Image Capture by a Digital Camera

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Light-surface-camera

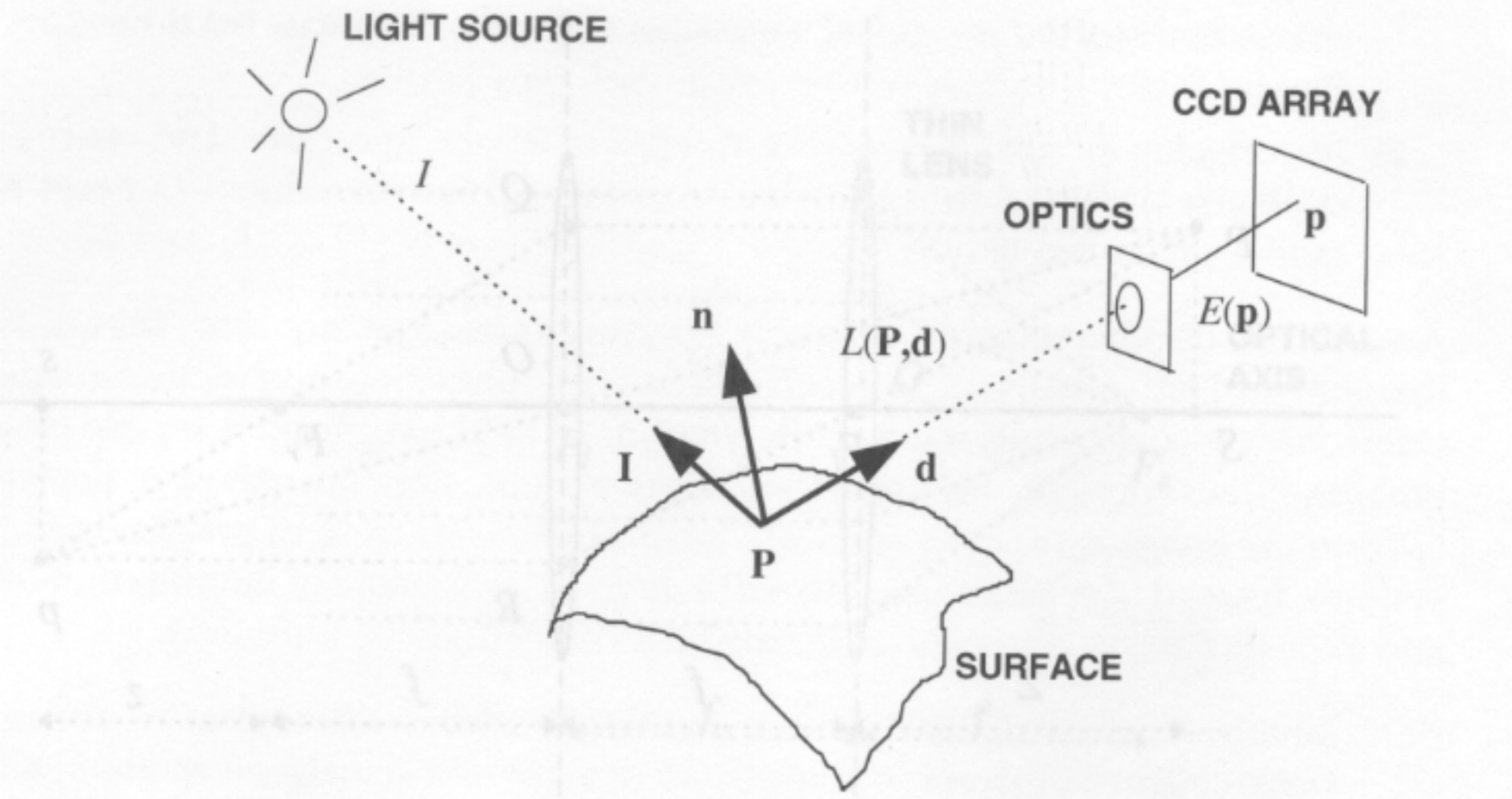
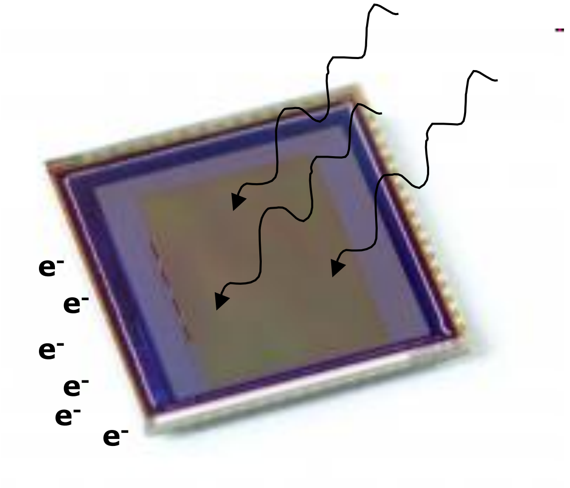


Figure 2.5 Illustration of the basic radiometric concepts.

CCD and CMOS cameras

- A photosensitive chip absorbs photons and converts them to electrical charges.
- The generated charge is always proportional to the radiation falling on the chip.
- Charges are collected differently in CCD and CMOS cameras.
- The most commonly used cameras are made of silicon and are sensitive in the 300-1000nm range.
- Different photosensitive materials must be used for other parts of the electromagnetic spectrum, e.g. InGaAs for thermal cameras.



