

New Techniques in Computational photography

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Some (tentative) definitions

- *computational imaging*
 - any image formation method that requires a digital computer
 - first used in medical imaging and remote sensing
- *computational photography*
 - computational imaging techniques that enhance or extend the capabilities of digital photography
 - output is an ordinary photograph, but one that could not have been taken by a traditional camera

19 papers on computational photography at SIGGRAPH 2007

- Image Analysis & Enhancement
 - Image Deblurring with Blurred/Noisy Image Pairs
 - Photo Clip Art
 - Scene Completion Using Millions of Photographs
- Image Slicing & Stretching
 - Soft Scissors: An Interactive Tool for Realtime High Quality Matting
 - Seam Carving for Content-Aware Image Resizing
- Light Field & High-Dynamic-Range Imaging
 - Veiling Glare in High-Dynamic-Range Imaging
 - Ldr2Hdr: On-the-Fly Reverse Tone Mapping of Legacy Video and Photographs
- Appearance Capture & Editing
 - Multiscale Shape and Detail Enhancement from Multi-light Image Collections
- Computational Cameras
 - Active Refocusing of Images and Videos
 - Multi-Aperture Photography
 - Dappled Photography: Mask-Enhanced Cameras for Heterodyned Light Fields and Coded Aperture Refocusing
 - Image and Depth from a Conventional Camera with a Coded Aperture
- Big Images
 - Capturing and Viewing Gigapixel Images
 - Efficient Gradient-Domain Compositing Using Quadrees
 - Image Upsampling via Imposed Edge Statistics
 - Joint Bilateral Upsampling
- Video Processing
 - Factored Time-Lapse Video
 - Computational Time-Lapse Video
 - Real-Time Edge-Aware Image Processing With the Bilateral Grid

Computational Photography

Film-like
Photography
with bits

Digital
Photography

Image processing applied to captured images to produce better images.

Examples:
Interpolation, Filtering, Enhancement, Dynamic Range Compression, Color Management, Morphing, Hole Filling, Artistic Image Effects, Image Compression, Watermarking.



Computational Camera

Computational Processing

Processing of a set of captured images to create new images.

Examples:
Mosaicing, Matting, Super-Resolution, Multi-Exposure HDR, Light Field from Multiple View, Structure from Motion, Shape from X.

Computational Imaging/Optics

Capture of optically coded images and computational decoding to produce new images.

Examples:
Coded Aperture, Optical Tomography, Diaphanography, SA Microscopy, Integral Imaging, Assorted Pixels, Catadioptric Imaging, Holographic Imaging.

Computational Sensor

Detectors that combine sensing and processing to create smart pixels.

Examples:
Artificial Retina, Retinex Sensors, Adaptive Dynamic Range Sensors, Edge Detect Chips, Focus of Expansion Chips, Motion Sensors.

Smart Light

Computational Illumination

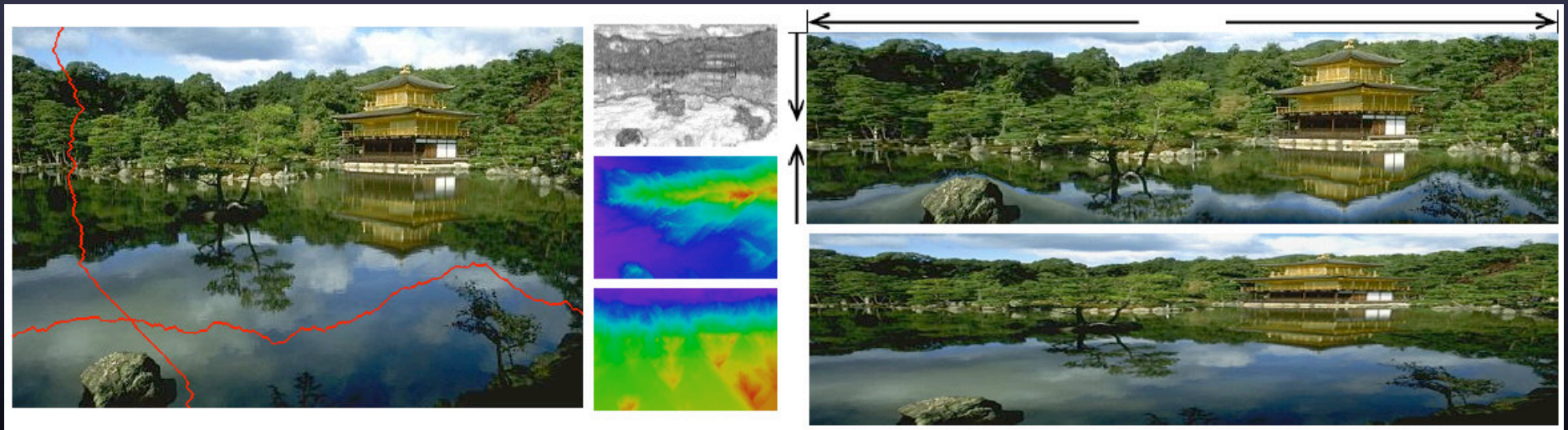
Adapting and Controlling Illumination to Create revealing image

Examples:
Flash/no flash, Lighting domes, Multi-flash for depth edges, Dual Photos, Polynomial texture Maps, 4D light source

Content-aware image resizing

[Avidan SIGGRAPH 2007]

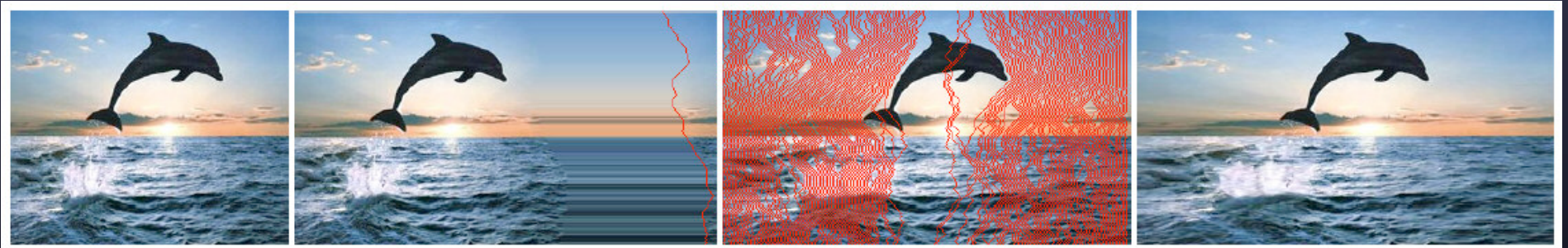
- to compress: remove pixels along lowest-energy seams, ordered using dynamic programming
- to expand: insert pixels along seams that, if removed in order, would yield the original image



Content-aware image resizing

[Avidan SIGGRAPH 2007]

- to compress: remove pixels along lowest-energy seams, ordered using dynamic programming
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Content-aware image resizing

[Avidan SIGGRAPH 2007]

- to compress: remove pixels along lowest-energy seams, ordered using dynamic programming
- to expand: insert pixels in order, with lowest energy
- application to object removal



Content-aware image resizing

[Avidan SIGGRAPH 2007]

- to compress: remove pixels along lowest-energy seams, ordered using dynamic programming
- to expand: insert pixels in order
- application to object removal
- Find the missing shoe!
(original in upper-left)



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- to expand: insert pixels in order
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(original in upper-left)

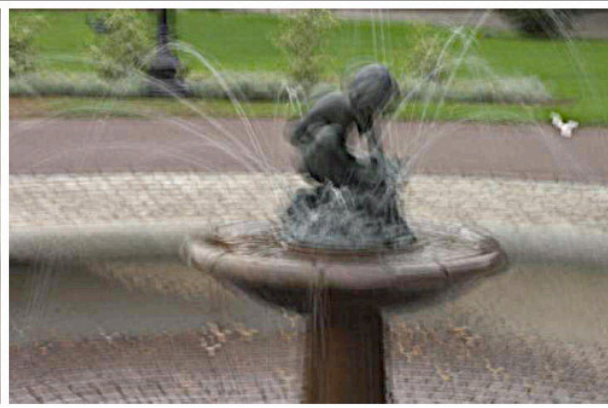


Removing camera shake

[Fergus SIGGRAPH 2006]



image with camera shake



Photoshop Unsharp Mask



deconvolution



blur kernel

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Gigapixel mosaicing

[xyrez.com]



The camera

Gigapixel mosaicing

[xyrez.com]



A gigapixel image of Half Dome

Gigapixel mosaicing

[xyrez.com]



Gigapixel mosaicing

[xyrez.com]



High dynamic range (HDR) imaging



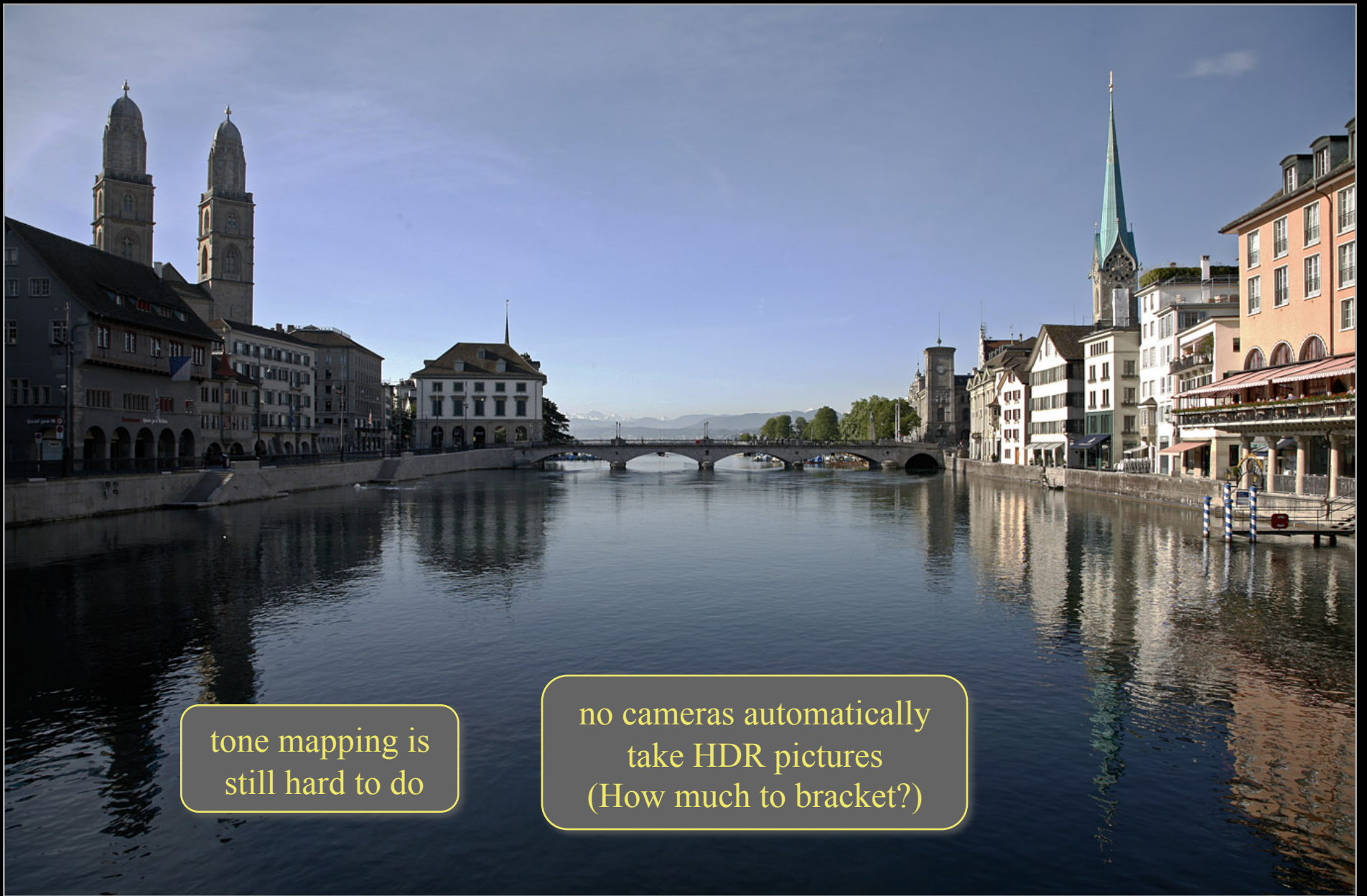
Too dark



Too bright



Tone mapped combination, but...



tone mapping is
still hard to do

no cameras automatically
take HDR pictures
(How much to bracket?)

Tone mapped combination, but...

Image stacks

[Agarwala SIGGRAPH 2004]



- multi-shot images
 - shoot until everybody has smiled at least once

Image stacks

[Agarwala SIGGRAPH 2004]



– segment

Digital Photomontage

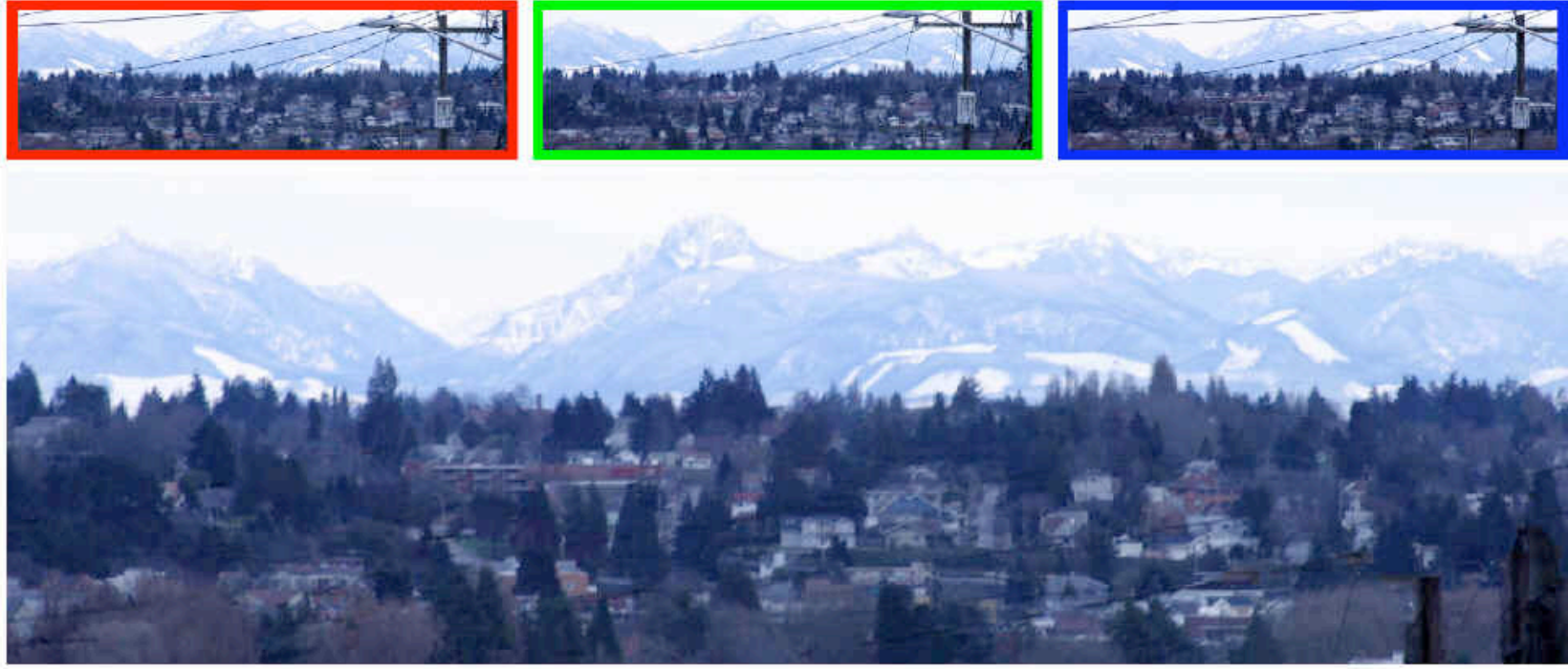
[Agarwala SIGGRAPH 2004]



