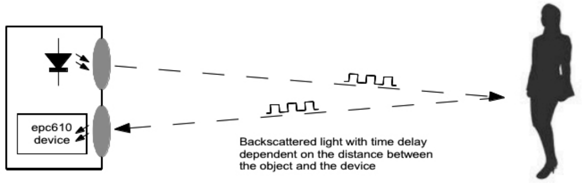
Kinect 360 (2009)



Correspondence Matching but projects active pattern, so texture not an issue.

Time of Flight Cameras

Kinect One (2013)



Relies on Optoelectronic delays and does not require parallax.

Time of Flight

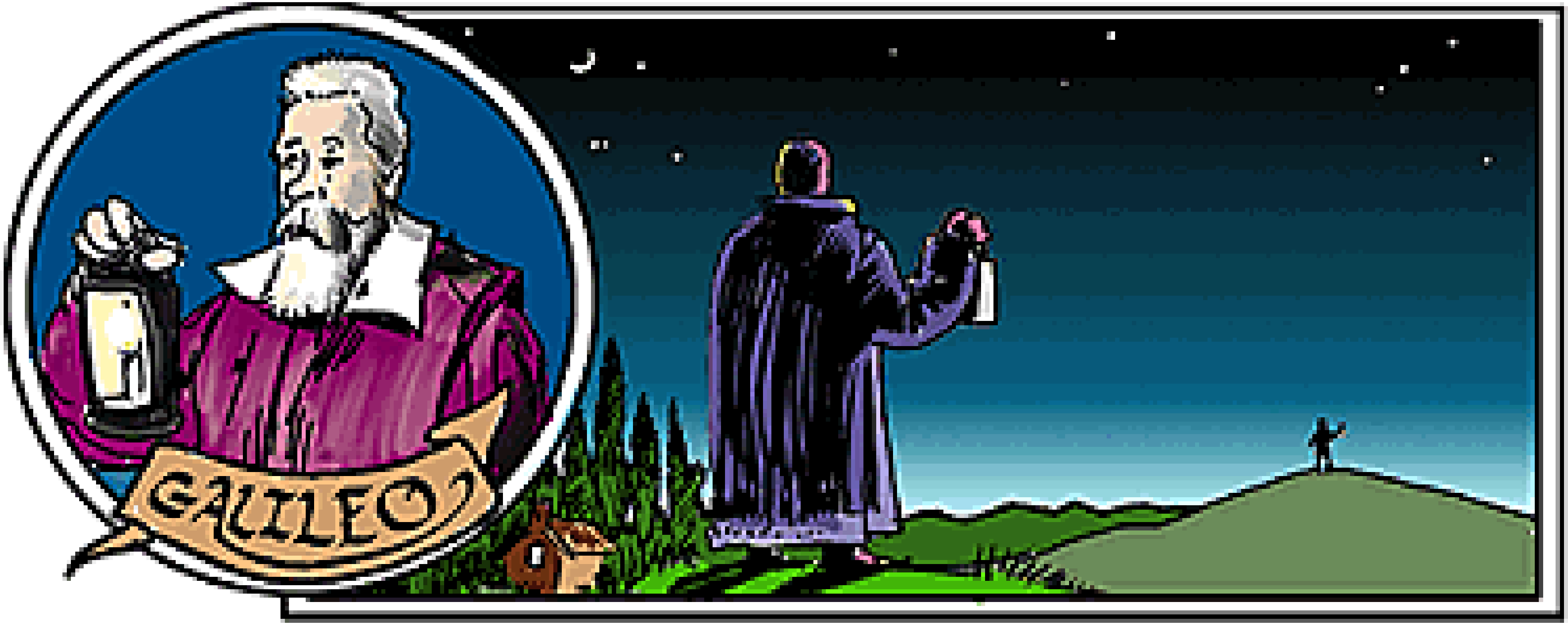
Time it takes for an object, particle, or wave to travel a distance through a medium.

LIDAR

Police Speed Gun

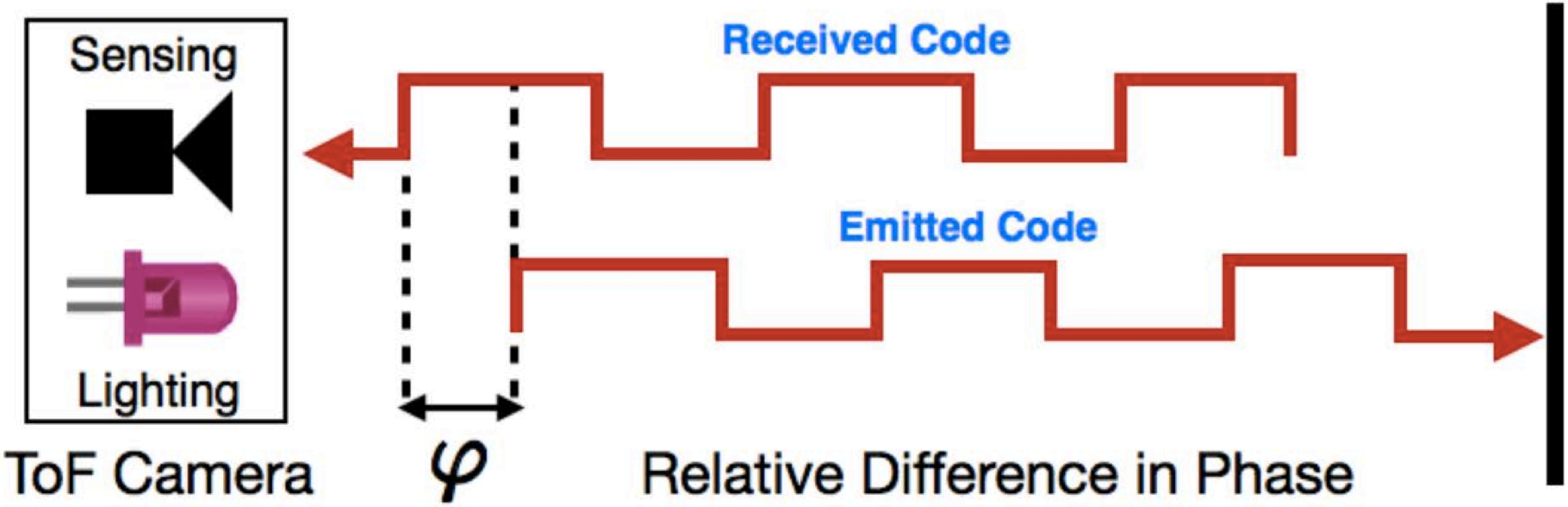
Microsoft Kinect

1638: First Time of Flight Camera?

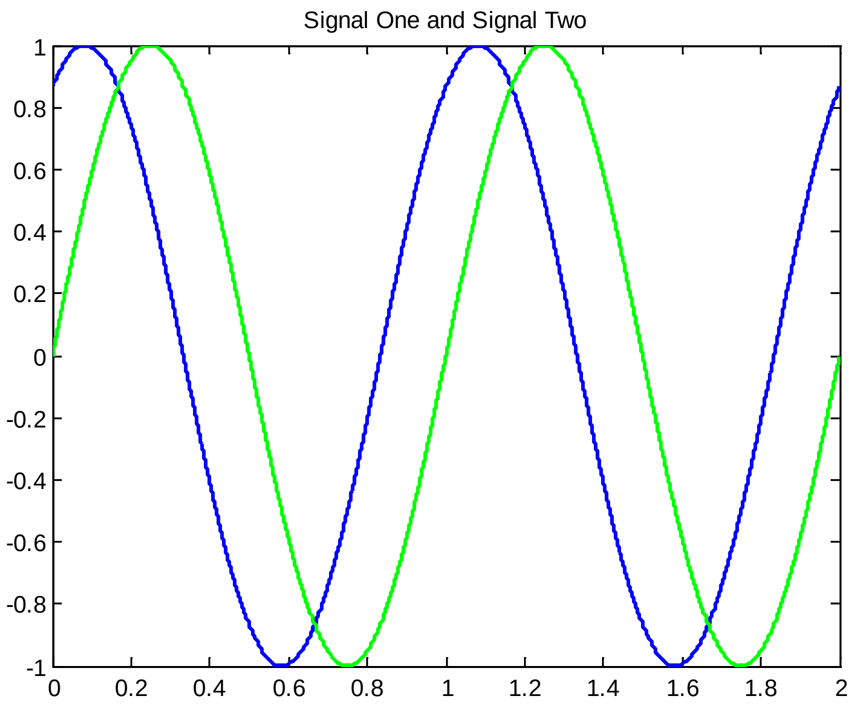


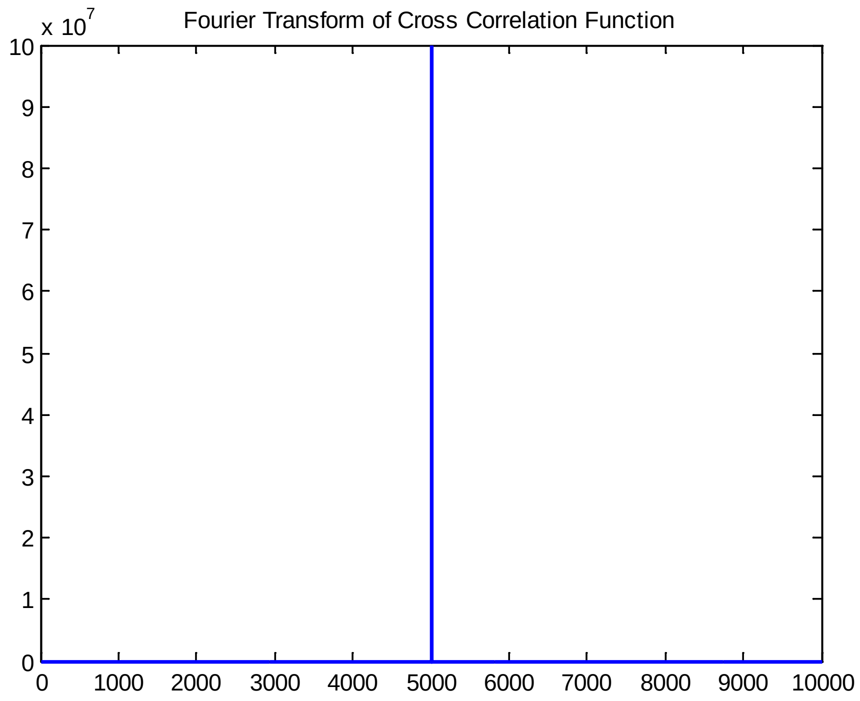
Graphic courtesy: phys.colorado.edu

2000: Time of Flight 3D Cameras



Review: Fourier Transform of Xcorr Encodes Phase

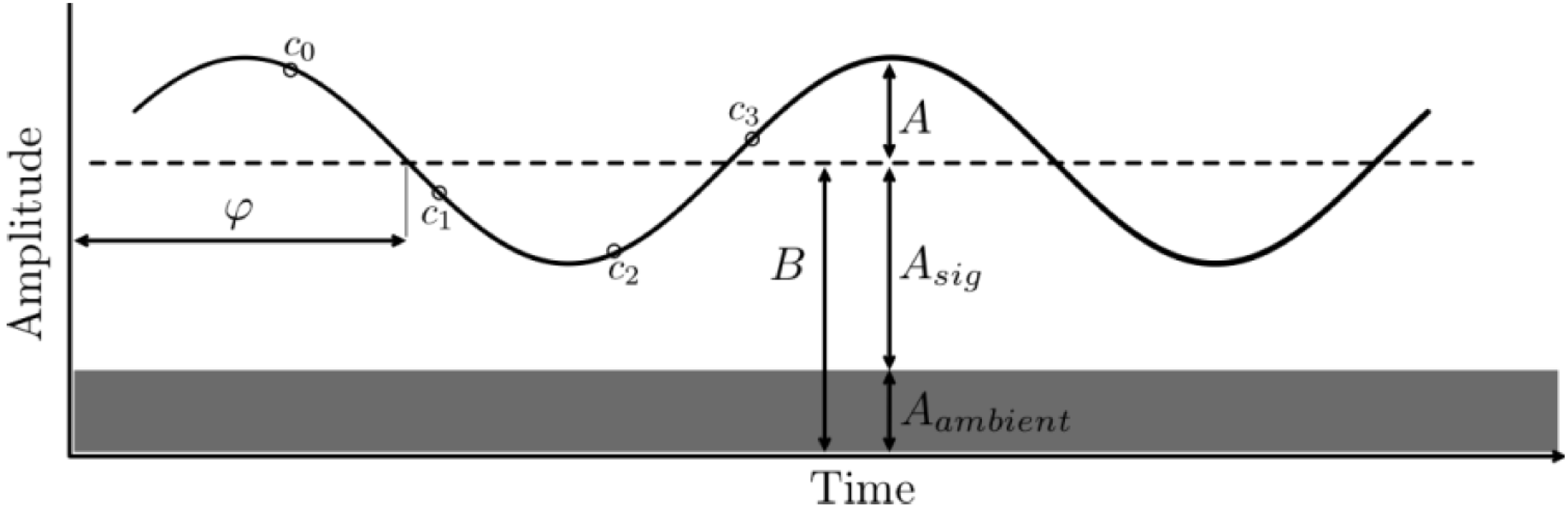





```
dt = 0.0001;
N = 20000;
t = 0:dt:(N-1)*dt;

phi1 = pi/3; phi2 = 0;
s1 = sin(2*pi*1*t + phi1);
s2 = sin(2*pi*1*t+ phi2);

xcFFT = conj( fft(s1) ) .*
fft(s2);

[~, fundamental_idx] =
max(xcFFT);

phase_difference = angle(
xcFFT(fundamental_idx) );
```

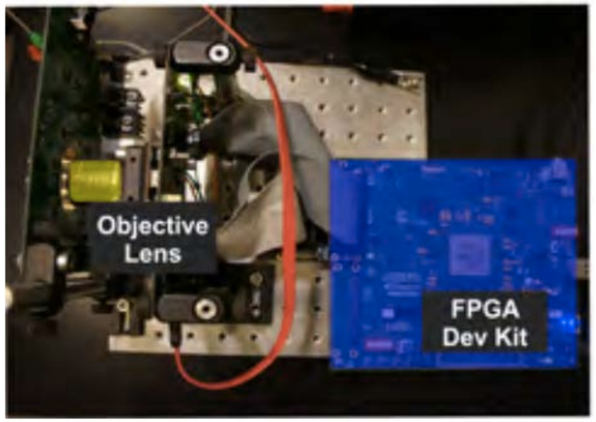
Key point: Conventional ToF sensors directly measure the cross-correlation function on the sensor level.

