CMOS Image Sensors: Tech Transfer from Saturn to your Cell Phone

Eric R. Fossum
Thayer School of Engineering at Dartmouth

Fermilab
November 18, 2013

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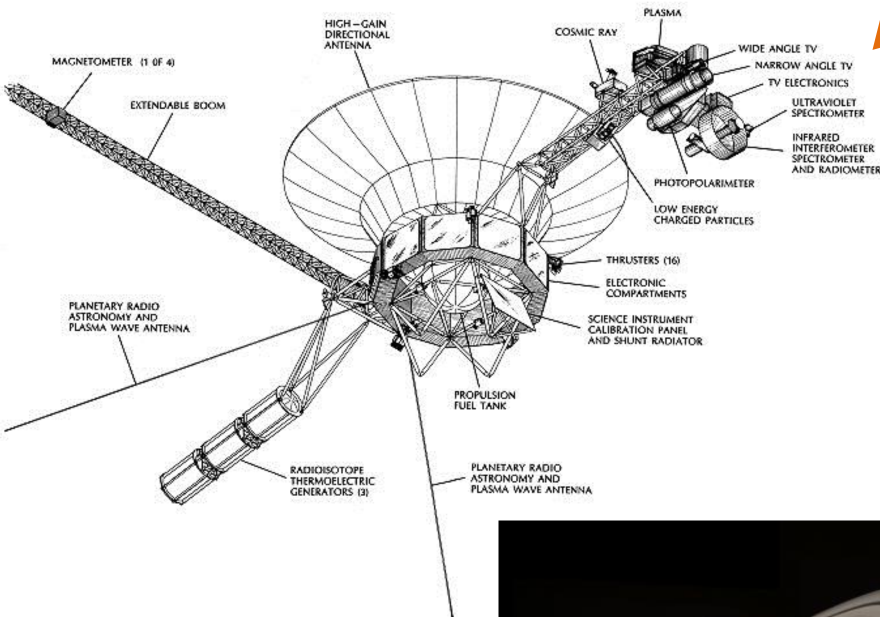
Step 1
“Necessity is the Mother of Invention”

Voyager (1977) ISS had vidicon cameras (wide angle and narrow angle)

Mass: 38.2 kg
Power (avg): 35.0 W



http://nssdc.gsfc.nasa.gov/nmc/experimentDisplay.do?id=1977-084A-01

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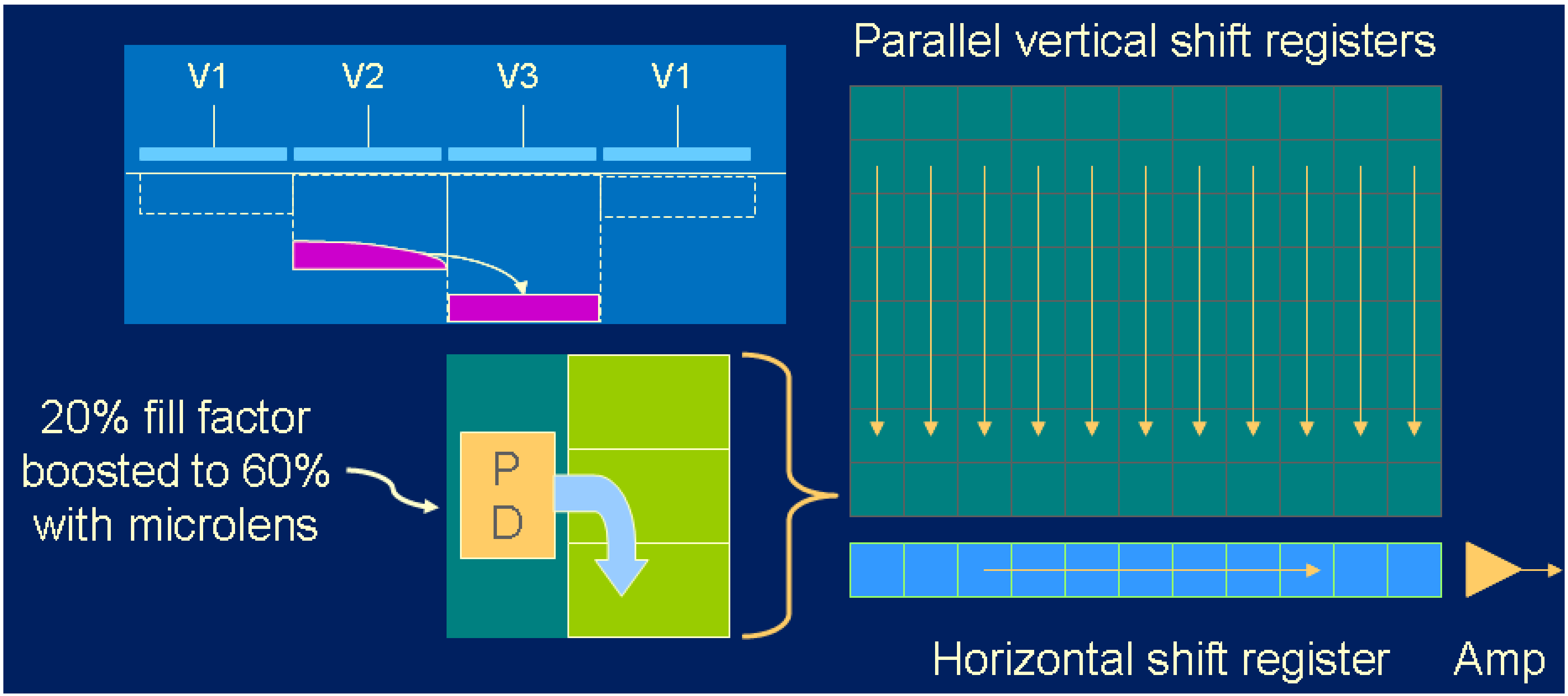
Charge-Coupled Device
1st Generation Image Sensor

- MOS-based charge-coupled devices (CCDs) shift charge one step at a time to a common output amplifier