– assemble

Digital Photomontage

[Agarwala SIGGRAPH 2004]



- remove foreground objects that don't appear in all shots as the camera translates (based on median filter)

Removing camera shake (again)

- deconvolve long-exposure (blurred) image, using short-exposure (noisy) image as prior [Yuan SIGGRAPH 2007]



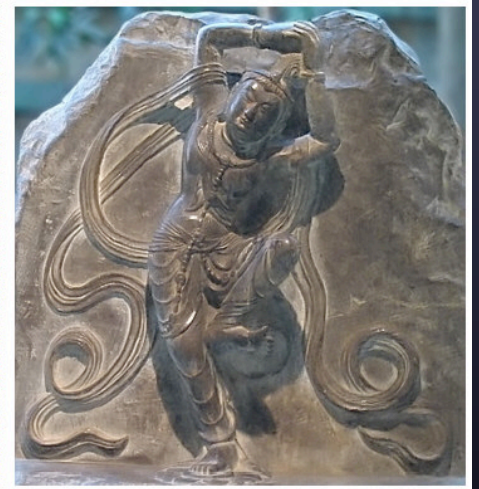
long exposure
(blurry)



short exposure
(dark)



same, scaled up
(noisy)

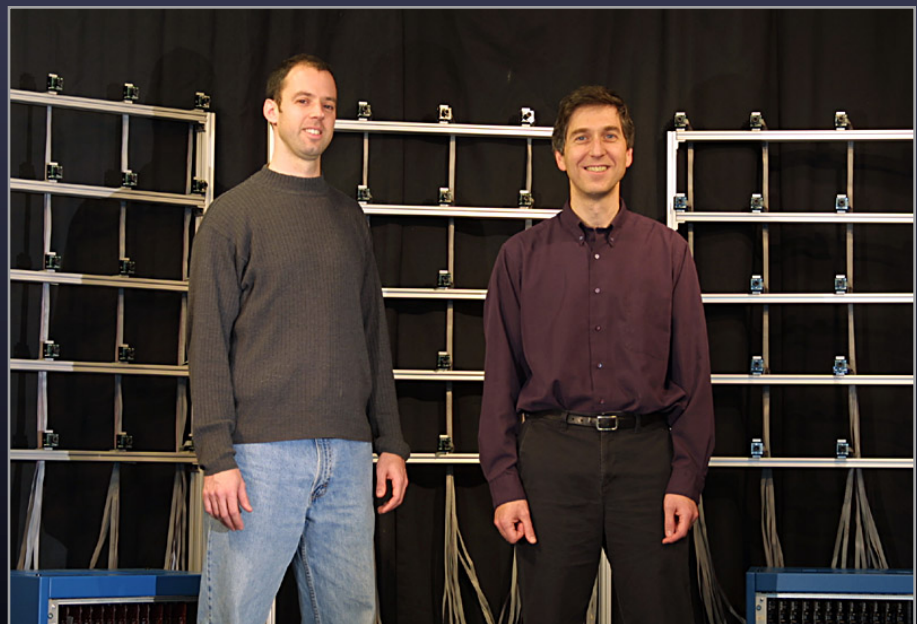
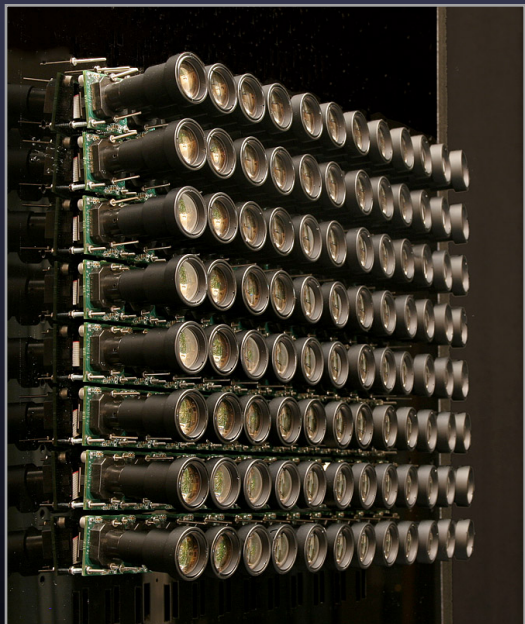


joint deconvolution

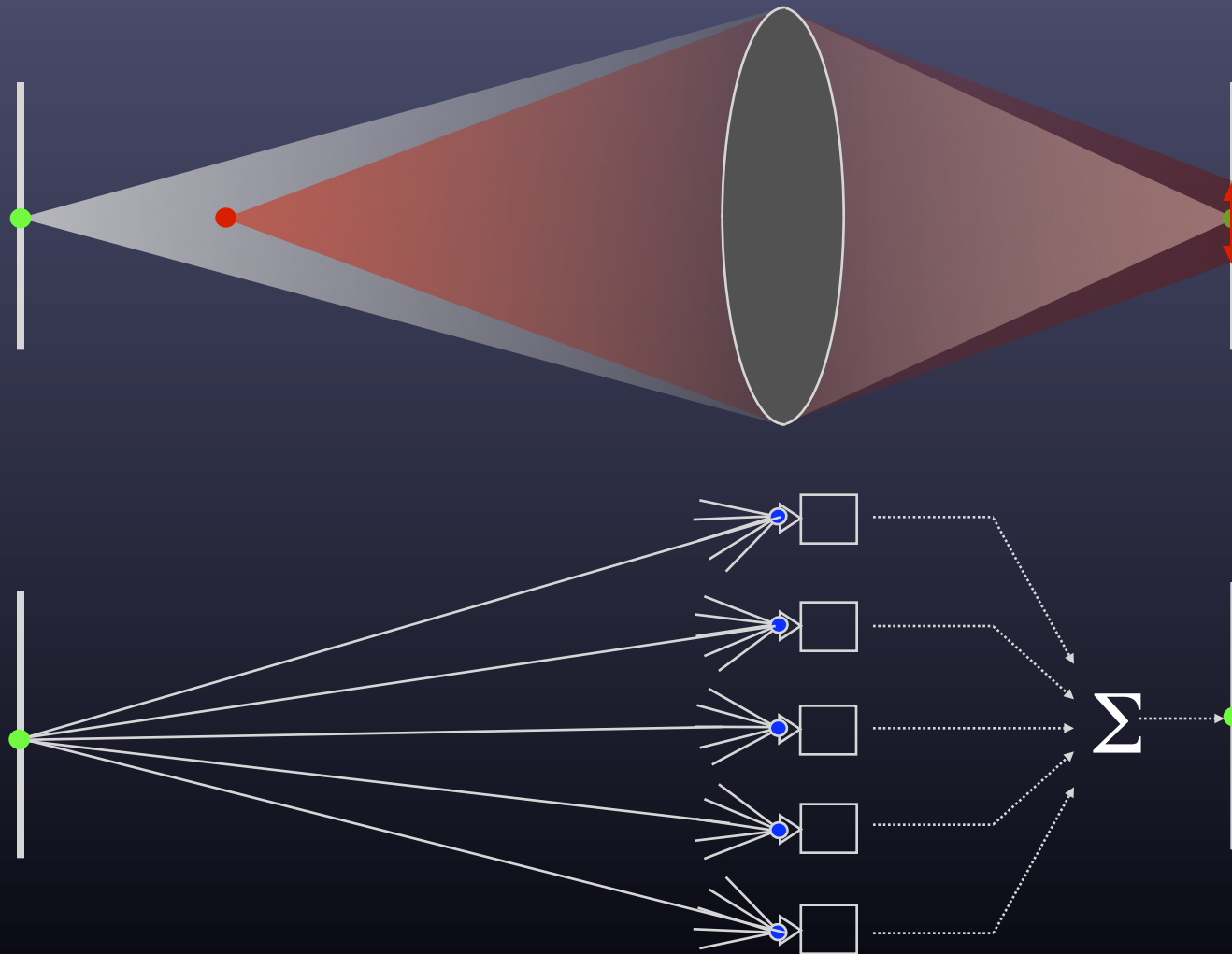
Stanford Multi-Camera Array

[Wilburn SIGGRAPH 2005]

- 640×480 pixels \times
30 fps \times 128 cameras
- synchronized timing
- continuous streaming
- flexible arrangement

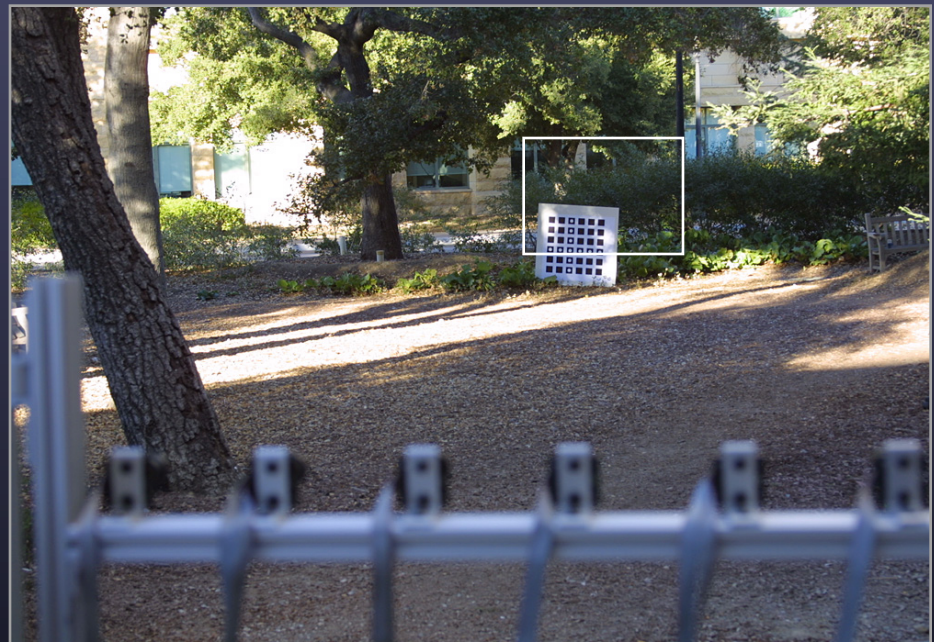
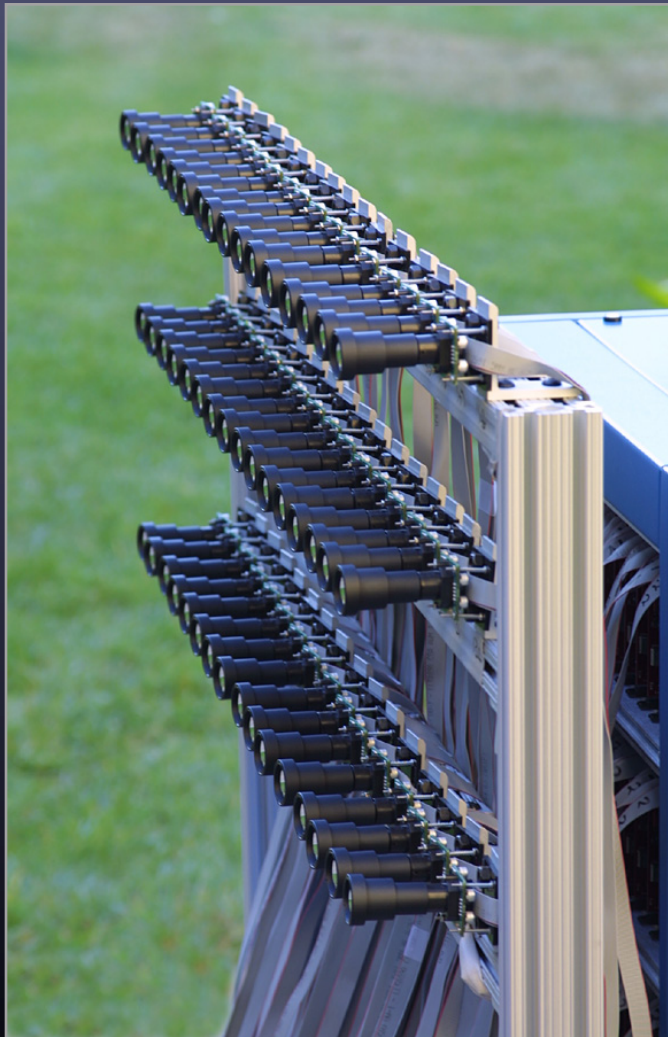


Synthetic aperture photography



Example using 45 cameras

[Vaish CVPR 2004]





one camera's view



synthetic aperture view

(movie is available at <http://graphics.stanford.edu/projects/array>)

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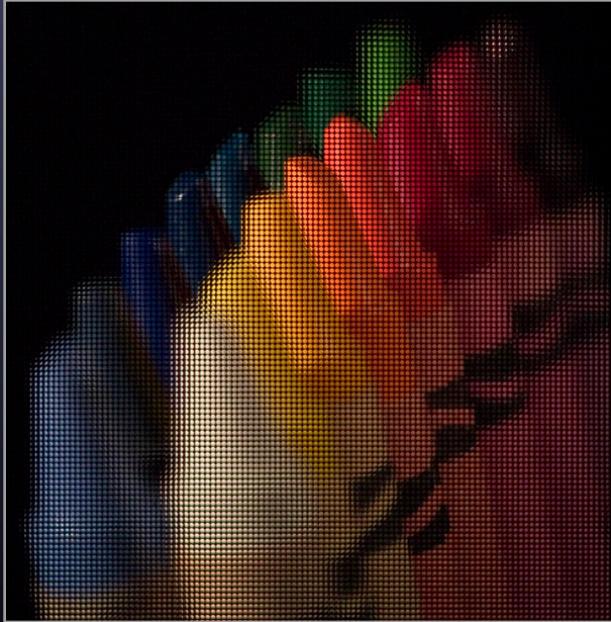
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Light field photography using a handheld plenoptic camera