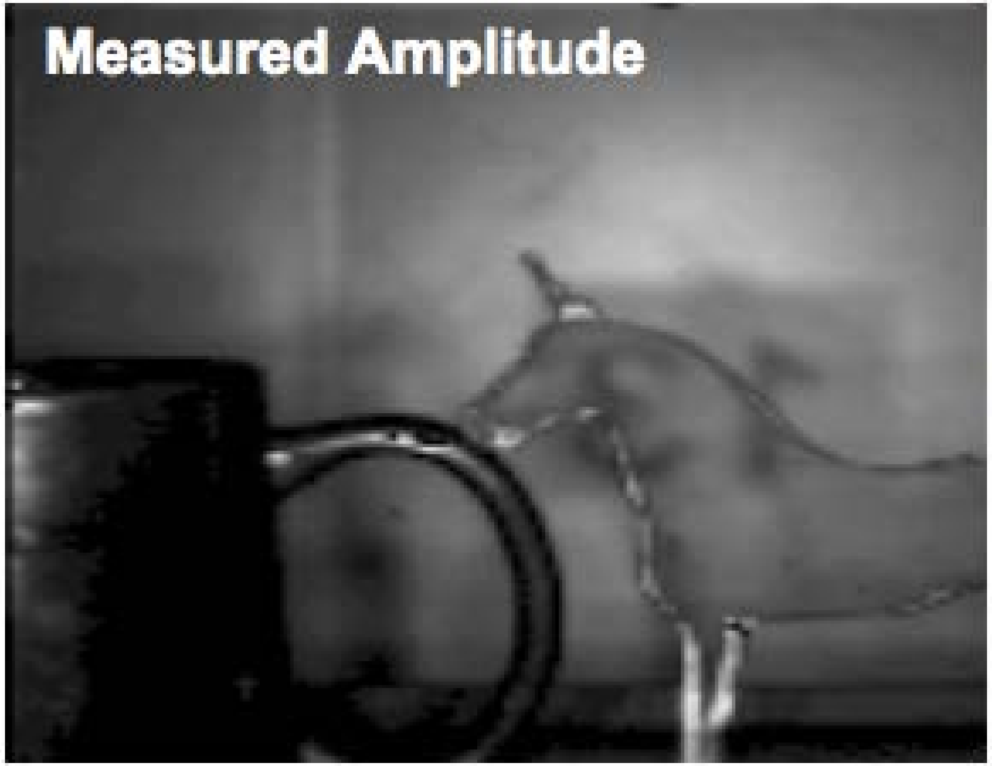
Output: Phase and Amplitude



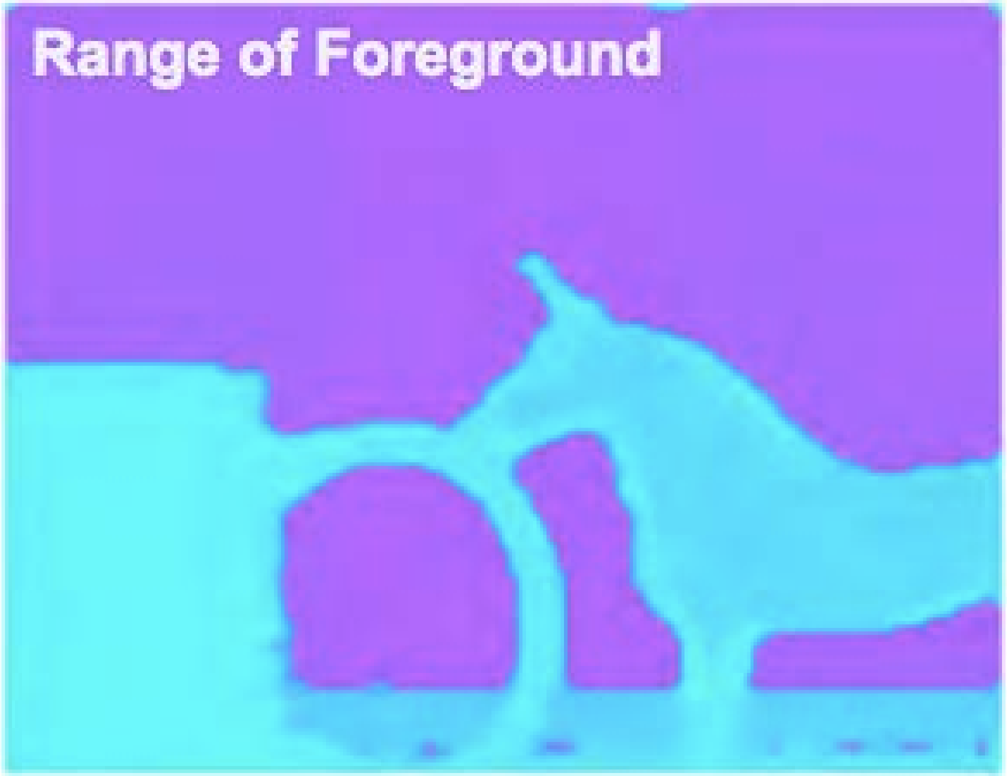
Depth and Monochrome Data from the Xcorr Function

Output: Phase and Amplitude





Reflection/Albedo (monochrome)



Phase/Range/Depth

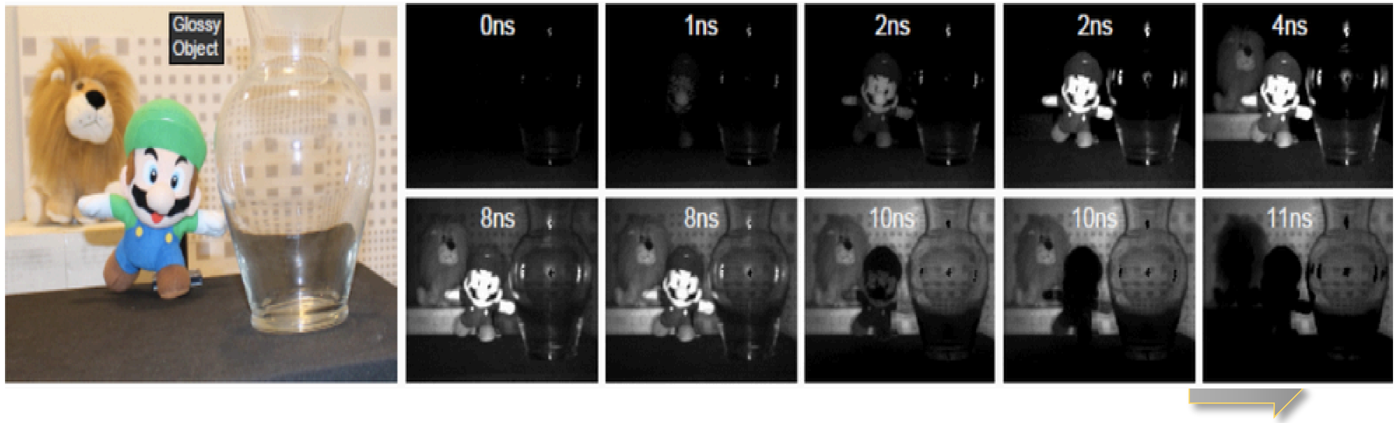
Nanophotography (Coded ToF)

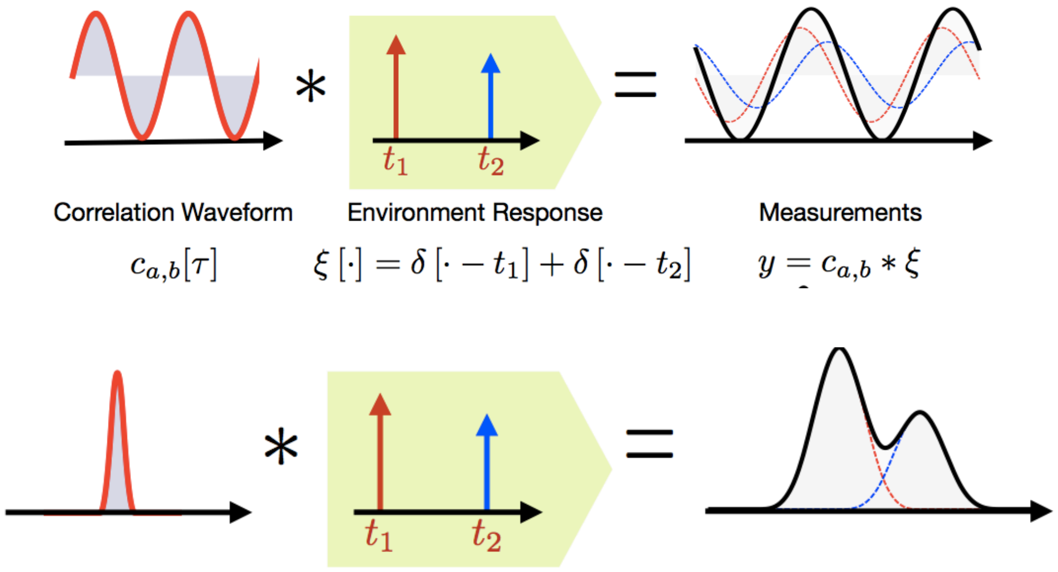
Coded Time of Flight Cameras: Sparse Deconvolution to Address Multipath Interference and Recover Time Profiles

Achuta Kadambi[1] Refael Whyte[1, 2] Ayush Bhandari[1] Lee Streeter[2]
Christopher Barsi[1] Adrian Dorrington[2] Ramesh Raskar[1]

[1]Massachusetts Institute of Technology [2]University of Waikato

ACM Transactions on Graphics 2013 (SIGGRAPH Asia)

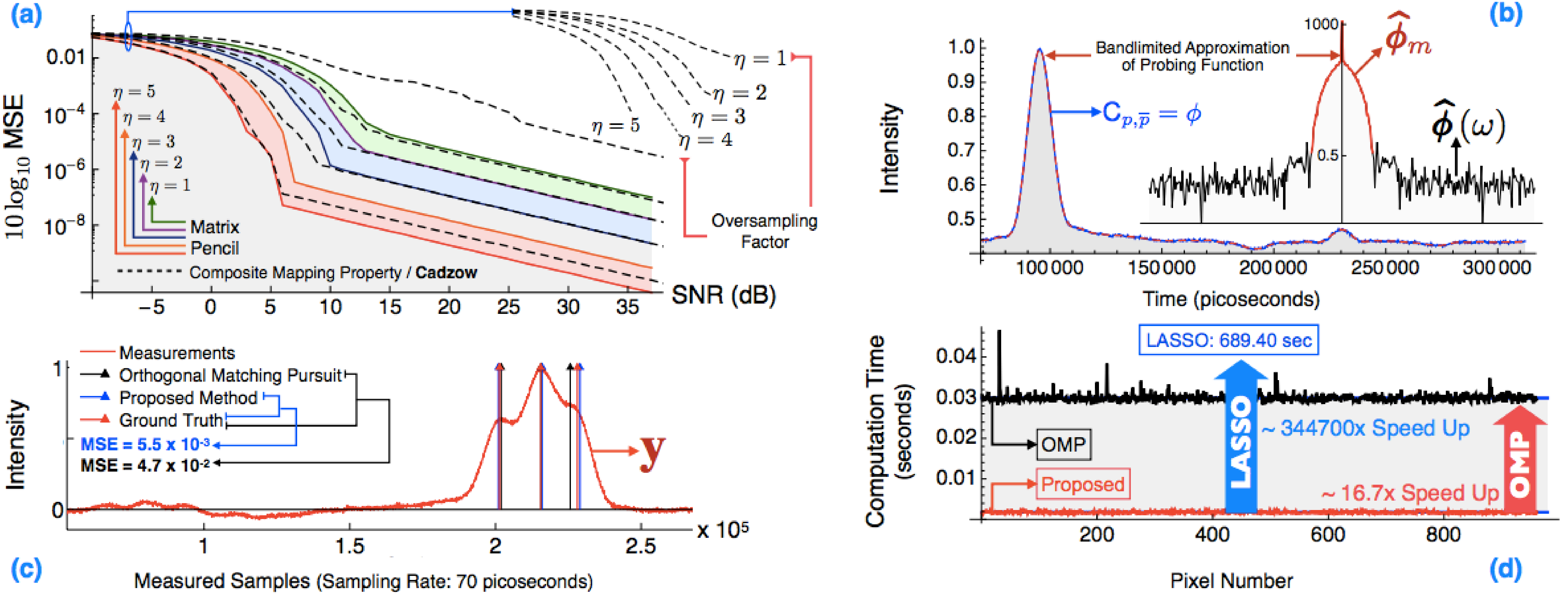




A Kadambi et al. ACM Trans. On Graphics

Cf. also work from Wolfgang Heidrich grp

Sparsity without Sparse Regularization?



A Bhandari, A Kadambi, R Raskar, ICASSP 2014

Previous: Color Time of Flight

Muttayane A, University of Waikato 2006

Not real-time. Sequential Capture

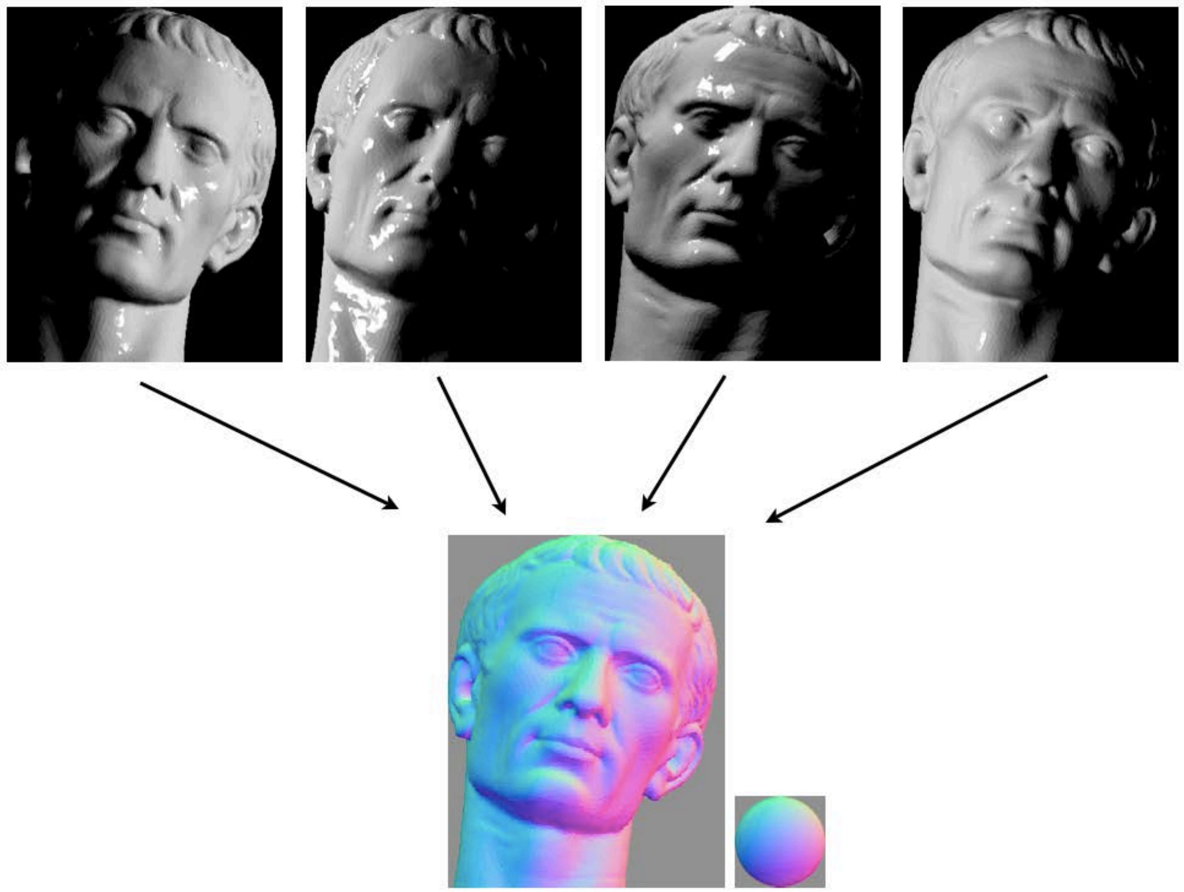
Illumination and Multiplexing

(Background)