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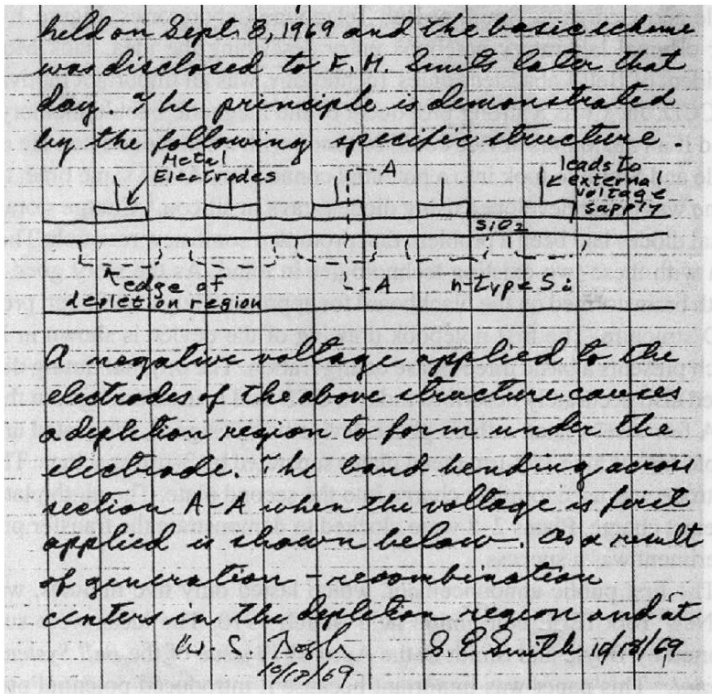
2009 Nobel Prize in Physics


held on Sept. 8, 1969 and the basic scheme was disclosed to F.H. Smith later that day. The principle is demonstrated by the following specific structure.

Metal Electrodes
A
leads to external voltage supply
SiO_2
edge of depletion region
A
n-type Si

A negative voltage applied to the electrodes of the above structure causes a depletion region to form under the electrode. The band bending across section A-A when the voltage is first applied is shown below. As a result of generation-recombination centers in the depletion region and at

W. S. Boyle 10/17/69
G. E. Smith 10/17/69

Figure 4. Original notes from the Boyle and Smith's brainstorm meeting on September 8 1969, when they made the first sketch of a CCD.

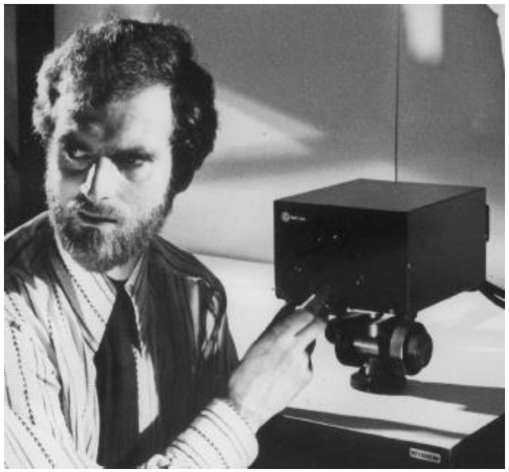
http://www.nobelprize.org/nobel_prizes/physics/laureates/2009/popular-physicsprize2009.pdf

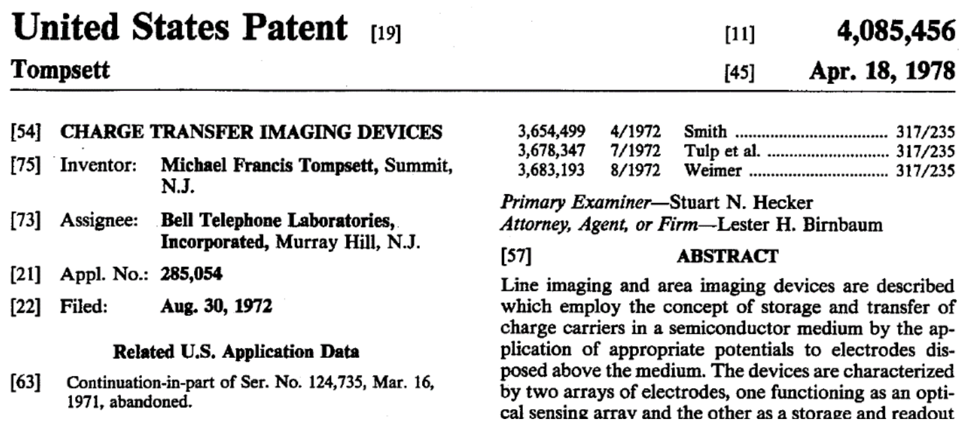

Photo: U. Montan
Willard S. Boyle


Photo: U. Montan
George E. Smith

"for the invention of an imaging semiconductor circuit – the CCD sensor"

2009 Nobel Prize in Physics
Possible Citation Blunder





United States Patent [19] [11] **4,085,456**

Tompsett [45] **Apr. 18, 1978**

[54] **CHARGE TRANSFER IMAGING DEVICES**

[75] Inventor: **Michael Francis Tompsett**, Summit, N.J.

[73] Assignee: **Bell Telephone Laboratories, Incorporated**, Murray Hill, N.J.

[21] Appl. No.: **285,054**

[22] Filed: **Aug. 30, 1972**

Related U.S. Application Data

[63] Continuation-in-part of Ser. No. 124,735, Mar. 16, 1971, abandoned.

