Applications of computational photography: HDR merging and digital refocusing

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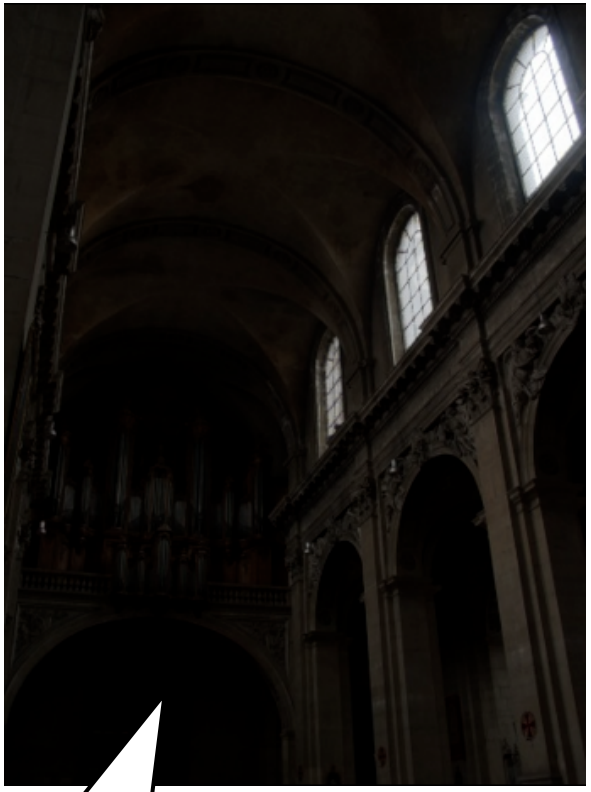
Computational photography

- Photography used to rely on optics (lens) and chemical reactions (analog film)
- Because the vast majority of cameras are digital today, each camera needs to do computation to take pictures
  - Bayes demosaicing
  - JPEG encoding,
  - etc.
- But it is possible to perform much more advanced computation, thus much extending the capabilities of cameras

HDR merging

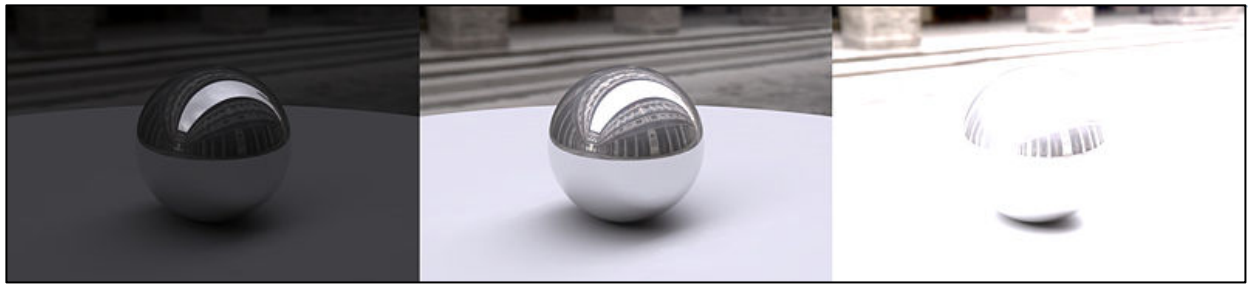
HDR image capture



Under-exposed

Over-exposed

Multi-exposure HDR capture



- Combine information from multiple-exposures
  - Weighted average
- Pros.
  - Can capture any dynamic range
  - Reduces noise level
  - Improves performance of small sensors (mobile phones)
- Cons.
  - Problematic for moving scenes

Multi-exposure in photography

- The first photographic films could capture very low dynamic range
- In 1858 H.P. Robinson used 5 exposures to capture a high dynamic range scene

1858 Robson *Fading away*
(combined 5 negatives)

- The dynamic range of film negatives improved significantly over the years

Impact of multi-exposure HDR

- Debevec, P.E. and Malik, J., *Recovering high dynamic range radiance maps from photographs, SIGGRAPH'97*
  - *2500 citations on Google Scholar*
  - *Not the first and not the best technique*
- *HDR Photography*
  - *Books on Amazon*
- *"HDR mode" in almost every mobile phone*

How to capture multi-exposure HDR? 1/3

- You need
  - A camera with "manual" mode: separate adjustment for exposure time (Tv) and aperture (Av)
    - Any DSLR or "prosumer" camera
  - Tripod (not necessary but recommended)
  - HDR merging software
    - For panoramas: Hugin from http://hugin.sourceforge.net/
    - Mac: PhotoSphere from http://www.anyhere.com/
    - Linux/PC/Mac: Luminance http://qtpfsgui.sourceforge.net/
    - Adobe Photoshop
    - And many more

How to capture multi-exposure HDR? 2/3

- Fix the setting of
  - ISO
    - The lower, the better – you are using a tripod
    - But higher ISO could be better in low light conditions
  - White-balance
  - Focus
    - switch to manual so it does not change between exposures
  - Aperture
  - Switch off image stabilization

How to capture multi-exposure HDR? 3/3

- Take a series of photographs
  - Increase/decrease exposure by 1 or 2 exposure values (EVs)
    - Stop when almost all pixels are white/black
  - You can use exposure bracketing to make the process faster
  - Copy images to your computer and load into HDR merging software
  - Some software can merge directly from RAW images, most will merge JPEGs
  - Tone-map

Camera response to light

Exposure time

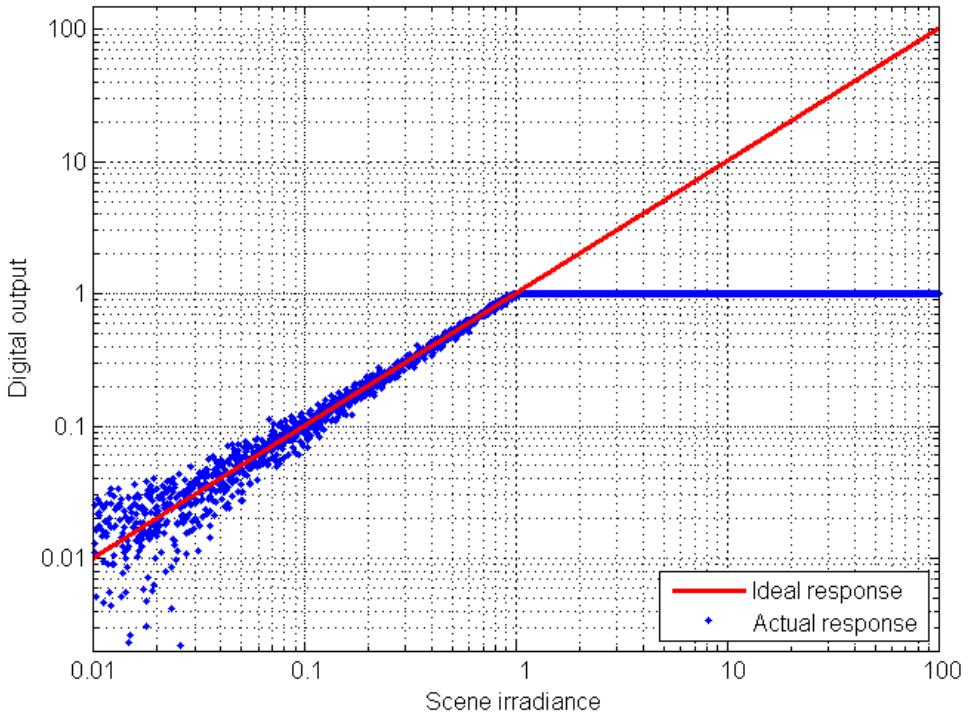
Saturation point

Captured value (from a RAW image)