Illumination and Photography

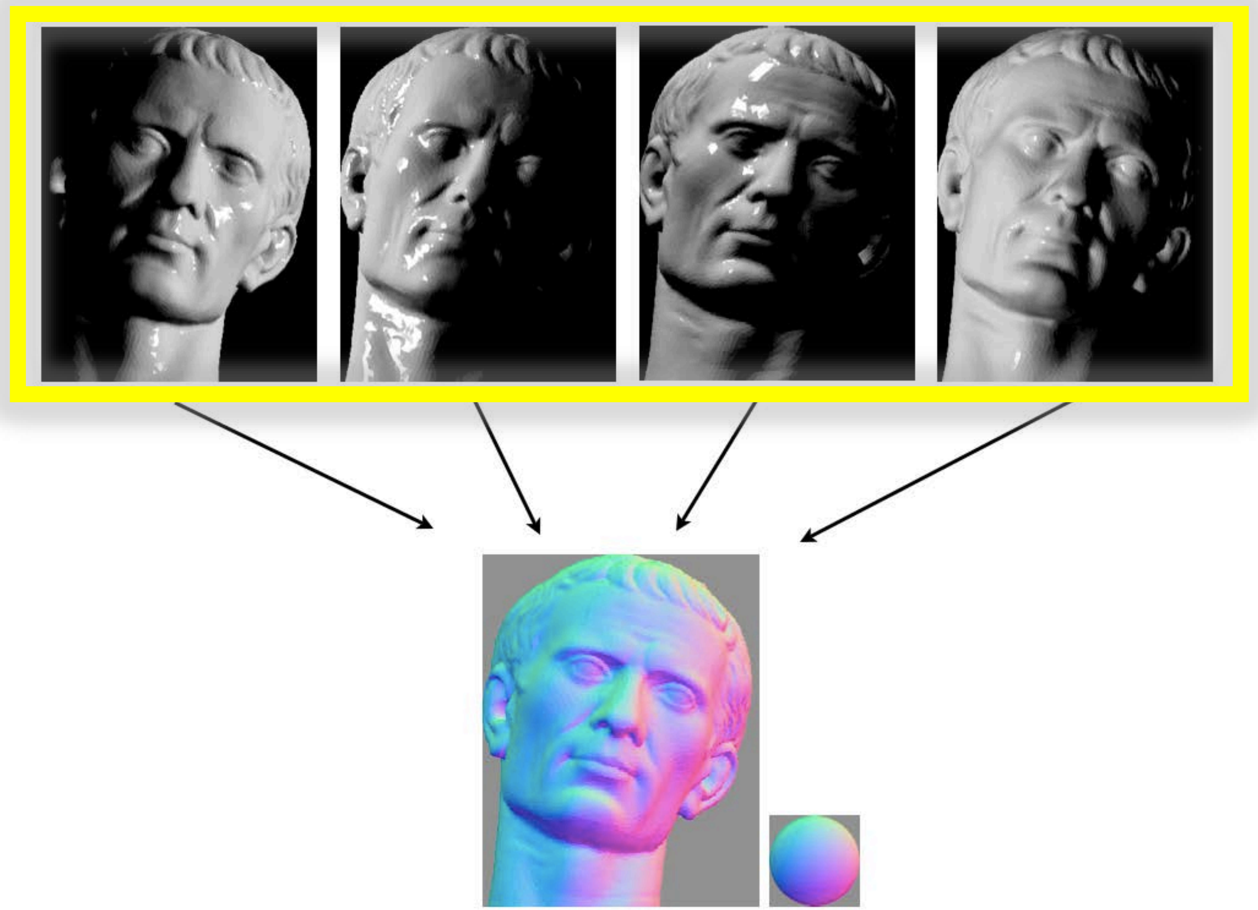
Ken Rockwell

Computational Lighting



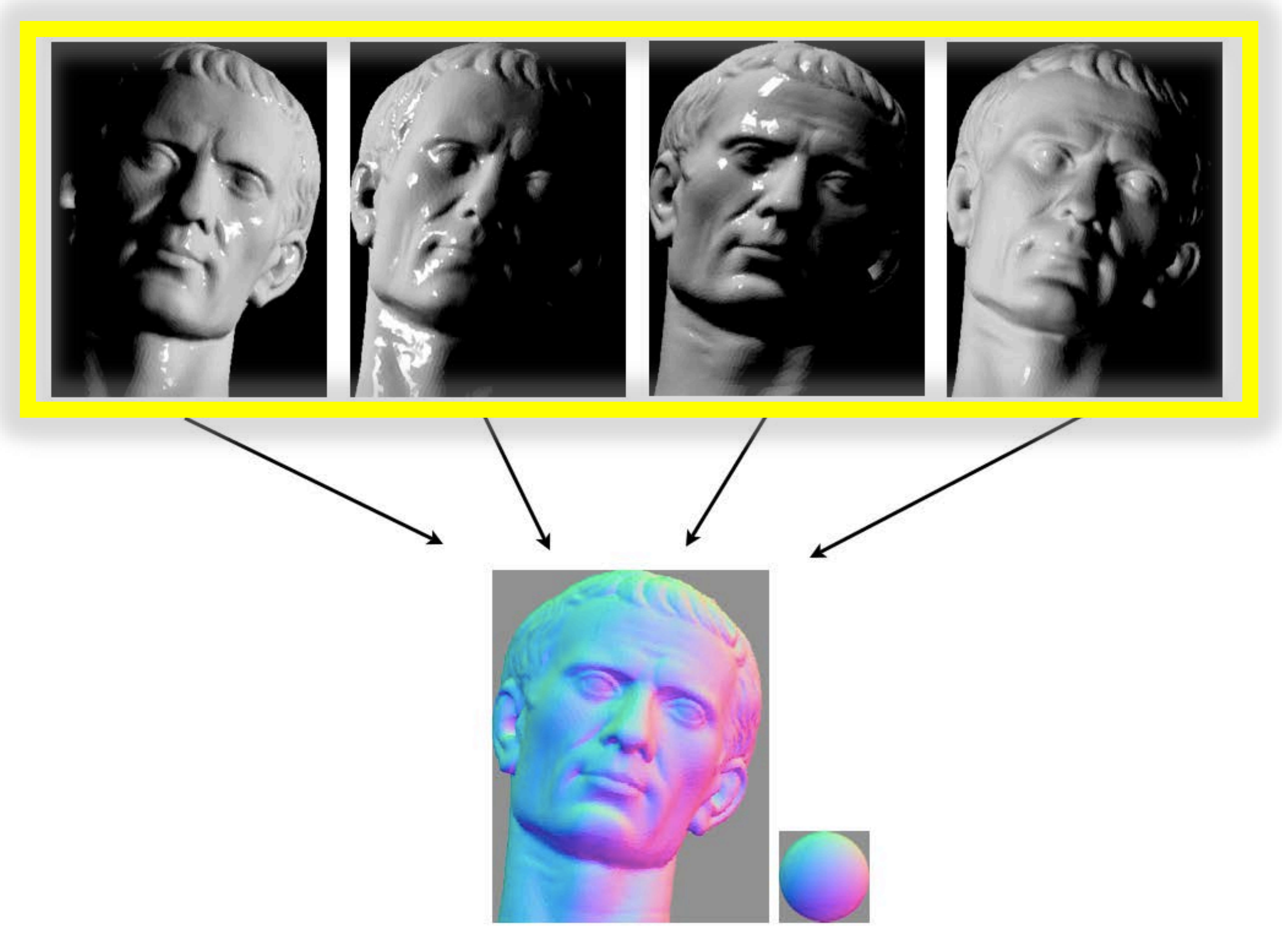
Photometric Stereo

Computational Lighting



Photometric Stereo

Computational Lighting



Photometric Stereo

Apple

Wu et al. PAMI 2011

Illumination Capture

Studio Lighting
No Relighting Not Dynamic

Increasing Computation

Illumination Capture

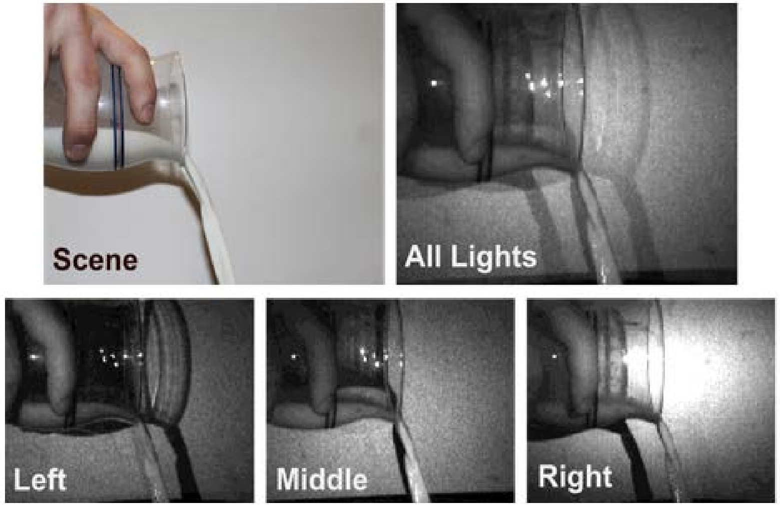
Studio Lighting
No Relighting Not Dynamic

Light Stage (Siggraph '04)
Dynamic Requires Fast Camera No Depth Information

Increasing Computation

Illumination Capture

Studio Lighting	Light Stage (Siggraph '04)	Time of Flight 3D Multiplexing
No Relighting Not Dynamic	Dynamic Requires Fast Camera No Depth Information	Dynamic Repurposes Depth Sensor 3D Scene Information



Increasing Computation

Illumination Multiplexing

Cast as a Linear Inverse Problem

$$y = Hx + \eta$$

A Theory of Multiplexed Illumination

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Dept. Electrical Engineering
Technion - Israel Inst. Technology
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yoav@ee.technion.ac.il

Shree K. Nayar and Peter N. Belhumeur
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Columbia University
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Multiplexed Fluorescence Unmixing

Marina Alterman , Yoav Y. Schechner
Department of Electrical Engineering
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Aryeh Weiss
School of Engineering
Bar-Ilan University,
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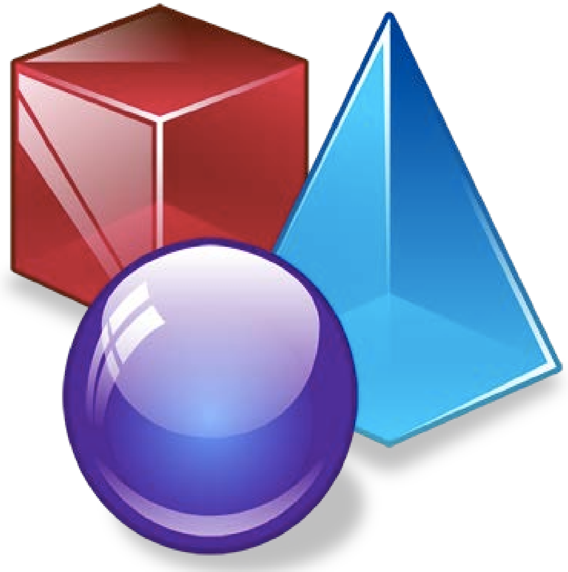
Illumination Multiplexing within Fundamental Limits

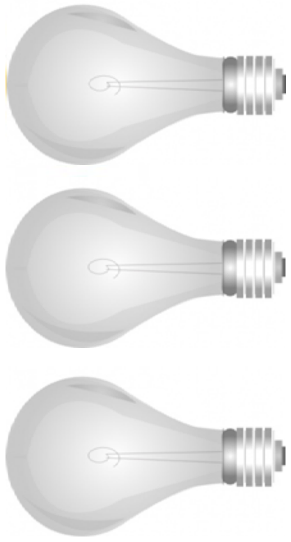
Netanel Ratner Yoav Y. Schechner
Department of Electrical Engineering
Technion - Israel Institute of Technology
Haifa 32000, ISRAEL
ratner@tx.technion.ac.il yoav@ee.technion.ac.il

2003 2007 2011

Sequential Multiplexing

At a single pixel!





$$\begin{bmatrix} I^{(1)}(x,y) \\ I^{(2)}(x,y) \\ I^{(3)}(x,y) \end{bmatrix} = \begin{bmatrix} ? & ? & ? \\ ? & ? & ? \\ ? & ? & ? \end{bmatrix} \begin{bmatrix} \alpha^{(1)} \\ \alpha^{(2)} \\ \alpha^{y} \end{bmatrix}$$

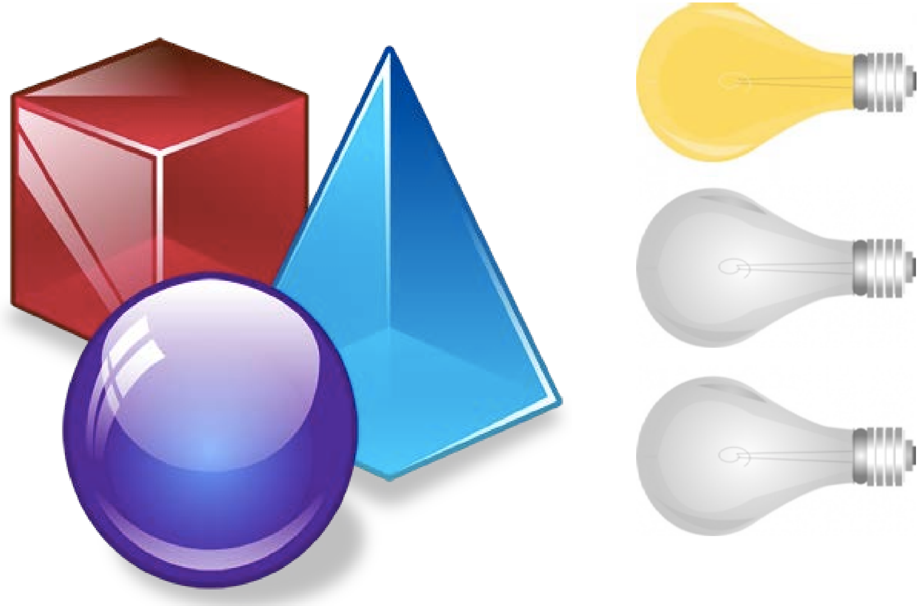
$$\mathbf{y} = \mathbf{H} \quad \mathbf{x}$$

Measured Amplitudes

Multiplexing Matrix

Recovered Amplitudes

Sequential Multiplexing



$$\begin{bmatrix} I^{(1)}(x,y) \\ I^{(2)}(x,y) \\ I^{(3)}(x,y) \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ ? & ? & ? \\ ? & ? & ? \end{bmatrix} \begin{bmatrix} \alpha^{(1)} \\ \alpha^{(2)} \\ \alpha^{y} \end{bmatrix}$$

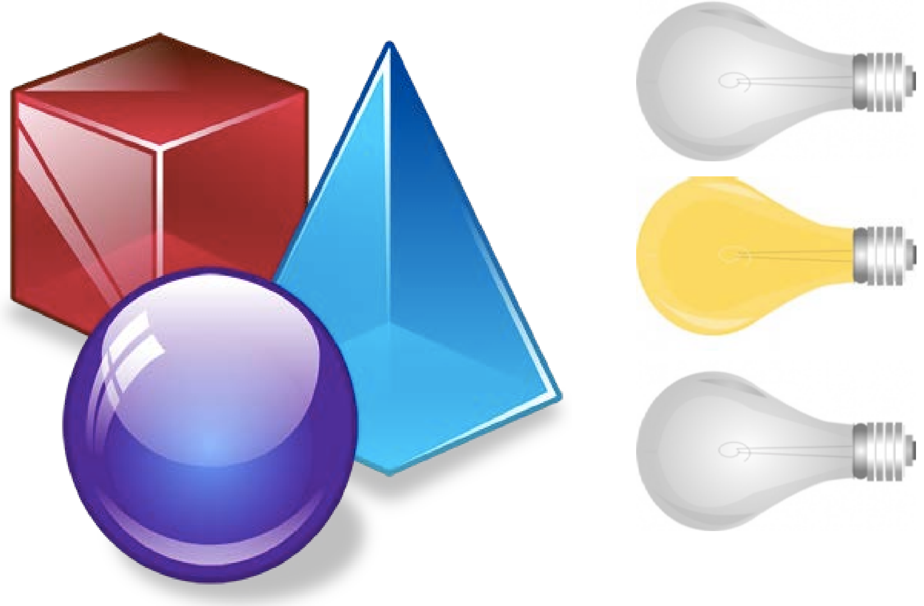
$$\mathbf{y} = \mathbf{H} \quad \mathbf{x}$$