3,654,499	4/1972	Smith	317/235
3,678,347	7/1972	Tulp et al.	317/235
3,683,193	8/1972	Weimer	317/235

Primary Examiner—Stuart N. Hecker
Attorney, Agent, or Firm—Lester H. Birnbaum

[57] **ABSTRACT**

Line imaging and area imaging devices are described which employ the concept of storage and transfer of charge carriers in a semiconductor medium by the application of appropriate potentials to electrodes disposed above the medium. The devices are characterized by two arrays of electrodes, one functioning as an optical sensing array and the other as a storage and readout

Gene Gordon – Former Lab Director Bell Labs wrote

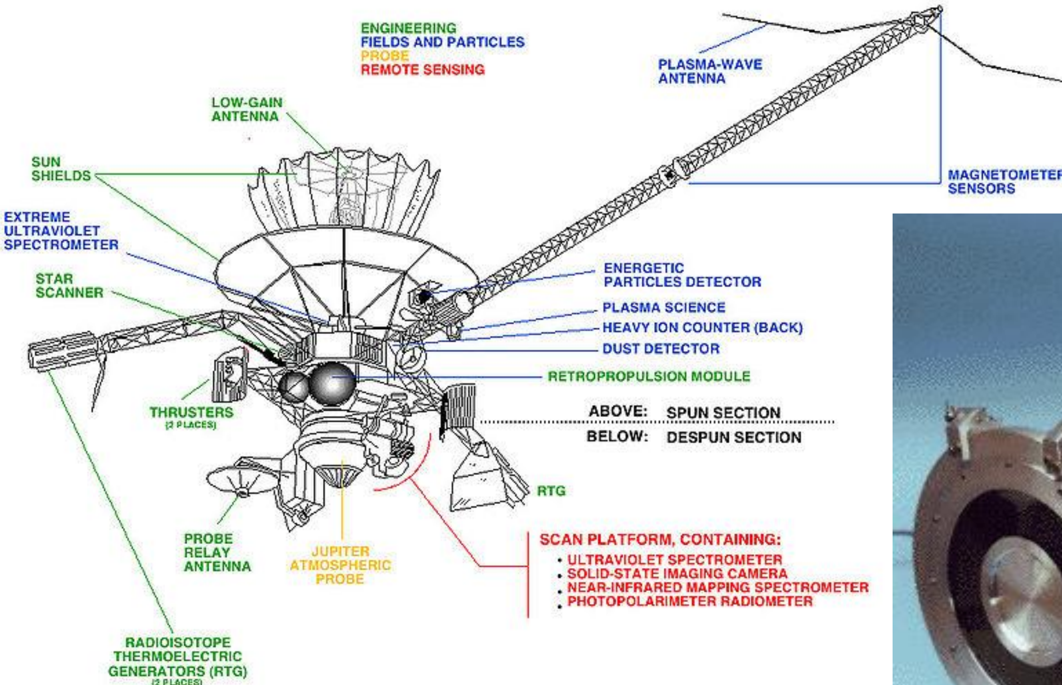
"The patent for the area device entitled "Charge Transfer Imaging Device" to which the Nobel award actually applies was in the name of Tompsett, and not Smith and Boyle. Their patent entitled Information Storage Device, had nothing to do with an imaging device. They never built an imaging device or any related device. Tompsett built the device of his patent, a color TV camera, and it worked. Since both Smith and Tompsett worked for me, I can say with great certainty that the award is a terrible injustice. The invention record is clear. How could the Nobel award committee mess up so badly?"

From M. Tompsett, "Many Pixels Make Light Work," 2013 IISW Snowbird, UT

http://en.wikinews.org/wiki/Controversy_raised_about_2009_Nobel_Prize_in_Physics

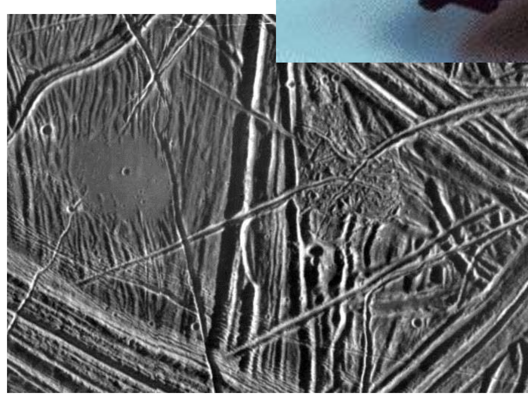
http://spectrum.ieee.org/podcast/semiconductors/devices/who-deserves-credit-for-the-nobelprizewinning-ccd

Galileo (1989) SSI had CCD cameras (wide angle and narrow angle)