Charge Generation

- Photons free electrons.
- The free electrons are collected in capacitors.
- Wavelength of the photons directly determines how many electrons will be freed.
- Quantum efficiency: $QE = \dfrac{\#\,\text{of electrons/sec}}{\#\,\text{of photons/sec}}$

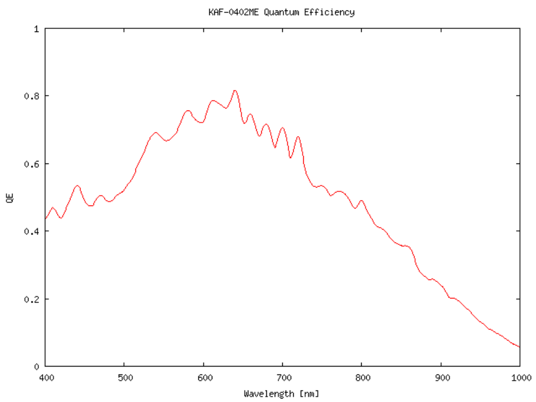


Image courtesy of Ralph Rogge http://www.astroph.de

Charge-Coupled Device (CCD) Sensor

- Main components: A photodetector and a shift register.
- Each capacitor transfers its contents to its neighbor.
- The last capacitor in the line transfer its charge into a charge amplifier.
- The amplifier converts the charge into a voltage.
- The sequence of voltages is sampled, digitized and stored in memory.

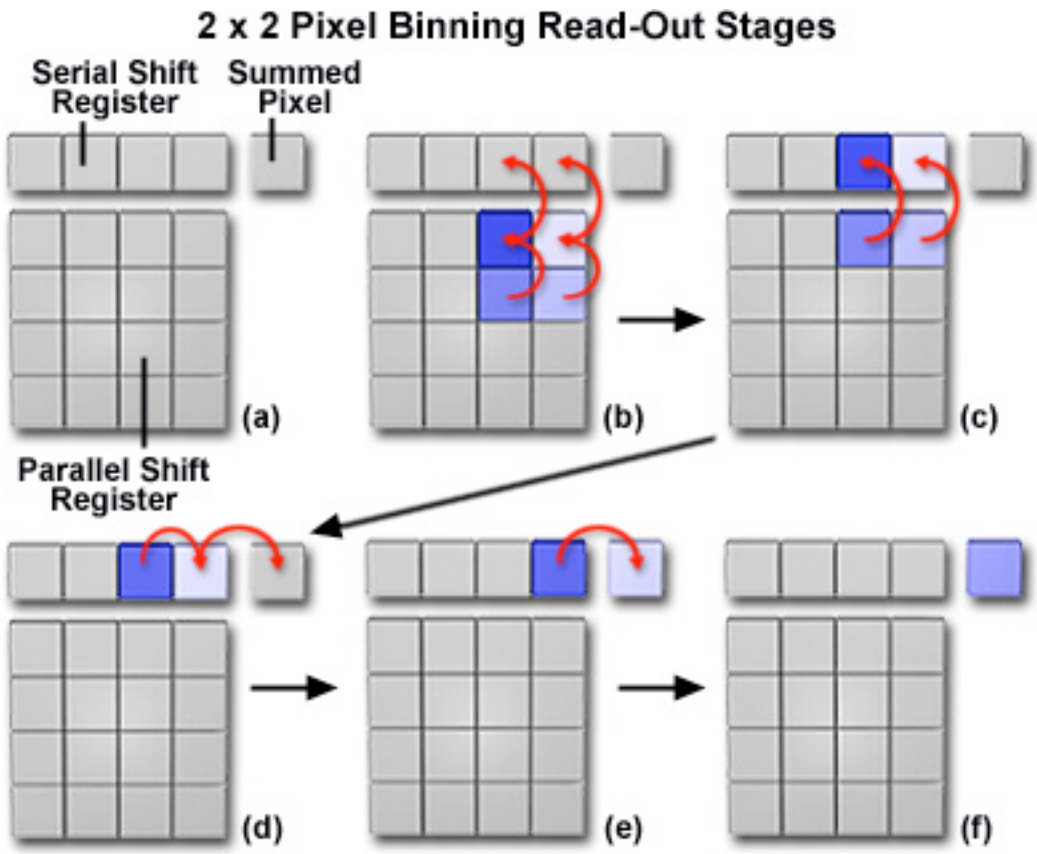


Figure 1

Images courtesy of Olympus.

CCD Sensor (continued)

- Serial operation
- Advantages:
  - cheap (easy to manufacture using existing fabrication techniques),
  - widely-tested
  - uniform response across pixels (especially in low signal cases)
- Disadvantages:
  - slow,
  - challenging scalability
  - entire image must be read out (no ROI)
  - overexposure can affect neighboring pixels (blooming)

CMOS Sensor
Complementary metal-oxide-semiconductor

- Main components: Photodetector and an active amplifier. (It is an integrated circuit)
- One amplifier per pixel.
- Per pixel: a photodiode + a number of transistors.
- Example setup: Each pixel is composed of a photodiode, a transfer gate, a reset gate, a selection gate and a source-follower readout transistor (a 4T cell).