Measured Amplitudes

Multiplexing Matrix

Recovered Amplitudes

Sequential Multiplexing



$$\begin{bmatrix} I^{(1)}(x,y) \\ I^{(2)}(x,y) \\ I^{(3)}(x,y) \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ ? & ? & ? \end{bmatrix} \begin{bmatrix} \alpha^{(1)} \\ \alpha^{(2)} \\ \alpha^{y} \end{bmatrix}$$

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Measured Amplitudes

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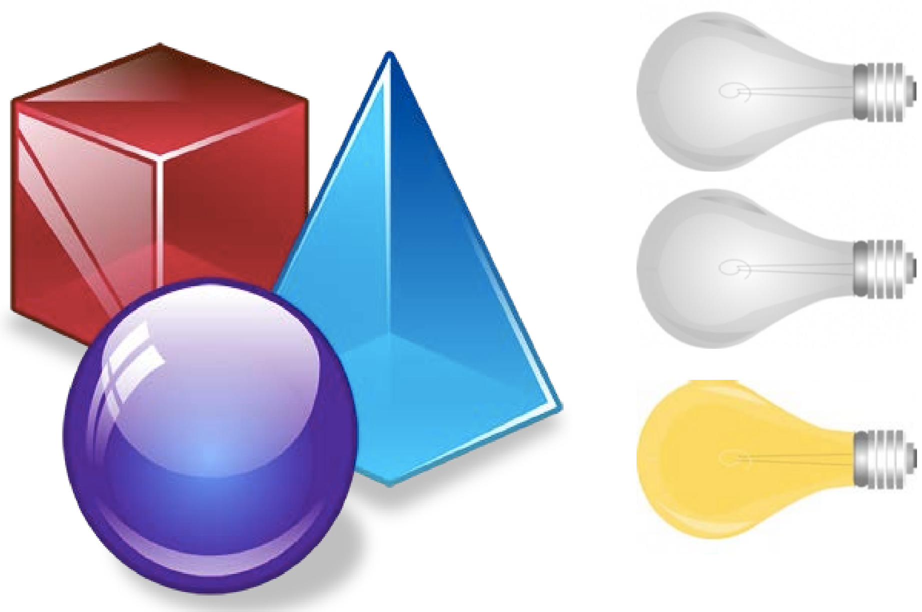
Sequential Multiplexing



$$\begin{bmatrix} I^{(1)}(x,y) \\ I^{(2)}(x,y) \\ I^{(3)}(x,y) \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \alpha^{(1)} \\ \alpha^{(2)} \\ \alpha^{y} \end{bmatrix}$$

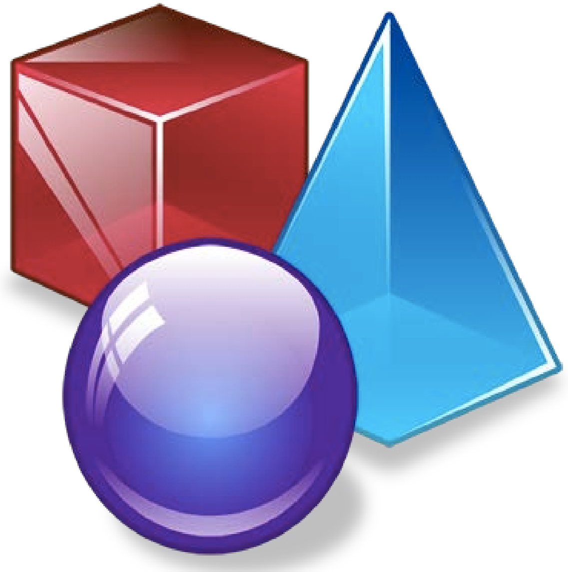
$$\mathbf{y} = \mathbf{H} \quad \mathbf{x}$$

Measured Amplitudes

Multiplexing Matrix

Recovered Amplitudes

Sequential Multiplexing



$$\begin{bmatrix} I^{(1)}(x,y) \\ I^{(2)}(x,y) \\ I^{(3)}(x,y) \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \alpha^{(1)} \\ \alpha^{(2)} \\ \alpha^{y} \end{bmatrix}$$

$$\mathbf{y} = \mathbf{H} \quad \mathbf{x}$$

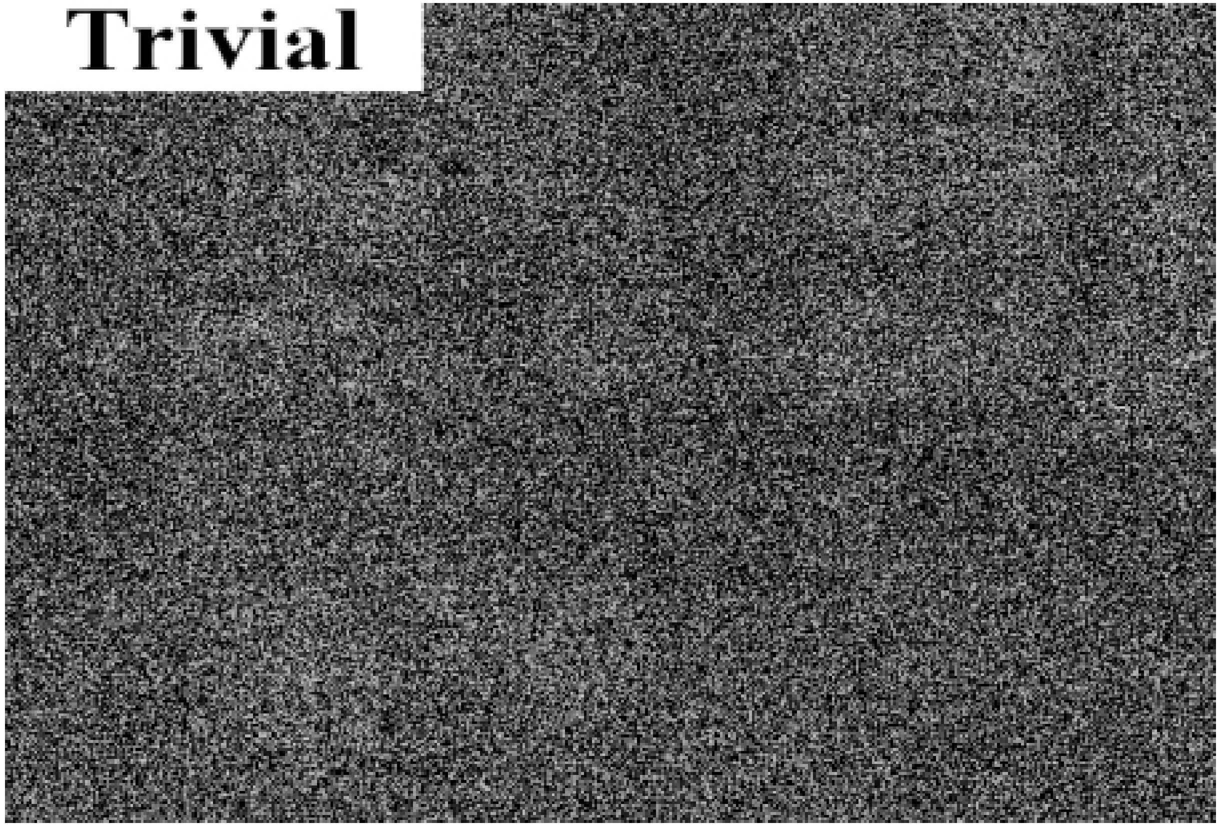
Measured Amplitudes

Multiplexing Matrix

Recovered Amplitudes

Easy to Invert!
But Not Optimal for SNR

Careful Choices boost SNR

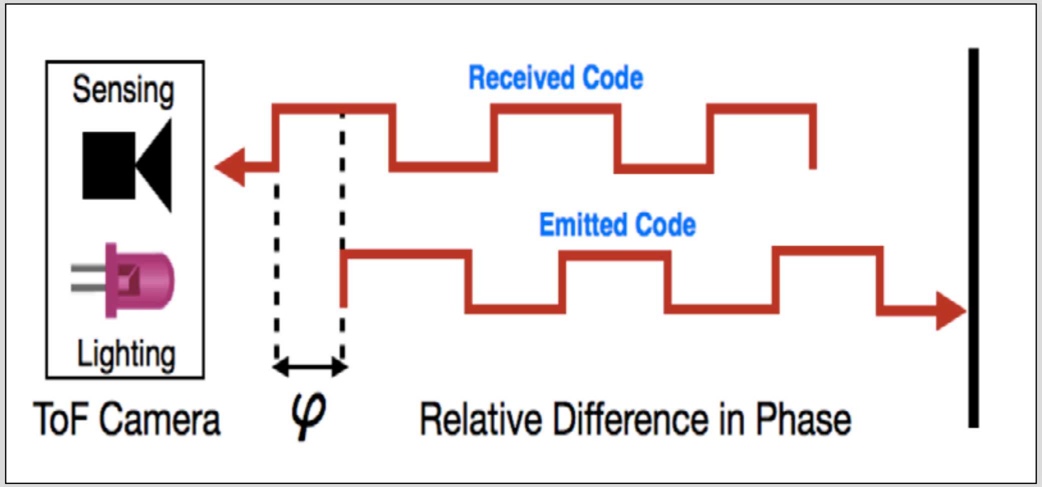


Ratner and Schechner 2007 CVPR

Main Contribution

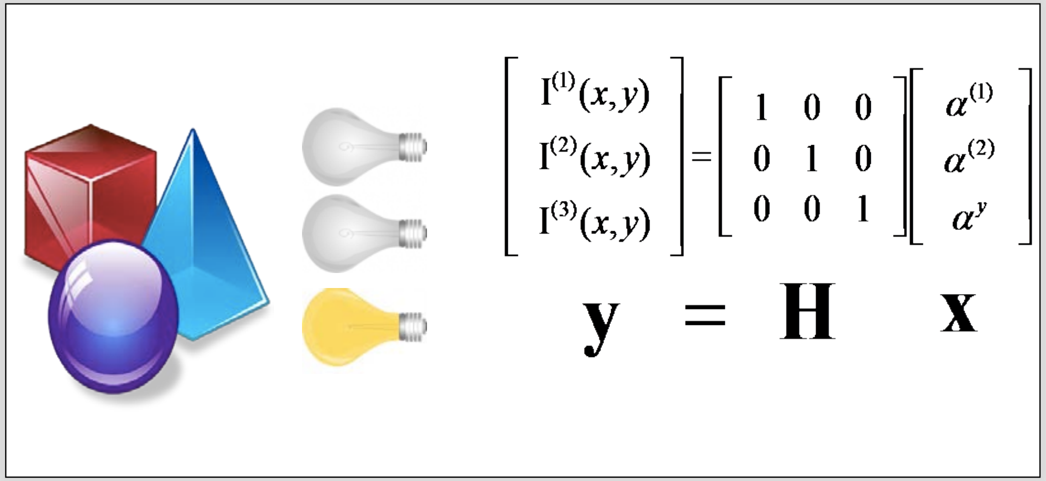
Nanosecond Coding

Time of Flight Cameras



Millisecond Coding

Illumination Multiplexing



Time of Flight + Reflectance Multiplexing

Upsampled Multiplexing

$$x \rightarrow \boxed{H^{\star}} \rightarrow \boxed{\downarrow W} \rightarrow y$$

Measured Amplitudes

Recovered Amplitudes

$$\begin{bmatrix} I^{(1)}(x,y) \\ I^{(2)}(x,y) \\ I^{(3)}(x,y) \end{bmatrix} = \begin{bmatrix} 1 & \cdots & 1 & & & & & & \\ & & & 1 & \cdots & 1 & & & \\ & & & & & & 1 & \cdots & 1 \end{bmatrix} \begin{bmatrix} 1 & & \\ \vdots & & \\ 1 & & \\ & 1 & \\ & \vdots & \\ & 1 & \\ & & 1 \\ & & \vdots \\ & & 1 \end{bmatrix} \begin{bmatrix} \alpha^{(1)} \\ \alpha^{(2)} \\ \alpha^{y} \end{bmatrix}$$