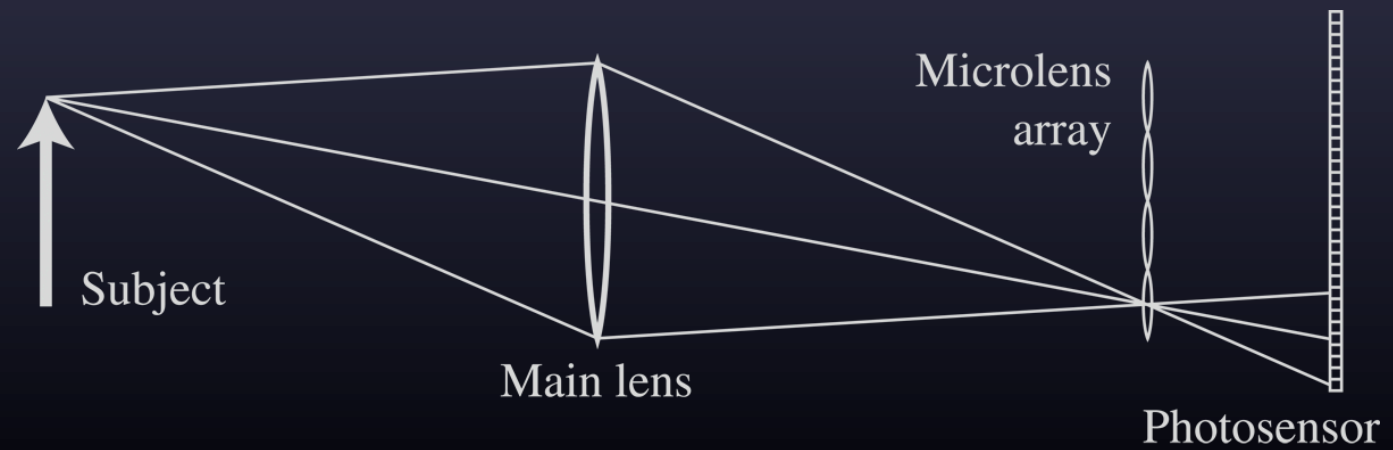
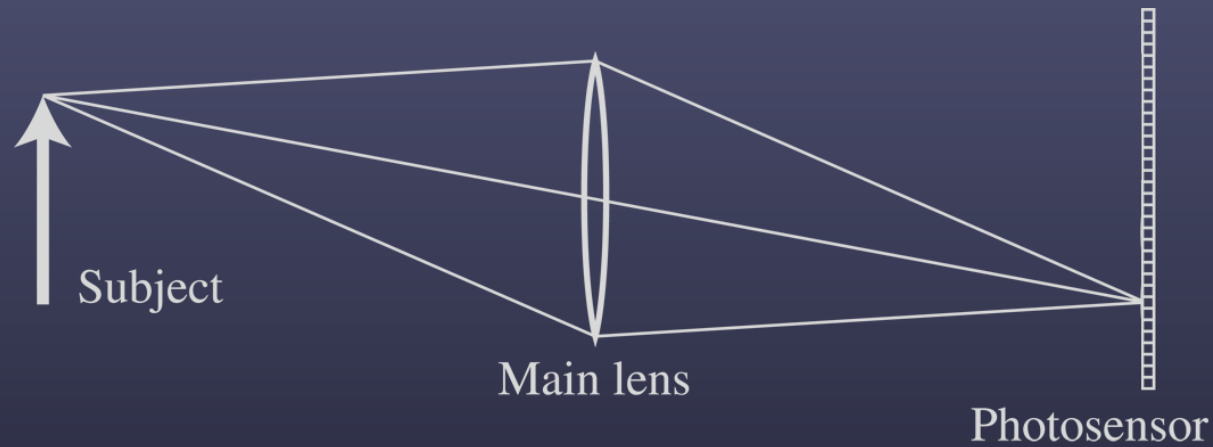
*Ren Ng, Marc Levoy, Mathieu Brédif,
Gene Duval, Mark Horowitz and Pat Hanrahan*

*(Proc. SIGGRAPH 2005
and TR 2005-02)*



Plenoptic camera

[Ng SIGGRAPH 2005]



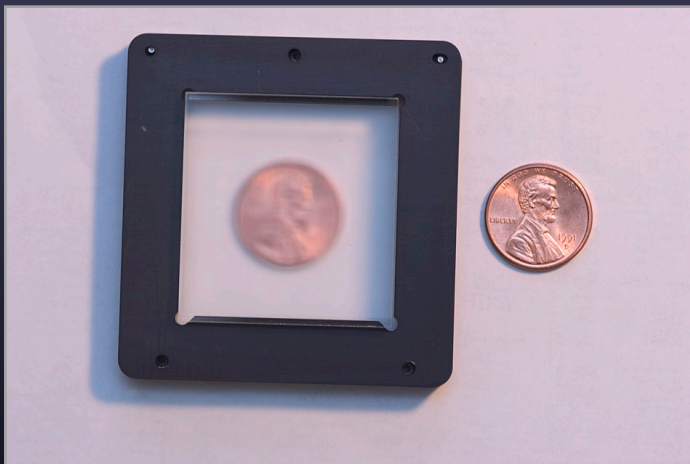
Prototype camera



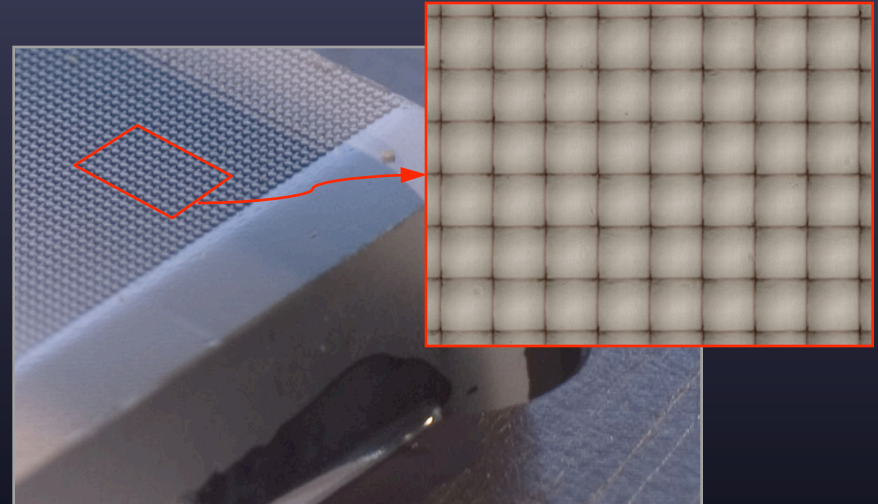
Contax medium format camera



Kodak 16-megapixel sensor



Adaptive Optics microlens array



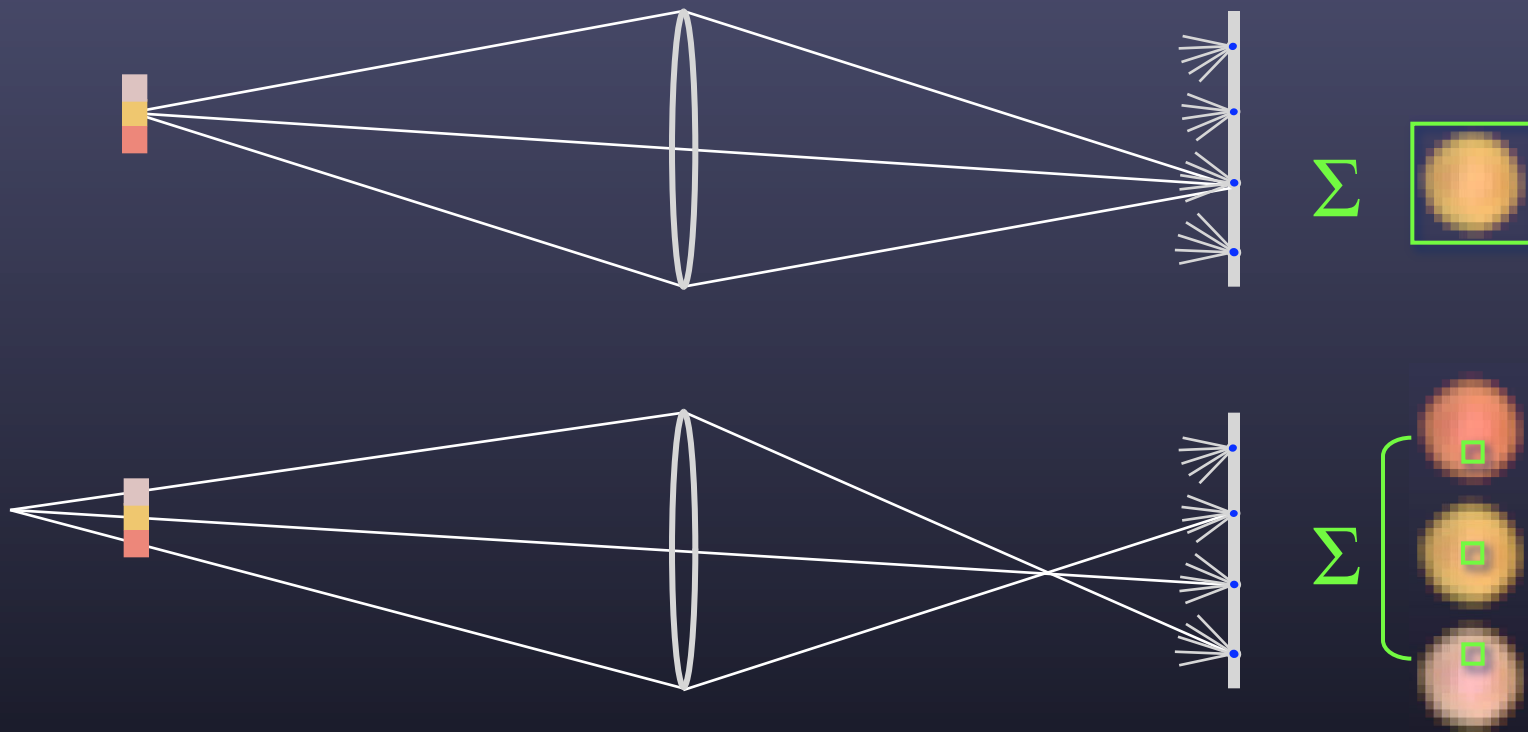
125 μ square-sided microlenses

$$4000 \times 4000 \text{ pixels} \div 292 \times 292 \text{ lenses} = 14 \times 14 \text{ pixels per lens}$$



Typical image captured by camera (show here at low res)

