How Does Computational Refocusing Work?
Recall: How Physical Focusing Works

Sensor / lens gap determines plane of physical focus.

Credit: Stanford CS 178
Computational Refocusing
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Computational Refocusing
Computational Refocusing

calculate ray projection
Computational Refocusing

focus close
Computational Refocusing

focus far
Output Image Pixel is Sum of Many Sensor Pixels

Virtual focal plane
Output Image Pixel is Sum of Many Sensor Pixels
Test Your Understanding
Sub-Aperture Images

Image from selecting same pixel under every microlens

Sub-aperture image, min u
Sub-Aperture Images

Image from selecting same pixel under every microlens

Sub-aperture image, max u
Sub-Aperture Images

Sub-aperture image, max $u$
Sub-Aperture Images

Sub-aperture image, min u
Raw Data - Array of Disks

Figure 1: Raw light field photograph read off the photosensor underneath the microlens array. The figure shows a crop of approximately one quarter the full image so that the microlenses are clearly visible in print.
Raw Data Re-Organized As Array of Sub-Aperture Images

Each sub-aperture image here is created by taking the same pixel in each disk image.
Shift-And-Add Refocusing Algorithm

(A): No refocus
(B): Refocus closer
(C): Refocus further
Sampling & Aliasing in Shift-And-Add Algorithm

(A): Unrefocused

(B): Sub-aperture

(C1): Undersampled, aliased

(C2): Adequately sampled
Performance of Digital Refocusing
Light Field Resolutions (Example)

M microlenses

Spatial (x,y) M x M

Directional (u,v) N x N

N pixels / microlens
Output Image Resolution

- Classical result is $M \times M$ output image resolution (under band limited assumption)
- Optimized algorithms obtain significantly higher resolution (e.g. 3x in each dimension) [e.g. Fiss et al., ICCP 2014]
Performance of Digital Refocusing

Extend depth of focus by a factor of N
Digitally Extended Depth of Field
Computationally Changing Depth of Field and Viewpoint
Computationally Extended Depth of Field

Conventional Lens at f/4

Conventional Lens at f/22

Light Field Lens at f/4, all-focus algorithm [Agarwala 2004]
Partially Extended Depth of Field

Original DOF

Extended DOF

Partially Extended DOF
Tilted Focal Plane
Tilted Focal Plane
View Camera, Scheimpflug Rule

Computational Change of Viewpoint

Lateral movement (left)
Computational Change of Viewpoint

Lateral movement (right)
Computational Change of Viewpoint

Forward movement
(wide angle effect)
Computational Change of Viewpoint

Backward movement
(orthographic effect)
Ray-Tracing as Physical Simulation
Ray Tracing in Lens Design

Lomography Petzval Portrait Lens
Ray Tracing in Computer Graphics

Gravity movie, source: www.solidangle.com
Ray Tracing in Light Field Camera Design

35mm-format 200 mm f/2 lens

6000x4000 sensor pixels
10x10 pixels per microlens
10 cm dragons
Simulation – Digital Refocusing Results
Simulation – Digital Refocusing Results
Simulation – Digital Refocusing Results
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Simulation – Digital Refocusing Results
Simulation – Digital Refocusing Results
Light Field Imaging Lenses - Optics and Computation
Modern Lens Designs Are Highly Complex

Photographic lens cross section
Modern Lens Designs Are Highly Complex

4 element mobile phone lens (on 24x36mm sensor)
Modern Lens Designs Are Highly Complex
Modern Lens Designs Are Highly Complex

Microscope objective
Modern Lens Designs Are Highly Complex

Canon 70-200mm F2.8. 23 glass elements, 3.28 lbs.
Lens Aberration Example

Real spherical lens does not converge rays to a single point.
Aberrations Are Fundamental & Unavoidable

Lens Design in 1839

Louis Daguerre

Chevalier Lens (f/16)
Lens Design in 1839

Joseph Petzval

Petzval Portrait Lens (f/3.6)
Lens Design in 1839

Joseph Petzval

Petzval Portrait Lens (f/3.6)
Petzval Portrait Lens
Petzval Portrait Lens

Lomography Petzval Lens
Recall: What Does a 2D Photograph Record?
Aberrations Are Curvature in the Ray-Space
Aberration Correction by Adding Elements
Aberration Correction by Adding Elements

Canon 70-200mm F2.8. 23 glass elements, 3.28 lbs.
Things to Remember

4D light field: radiance along every ray

Light field camera
- Capture light field flowing into lens in every shot
- Light field sensor = microlens array in front of sensor

Computational refocusing
- Refocusing = reproject rays assuming new sensor depth
- Can think of this as shift-and-add of sub-aperture images
To Be Continued