$$V_i(x,y) = \min\{X(x,y)\,t_i + n,\ V_{max}\}$$

True radiance

Noise



Model of camera noise

$$n \sim N(0, \sigma_i^2(x,y))$$

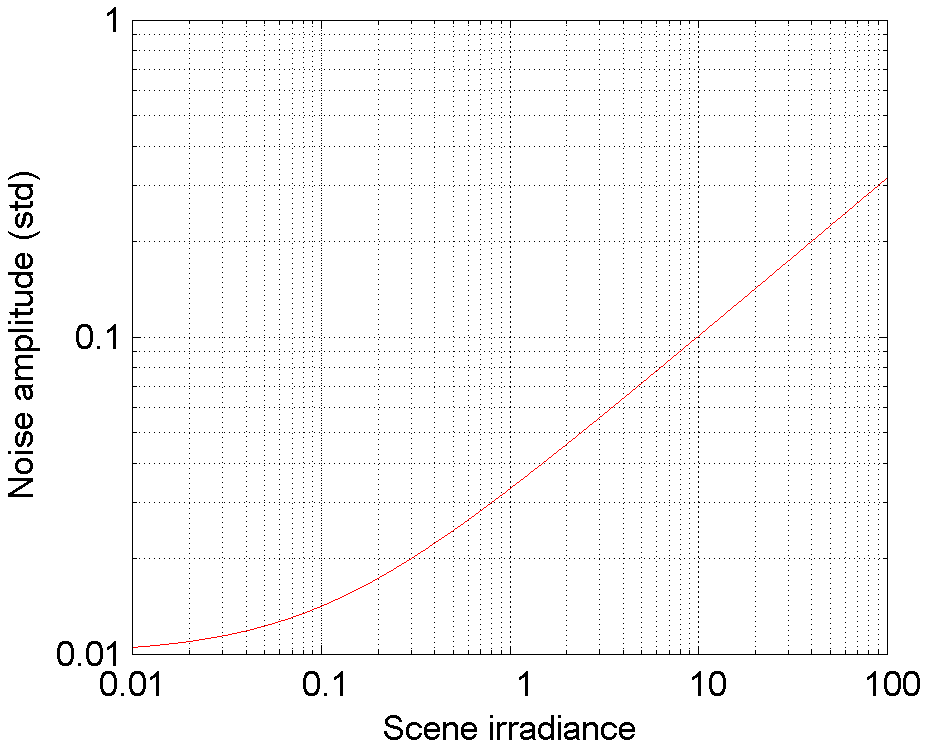
Variance of noise

Registered digital value

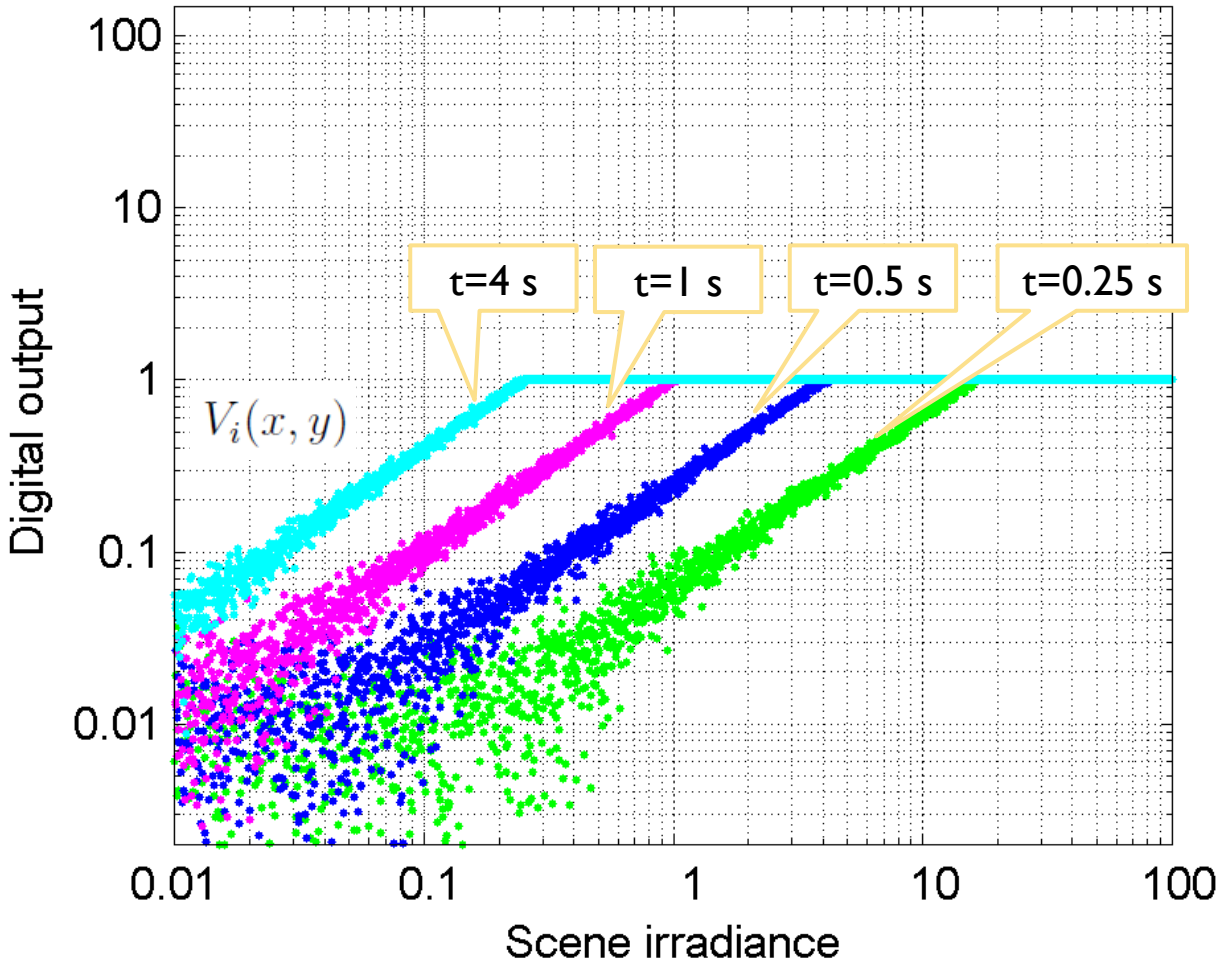
$$\sigma_i^2(x,y) \approx \underbrace{\alpha\, V_i(x,y)}_{} + \beta$$