Digital refocusing



Example of digital refocusing



Example of digital refocusing



Example of digital refocusing



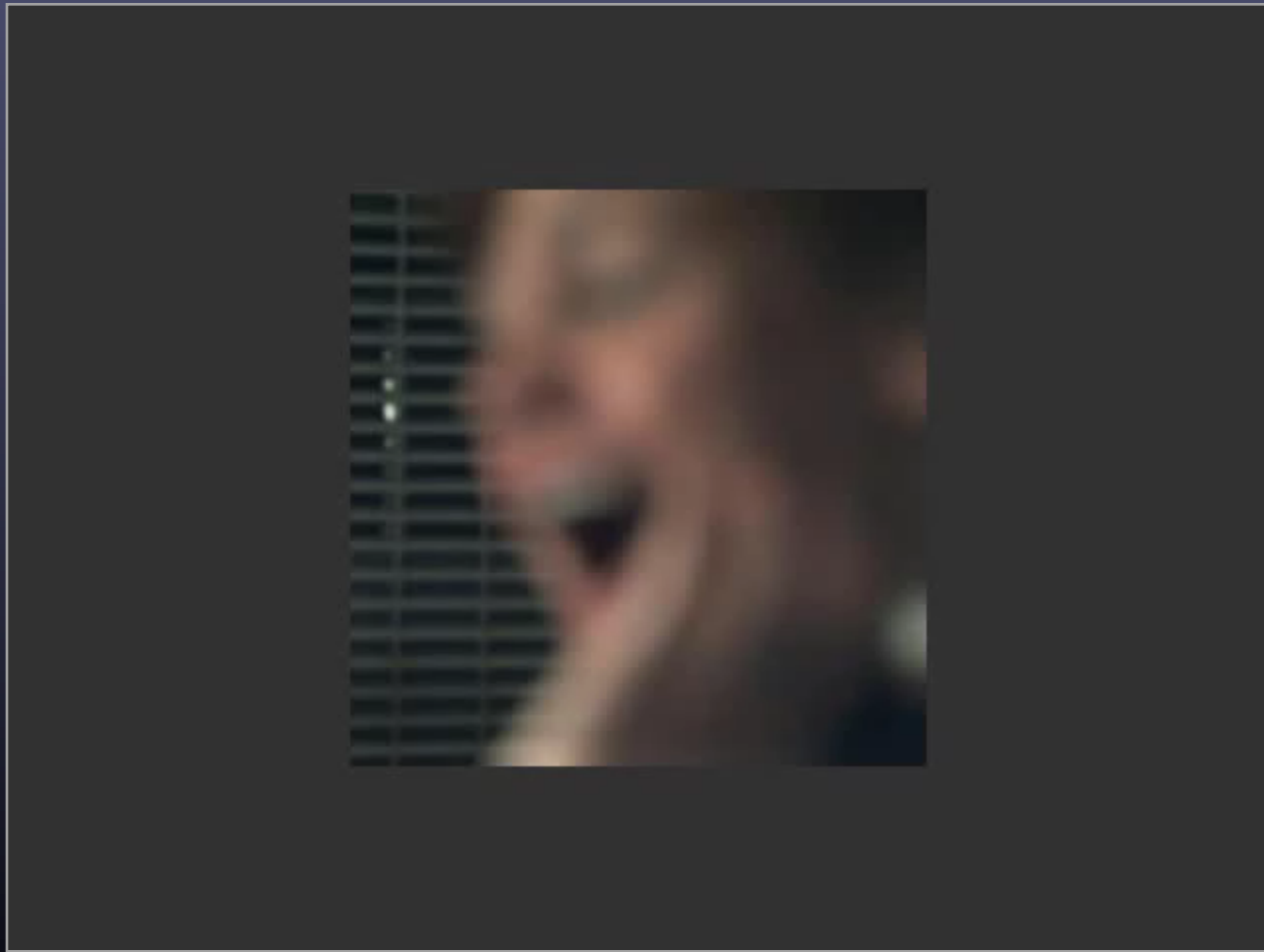
Example of digital refocusing



Example of digital refocusing



Refocusing portraits

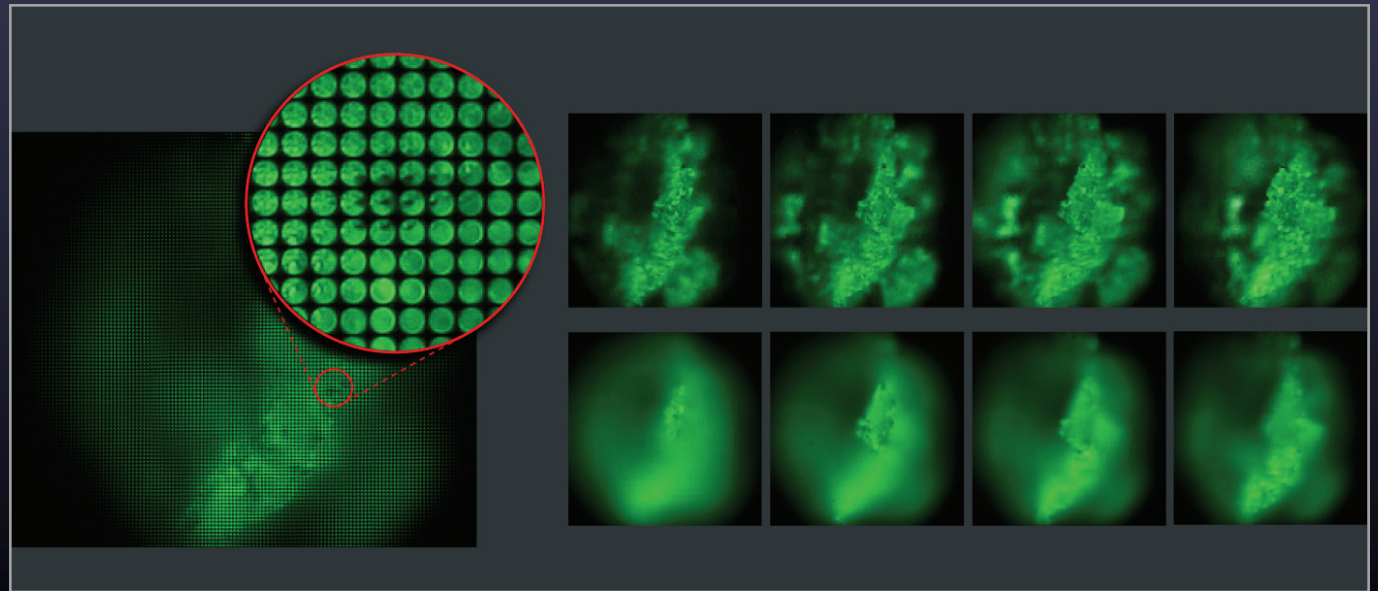
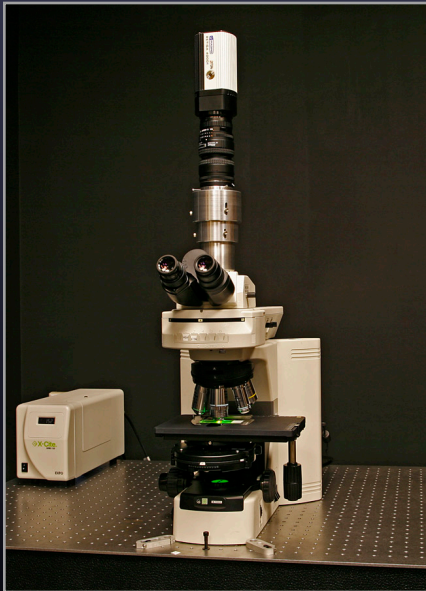


(movie is available at <http://refocusimaging.com>)

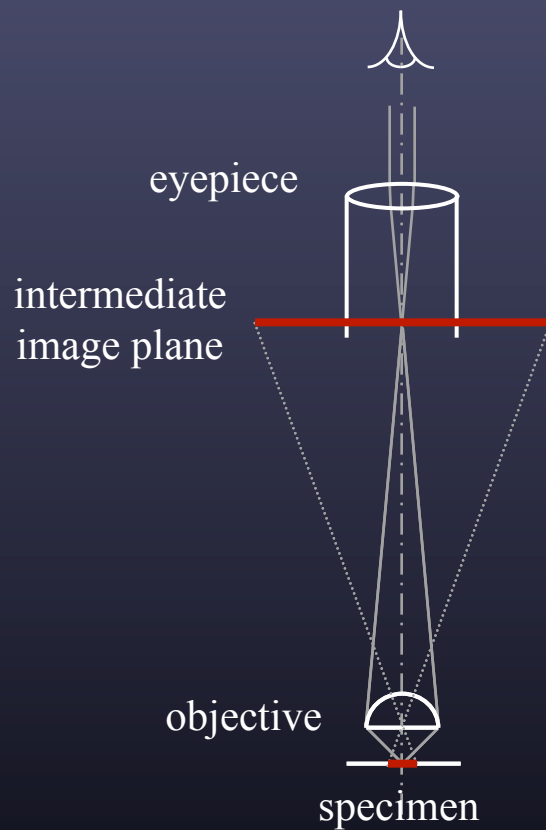
Light Field Microscopy

*Marc Levoy, Ren Ng, Andrew Adams,
Matthew Footer, and Mark Horowitz*

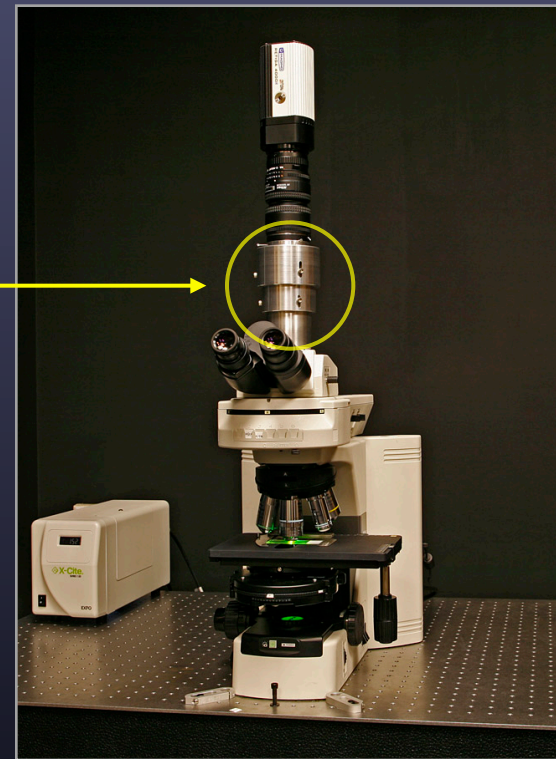
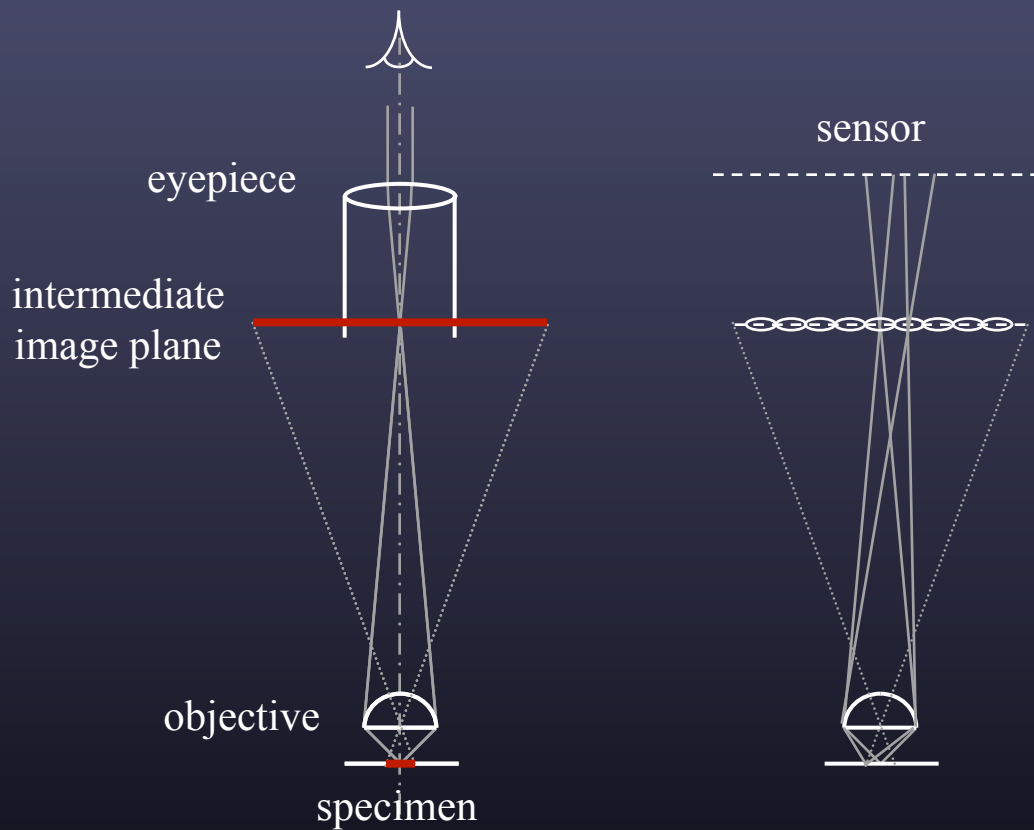
(Proc. SIGGRAPH 2006)



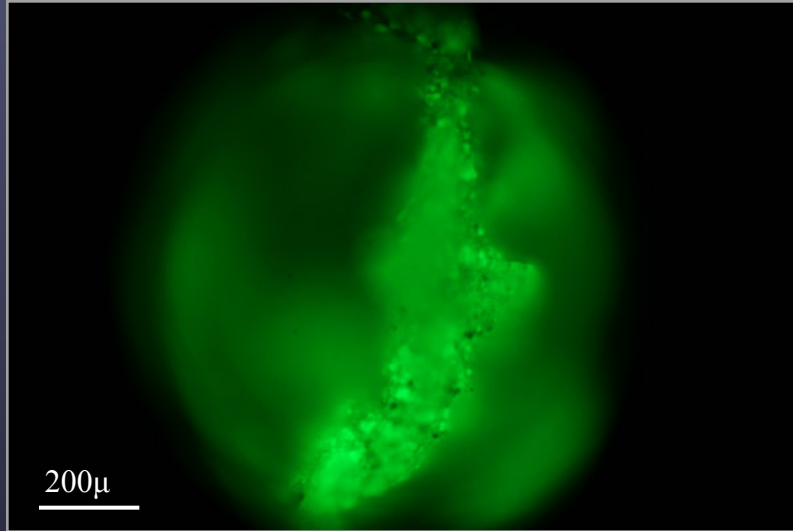
A traditional microscope



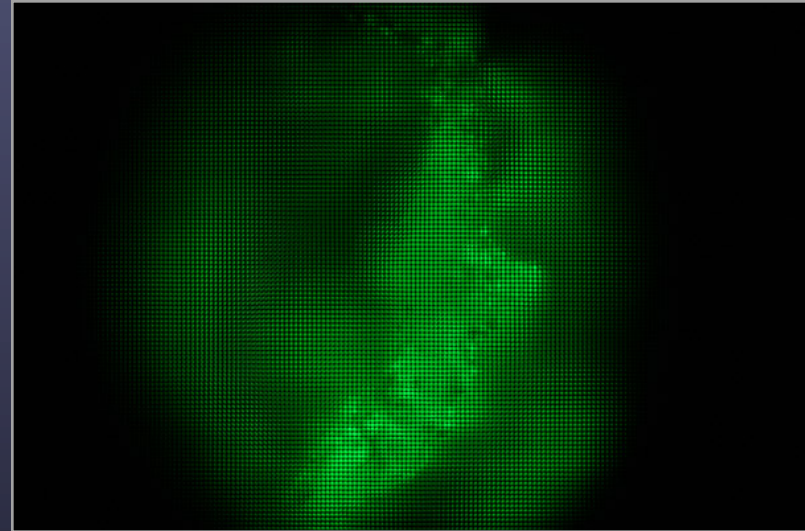
A light field microscope (LFM)



Example light field micrograph



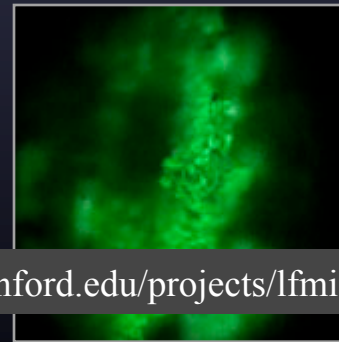
ordinary microscope



light field microscope



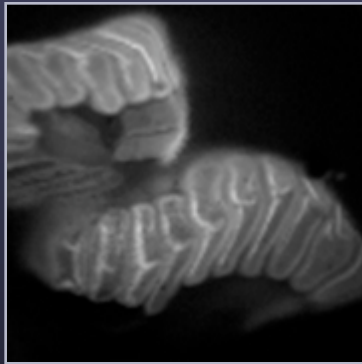
focal stack



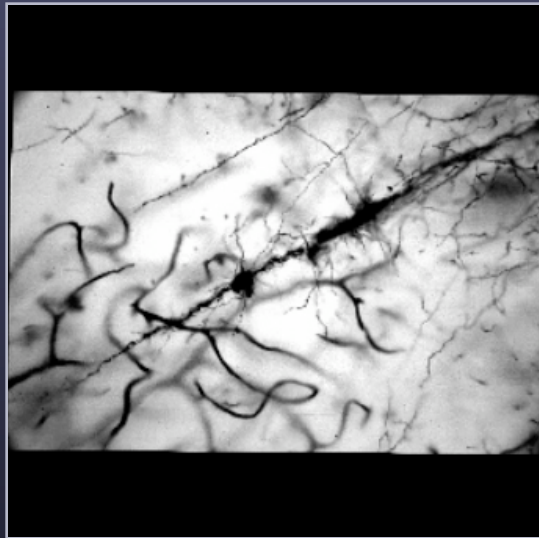
panning sequence

(movies are available at <http://graphics.stanford.edu/projects/lfmicroscope>)

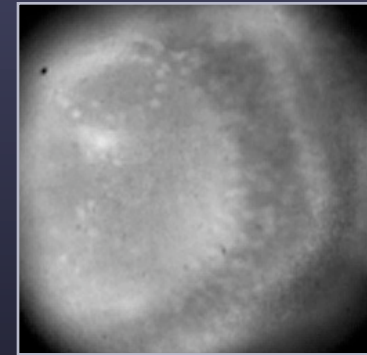
Other examples



fern spore
(60x, autofluorescence)



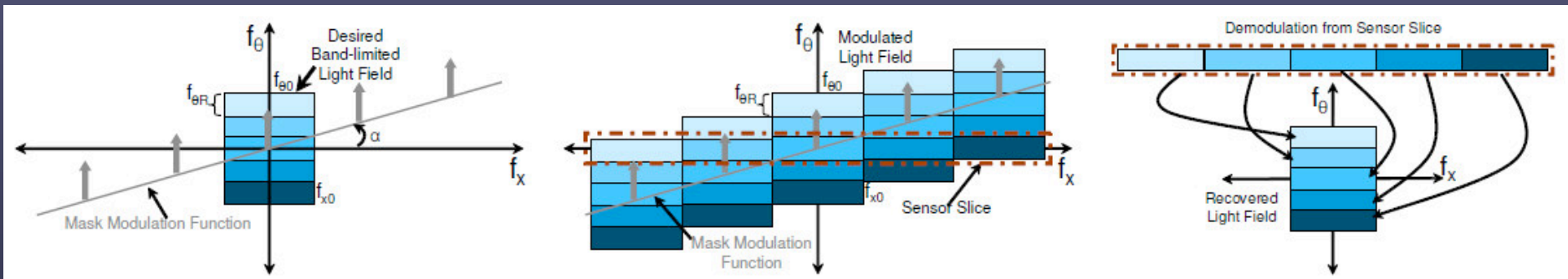
Golgi-stained neurons
(40x, transmitted light)



zebrafish optic tectum
(calcium imaging
of neural activity)

(movies are available at <http://graphics.stanford.edu/projects/lfmicroscope>)