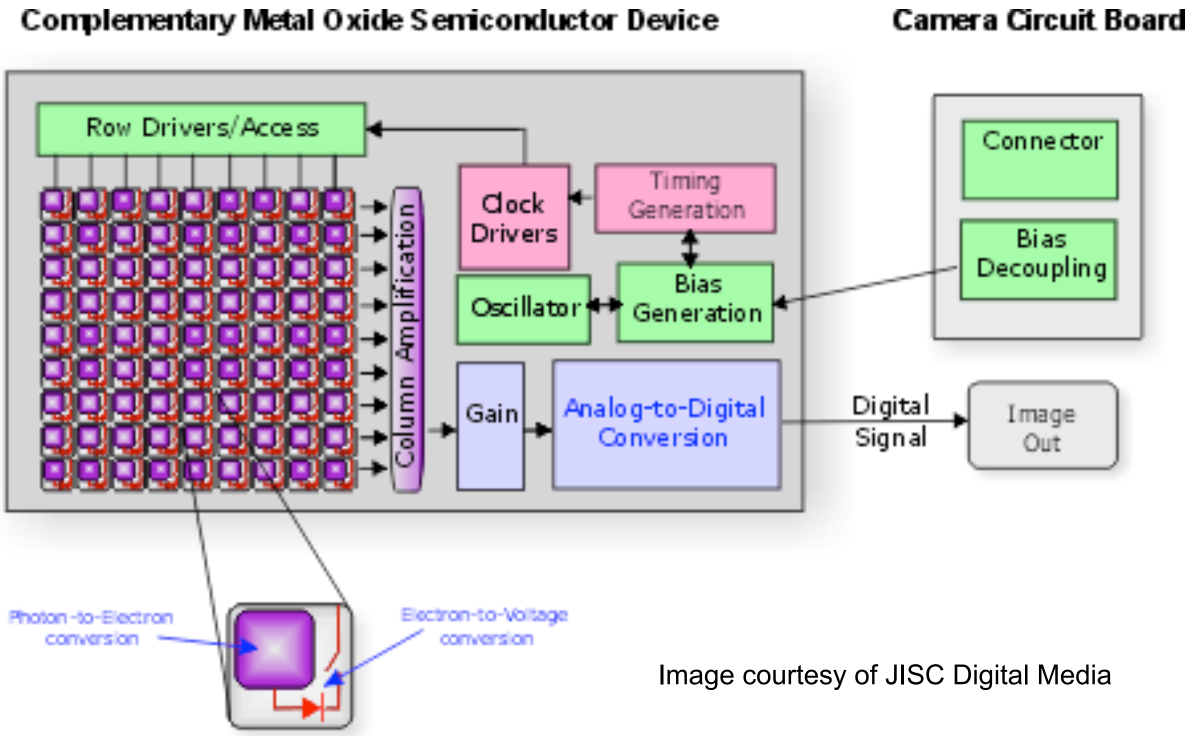


Image courtesy of JISC Digital Media

CMOS Sensor
Complementary metal-oxide-semiconductor

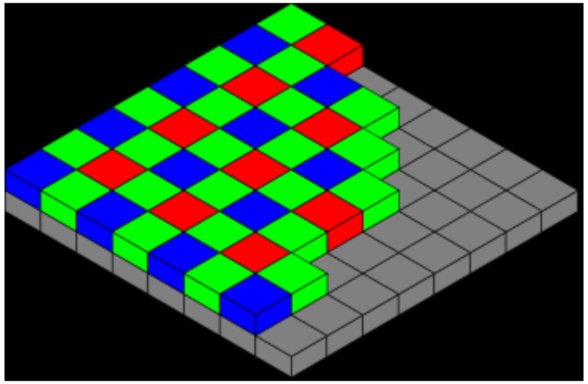
- Parallel operation
- Advantages:
  - fast,
  - lower power consumption,
  - on-chip processing,
  - can read a subregion of an image (ROI)
- Disadvantages:
  - challenging to manufacture (packing transistors on top of a pixel),
  - lower light sensitivity
  - could produce non-uniform response across pixels

Color Cameras

- Most color cameras give a triplet of color values per pixel (R,G,B).
- Either a separate chip is used per color, or a filter composed of a mosaic of smaller individual color filters is laid over the CCD chip.

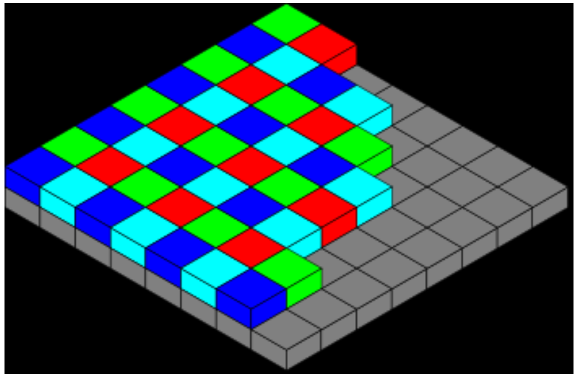
Bayer filter

50% G, 25% R, 25% B



RGBE filter

equal distribution



Images courtesy of Wikipedia http://en.wikipedia.org

3 CCD chip

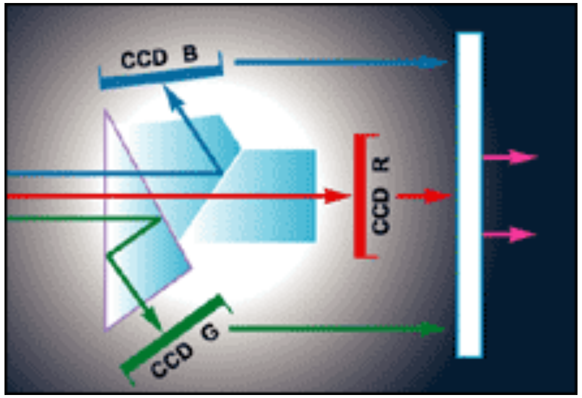


Image courtesy of Canon

http://www.usa.canon.com/tro

Digital Image

- We get a rectangular grid of pixels (**pict**ure **el**ements). Each pixel has:
  - A unique location
  - Some value(s) associated with it.
- For grayscale images, the pixel value is a single integer which is proportional to the amount of light (irradiance) incident on the corresponding patch of the photosensitive chip.
- For color images, each pixel has three values:
  - a Red value, which corresponds to the amount of light incident on the corresponding sensor area and is in the range of wavelengths centered around 650nm.
  - a Green value, which corresponds to the amount of light incident on the corresponding sensor area and is in the range of wavelengths centered around 550nm.
  - a Blue value, which corresponds to the amount of light incident on the corresponding sensor area and is in the range of wavelengths centered around 450nm.