Signal-dependent noise component

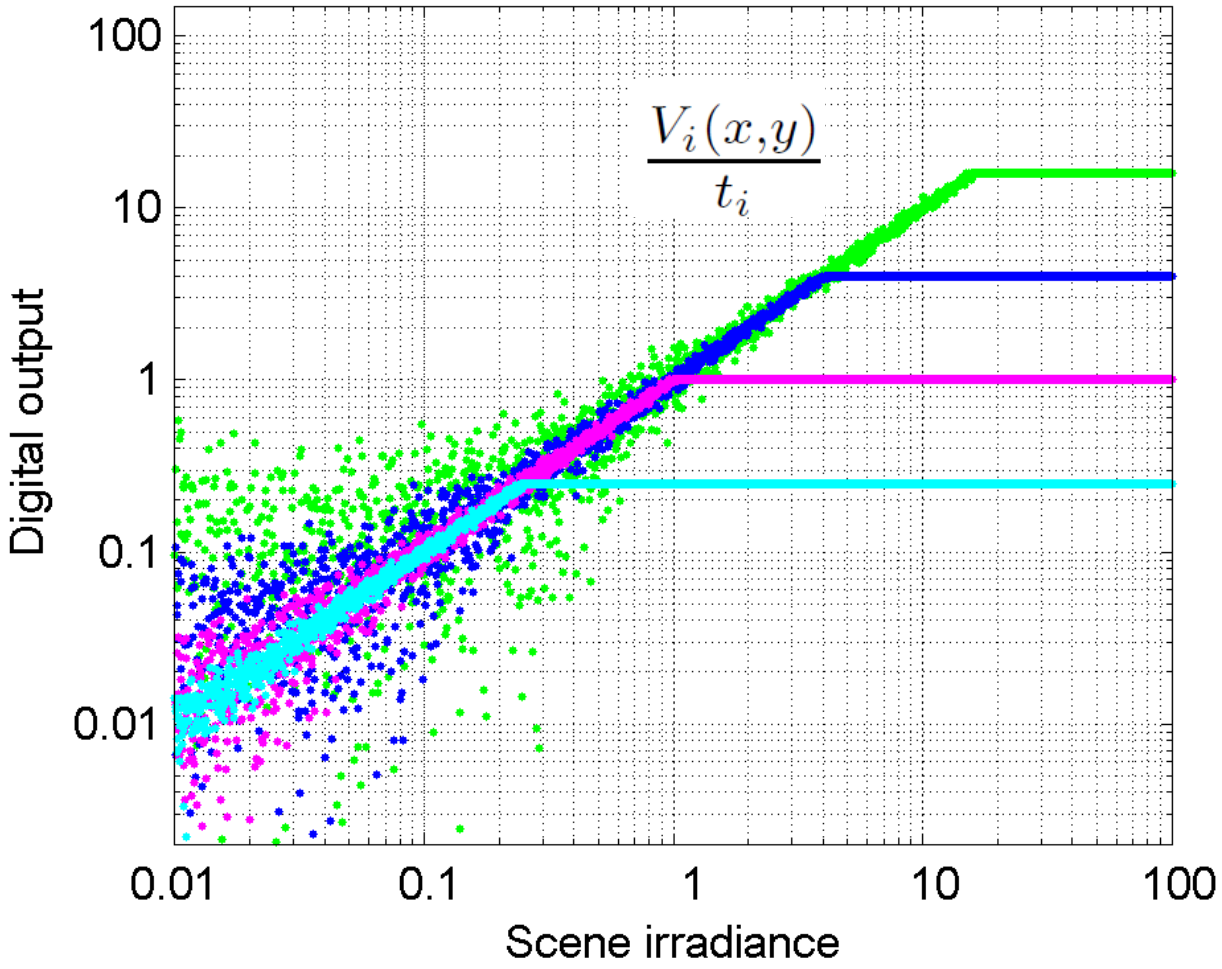
Signal-independent noise component



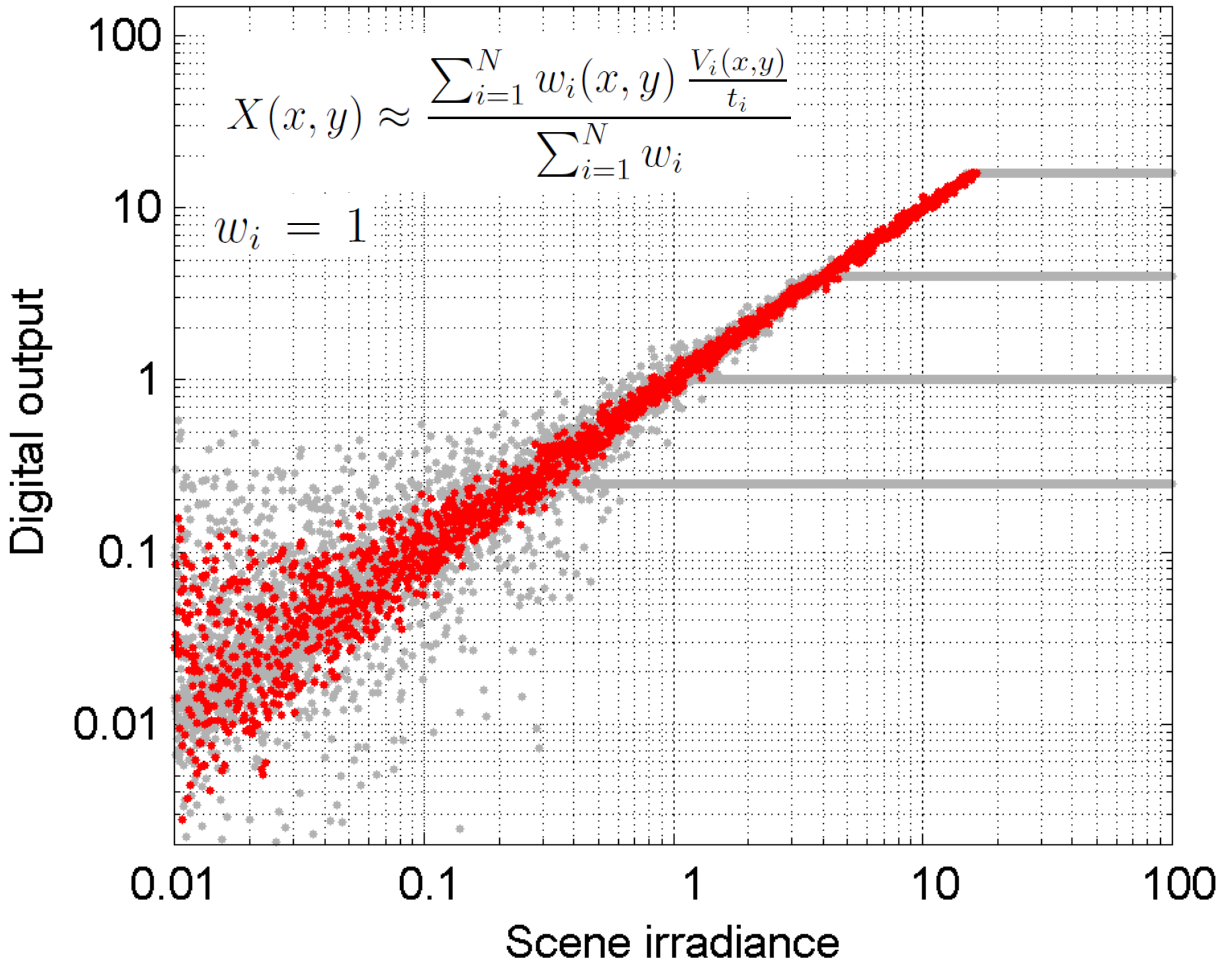
HDR capture: 4 images, each with different exposure time



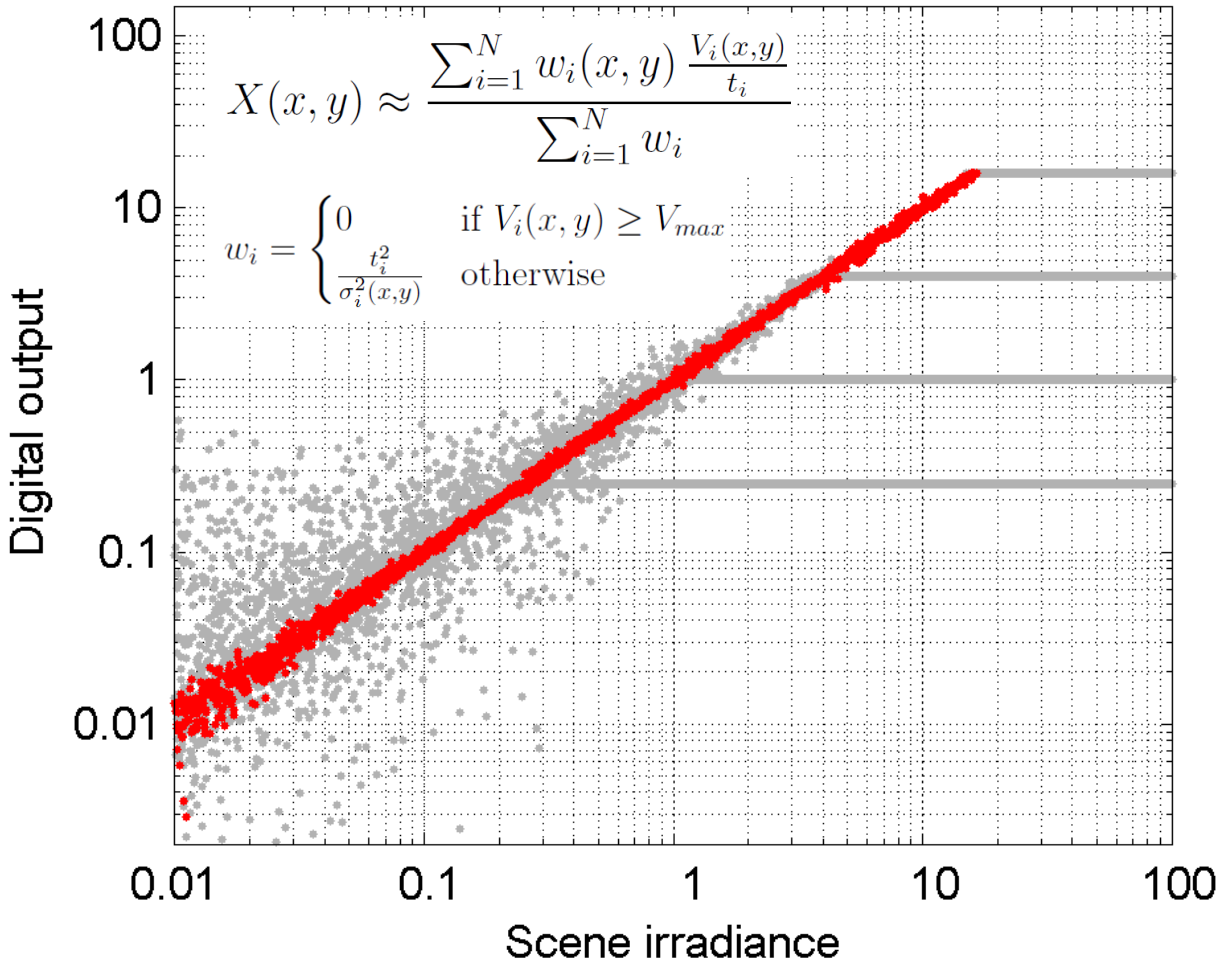
Adjust values for exposure time



Average values - naive average



Average values – minimum-variance unbiased estimator



Note on HDR-mode in cameras

- Newer iPhones, Android phones and some cameras offer "HDR" mode
- But as of today, none of these devices is able to store actual HDR image
- The HDR mode takes multiple exposures and tone-maps the image before it is stored as JPEG
- For mobile phones (small sensors), HDR mode enables to capture the dynamic range comparable to DSLR cameras (large sensors)
  - Dynamic range and quality (noise) rarely surpasses that of DSLR cameras

High dynamic range (video) cameras

- Prototypes exist but are expensive
  - Usually build from 2 or more low-dynamic range sensors
- Professional (cinematographic) cameras offer extended dynamic range