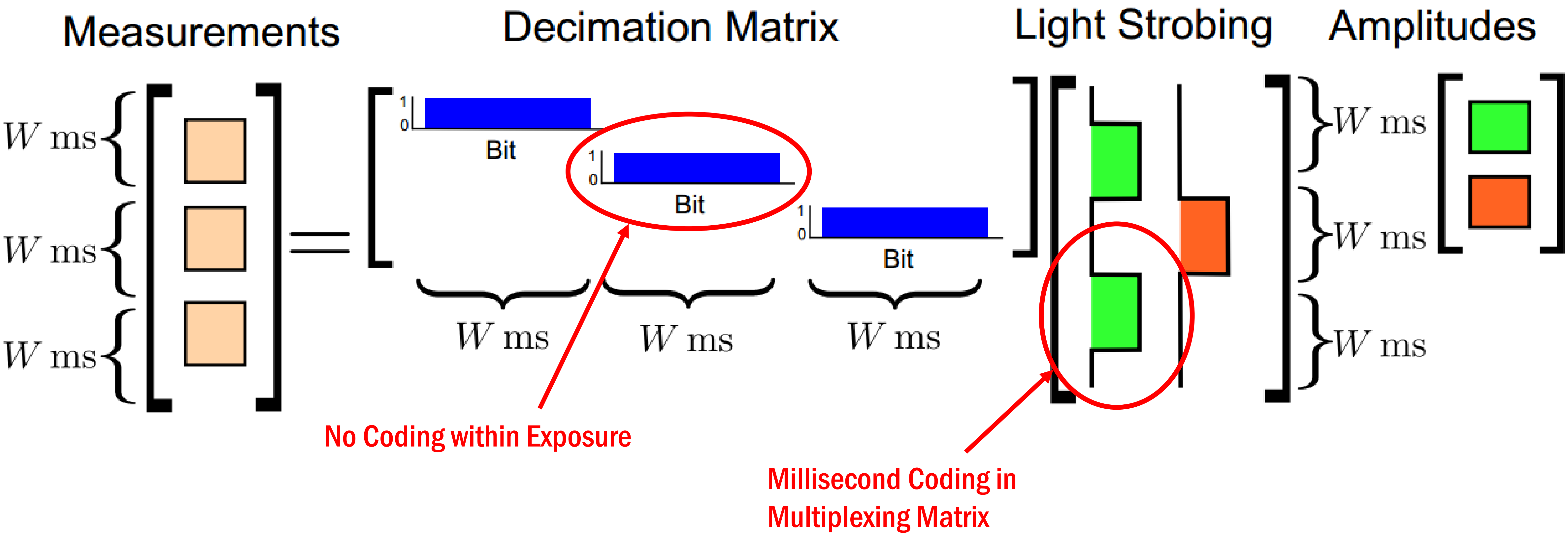
Decimation Matrix

Upsampled Strobing Matrix

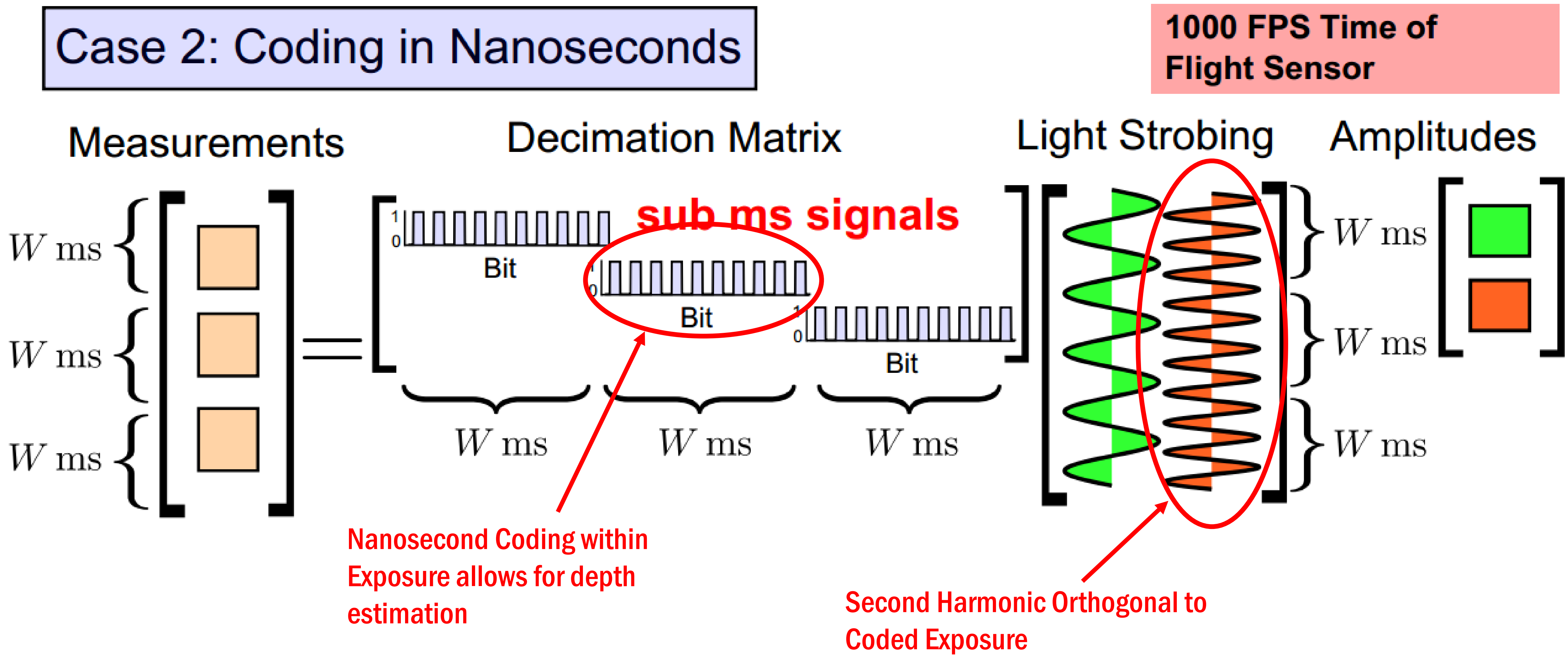
Millisecond Coding with High Speed Camera

Case 1: Coding in Milliseconds

1000 FPS High Speed Time Multiplexing



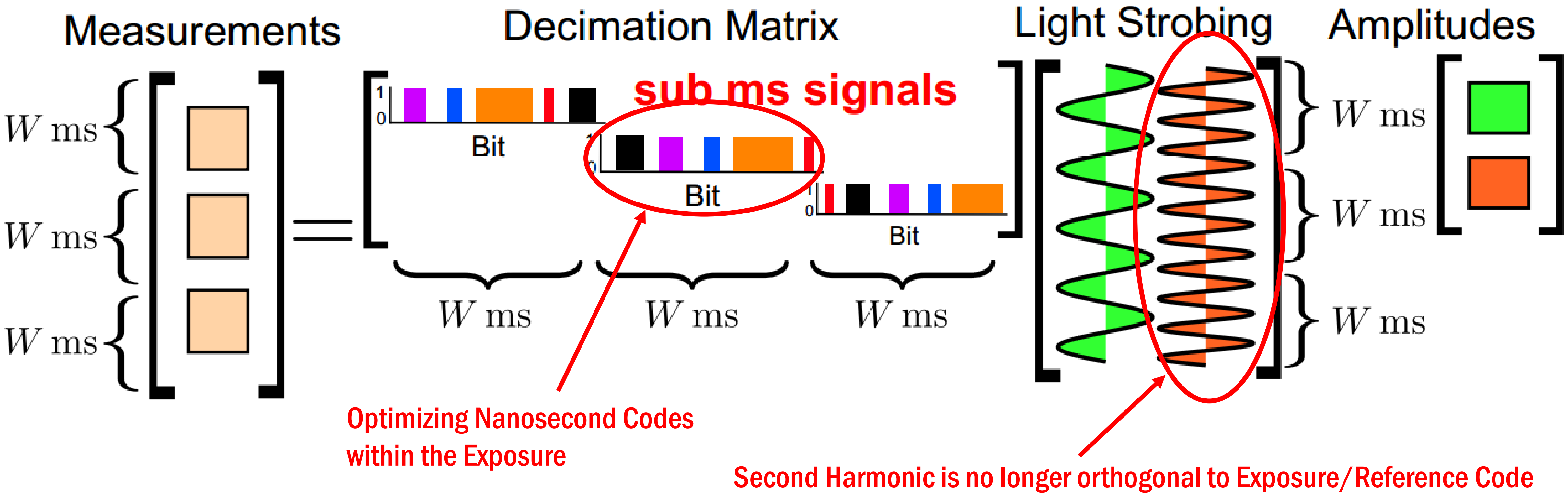
Nanosecond Coding with Time of Flight Sensor



“Optimal” Nanosecond Coding

Case 3: Optimized Nanosecond Codes

Nanosecond Coding in each 1ms Exposure



Comparing Inverse Problems

Conventional Multiplexing

$$\mathbf{y} = \mathbf{H}\mathbf{x}$$

y_i : Measured Intensity at i-th Image

$\mathbf{H}$: Millisecond Strobing Pattern of Lights

x_i : Amplitude of the i-th Illumination Source

Time of Flight 3D Multiplexing

$$\mathbf{T}\mathbf{y} = \mathbf{T}\mathbf{L}\mathbf{x}$$

$\mathbf{T}$: Toeplitz Circulant Matrix of Reference Code

Electronic Computation

$\mathbf{L}$: Upsampled Light Source Strobing Pattern

Optical Computation

Comparing Inverse Problems

Conventional Multiplexing

$$\mathbf{y} = \mathbf{H}\mathbf{x}$$

y_i : Measured Intensity at i-th Image

$\mathbf{H}$: Millisecond Strobing Pattern of Lights

x_i : Amplitude of the i-th Illumination Source

Time of Flight 3D Multiplexing

$$\mathbf{T}\mathbf{y} = \mathbf{T}\mathbf{L}\mathbf{x}$$

$\mathbf{T}$: Toeplitz Circulant Matrix of Reference Code

Electronic Computation

$\mathbf{L}$: Upsampled Light Source Strobing Pattern

Optical Computation

Goal Solve for T and L

A Simple Option: Optimization

Merges some constraints of the optimization program to the physical constraints.

No problem…

$$\boldsymbol{\Sigma} = \mathbb{E}\left[(\hat{\mathbf{x}} - \mathbb{E}[\hat{\mathbf{x}}])(\hat{\mathbf{x}} - \mathbb{E}[\hat{\mathbf{x}}])^\top\right]$$

$$\mathbf{M}^\star = \mathbf{T}^\star \mathbf{L}^\star. \quad \mathcal{C} \subset \mathbb{R}^{m \times p}$$

$$\{\mathbf{T}^\star, \mathbf{L}^\star\} = \underset{\mathbf{T},\mathbf{L}}{\arg\min} \| \mathbf{M}^\star - \mathbf{TL}\|_F \quad \text{s.t.}$$

$$\mathbf{c}_\omega = \mathbf{Mx} + \boldsymbol{\eta}$$

$$1 \succcurlyeq \text{vec}(\mathbf{T}) \succcurlyeq 0, \quad 1 \succcurlyeq \text{vec}(\mathbf{L}) \succcurlyeq 0, \quad \mathbf{T} \in \mathcal{C}$$

$$\underset{\mathbf{C}\in\mathcal{C}}{\arg\min} \| \mathbf{T}^{(k)} - \mathbf{C}\|_F$$

$$\mathbf{M}^\star = \underset{\mathbf{Q}}{\arg\min}\, \text{tr}(\mathbf{Q}) \;\; \text{s.t.}$$

$$1 \succcurlyeq \text{vec}(\mathbf{M}) \succcurlyeq 0, \;\; \mathbf{Q} \succcurlyeq (\mathbf{M}^\top \boldsymbol{\Sigma}^{-1} \mathbf{M})^{-1}$$

$$\text{MSE} = \frac{1}{n}\text{tr}\left[(\mathbf{M}^\top \boldsymbol{\Sigma}^{-1} \mathbf{M})^{-1}\right]$$

$$\underset{\mathbf{M}}{\arg\min}\; \tfrac{1}{n}\text{tr}\left[(\mathbf{M}^\top \boldsymbol{\Sigma}^{-1} \mathbf{M})^{-1}\right] \quad \text{s.t.} \quad 1 \succcurlyeq \text{vec}(\mathbf{M}) \succcurlyeq 0$$

Finding the Closest Circulant Matrix admits a closed form solution.

Remarks on Optimality

$$\boldsymbol{\Sigma} = \mathbb{E}\left[\left(\hat{\mathbf{x}} - \mathbb{E}[\hat{\mathbf{x}}]\right)\left(\hat{\mathbf{x}} - \mathbb{E}[\hat{\mathbf{x}}]\right)^\top\right]$$

$$\{\mathbf{T}^\star, \mathbf{L}^\star\} = \arg\min_{\mathbf{T},\mathbf{L}} \|\, \mathbf{M}^\star - \mathbf{T}\mathbf{L}\|_F \quad \text{s.t.}$$

$$\mathbf{M}^\star = \mathbf{T}^\star\mathbf{L}^\star. \quad \mathcal{C} \subset \mathbb{R}^{m\times p}$$

$$\mathbf{c}_\omega = \mathbf{M}\mathbf{x} + \boldsymbol{\eta}$$

$$1 \succcurlyeq \mathrm{vec}(\mathbf{T}) \succcurlyeq 0, \quad 1 \succcurlyeq \mathrm{vec}(\mathbf{L}) \succcurlyeq 0, \quad \mathbf{T} \in \mathcal{C}$$

Details in the Paper!

$$\arg\min_{\mathbf{C}\in\mathcal{C}} \|\, \mathbf{T}^{(k)} - \mathbf{C}\|_F$$

$$\mathbf{M}^\star = \arg\min_{\mathbf{Q}} \mathrm{tr}(\mathbf{Q}) \;\; \text{s.t.}$$

$$1 \succcurlyeq \mathrm{vec}(\mathbf{M}) \succcurlyeq 0, \;\; \mathbf{Q} \succcurlyeq \left(\mathbf{M}^\top\boldsymbol{\Sigma}^{-1}\mathbf{M}\right)^{-1} \quad \mathrm{MSE} = \frac{1}{n}\mathrm{tr}\left[\left(\mathbf{M}^\top\boldsymbol{\Sigma}^{-1}\mathbf{M}\right)^{-1}\right]$$

$$\arg\min_{\mathbf{M}} \; \tfrac{1}{n}\mathrm{tr}\left[\left(\mathbf{M}^\top\boldsymbol{\Sigma}^{-1}\mathbf{M}\right)^{-1}\right] \quad \text{s.t.} \quad 1 \succcurlyeq \mathrm{vec}(\mathbf{M}) \succcurlyeq 0$$

Finding the Closest Circulant Matrix admits a closed form solution.

ToF Multiplexing is Preconditioning on the Toeplitz Matrix

$$\mathbf{y} = \mathbf{L}\mathbf{x} \xrightarrow{T(\cdot)} \mathbf{T}\mathbf{y} = \mathbf{T}\mathbf{L}\mathbf{x}$$

L is the multiplexing matrix.
(light switching pattern

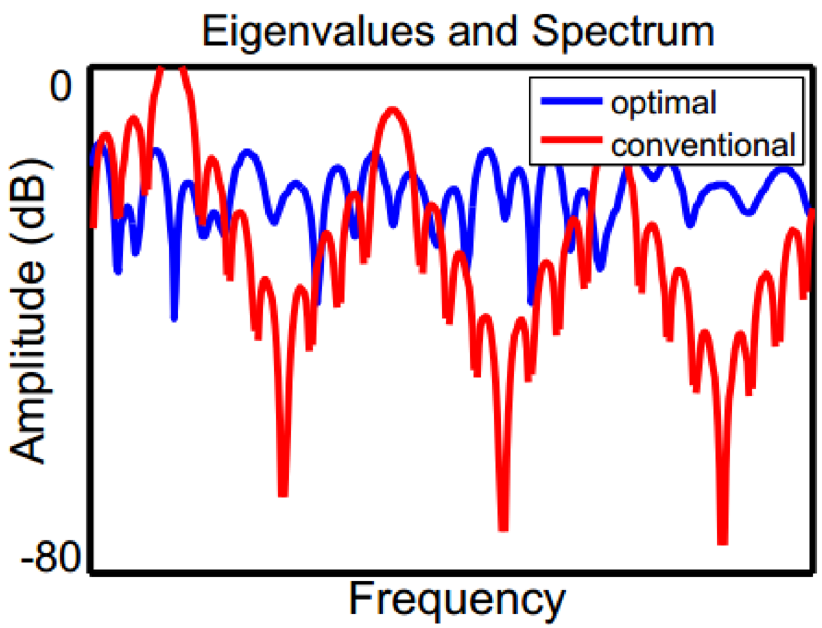
T is a Toeplitz Circulant Matrix

Proposition 3.1

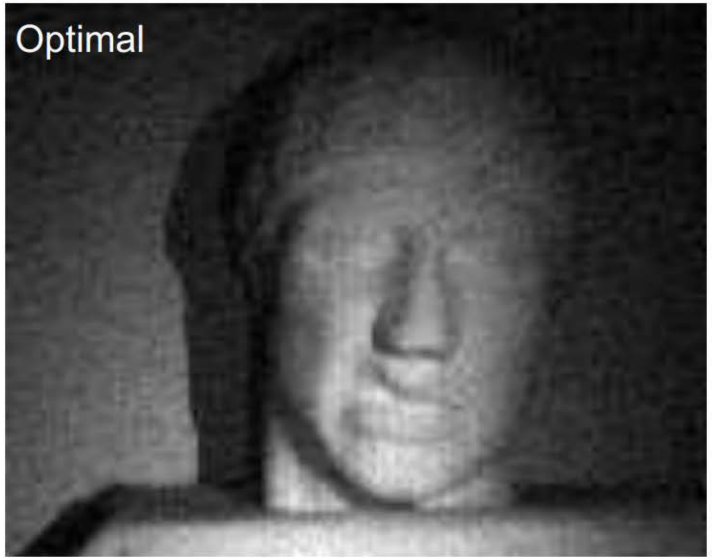
*Suppose for millisecond multiplexing, **H** is orthogonal. Then the nanosecond light strobing matrix **L** is orthogonal and the optimal exposure code **r** is broadband in frequency domain.*

→ Shortcut to Avoid Optimization
→ "Optimal" in what sense?