Example Image

```
P2
# feep.pgm
24 7
15
0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
0  3  3  3  3  0  0  7  7  7  7  0  0 11 11 11 11  0  0 15 15 15 15  0
0  3  0  0  0  0  0  7  0  0  0  0  0 11  0  0  0  0  0 15  0  0 15  0
0  3  3  3  0  0  0  7  7  7  0  0  0 11 11 11  0  0  0 15 15 15 15  0
0  3  0  0  0  0  0  7  0  0  0  0  0 11  0  0  0  0  0 15  0  0  0  0
0  3  0  0  0  0  0  7  7  7  7  0  0 11 11 11 11  0  0 15  0  0  0  0
0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
```

Pixel value

- The value I[p] recorded at a pixel p is proportional to the irradiance E(p) incident on the photosensitive cell that corresponds to pixel p.
- $I[p] = g\, E(p)^{1/\gamma} + d$

  where g = camera gain. A scaling factor introduced by the A/D conversion process.

  γ = camera gamma (indicating non-linear response). Photographic film, old CRT monitors and LCD monitors have non-linear responses

  d= camera dark current. No light incident on the sensor still generate a signal. Free electrons (i.e. from heat) are captured by the capacitor and create non-zero values per pixel.

Non-traditional Cameras

- Omni-directional cameras
- Light-field cameras
- Polarization cameras
- High Dynamic Range (HDR) cameras
- Thermal (mid-IR) cameras
- Multispectral (hyperspectral) cameras

Omni-directional cameras

- Omni-directional = in all directions = panoramic
- Motivation: obtain a large field of view.
- Different types of sensors:
  - Rotating camera (first patented in 1843)
  - Camera with a fish-eye lens (first built by Nikon 1962)
  - Cluster of cameras
  - Combination of mirrors and lenses (Yagi and Kawato 1990)
- Surveillance and navigation applications.

Image courtesy of Seitz Phototechnik AG http://www.roundshot.ch

Image courtesy of Nikon "Eye of Nikon" http://www.mir.com.my/br/photography

Image courtesy of Immersive Media http://www.immersivemedia.com

Image courtesy of FullView http://www.fullview.com

A multi-camera example

- The ASTRO-Sensor series is an example of an omni-directional stereo setup that can obtain full color images and depth images at 15 fps.

The Jupiter model is composed of 20 stereo units. It requires 10 PCs to process the stereo data.

The Venus series is better suited for navigation applications.

All images courtesy of ViewPLUS http://ww.viewplus.co.jp

Catadioptric sensor design

- A catadioptric sensor uses a combination of mirrors (catoptron) and lenses (dioptrics) and cameras in a carefully arranged configuration to capture a much wider field of view.
- Typically curved mirror shape.
- Single image with usually wider field of view than fish-eye lenses.
- No moving parts.
- No registration.

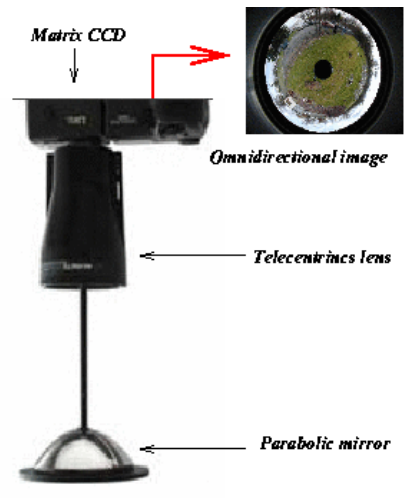


Image courtesy of Simon Lacroix and Jose Gonzalez http://www.laas.fr/~simon/eden/rover/perception/pano.php

Catadioptric cameras

Captured image often needs to be unwarped.

Images courtesy of Neovision
http://ww.neovision.cz

Image courtesy of O-360
http://ww.o-360.com

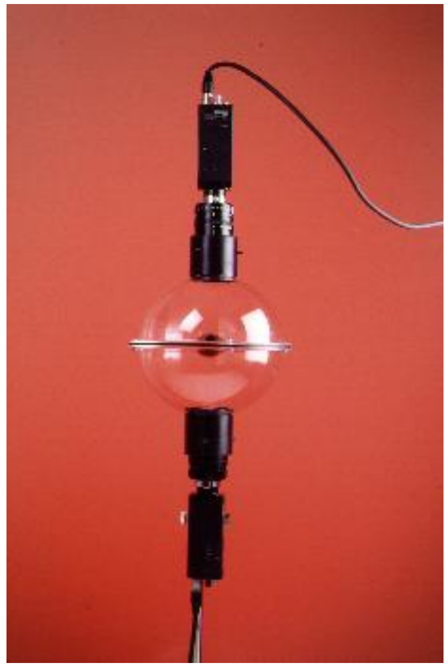


Image courtesy of Columbia University CAVE Laboratory http://ww1.cs.columbia.edu/CAVE

Mirror Design

- In most catadioptric cameras, the mirror is a swept conic section:
  - Cone
  - Sphere
  - Ellipsoid
  - Hyperboloid
  - Paraboloid
- In a convex surface of revolution, knowing the shape of the generating curve is sufficient for knowing the shape of the mirror.