Mass: 29.7 kg
Power (avg): 15 W
CCD: 800x800 pixels

Callisto

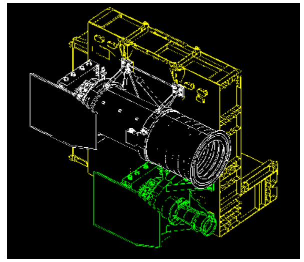


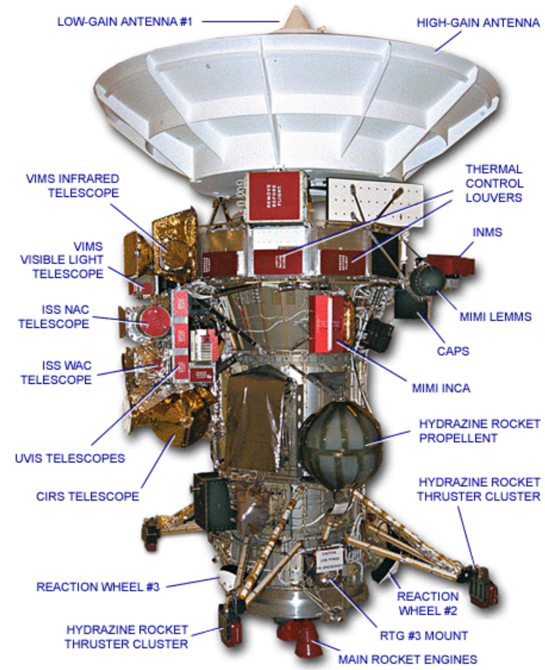
Europa

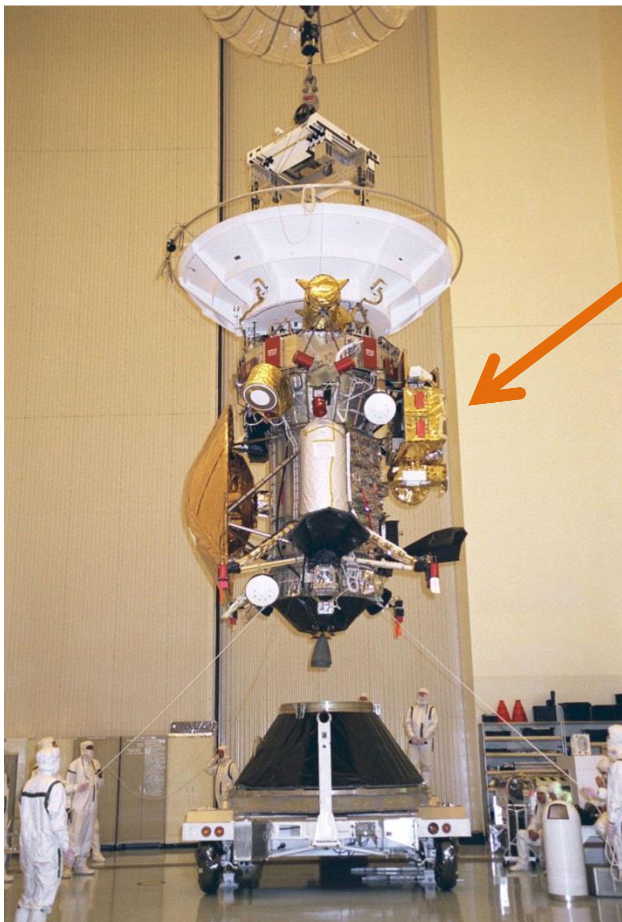
http://en.citizendium.org/wiki/Galileo_Probe

Cassini (1997) ISS has CCD cameras (wide angle and narrow angle)

Mass: 57.83 kg
Power (avg): 30.0 W
CCD: 1024x1024 pixels







NASA’s Administrator Daniel Goldin
“Faster, Better, Cheaper”

Need to Miniaturize Cameras
On Future Spacecraft

Smaller payload mass = Smaller rockets
Smaller payload volume = Less radiation shielding (less mass)
Less power = Smaller power generation on-board

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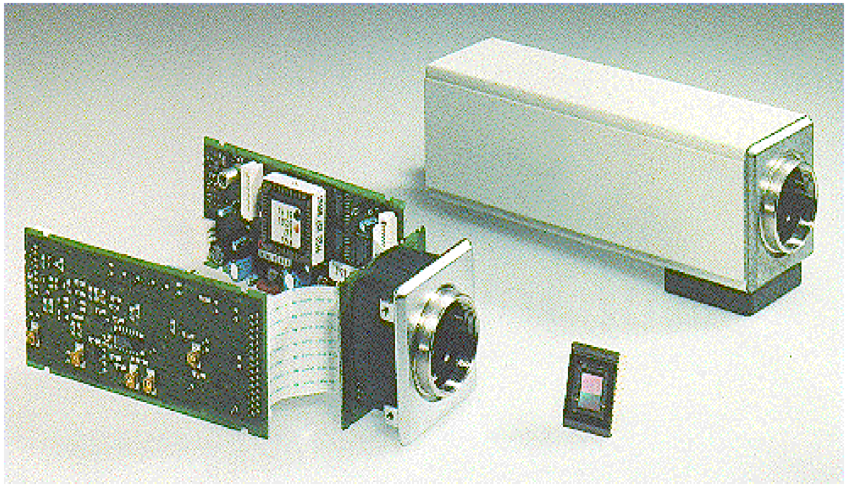
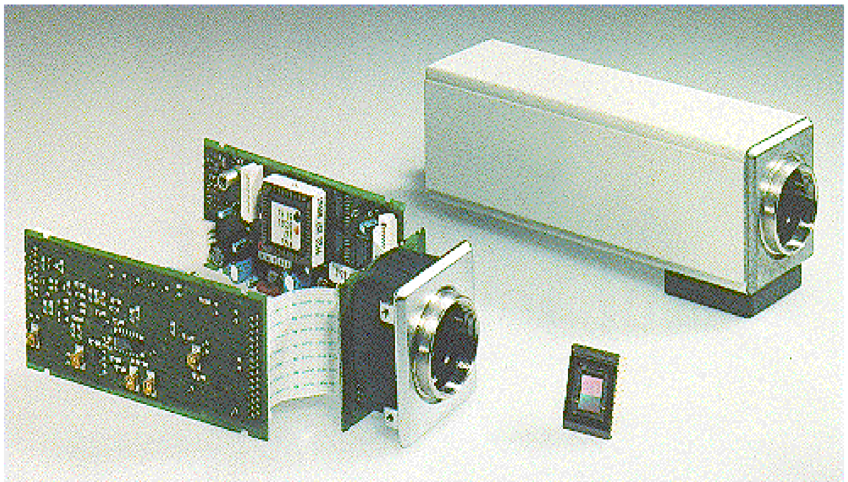
Step 2
Invent a New Technology



CCD cameras have many components and consume significant power.

BUT, the CCD is not amenable to electronics integration

Step 2
Invent a New Technology



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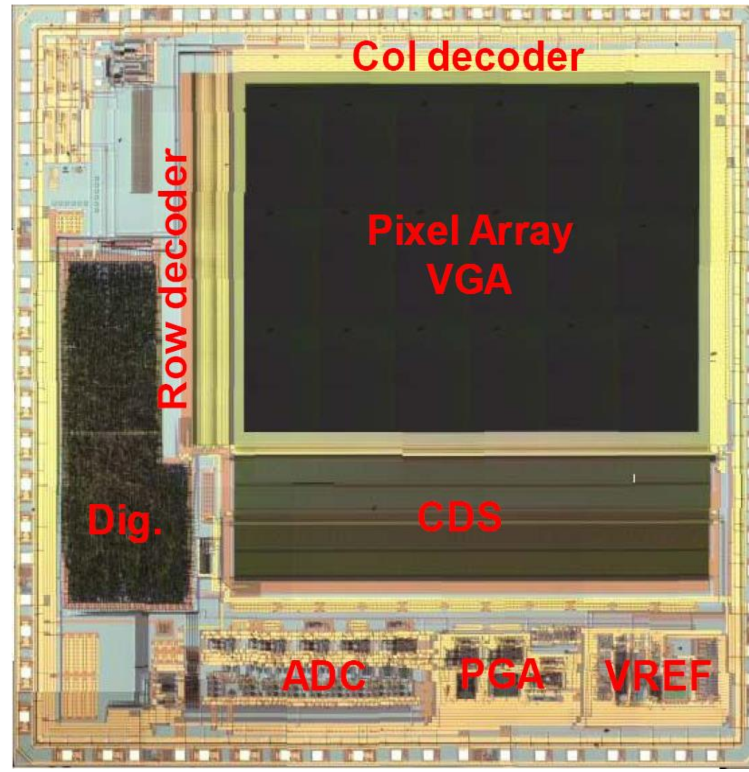