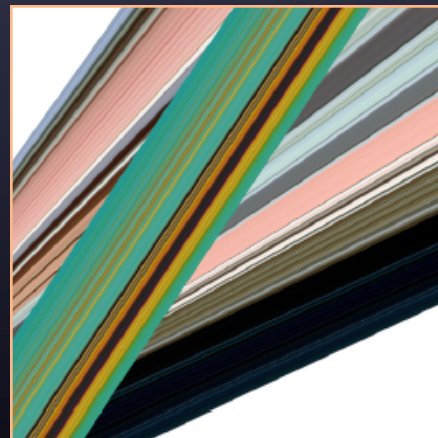
Alternatives to microlenses



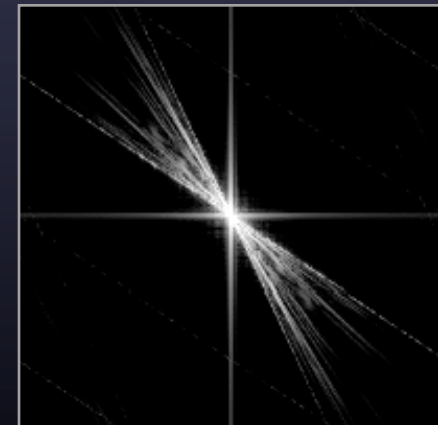
- heterodyning using structured masks
[Veeraraghavan & Raskar SIGGRAPH 2007]



3D scene

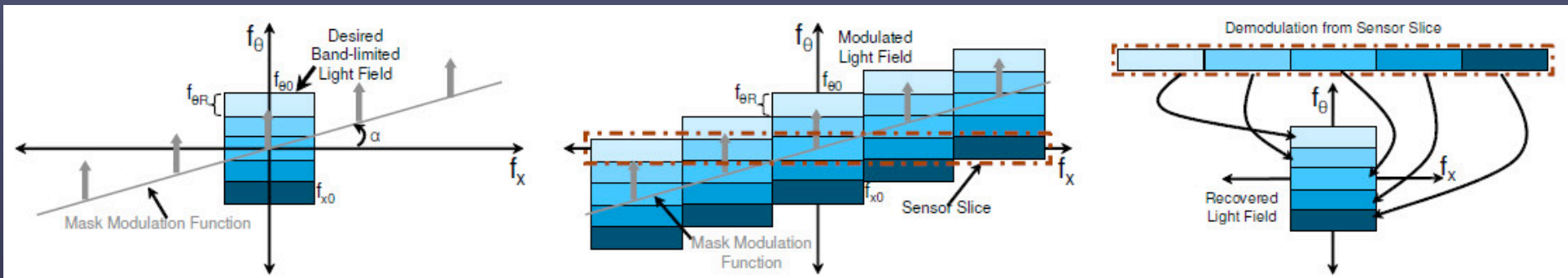


ray space



Fourier transform

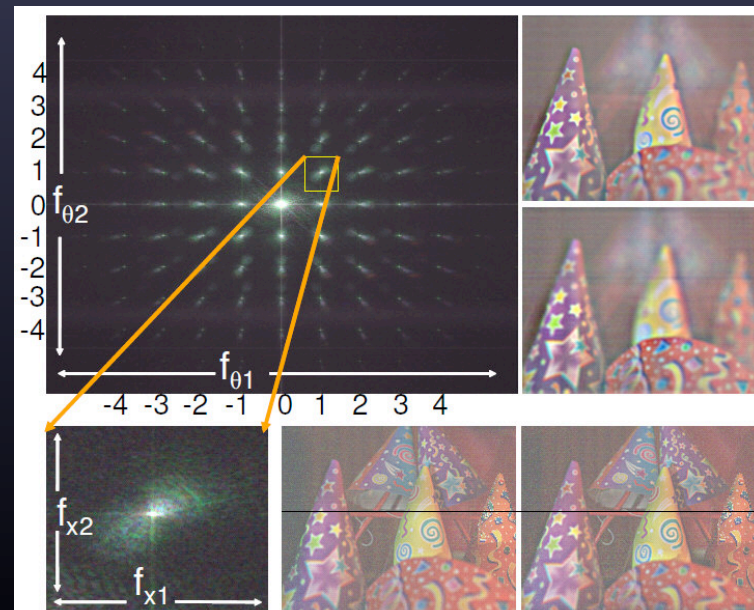
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[Veeraraghavan & Raskar SIGGRAPH 2007]

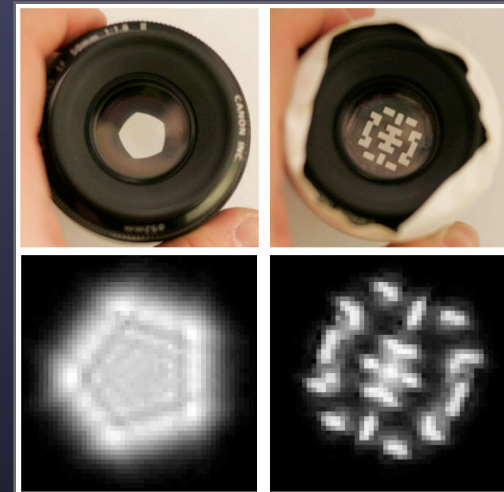
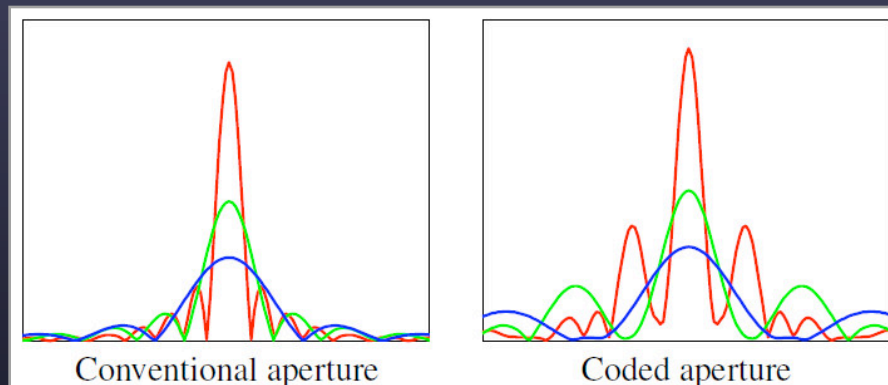


mask



Controlling focus using coded or structured apertures

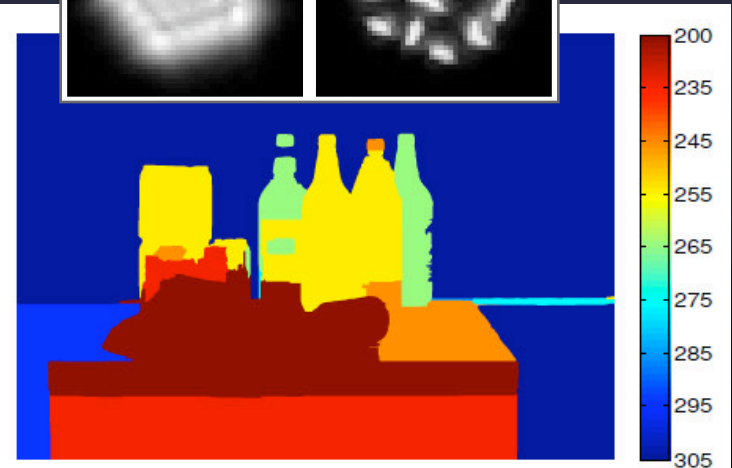
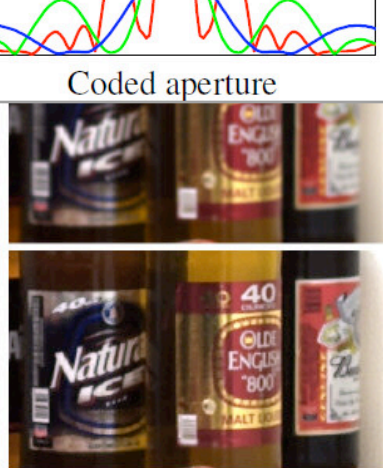
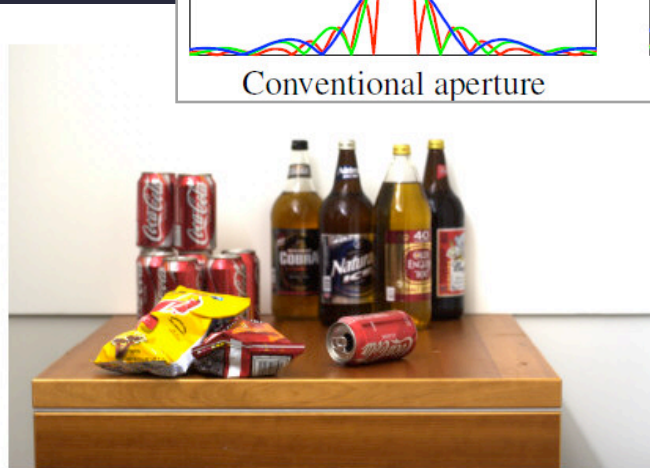
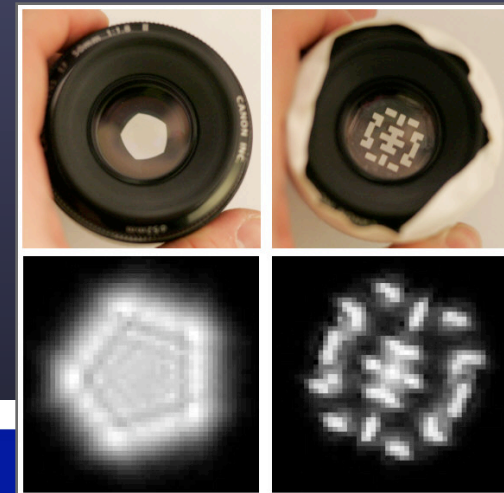
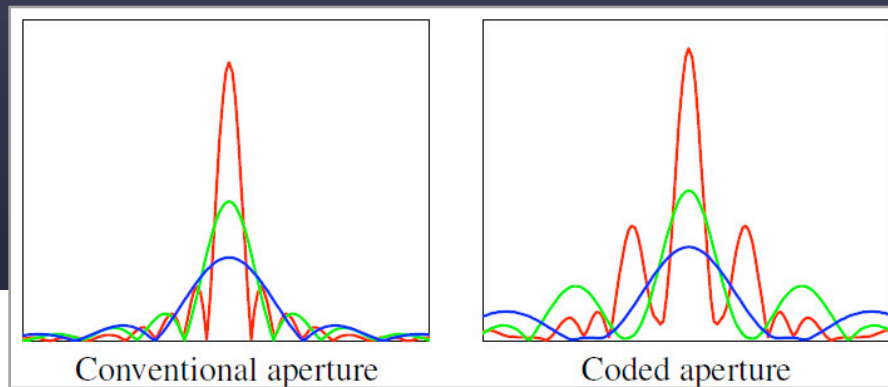
- binary mask at the aperture plane
[Levin & Fergus SIGGRAPH 2007]



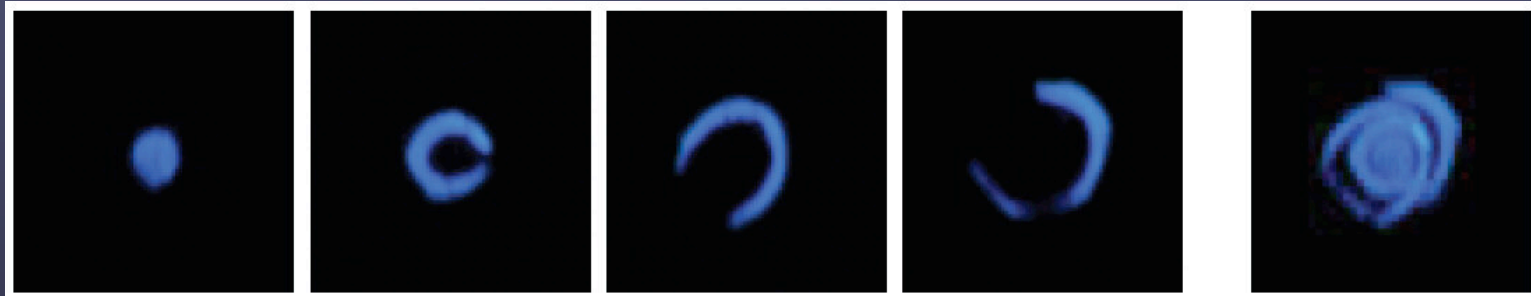
Fourier transforms of blur patterns
for different amounts of defocus
(note locations of zeros)

Controlling focus using coded or structured apertures

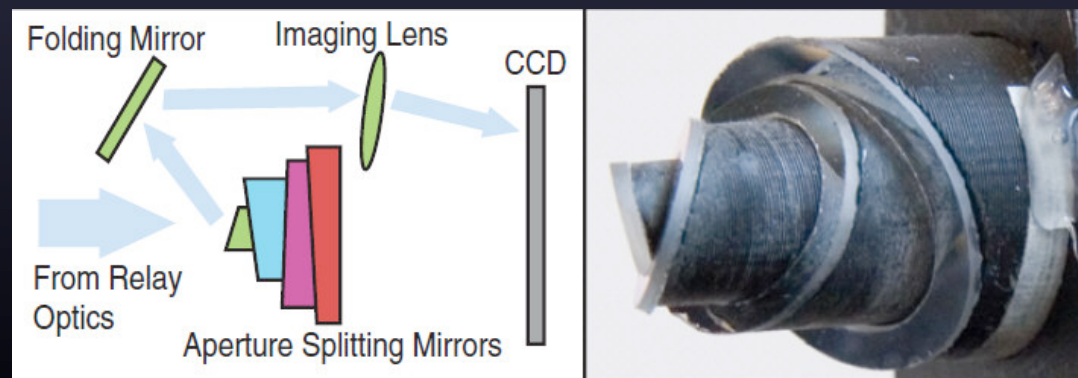
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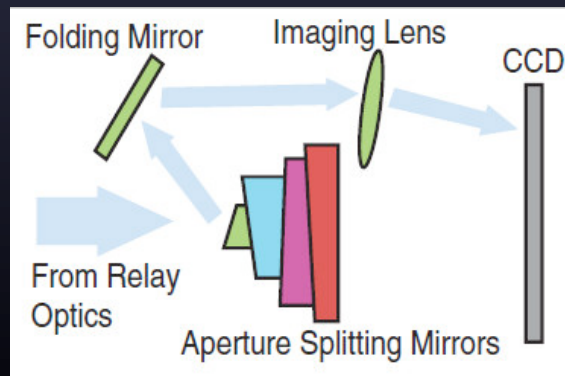
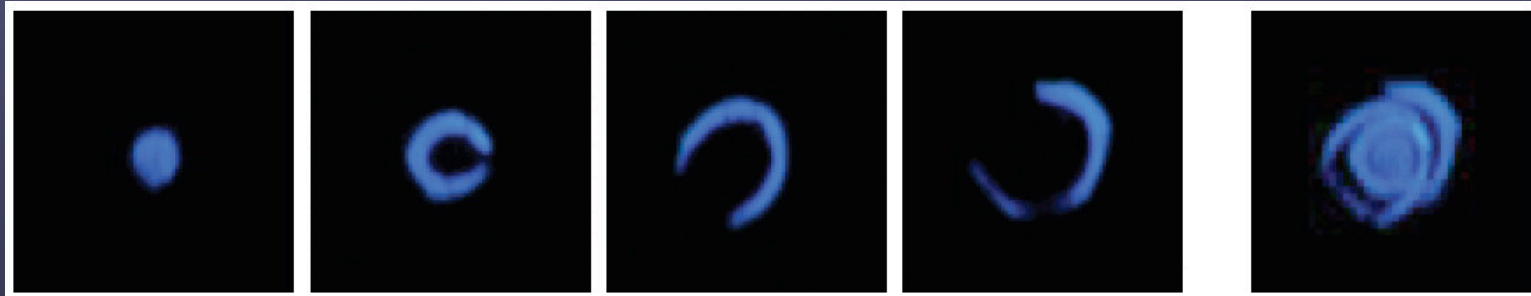
Controlling focus using coded or structured apertures