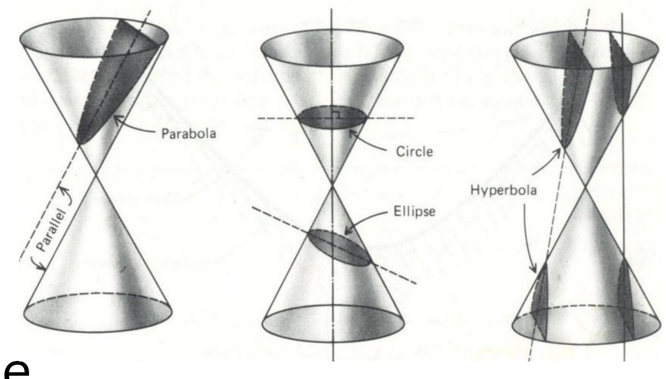
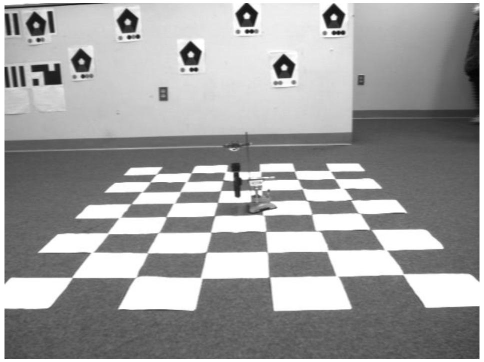
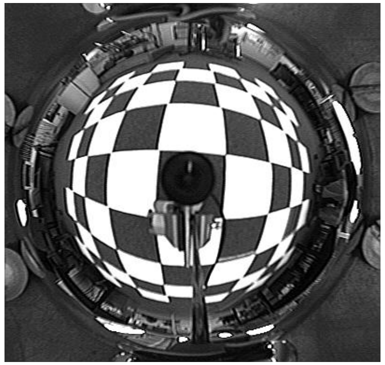


Image courtesy of Keith G. Calkins
http://www.andrews.edu/~calkins/math.webtexts/geom09.html

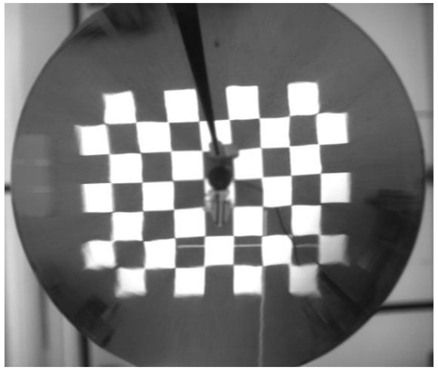


Calibrating scene at GRASP Lab, UPenn



Omnicam with spherical mirror

Omnicam with parabolic mirror

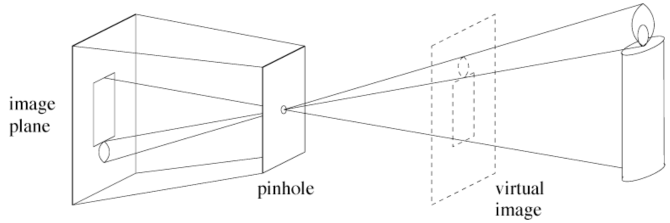


Omnicam with conic mirror

Images courtesy of Andy Hicks http://www.math.drexel.edu/~ahicks/design/rectifying.html

Why Conics?

Single center of projection
(Fixed Viewpoint constraint)
- almost -



Traditional perspective projection

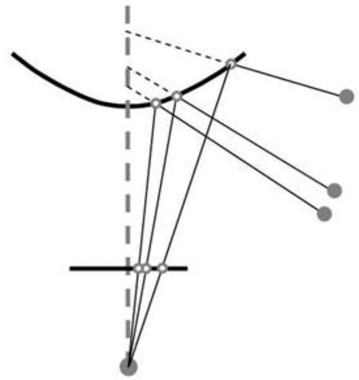


Image courtesy of Davide Scaramuzza
http://asl.epfl.ch/~scaramuz/

When the single center of projection is not satisfied, the rays are tangents on caustic surfaces.

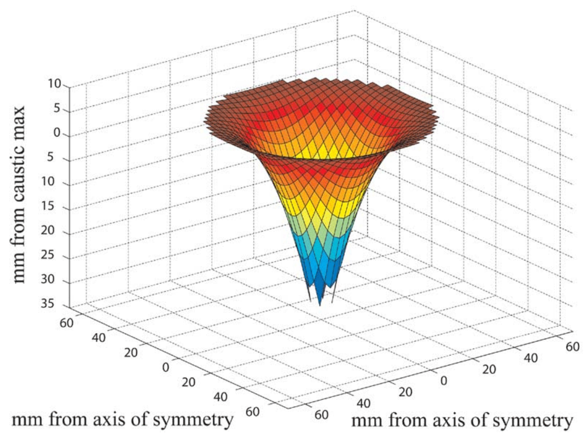


Image courtesy of Shree Nayar
http://www1.cs.columbia.edu/CAVE/projects/non-single

Conic Mirror

- Center of projection at the apex of the cone.
- Either place the pinhole at the apex (omnicam of limited value) or place the pinhole on the axis of the cone at some distance d and get a locus of effective viewpoints which lie on a circle.