CMOS Active Pixel Sensor
With Intra-Pixel Charge Transfer
Camera-on-a-chip

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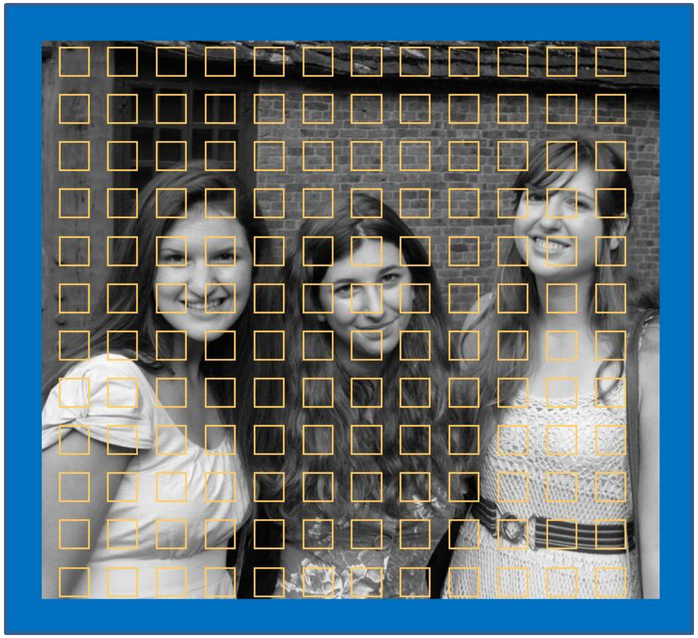
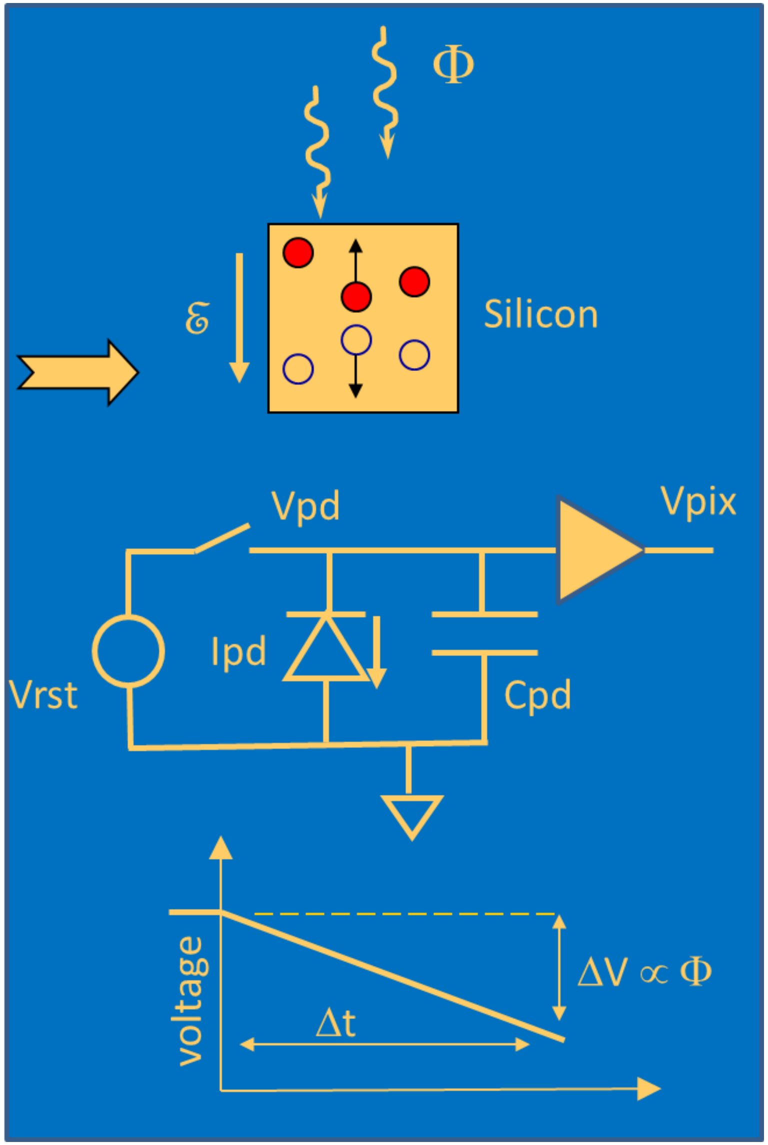
Active Pixels





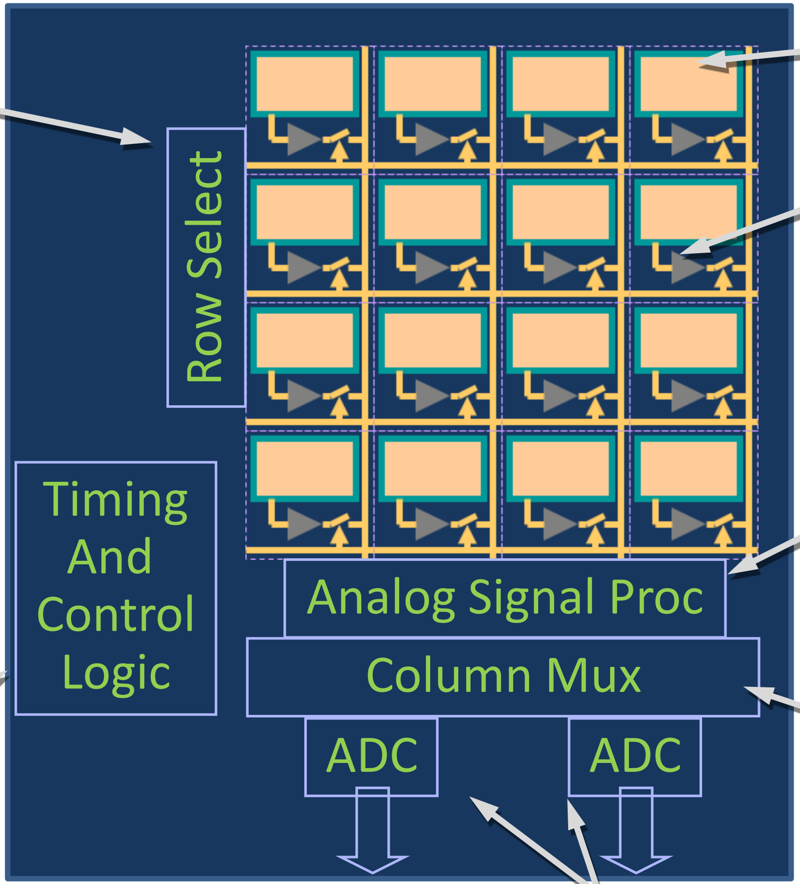
CMOS Active Pixel Sensor
2nd Generation Image Sensor