Finding Optimal Codes allows a Well Conditioned Problem



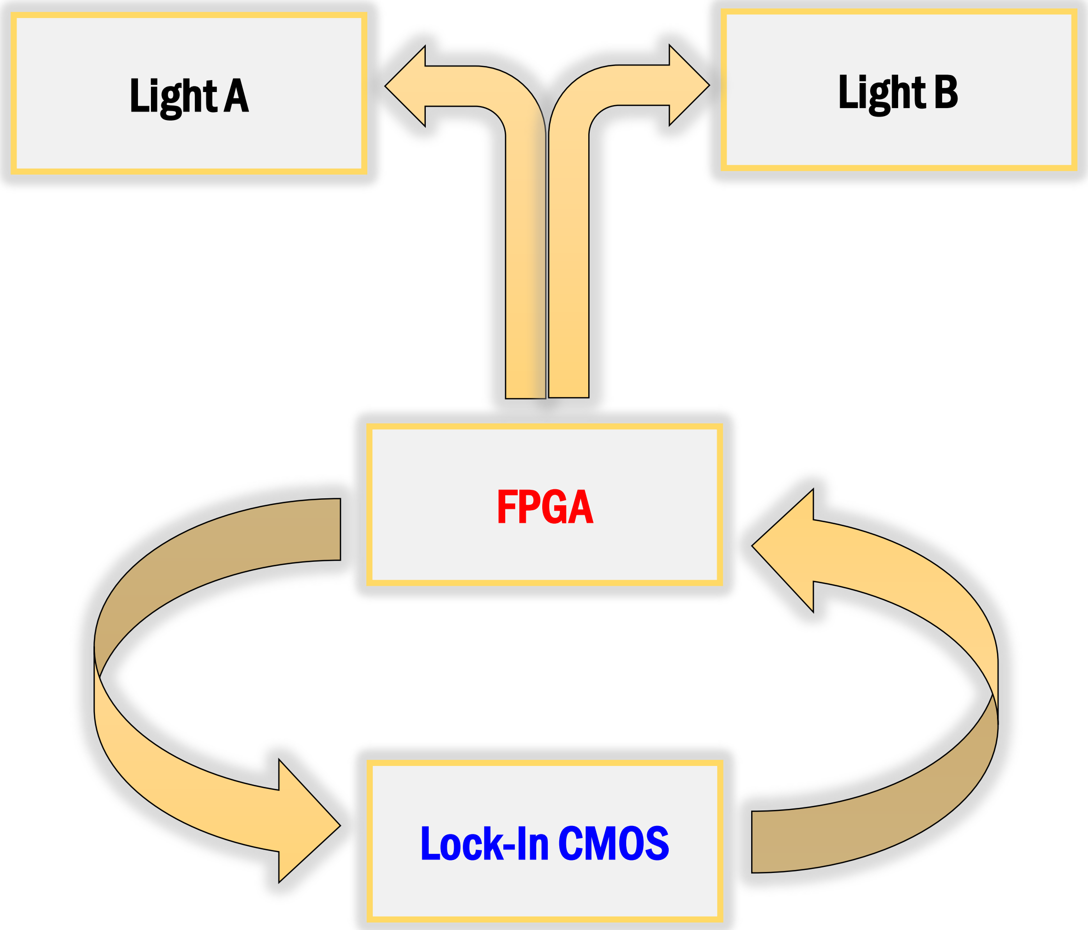
(a) Ill Conditioned



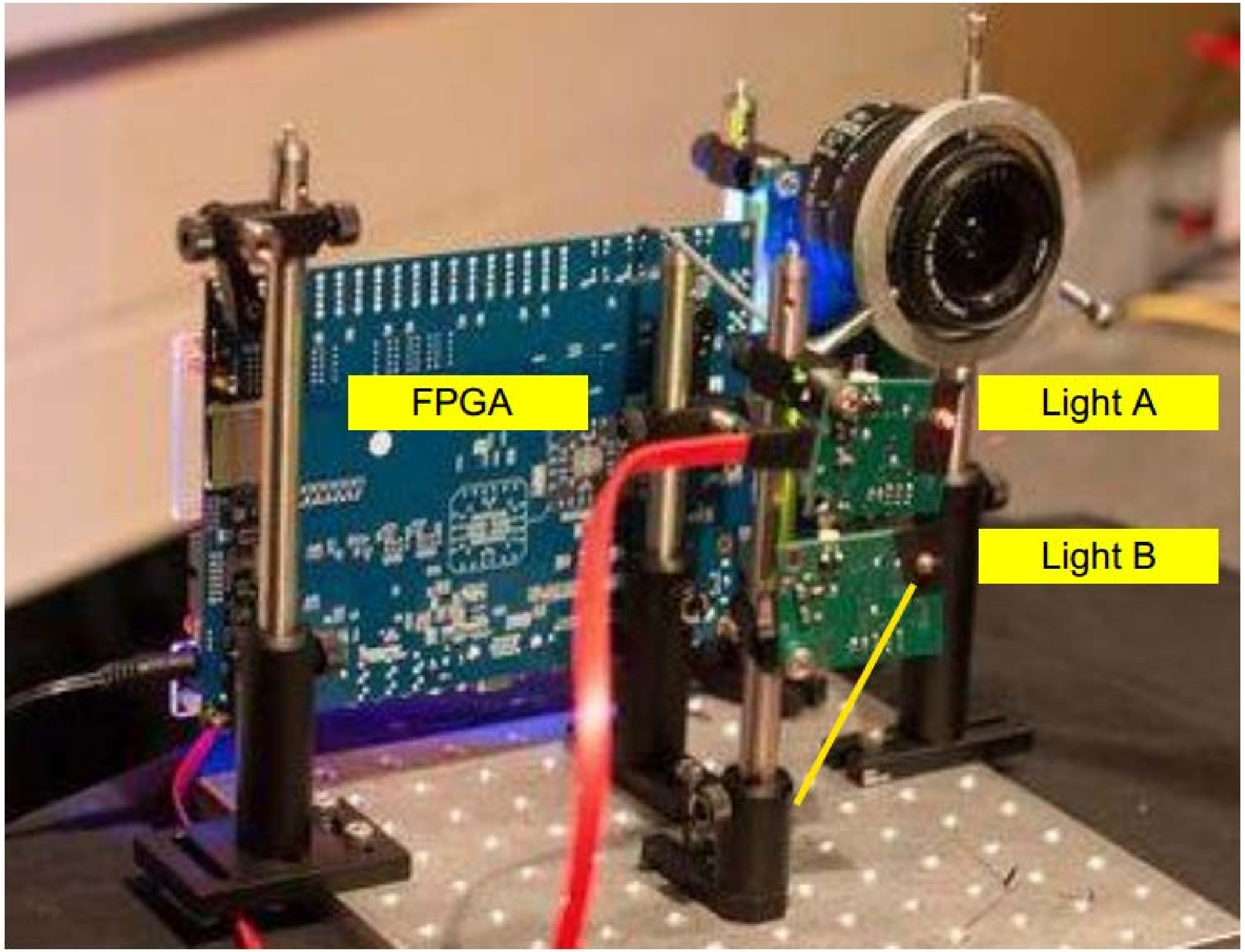
(b) Better Conditioned

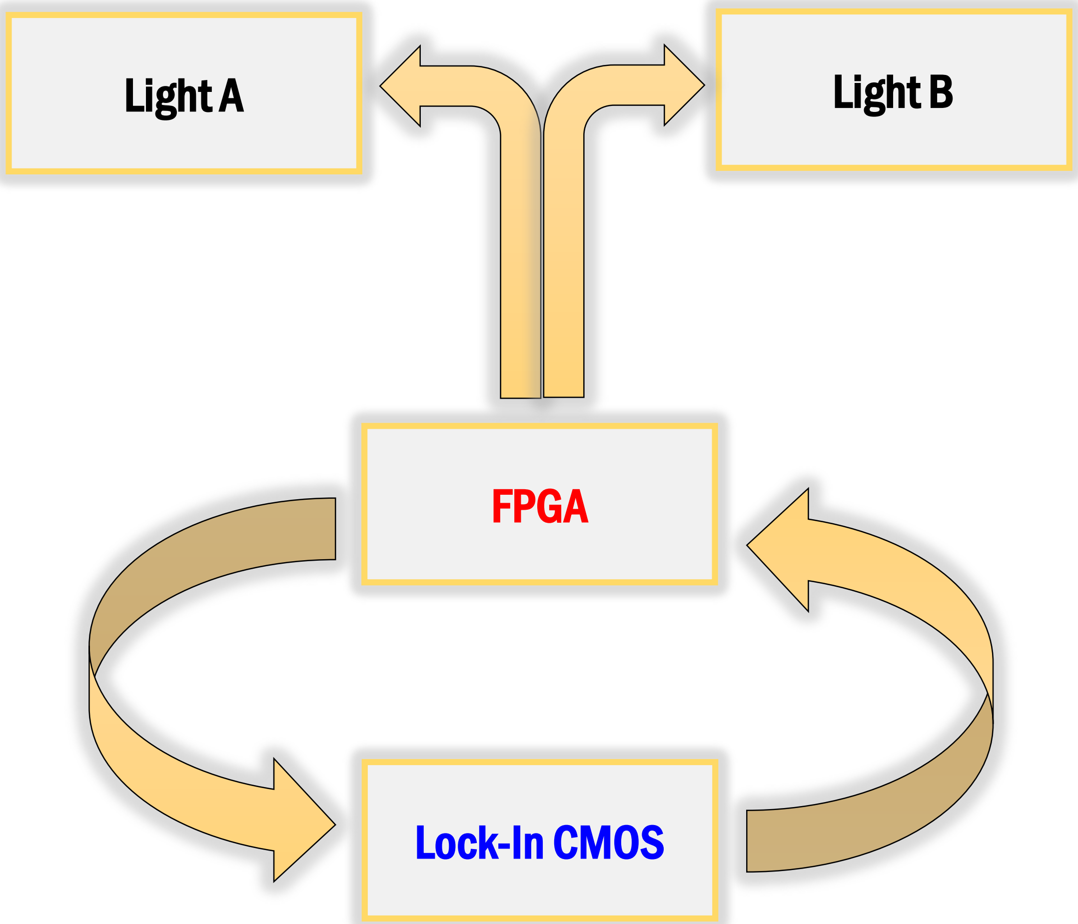
Prototype Camera

Reproducibility
CMOS Sensor: **PMD Part Number 19k-3**
Solid State Light Source: **Sony Part Number SLD1239JL-54**
FPGA: **Altera Cyclone IV**
Fast ADC: **Analog Devices AD9826**



Prototype Camera



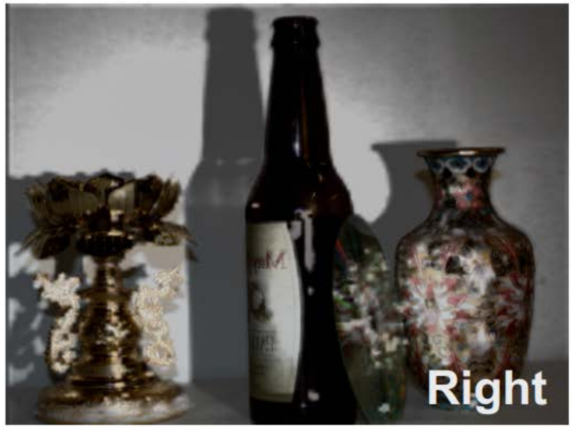


Consumer Applications

Shoot Now, Relight Later

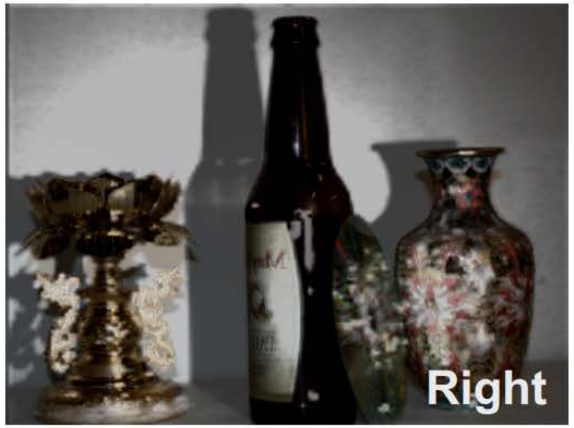
Consumer Applications

Shoot Now, Relight Later



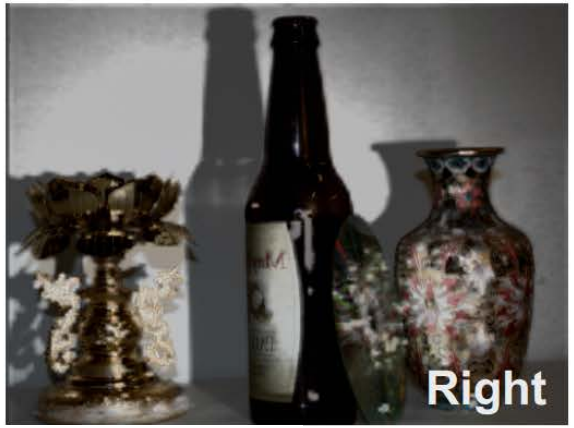
Consumer Applications

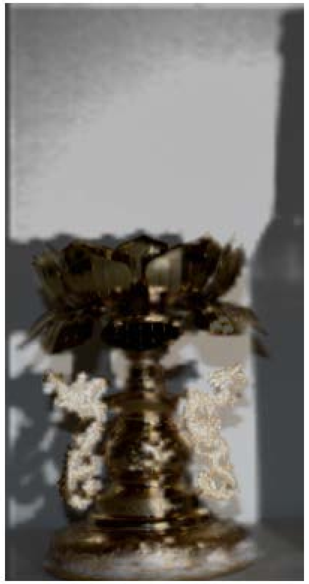
Shoot Now, Relight Later



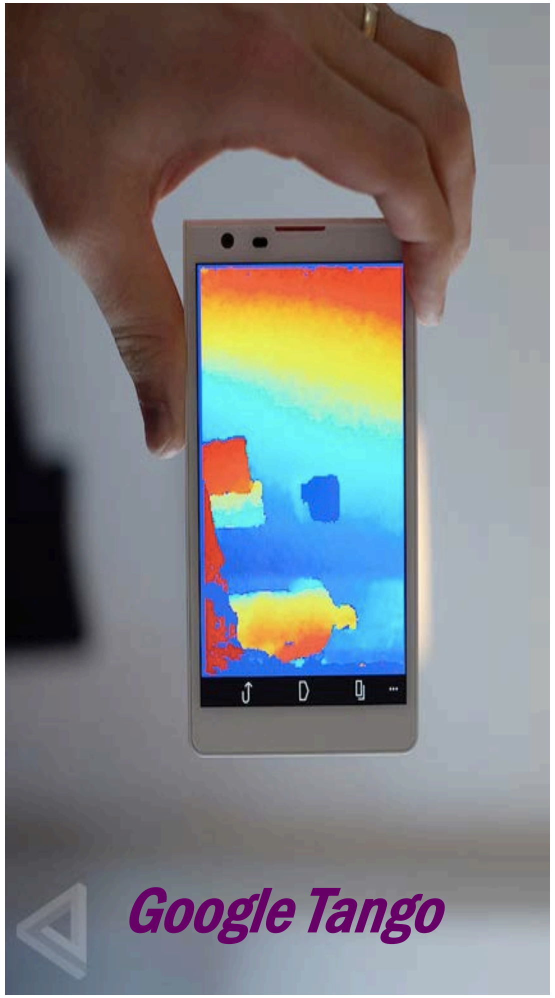
Consumer Applications

Shoot Now, Relight Later



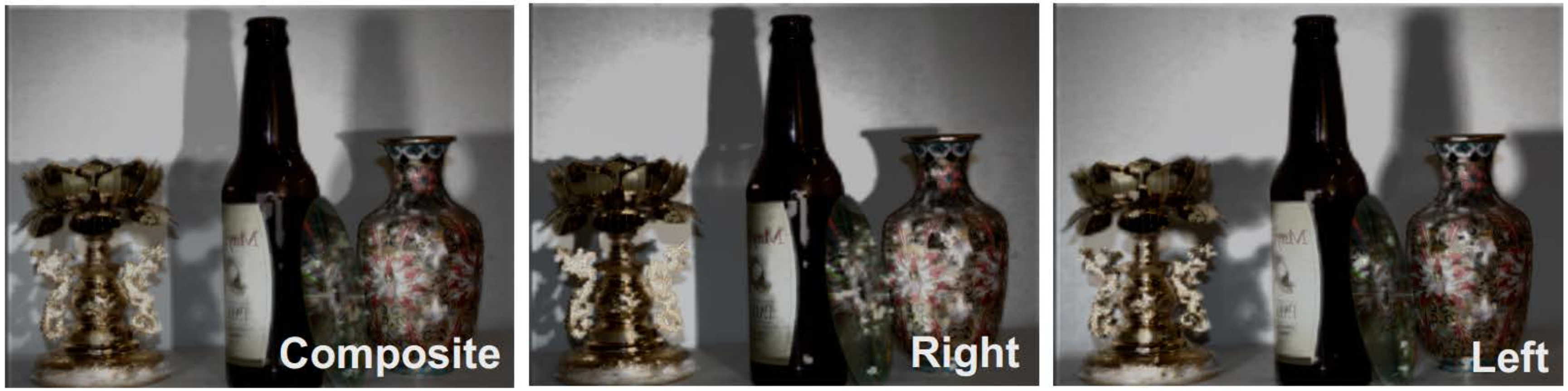


Enhance Mobile Experience?