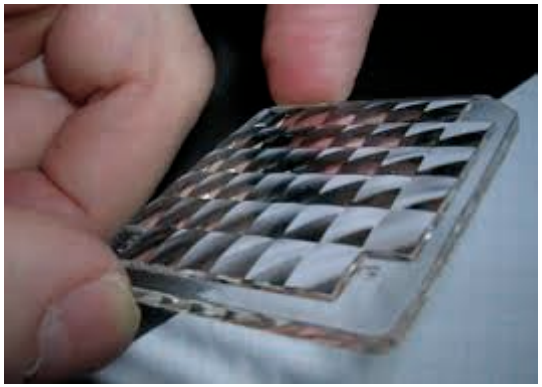
B/W prototype camera
with a log-response sensor

HDR photography resources

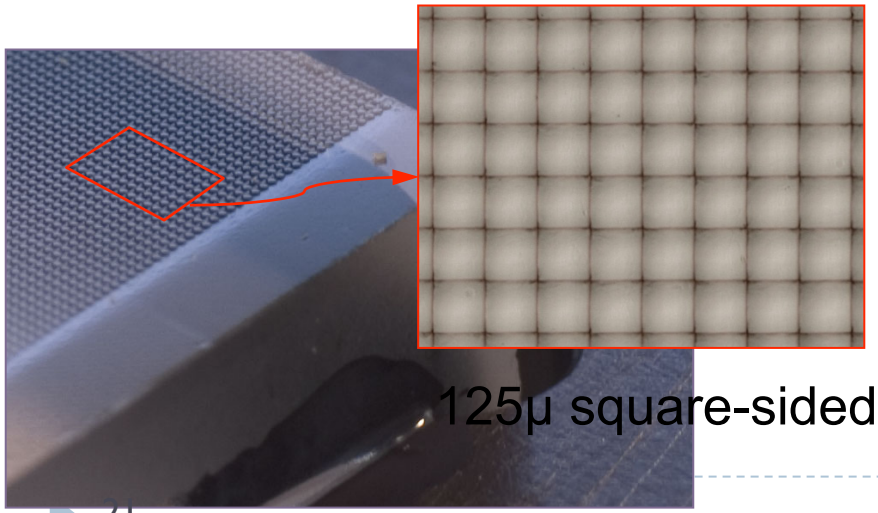
- Tutorial on how to use free software to create an HDR image
  - http://garmahis.com/tutorials/hdr-tutorial-free-software/
- General FAQ about shooting HDR images:
  - http://www.hdrlabs.com/tutorials/index.html
- Tutorials that involve commercial software:
  - http://speckyboy.com/2009/03/25/19-tutorials-for-creating-beautiful-hdr-high-dynamic-range-imagery/
- Some test HDR images (to experiment with tone-mapping)
  - http://pfstools.sourceforge.net/hdr_gallery.html

Light fields

Digital Refocusing using Light Field Camera



Lenslet array



125μ square-sided microlenses

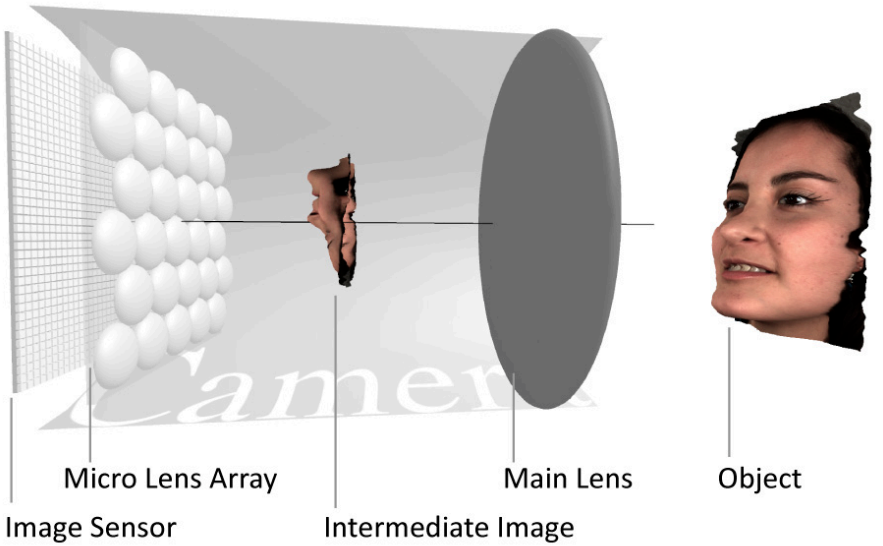
[Ng et al 2005]

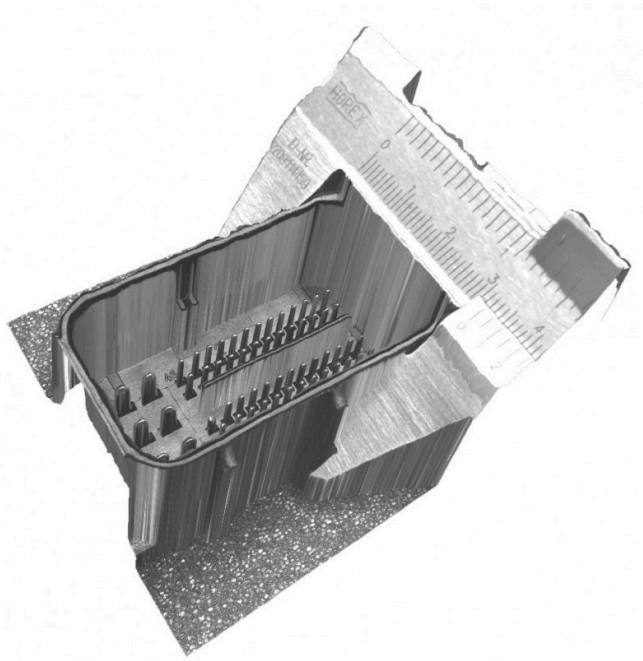
Lytro-cameras

- First commercial light-field cameras
- Lytro illum camera
  - 40 Mega-rays
  - 2D resolution: 2450 x 1634 (4 MPixels)
- www.lytro.com