Read pixel signals out thru switches and wires

Row select logic chooses which row is selected for readout.

Photodetector converts photons to electrons

Amplifier converts electrons to voltage after complete intrapixel charge transfer



Analog signal processor suppresses noise and further amplifies signal

Column multiplexer selects particular column(s) for routing to ADC(s)

Timing and control logic controls the timing of the whole sensor

Analog-to-digital converters (ADC) converts signal from volts to bits (usually 10-12 bits resolution)

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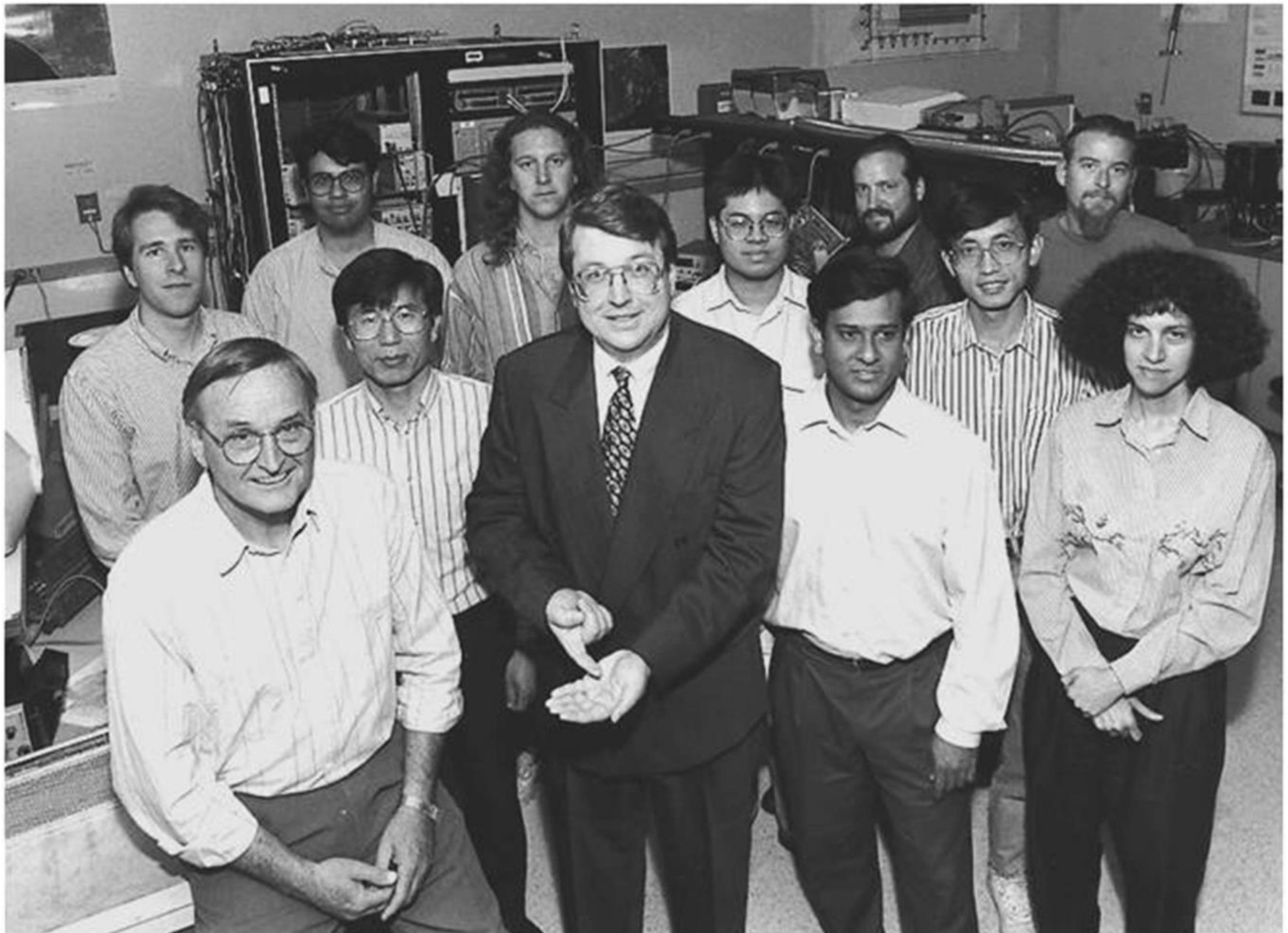
Most of the JPL Team



Advanced Imager Technology Group, Jet Propulsion Laboratory, California Institute of Technology 1995
Back row: Roger Panicacci, Barmak Mansoorian, Craig Staller, Russell Gee, Peter Jones, John Koehler
Front row: Robert Nixon, Quisup Kim, Eric Fossum, Bedabrata Pain, Zhimin Zhou, Orly Yadid-Pecht

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Step 3
Technology Transfer

To fulfill a secondary NASA mission to strengthen US Industry
JPL/Caltech signed Technology Cooperation Agreements with

- AT&T Bell Labs
- Kodak
- Schick Technologies (startup)

And other agreements/visits with

- National Semiconductor
- Motorola
- Intel
- EG&G Reticon
- etc.