- multiple concentric annulus apertures
[Green & Durand SIGGRAPH 2007]

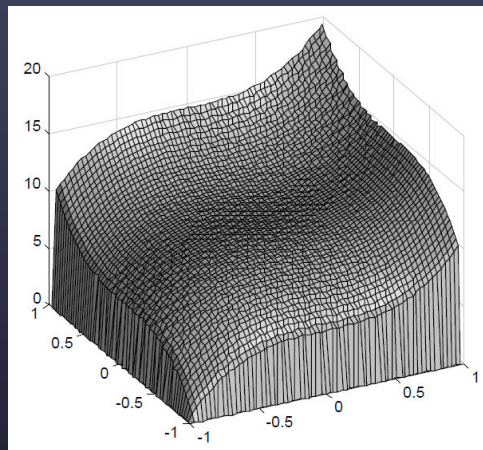


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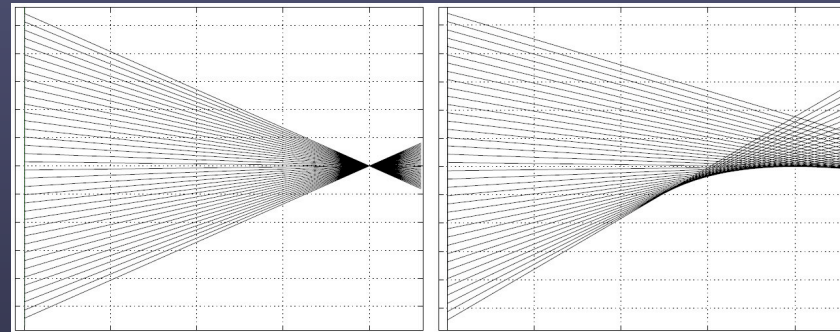


Wavefront coding

[Dowski 1995]

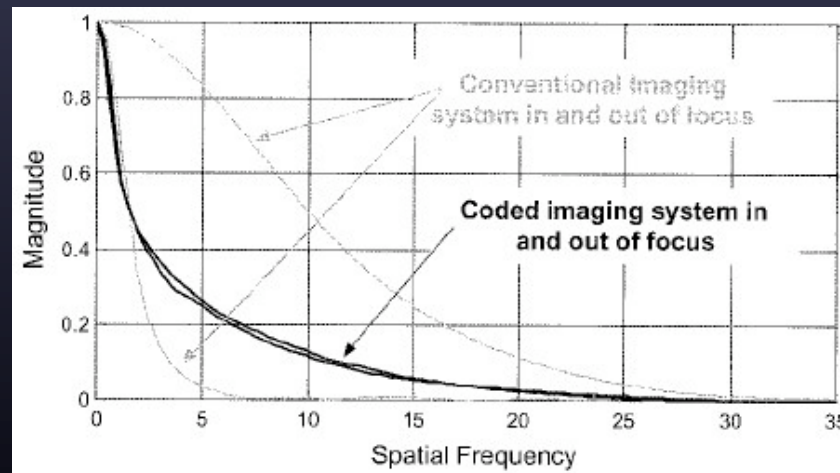


profile of
cubic phase plate



ray trace through
a normal lens

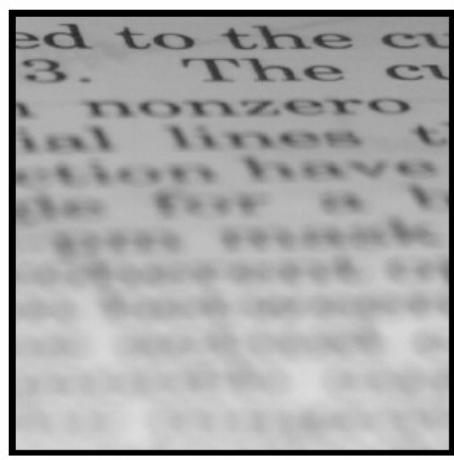
lens plus
cubic phase plate



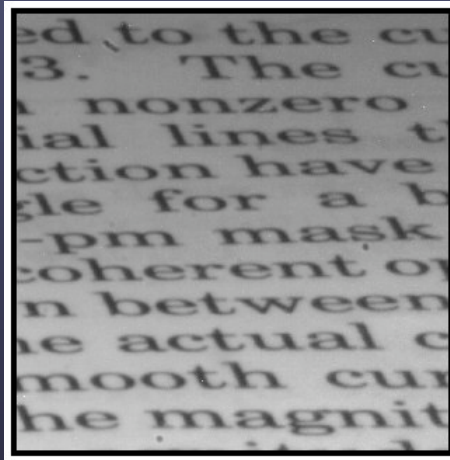
MTFs through lens and cubic phase plate

Wavefront coding

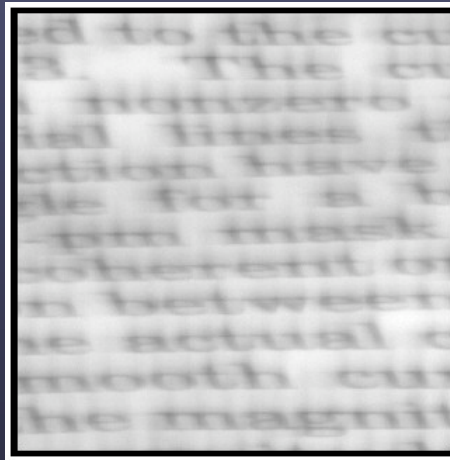
[Dowski 1995]



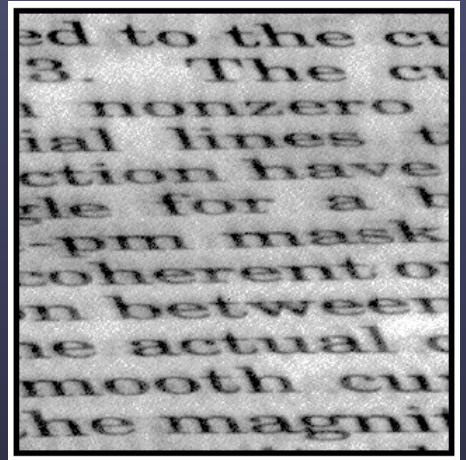
normal lens



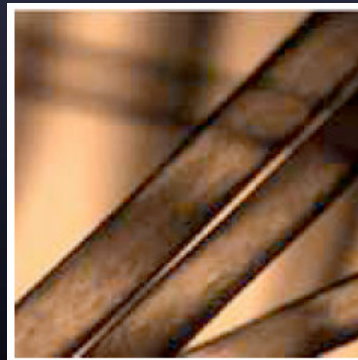
stopped down



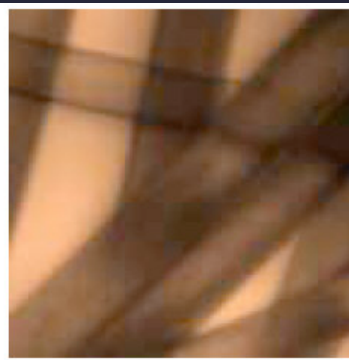
wavefront coded



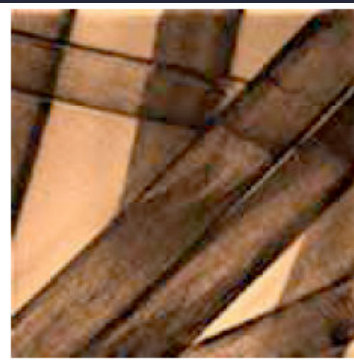
after processing



normal



wavefront



processed

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Photography
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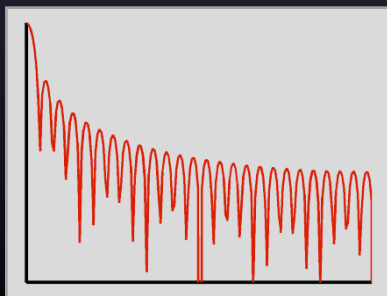
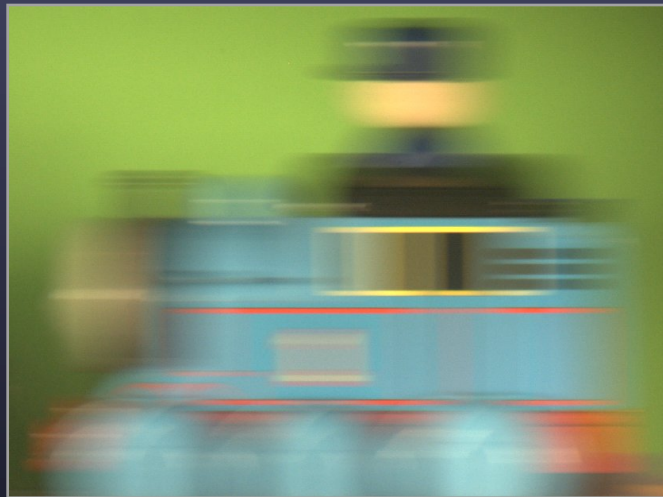
Examples:
Flash/no flash, Lighting domes, Multi-flash for depth edges, Dual Photos, Polynomial texture Maps, 4D light source



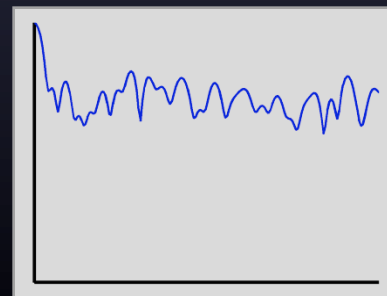
Coded-exposure photography

[Raskar SIGGRAPH 2006]

continuous shutter



fluttered shutter

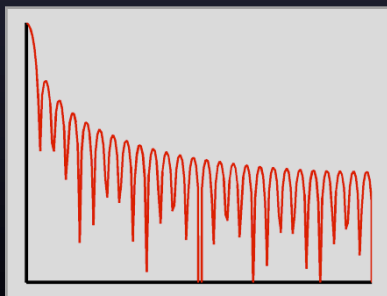
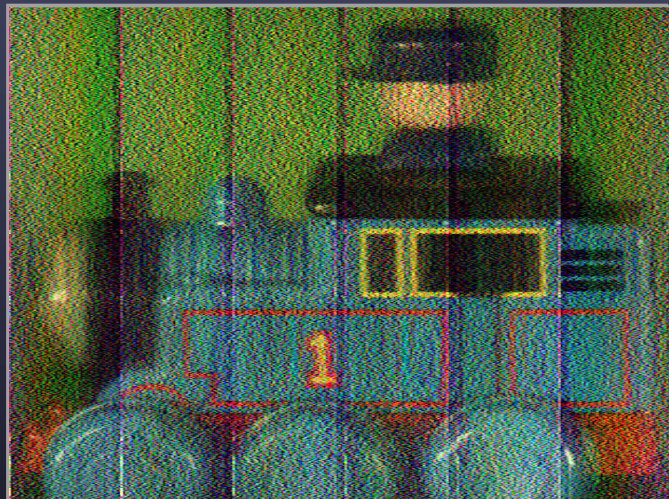


Fourier transforms

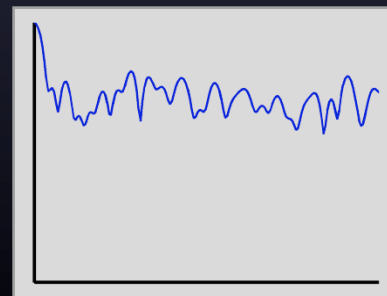
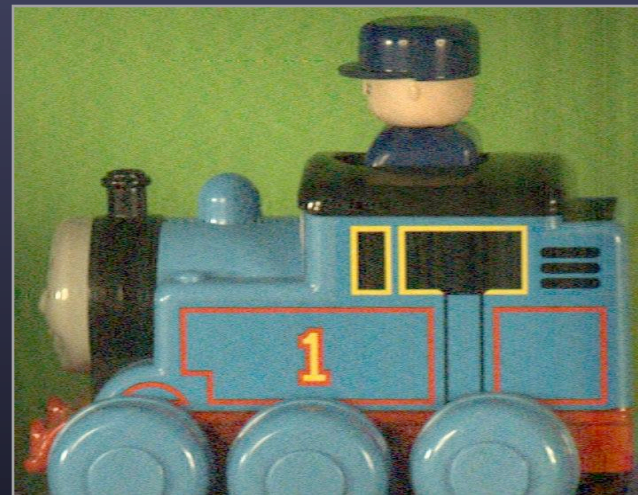
Coded-exposure photography

[Raskar SIGGRAPH 2006]

continuous shutter



fluttered shutter



Fourier transforms



Computational Photography

Film-like
Photography
with bits

Digital
Photography

Image processing applied to captured images to produce better images.

Examples:
Interpolation, Filtering, Enhancement, Dynamic Range Compression, Color Management, Morphing, Hole Filling, Artistic Image Effects, Image Compression, Watermarking.

Computational Camera

Computational Processing

Processing of a set of captured images to create new images.

Examples:
Mosaicing, Matting, Super-Resolution, Multi-Exposure HDR, Light Field from Multiple View, Structure from Motion, Shape from X.

Computational Imaging/Optics

Capture of optically coded images and computational decoding to produce new images.

Examples:
Coded Aperture, Optical Tomography, Diaphanography, SA Microscopy, Integral Imaging, Assorted Pixels, Catadioptric Imaging, Holographic Imaging.

Computational Sensor

Detectors that combine sensing and processing to create smart pixels.

Examples:
Artificial Retina, Retinex Sensors, Adaptive Dynamic Range Sensors, Edge Detect Chips, Focus of Expansion Chips, Motion Sensors.