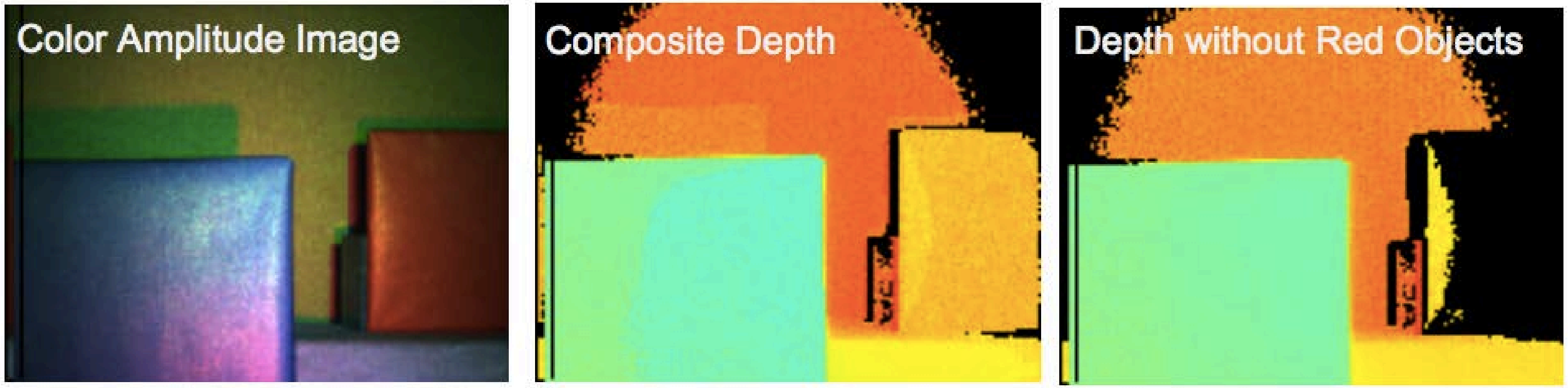


Consumer Applications

Shoot Now, Relight Later



RGBD Time of Flight with One Sensor



Future Work in 3D Multiplexing

- **Multiplexing for Depth Accuracy?**
- **Multiplexing and Photometric Approaches?**
- **Hyperspectral RGBD?**

Achuta Kadambi
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Media Laboratory, MIT

Coding in Time not Space

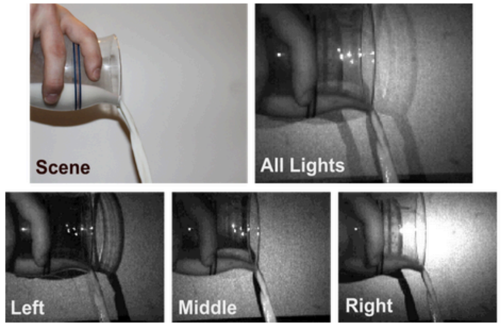
web.media.mit.edu/~achoo/demux/

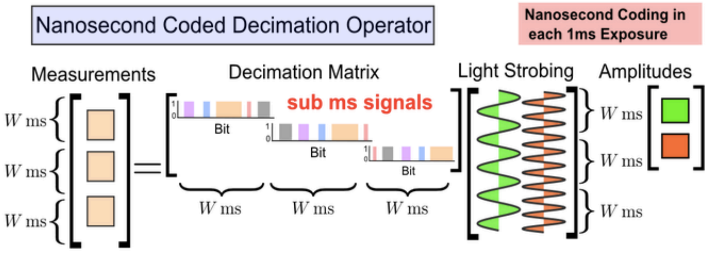
Demultiplexing Illumination via Low Cost Sensing and Nanosecond Coding

Achuta Kadambi[1] Ayush Bhandari[1] Refael Whyte[2] Adrian Dorrington[2] Ramesh Raskar[1]

[1]Massachusetts Institute of Technology [2]University of Waikato

IEEE ICCP 2014, Santa Clara CA





Forward Model for Illumination Multiplexing in Time of Flight Cameras

Figure 1: Demultiplexing Illumination with a Time of Flight Camera. The scene is in upper-left. A ToF camera is synced to 3 light sources; we measure all three light sources (upper-right) and can decompose as if only one of the individual light sources was on. Note the distinction of shadows in the separated images.

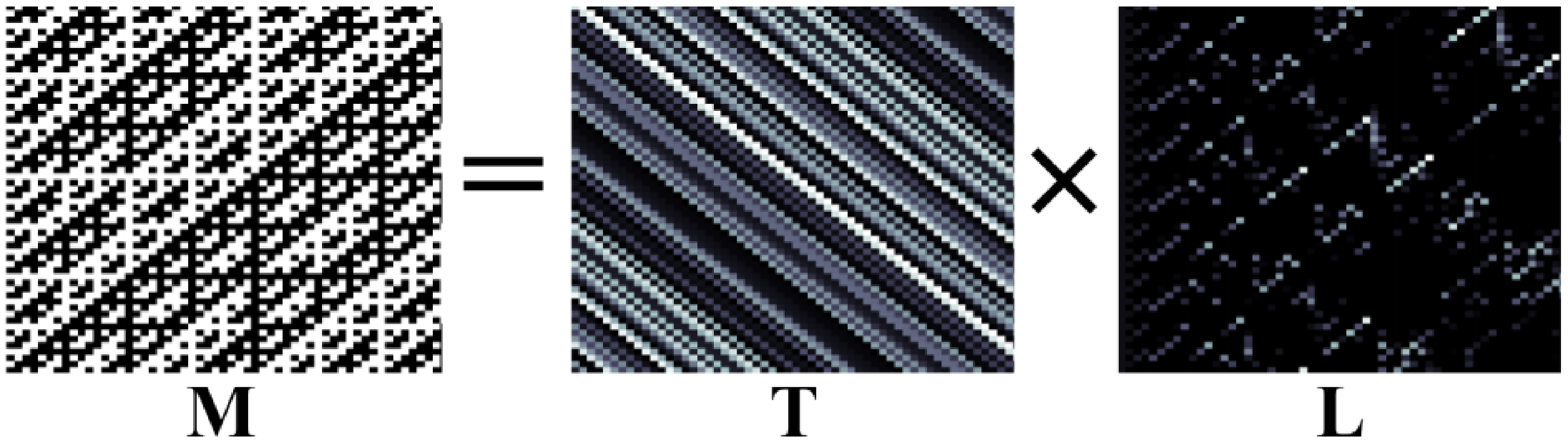
Project Webpage: www.media.mit.edu/~achoo/demux
Personal Webpage: www.media.mit.edu/~achoo/

Collaborators:

Achuta Kadambi
Ayush Bhandari
Refael Whyte
Adrian Dorrington
Ramesh Raskar

Thanks To:
Hisham Bedri (MIT)
Boxin Shi (MIT)
Gordon Wetzstein (MIT)
Moshe Ben-Ezra (MIT)

Optimizing over the Product



$$\mathbf{c}_\omega = \mathbf{M}\mathbf{x} + \boldsymbol{\eta}$$

$$\boldsymbol{\Sigma} = \mathbb{E}\left[\left(\hat{\mathbf{x}} - \mathbb{E}[\hat{\mathbf{x}}]\right)\left(\hat{\mathbf{x}} - \mathbb{E}[\hat{\mathbf{x}}]\right)^\top\right]$$

$$\text{MSE} = \frac{1}{n}\text{tr}\left[\left(\mathbf{M}^\top \boldsymbol{\Sigma}^{-1}\mathbf{M}\right)^{-1}\right]$$

Optimizing over the Product

$$\mathbf{c}_\omega = \mathbf{M}\mathbf{x} + \boldsymbol{\eta}$$

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$$\text{MSE} = \frac{1}{n}\mathrm{tr}\left[\left(\mathbf{M}^\top \boldsymbol{\Sigma}^{-\mathbf{1}} \mathbf{M}\right)^{-1}\right]$$

$$\underset{\mathbf{M}}{\arg\min}\ \tfrac{1}{n}\mathrm{tr}\left[\left(\mathbf{M}^\top \boldsymbol{\Sigma}^{-1} \mathbf{M}\right)^{-1}\right] \quad \text{s.t.} \quad 1 \succcurlyeq \mathrm{vec}(\mathbf{M}) \succcurlyeq 0$$

Optimizing over the Product

$$\mathbf{c}_\omega = \mathbf{M}\mathbf{x} + \boldsymbol{\eta}$$

$$\boldsymbol{\Sigma} = \mathbb{E}\left[\left(\hat{\mathbf{x}} - \mathbb{E}[\hat{\mathbf{x}}]\right)\left(\hat{\mathbf{x}} - \mathbb{E}[\hat{\mathbf{x}}]\right)^\top\right]$$

$$\text{MSE} = \frac{1}{n}\mathsf{tr}\left[\left(\mathbf{M}^\top\boldsymbol{\Sigma}^{-1}\mathbf{M}\right)^{-1}\right]$$

$$\arg\min_{\mathbf{M}} \tfrac{1}{n}\mathsf{tr}\left[\left(\mathbf{M}^\top\boldsymbol{\Sigma}^{-1}\mathbf{M}\right)^{-1}\right] \quad \text{s.t.} \quad 1 \succcurlyeq \text{vec}(\mathbf{M}) \succcurlyeq 0$$

$$\mathbf{M}^\star = \arg\min_{\mathbf{Q}} \mathsf{tr}(\mathbf{Q}) \ \text{ s.t.}$$

$$1 \succcurlyeq \text{vec}(\mathbf{M}) \succcurlyeq 0, \ \ \mathbf{Q} \succcurlyeq \left(\mathbf{M}^\top\boldsymbol{\Sigma}^{-1}\mathbf{M}\right)^{-1}$$

Q is positive semidefinite

Non-negative Matrix Factorization with Circulant Constraints

$$\mathbf{M}^\star = \mathbf{T}^\star \mathbf{L}^\star.$$

$$\{\mathbf{T}^\star, \mathbf{L}^\star\} = \arg\min_{\mathbf{T},\mathbf{L}} \| \mathbf{M}^\star - \mathbf{T}\mathbf{L}\|_F \quad \text{s.t.}$$

$$1 \succcurlyeq \text{vec}(\mathbf{T}) \succcurlyeq 0, \quad 1 \succcurlyeq \text{vec}(\mathbf{L}) \succcurlyeq 0, \quad \mathbf{T} \in \mathcal{C} \quad \mathcal{C} \subset \mathbb{R}^{m \times p}$$

$$\arg\min_{\mathbf{C}\in\mathcal{C}} \| \mathbf{T}^{(k)} - \mathbf{C}\|_F$$

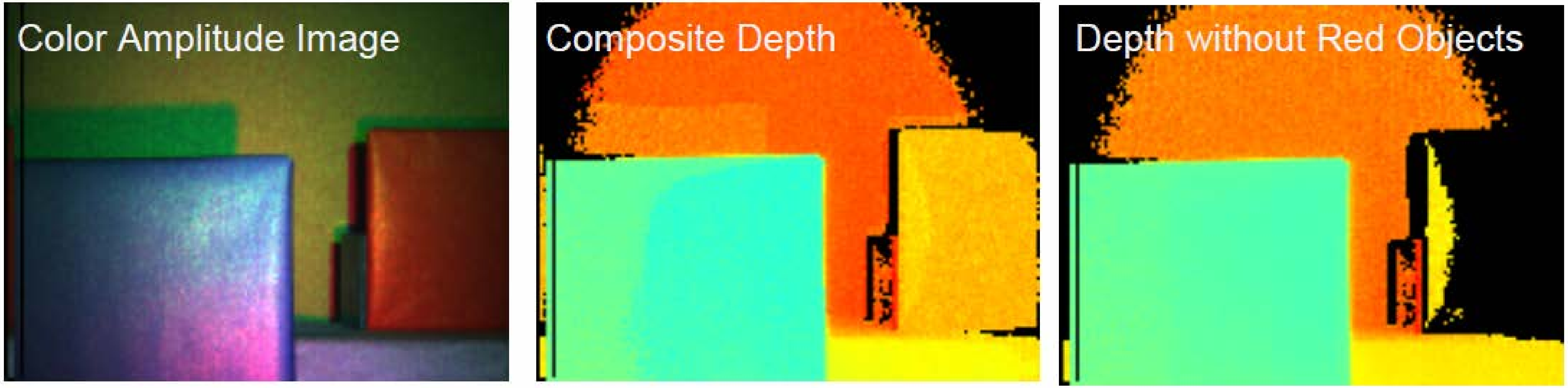
Finding the Closest Circulant Matrix admits a closed form solution.

Real-time Illumination Multiplexing

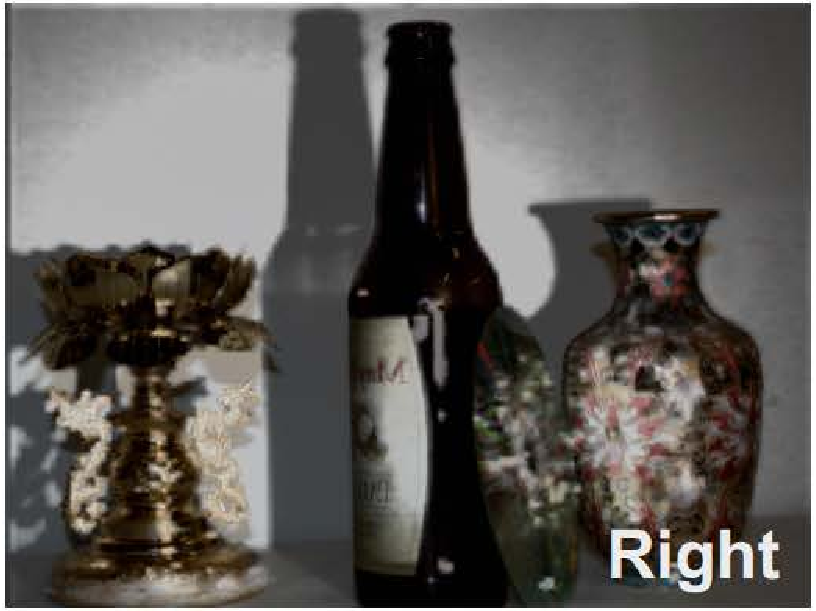
Single-chip Color ToF Camera

Key Benefit is that there is no Bayer mask so spatial resolution is preserved.

No limit to real-time performance since we are already multiplexing samples.