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⇒ Entrenched industry moves slowly in adopting new technologies so in February 1995 we founded Photobit Corporation to commercialize the CMOS image sensor technology ourselves

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Step 4
Get a Lucky Break

Science & Technology

INVENTIONS

NASA'S TINY CAMERA HAS A WIDE-ANGLE FUTURE

It may still be in the lab, but the latest advance in capturing images has very bright prospects, indeed

Get ready for the camera-on-a-chip. Since the 1970s, camera makers have dreamed of a one-chip camera containing all the components necessary to take a snapshot or make a movie. With all the smarts on one chip instead of several, designers figure they could make a camera small and cheap enough to open vast new markets for everything from dolls that "see" to rear-bumper cameras that would help drivers back up.

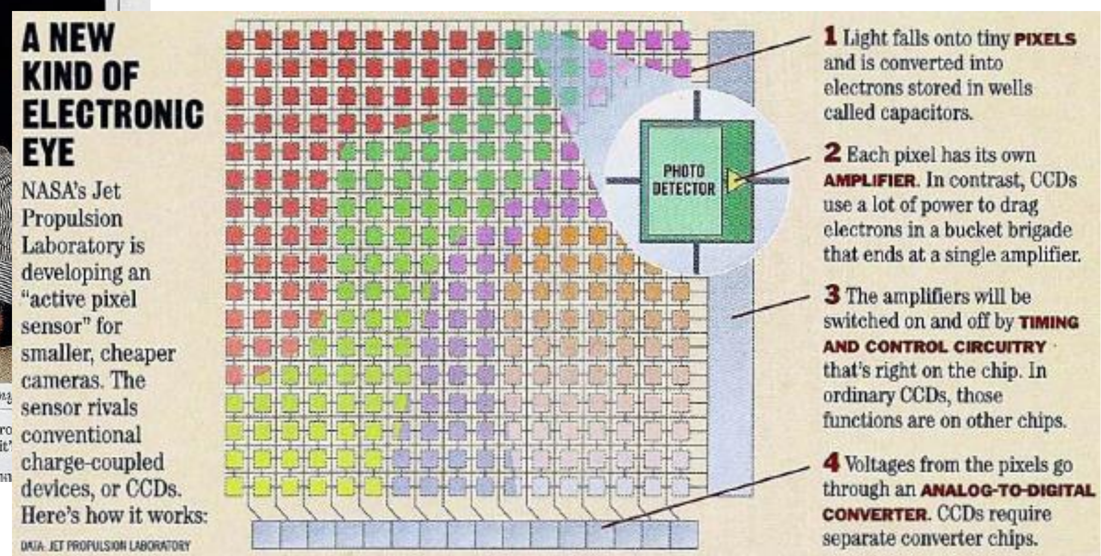
Such devices are impractical with today's standard electronic image sensor. It's called a CCD, for charge-coupled device, and it's at the heart of every fax machine and camcorder. Japanese powerhouses such as Sony, Matsushita, and NEC churn out millions a year. CCDs offer good image quality. But they are costly, power-hungry, and—with the accessory chips they require—bulky.

TEAMWORK. Now, the one-chip dream appears on the verge of being fulfilled, thanks to three inventors from NASA's Jet Propulsion Laboratory at California Institute of Technology in Pasadena. The leader is Eric R. Fossum, 37, who

FOSSUM: *The project leader and his co-inventors will share in an*

cost much less than CCDs. One chip can incorporate all manner of electronic controls that are usually on multiple chips,

ter for Space Microelectro gy at JPL. "For them, it' leapfrog the Japanese."

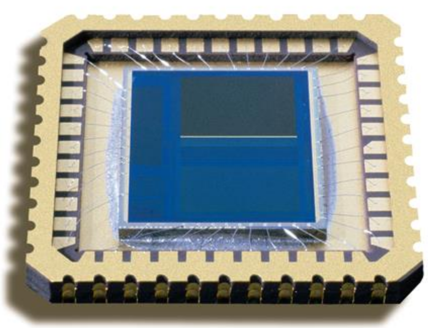


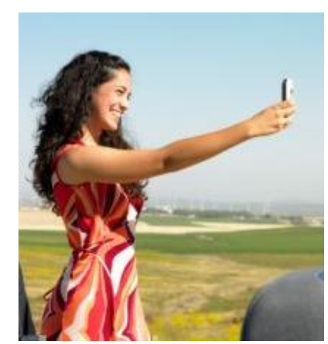
March 6, 1995 Business Week article

Step 5
Perspiration Phase

1995-2001 Photobit grows to about 135 persons

- Self funded with custom-design contracts from private industry
- Important support from SBIR programs (NASA/DoD)
- Later, investment from strategic business partners to develop catalog products
- Over 100 new patent applications filed



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The Photobit Team Circa 2000

Step 6
Miller Time

Nov. 2001 – Photobit acquired by Micron Technology

Meanwhile, by 2001 there were many competitors emerging in the CMOS image sensor business due in part to the earlier efforts to promote the transfer the technology.

Examples: Toshiba, ST Micro, Omnivision

Later, came Sony and Samsung (now #1, #2 in worldwide market)

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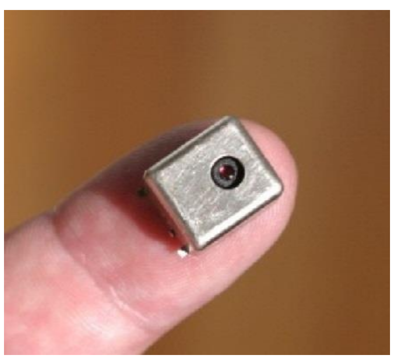
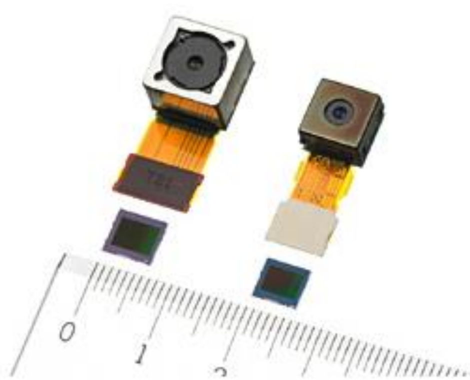
Step 7
The Technology Has a Life of its Own

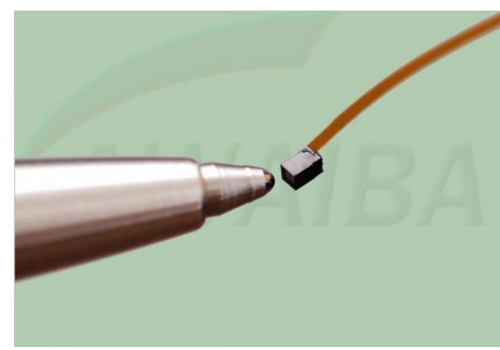
- Today, about 2 billion cameras are manufactured each year that use the CMOS image sensor technology we invented at JPL, or more than 60 cameras per second, 24/7/52
- Semiconductor sales of CMOS image sensors exceeded $7B in 2012 heading to $10B by 2016.
- Caltech has successfully enforced its patents against all the major players.
- NASA is now just adopting the technology for use in space.



