Logistics

- PA1 is out. Due 11/8, 11:30 AM: [https://www.cs.rochester.edu/courses/572/fall2021/assignments.html](https://www.cs.rochester.edu/courses/572/fall2021/assignments.html).

  - Asks you to explore camera signal processing pipeline. Get all points with just demosaic, but explore other stages we discussed in the class.
Computational Photography

- Use image signal processing algorithms to:
  - (1) simplify optics and sensors.

  **Portrait mode:** simulate a large aperture
  **HDR mode:** simulate a high dynamic range sensor
Computational Photography

Use image signal processing algorithms to:

- (2) do things that conventional optics/sensors *alone* can’t do. Usually requires optics, sensor, algorithm co-design, e.g., light field imaging.

https://www.dpreview.com/reviews/lytro
What is Light Field?

Plenoptic function: a 4D function describing a ray in the free space.

Light radiance doesn’t change along the ray direction.

Radiance gathered at P is the same as the total radiance gathered at P1 and P2.
The Light Field Inside a Camera

Simplifying 4D to 2D
Simplifying 4D to 2D

Lens/Aperture (u)

Sensor (s)

Key idea in light-field imaging: capturing and measuring these individual rays (the light field) inside a camera would allow us synthesize any image (simulate any image formation process).
The Light Field Inside a Camera

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- **Key challenge**: how to measure each individual ray. Since there are infinitely rays, it’s necessarily a sampling process.
The Light Field Inside a Camera

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- **Trade-off**: the resolution in which we can sample the light-field vs. the resolution of the synthesized image.
The Light Field in a Pinhole Camera

Each point corresponds to a ray between the lens and the sensor. Each pixel in a pinhole camera measures the energy coming from the corresponding ray.
The Light Field with a Lens (In-Focus Point)

Lens: \((u, v)\) plane

Sensor: \((s, t)\) plane

Pixel 1  Pixel 2

Graph:

- \(u\) axis
- \(s\) axis
- Points:
  - \((0.5, 1)\)
  - \((1, 0.5)\)
  - \((1, 1)\)
The Light Field with a Lens (In-Focus Point)

Each pixel now measures the energy integration of all rays passing through the lens (aperture), losing the direction information!
The Light Field with a Lens (Out-of-Focus Point)

Lens: (u, v) plane

Sensor: (s, t) plane

Pixel 1

Pixel 2
The Light Field with a Lens (Out-of-Focus Point)

Lens: (u, v) plane

Sensor: (s, t) plane
The Light Field with a Lens (Out-of-Focus Point)

Lens: (u, v) plane

Sensor: (s, t) plane
The Light Field with a Lens (Out-of-Focus Point)

Pixel 1 measures the energy integration of all rays passing through the lens (aperture) that hit pixel 1, but from multiple scene points, losing the direction information!
Thought Experiment: How to Digitally Refocus?

- Pixel 1
- Pixel 2

Diagram showing the relationship between object distance (s) and image plane (u) for two different pixels.
Thought Experiment: How to Digitally Refocus?

What would the pixel value of the scene point be if it’s captured in-focus? It’s equivalent to estimating the pixel value at a hypothetical in-focus sensor, which is equivalent to **integrating the energy of the three rays**!
Thought Experiment: How to Digitally Refocus?

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What are the energies of these three rays? Lost in conventional camera captures. Key question: how to capture individual ray information, i.e., the light field?
How to Capture the Light Field?

The microns array plane becomes the (s, t) plane. Each microlens covers multiple pixels.
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How to Capture the Light Field?

Not to scale

Each pixel responsible for a small bundle of rays between lens and sensor. We can measure these ray bundles independently now!

The microns array plane becomes the (s, t) plane. Each microlens covers multiple pixels.
How to Capture the Light Field?

The pixel value integrates rays across an entire microlens, which is:
- bigger than the pixel itself — **lower spatial resolution**, but
- smaller than the main lens — **higher LF sampling resolution**.
How to Capture the Light Field?

Key trade-off: Compared to conventional cameras, each pixel provides higher light field sampling resolution (in the u/v plane), but lower spatial resolution (in the s/t plane).

The pixel value integrates rays across an entire microlens, which is:
- bigger than the pixel itself — **lower spatial resolution**, but
- smaller than the main lens — **higher LF sampling resolution**.
Trade-Off

The conventional camera: higher spatial resolution, lower (no) light field sampling resolution.
Trade-Off

Pixel Size

uLens Size
Reconstructing Photos

Integrating this column gets us the pixel value if we were to replace each microlens with an equally big pixel. Lower resolution image than what’s taken by a conventional camera.
Reconstructing Photos at a New Focal Plane

Microlens array: (s, t) plane

Lens/Aperture (u, v) plane

Sensor

P1 P2 Pn

Not to scale
Reconstructing Photos at a New Focal Plane

Not to scale

New Focal Plane

Lens/Aperture
(u, v) plane

Microlens array:
(s, t) plane

Sensor

P1 P2 Pn
Reconstructing Photos at a New Focal Plane

Not to scale

Lens/Aperture (u, v) plane

Microlens array: (s, t) plane

Sensor

New Focal Plane

Integrating these pixels gets us the pixel value as if the scene point is captured in-focus.
Light Field Data

Raw light field image as captured by the sensor. Each disk is the image formed under each microlens.

Conventional photo computed from light field data.

Pixels under one microlens capture different scene points.

Pixels under one microlens capture the same scene points.

Digital Light Field Photography, Ren Ng, 2006
Ways of Using Light Field

“See through”

Refocusing

Extended Depth of Field (stacking photos focused at different depths.)

Changing perspective (extracting the shown pixel under each microlens)

Subject

Main lens

Sensor

Microlens array
Prototypes and Commercial Products

Stanford Multi-Camera Array

Lytro ILLUM (2014):
~14 pixels / microlens

Raytrix (Max 25% of original image sensor resolution)

https://raytrix.de/products/
http://graphics.stanford.edu/projects/lightfield/
Reference Material

- **Light field**
  - Light Fields and Computational Imaging, IEEE Computer, 2006
  - Light Field Photography with a Hand-held Plenoptic Camera, Stanford CTSR 2005-02

- **VR videos**
  - Facebook Surround 360 Code
  - High-level algorithm pipeline of Facebook Surround 360
  - Jump: Using omnidirectional stereo for VR video, illustrating key concepts in Jump VR.
  - Rendering Omni-directional Stereo Content, talking about graphics rendering for stereo VR.