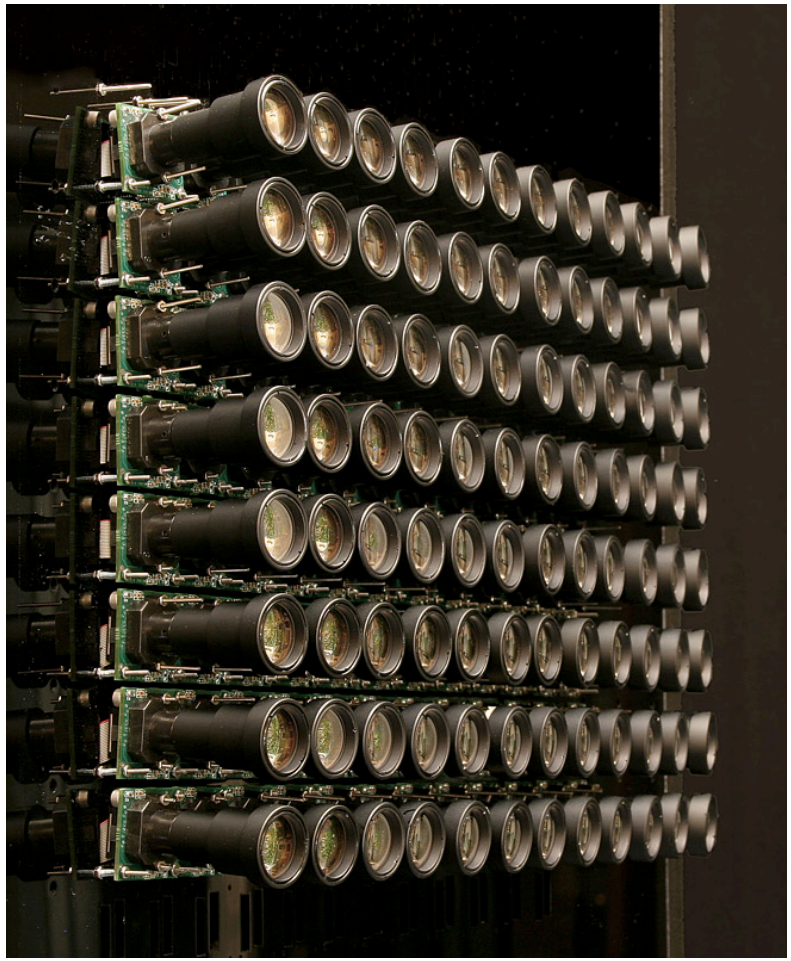
Raytrix camera

- Similar technology to Lytro
- But profiled for computer vision applications



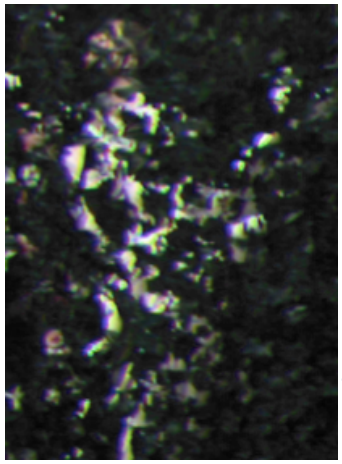


Stanford camera array



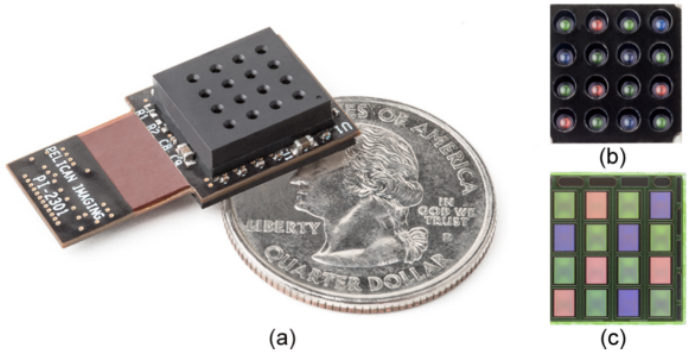
96 cameras

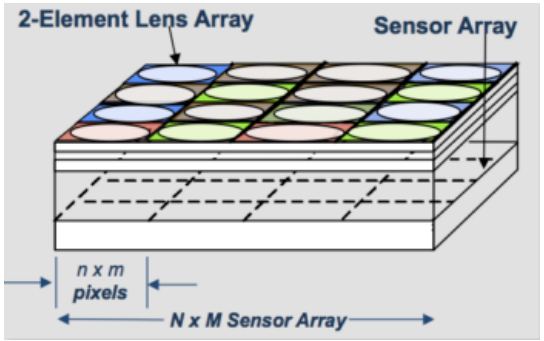
Application: Reconstruction of occluded surfaces

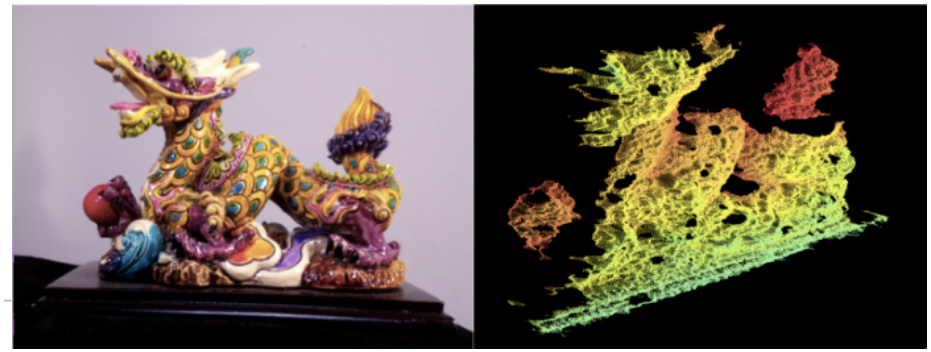


PiCam camera array module

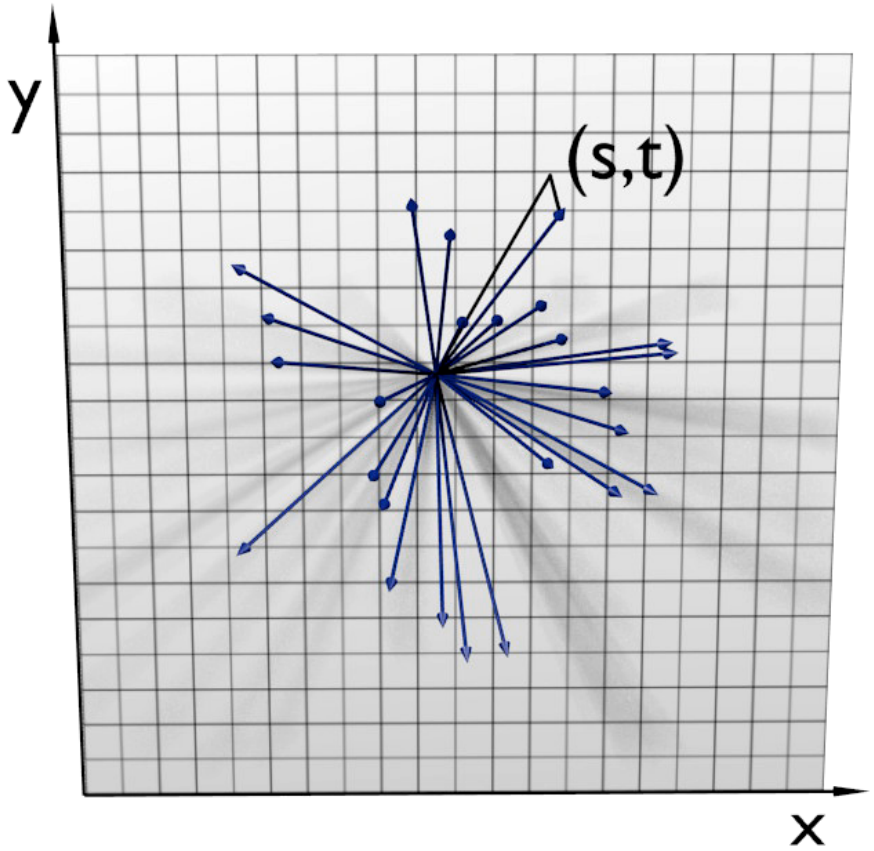
- Array of 4 x 4 cameras on a single chip
- Each camera has its own lens and senses only one spectral colour band
  - Optics can be optimized for that band
- The algorithm needs to reconstruct depth