Siimpel MEMS AF
2 Mpix camera ~2007



16Mpix camera modules
From Sony ~2012



Endoscopy Camera
From Awaiba ~2012

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New Technology Invariably Brings New Social Issues

Instant communications (e.g. Facebook)

Rapid Social Change (Arab Spring)

Inappropriate use

Visual overload (e.g. Japanese Tsunami)

Security v. Privacy

New Weapons

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Use in High Energy Physics

Early cross-fertilization between high energy particle detectors (e.g. hybrid arrays) and monolithic CMOS active pixel sensor

Cheesy metrics via Google Scholar search:
"fossum" and "collider“ - 104 hits
"active pixel sensor" and "collider“ – 462 hits

Relatively recent article:

“R&D paths of pixel detectors for vertex tracking and radiation imaging,”

Marco Battaglia, Cinzia Da Viá, Daniela Bortoletto, Richard Brenner, Michael Campbell, Paula Collins, Gianfranco Dalla Betta, Marcel Demarteau, Peter Denes, Heinz Graafsma, Ingrid M. Gregor, Alex Kluge, Vito Manzari, Chris Parkes, Valerio Re, Petra Riedler, Giuliana Rizzo, Walter Snoeys, Norbert Wermes, Marc Winter in Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, Volume 716, 11 July 2013, Pages 29-45

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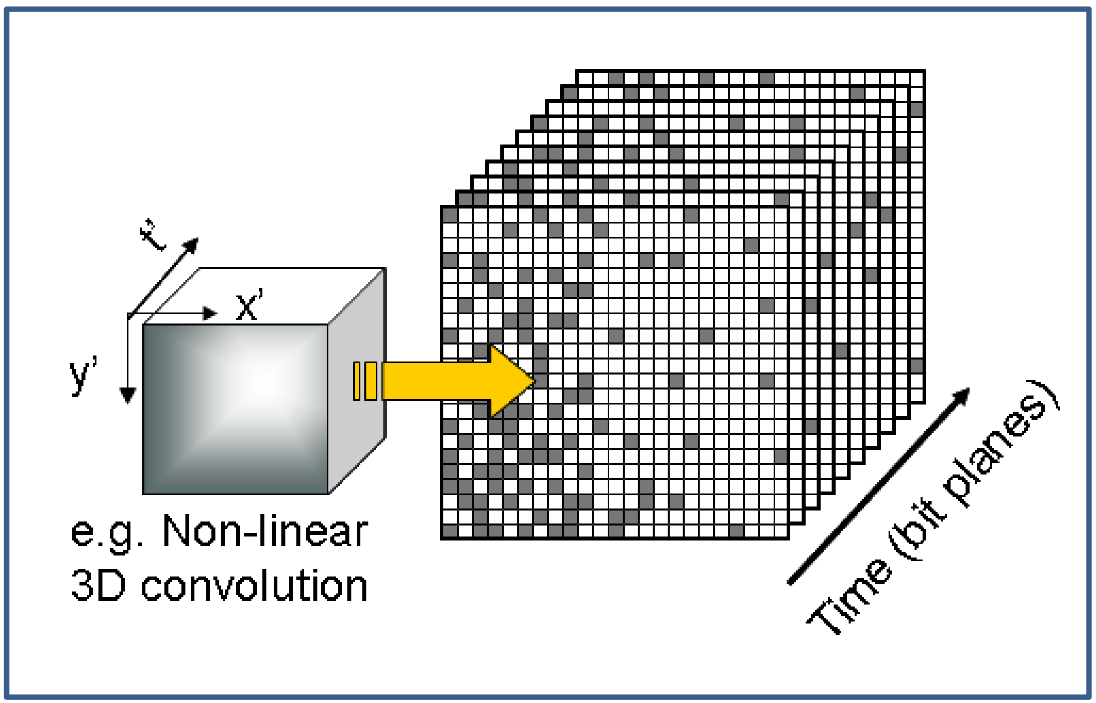
Quanta Image Sensor
A 3rd Generation Image Sensor?

Jot = specialized SDL pixel, sensitive to a single photoelectron with binary output, “0” for no photoelectron, “1” for at least one photoelectron.



Many jots are needed to create a single image pixel.

e.g. 16x16x16 = 4,096

A QIS might have 1G jots, read out at 1000 fields/sec or 0.5 Tbits/sec

See, for example: [Early Research Progress on Quanta Image Sensors](http://www.imagesensors.org/Past%20Workshops/2013%20Workshop/2013%20Papers/09-2_010_Fossum2_paper_revised.pdf)
http://www.imagesensors.org/Past%20Workshops/2013%20Workshop/2013%20Papers/09-2_010_Fossum2_paper_revised.pdf

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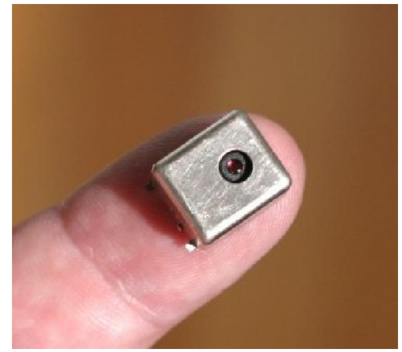
Summary

Invention and Promise

+15 years



From the Voyager Spacecraft

To a Fantastic Voyage

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