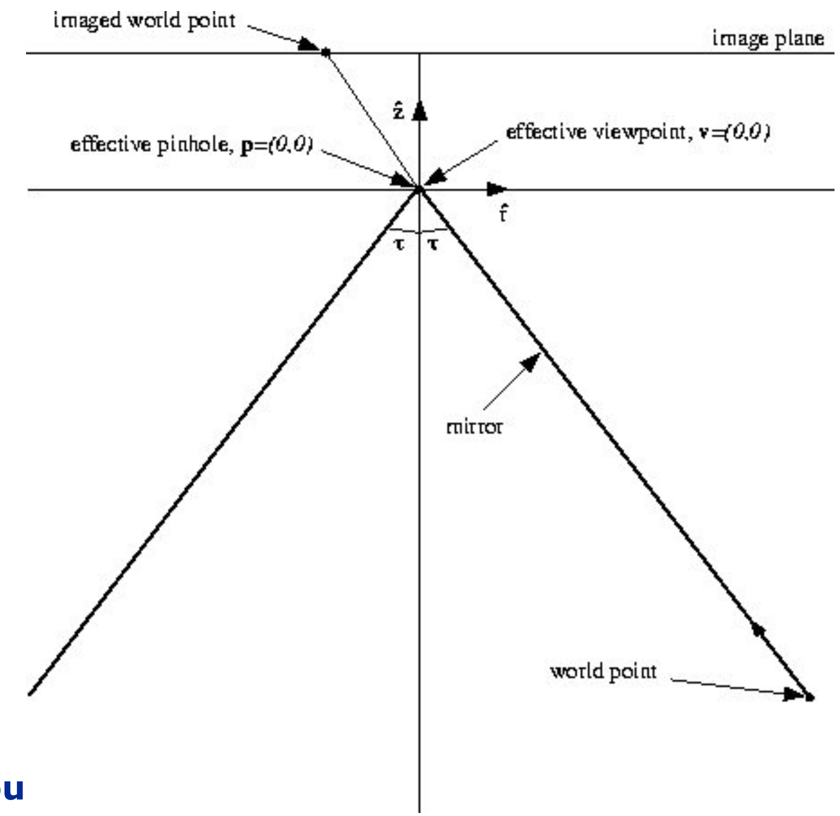


Image courtesy of Simon Baker and Shree Nayar
"Single Viewpoint Catadioptric Cameras",
Panoramic Vision, pp. 39-71, 2001.

Spherical mirror

- Center of projection at the center of the sphere.
- Consequence: No single effective viewpoint, but rather a computable locus of points.

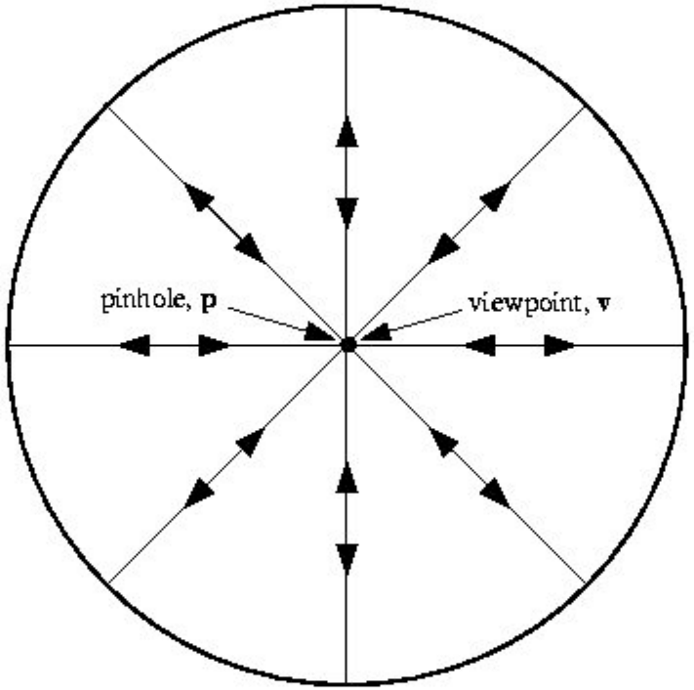


Image courtesy of Simon Baker and Shree Nayar
"Single Viewpoint Catadioptric Cameras",
Panoramic Vision, pp. 39-71, 2001.

Ellipsoidal mirror

- Center of projection at the foci of the ellipsoid.
- Unrealizable solution.

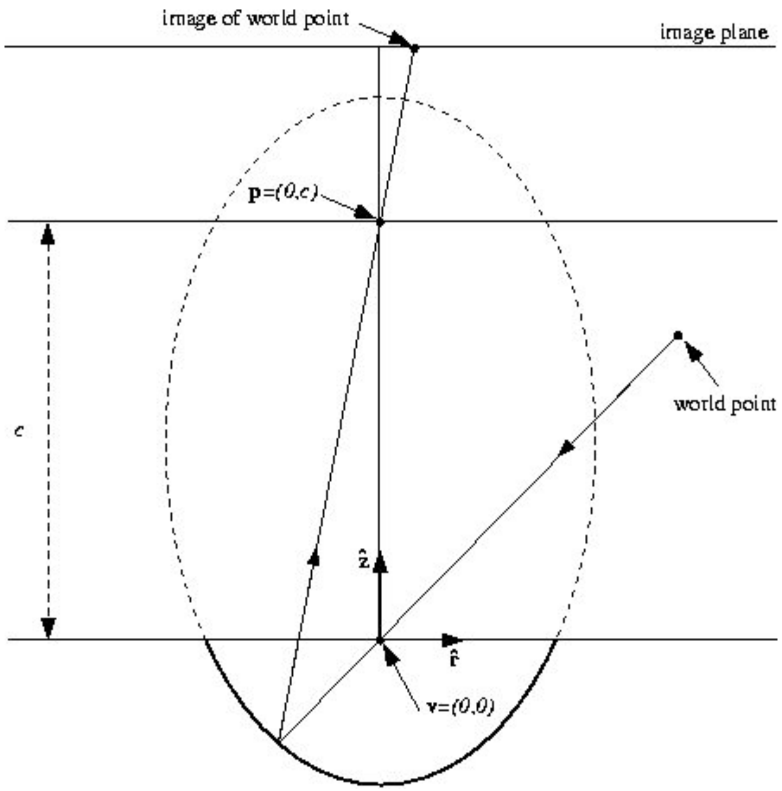


Image courtesy of Simon Baker and Shree Nayar
“Single Viewpoint Catadioptric Cameras”,
Panoramic Vision, pp. 39-71, 2001.

Paraboloidal mirror

- Center of projection at the focus of the paraboloid.
- Realizable solution with orthographic projection lens.