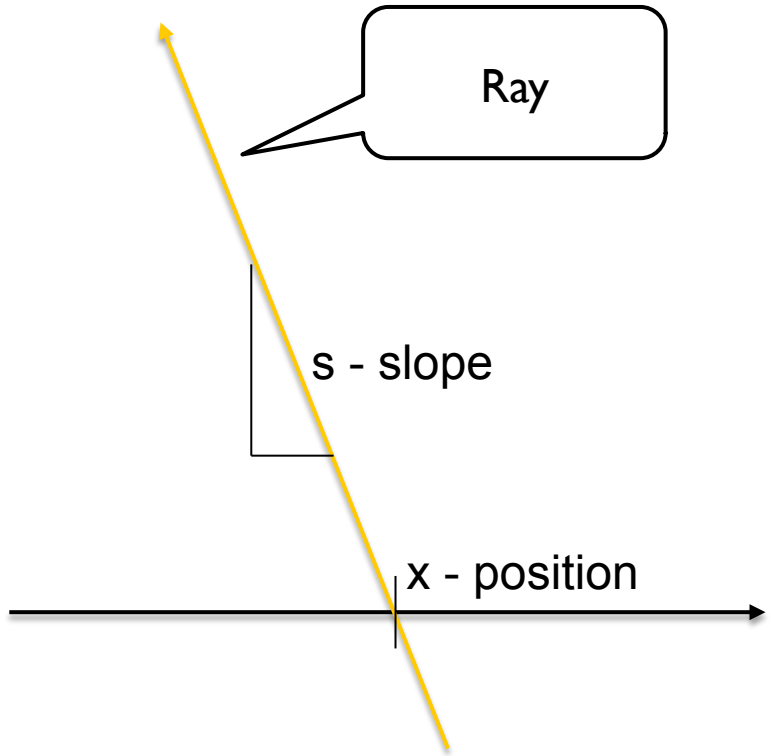




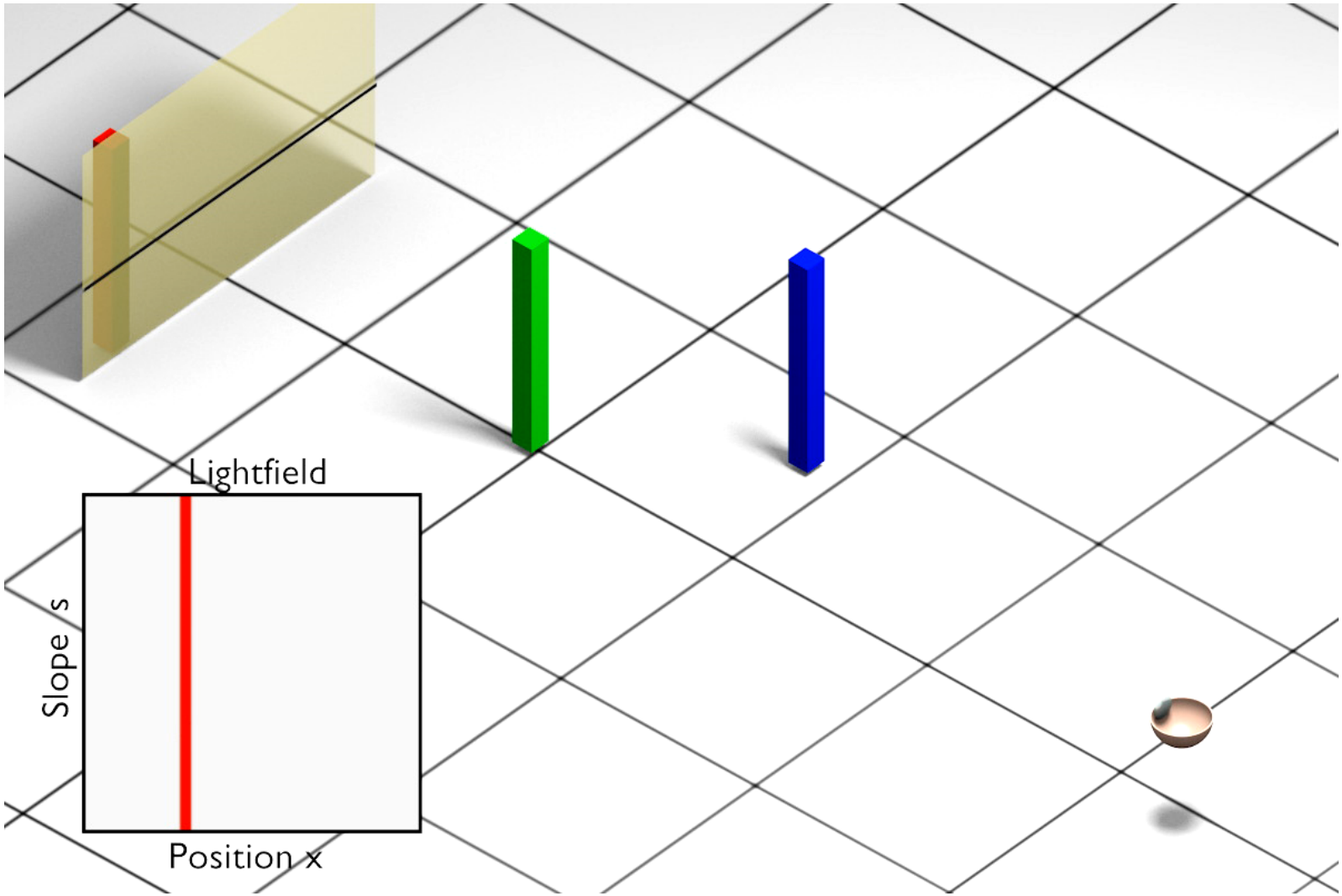
4D Light field



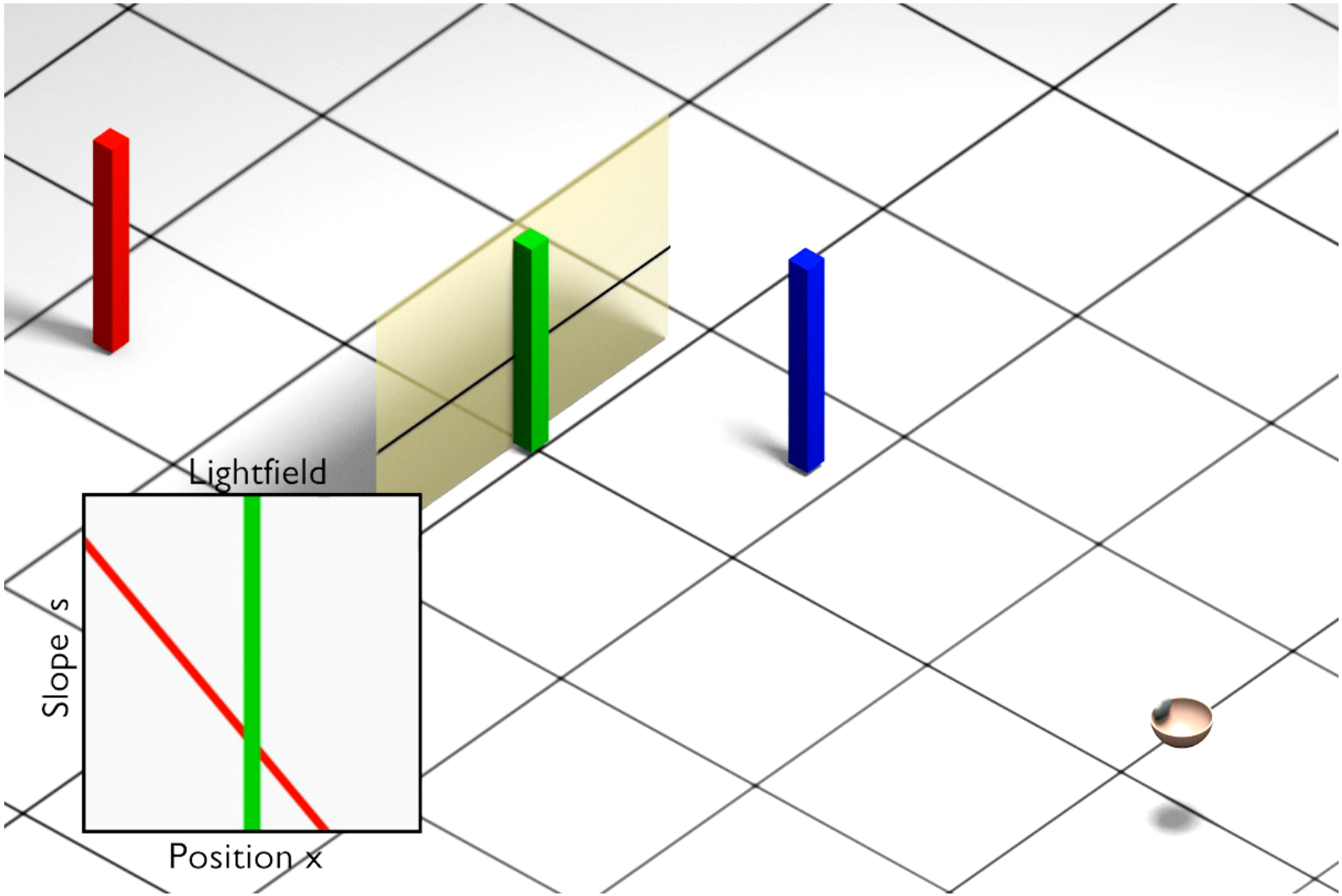
2D slice of the light field



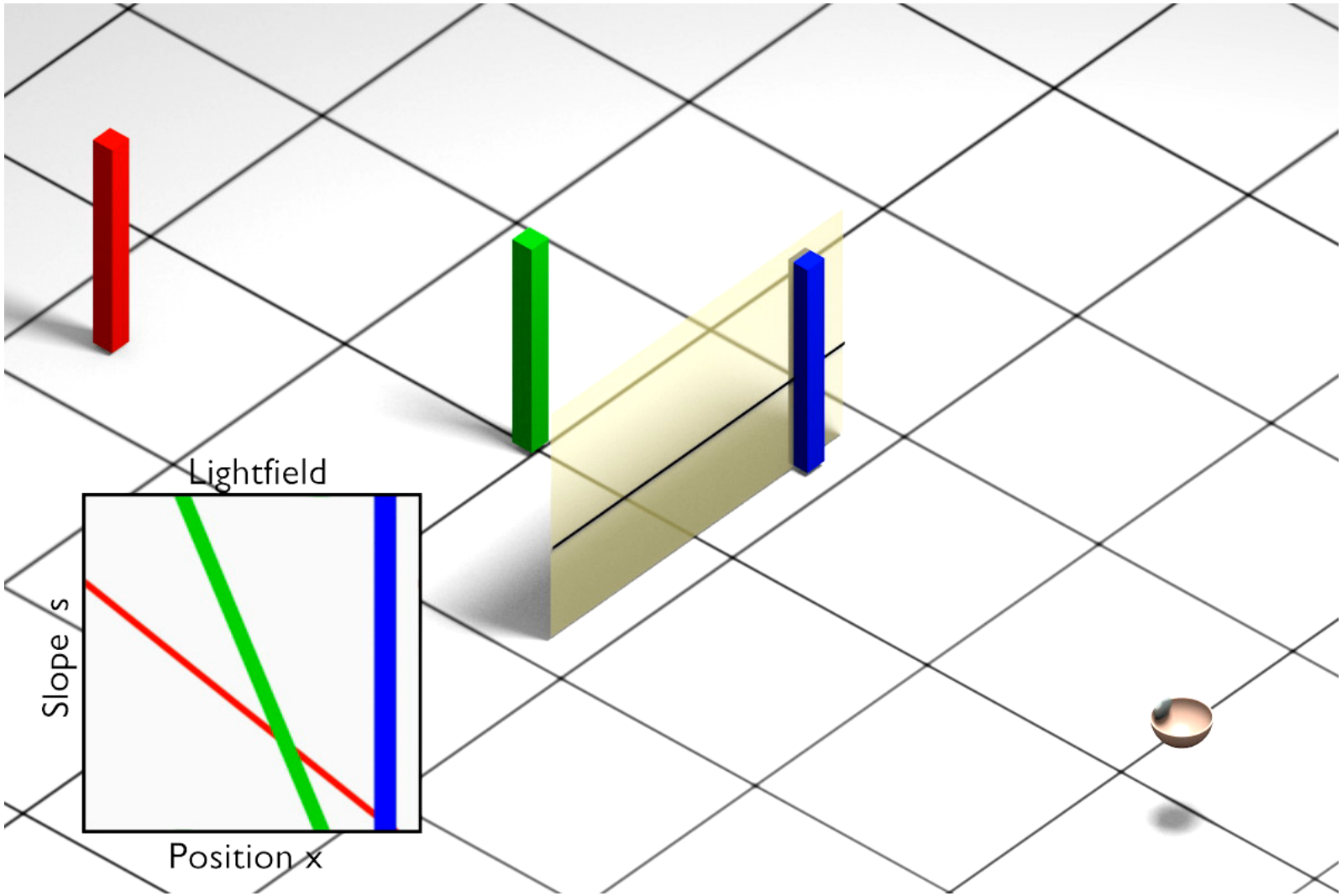
Lightfield - example



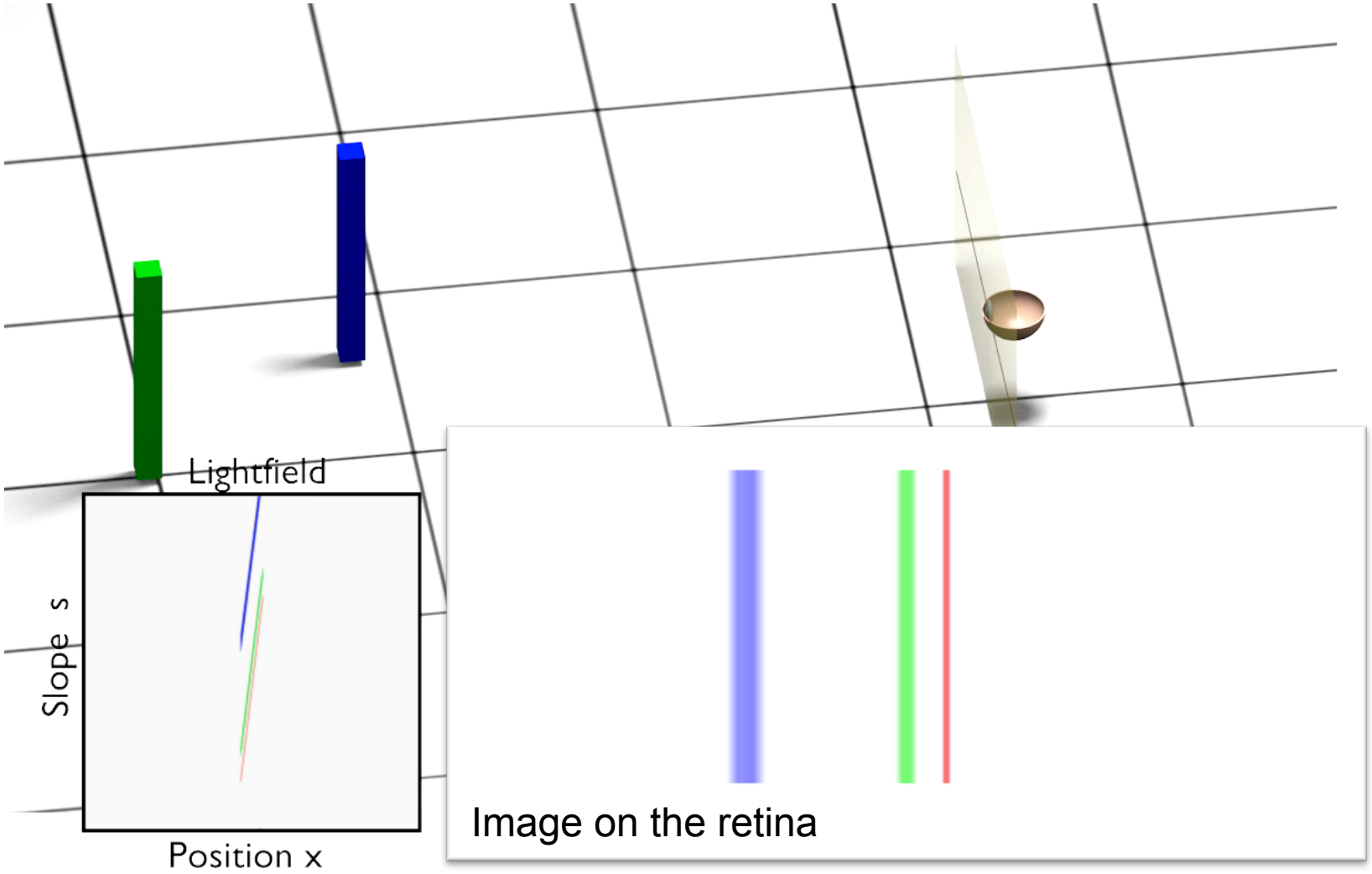
