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

Sensor / lens gap determines plane of physical focus.

Credit: Stanford CS 178
Computational Refocusing
Computational Refocusing
Computational Refocusing

-focus far-
Computational Refocusing
Computational Refocusing
Computational Refocusing

compute ray projection
Computational Refocusing

focus close
Computational Refocusing

focus far

CS184/284A
Output Image Pixel is Sum of Many Sensor Pixels
Output Image Pixel is Sum of Many Sensor Pixels
Shift-And-Add 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**
- **N pixels / microlens**
- **Spatial (x,y)**: $M \times M$
- **Directional (u,v)**: $N \times N$
Output Image Resolution

- Classical result is $M \times M$ output image resolution (under band limited assumption)
- Current state-of-the-art 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

N pixels
Digitally Extended Depth of Field

f / 4

f / 22
Accuracy of sensor position is reduced because of ability to refocus after the fact. This effective depth of focus increases linearly with directional resolution (8 times larger if directional resolution of light field is 8x8)
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

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)
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
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
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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.