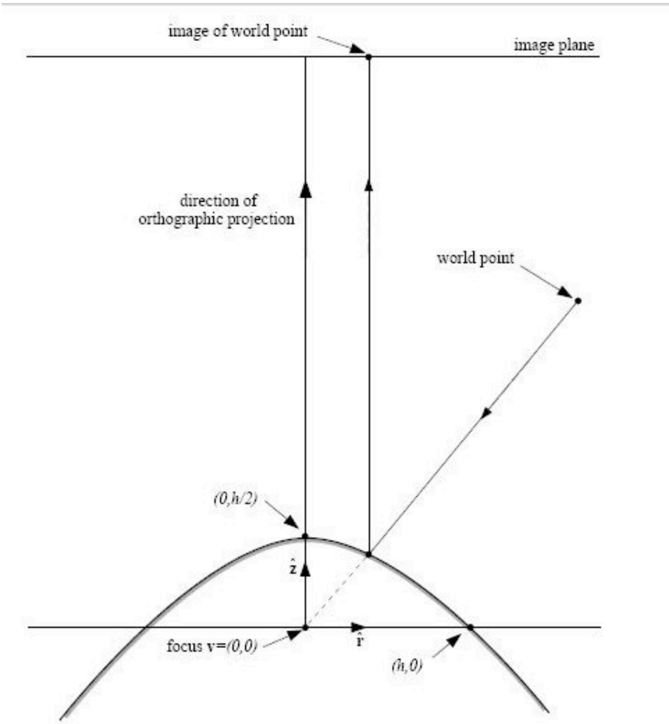


Image courtesy of Simon Baker and Shree Nayar
"Single Viewpoint Catadioptric Cameras",
Panoramic Vision, pp. 39-71, 2001.

Hyperboloidal mirror

- Center of projection at the foci of the hyperboloid.
- Realizable solution with perspective projection lens.

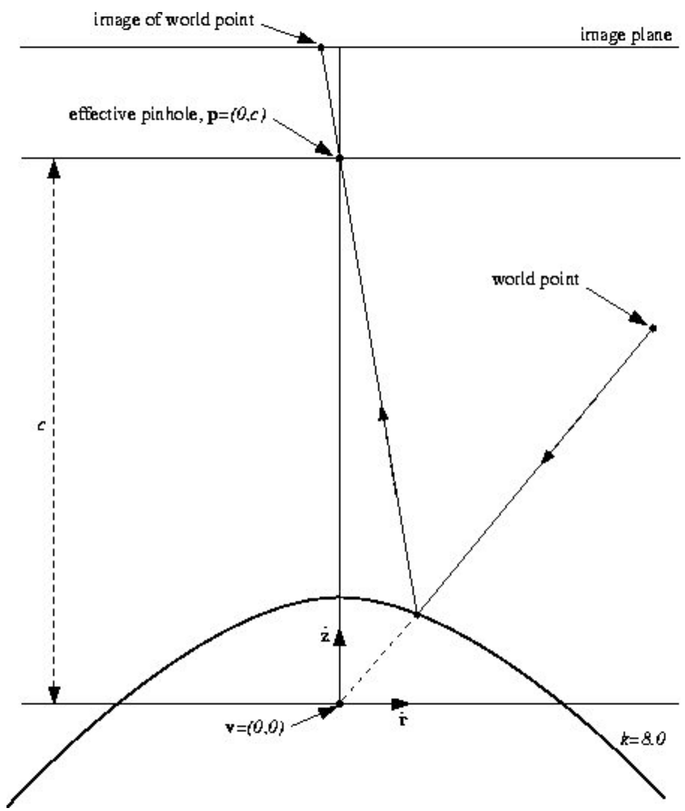


Image courtesy of Simon Baker and Shree Nayar
“Single Viewpoint Catadioptric Cameras”,
Panoramic Vision, pp. 39-71, 2001.

Light Field cameras

- Also known as plenoptic cameras
- Motivation: Better focused images
- Refocusing after data capture
- By placing an array of lenses in front of the sensing chip, one simultaneously captures the same scene from somewhat different perspectives and/or focal lengths.

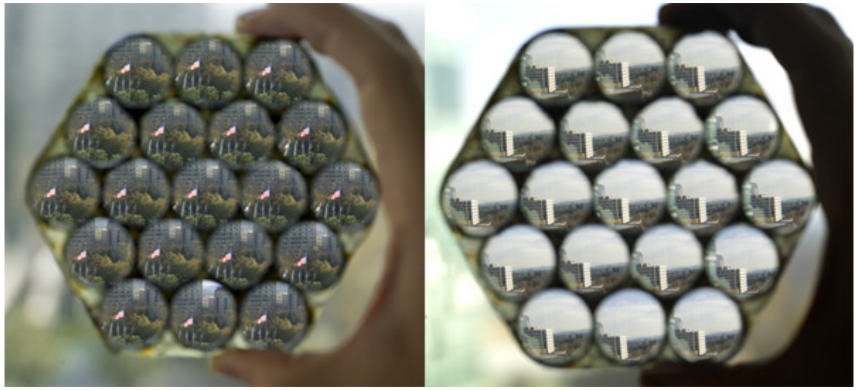


Image courtesy of Adobe

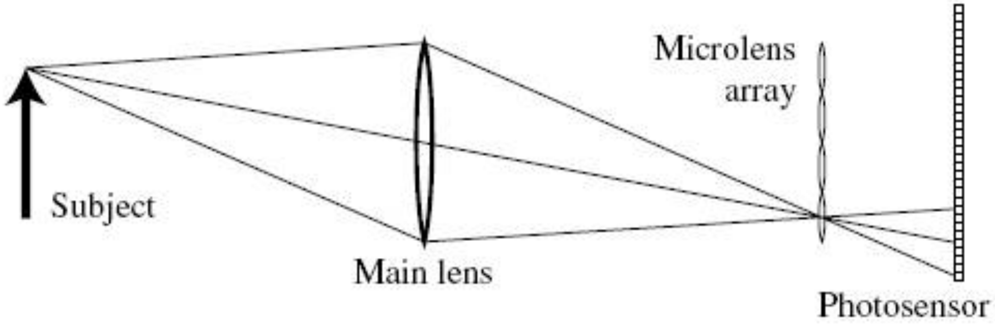
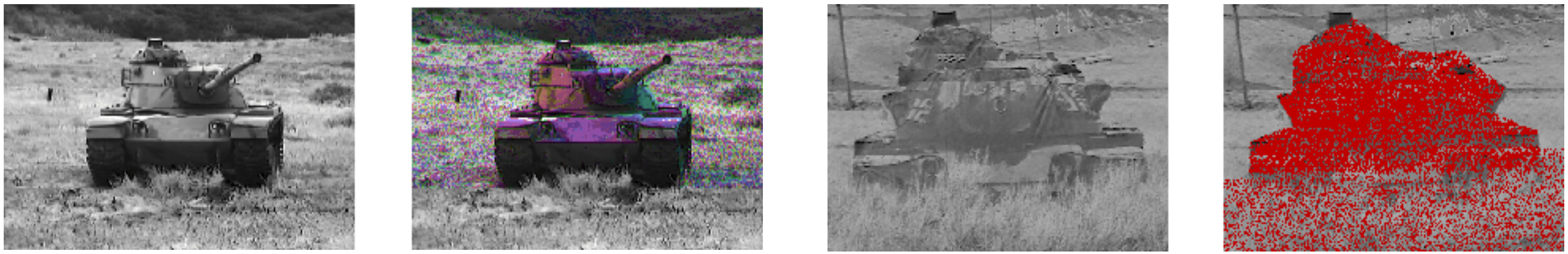