Lightfield - example



Lightfield - example



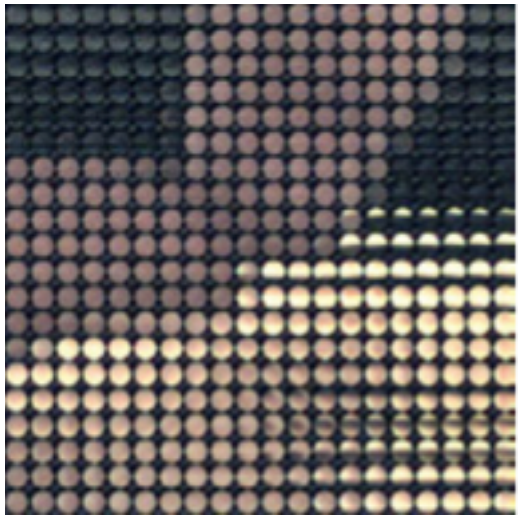
Lightfield - example

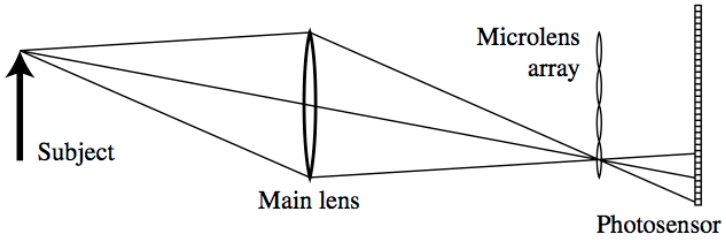


Refocusing and view point adjustment

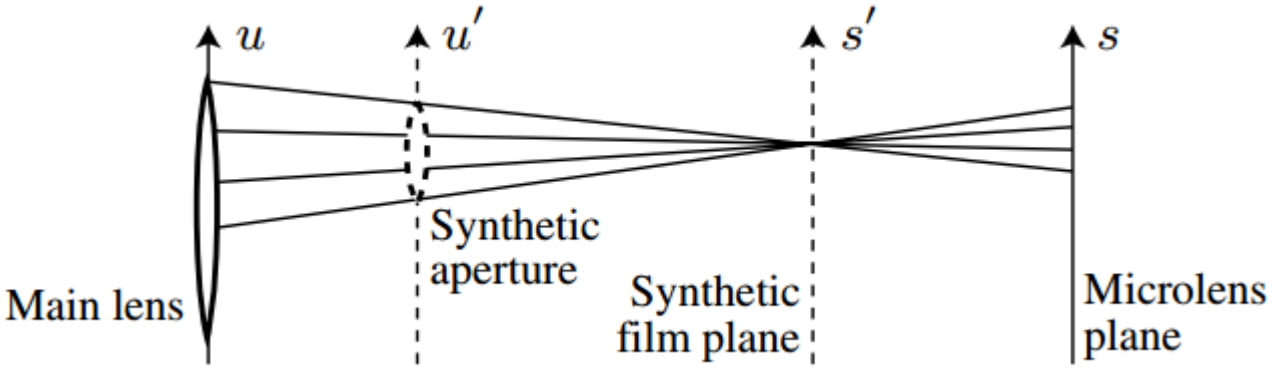
Screen capture from http://www.lytro.com/