Smart Light

Computational Illumination

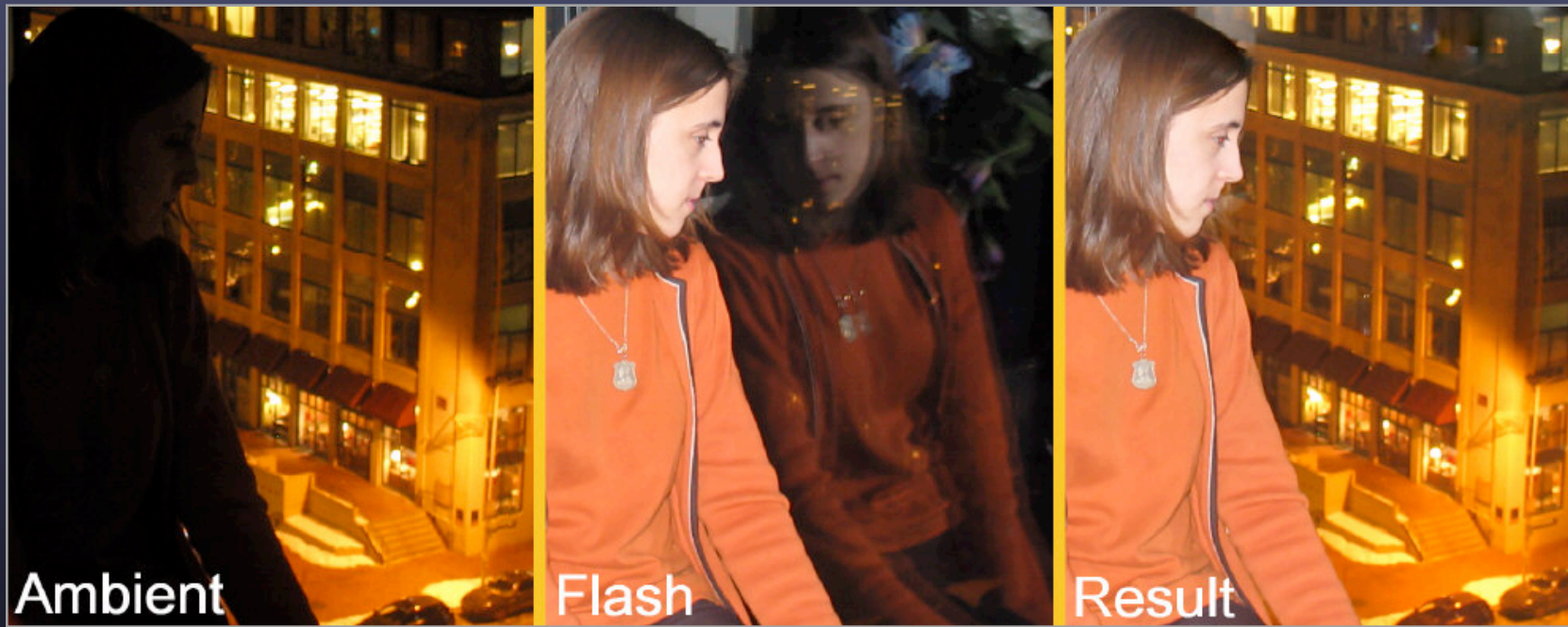
Adapting and Controlling Illumination to Create revealing image

Examples:
Flash/no flash, Lighting domes, Multi-flash for depth edges, Dual Photos, Polynomial texture Maps, 4D light source

[Nayar, Tumblin]

Flash-noflash photography

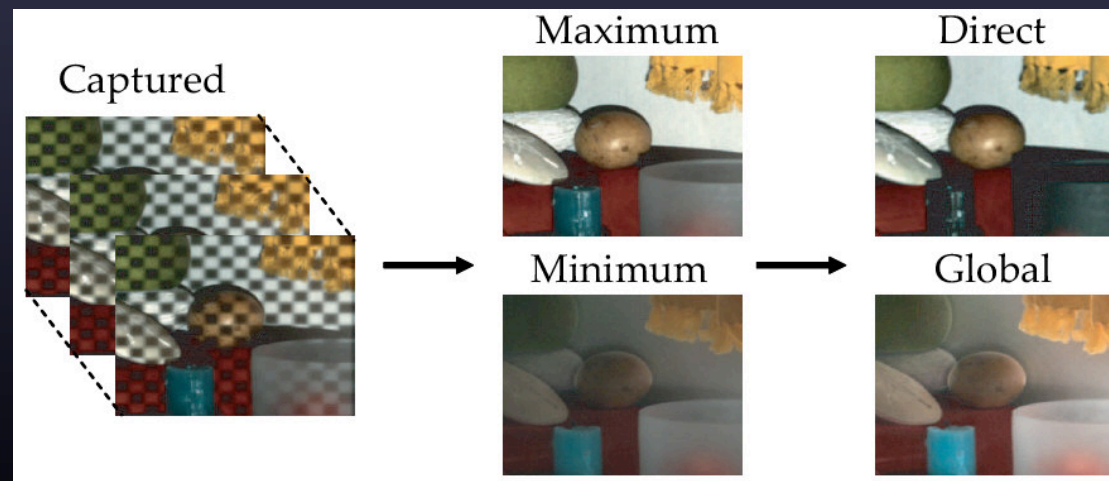
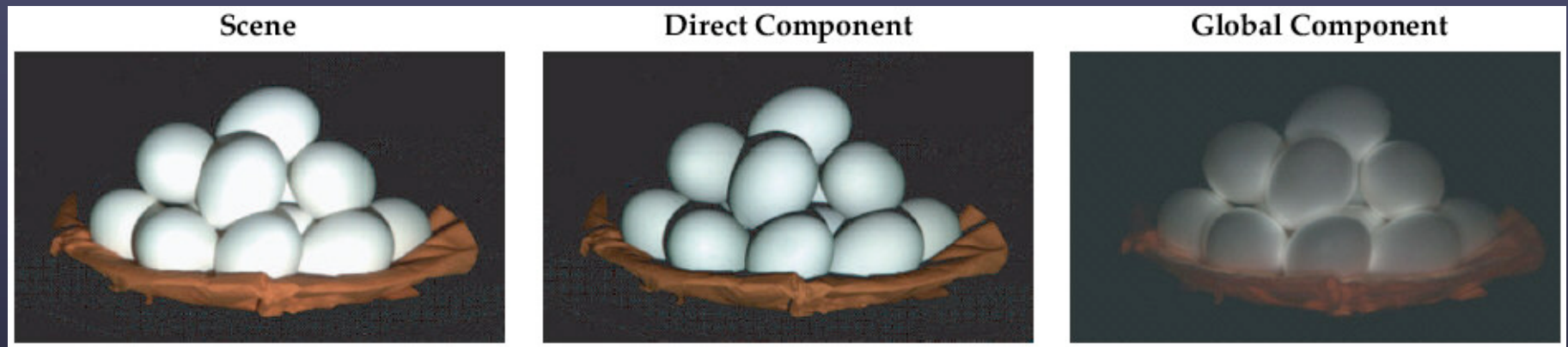
[Agrawal SIGGRAPH 2005]



- compute ambient + flash – features in sum that don't appear in ambient alone (as determined from image gradients) (except where ambient image is nearly black)

Separation of direct and global reflections

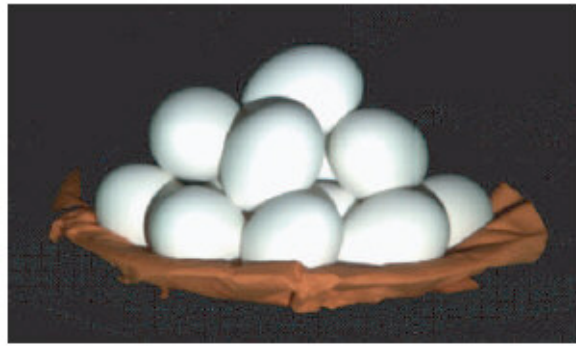
[Nayar SIGGRAPH 2006]



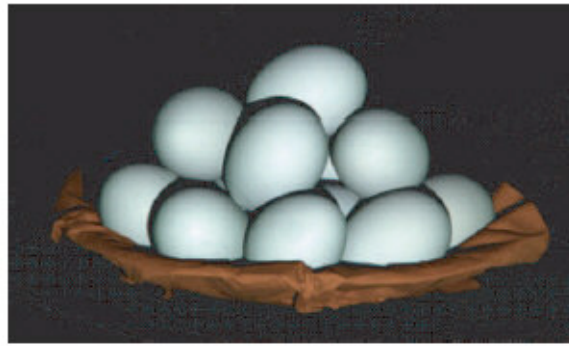
Separation of direct and global reflections

[Nayar SIGGRAPH 2006]

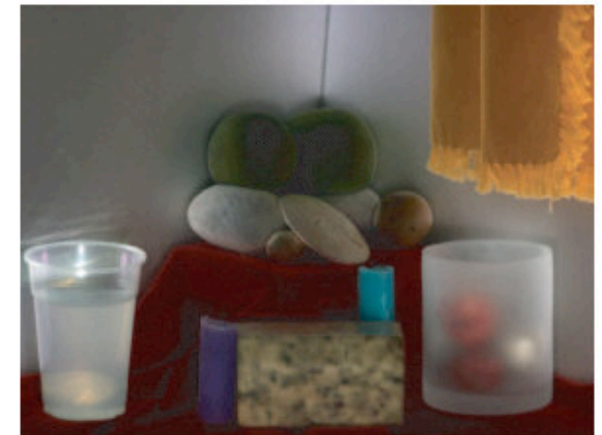
Scene



Direct Component

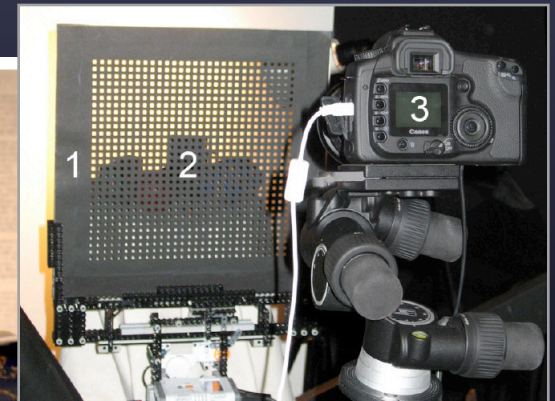


Global Component



Other applications of structured masks conjugate to the scene (not the aperture)

- using structured illumination to separate singly from multiply scattered light in 3D scenes [Nayar SIGGRAPH 2006]
- using a structured mask to reduce veiling glare in cameras, i.e. scattering in the camera body & optics [Talvala SIGGRAPH 2007]



before and after
glare removal

Large online photo collections

- Facebook
 - 3 billion photos
- Flickr
 - 9 billion photos
- Google Library Project
 - 50 million books \times 300 pages = 15 billion images
- Google Earth
- Google StreetView Project
 - formerly the Stanford CityBlock Project

Computational photography using online photograph collections

- scene completion
- texture synthesis
- image-based image search

Image inpainting / image completion

- extrapolation along isophotes
+ anisotropic diffusion
to prevent crossings
[Bertalmio & Sapiro SIGGRAPH 2000]

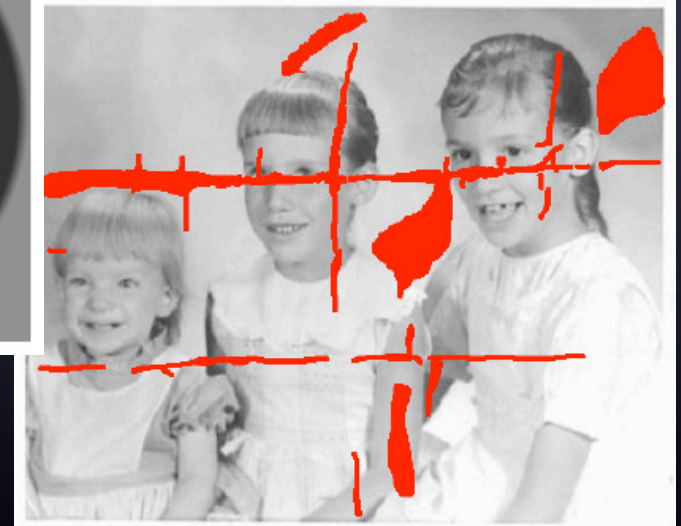
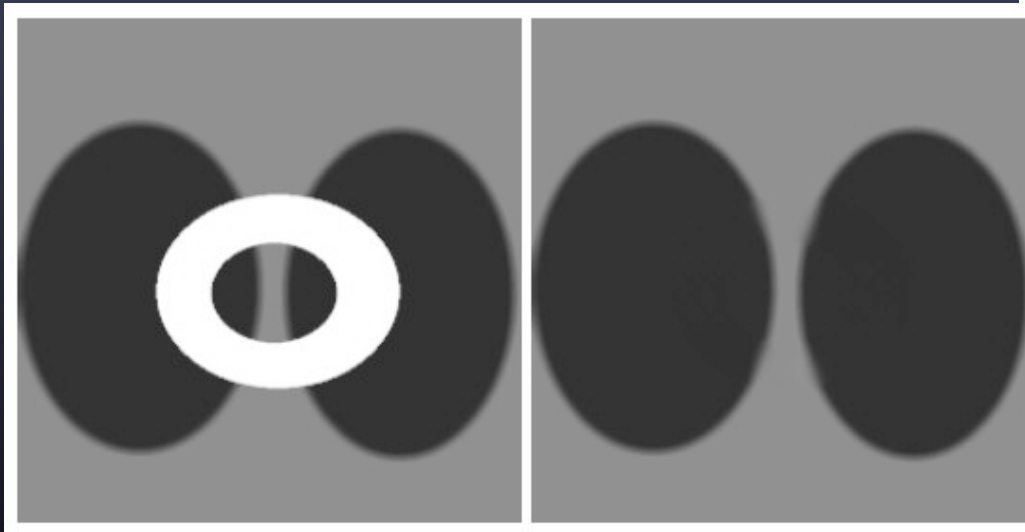


Image inpainting / image completion

- extrapolation along isophotes
+ anisotropic diffusion
to prevent crossings
[Bertalmio & Sapiro SIGGRAPH 2000]
- extrapolation for structure
(from edge-preserving smoothing)
+ texture synthesis for the rest
[Bertalmio & Sapiro CVPR 2003]