Image courtesy of Ren Ng et al
http://graphics.stanford.edu/papers/lfcamera

Image courtesy of MERL

Polarization cameras

- Polarization of light conveys important material information and enhances object visibility in some bad-weather conditions.
- Animals (shrimp, birds) can sense light polarization and use it for orientation and species identification
- Idea: Place differently oriented linear polarizers in-front of the camera lens.



A Real (left) versus a decoy tank (right) as imaged by a traditional grayscale and a polarization camera. Images courtesy of L. Wolff.

Underlying principle

- Most of the light around us is unpolarized.
- A linear polarizer will only transmit light waves that are oscillating in its orientation.
- Naturally occurring light can be partially linearly polarized: skylight on a sunny day (except sunrise and sunset), underwater (55% linearly polarized).
- Some materials, e.g. grass, diffuse paints, plastics, marine animals will depolarize light.
- Materials like metals will preserve polarization.
- Other materials like water, glass, dirt, rocks polarize light.
- In bad weather (fog) the scattered light and the directly transmitted light have distinct polarization behavior.
- Drawback: dim images

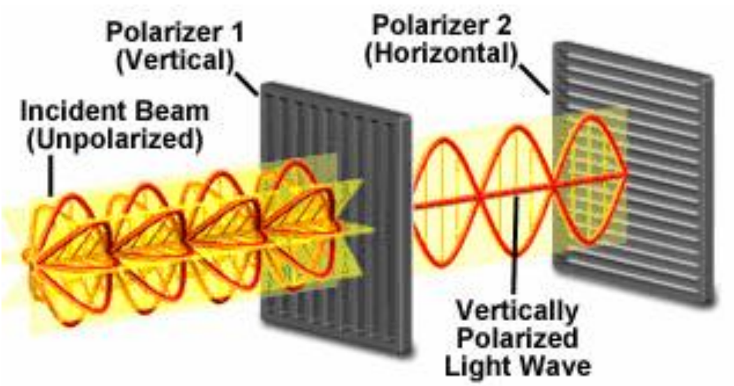


Image courtesy of Olympus
http://www.olympusmicro.com/primer/lightandcolor/polarizedlightintro.html

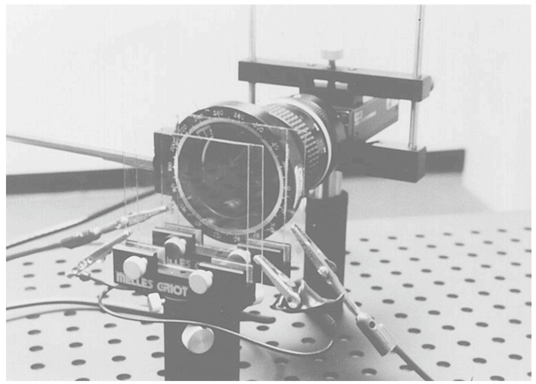


Image courtesy of Larry Wolff

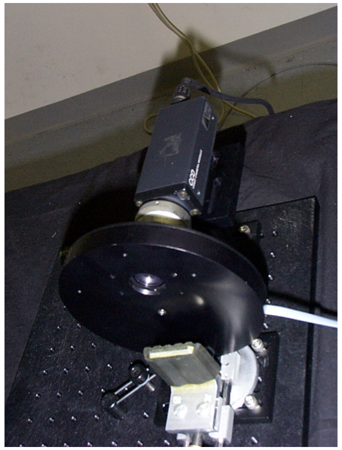
High Dynamic Range cameras

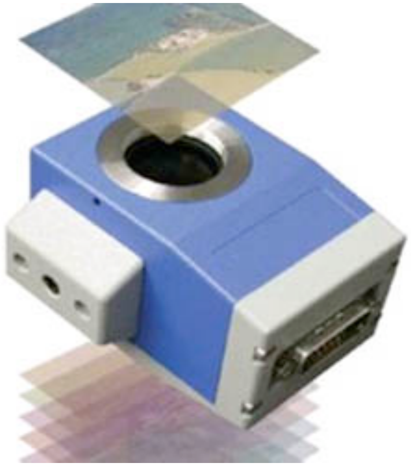
- A high dynamic range image is obtained by taking multiple images using different exposure times.
- Current HDR cameras are CMOS based. They use multiple exposure times per scene and integrate the individual exposure readings.

Images courtesy of S. Nayar.

Multispectral cameras

- Idea: Instead of capturing 3 color values (R,G,B) per pixel, light in 10s or 100s of very narrow color bands.
- Hardware: place color glass filters in-front of the lens, or use electronically tunable filters





Images courtesy of CRI and OKSI.

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