Light field image – with microlens array





Digital refocusing



- To refocus – synthetic film plane needs to be shifted
- Generating refocused image requires computing the integral:

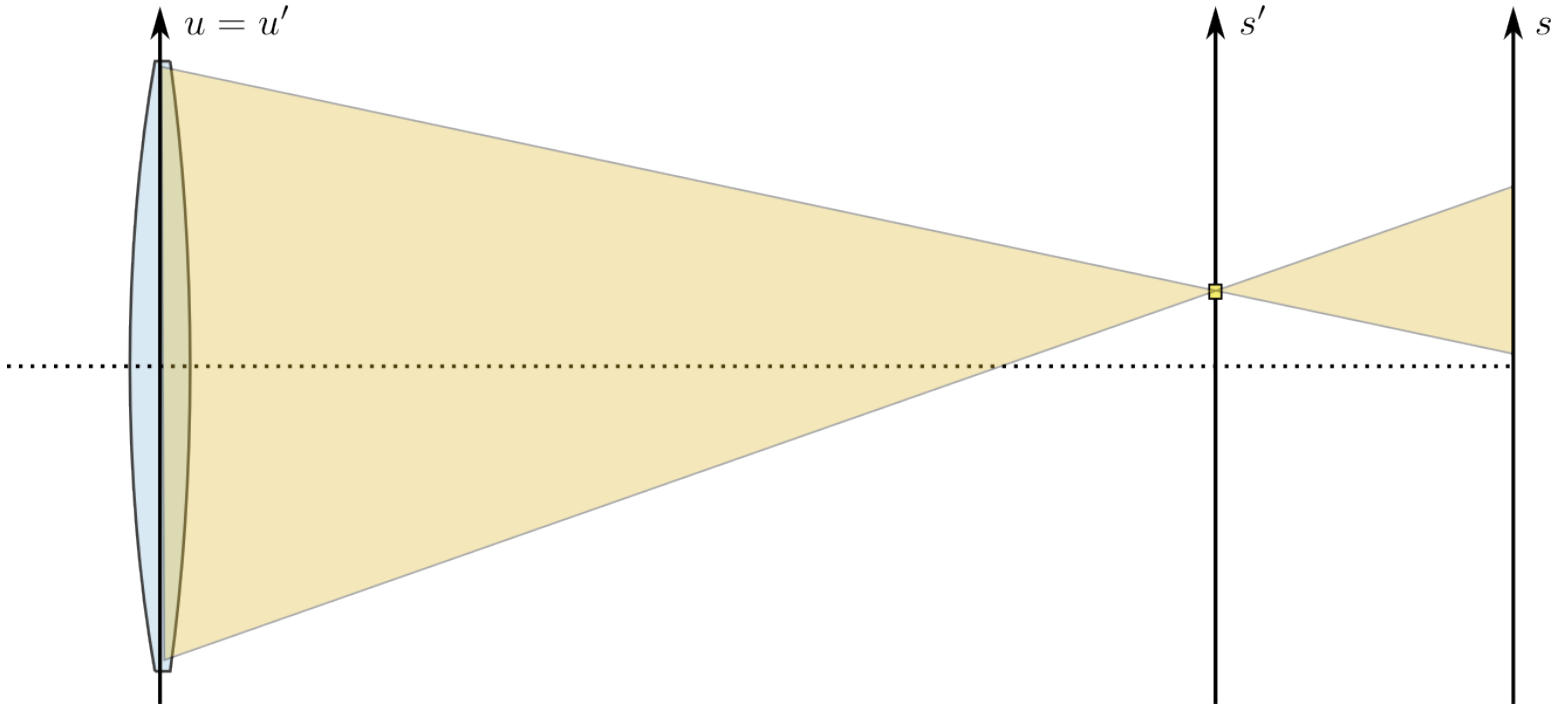
$$\overline{E}(s',t') = \int\int L'(u',v',s',t')A(u',v')\,du\,dv$$

Pixel coordinates film plane

Ray direction (coords on aperture plane)

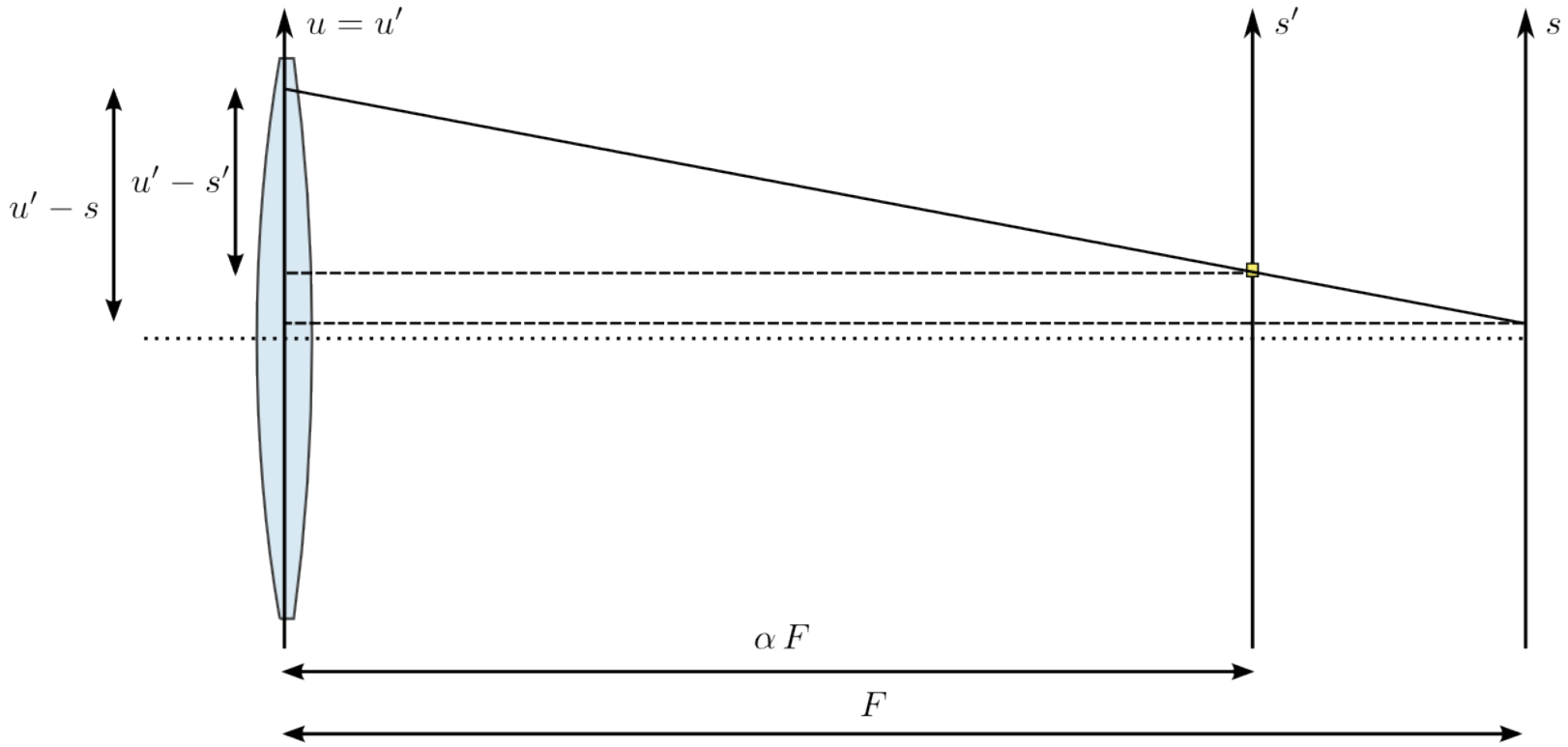
Synthetic aperture (0 or 1)

Digital refocusing



- For each pixel on the s't' plane
  - Integrate all rays passing through that pixel

Digital refocusing



$$\overline{E}(s', t') = \iint L\left(u', v', u' + \frac{s' - u'}{\alpha}, v' + \frac{t' - v'}{\alpha}\right) du'\, dv'$$

References

- HDR merging - more detailed noise model
  - Granados, M., Ajdin, B., Wand, M., Theobalt, C., Seidel, H. P., & Lensch, H. (2010). Optimal HDR reconstruction with linear digital cameras. In *Computer Vision and Pattern Recognition (CVPR), 2010 IEEE Conference on* (pp. 215–222). IEEE.
  - Hasinoff, S. W., Durand, F., & Freeman, W. T. (2010). Noise-optimal capture for high dynamic range photography. In *Computer Vision and Pattern Recognition (CVPR), 2010 IEEE Conference on* (pp. 553–560). IEEE.
- Light field – refocusing
  - Ng, Ren and Levoy, Marc and Bredif, M. and D., & Gene and Horowitz, Mark and Hanrahan, P. (2005). *Light field photography with a hand-held plenoptic camera*.