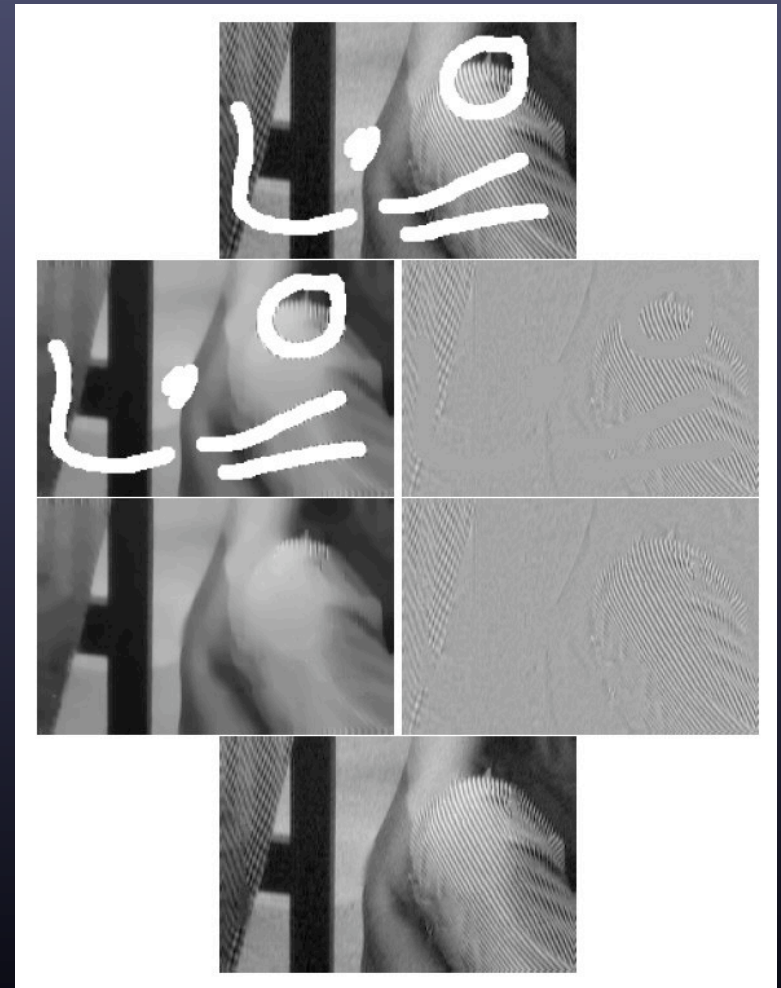
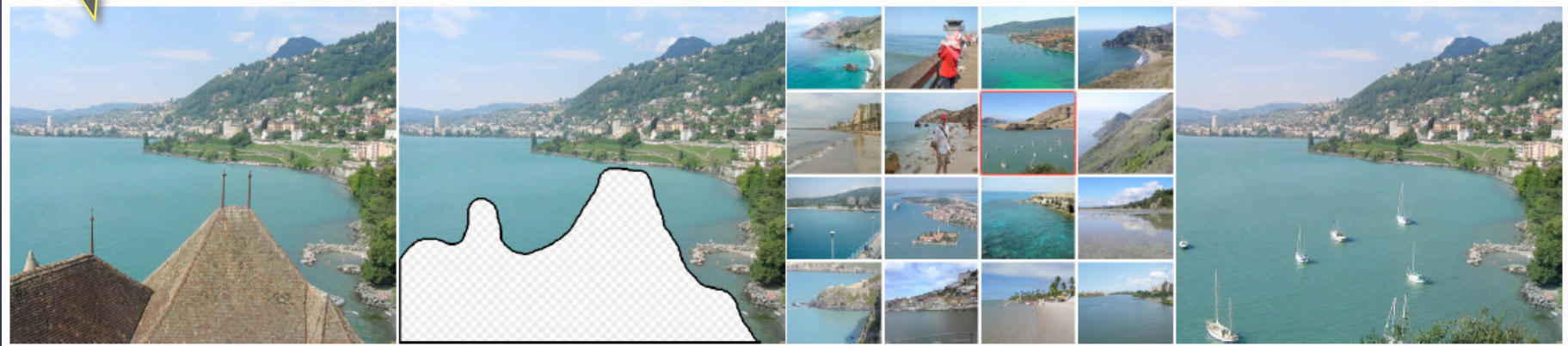


Image inpainting / image completion

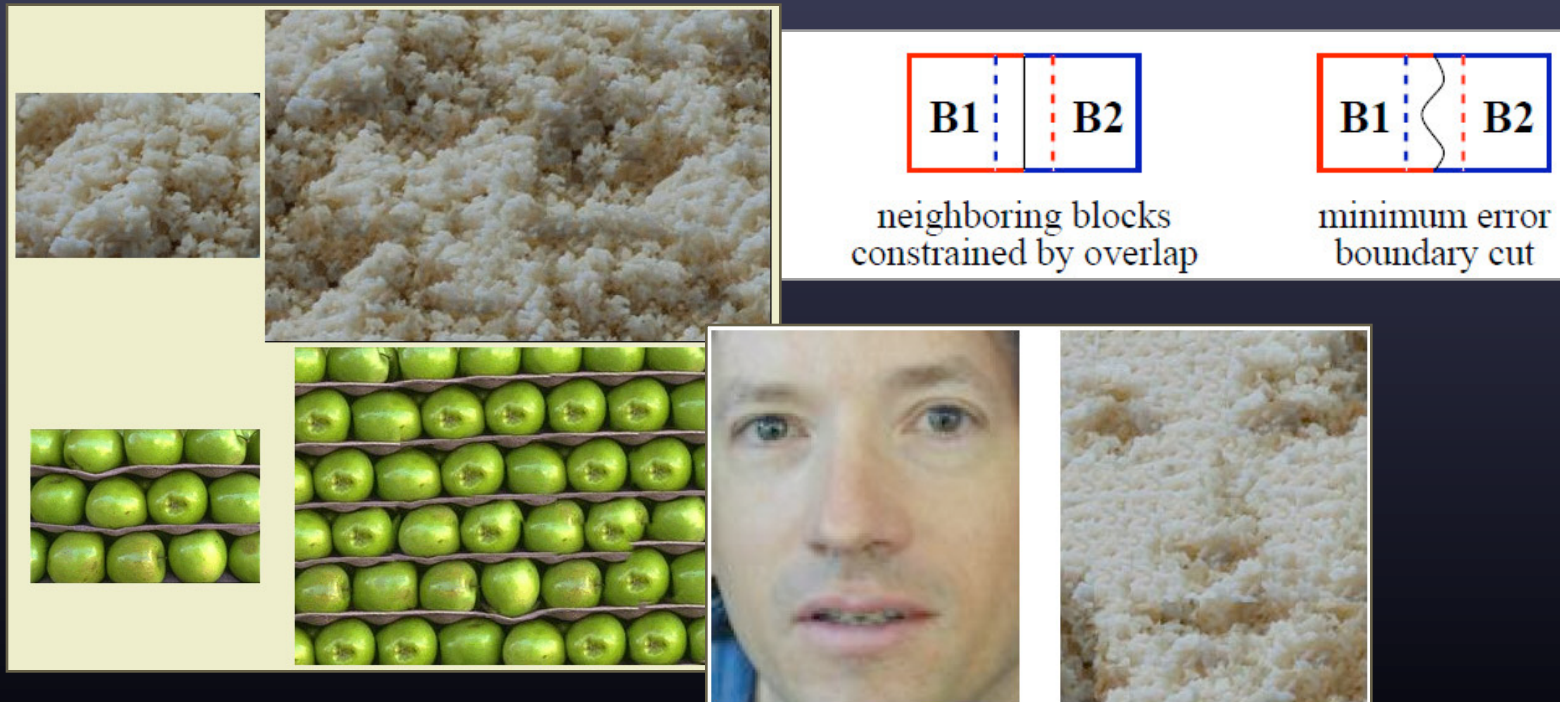
original
photograph



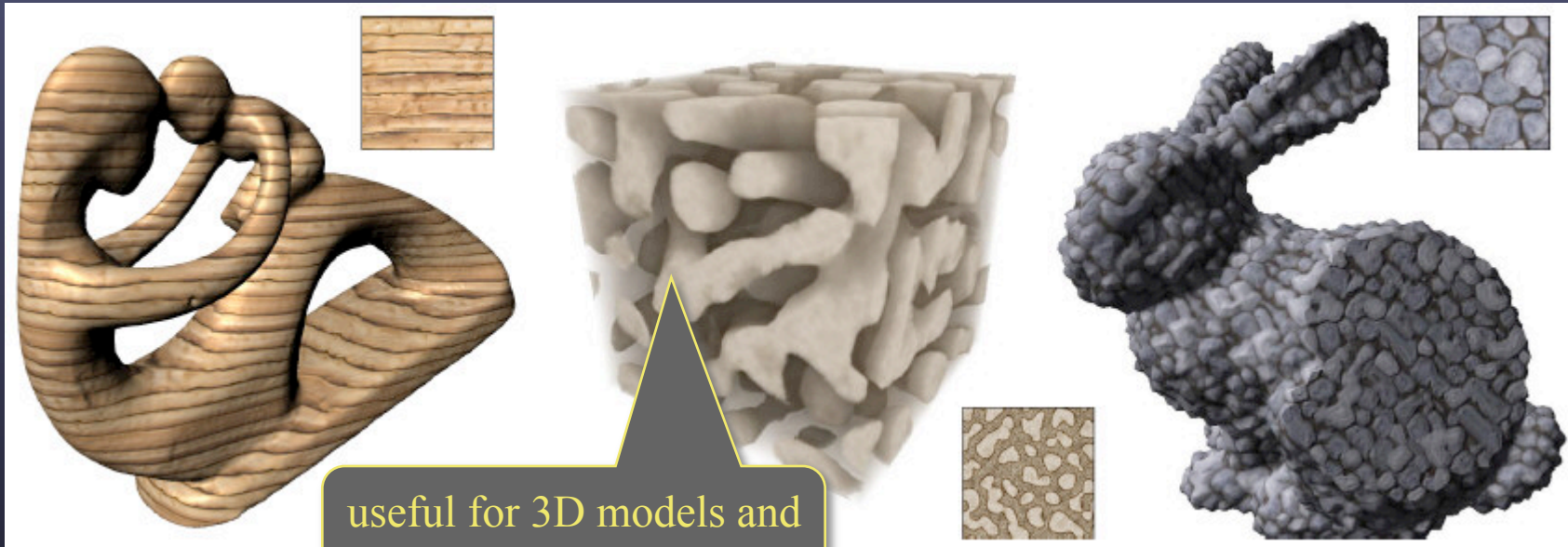
- search for matches from a large database
+ seam finding using graph-cut algorithm
+ gradient blending & integration
[Hays & Efros SIGGRAPH 2007]

App #2 for large image collections: texture synthesis

- tiling from exemplar with overlaps (“quilting”)
+ seam-finding using graph-cut algorithm
[Efros & Freeman SIGGRAPH 2001]



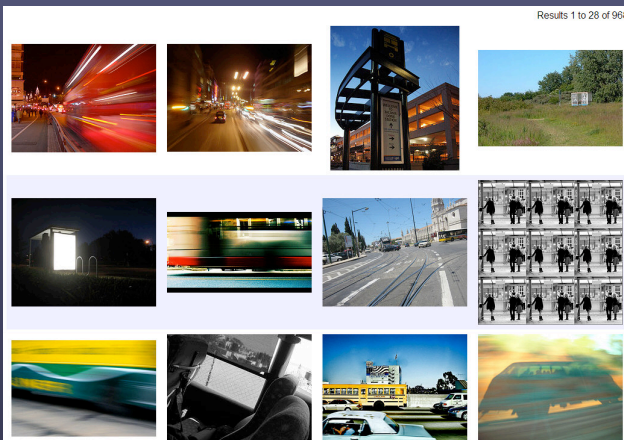
App #2 for large image collections: texture synthesis



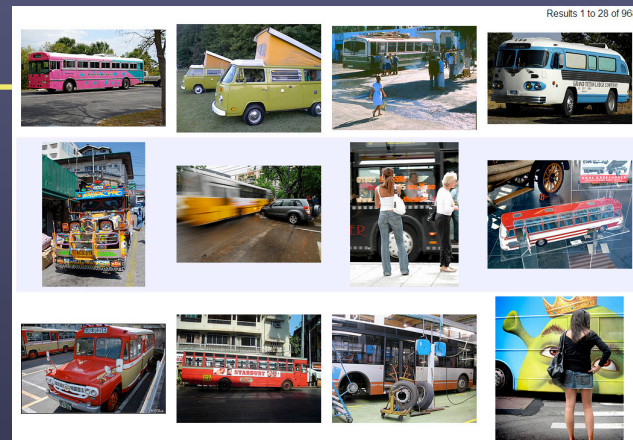
useful for 3D models and
volume data

- neighborhood search from 3D exemplar
+ histogram matching to enforce appearance
[Kopf et al. SIGGRAPH 2007]

App #3: image-based image search



text only (left)
and text + “look like” (right)



- search on text tags + feature-based classification using categories learned from manually tagged training sets [hot topic in CVPR community]

beholdTM

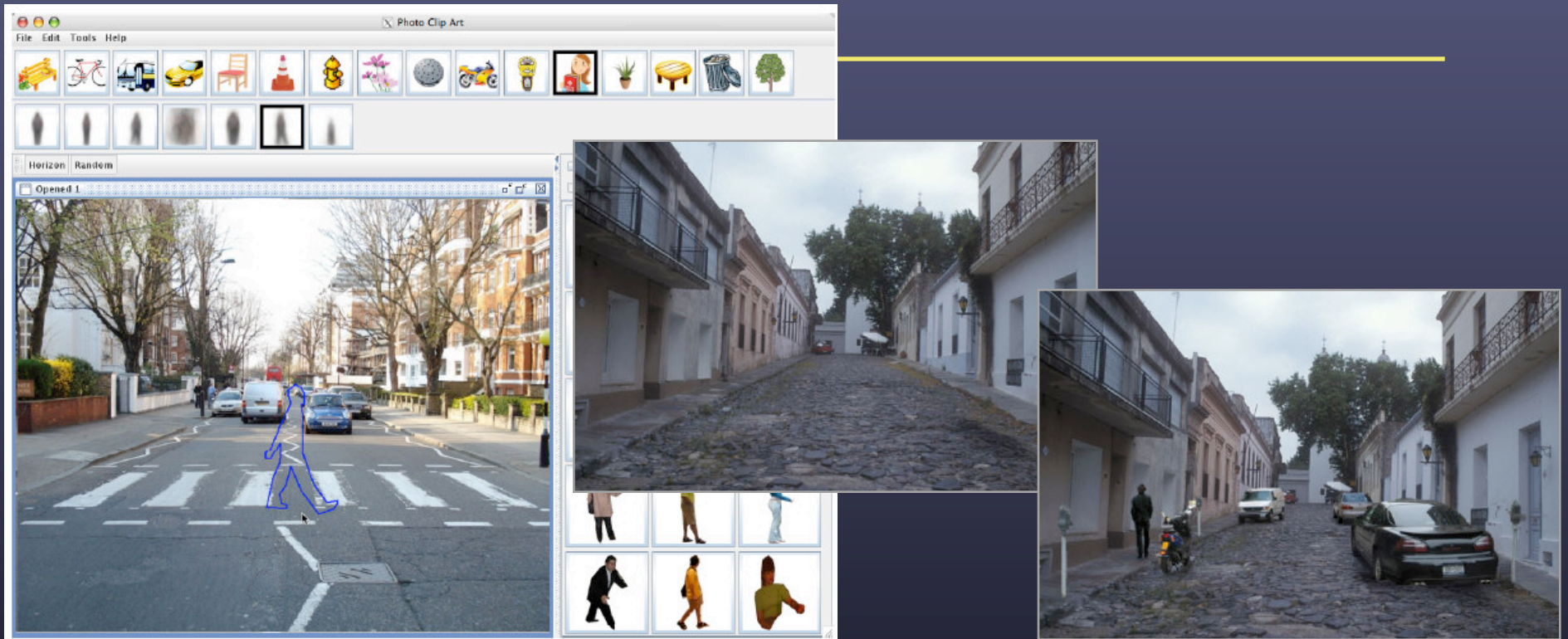
find images tagged with (can be blank)
that **look like** a picture of (a)
and are free to use

Example queries: Beetle ([car](#)) / ([bug](#)) [Tokyo skyline](#) [Roof texture](#) [Dog face](#)

Searching **1,040,000 high quality** images from [Flickr](#)

© 2005-2007 [About Behold](#) [Blog](#) [Discussion](#) [Chat to the developer](#)

App #3: image-based image search



- segmentation of “photo clip art” from background
+ estimation of object size, orientation, and lighting
+ gradient blending & integration
[Lalonde & Efros SIGGRAPH 2007]

Other applications of image-based image-search

- Tell me about this building/painting.
- Where have I seen this person before?
- Find this (broken part) in an online catalog.
- Show me an online review of this restaurant.