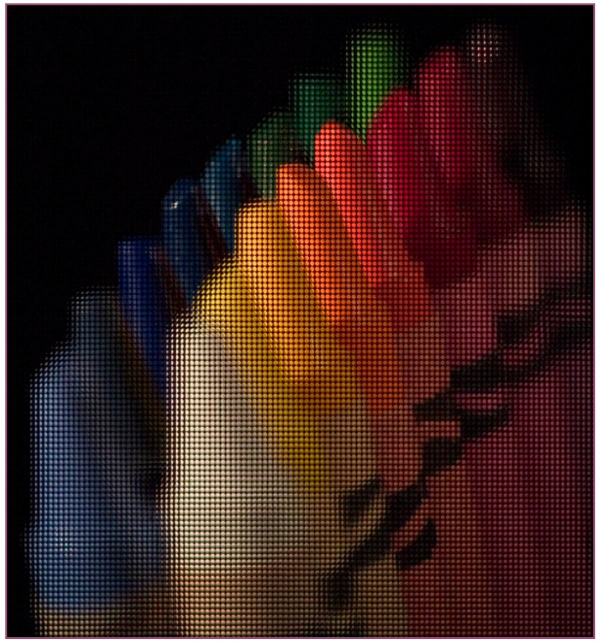
Application to Scene Relighting



Lighting is Important

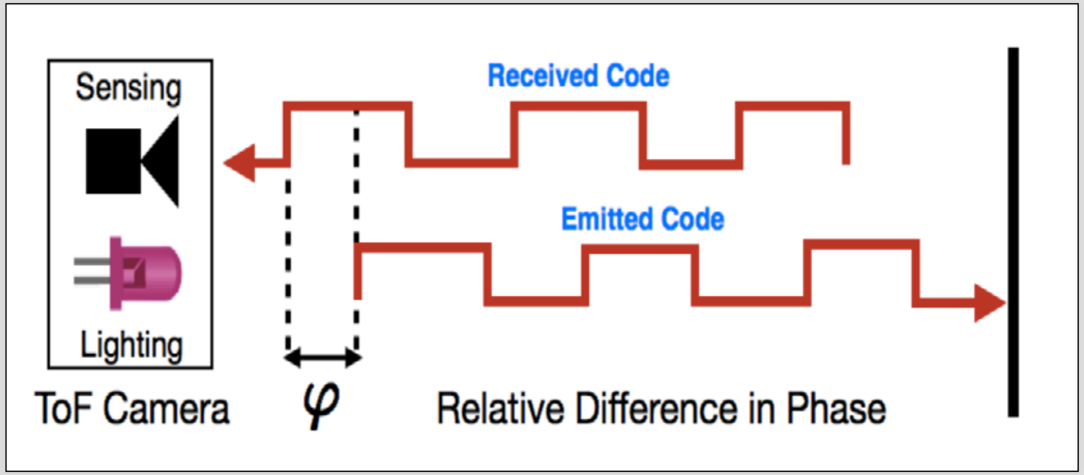
Ken Rockwell

Capture Visual Information → Prune Post-process

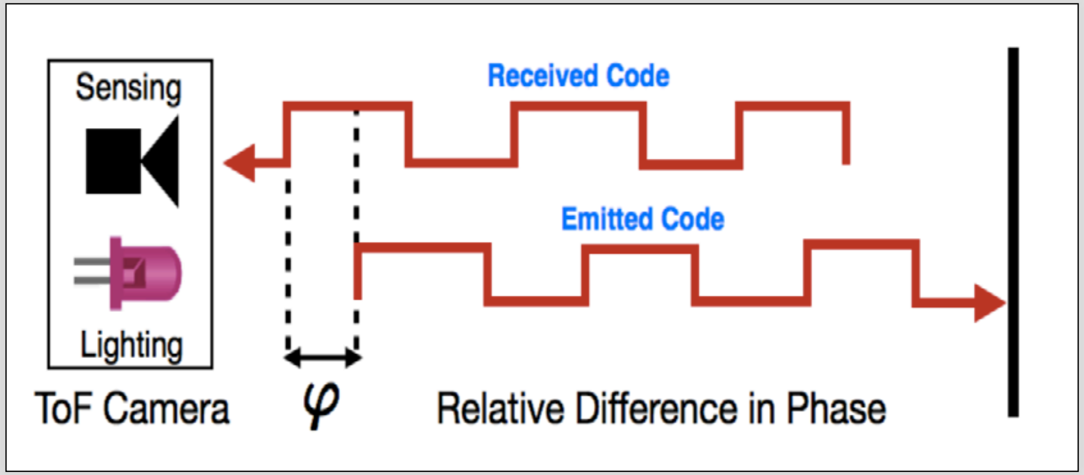


LYTRO

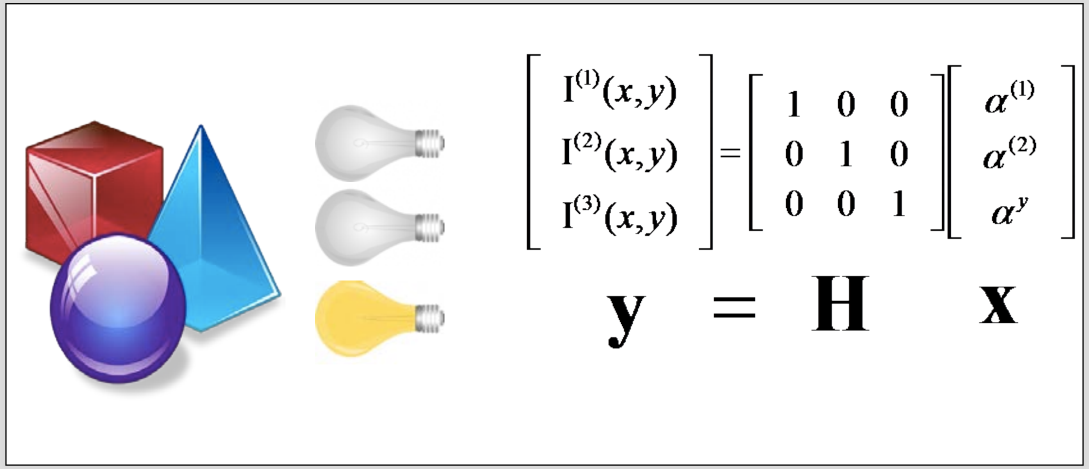
Time of Flight Cameras



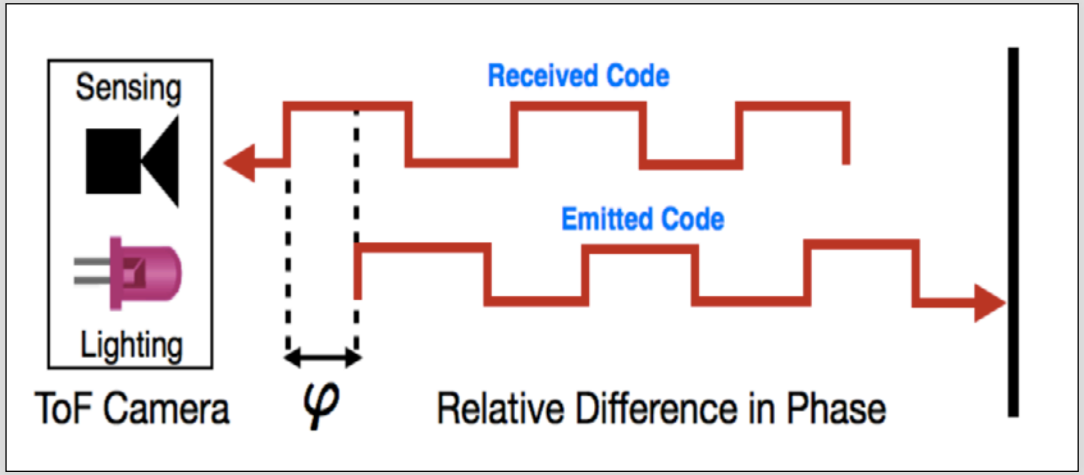
Time of Flight Cameras



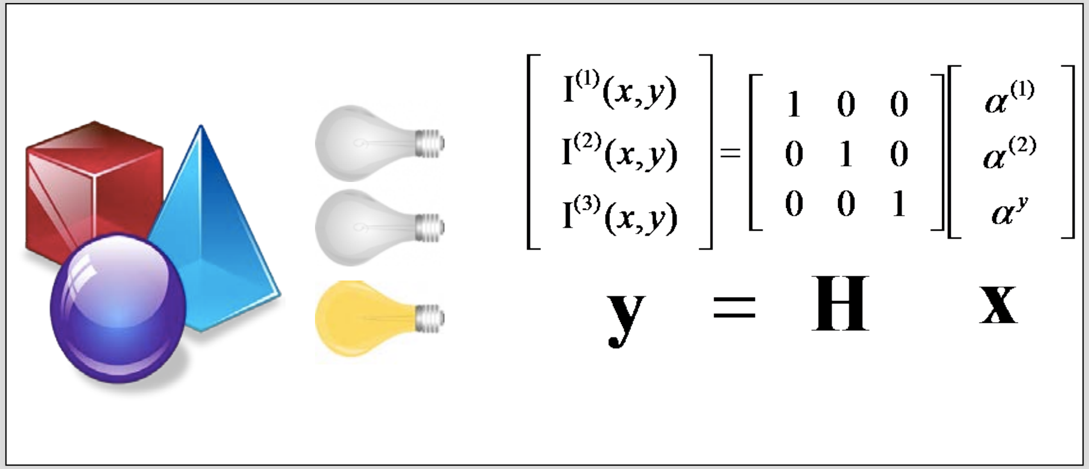
Illumination Multiplexing



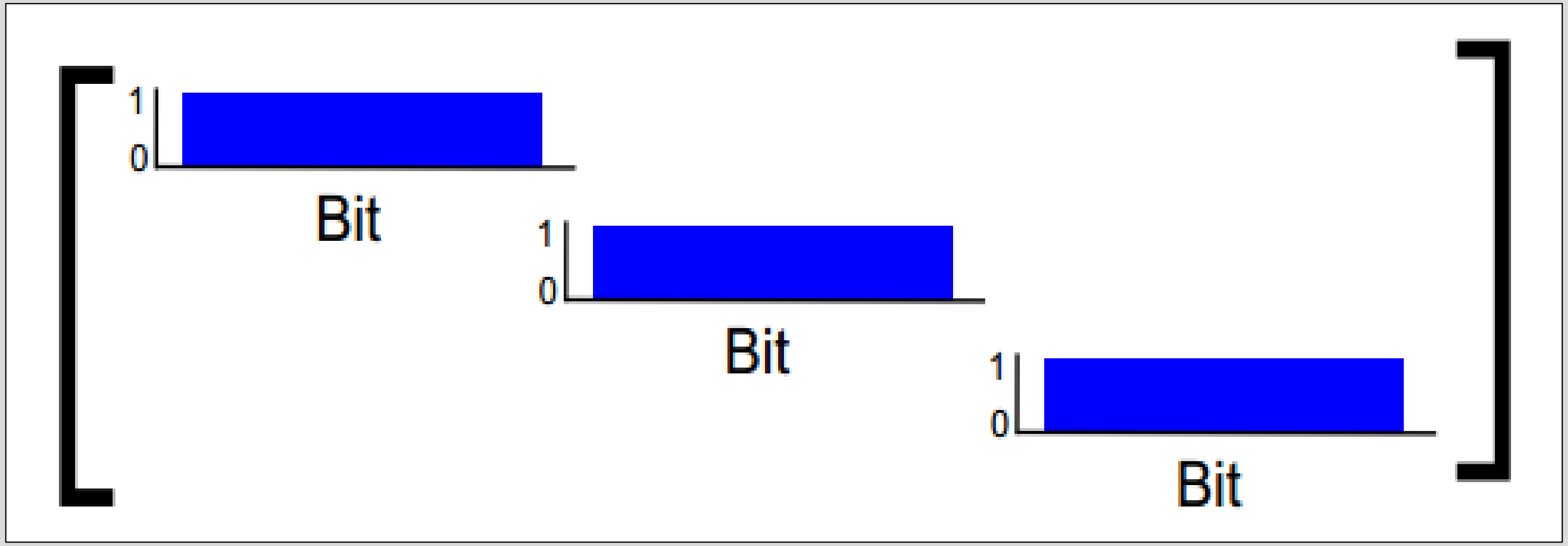
Time of Flight Cameras



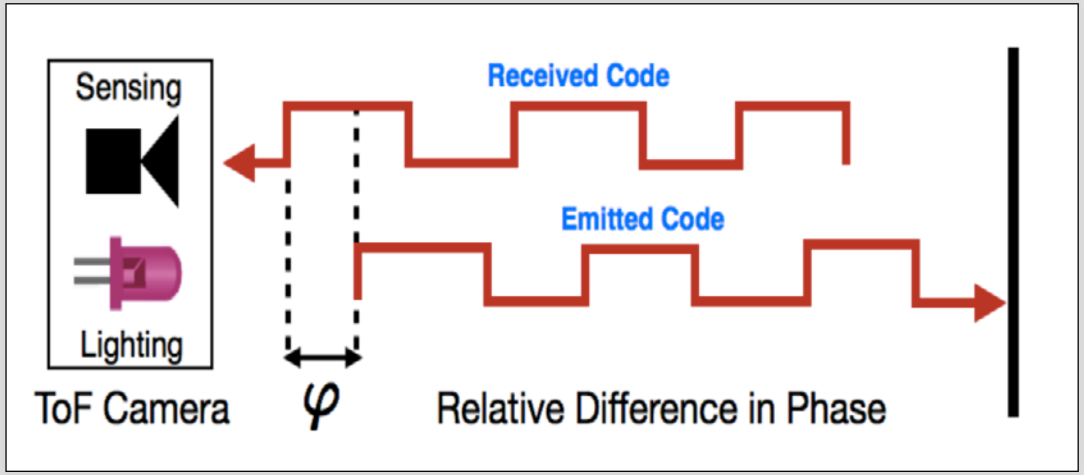
Illumination Multiplexing



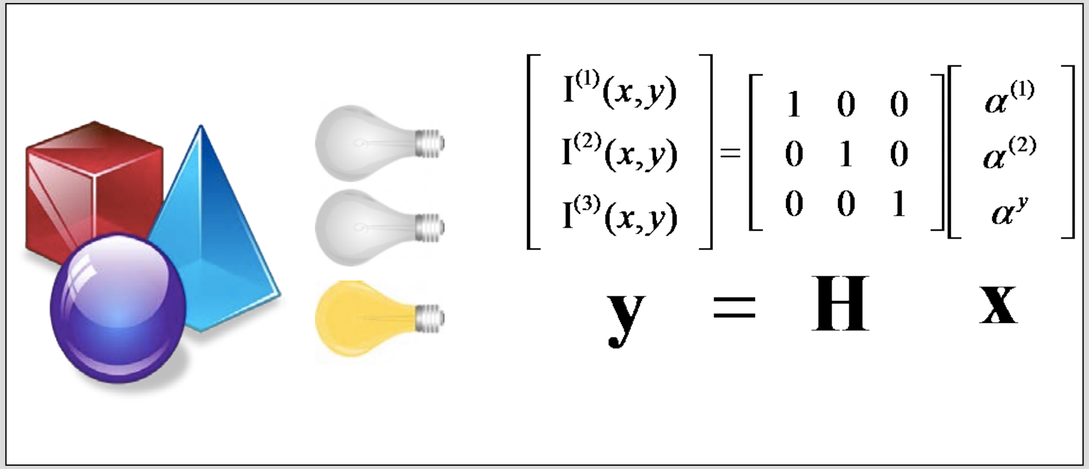
Decimation Matrix



Time of Flight Cameras



Illumination Multiplexing



Decimation Matrix